Technical Consideration and Impact of Converting Overhead Power Lines to Underground Power Cables

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By

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ABSTRACT

In the modern era, overhead transmission lines become irrelevant in the development of new cities as underground cables become mandatory. Nonetheless, it is crucial to understand overhead line technology in order to model the next generation of power networks, as most of the power networks still comprise overhead lines.

This field of study was exposed to methodical and thorough research; there is a common perspective which is shared amongst multinational power engineers and researchers, that underground transmission cabling bestows mammoth improvements & benefits when compared to its predecessor technology of overhead lines. However, the overhead technology is still dominating and is in use all over the world.

A comprehensive overview of the overhead power network along with its structure was dedicatedly elaborated on. For decades, power has been transmitted via a relatively low cost medium, commonly known as overhead lines. Since then, substantial transformations have been occurring to improve the reliability of overhead networks. A load flow technique is often employed to analyse and design an improved overhead power network. An overview of overhead power networks has also been extensively further explored in this research. Various conductors used in overhead lines have also been discussed.

As power loss is a major concern for transmission systems, an elaborative study on power losses in overhead lines has also been included.

This research investigates the technical trends of moving overhead lines to underground cables. It will discuss local & overseas experience and practices in this area, hence develop a proposal solution in accordance with the local conditions and regulation. New ideas are contributing in the development of underground system significantly, which enhance reliability, efficiency and lowering the cost of installation and maintenance. These ideas cover various phases of an underground system.

The objective of this research is to investigate the effect of new technology and practices on moving overhead lines to underground cables to improve occupational health and safety of personal, worker wellbeing (e.g. reduce risks of fatal accidents caused by cars hitting power poles) and reliability of electricity supply, as well as improve in the landscape.

Load flow analysis and other industrial based specialised software applications were utilised to investigate and develop various sub-transmission network models. The results obtained from the load flow analysis provided crucial information about the network.

The Victorian overhead power network has been examined in an attempt to efficiently design an underground network for Victoria. It has become mandatory for most modern cities worldwide to use underground power cables. This demonstrates that undergrounding has become economically and technologically feasible. Various advantages have been presented about underground cables in this chapter. However, there are significant challenges in the underground network as much as it has benefits. It is essential to carefully design and implement an underground power network.

This research contributed directly to the body of knowledge of power transmission and distribution systems. More specifically, it contributes to the overhead transmission lines undergrounding framework. The research produced reference guidelines for Victorian underground sub-transmission and distribution networks. The research made a unique technical contribution to the processes and procedures of undergrounding overhead power lines in Victoria as well as laid emphasis on portability aspects for potential adoption by other Australian states.

Declaration

"I, **Hassan Al-Khalidi**, declare that the PhD thesis entitled **Technical Consideration and Impact of Converting Overhead Power Lines to Underground Power Cables** is no more than 100,000 words in length including quotes and exclusive of tables, figures, appendices, bibliography, references and footnotes. This thesis contains no material that has been submitted previously, in whole or in part, for the award of any other academic degree or diploma. Except where otherwise indicated, this thesis is my own work".

Signature　　　　　　　　　　　　Date　14 / 08 / 2009

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List of Abbreviations

3D	three-Dimensional
AAAC	All Aluminium Alloy Conductor
AACSR	All Aluminium Alloy Conductor Steel Reinforced
ac	Alternating Current
ACAR	Aluminium Conductor Alloy Reinforced
ACSR	Aluminium-Conductor Steel-Reinforced
CBDs	Central Business Districts
CIE	Centre for International Economics
CMOS	Customer Minutes Off-Supply
dc	Direct Current
DNSP	Distribution Network Service Providers
DTS	Distributed Temperature Sensor
EDSA	Electrical power system Design Simulation and power Analytics
EHV	Extra High Voltage
EMF	Electric and Magnetic Fields
FODT	Fibre Optic Distributed Temperature
FPSC	Florida Public Service Commission
GDP	Gross Domestic Product
GIL	Gas Insulated Lines
GPIR	Ground-Penetrating Image Radar
HTS	High Temperature Superconductive
HV	High Voltage

IPART	Independent Pricing and Regulatory Tribunal
IPRT NSW	Independent Pricing and Regulatory Tribunal of New South Wales
JLARC	Joint Legislative Audit and Review Commission
LV	Low Voltage
MV	Medium Voltage
NGOs	Non-Government Organisations
NSW	New South Wales
ORNL	Oak Ridge National Lab
PSEG	Public Service Electric and Gas Company
PSS/E	Power System Simulator for Engineering
ROI	Return On Investment
SAIDI	System Average Interruption Duration Index
SAIDI	System Average Interruption Duration Index
SCC	State Corporation Commission
UAE	United Arab Emirates
WMTS	West Melbourne Terminal Station
XLPE	cross Linked Polyethylene

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1. H. Al-Khalidi & A. Kalam, “Enhancing Security of Power Transmission and Distribution Networks with underground cables” AUPEC 05, September 25-28, Hobart, Tasmania, Australia.

2. A. Kalam & H. Al-Khalidi, Victoria University, Australia, D Willén, Ultera, NKT Research, Denmark, “HTS Cable and its Anticipated Effects on Power Transmission Networks” IEE ACDC 2006, March 28th-31st, London, UK.

3. H. Al-Khalidi & A. Kalam, Victoria University, Australia, “The Impact of Underground Cables on Power Transmission and Distribution Networks” PECon 2006, November 28 and 29, Putra Jaya, Malaysia.

4. H. Al-Khalidi, A. Kalam, A. Maungthan Oo, Victoria University, Australia, “Investigation of aging devices in power network”, AUPEC 2006, December 10-19, Melbourne, Australia.

5. H. Al-Khalidi & A. Kalam, Victoria University, Australia, “Reduction in sub-transmission loss using underground power cables”, AUPEC 2008, December 14-17, Sydney, Australia.

6. A. Hadbah, A. Kalam, H. Al-Khalidi, Victoria University, Australia, “The subsequent security problems attributable to increasing interconnectivity of SCADA systems”, AUPEC 2008, December 14-17, Sydney, Australia.

7. H. Al-Khalidi & A. Kalam, Victoria University, Australia, “Savings in Transmission losses using Underground Cables Compared to Overhead Lines”, Transactions IEEE Pakistan, 2008, Pakistan.

CHAPTER 1

THESIS OVERVIEW

1.0 Introduction

In most countries around the world, the electricity sector has been liberalised forcing the electricity utilities to operate increasingly on commercial terms. Therefore, utilities must develop greater flexibility and security in terms of the supply and distribution of electricity, in the best and in the most effective environmentally-friendly way possible.

Replacing overhead lines with underground cables has been an increasing trend in Europe over the last decade. New cable technology combined with improved production processes and specifications of international testing has led to increased usage of underground cables [1]. Australia has fallen well behind other countries in such moves, mainly due to:

- Low density and demographics of Australian cities,
- High cost of underground systems, and
- Limited restrictions on using overhead lines.

Currently, due to greater public environmental awareness, restrictions on land usage, and higher demand for reliable and efficient electricity supply, a marked increase in the use of underground cable network is expected [2]. Frequent and major power outages cause many concerns. Some of these concerns relate to the security and reliability of the power systems. Ageing assets also play a big role in more frequent outages (most of the outages and disruptions usually occur on the distribution part of the power network) [3].

A typical overhead power network consists of power generation, transmission and distribution systems. Figure 1.1 shows the different stages of a typical overhead power network [4]. Distribution parts of the network contribute to most of the outages mainly due to their physical location close to natural vegetation e.g. trees, bushes etc. In Australia, trees are well known to cause the highest number of overhead outages [3].

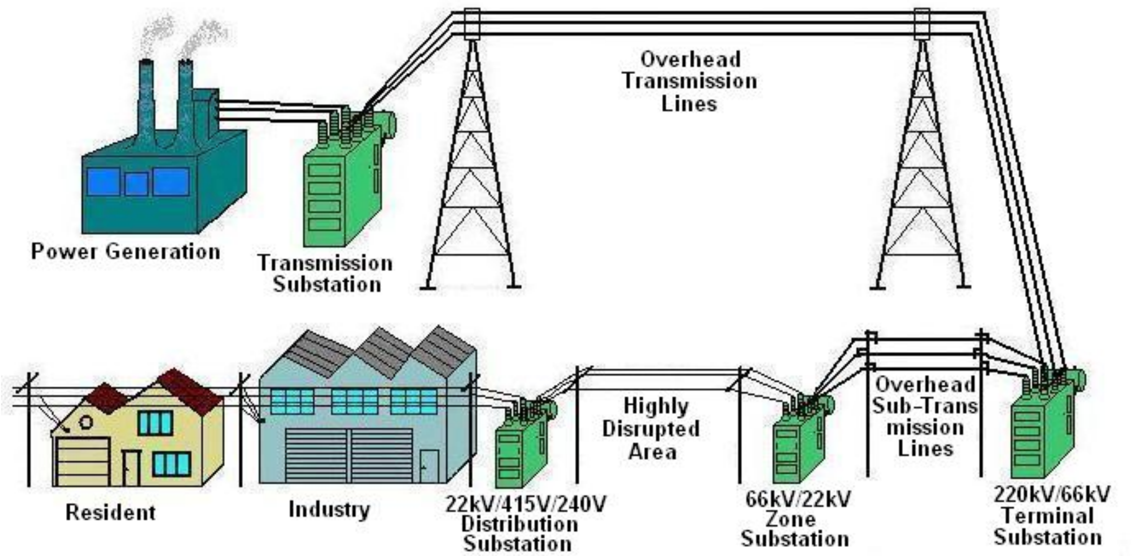


Figure 1.1: Power network with overhead transmission and distribution systems [4]

Various projects on the conversion of overhead lines to underground cables have been successfully carried out in many countries including Australia; most of these projects are designed to meet the local conditions of the cable route, yet many technical issues have been raised before and during project implementation. These issues will not only affect the delivery but the ongoing performance of the network. This research discusses the implications of this process and recommends scenarios for installing and maintaining underground cables to provide an efficient, reliable and economical electricity supply [3].

Although there are few researches and reports delivered on moving overhead lines to underground cables but not to the extent of investigating the implementation of new technology and its effect on electricity supply from efficiency, reliability and economic points of view. Research efforts discussed in references [1, 2, 5-9], have been continuing on the reliable movement of overhead power lines to underground cables. Most of these studies are independently prepared by individuals or research organisations for local government and councils. The foci of these studies have been mainly concentrated on specific local routes. Perhaps Putting Cables Underground Working Group report [9] was the only comprehensive report that covers putting overhead power lines underground in Australia, the report was relinquished in 1998 and it covers various aspect of the moving process but it did not discuss or presented the possibility of using new type of underground cables or using new techniques in placing power cables underground over the whole of Australia.

This thesis will investigates the various technical aspects of moving overhead lines to underground, which may include new way of placing underground cables in Victoria and adopting new cable technologies such as the new type of cross Linked Polyethylene (XLPE) cables and High Temperature Superconductive (HTS) cables. Most of these discussions are based on local and overseas experiences and in accordance with their local conditions and regulations.

The research in the thesis moves further with a pioneering project which investigates the technical aspects of converting overhead power lines to underground cables and their effects on the Victorian power network, in particular. The research also looks into the state of the art technology of HTS cables. It further explores ways of utilising this technology in combination with the existing ones by using XLPE cables so as to effectively and efficiently model the Victorian power network.

1.1 Motivation

The technical considerations for moving overhead networks to underground will have a great impact on the network in terms of safety and reliability. Analysing these considerations and employing new technologies will enhance the delivery of power in terms of safety and reliability. Improving the overall process of moving overhead lines to underground cables has always been the aim of utilities that plan or consider such a move. Earlier researches and contemporary studies [5, 7, 9, 10] show that underground cables can improve the efficiency and reliability of the electricity supply and reduce the risks of fatal accidents caused by cars hitting power poles as well as improve the landscape.

The main causes of overhead power transmission and distribution networks interruption are in fact unplanned external causes such as storms, bushfires, lightning, trees, animals, vehicle accidents and vandalism. Interruptions can also be caused by equipment and line or cable failure due to overload and ageing. However, overhead networks are much more vulnerable to external causes. In general, the maintenance works required for overhead networks are about twice the number as compared to those for underground power networks [3].

From the research on Victorian local distribution company, Citipower 2004 performance report [11], it was found that 70% of outages are attributed to the overhead network and 30% to the underground network. The average duration for an overhead fault is 50-55 minutes with an average duration of approximately 65 minutes for an underground fault. These figures are based on the System Average Interruption Duration Index (SAIDI). The higher duration for the underground network is a reflection of the time it takes to effect repairs.

For many decades, overhead lines had proven to be a reliable solution, both technically and economically. Back then, no other alternative and competitive system was available and there was little concern for the environmental aspect when planning and constructing a new electrical network. However, modern technology, with its continuous development of manufacturing and installation, makes it possible for underground systems to be competitive with overhead lines - technically, environmentally and economically. Whilst most overhead interruptions occur for a short period of time, mainly less than a second due to surge strikes, other permanent interruptions are usually caused by external factors [12].

As reliability and efficiency have become a major factor, moving overhead lines underground has become a vital concern to Victorian utilities. As part of a long term investigation into the improvement of infrastructure and safety of the Victorian electricity supply, a comprehensive study on moving overhead lines underground focusing on local environments is a necessity. It is therefore essential to have a technically reliable guide for the future implementation of underground power cables for the state, one with the potential to be utilised by other states as well.

1.2 Research methodologies and techniques

This research aims to study the existing overhead power network in Victoria and proposes a technical model for converting overhead power lines to underground. The modelling, design, implementation, simulation and development were carried out using Electrical power system Design Simulation and power Analytics (EDSA) - Paladin® and Power System Simulator for Engineering (PSS/E)®. The subsequent sections will provide detailed elaborations of the proposed methodologies and techniques. The methodologies, techniques and analysis details are as follows:

1.2.1 Analysis of the current power networks

Primary research was carried out to study the existing overhead power network along with the underground cables. Thorough research was further carried out to investigate local and overseas models of underground cables. This provides vital information on the various methods and techniques used in undergrounding cables. The literature survey further suggests that up until now, little or no research has been undertaken to analyse power networks incorporating new technologies, like HTS cables in order to convert overhead power lines to underground. Thus detailed research was carried out, in this study, on the load flow analysis of the power network so as to examine the current behavioural patterns of the network and to provide insight into how the network will appear in the future?

1.2.2 Investigation of the Victorian overhead power networks

Network parameters and performance results were obtained after comprehensive study of the Victorian overhead power networks. A section of the large power network was selected to effectively study the behaviour of the overall network as it was impossible to conduct the investigation over the whole Victorian power network. Network behaviour was investigated and an efficient underground cables model was developed.

1.2.3 Development and analysis of the Victorian overhead power networks

After obtaining overhead power network real data for the year 2007 on the selected section, an overhead network model was developed in order to perform further simulation. The results obtained from the simulation are based on normal operations or steady state conditions, and abnormal or at fault conditions. The results are used as a reference to compare the other setup and configuration results of the network.

1.2.4 Development and analysis of the Victorian overhead power networks with 2011 forecast

This model is similar to the overhead model as described in Section 1.2.3 with the exception of loading demand, moreover, a 2011 forecast load demand was used to determine the new overall load flow and identify the elements under stress in the network. Figure 1.2 shows Citipower zone substations loadings for 2007 and the forecast loadings of 2011 based on reference [11].

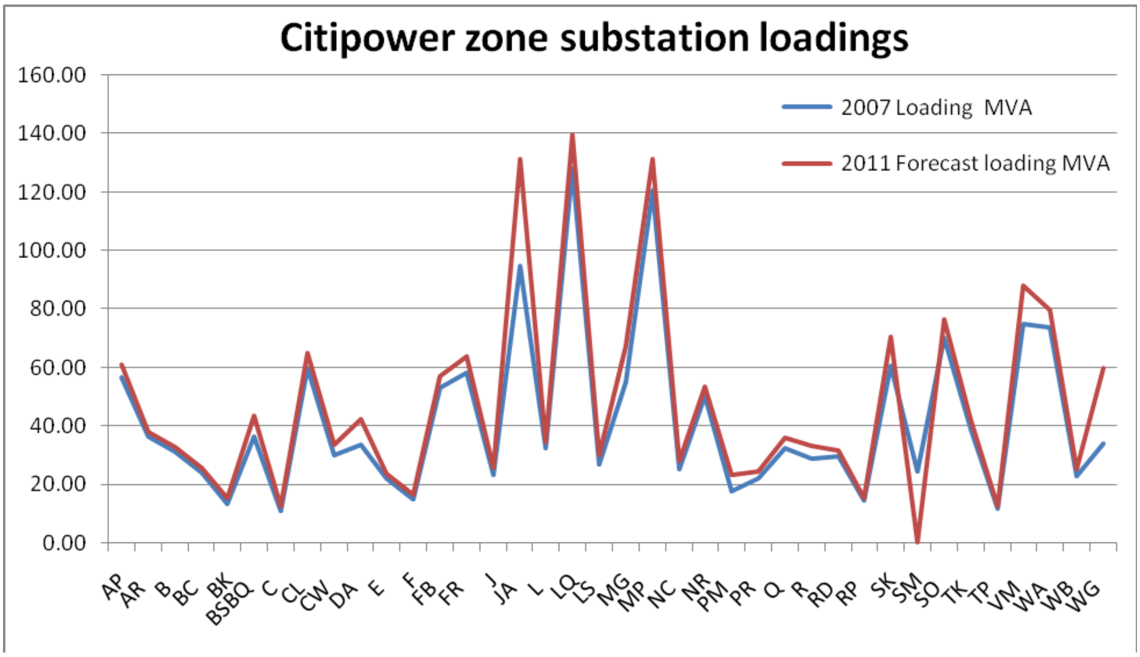


Figure 1.2: Citipower zone substation 2007 and forecast 2011 loadings [11]

1.2.5 Development and analysis of the Victorian underground power networks

An underground model was developed based on the overhead model with the exception of line parameters. In this scenario, XLPE cable parameters were used instead of traditional overhead line parameters.

In cases where the cable rating was less than the overhead line, cable selection was made based on either using a higher cable rating or using double circuits. All other network parameters were kept, where possible, to provide a smooth transition from an overhead to an underground model.

1.2.6 Development and analysis of the Victorian overhead power networks with 2011 forecast

This model is similar to the underground model as described in Section 1.2.5 with the exception of using 2011 loading demand. Furthermore, the 2011 load forecast which is used in this model was same as the loading forecast used in the 2011 forecast overhead model. This enables a comparison to be drawn between the two models, to determine the new overall load flow and to identify the elements under stress in the network in this model.

1.2.7 Development and analysis of the Victorian hybrid power networks

Two types of contemporary cable technologies were used in the development of the hybrid cables underground model. In this model, selected lengths of HTS cable were used in conjunction with XLPE cables that have approximately the same or higher rating as the underground model. The forecasted load demand for the year 2011 was deployed only in the development of the network with various configurations. One voltage level has been used to highlight the potential benefits of HTS cables in handling massive capacity and providing a great load flow venue in the network. The result of this model was then compared with the results obtained from a similar configuration for overhead and underground models.

1.2.8 Model optimisation of the Victorian underground power network

Based on the earlier developed models and their results, a final optimised underground network model was acquired for the Victorian power network. The highest priorities were given to the overall safety, efficiency and reliability which was incorporated in this model, as this is vital for any power network. The results obtained from this model demonstrate that a promising overall performance can be achieved for more reliable and flexible power flow in the network.

1.3 Originality of the Thesis

This research contributes directly to the knowledge of power system transmission and distribution. More specifically, it contributes to the knowledge of overhead lines and underground cables systems. The research produces reference guidelines for Victorian underground sub-transmission and distribution networks. The research makes a unique technical contribution to the process of moving overhead power lines to underground cables in Victoria and its potentialities for other Australian states.

This research contributes to knowledge in the following specific areas:

(1) in identifying the requirements of the technical aspect of moving overhead power lines to underground in Victoria, the proposed research is of immense benefit to the Victorian overhead sub-transmission and distribution network as it provides a technical proposal for migrating to the underground network;

(2) it investigates the implementation of a new cable technology and its effect on the electricity supply from the points of view of efficiency, reliability and economics;

(3) it presents a unique simulated model that produces a new voltage level of the new underground cable technology, HTS, to be used in small section of the Victorian power network;

(4) it reveals the intermingled implementation of the new cable technology, HTS, with the traditional underground cable technology, XLPE, and their simulated performance;

(5) it demonstrates a substantial reduction in the impact of the power network on the environment, which includes Electric and Magnetic Fields (EMF) and pollution in addition to the exponential improvement of public safety.

1.4 Objectives

This study develops a load flow model to pinpoint problems in existing overhead network and determine the effects of the underground cables on Victorian power network overall. After developing the flow model, load flow analysis is performed. The purpose of this flow analysis is to compute accurate steady-state voltages of all transmission and distribution sections in the network. Also it gives the necessary data needed to confidently plan improvements to existing network and justify the recommendation of this study.

1.5 Organisation of the Thesis

This thesis contains eight chapters and is organized as follows:

Chapter 1 provides a basic introduction to the research as well as the motivation behind this research. This chapter also includes the research methodologies and techniques and the contribution of this research to the knowledge of science and engineering.

Chapter 2 presents a literature review of recent developments in both overhead and underground transmission and distribution power networks. Furthermore, an investigation of the current overhead power network is presented in Chapter 3. Meanwhile, an elaboration on the development and analysis of the Victorian overhead power network model is covered in Chapter 4.

Underground cable technology and underground power networks are explored in Chapter 5, whereas Chapter 6 further emphasises the details of the development and analysis of the underground power network model.

An in-depth view of the development and analysis of an optimised model for Victoria's power network that consists of hybrid underground cable technologies is further portrayed in Chapter 7. Finally, conclusions and recommendations for future work are discussed in Chapter 8.

CHAPTER 2

LITERATURE REVIEW

2.0 Introduction

The purpose of this chapter is to provide the necessary background required for understanding the moving of overhead power lines to underground. It also highlights the concepts that relate to power network transmission and distribution media conversion as well as recent developments and research in this field. It further discusses the advantages and limitations of each concept, as well as their anticipated effects on the surroundings and the reliability of the power network overall.

To facilitate the understanding of present undergrounding research and practices, it is essential to investigate the early introduction of underground cables to the power network. While undergrounding overhead lines is not a new topic and has been going on for many decades, especially for low to medium voltage, in the past, the limited adoption of the conversion was mainly due to the high cost associated with underground cables and their installation, and limited environmental concerns related to the overhead lines [13].

Historically underground cables have been associated with high cost (approximately twice the cost of overhead lines), attributed to:

- cost of insulation and protection that underground cables require as they are normally laid about a meter or so below ground;
- the extra space required for cable connection;
- the limited utilisation of the easement due to the necessity to access the cable for repair and maintenance work;
- the requirement for reactive power compensation at 400kV at every 15 – 20 km due to ac current.

As a result of impedance difference, it is difficult to connect underground cables to an existing overhead network, and to resolve this issue, meshed networks have to be reconfigured and partially operated, which necessitates the requirement for power transformation increase, hence this incurs more investment costs [7].

However, since the early 70’s, the undergrounding of power cables started getting more attention, hence limited installation of high and extra high voltage began. Another factor that contributed to the acceleration of this process is the increased awareness, in public, about benefits gained on environmental and aesthetic grounds. In any case the high cost has always been the main reason for reluctance among utilities to remove overhead lines [13].

To highlight these, this chapter is arranged to provide deeper understanding of overhead and underground lines. Section 2.1 elaborates issues related to overhead power networks. Overhead transmission lines and their environmental effects are discussed in Section 2.2. As understanding the fundamentals is so critical in developing future power networks, a detailed elaboration is given in Section 2.3. The chapter is concluding remarks are in Section 2.4.

2.1 Issues with Power Networks

In recent years, there has been increasing interest in and attention to underground power networks, due to the belief, which is adapted by many public groups and research bodies around the world, that undergrounding will help tackle many of the issues surrounding power networks, such as reliability, environmental and health issues, just to name a few. Various research studies [5-7, 9, 10, 14, 15] were carried out by many public groups and research organizations around the world looking at a mixture of underground power network issues. Many of these researchers have identified various issues concerning power networks but due to the nature of this work which is only concerned about subtransmission and distribution networks, this thesis will thus, only target and examine a series of case studies that are relevant to the scope of the aforementioned issues in both underground and overhead networks.

2.1.1 Research literature on overhead and underground power networks

There have been various research studies and innovations carried out around the world in overhead line and underground cable. Europe leads the world in underground technologies. The following sub-sections discuss a range of research and findings conducted in Australia, Europe and United States.

a) Australian Scenario

Most of the Australian states are looking towards moving their overhead networks to underground. The local government of NSW is looking at various ways to increase underground lines both in urban and regional areas. The Minister for Energy asked the Independent Pricing and Regulatory Tribunal (IPART) to assess long term costs and benefits. Though there is a concern for the extremely high cost for undergrounding, nonetheless, due to the pressure from the public, the ministry is looking at ways to implement it in an economical way. Table 2.1 shows the percentage for both low and high voltage of underground cables in NSW [10].

Table 2.1: Percentage of cables underground in NSW [10]

	Whole of NSW underground		**Urban centres underground**	
	LV mains	**HV mains**	**LV mains**	**HV mains**
EnergyAustralia	23	36	25	63
Integral Energy	39	17	39	24
Country Energy	8	1	14	17
Australian Inland Energy	2	<1	-	-

An initiative from the NSW government, together with electricity companies and various community groups are currently investigating the likelihood of implementing a much wider undergrounding program. Specifically, it is considering undergrounding electricity lines carrying voltages of up to 22kV in urban and regional areas [10].

Local councils often need Distribution Network Service Providers (DNSP) to underground both low and high voltage distribution lines in newly developed areas. In these cases, developers of the area install the underground cabling and when completed, the ownership of these assets are transferred to the DNSP [10].

However, in already established suburban areas where overhead construction already exists, the DNSP or other parties such as local councils may initiate an undergrounding project. Whenever considering any undergrounding project, EnergyAustralia states: “undergrounding schemes are initiated in areas where supply reliability is below an acceptable standard, for example the Northern Beaches programs over the last 10 years”. Undergrounding low voltage cables only provides supply reliability improvements for customers in the immediate vicinity [10].

The Australian government initiated a study to address the community concerns to investigate the possibility of moving overhead power lines and telecommunication cables underground [9]. The common concerns about the overhead lines are:

- unsightly appearance;
- vulnerable to weather damages;
- risk of motor vehicle collision with the power poles, and
- risk of direct conductor contacts.

Undergrounding has been carried out in most central business districts and mandatory planning policies have been adopted by all federal states and territories that all new estate must have their power and telecommunication services underground. While there is no current enforcement encouraging the initiation of undergrounding, yet there are some obligatory measurements to underground communication cables within six months of undergrounding power lines [9].

The literature survey has revealed many reports on undergrounding [1, 5, 6, 8-10, 15-18] covering the technical, costing and regulatory aspects of undergrounding. Focusing on available practices and technologies, it estimates the total cost of undergrounding both power lines and telecommunication cables for urban and suburban Australia to be around $23.37 billion. This will cost a house hold an average of $5,516 for such a move, with a potential of reducing the cost by up to 35% over five years if a number of innovative ideas identified by reference [9] were implemented.

b) European Scenario

Reference [13] provides a report on undergrounding of electricity lines in Europe which summarises the current position of overhead lines and underground cables in Europe as per network voltage and presents its findings in three categories:

- Low to Medium: a distribution network which consists of low voltages (200 to 400V) and medium voltages (10 to 50kV)
- High: considered as distribution in some countries and transmission in others. This network consists of high voltages (60 to 150kV)
- Extra High: a main transmission network which consists of extra high voltages (220 to 400kV).

Table 2.2 highlights the lengths of the Low Voltage (LV) networks and the associated percentage of underground cables installed in a number of European countries in the period 1999 to 2000. This table shows that most of the countries covered by the report have achieved a high rate of underground cables compared to overhead lines in their low voltage networks.

Table 2.2: Status of European low voltage networks [13]

	km of network	Length of network (m/habitant)	Percentage underground
Netherlands	145,000	8.9	100 %
UK	377,000	6.4	81 %
Germany	926,000	11.3	75 %
Denmark	92,000	17.6	65 %
Belgium	108,000	10.6	44 %
Norway	185,000	41.3	38 %
Italy	709,000	12.1	30 %
France	632,000	10.5	27 %
Portugal	112,000	11.9	19 %
Spain	241,000	6.0	17 %
Austria	65,000	8.0	15 %

Table 2.3 demonstrates the Medium Voltage (MV) networks lengths and the percentage of underground cables installed in a number of European countries.

Table 2.3: Status of European medium voltage networks [13]

	km of network	Length of network (m/habitant)	Percentage underground
Netherlands	101,900	8.9	100 %
Belgium	65,000	6.4	85 %
UK	372,000	6.3	81 %
Germany	475,000	5.8	60 %
Denmark	55,000	10.5	59 %
Sweden	98,700	12.3	53 %
Italy	331,000	5.7	35 %
France	574,000	9.5	32 %
Norway	92,000	20.5	31 %
Spain	96,448	2.4	30 %
Portugal	58,000	6.1	16 %
Austria	57,000	7.0	15 %

Table 2.3 confirms what has already been mentioned in Table 2.2 that most of the countries are well advanced in adopting underground cable lines in their medium voltage networks.

Correspondingly Tables 2.4 and 2.5 disclose the High Voltage (HV) and Extra High Voltage (EHV) networks respectively, the lengths and the percentage of underground cables installed in a number of European countries. Although at high voltage, the undergrounding percentage rate varies somehow between low to medium, however countries like Netherlands, UK, Denmark and Switzerland scored a higher percentage especially in the extra high voltage networks compared to other countries listed in the Tables 2.4 – 2.5.

Table 2.4: Status of European high voltage network [13]

	High Voltage		
	60-90-110-150 kV		
	km of network	km of Underground	%
Denmark	8,005	1,673	20.9
UK	25,825	3,789	14.8
Netherlands	6,457	905	14.0
Switzerland	6,080	680	11.2
Germany	76,349	4,740	8.2
Belgium	5,172	396	7.6
France	50,513	1,984	3.9
Portugal	9,311	258	3.8
Norway	19,825	624	3.2
Italy	36,677	449	1.2

Table 2.5: Status of European extra high voltage network [13]

	Extra High Voltage					
	220-275 kV			380-400 kV		
	km of network	km of Underground	%	km of network	km of Underground	%
Denmark	5,578	375	6.5			
UK	3,029	71	2.3	788	11	1.4
France	27,890	813	2.9	20,794	2.5	0.01
Italy	13,641	387	2.8	9,751	9	0.1
Norway	6,049	64	1.1	2,316	36	1.8
Netherlands	648	6	0.9	1,979	0.4	0.02
Germany	21,545	35	0.2	18,314	62	0.3
Switzerland	5,822	22	0.4	1,800	-	0
Portugal	4,409	-	0	1,234	-	-
Belgium	267	-	0	883	-	0

It is clearly noted that HV and EHV underground sections of the network are only constructed in urban or semi urban areas and in areas with environment or historic restrictions. Therefore, the high cost of undergrounding cables in such areas compared to overhead lines reinforces the conclusion outlined before which is that the percentage of undergrounding at high voltage levels in the European countries is still low [13].

Various countries around the globe have always had the aspiration of upgrading their overhead power lines, telephone lines, cable TV lines, and optical cables to underground. Jey et al. [19] remarks that many power consumers around the world find it hard to believe that, with 21st technologies controlling 21st century economies, electrical engineers are still relying on 19th century wooden poles. Utilities and cable companies dealing with sewer, gas and water are digging up streets all year round. This leads to a fair question directed at the public officials: why are they not implementing a policy of utility corridors for burying all services together? [19].

Many customers and end users who are longing for infinite bandwidth already have sanitary sewers, storm drains, waterlines, hot water pipes and natural gas lines reaching their premises. It makes all the sense in the world to build the power cables in these existing rights of way on conduits, ducts, sanitary sewers, storm drains, water mains, hot water pipes, and gas pipes. Building underground power cables will meet customers' basic needs that they have forever been longing for and they should always remember that paying undue attention to a return on their investment so early in the process is an unproductive exercise [19].

When was there ever a time when the leaders in charge of sewers, drinking water lines, hot water pipes, electricity grids, hydropower stations, roads, bridges, transportation systems, hospitals, museums, parks, and opera halls, were questioned: as to what the return on the investment has been for the past century? Would customers have enjoyed the same quality of life without these services? Civil engineers are in an ideal position to guide these industries with their unique talents in planning, execution, and serving their commitment [19].

Jey et al. [19] has provided a comprehensive global survey about moving overhead lines around the world. The result of this study, which is given in Table 2.6, indicates that most countries around the world would prefer to move their overhead power lines underground.

Although, they have considerably lower Gross Domestic Product (GDP) ranking, yet countries such as Denmark, Germany, Holland, Hong Kong, Iceland, Israel, Singapore, Sweden, Switzerland and United Arab Emirates (UAE) just to name a few [19], have already converted all or most of their overhead lines underground.

Table 2.6: Global power transmission and distribution practices [19]

Country	Dist. Volt. (kV)	Dist. Line Length (km)	% U/G	Trans. Volt. (kV)	Trans. line length (km)	% U/G for trans.	Population (Million)	Size (sq km)
Algeria	5.5 to 30	172,424		60, to 500	11,912		28.7	2,381,740
Argentina	6.5 to 66			132 to 500	32,447		35	2,766,890
Australia	11 to 44	314,805	6	66 to 500	75,195		20.0	7,617,930
Austria	1 to 36			110 to 380	9,611	7	8.2	82,738
Belgium	.23 to 29	176,756	64	30 to 380	8,717	32	10.3	30,230
Brazil	.22 to 34.5	4,000,000	1	138 to 750	170,000	0	182.0	8,456,510
Canada					155,328		32.2	9,220,970
Chile	6.6 to 66			110 to 500	10,561		15.7	748,800
China	.5 to 220	7,300,000	20	35 to 500	163,300		1,287	9,326,410
Croatia	.4 to 35	121,465	24	110 to 400	7,236		4.4	56,414
Czech	.4 to 35	97,000	24	110 to 400	6,520	1	4.3	56,600
Denmark	10 to 24	59,299	59	30 to 400	14,481	21	5.4	42,394
Egypt	3 to 30	242,346		66 to 500	18,495		74.8	995,950
Estonia	6 to	61,159		110,330	4,980		1.5	45,000
Finland	.23 to 110	354,243	21	110 to 400	21,526		5.2	305,470
France	.22 to 20	1,206,000	29	220 to 400	100,000	3	60.0	545,630
Germany	.4-110	1,550,800	72	220to 380	36,800	0.5	82.5	357,026
Greece	<150	170,000		66 to 400	10,000		10.7	130,800
Holland	1 to 30	249,936	100	50 to 380	12,352	31	16.0	33,883
Hong Kong	.22 to 33	17,000	85	132 to 400	1,600	50	7.4	1,042
Hungary	10 to 120	65,800	16	120 to 750	3,900	1	10.2	92,030
Iceland	1 to 24	8,132	100	110 to 400	1,917		0.3	106,000
India	2.2 to 15	5,084,126		32 to 400	35,790		945.0	3,287,590
Iran	6 to	433,487		63 to	60,516		62.5	1,648,000

	33			400				
Ireland	5 to 38	80,000		110 to 400	5,800		3.6	70,280
Israel	13.2 to 33	21,140	33	161 to 400	4,800	2	6.0	20,330
Italy	.22 to 20	1,031,000		132 to 400	65,863	2	58.0	294,020
Japan	.1 to 6.6	1,274,664	5	22 to 500	165,667	12	127.0	374,744
Jordan	.4 to 33	35,477	16	132,400	3,037		5.3	92,300
Korea (S)	6.6 to 22.9	366,983	10	66 to 765	27,937	7	48.0	98,190
Mexico	2.4 to 85	622,059	2	115 to 400	72,000	1	105.0	1,923,040
Morocco	5.5 to 30	28,769		60 to 225	13,609		31.7	446,300
New Zealand	11 to 65	160,739		110 to 350	17,667	12	4.0	268,680
Norway	1 to 72	200,000		60 to 420	18,246		4.5	307,860
Oman	.433 to 33	15,616		33 to 132	6,580		2.8	212,460
Poland	15 to110	644,900		220 to 750	12,610		38.6	304,465
Portugal	1 to 130	187,272		150 to 400	11,918		10.1	91,951
Saudi	13.8 to 33	109,000	35	66 to 380	19,000		24.0	1,960,582
Singapore	.4 to 22		100	66 to 400		100	4.6	683
Slovenia	.4 to 35	57,600	43	110 to 400	2,600	0	2.0	20,000
S. Africa	22 to 165	256,384		220 to 765	26,443		42.8	1,219,912
Spain	.38 to 132	550,000	23	220,400	32,240	1	40.2	504,750
Sweden	.4 to 145		80	132 to 400	30,665		9.0	410,934
Swiss	1 to 20	250,000	80	60 to 400	20,000		7.3	39,770
Tunisia	10 to 30	66,500		90 to 225	3,150		9.0	163,610
Turkey	6.3 to 34.5			66 to 380			68.0	770,760
UAE	11 to 33		80	132 to 400	1,600	10	4.0	82,880
UK	.23 to 132	615,907	60	275,400	13,912	5	60.0	241,590
USA	<69	4,793,656	8	69 to 765	607,494	0.4	290.0	9,158,960
Yugoslav	3.8 to 35	147,072		110 to 400	10,868		10.6	102,173
Venezuela	.12 to 69			115-765	22,212		24.0	912,050

c) North American Scenario

InfraSource Technology, which is a leading provider of infrastructure construction services for electric power, gas, telecommunications, and energy intensive industries in the United States, has compiled an inclusive report on undergrounding studies in Florida – US [5]. This report stated that overhead construction is a common practice in Florida, however, privately owned utilities have to have a mechanism whereby customers can choose to move their existing overhead services to underground, which of course comes at an additional cost.

Brown [5], InfraSource has initiated a case study to investigate the implication of undergrounding the existing overheard infrastructure in Florida as a response to the order of the Florida Public Service Commission, which instructed each privately-owned utility to establish a collaborative research plan to investigate possible means of enhancing and developing a storm proof power network. The extent of this project is basically focused on hurricanes and its effects on the performance of underground power networks as well as the advantages of underground power networks in normal wind-free circumstances.

Maney [20] shows how the traditional practice, by power utilities, is to go overhead for all voltages, which is due to the fact that utilities are accustomed to focus on direct costs such as Return On Investment (ROI), maintenance and operational costs. However, they seem to deviate from this practice in two instances: when it is more economically viable to go underground, or when customers - in newly developed housing estates - request underground and will agree to bear the extra cost associated with undergrounding.

Although, using underground distribution lines is a very common practice in the U.S., it is a different story when it comes to high-voltage transmission lines. In the state of Virginia, underground lines make up a very small portion of transmission lines. On the other hand, Europe is known for its extensive use of undergrounding, though it is not yet considered as common practice [16].

In general, underground transmission lines are more expensive to install than overhead lines. The cost of underground lines tends to bloat due to the high cost of materials such as cables and insulating fluid. Overhead lines insulation is achieved by using a free to use insulator “Air”, while underground cables’ thickness, which is required to provide appropriate insulation, exponentially adds to the cost of undergrounding transmission [16].

2.1.2 Benefits and limitation of underground power networks

According to Independent Pricing and Regulatory Tribunal of New South Wales (IPRT NSW) [10], the benefits of undergrounding, which may accrue to the wider community, are those comprising the external costs of overhead networks. These costs (or negative externalities) can be seen as a by-product of having power supplied by overhead electricity cables. They include:

- actual or perceived impacts on the visual amenity of local environments;

- motor vehicle accidents that involve collisions with electricity poles;
- the costs to consumers of power outages that result from storm damage to overhead lines.

External costs are much less tangible than the avoided costs which accrue to DNSP, and the value of avoiding many of them by placing overhead infrastructure underground cannot be quantified in any absolute sense. Based on a Centre for International Economics (CIE) assessment, the Tribunal estimates the value of the quantifiable benefits of the proposed program to range between around $535 and $625 million over 40 years in net present value terms, or $350-$400 per connection or lead in. This is equivalent to around 40% of the estimated cost of the proposed undergrounding program, assuming an optimally planned approach is used [10].

This project had several quantifiable benefits that were reported such as:

- decrease in costs associated with motor vehicle accidents that involve collisions with power poles;
- improvement in energy supply reliability;
- elimination of overhead network maintenance costs;
- increase in DNSP revenues due to substantial decrease in outages associated with overhead network losses.

These benefits and estimated value over the project phase along a period of 40 years in net present value terms have been highlighted in Table 2.7 [10].

Table 2.7: Potential benefits from undergrounding cables across NSW [10]

Item	Present value over project span
Reduction in motor vehicle accident costs	$230-$260 million
Improvements in reliability of supply	$55-$115 million
Reduction in maintenance costs	$105 million
Reduction in revenue losses	$145 million
TOTAL	$535-$625 million
Benefits per lead in	$350-$400
Benefits as a proportion of optimised system costs	40 per cent

Furthermore, this project has also reported some unquantifiable benefits which include, but are not restricted to the following [10]:

- improvement of public amenity associated with less overhead power lines outside residence and commercial areas;
- improvement of utilities workplaces safety;
- better landscaping and vegetation management;
- improvement of public safety with the elimination of overhead lines which reduces accidents associated with contacting overhead lines;
- potential of improving health risk of electromagnetic fields.

The working group estimates that the quantifiable benefits represent around 10% of the total cost. There are some other indirect advantages such as beautifying landscapes allowing more trees to be planted and the likelihood of property value improvement. The eventual direct advantages of undergrounding include [9]:

- decrease in motor vehicle collisions with poles accidents;
- saving in transmission losses;
- savings in power losses due to overhead outages;
- savings in maintenance costs;
- savings in tree pruning costs;
- potential of increasing property values;
- decline in electrocutions;
- reduction in greenhouse gas emissions (due to reduced transmission losses);
- lowering of bushfire risks.

The most direct benefit noticed by the study was the decrease in motor vehicle collisions that were estimated to cost between $105 and $160 million per year. Table 2.8 summarises the best estimate of the direct benefits found by the study [9].

Table 2.8: Annual undergrounding benefits indicative assortment [9]

Type of benefit	Annual benefits (a) ($ per km of line)	
	Minimum	**Maximum**
Reduced motor vehicle accidents	1 358	2 793
Maintenance costs.	18	1 531
Tree trimming	35	1 120
Reduced transmission losses	0	292
Total	1 411	5 736

Jey et al. [19], provided a comprehensive global survey about moving overhead lines around the world. The results of this study which is given in Table 2.5 indicate that most countries around the world would prefer to move their overhead power lines underground due to the following factors:

- Increased public environmental awareness;
- City planning with increased population;
- Power frequent outage cost;
- Reduced maintenance cost;
- High transmission loss;
- Electrocution prevention;
- Bushfire risks reduction;
- Reduced severity of auto accidents;
- Reduction in cost of tree pruning;
- Improved amenities;
- Improved real estate value.

Some of the highlighted advantages of undergrounding include but are not limited to:

- Reliability effects, private and public advantages;
- Reduction of outages and changes in restoration times;
- Maintenance and operation cost reduction;
- Reduced vegetation management costs.

In addition, this case study has conducted a survey which explored the possibility of developing a sound and realistic standard which can be used to evaluate and measure the advantages, limitations and costs of undergrounding overheard power networks.

Finally, this study has concluded that the Florida Public Service Commission (FPSC) along with many other utilities in Florida are keen on converting all of their overhead power networks to underground to achieve optimum performance and a better fault tolerance and improved amenities as well as a storm resilient power grid. Furthermore, it finds that failure rates and reliability modelling of the power network during storms, as functions of storm strength, have not been attended to by any literature, whether academic or industrial, up until year 2006. It also has emphasised the non quantifiable benefits of undergrounding, such as the added value to real estate and the overall improved landscape which ultimately leads to the increased GDP value of the city [5].

Transmission lines, as many property valuation surveys suggest, have a negative impact on property values. Joint Legislative Audit and Review Commission (JLARC) in reference [16] has reported that this can be as much as 15%. Furthermore, the author founds that the decrease of property values varied between 3-5% among single family residences near Henrico's transmission lines in Virginia, US. They added that the two main factors that influence the decrease in these property values are: the perception that transmission lines are unpleasant to the eye as well as the belief of some people that EMF can cause health concerns. It is only fair to mention, that amenities such as freeways, airports or landfills may decrease property values just as much, if not more, than transmission lines.

However, despite earlier given factors, when most power utilities are asked why they don't move their overhead lines underground, their response and prime excuse would be the high cost associated with this technology and the already highly congested underground corridors: with social utilities such as water pipes, sewers, gas mains and telephones [19].

Johnson [15] argues that undergrounding overhead lines requires a hefty bill to be paid, due to the estimated cost of up to 10 times what it costs to install overhead power lines. When compared to overhead power systems, underground power systems tend to have fewer outages, but these outages are usually much longer than those of their overhead counterparts. In addition, underground power systems are still susceptible to outages during extreme weather conditions. Furthermore, Johnson [15] strongly disputes that undergrounding adds no substantial benefits to the network's reliability, which makes paying an enormous price tag totally unacceptable for such an exercise.

On the other hand, Johnson [15] believes some ad-hoc benefits of undergrounding do exist such as improved aesthetics. Despite the unquantifiable benefits of undergrounding, many communities are still demanding the removal of their power lines because of the real and substantial socio-economical benefits that are felt and harvested by improved aesthetics, which in turn is echoed through the improved tourism figures and many more cascading advantages. Therefore, the justification of undergrounding projects can not be evaluated using the traditional economical matrices alone. Thus, giant obstacles are often placed in front of public decision makers when assigning budgets towards the aesthetic benefits of undergrounding.

2.1.3 Power outages nationally and internationally

Wild weather conditions have always renewed the demand for retrofitting the overhead network to underground. After all, underground cables are mostly immune from the weather elements that cause most of the outages in the overhead network and they are less susceptive to the damage caused, for instance, by wind, storm, ice or other wild weather conditions.

There have been many concerns expressed by various community groups in New South Wales (NSW) - Australia for overhead lines. Power customers are worried about overhead lines during storms and bush fires as they are prone to major service disruptions. Another concern shown by the general public for overhead lines is the aesthetic look making them very messy and unsafe [10].

Overhead power lines have become a concern for many members of the community in NSW. Particularly, the community is concerned about the potential for overhead lines to be damaged in storms and bushfires, and power outages resulting from this damage. The estimated ROI benefit is equivalent to around 40% of the cost for the proposed undergrounding project [10].

In December 1999, severe storms destroyed large parts of the French power network and as a consequence many power blackouts were encountered. In the aftermath to this event, French authorities made the decision of undergrounding many critical parts of the network to improve reliability and secure power supply during abnormal weather conditions. There are other similar cases in the European countries where extreme weather conditions have fast-tracked undergrounding the overhead power network [13].

In the wake of the worst ice storm that occurred in the eastern Canadian region around 10 years ago, HydroQubec decided to move their overhead lines underground due to the sheer damage and the severity of the consequences of this mighty storm which caused a major outage for prolonged periods of time [19].

Mother Nature will always continue to expose the vulnerabilities of overhead power grids and the aforementioned cases of natural disasters are just some of many that have taken place around the world. Therefore, one feels compelled to mention more of these disasters: like the 14th August 2003 blackout due to transmission line overheating and sagging on a tree, this blackout affected 12 American and Canadian states and provinces with an estimated US$14 billion of economical loss. A similar scenario occurred in the same year on the 28th of September in Austria, France, Italy and Slovenia where an outage affected 60 million people attributed to a tree flashover [19].

In the Canadian province of Ontario, power outages on overhead lines happen on a regular basis due to the harsh windy weather – wind faster than 80kph - pattern. Surely, this sends a negative message to the general public in Ontario and illustrates a clear negligence on behalf of the utilities, which are responsible for providing a reliable power system. In addition, the population of that region almost believes that these utilities did not have the interest of the customers as their first priority [19].

In 1994, Maney [20] predicted that by 2000 many utilities are expected to underground their distribution network. He claimed that the drives for such moves include:

- improved high quality underground cables;

- advanced techniques used in both detecting underground faults and installing underground cables, for instance, direct burial or directional boring.

Overhead lines have always been the preferred short term investment by the utilities to meet their stockholders' profit expectation, as overhead lines have less complexity and overall easier installation and maintenance than underground cables. Basically, overhead lines have always used the same technology: bare wires insulated by ceramic insulators on the poles and air used as insulation medium between wires. Nevertheless, the costs of recovering overhead networks after storm damages are conceded to the customers [20].

Unlike overhead lines, underground cables do not have the advantage of air ventilation; therefore, they have to be installed prudently to be able to dissipate the heat generated during operation. Heat dissipation in underground cables has a great impact on the cable performance and its operating life span. When overhead lines overheat they can sag and their rating might decline, meanwhile when a cable overheats repeatedly its insulation might get damaged which in turn leads to insulation breakage and ultimately a fault may occur. Thus, planning engineers must exercise extra precision and skill when designing an underground power network and take into consideration the cable heat transfer problem for continued loading [20].

Further to the aforementioned reasons, power utilities do not seem keen on undergrounding because of the fact that there are no legal obligations to force them to consider societal costs and of course there is no competition amongst the utilities to foster such a move [20].

Furthermore, natural disasters were behind the outage which affected over 10 million people on the American east coast as a result of Hurricane Isabel and its sheer destructive power. As a result a major power company in that region has incurred a cost of US$128 million to restore power supply to the affected area. Eventually, this cost was recovered one way or another and this was felt by the average American customer [19].

In a survey completed in the late 1990s, it was stated that on average an American consumer will experience more than 40 power outages a year. It did not stop there: the matter has been getting worse especially in the past 6 years [19].

A privately owned power utility has mentioned, in their annual report for 2003, that on average they had one outage a day somewhere in their power grid; the majority of these outages were attributed to severe weather, auto accidents and animals contacting the wires [19].

Power outages have enormous affects on societies and their main infrastructures. Loss of power means shortage in:

- drinking water supply;
- heating or cooling;
- sewage treatment;
- interrupted transportation, communications and fire-fighting capability;
- ability to evacuate high rise buildings in a timely manner, and many other service disruptions.

Faults related to auto accidents cost the Australian utilities in excess of $250 million per year while the American counterparts pay in excess of US$5 billion per year [19].

Maney [20], emphasises the brutal force of natural and weather related losses such as ice, hail and other storms, e.g. Northwest Florida suffered from the famous Alberto tropical storm in 1994 which caused a power outage that affected over 1800 customers for several days. Similarly, in 1994 the Richmond, VA, Times Dispatch reported five storms that were responsible for leaving hundreds of thousands of customers out of power for weeks at a time. In addition to the apparent cost of power outages, end customers such as retailers, restaurants and food stores suffer from a massive loss due to the spoiled food supplies in their freezers.

Another devastating effect of hurricanes was experienced in Florida due to Hurricane Andrew: during the aftermath of this natural catastrophe it was initially estimated that 1.4 million customers were left in the dark, 2 weeks later a local paper reported that 97,000 were still waiting for their power to be reconnected. Furthermore, it was estimated that over 60% of overhead powerlines and 3% of underground cables needed replacement. This clearly indicates the advantage of underground over overhead in stormy and severe weather conditions [20].

In 2005 after hurricane Katrina, which ripped through New Orleans and destroyed power systems throughout Louisiana and Mississippi, hurricane Rita caused yet more destruction and mayhem not only across these regions but extended to Arkansas and Texas. Entergy, the regional power supplier, recorded outages to more than 1 million customers following Katrina as well as more than 766,000 customers suffering black outs because of Rita. Entergy claimed to have restored power to more than 75% of the affected regions in less than three weeks when Rita first incapacitated the power supply to these regions. However, more than 150,000 of those affected by Katrina were still in the dark due to widespread flooding and landslides.

Entergy claimed to have employed over 10,000 contractors and crewmen to carry out maintenance work on both hurricanes Katrina and Rita’s affected sites. Rita knocked down more than 6,120kms of transmission lines when it reached its full destruction strength. Figure 2.1 shows the devastating effects of hurricane Katrina [21].

Figure 2.1: The devastating effects of wild weather – hurricane Katrina 2005 [21]

Although, underground transmission lines are less inclined to be affected by the elements such as lightning, high winds and storms, the advantage of having them can be sometimes over emphasised. Virginia's State Corporation Commission (SCC) claimed that almost all the damage that occurs to overhead lines usually takes place around the distribution level rather than the transmission level. According to SCC, overhead lines are preferable for reliability reasons, as underground lines have proven to require longer repair times than their overhead counterparts [16].

2.1.4 Environmental Issues concerning power networks

The relationship between overhead lines and underground cables has been widely investigated in reference [16]: a study was carried out by JLARC about the policies and criteria used by SCC. This study evaluated the feasibility of moving overhead transmission lines underground in the state, including costs and the impact of such a move on the property values. The study concluded that the technologies are readily available but it would be an expensive exercise in average priced-areas (4 to 10 times more expensive than overhead). However, it could be considered a cheap exercise, in fact cheaper than overhead lines when the land value is extremely high because it would then require smaller rights-of-way.

SCC has demanded that utilities address potential environmental impacts in their transmission line applications. Residential property owners, environmental groups, and local governments have often promoted underground construction as the preferred way to address concerns regarding the environmental impact of transmission lines. However, the SCC did not find that undergrounding was necessary in order to diminish these concerns and undergrounding was only ordered where a viable overhead right-of-way did not exist or where the party requesting the undergrounding agreed to wear the cost [16].

Another worthwhile shining example of underground power cables would be the Salt River project in Phoenix, Arizona, where all services moved underground; they have been determined to move more than 100 km of overhead cables underground every year [19].

Further to the aspects discussed earlier, the negative impact of overhead may include the use of wood poles which are treated with highly toxic chemicals that could leak into the grounds and hence affect the surrounding soil and the food chain which is grown in the area. Thus, the move to underground sees a significant reduction in the use of these poles. The extent of the environmental damage which is caused by these toxic poles does not stop at contaminated soils, it reaches beyond that as it is evident in Florida, where it was reported to FPSC that 20 public and private wells including the main well region of Miami city were contaminated due to the high concentration of the toxic chemicals which were released by the wood pole treatment plants. This massive accumulation of mutagenic compounds has adverse effects on the population's health and well being, which are yet to be determined by the experts [20].

The public seems to be more aware of the obvious advantages that undergrounding can bring with it, but the lack of official support from the relevant authorities has left the private citizen no choice but to form activists groups. The public believes that through court actions they will be able to collect a reasonable amount of data for analysis and to further support their case against the giant utilities, which are to date still reluctant to engage directly with the community to solve this problem. Of course, having a national policy would be seen as a victory to these groups and would enable the public to reap the rewards of such policy by forcing utilities to take action towards more realistic in-depth cost-benefit analysis of undergrounding urban power lines [20].

2.1.5 Health and safety issues concerning power networks

In the United States, the growing demand is clearly exhibited by motivated activists who constantly rally and lobby giant utilities and government bodies when they propose new overhead powerlines. In other words, these organised groups argue that they are rejecting the new overhead powerlines on the basis of health issues due to the exposure to electromagnetic fields as well as their effect on property devaluation. Some of these non-government organisations (NGOs) which are dedicated to achieving a safer power delivery through undergrounding include:

- The Electromagnetic Radiation Alliance (national and international)
- Citizens Opposed to Unsafe Power (PA)
- Alliance to Limit Electromagnetic Radiation Today (CT)
- Coalition for Safe Electric Power (VA)
- Parents Against an Unsafe Environment (PA)
- Michigan Safe Energy Fund (MI)
- Concerned Citizens for Power Line Safety (FL)
- Citizens for Power Lines Underground etc.

In reference [20], the authors believe that power utilities are not admitting in public about the existence of safer methods of power delivery, such as undergrounding, merely for legal reasons as they do not wish to end up defending an overwhelming number of potential lawsuits in court rooms across the country.

The rising concern about EMF generated by transmission lines is often reported as a main cause of childhood leukaemia. However, rigorous scientific research has been unable to determine if there is a fundamental link between EMF and cancer, particularly leukaemia, nevertheless, statistically frequent correlation has been observed[16].

2.2 Conclusion

This chapter provided the necessary background in the transition of overhead lines to underground for distribution and transmission power networks. Both benefits and limitations have been explored for underground and overhead technologies. Various cable technologies have also been extensively discussed. From the extensive research carried out, it is agreed by the multinational power engineers and researchers, that underground transmission cabling provides enormous benefits compared to its predecessor technology of overhead lines. However, the overhead technology is still dominating and is in use all over the world. The next chapter dedicatedly elaborates the comprehensive overview of overhead power networks along with its structure.

CHAPTER 3

OVERHEAD POWER NETWORKS

3.0 Introduction

The literature and research findings of power network technologies were presented in Chapter 2. The comprehensive overview of the overhead power network and its structure is presented in Section 3.1. The reliability issues of the power network were examined by investigating a section of Melbourne's overhead power network which is presented in Section 3.2. As there are various types of conductors available in the market, Section 3.4 elaborates many types of overhead power line conductors to compare with the underground cables. Load flow analysis and power losses in overhead lines are presented in Sections 3.5 and 3.6 respectively as understanding this analysis is vital to comprehend various models developed which will be discussed in the forthcoming chapters. Concluding remarks are provided in the final section of this chapter.

3.1 Overhead Power Network Overview

Overhead lines employ a free and natural insulation medium - Air - to insulate long exposed conductors. Overhead lines are almost always favoured over their much more expensive counterpart, underground cables, due to the unavailability of inexpensive alternatives to supply electricity, especially at high voltage levels [22].

In general, costs of both construction types (overhead and underground) are greatly affected by many factors, such as, material and labour as well as soil and topographical factors. However, in certain circumstances underground cables tend to be favoured over overhead lines due to the route condition. For instance, constructing an underground cable in a green field area is more feasible and cost justifiable than constructing overhead lines [22].

Overhead conductors are governed with strict rules and regulations, such as clearance from ground and nearby buildings, including easement and impact of EMF as well as swing of conductors to allow wind blowing across the lines at specific speeds. Usually, the line height is determined by the maximum conductors' sag between towers. When designing overhead power grids, engineers should consider these factors as well as extreme weather conditions with high current loading in hot temperatures or cold weather conditions with low load and their implication for conductor's stress levels [22].

The common type of overhead line is an Aluminium-Conductor Steel-Reinforced (ACSR) conductor, which is used usually for LV and MV distribution networks that require small conductor sizes. This type of overhead line is fabricated by winding Aluminium wires that conduct the current around a core of steel strands in which they enforce the mechanical strength of the entire conductor. Overhead lines require some sort of support to keep them off the ground and have clearance required for their operation. They can be hung on a selection of types of supports: most obvious for LV and MV are wooden, concrete or steel poles; meanwhile for higher voltages, steel towers are the typical construction [22].

In addition to double-sided line clearance, many types of insulated overhead lines are commonly used in bushy topography to prevent physical contact with trees or to avoid conductor clashing which leads to a short circuit and can instigate a fault. Therefore, insulated overhead lines are considered safer than exposed lines [22].

In the UK and the USA, individually insulated conductors are commonly used for distribution, while in some parts of Europe, such as France and Italy, self-supported aerial cables are widely employed for distribution services. There are other types of constructions which utilise an insulated neutral instead of bare wires. Naturally, insulation of MV lines is more costly than LV; therefore the constructions mentioned earlier are only feasible under certain situations. Thus, covered conductors for MV areas are more price-smart solutions as far as utilities are concerned [22].

In HV levels there are a couple of conductor types that are commonly used for transmitting 36 kV and higher, such as the ACSR and All Aluminium Alloy Conductor (AAAC). However, Aluminium Conductor Alloy Reinforced (ACAR) and All Aluminium Alloy Conductor Steel Reinforced (AACSR) are less commonly used than ACSR due to the significant price difference. ACSR has many benefits which made it popular in the past. Some of these advantages are: mechanical strength, excellent manufacturing capacity (which effectively meets the market demand) and its cost effectiveness [23].

3.2 Reliability Issues in Power Network

There is an on-going demand from consumers for a more reliable and economical power supply. Many factors contribute to determining the reliability of a power network: design, construction, operation and maintenance which have their combined input into the overall power network reliability. Moreover, liberalisation of the electricity sector along with adopting new technology commercially puts great pressure on electricity utilities to operate not only economically but reliably and securely too.

The main causes of overhead power transmission and distribution network interruption are in fact unplanned external causes, like storms, bushfires, lightning, trees, animals, vehicle accidents and vandalism. Interruptions can also be caused by equipment and line or cable failure due to overload and ageing. However, overhead networks are more vulnerable to the external causes; adding to that, in general, the maintenance works required for overhead networks are about twice the number compared to the underground power networks maintenance works.

Frequent and major power interruptions cause many concerns. Some of them relate to the power systems' security and reliability. Ageing assets can play a big role in more frequent power interruptions (most of the outages and disruption usually occur on the distribution part of the power network).

According to Mutton et al. report [3], 85% of all Customer Minutes Off-Supply (CMOS) results from faults on the 22kV distribution system. The low voltage network to a consumer's property accounts for only 4% and, although faults at zone substations and on sub transmission circuits impact on a large number of customers, they account for only 11% of customer minutes off-supply. The top three causes of outages account for 50% of all outages (Trees 23%, No Identified Cause 14% and Planned Outages 13%). Lightning, animals or birds and high voltage conductor failures each account for around 7%. In 1999, trees caused more than 80% of faults on the two worst short rural 22kV feeders (Belgrave 24 and Kinglake 2). Figure 3.1 shows the percentage of top causes for outages during 1997 to 1999 by CMOS of a local power distribution network SP AusNet (formerly known as TXU) [3].

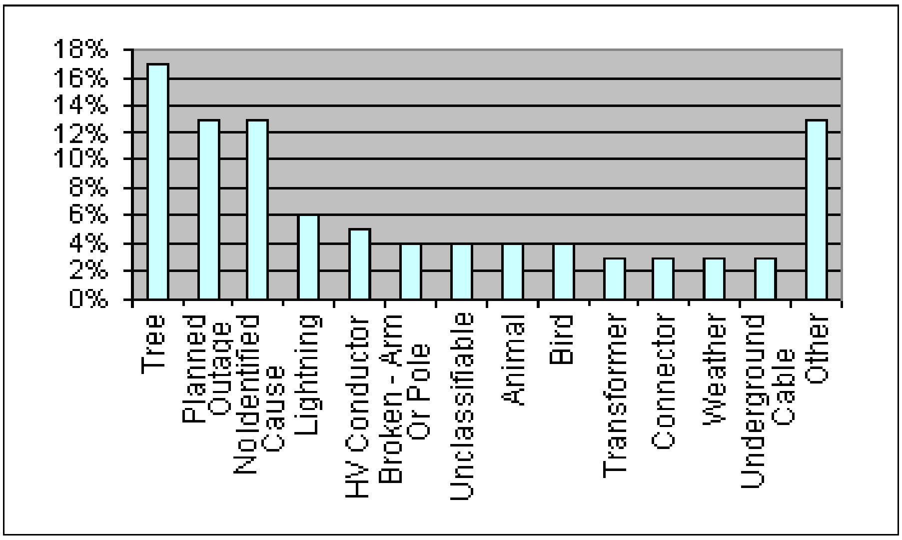


Figure 3.1: Average CMOS over three years [3]

3.3 Types of Overhead Power Line Conductors

Overall, there are a number of different overhead line conductor types which are usually installed by spacing between the individual conductors in order to acquire various voltage ratings. The following are the three major types [24]:

AAC - All Aluminium Conductor

AAAC - All Aluminium Alloy Conductor

ACSR - Aluminium Conductor Steel Reinforced

Each of these overhead conductors has its own features, advantages and disadvantages. Table 3.1 summarises some of these features. Moreover, these features constitute many of the factors that an engineer would have to take into account when determining the type of conductors required for designing an overhead network. A short list, which highlights some of these important factors is as follows [24]:

- Section length

  The length of an overhead line can be decided with the following factors taken into account: terrain of line easement, quantity and quality of conductors, local climate conditions, nature of load and the required safety procedures.

- Degree of sagging

  Degree of sagging is determined by measuring the catenary curve which takes into account the ratio of line span and weight as well as the structure required to support the conductor above the ground.

- Daily conductor stress

  The daily conductor stress is the unit which measures the variation of conductor stress under the normal operation load at or around the mean temperature with minimal or no high demand on existing load.

- Surrounding environment temperature

  Local climate has an explicit impact on the conductor temperature. Thus evaluating the actual operating temperature of a conductor is considered as an essential exercise in order to enhance conductor capacity utilization and mitigate the risk of sagging.

Table 3.1: Overhead line conductors - types and features - [24]

Cable	AAC	ACSR	AAAC
Category	All Aluminium Conductors; comprises a single or multiple strands made of hard drawn 1350 Aluminium Alloy.	Aluminium Conductor Steel Reinforced; comprises a solid or stranded steel core surrounded by one or more layers of strands of 1350 aluminium	A high strength Aluminium-Magnesium-Silicon Alloy cable;
Pros	1. excellent corrosion resistance 2. conductor of choice in coastal areas 3. heavily used in urban areas as spans are short but high conductivity is required	4. Mainly used for overhead ground wires 5. extra long spans 6. makes the best candidates for river crossing …etc	7. offers excellent electrical characteristics 8. excellent sag-tension characteristics 9. superior corrosion resistance
Cons	10. low strength-to-weight ratio 11. limited use in transmission lines and rural distribution because of the long spans	12. inner core wires may require zinc coating (galvanized) steel	13. limited use 14. thermal coefficient of expansion is greater ACSR

3.4 Load Flow Analysis

Load flow analysis, by and large referenced as load flow, is the most important tool used in power system analysis, design and planning. It is an essential tool power utilities use for planning, operating, efficiency and power exchange. Power flow is also necessary for other network situations, for instance, transient stabilities or for contingency scenarios.

acload-flow analysis is essential when determining the capability of a distribution network under different network configuration and loading conditions. A typical report of the load flow analysis should accommodate the losses of various parts of the network such as: infeed power sources whether generated within the network or transformer substations; infeed obtained from higher voltage network. Generally speaking, carrying out this type of analysis on MV and LV networks is a much simpler task – due to their radial configuration – than its HV counterparts. However, radial networks tend to have a very high number of load points thus obtaining readings on individual points is restricted to the annual unit consumption at a known LV level [22].

In addition to system losses, load flow analysis is highly affected by the characteristics and loading of each node point at each section of the network. Microprocessor units are usually used at incoming supply and outgoing feeders to complement the load data necessary to carry out the system analysis, due to the fact that only a small amount of load data is collected from maximum demand indicators at MV networks [22].

Correction factors are commonly used in system analysis when carried out on MV and LV networks in order to achieve flawless results with unrealistically very high value for the total current flows. This is merely due to the fact that in some cases, the maximum possible demand of customers' appliances is hard to estimate as their ratings and quantities are simply unknown. This is where lowering the estimated rate of all loads becomes vital so that the simultaneous maximum demand of the group of loads equates to the total of individual loads. Lowering the rating is usually achieved by applying a coincidence factor which is defined as the ratio of the simultaneous maximum demand of a group of load points to the sum of the maximum demands of the individual loads [22].

3.5 Conclusion

For decades, power has been transmitted via a relatively low cost medium, commonly known as overhead lines. Since then, substantial transformations have been occurring to improve the reliability of overhead networks. A load flow technique is often employed to analyse and design an improved overhead power network. Chapter 3 has provided an overview of overhead power networks.

This chapter has also extensively explored overhead power networks various aspects as well as the major factors that form the core requirements of a reliable power network. Various conductors used in overhead lines have also been discussed. As power loss is a major concern for transmission systems, an elaborative study on power losses in overhead lines has also been included. The next chapter looks at the Victorian overhead power network in an attempt to efficiently design an underground network for Victoria.

CHAPTER 4

DEVELOPMENT AND ANALYSIS OF VICTORIAN OVERHEAD POWER NETWORK MODEL

4.0 Introduction

Further to the general overview of overhead power networks presented in chapter 3, this chapter discusses and presents the existing Victorian overhead network model which is based on sub-models developed separately then combined together to form the overall overhead model. A load flow analysis will be carried out on this model where the results obtained from this study will be further verified and used as a bench mark to validate future models that will be developed in following chapters.

It is of great significance to mention that the overhead model was developed using two industrial power software applications; this step constitutes an integral part of this study so that it provides a mechanism for the comparison, verification and validation of the obtained results.

4.1 Power Loss in Overhead Lines

Power losses in overhead lines are the representation of the amount of lost power from the generated power that did not deliver to load. These losses are attributed to the resistance of various components of the power network mainly transmission lines. Losses depend on the network conditions such as loading, network topology, type of network, location of generation and load as well as power demand. The average power loss in transmission lines would be 3% of the transmitted power, with maximum loss occurring at peak power demand. Given the nonlinear nature of losses, it will be a tricky task trying to put a figure of how much the loss can cost. Consequently, measuring losses directly can not be performed. On the other hand power flow analysis utilised by computer software can calculate and give very close indication about exact transmission losses. The results obtained from such software will also give comprehensive information about the losses associated with particular loads or customer [25].

Overhead transmission lines have traditionally played a major role in delivering power from remote generation plants, where energy sources are located away from loads, with distances of over hundreds of kilometres. As technology advances, various developments have identified the core weakness of transmission technologies/capabilities. In today's competitive era, energy has become the prime commodity for developed and developing countries. For decades, power engineers had overlooked the importance of transmission capabilities along with its losses. Approximately 70% of the energy is lost in the process of generation and transmission; underground transmission cabling technology brings new hope in substantially saving transmission losses.

Despite the simplicity and low cost of overhead transmission lines, they induce reactive power to the power network. This reactive power is proportional to the length and load of transmission line. Therefore more reactive power is generated. Consequently, series compensation can be substantially utilised to offset the generated reactive power [26].

Please refer to Appendix A for more information about power loss calculation.

4.2 General Overview of Victorian Overhead Power Network

Overhead lines have been a dominant transmission medium in Australia for many years, mainly due to their simple structure, lower solution cost, and ease in locating and repairing faults. Depending on the nature of the fault, overhead line faults may last from a few milliseconds to days, with the longer duration caused by extreme weather, bush fires and other abnormal conditions. It is very likely that overhead line faults can strike 100 times more than underground due to external causes such as wind loading, lightning surges and tracking on dirty insulators [27]. Most of the faults last only momentarily, which are intercepted easily by power system protection techniques.

There are a number of power distribution companies in Victoria. Citipower and Powercor's combined networks deliver electricity to nearly a million customers throughout Victoria, from central Melbourne, west to the borders of South Australia to New South Wales and, according to the company's latest report, it operates the most reliable electricity network in Australia.

Citipower Subtransmission lines are configured in an efficient manner to supply its zone substations, in which the lines are connected to the terminal stations using loop and/or meshed topology. This redundancy based configuration of lines that supply each zone substation provides extra continuity and security of electricity supply in the case of individual lines being unavailable due to maintenance or disruption of service.

Citipower owns a power network that consists of around 61,000 poles and more than 4,270km of overhead lines, service lines and over 2,220km of underground cables. Overall, Citipower runs 38 zone substations, 83 subtransmission lines, around 3200 distribution substations and 600 distribution feeders. Moreover, Citipower utilises zone substations to transform subtransmission line voltages – in Victoria 66kV or 22kV - down to distribution voltages which are 11kV or 6.6kV in addition distribution feeders are used to supply the distribution substations [28].

Citipower must plan its distribution network future expansion due to the Victorian regulation which clearly states that planning the augmentation of distribution networks is the business owner's responsibility. Augmentation planning is usually carried out to provide efficient, secure and reliable supply to customers. Thus Citipower takes its augmentation planning very seriously to match its network capacity which is mostly motivated by geographical swing due to new urban development as well as customer demand. Figure 4.1 exhibits the scope of the Citipower network of the areas supplied by each zone substation. It is worth mentioning that this map is not intended to show overlapping between adjacent zone substations as it is designed to show zone supply areas.

Overhead network data were obtained from Citipower and its publications from the public domain. Some of network data were not available; therefore the following assumptions were made for the development of the network:

1. Lines to be treated as a single section line although they might consist of multiple section to simplify the models.

2. Summer circuit rating has been used in load flow analysis which has a lower line rating than winter to accommodate for worse case scenarios.

3. Where power factor is not given, 85% was used for residential load and 95% used for industrial load.

4. n-1 (n elements in service) redundancy configuration has been applied to all models and sub models to maintain Citipower n-1 network configuration; in other words if an individual subtransmission line was out of service the supply to its zone substation would not be lost.

5. No corrective measures such as opening or closing circuit breakers or phase shifters regulating, which normally carried out by power utility for n-1 redundancy configuration have been accommodated for in the simulation.

Appendix B lists Citipower zone substations information, where as Appendices C and D show West Melbourne Terminal Station' (WMTS) sub-transmission lines information and single line diagram respectively.

Separate sections of the Citipower power network were developed individually for each terminal station; separate sections for 66kV and 22kV voltage levels were created using Advanced Power Flow Program EDSA power tool. The overhead network model was developed in order to perform load flow analysis to calculate the overall power losses in the entire network feeders. The results obtained from the simulation are based on normal operations or steady state conditions as well as abnormal or at fault conditions. The obtained results were used as a benchmark to compare the other setup and configuration results of the network.

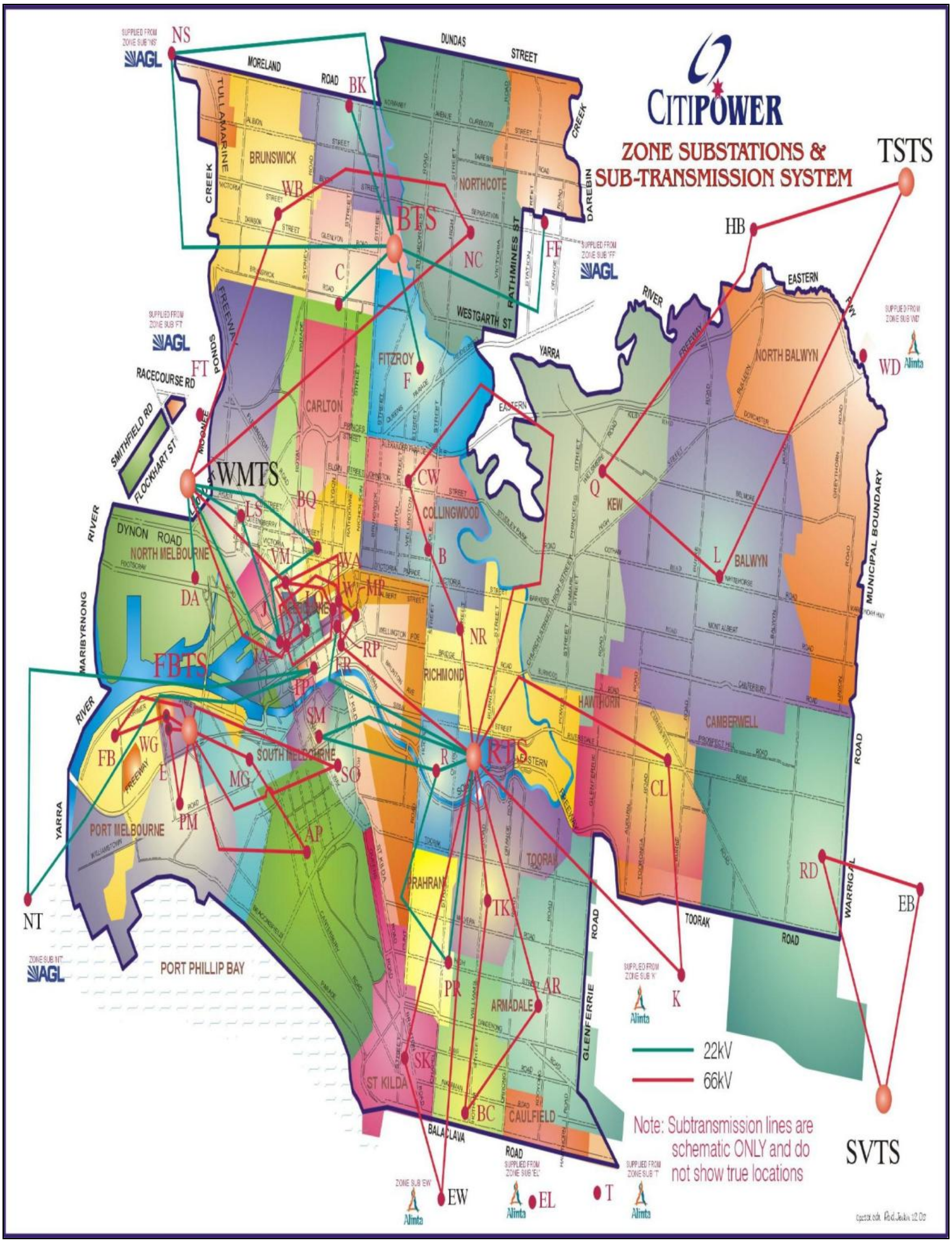


Figure 4.1: C-itipower – zone substation and sub-transmission system [28]

4.3 WMTS 2007 Overhead Base Model

This model comprises of multiple sub-models; these include the 66kV and 22kV WMTS terminal station loops which are presented in Figure 4.1. After obtaining the flow analysis of the two voltage levels, a submission of all power losses, which basically represents the loading demand of the WMTS for the year 2007, is identified to undergo further analysis.

4.2.1 EDSA WMTS 66kV overhead base sub-model

The configuration of this base sub-model closely matches the existing Citipower section of the network with zone substation loading obtained from the company's 2007 planning report [11]. Additionally, WMTS 66kV overhead network parameters for 2007 were obtained from Citipower annual report, then used to develop and analyse this sub-model. Figure 4.2 shows the WMTS terminal station 66kV section of the network base sub-model.

It can also be noted that a summary of the load flow analysis results is situated close to the bus, line or transformer in Figure 4.2. The summary includes an arrow that reveals the direction of power flow. Real and reactive power are also shown close to each bus, line or transformer in terms of positive values, which denote whether the power flow direction is out from the bus and vice versa or whether negative values are applied for power flow direction in the bus. Accordingly, summing up of the four power flow values for each line or feeder will provide real and reactive power losses in the specific line.

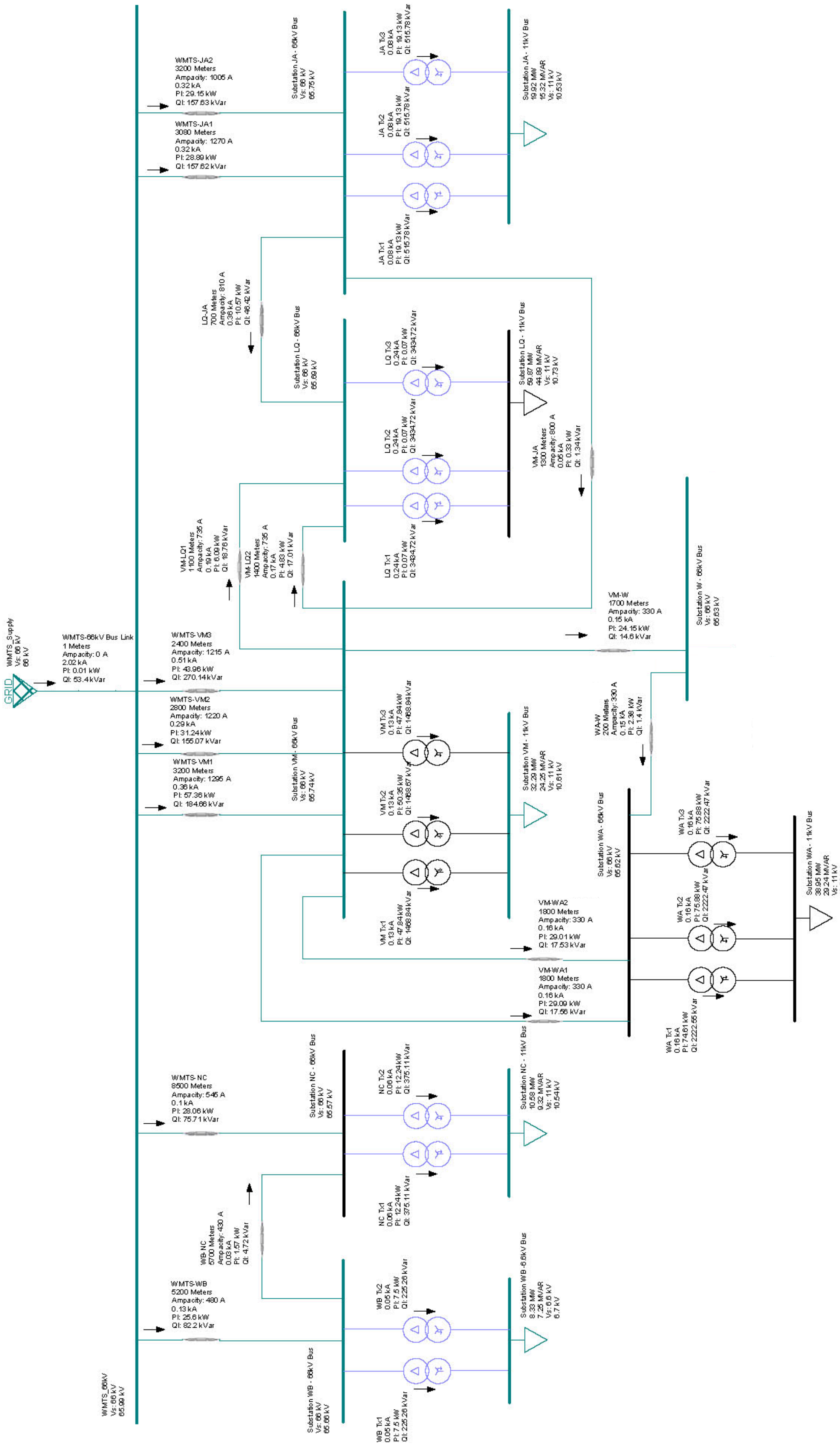


Figure 4.2: WMTS 66kV overhead base sub-model

Another observation that can be drawn from the Figure 4.2 is that sections or elements of the network are colour coded according to their loading in normal operating conditions;

Bus voltage violation:

- Under limit or less than 95% of rating is displayed in blue
- Range between 96% - 104% of rating is displayed in black
- Over limit or higher than 105% of rating is displayed in Red colour

Current violation:

- Under limit or less than 50% of rating is displayed in green colour
- Range between 51% - 99% of rating is displayed in black colour.
- Over limit or higher than 100% of rating is displayed in orange colour.

Transformer violation:

- Under limit or less than 50% of rating is displayed in light blue colour.
- Range between 51% - 99% of rating is displayed in black colour.
- Over limit or higher than 100% of rating is displayed in yellow colour.

Table 4.1 illustrates the bus results of flow analysis performed on the WMTS 66kV sub-model. The table also lists bus parameters including name, real and reactive generated powers, real and reactive static loads and load flow results from which the real and reactive power losses are obtained with bus current rating and power factor incorporated.

Table 4.1: WMTS 66kV overhead EDSA load flow bus results

Bus Info	Generation		Static Load		Load Flow Results				
Name	**MW**	**MVAR**	**MW**	**MVAR**	**To Bus Name**	**MW**	**MVAR**	**Amp**	**%pf**
Sub JA 66	0.00	0.00	0.00	0.00	Sub LQ 66	28.77	28.60	356	70.9
Sub JA 66	0.00	0.00	0.00	0.00	Sub LQ 66	28.77	28.60	356	70.9
					Sub VM 66	3.77	3.66	46	71.7
					WMTS 66	-26.23	-24.58	316	73.0
					WMTS 66	-26.28	-24.55	316	73.1
Sub LQ 66	0.00	0.00	0.00	0.00	Sub JA 66	-28.76	-28.55	356	71.0
					Sub VM 66	-16.65	-13.76	190	77.1
					Sub VM 66	-14.45	-12.88	170	74.7
Sub NC 66	0.00	0.00	0.00	0.00	Sub WB 66	-2.32	-2.60	31	66.5
					WMTS 66	-8.29	-7.47	98	74.3
Sub VM 66	0.00	0.00	0.00	0.00	Sub JA 66	-3.77	-3.66	46	71.7
					Sub LQ 66	16.66	13.78	190	77.1
					Sub LQ 66	14.46	12.90	170	74.6
					Sub W 66	12.31	11.26	147	73.8
					Sub WA 66	13.50	12.36	161	73.7
					Sub WA 66	13.45	12.34	160	73.7
					WMTS 66	-32.94	-24.38	360	80.4
					WMTS 66	-24.76	-22.59	294	73.9
					WMTS 66	-41.35	-40.66	509	71.3
Sub W 66	0.00	0.00	0.00	0.00	Sub VM 66	-12.28	-11.25	147	73.7
					Sub WA 66	12.28	11.25	147	73.7
Sub WA 66	0.00	0.00	0.00	0.00	Sub VM 66	-13.47	-12.34	161	73.7
					Sub VM 66	-13.43	-12.32	160	73.7
					Sub W 66	-12.28	-11.25	147	73.7
Sub WB 66	0.00	0.00	0.00	0.00	WMTS 66	-10.67	-10.31	130	71.9
					Sub NC 66	2.32	2.60	31	66.5
WMTS 66	0.00	0.00	0.00	0.00	Sub WB 66	10.69	10.39	130	71.7
					Sub JA 66	26.26	24.74	316	72.8
					Sub JA 66	26.31	24.71	316	72.9
					Sub NC 66	8.32	7.55	98	74.1
					Sub VM 66	32.99	24.56	360	80.2
					Sub VM 66	24.80	22.75	294	73.7
					Sub VM 66	41.40	40.93	509	71.1
					Total losses	**0.36**	**1.23**		

The load flow results obtained in Table 4.1 are summarised in Table 4.2. The table shows, in two different columns, the power delivered to and from the line and in the last two columns it lists the power difference or power losses. The total real power losses were found to be 352.5 kW; in addition total reactive power was found to be 1,222.3 kVAR.

Table 4.2: WMTS 66kV overhead lines losses

Branch	**From -> To Flow**		**To -> From Flow**		**Losses**	
Name	**MW**	**MVAR**	**MW**	**MVAR**	**kW**	**kVAR**
LQ-JA	-28.759	-28.552	28.770	28.598	10.6	46.4
VM-JA	-3.769	-3.663	3.770	3.665	0.3	1.3
VM-LQ1	16.661	13.776	-16.655	-13.757	6.1	18.8
VM-LQ2	14.458	12.898	-14.454	-12.881	4.8	17.0
VM-W	12.308	11.265	-12.284	-11.250	24.2	14.6
VM-WA1	13.495	12.361	-13.466	-12.343	29.1	17.6
VM-WA2	13.454	12.337	-13.425	-12.320	29.0	17.5
WA-W	-12.282	-11.249	12.284	11.250	2.4	1.4
WB-NC	-2.317	-2.600	2.318	2.604	1.6	4.7
WMTS-JA1	26.261	24.741	-26.232	-24.583	28.9	157.6
WMTS-JA2	26.311	24.708	-26.282	-24.550	29.2	157.6
WMTS-NC	317	7.546	-8.289	-7.470	28.1	75.7
WMTS-VM1	32.993	24.560	-32.936	-24.376	57.4	184.7
WMTS-VM2	24.796	22.746	-24.765	-22.591	31.2	155.1
WMTS-VM3	41.396	40.934	-41.352	-40.664	44.0	270.1
WMTS-WB	10.692	10.390	-10.666	-10.308	25.6	82.2
			Total power losses		**352.5**	**1222.3**

WMTS 66kV line's real and reactive power losses are shown in Figure 4.3; the figure demonstrates that the power losses are line impedance dependents, as it can be observed that although line WMTS – VM3 is shorter in length than its counterpart WMTS – VM2, however, its real and reactive power losses are much higher and the clear reason for that is its higher impedance.

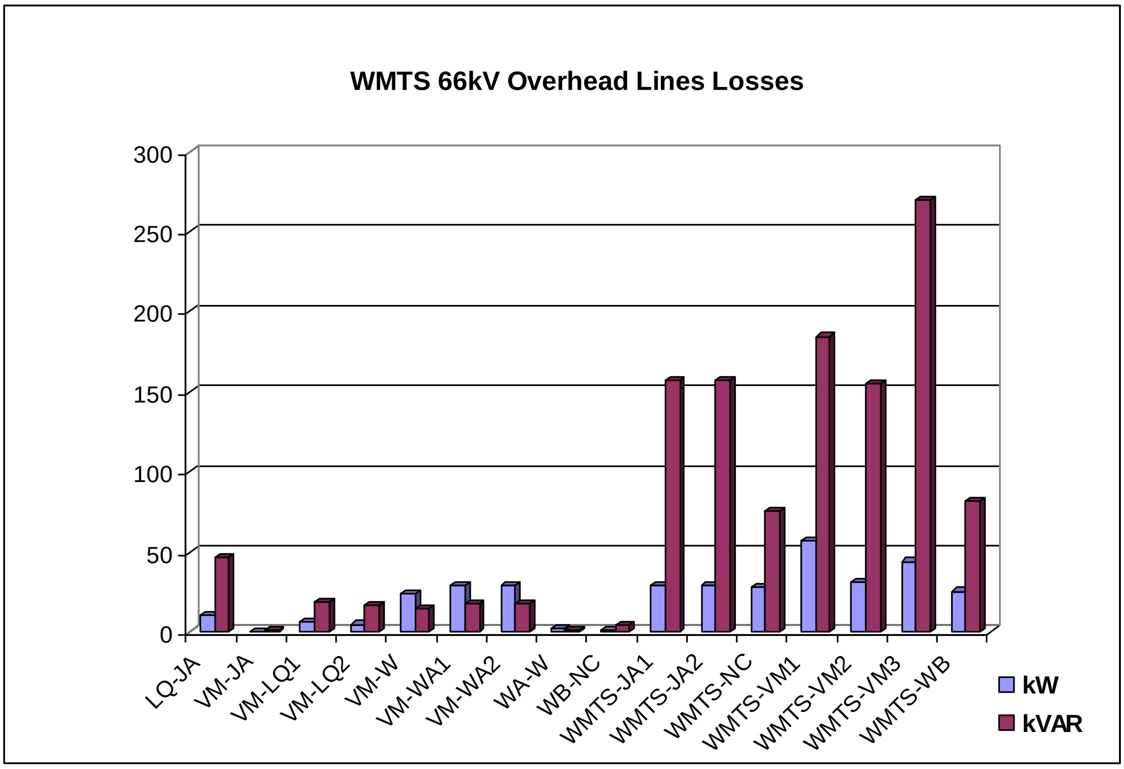


Figure 4.3: WMTS 66kV overhead lines power losses

4.2.2 PSS/E WMTS 66kV overhead base sub-model

The configuration and parameters of this base sub-model with the year 2007 loading demand has been obtained directly from Citipower as a file. The file was then simulated using PSS/E software. Table 4.3 shows the results of this simulated sub-model.

Table 4.3: PSS/E WMTS 66kV overhead lines losses

FROM BUS NAME	SHUNT MW/MVAR	TO BUS NAME	LOAD FLOW kW	kVAR	RATING AMPS	%I	SET A
WMTS 66	0.00	JA 66	38297.8	17654.7	366		
JA 66	0.00	WMTS 66	-38260.2	-17488.3	374		
WMTS 66	0.00	JA 66	38297.8	17654.7	366		
JA 66	0.00	WMTS 66	-38260.2	-17498.3	374		
WMTS 66	0.00	NC 66	13755.9	7138.1	135	28	480A
NC 66	0.00	WMTS 66	-13725.8	-7044.4	136	28	480A
WMTS 66	0.00	VM1 66	89382.3	58078.7	926		
VM1 66	0.00	WMTS 66	-89315.5	-57891.7	927		
WMTS 66	0.00	VM2 66	35641.6	18355.5	348		
VM2 66	0.00	WMTS 66	-35599.9	-18135.8	352		
WMTS 66	0.00	VM3 66	90188.2	56242.5	924		
VM3 66	0.00	WMTS 66	-90150	-56045.4	939		
WMTS 66	0.00	WB 66	17937.3	9644.2	177	37	480A
WB 66	0.00	WMTS 66	-17891.5	-9494.4	183	38	480A
JA 66	0.00	LQ2 66	29.317	-28.898	366		
LQ2 66	0.00	JA 66	-29.212	-28.852	366		
JA 66	0.00	VM2 66	5036.1	8257.6	84		
VM2 66	0.00	JA 66	-5035	-8253.1	84		
LQ1 66	0.00	VM1 66	-49740.8	-32777.1	523		
VM1 66	0.00	LQ1 66	49744	32789.3	517		
LQ3 66	0.00	VM3 66	-50143.1	-32107.2	529		
VM3 66	0.00	LQ3 66	50186.3	32134.9	521		
W1 66	0.00	VM3 66	-21787.2	-13855.3	230		
VM3 66	0.00	W1 66	21840.2	13877.7	226		
W1 66	0.00	WA3 66	21787.2	14595.3	230		
WA3 66	0.00	W1 66	-21781.7	-14591.6	230		
NC 66	0.00	WB 66	-3965.1	-2363.9	42	10	430A
WB 66	0.00	NC 66	3967.8	2369.2	40	9	430A
VM1 66	0.00	WA1 66	21511.6	13316.7	222		
WA1 66	0.00	VM1 66	-21458.4	-13254.1	226		
VM2 66	0.00	WA2 66	22221.5	14374.3	231		
WA2 66	0.00	VM2 66	-22193.9	-14320.5	235		
		Total power losses	**487.405**	**1362.346**			

The results in results Table 4.3 were compared to the results obtained earlier from Table 4.2 and it is fair to conclude that there is a close similarity between real and reactive power losses in simulation results obtained from both power software applications. Thus, the validity of the WMTS 66kV base sub-model developed in Section 4.1.1 has proven to be correct. (i.e. EDSA and PSSE) because it has exhibited many similarities with a degree of discrimination in minor tolerance. Figure 4.4 shows results obtained from the comparison of WMTS 66kV power losses, again acquired from both EDSA and PSSE software.

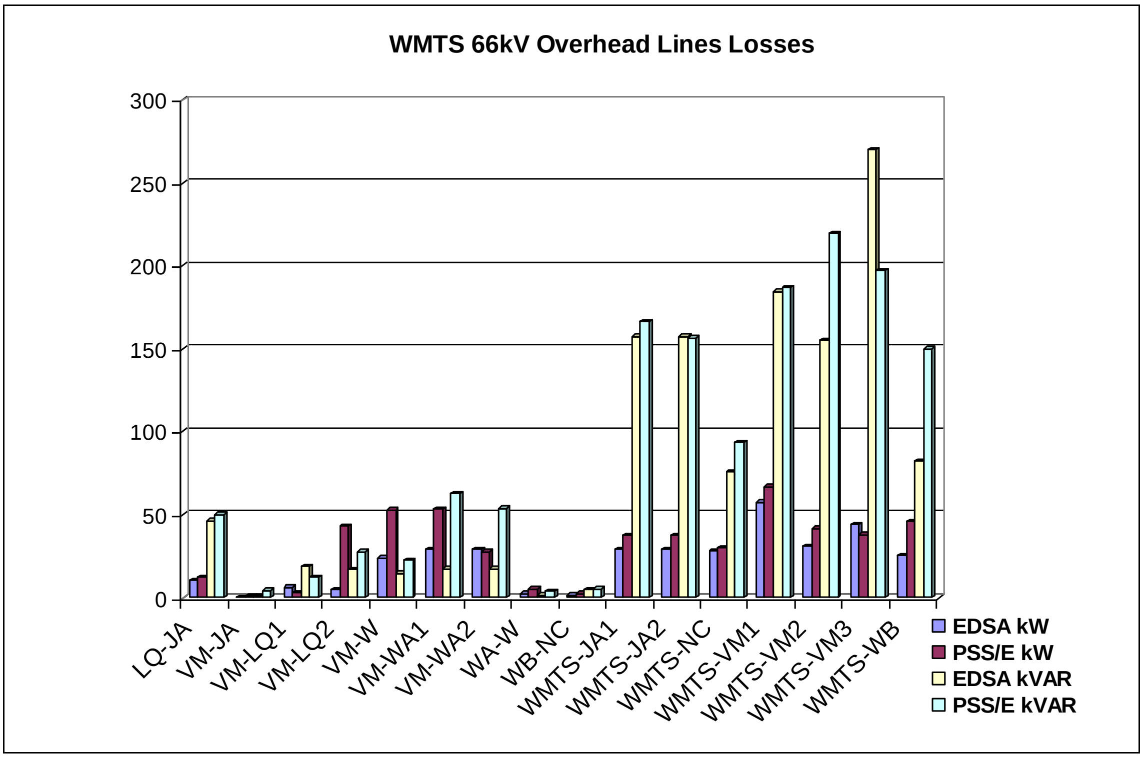


Figure 4.4: WMTS 66kV power losses comparison of both EDSA and PSS/E

4.2.3 EDSA WMTS 22kV overhead base sub-model

The configuration of this base sub-model has many similarities to the WMTS 66kV sub-model exhibited earlier in Section 4.2.1, which closely matches the existing Citipower section of the network. Again the 2007 zone substation loading demand parameters were acquired from the company's 2007 planning report. Figure 4.5 shows the WMTS terminal station 22kV section of the network base sub-model.

The developed sub-model in Figure 4.5 shows the WMTS terminal station 22kV section of the network base sub-model and a load flow analysis on the model was carried out to obtain power loss figures. Again Figure 4.5 shows the summary of the load flow analysis results situated close to the bus, line or transformer.

The lists of bus parameters in Table 4.4 of the WMTS 22kV sub-model comprises of name, real and reactive generated power, real and reactive static load and load flow results where real and reactive power losses can be obtained with the bus current rating and power factor incorporated as well.

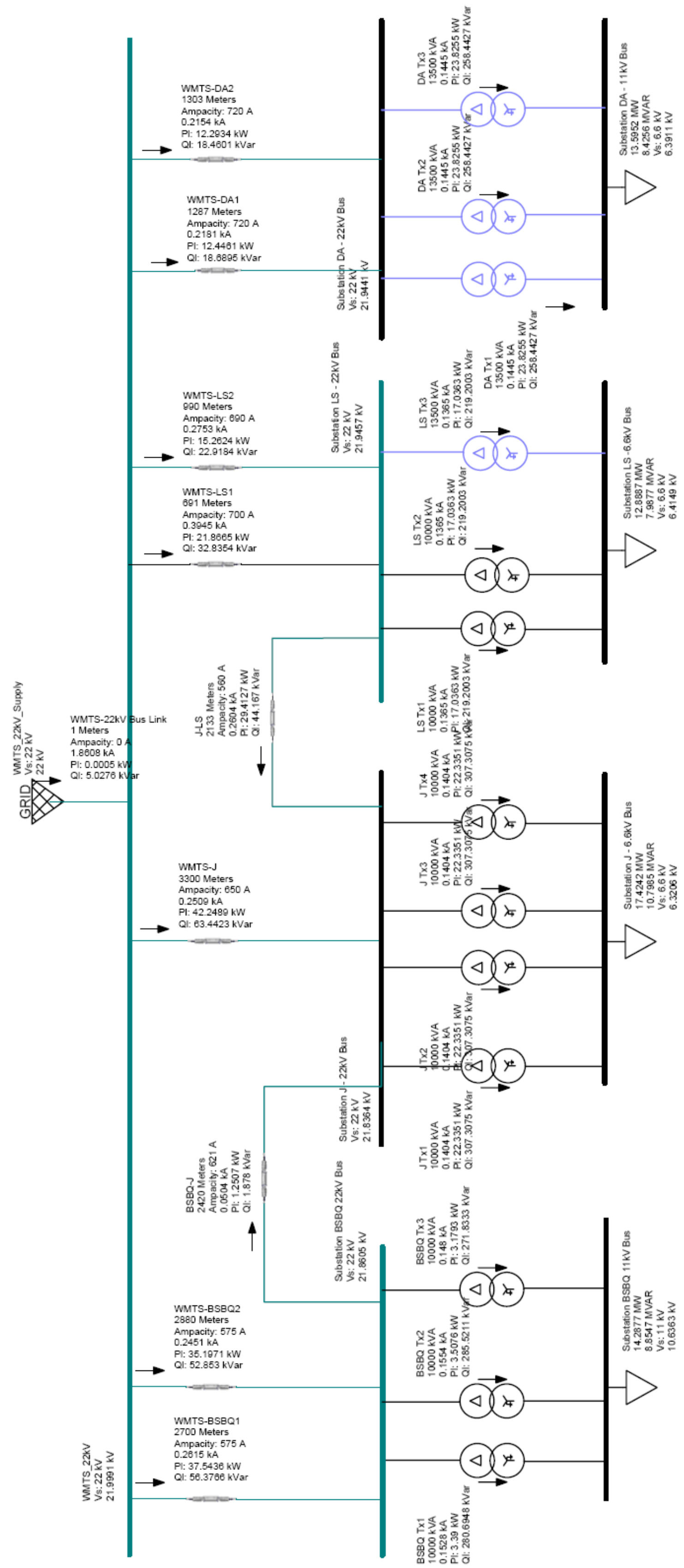


Figure 4.5: WMTS 22kV overhead sub-model

Table 4.4: WMTS 22kV overhead EDSA load flow bus results

Bus Info	Generation		Static Load		Load Flow Results				
Name	**MW**	**MVAR**	**MW**	**MVAR**	**To Bus Name**	**MW**	**MVAR**	**Amp**	**%pf**
Sub BSBQ 22	0.00	0.00	0.00	0.00	Sub J 22	1.56	1.1	50	81.8
					WMTS 22	-8.19	-5.57	261	82.7
					WMTS 22	-7.67	-5.22	245	82.7
Sub DA 22	0.00	0.00	0.00	0.00	WMTS 22	-6.88	-4.63	218	83
					WMTS 22	-6.79	-4.57	215	83
Sub J	0.00	0.00	0.00	0.00	Sub BSBQ 22	-1.56	-1.1	50	81.8
					Sub LS 22	-8.12	-5.58	260	82.4
					WMTS 22	-7.84	-5.35	251	82.6
Sub LS 22	0.00	0.00	0.00	0.00	Sub J 22	8.14	5.62	260	82.3
					WMTS 22	-12.42	-8.4	394	82.8
					WMTS 22	-8.67	-5.87	275	82.8
WMTS 22	0.00	0.00	0.00	0.00	Sub BSBQ 22	8.22	5.63	261	82.5
					Sub BSBQ 22	7.71	5.27	245	82.5
					Sub DA 22	6.89	4.65	218	82.9
					Sub DA 22	6.8	4.59	215	82.9
					Sub J 22	7.88	5.42	251	82.4
					Sub LS 22	12.44	8.44	394	82.8
					Sub LS 22	8.68	5.89	275	82.8
					Total losses	**0.18**	**0.32**		

The load flow results obtained in Table 4.4 are summarised in Table 4.5. The table shows, in two different columns, the power delivered to and from the line and in the last two columns it lists the power difference or power losses. The total real power losses were found to be 207.5 kW; in addition the total reactive power was found to be 311.7 kVAR.

Table 4.5: WMTS 22kV overhead lines power losses

Branch	From -> To Flow		To -> From Flow		Losses	
Name	**MW**	**MVAR**	**MW**	**MVAR**	**kW**	**kVAR**
BSBQ-J	1.561	1.098	-1.56	-1.096	1.3	1.9
J-LS	-8.115	-5.58	8.145	5.624	29.4	44.2
WMTS-BSBQ1	8.223	5.626	-8.186	-5.569	37.5	56.4
WMTS-BSBQ2	7.709	5.274	-7.674	-5.221	35.2	52.9
WMTS-DA1	6.887	4.648	-6.875	-4.629	12.4	18.7
WMTS-DA2	6.803	4.59	-6.791	-4.572	12.3	18.5
WMTS-J1	7.878	5.416	-7.836	-5.352	42.2	63.4
WMTS-LS1	12.439	8.436	-12.417	-8.404	21.9	32.8
WMTS-LS2	8.682	5.888	-8.667	-5.866	15.3	22.9
			Total power losses		**207.5**	**311.7**

Real and reactive power losses of WMTS 22kV overhead lines are exhibited in Figure 4.6. The figure demonstrates that the power losses are line impedance dependent, as can be observed clearly in the fact that although line WMTS – BSBQ1 is shorter in length than its counterpart WMTS – BSBQ2, however, its real and reactive power losses are higher and the reason for that is the higher current passing through it which in turn causes higher power losses.

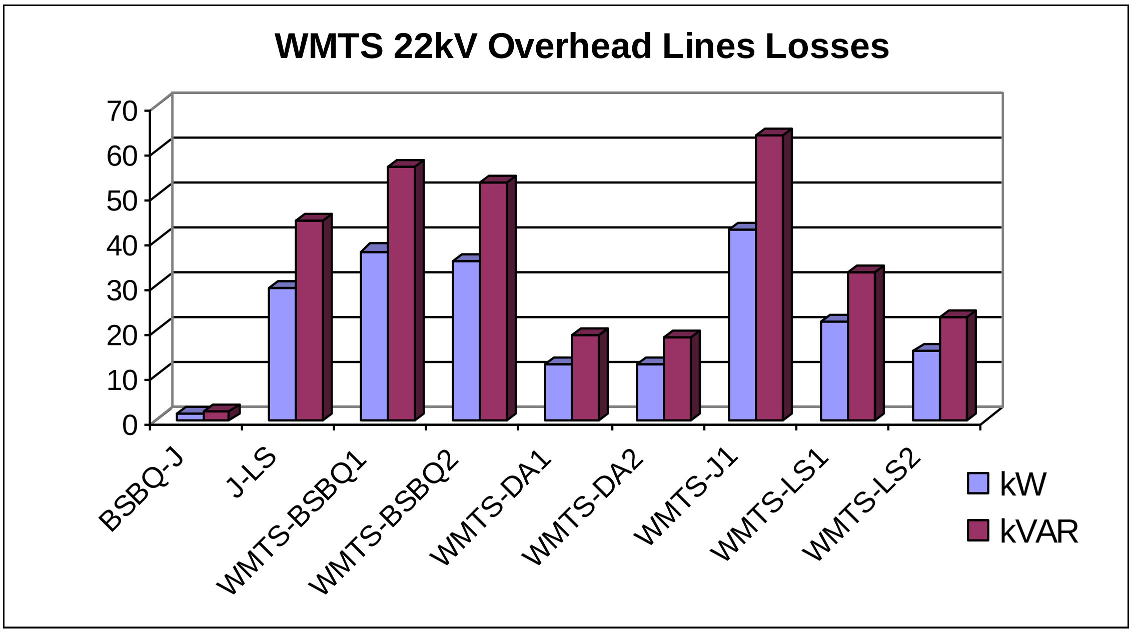


Figure 4.6: WMTS 22kV overhead lines power losses

4.2.4 PSS/E WMTS 22kV overhead base sub-model

The configuration and parameters of this base sub-model with the year 2007 loading demand has been obtained directly from Citipower as a file. The file was then simulated using PSS/E software, Table 4.6 shows the results of this simulated sub-model.

The results in Table 4.6 compare the results obtained earlier from Table 4.5. The comparison demonstrates a close similarity of real and reactive power losses. In other words, both simulation results obtained from two different power softwares are agreed. Thus the validity of the WMTS 22kV base sub-model developed in Section 4.1.3 is confirmed. Figure 4.7 shows a comparison of WMTS 22kV power losses acquired from both EDSA and PSSE softwares.

Table 4.6: PSS/E WMTS 22kV overhead lines power losses

FROM BUS NAME	SHUNT MW/MVAR	TO BUS NAME	LOAD FLOW kW	kVAR	RATING AMPS %I	SET A
BSBQ 22	0.0	J 22	9272.8	4614.5		
J 22	0.0	BSBQ 22	-9271.2	-4612.3		
J 22	0.0	LS 22	-5967.3	-7936.4		
LS 22	0.0	J 22	5997.6	7982.2		
BSBQ 22	0.0	WMTS 22	-15048.2	-8048.7		
WMTS 22	0.0	BSBQ 22	15089.2	8107		
BSBQ 22	0.0	WMTS 22	-16806.5	-8975.2		
WMTS 22	0.0	BSBQ 22	16845.3	9030.6		
DA 22	0.0	WMTS 22	-10678.7	-6631.3		
WMTS 22	0.0	DA 22	10692.1	6650.7		
DA 22	0.0	WMTS 22	-9868.6	-6351.2		
WMTS 22	0.0	DA 22	9882.1	6375.1		
J 22	0.0	WMTS 22	-12386.9	-10464.4		
WMTS 22	0.0	J 22	12430	10533.2		
LS 22	0.0	WMTS 22	-13165.2	-12183.2		
WMTS 22	0.0	LS 22	13185	12226.3		
LS 22	0.0	WMTS 22	-11895.2	-10121.4		
WMTS 22	0.0	LS 22	11910.8	10147.6		
	Total power losses		**217.1**	**343.1**		

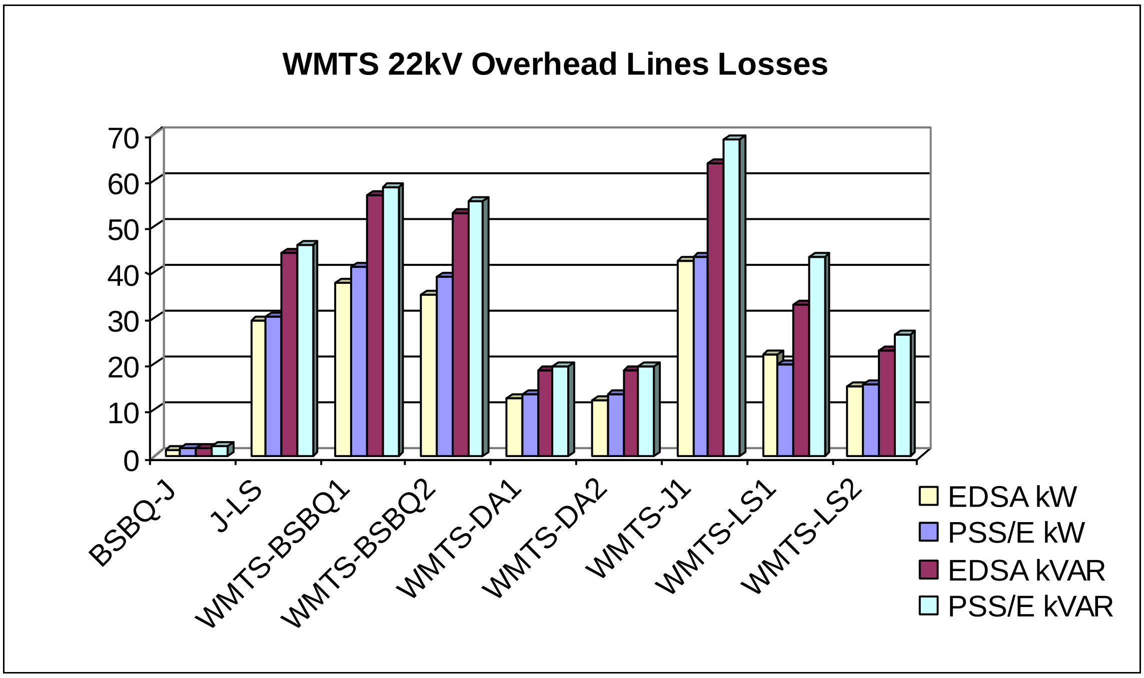


Figure 4.7: WMTS 22kV power losses comparison of both EDSA and PSS/E

To summarise this section, the summation of power losses found in 22kV and 66kV loops are presented as the total power losses in the WMTS section of Citipower for existing network configuration with 2007 loading demand.

Total real power losses = 207.50 + 352.50 = 560.00 kW

Total reactive power losses = 311.7 + 1222.3 = 1534.00 kVAR

4.4 WMTS 2011 Overhead Forecast Model

This model consists of a series of sub-models; these include the 66kV and 22kV WMTS terminal station loops indicated in Figure 4.1. Forecast load demands for the year 2011 are used in these sub-models. After obtaining the flow analysis of the two voltage levels, a submission of all power losses which basically represents the loading demand forecast of WMTS for the year 2011 is identified for further analysis.

4.3.1 WMTS 66kV overhead 2011 forecast sub-model

In this sub-model, a 2011 forecast load demand is used to determine the new overall load flow and identify stressed or exceeded rating elements in the network. After the first attempt to run the load flow analysis, the load flow analysis failed to converge as several elements were identified as stressed to well over their 100% rating, Figure 4.8 shows the WMTS 66kV overhead 2011 forecast demand sub-model I; it can be noted that there are few lines or feeders and transformers that are well stressed, with some exceeding 130% of rating.

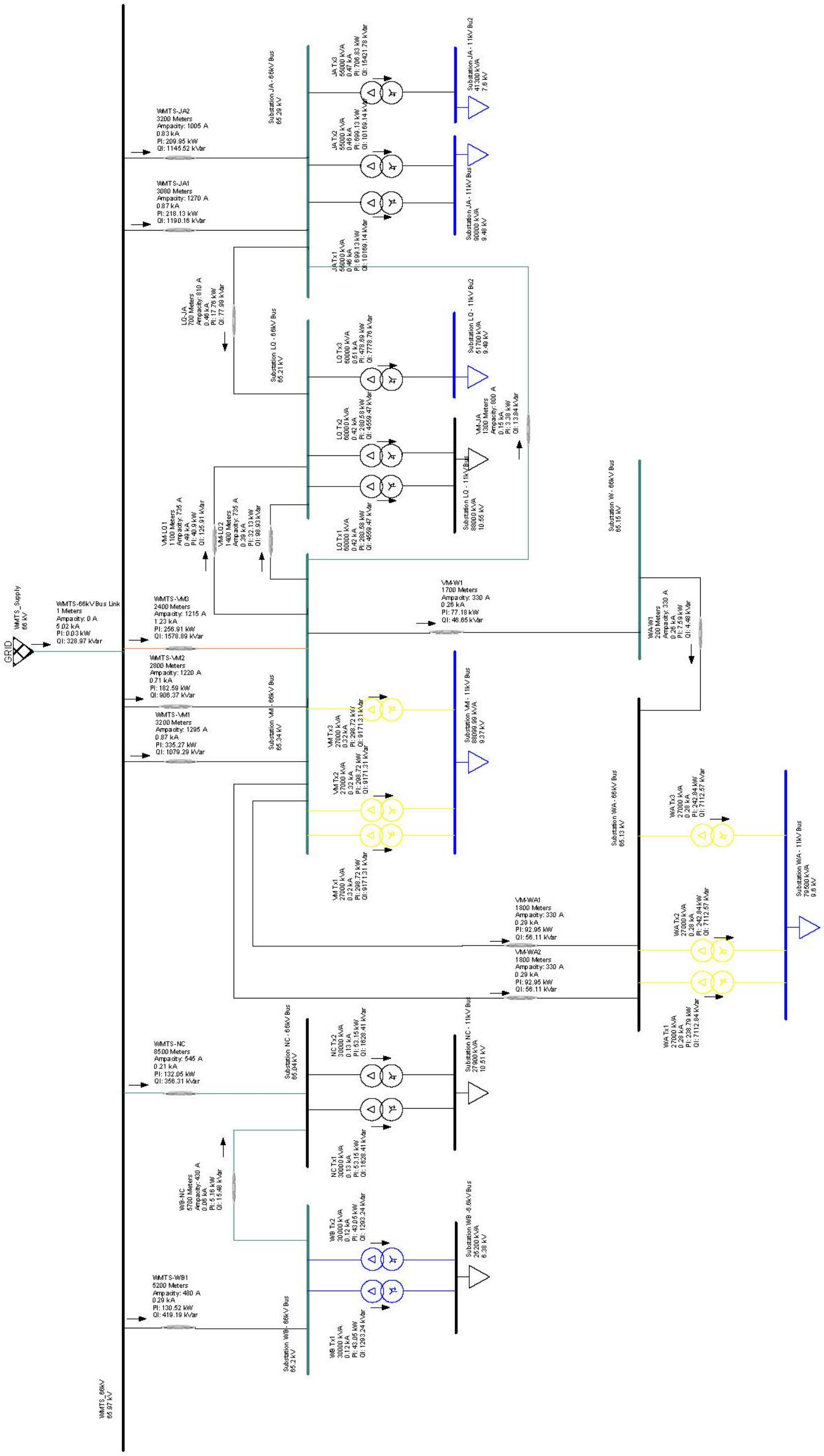


Figure 4.8: WMTS 66kV overhead 2011 forecast sub-model I

An expected finding from Figure 4.8 reveals that many elements in the sub-model will be exceeding their 100% rating. These elements are identified by their colour coding; the line WMTS – VM3 is clearly over 100% loaded and it is found to be 101.3% meanwhile VM zone substation transformers are found to be loaded to 132.7% and are loaded to 116.5%. Additionally there were other elements identified when n-1 redundancy configuration was used. After identifying all the elements over stressed in this sub-model, single or double circuits were added to keep in line with Citipower n-1 redundancy configuration. Also new transformers have been added or existing transformers upgraded to enable the load flow analysis convergence. Figure 4.9 shows the updated WMTS 66kV overhead 2011 forecast sub-model where all elements are operating under their 100% rating and n-1 Citipower redundancy configuration is maintained.

The bus results of flow analysis performed on the WMTS 66kV overhead 2011 forecast sub-model II are presented in Table 4.7. The table lists bus parameters including the current rating.

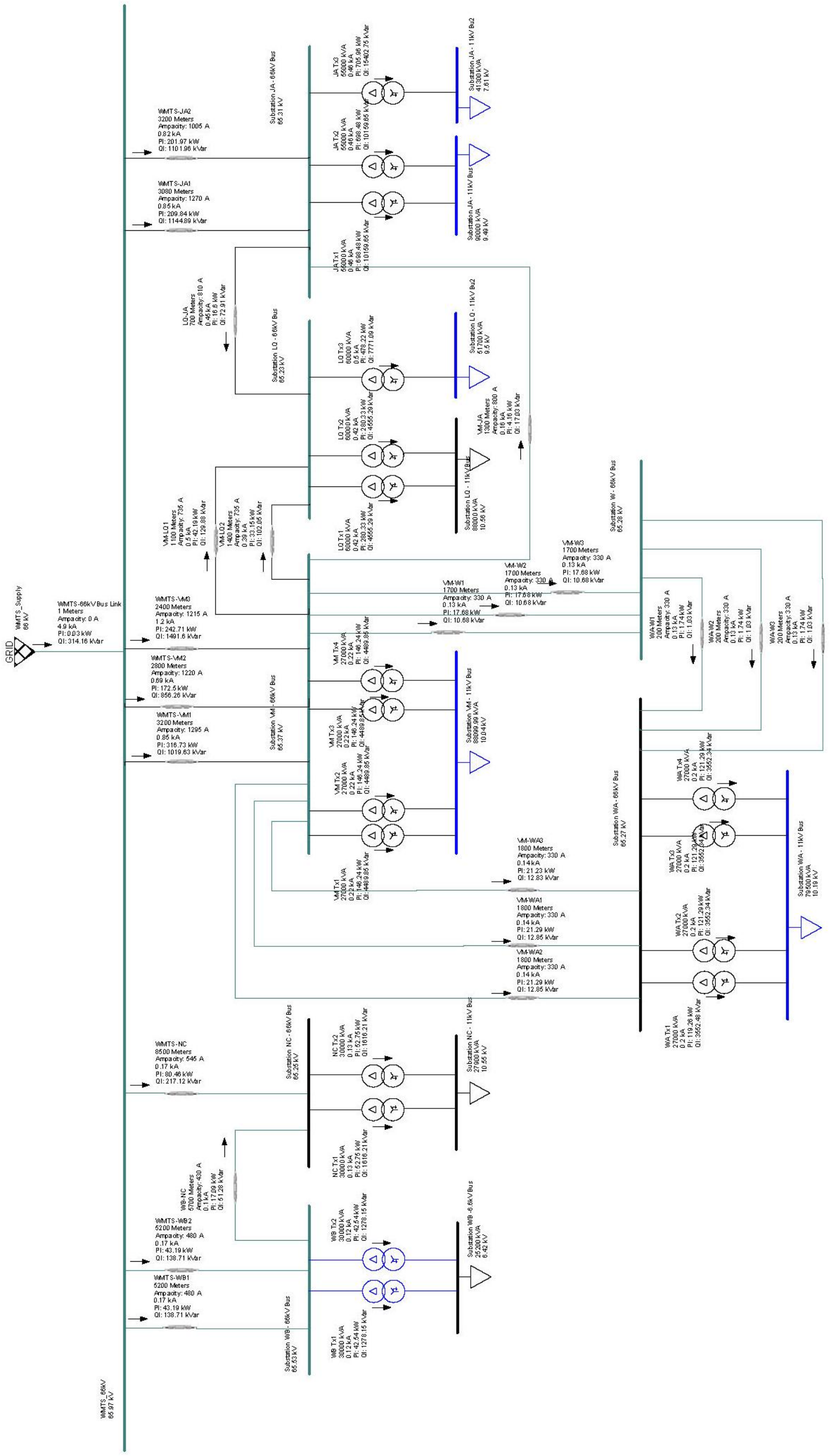


Figure 4.9: WMTS 66kV overhead 2011 updated forecast sub-model II

Table 4.7: WMTS 66kV overhead 2011 updated forecast load flow results

Bus Info	Generation		Static Load		Load Flow Results				
Name	**MW**	**MVAR**	**MW**	**MVAR**	**To Bus Name**	**MW**	**MVAR**	**Amp**	**%pf**
Sub JA 66	0.00	0.00	0.00	0.00	Sub LQ 66	36.73	34.65	446	72.7
					Sub VM 66	-12.03	-14.25	165	64.5
					WMTS 66	-66.69	-69.39	851	69.3
					WMTS 66	-64.19	-66.79	819	69.3
Sub LQ 66	0.00	0.00	0.00	0.00	Sub JA 66	-36.72	-34.58	446	72.8
					Sub VM 66	-42.6	-37.02	500	75.5
					Sub VM 66	-33.48	-29.09	393	75.5
Sub NC 66	0.00	0.00	0.00	0.00	Sub WB 66	-7.58	-8.54	101	66.4
					WMTS 66	-13.46	-13.13	166	71.6
Sub VM 66	0.00	0.00	0.00	0.00	Sub JA 66	12.03	14.27	165	64.5
					Sub LQ 66	42.66	37.15	500	75.4
					Sub LQ 66	33.51	29.19	393	75.4
					Sub W 66	10.21	9.86	125	71.9
					Sub W 66	10.21	9.86	125	71.9
					Sub W 66	10.21	9.86	125	71.9
					Sub WA 66	11.19	10.82	137	71.9
					Sub WA 66	11.19	10.82	137	71.9
					Sub WA 66	11.16	10.80	137	71.9
					WMTS 66	-74.71	-59.86	846	78.0
					WMTS 66	-55.80	-54.97	692	71.2
					WMTS 66	-92.91	-98.65	1197	68.6
Sub W 66	0.00	0.00	0.00	0.00	Sub VM 66	-10.19	-9.85	125	71.9
					Sub VM 66	-10.19	-9.85	125	71.9
					Sub VM 66	-10.19	-9.85	125	71.9
					Sub WA 66	10.19	9.85	125	71.9
					Sub WA 66	10.19	9.85	125	71.9
					Sub WA 66	10.19	9.85	125	71.9
Sub WA 66	0.00	0.00	0.00	0.00	Sub VM 66	-11.17	-10.81	137	71.9
					Sub VM 66	-11.17	-10.81	137	71.9
					Sub VM 66	-11.14	-10.78	137	71.8
					Sub W 66	-10.19	-9.85	125	71.9
					Sub W 66	-10.19	-9.85	125	71.9
					Sub W 66	-10.19	-9.85	125	71.9
Sub WB 66	0.00	0.00	0.00	0.00	Sub NC 66	7.60	8.59	101	66.2
					WMTS 66	-13.35	-13.85	169	69.4
					WMTS 66	-13.35	-13.85	169	69.4
WMTS 66	0.00	0.00	0.00	0.00	Sub JA 66	66.90	70.54	851	68.8
					Sub JA 66	64.39	67.89	819	68.8
					Sub NC 66	13.54	13.35	166	71.2

Sub VM 66	75.03	60.88	846	77.7
Sub VM 66	55.97	55.82	692	70.8
Sub VM 66	93.15	100.14	1197	68.1
Sub WB 66	13.39	13.99	169	69.2
Sub WB 66	13.39	13.99	169	69.2
Total losses	**1.54**	**6.55**		

The load flow results obtained in Table 4.7 are summarised in Table 4.8. The table shows in two different columns the power delivered to and from the line and in the last two columns it lists the power difference or power losses. The total real power losses were found to be 1545.8 kW; in addition total reactive power was found to be 6,555.7 kVAR.

The WMTS 66kV line's real and reactive power losses are shown in Figure 4.10. The figure demonstrates that the power losses are line impedance dependent, as it can be observed that although line WMTS – VM3 is shorter in length than its counterpart WMTS – VM2, however it's real and reactive power losses are much higher. The interpretation for this is due to its current rating which is less than WMTS – VM2 yet it carries almost double the amount of current passing through, as current always tends to pass through shorter paths. As a result, it will produce higher losses.

Table 4.8: WMTS 66kV overhead 2011 updated forecast lines losses

Branch	From -> To Flow		To -> From Flow		Losses	
Name	MW	MVAR	MW	MVAR	kW	kVAR
LQ-JA	-36.718	-34.577	36.734	34.649	16.6	72.9
VM-JA	12.034	14.267	-12.029	-14.250	4.2	17.0
VM-LQ1	42.655	37.150	-42.613	-37.020	42.2	129.9
VM-LQ2	33.515	29.189	-33.482	-29.087	33.1	102.0
VM-W1	10.211	9.860	-10.193	-9.850	17.7	10.7
VM-W2	10.211	9.860	-10.193	-9.850	17.7	10.7
VM-W3	10.211	9.860	-10.193	-9.850	17.7	10.7
VM-WA1	11.195	10.818	-11.173	-10.805	21.3	12.9
VM-WA2	11.195	10.818	-11.173	-10.805	21.3	12.9
VM-WA3	11.160	10.797	-11.139	-10.784	21.2	12.8
WA-W1	-10.191	-9.849	10.193	9.850	1.7	1.0
WA-W2	-10.191	-9.849	10.193	9.850	1.7	1.0
WA-W3	-10.191	-9.849	10.193	9.850	1.7	1.0
WB-NC	-7.582	-8.542	7.600	8.593	17.1	51.3
WMTS-JA1	66.897	70.539	-66.687	-69.394	209.8	1144.9
WMTS-JA2	64.389	67.893	-64.187	-66.791	202.0	1102.0
WMTS-NC	13.541	13.348	-13.461	-13.130	80.5	217.1
WMTS-VM1	75.032	60.884	-74.715	-59.865	316.7	1019.6
WMTS-VM2	55.970	55.822	-55.798	-54.966	172.5	856.3
WMTS-VM3	93.149	100.142	-92.906	-98.650	242.7	1491.6
WMTS-WB1	13.389	13.986	-13.346	-13.847	43.2	138.7
WMTS-WB2	13.389	13.986	-13.346	-13.847	43.2	138.7
			Total power losses		**1545.8**	**6555.7**

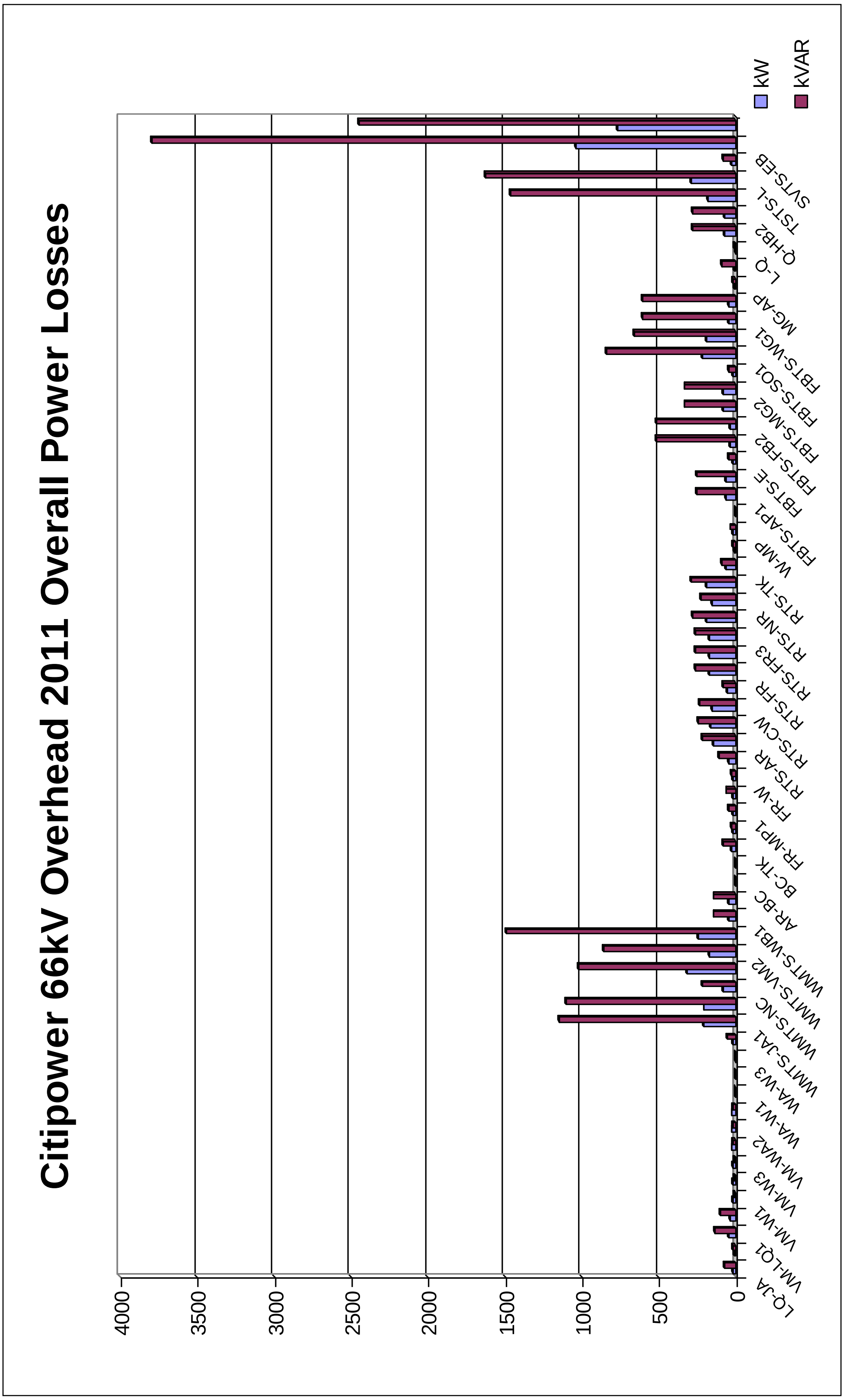


Figure 4.10: WMTS 66kV overhead 2011 forecast lines power losses

4.3.2 WMTS 22kV overhead 2011 forecast sub-model

The configuration of this base sub-model has many similarities to the WMTS 66kV sub-model exhibited earlier in Section 4.3.1, where a load demand of 2011 forecast load demand is used to determine the new overall load flow and identify the elements under stress in the network. After identifying all the elements under stress in this sub-model, single or double circuits are added to keep in line with Citipower n-1 redundancy configuration. Also new transformers have been added or upgraded to enable the load flow analysis to converge. Figure 4.11 shows the updated WMTS 22kV overhead 2011 forecast sub-model.

After performing load flow analysis on the WMTS 22kV overhead 2011 forecast sub-model, the bus results were listed in Table 4.9. The table lists bus parameters including the current rating.

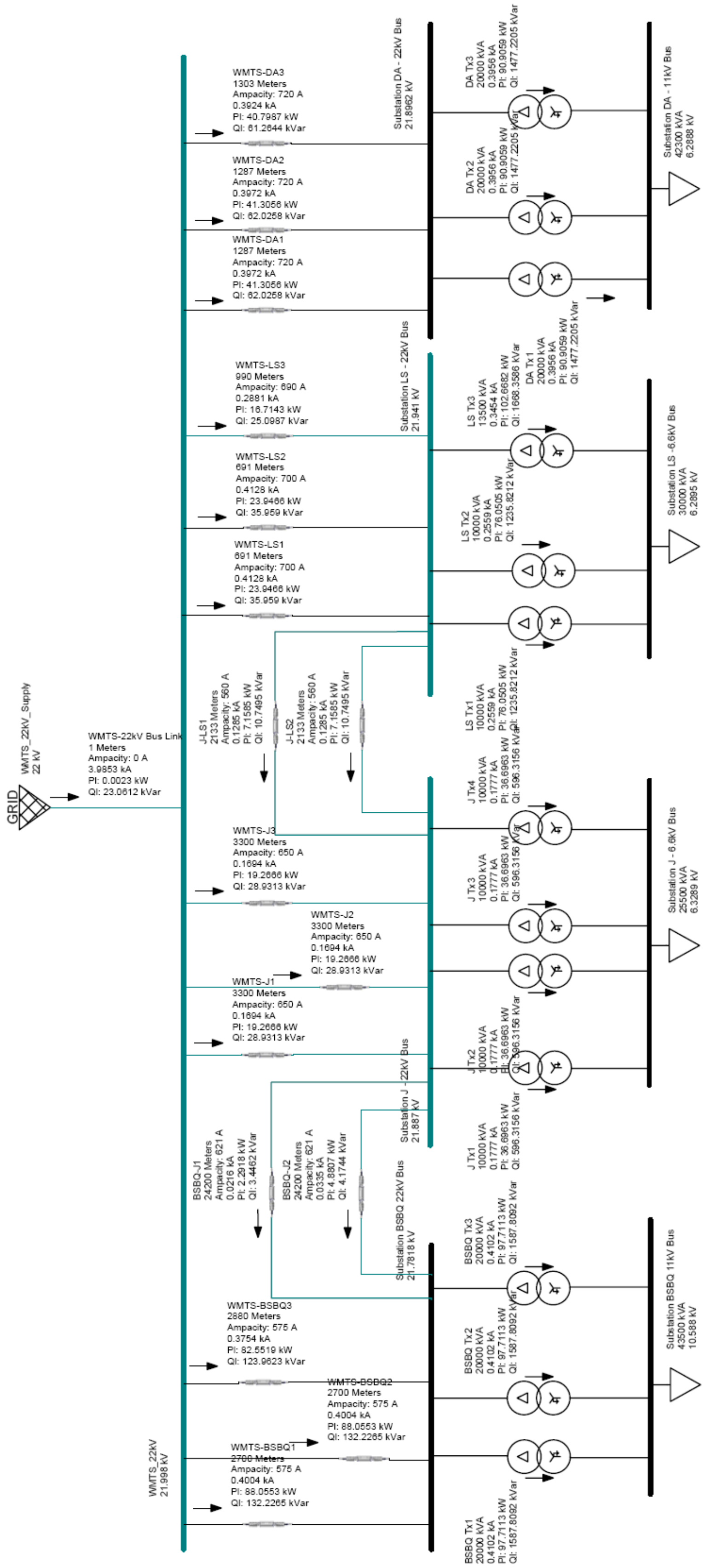


Figure 4.11: WMTS 22kV overhead 2011 forecast sub-model

Table 4.9: WMTS 22kV overhead 2011 forecast load flow results

Bus Info	Generation		Static Load		Load Flow Results				
Name	**MW**	**MVAR**	**MW**	**MVAR**	**To Bus Name**	**MW**	**MVAR**	**Amp**	**%pf**
Sub BSBQ 22	0.00	0.00	0.00	0.00	Sub J 22	-0.64	-0.51	22	78.5
					Sub J 22	-1.17	-0.48	34	92.4
					WMTS 22	-12.07	-9.09	400	79.9
					WMTS 22	-11.32	-8.52	375	79.9
					WMTS 22	-12.07	-9.09	400	79.9
Sub DA 22	0.00	0.00	0.00	0.00	WMTS 22	-12.13	-8.94	397	80.5
					WMTS 22	-12.13	-8.94	397	80.5
					WMTS 22	-11.98	-8.83	392	80.5
Sub J 22	0.00	0.00	0.00	0.00	Sub BSBQ 22	0.64	0.51	22	78.4
					Sub BSBQ 22	1.17	0.49	34	92.3
					Sub LS 22	-4.01	-2.77	128	82.3
					Sub LS 22	-4.01	-2.77	128	82.3
					WMTS 22	-5.21	-3.76	169	81.1
					WMTS 22	-5.21	-3.76	169	81.1
					WMTS 22	-5.21	-3.76	169	81.1
Sub LS 22	0.00	0.00	0.00	0.00	Sub J 22	4.01	2.78	128	82.2
					Sub J 22	4.01	2.78	128	82.2
					WMTS 22	-12.52	-9.45	413	79.8
					WMTS 22	-8.74	-6.60	288	79.8
					WMTS 22	-12.52	-9.45	413	79.8
WMTS 22	0.00	0.00	0.00	0.00	Sub BSBQ 22	12.16	9.22	400	79.7
					Sub BSBQ 22	11.40	8.64	375	79.7
					Sub BSBQ 22	12.16	9.22	400	79.7
					Sub DA 22	12.17	9.00	397	80.4
					Sub DA 22	12.17	9.00	397	80.4
					Sub DA 22	12.02	8.89	392	80.4
					Sub J 22	5.23	3.79	169	81.0
					Sub J 22	5.23	3.79	169	81.0
					Sub J 22	5.23	3.79	169	81.0
					Sub LS 22	12.54	9.49	413	79.8
					Sub LS 22	8.76	6.62	288	79.8
					Sub LS 22	12.54	9.49	413	79.8
					Total losses	**0.5**	**0.78**		

The load flow results obtained in Table 4.9 are summarised in Table 4.10. The table shows in two different columns the power delivered to and from the line and in the last two columns it lists the power difference or power losses.

The total real power losses were found to be 526.2 kW; in addition the total reactive power was found to be 786.5 kVAR.

Table 4.10: WMTS 22kV overhead 2011 forecast lines losses

Branch	**From -> To Flow**		**To -> From Flow**		**Losses**	
Name	**MW**	**MVAR**	**MW**	**MVAR**	**kW**	**kVAR**
BSBQ-J1	-0.639	-0.505	0.641	0.509	2.3	3.4
BSBQ-J2	-1.168	-0.483	1.173	0.488	4.9	4.2
J-LS1	-4.007	-2.767	4.014	2.778	7.2	10.7
J-LS2	-4.007	-2.767	4.014	2.778	7.2	10.7
WMTS-BSBQ1	12.159	9.217	-12.071	-9.085	88.1	132.2
WMTS-BSBQ2	11.399	8.641	-11.316	-8.517	82.6	124.0
WMTS-BSBQ3	12.159	9.217	-12.071	-9.085	88.1	132.2
WMTS-DA1	12.167	9.003	-12.125	-8.941	41.3	62.0
WMTS-DA2	12.167	9.003	-12.125	-8.941	41.3	62.0
WMTS-DA3	12.017	8.893	-11.977	-8.832	40.8	61.3
WMTS-J1	5.227	3.789	-5.207	-3.760	19.3	28.9
WMTS-J2	5.227	3.789	-5.207	-3.760	19.3	28.9
WMTS-J3	5.227	3.789	-5.207	-3.760	19.3	28.9
WMTS-LS1	12.545	9.487	-12.521	-9.451	23.9	36.0
WMTS-LS2	8.756	6.621	-8.739	-6.596	16.7	25.1
WMTS-LS3	12.545	9.487	-12.521	-9.451	23.9	36.0
			Total power losses		**526.2**	**786.5**

The WMTS 22kV overhead line's real and reactive power losses are shown in Figure 4.12. The figure demonstrates that the power losses are line impedance dependent, as it can be observed that although the line WMTS – BSBQ1 is shorter in length than its counterpart WMTS – BSBQ2, however its real and reactive power losses are much higher and the reason for that is the higher current passing through it.

To sum up this section, the summation of power losses found in 22kV and 66kV loops are presented as the total power losses in the WMTS section of Citipower for network configuration with a forecast 2011 loading demand.

Total real power losses = 526.2 + 1545.8 = 2072.00 kW

Total reactive power losses = 786.5 + 6555.7 = 7342.20 kVAR

A better representation of the power loss comparison for the Citipower WMTS section of the overhead network with power losses obtained from both 2007 and 2011 loading demand is shown in Figure 4.13.

As can be seen, the losses for the forecast year 2011 are three and a half times more than the losses for the year 2007; this observation can be interpreted as due to the high amount of current that flows through the inductor of the lines which causes greater losses.

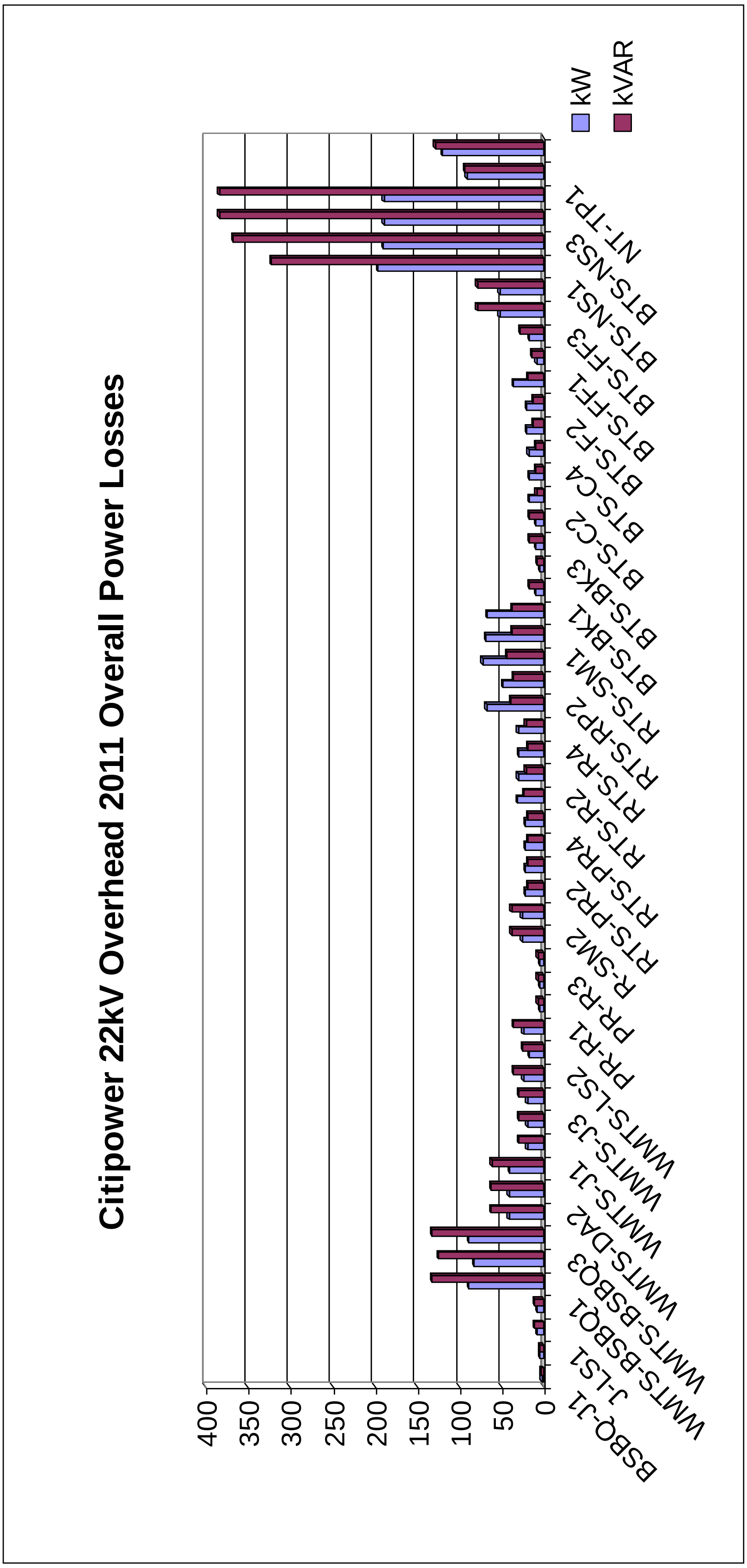


Figure 4.12: WMTS 22kV overhead 2011 forecast lines power losses

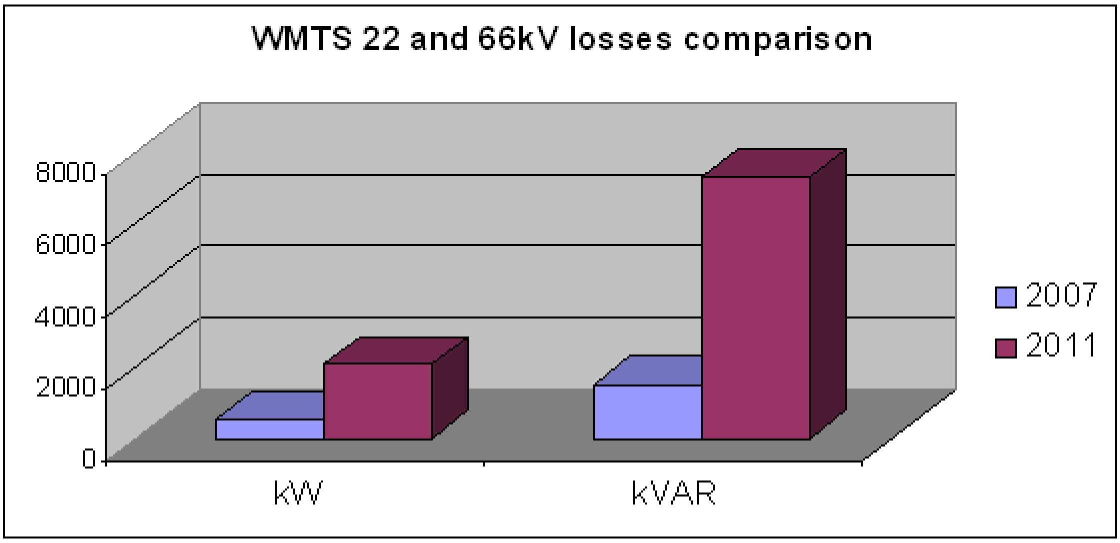


Figure 4.13: WMTS 22kV and 66kV overhead power loss comparison

Another observation that can be drawn from WMTS both 22kV and 66kV forecast sub-modules is that some of the lines have been duplicated and some transformers have been upgraded to keep the n-1 citipower configuration in position. These additional elements are:

VM – W2, VM – W3, WA – W2, WA – W3, WMTS – WB2, BSBQ – J2, J – LS2, WMTS – BSBQ3, WMTS – DA3, WMTS – J2, WMTS – J3, WMTS – LS3, VMTx4 and WATx3.

Meanwhile upgraded elements are:

DA transformers 1-3 has been upgraded from 13.5 MVA to 20 MVA; and BSBQ transformer 1-3 has been upgraded from 10 MVA to 20 MVA.

4.5 Citipower 2007 Overhead Overall Power Losses

Data for the remaining terminal stations' loops of overhead network is found in Figure 4.1. Most of this data was obtained from Citipower and its publications from the public domain with the exception of the assumptions mentioned earlier in Section 4.1. Separate sub-models were developed individually for each terminal station with separate sections for 66kV and 22kV voltage levels.

Appendix E lists Citipower Terminal stations overhead sub-models.

Following the load flow analysis of the two voltage levels, 66kV and 22kV, a submission of all power losses is given in Tables 4.11 and 4.12 to undergo further analysis, which basically represents the loading demand of WMTS for the year 2007.

Table 4.11: Citipower 66kV overhead overall lines losses

Branch Name	kW losses	kVAR losses
LQ-JA	10.6	46.4
VM-JA	0.3	1.3
VM-LQ1	6.1	18.8
VM-LQ2	4.8	17.0
VM-W	24.2	14.6
VM-WA1	29.1	17.6
VM-WA2	29.0	17.5
WA-W	2.4	1.4
WB-NC	1.6	4.7
WMTS-JA1	28.9	157.6
WMTS-JA2	29.2	157.6

WMTS-NC	28.1	75.7
WMTS-VM1	57.4	184.7
WMTS-VM2	31.2	155.1
WMTS-VM3	44.0	270.1
WMTS-WB	25.6	82.2
AR-BC	1	2.7
B-CW	1.1	2.9
BC-TK	17.3	45.8
CL-K	0.3	1
FR-MP1	1.4	4.7
FR-MP2	1.7	5.8
FR-W	0.3	1
NR-B	29.3	71.4
RTS-AR	20.5	84.3
RTS-CL	70.5	208
RTS-CW	58.2	212.8
RTS-EW	40.8	117.1
RTS-FR1	29.7	98.4
RTS-FR2	29.7	98.4
RTS-FR3	30	98.8
RTS-K	34.6	173.4
RTS-NR	155.2	486
RTS-SK	105.8	259.1
RTS-TK	37.7	120
SK-EW	2.9	9.4
W-MP	0.4	1.5
E-PM	0.2	0.5
FBTS-AP	22.1	88.7
FBTS-E	3.4	9.3
FBTS-FB	31.4	514.7
FBTS-MG	30.6	131.4
FBTS-PM	1.7	5.4
FBTS-SO1	23.4	91.3
FBTS-SO2	20.9	71.4
FBTS-WG	58.5	794.4
MG-AP	0.5	2.7
WG-FB	2.8	37.9
L-Q	0.4	1.3
Q-HB	44.4	176.3
TSTS-HB	86.3	710
TSTS-L	137.4	779.5
EB-RD	1.5	4.5
SVTS-EB	93.2	340.3
SVTS-RD	71.9	229.4
Total overall power losses:	**1,651.5**	**7,313.8**

Both the real and reactive power losses of Citipower 66kV overhead lines are shown in Figure 4.14. The figure demonstrates that the power losses are line impedance dependent and the higher current passing and longer length of line will result in higher power losses in that particular line.

The Citipower 22kV overhead lines for both real and reactive power losses are summarised in Table 4.12.

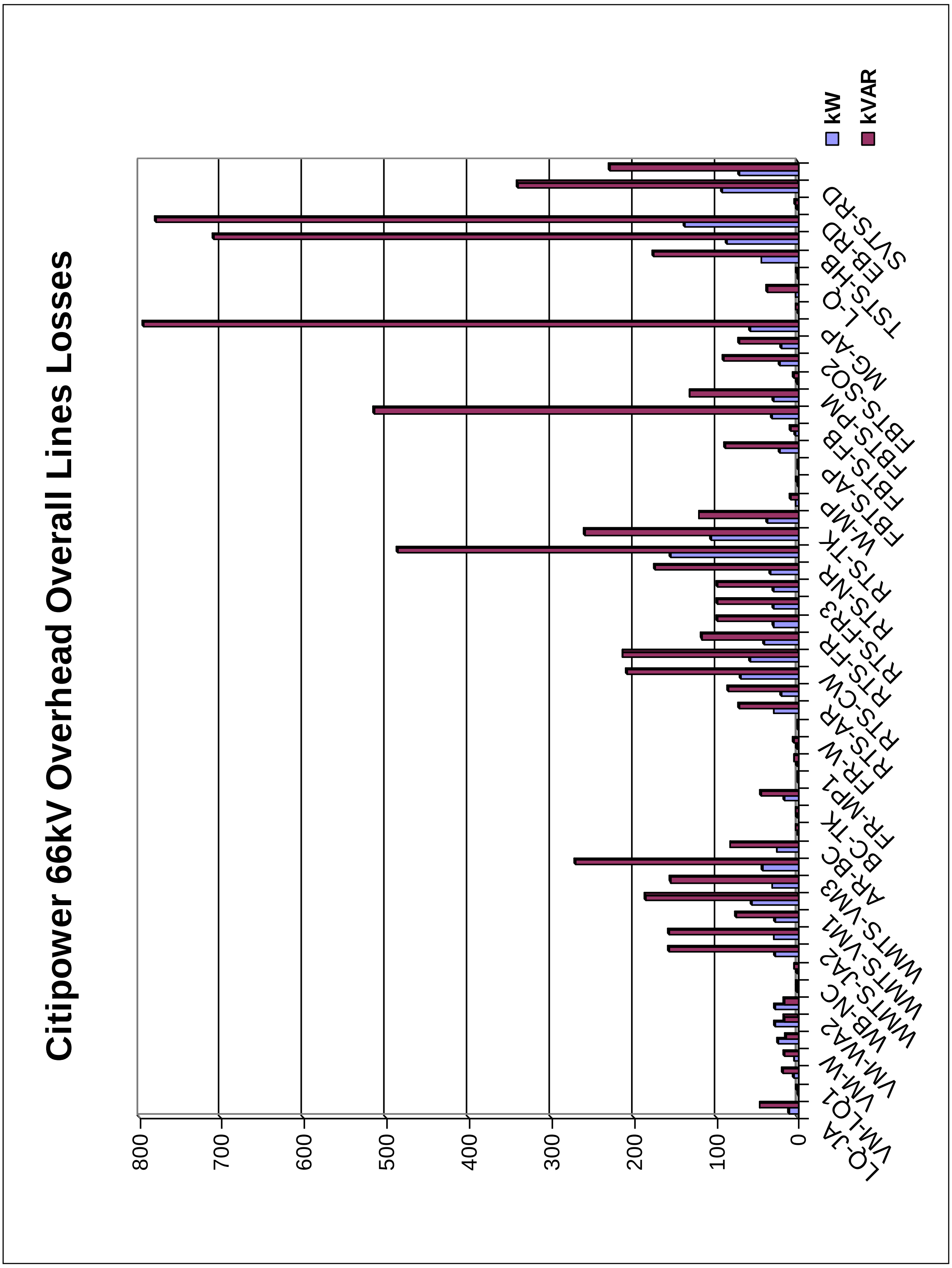


Figure 4.14: Citipower 66kV overhead overall power loss

Table 4.12: Citipower 22kV overhead overall lines losses

Branch Name	kW losses	kVAR losses
BSBQ-J	1.3	1.9
J-LS	29.4	44.2
WMTS-BSBQ1	37.5	56.4
WMTS-BSBQ2	35.2	52.9
WMTS-DA1	12.4	18.7
WMTS-DA2	12.3	18.5
WMTS-J1	42.2	63.4
WMTS-LS1	21.9	32.8
WMTS-LS2	15.3	22.9
PR-R	15.5	8.5
R-SM	4	2.3
RTS-PR2	16.2	14
RTS-PR3	16.2	14
RTS-R1	8.2	6.1
RTS-R2	8.1	5.6
RTS-R3	7.9	5.1
RTS-RP1	9.4	5.4
RTS-RP2	6.6	5
RTS-RP3	10.1	6
RTS-SM1	10.3	5.6
RTS-SM2	10.1	5.7
BTS-BK1	2.5	4.7
BTS-BK2	1.2	2.1
BTS-BK3	2.5	4.7
BTS-C2	12.9	6.6
BTS-C3	13.2	6.7
BTS-C4	13.5	6.9
BTS-F1	5.8	3.6
BTS-F2	5.8	3.6
BTS-F3	10.2	5.2
BTS-FF1	9	15.6
BTS-FF2	18.3	30.5
BTS-FF3	35.8	57.5
BTS-NS1	107.7	177.1
BTS-NS2	104.3	201.7
BTS-NS3	103.7	210.8
NT-TP1	22.1	22.6
NT-TP2	29.1	31.1
Total overall power losses:	**827.7**	**1,186.0**

Similarly, Citipower 22kV overhead lines with both real and reactive power losses are represented in Figure 4.15. The figure demonstrates that power losses are line impedance dependent and the higher current passing and longer length of line will result in higher power losses in that particular line.

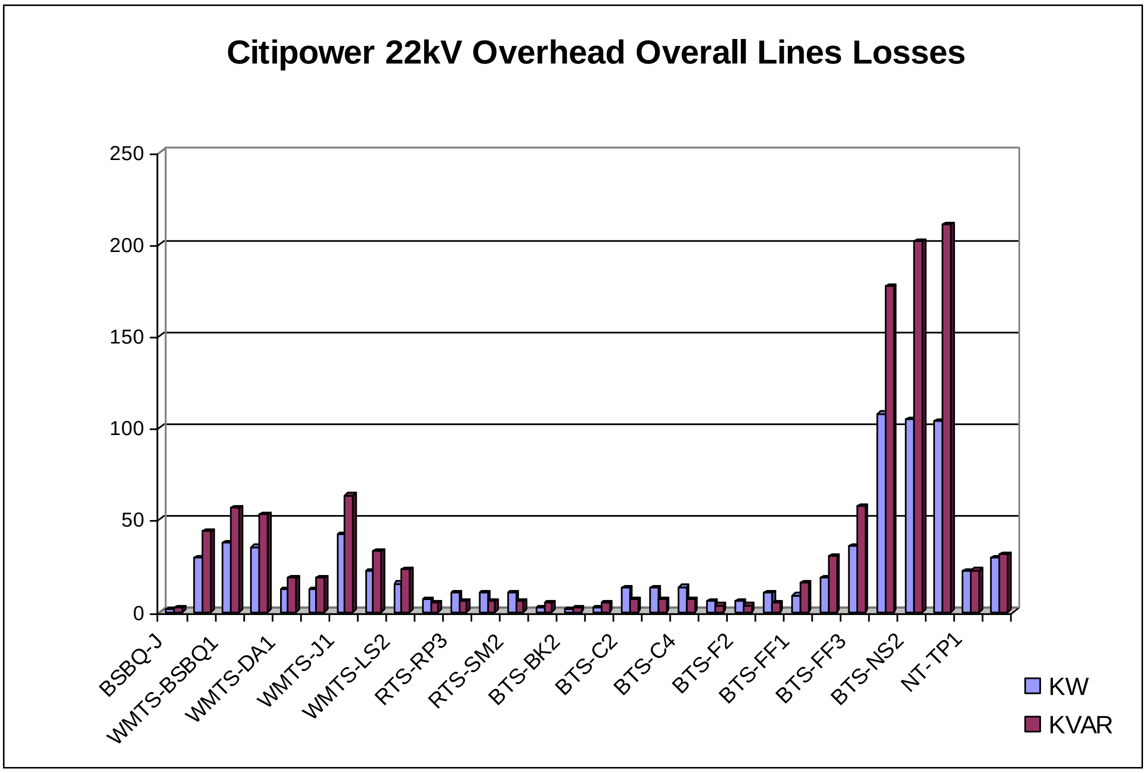


Figure 4.15: Citipower 22kV overhead overall power loss

A combined summation of power losses is found in Tables 4.11 and 4.12 for 22kV and 66kV loops which illustrate the total power losses in the Citipower for the overhead network configuration with a 2007 loading demand.

Total real power losses = 827.7 + 1,651.5 = 2,479.2 kW

Total reactive power losses = 1,186.0 + 7,313.8 = 8499.8 kVAR

4.6 Citipower 2011 Forecast Overhead Overall Power Losses

Overhead network data, for the year 2011, of all terminal stations loops found in Figure 4.1 were again obtained from Citipower publications. Some of the network data were not available; therefore assumptions in Section 4.1 were used for the development of the network. Separate sub-models were developed individually for each terminal station with separate sections for 22kV and 66kV voltage levels.

Appendix H lists Citipower Terminal stations overhead Forecast 2011 sub-models.

After obtaining the flow analysis of the two voltage levels, a submission of all power losses, which represents the loading demand of WMTS for the year 2011, is given in Tables 4.13 and 4.14 to undergo further analysis.

Table 4.13: Citipower 66kV overhead 2011 forecast overall lines losses

Branch Name	kW losses	kVAR losses
LQ-JA	16.6	72.9
VM-JA	4.2	17
VM-LQ1	42.2	129.9
VM-LQ2	33.1	102
VM-W1	17.7	10.7
VM-W2	17.7	10.7
VM-W3	17.7	10.7
VM-WA1	21.3	12.9
VM-WA2	21.3	12.9
VM-WA3	21.2	12.8
WA-W1	1.7	1
WA-W2	1.7	1
WA-W3	1.7	1
WB-NC	17.1	51.3
WMTS-JA1	209.8	1144.9
WMTS-JA2	202	1102
WMTS-NC	80.5	217.1
WMTS-VM1	316.7	1019.6
WMTS-VM2	172.5	856.3
WMTS-VM3	242.7	1491.6
WMTS-WB1	43.2	138.7
WMTS-WB2	43.2	138.7
AR-BC	1.2	1.8
B-CW	0.3	0.5
BC-TK	29.7	78.5
CL-K	14.6	22
FR-MP1	13.5	46.4
FR-MP2	16.6	57.3
FR-W	15.4	23.2
NR-B	44.1	107.5
RTS-AR	142.2	213.8
RTS-CL	160.4	241.2
RTS-CW	156.3	235.1
RTS-EW	50.7	76.3
RTS-FR1	173	260.2
RTS-FR2	173	260.2
RTS-FR3	173	260.2
RTS-K	186.8	280.9
RTS-NR	150.8	226.7
RTS-SK	189.7	285.3
RTS-TK	61	91.8

SK-EW	6.3	20.5
W-MP	19.9	29.9
E-PM	0.02	0.05
FBTS-AP1	63	252.6
FBTS-AP2	63	252.6
FBTS-E	16.8	45.7
FBTS-FB1	31.3	512.7
FBTS-FB2	31.3	512.7
FBTS-MG1	76.3	328.3
FBTS-MG2	76.3	328.3
FBTS-PM	14.3	44.5
FBTS-SO1	214.9	837.2
FBTS-SO2	191.3	655.4
FBTS-WG1	44.4	602.9
FBTS-WG2	44.4	602.9
MG-AP	3.4	17.4
WG-FB	6.4	86.5
L-Q	1.4	4.3
Q-HB1	70.1	278.1
Q-HB2	70.1	278.1
TSTS-HB	178.2	1466
TSTS-L	286.9	1627.6
EB-RD	25.1	78
SVTS-EB	1040.3	3797
SVTS-RD	766.1	2444.5
Total overall power losses:	**6639.62**	**24428.35**

The Citipower 66kV overhead overall line's real and reactive power losses are shown in Figure 4.16. The figure demonstrates that the power losses are line impedance dependent and the higher current passing and longer length of line will result in higher power losses in that particular line.

The Citipower 22kV overhead line's both real and reactive power losses are summarised in Table 4.14.

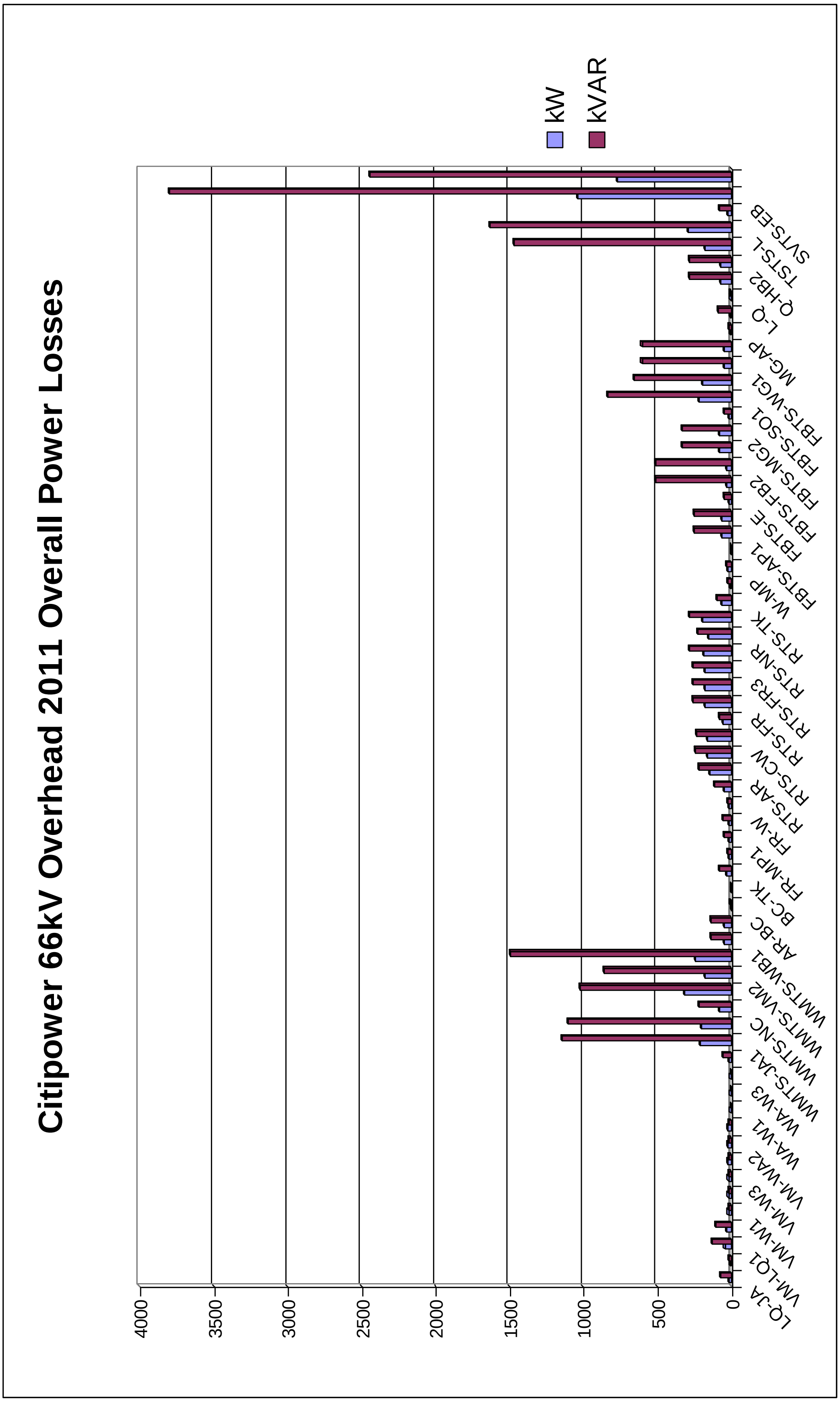


Figure 4.16: Citipower 66kV overhead 2011 forecast overall power losses

Table 4.14: Citipower 22kV overhead 2011 forecast overall power losses

Branch Name	kW losses	kVAR losses
BSBQ-J1	2.3	3.4
BSBQ-J2	4.9	4.2
J-LS1	7.2	10.7
J-LS2	7.2	10.7
WMTS-BSBQ1	88.1	132.2
WMTS-BSBQ2	82.6	124
WMTS-BSBQ3	88.1	132.2
WMTS-DA1	41.3	62
WMTS-DA2	41.3	62
WMTS-DA3	40.8	61.3
WMTS-J1	19.3	28.9
WMTS-J2	19.3	28.9
WMTS-J3	19.3	28.9
WMTS-LS1	23.9	36
WMTS-LS2	16.7	25.1
WMTS-LS3	23.9	36
PR-R1	4.6	7
PR-R2	4.6	7
PR-R3	4.6	7
R-SM1	25.3	38.1
R-SM2	25.3	38.1
RTS-PR1	21.1	18.2
RTS-PR2	21.2	18.3
RTS-PR3	21.2	18.3
RTS-PR4	21.2	18.3
RTS-R1	30.6	22.7
RTS-R2	30	20.7
RTS-R3	29.2	19
RTS-R4	30	20.7
RTS-RP1	67.4	38.7
RTS-RP2	47.6	35.7
RTS-RP3	72.1	43.3
RTS-SM1	68.2	37.1
RTS-SM2	67.1	37.5
BTS-BK1	9	17
BTS-BK2	4.3	7.8
BTS-BK3	9	17
BTS-BK4	9	17
BTS-C2	16.7	8.5
BTS-C3	17	8.7
BTS-C4	17.5	8.9

BTS-F1	20.2	12.7
BTS-F2	20.2	12.7
BTS-F3	35.4	18
BTS-FF1	8.3	14.3
BTS-FF2	16.8	27.9
BTS-FF3	52.1	78.4
BTS-FF4	52.1	78.4
BTS-NS1	196.2	322.7
BTS-NS2	190	367.5
BTS-NS3	188.9	384
BTS-NS4	188.9	384
NT-TP1	91.1	92.9
NT-TP2	120	128.2
Total overall power losses:	**2380.2**	**3238.8**

The Citipower 22kV overhead overall line's real and reactive power losses are graphically represented in Figure 4.17. The figure demonstrates that power losses are line impedance dependent and the higher current passing and longer length of line will result in higher power losses in that particular line.

A combined summation of power losses that was found in Tables 4.13 and 4.14 for 22kV and 66kV loops which are presented as the total power losses in the Citipower for overhead network configuration with a 2011 forecast loading demand.

Total real power losses = 6639.62 + 2380.20 = 9019.82 kW

Total reactive power losses = 24428.35 + 3238.80 = 27667.15 kVAR

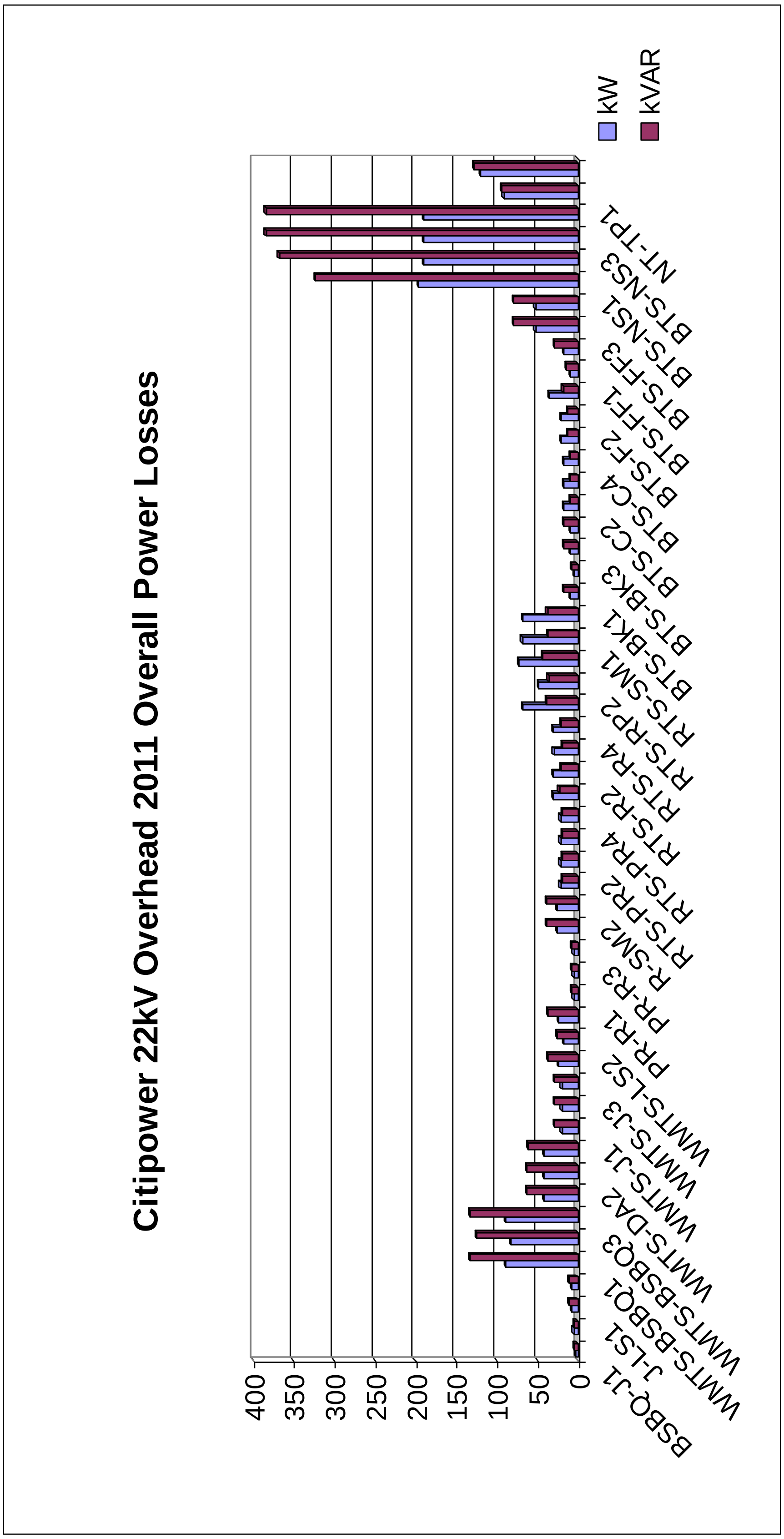


Figure 4.17: Citipower 22kV overhead 2011 forecast overall power loss

A clearer representation of the comparison of power losses for the overall Citipower overhead network with power losses obtained from both 2007 and 2011 loading demand is shown in Figure 4.18.

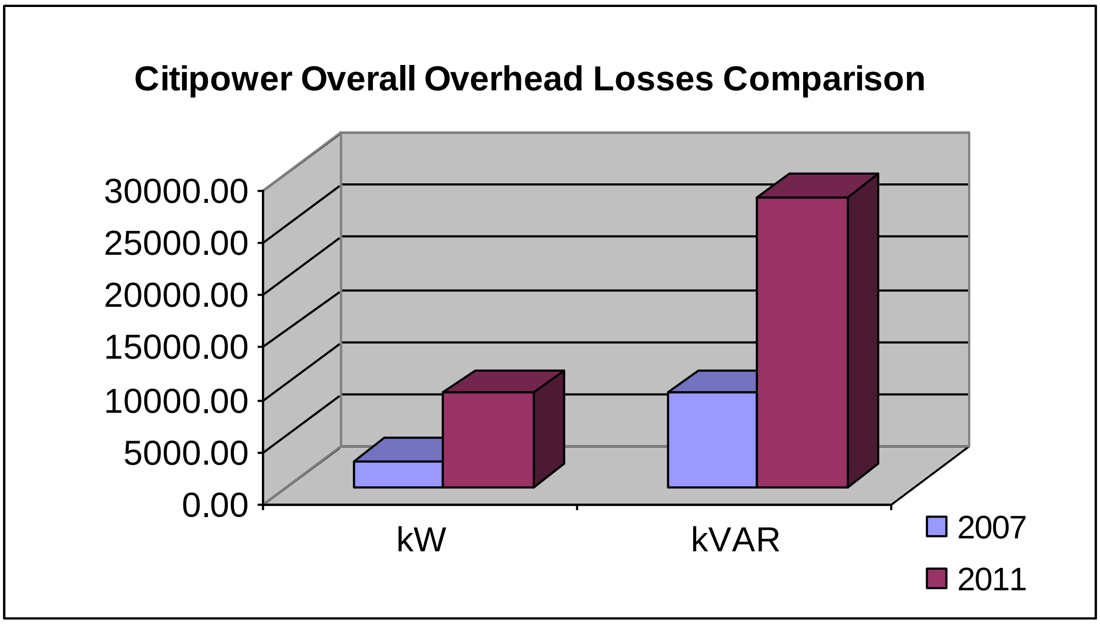


Figure 4.18: Citipower overall overhead power loss comparison

As can be seen, the losses for the forecast year 2011 are almost three and a half times more than the losses for the year 2007, Moreover there are many lines duplicated to keep the Citipower n-1 configuration; the added lines reduced the power losses due to the fact that less current will pass through the same lines and it will produce less power losses.

4.7 Conclusion

A Comprehensive analysis and development of Victorian overhead power network sub-models were presented in detail in this chapter. In addition, an elaboration on overall overhead network sub-models was discussed in chapter 3. These analyses are of great significance for future growth and for the safe operation of the Victorian power network. Various forecasted models were analysed and critical analysis has been provided to determine the need to add additional lines and transformers to enable the handling of the additional forecasted load in the network.

Load flow analyses and other industrial based specialised software were used to investigate and develop various sub-transmission network models. The results obtained from the load flow analyses provided crucial information about all buses in the network. Some buses were exceeding their normal operation values or nominal values so an action was made to rectify the problem associated with any abnormality in the network; The Citipower n-1 redundancy configurations were met in all developed sub-models.

Another outcome of the load flow analysis was the determination of the real and reactive power losses at each line and the effect of forecasted loading on the losses was identified.

The next chapter looks at the Victorian overhead power network in an attempt to efficiently design an underground network for Victoria.

CHAPTER 5

UNDERGROUND POWER NETWORKS

5.0 Introduction

Undergrounding is no longer perceived as a prohibitively expensive exercise due to its the advancement of technology in underground cables as discussed earlier in this thesis. The cost of undergrounding is very encouraging practically when installed in newly developed estates. However, old established areas will continue to remain serviced by overhead power lines due to the expensive conversion exercise at this point in time.

A typical underground power sub-transmission and distribution system with the other stages of the power network including generation and overhead transmission is shown in Figure 5.1.

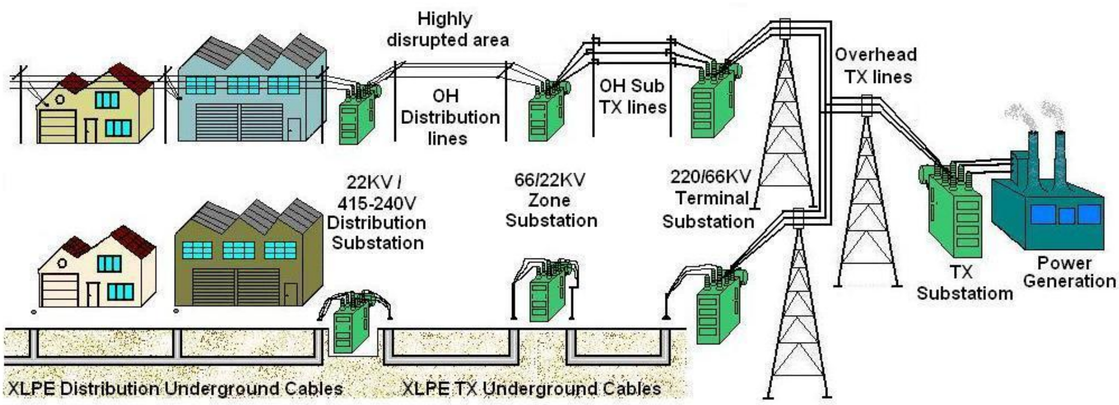


Figure 5.1: Power Network with underground sub-transmission and distribution systems [4]

Despite the added reliability that could be gained from undergrounding, it is important to know that fault detection and elimination is much more time and money consuming than its overhead counterpart.

Even shorter interruption time in overhead lines, does not hold as a viable discussion point when arguing against installing underground solutions. Furthermore, the total loss of revenues is far less when undergrounding than using overhead and that's primarily due the significantly decreased fault frequency [29].

5.1 General Overview

The electric energy industry dates from the late 18th (1882) century when Thomas Edison created the first underground system of commercial electricity distribution. This system, as humble as it may have been with a capacity to deliver 100 Volts of direct current, however, was the corner stone of a greater system which witnessed the birth of the transformer four years later (1886). The transformer made distribution for long distance a dream comes true, thanks to the Alternating Current (ac) electric pressure which reached 1000 Volts and then dropped the current to safer levels for domestic use, similar to Direct Currents (dc). This great invention opened the door wide for commercial distribution especially when overhead lines were easily utilised due to their relatively low cost [29].

Needless to say, that these relatively inexpensive overhead lines systems have contributed to the rapid growth of rural and suburban communities in the out skirts of major cities. But with the growth of populations and boom of business around the globe, due to the industrial revolution post World War II, Central Business Districts (CBDs) around the world started to see a shift from the traditional overhead lines and they started building underground systems for aesthetical and economical reasons. The continuous development in technology and plastic fabrication post World War II has led to the wide expansion of underground systems in those urban and metropolitan areas with new creative designs of curvy streets and closes. Consequently, this has made thinking of using overhead less appealing to infrastructure developers, as it is more material and man power exhaustive and demanding than its more aesthetically appealing and environmentally friendly and lower cost underground systems. Furthermore, undergrounding has witnessed a huge reduction in cost in the past 5 decades due to technological advancement in cable fabrication and installation techniques such as direct burial of extra long spans between splices [29].

5.2 Voltage Regulation

In general, electricity is transmitted in high voltage from the generation plants to distribution substations. Voltages at distribution stages are much lower than their levels at the generation stages where they are distributed to different loads. Finally, they are dropped further to much lower levels where they will be used by domestic consumers [29].

Normally, generated voltage could reach 20kV or more; this voltage is then raised to approximately 140kV by transformers to prepare it for high load transmission over long distance routes to reach transmission substations where voltage levels are stepped down to approximately 69kV to enter into low load distribution substations in designated areas and this where the main voltage is regulated between 120 or 240 Volts by distribution transformers [29].

5.3 Overhead vs. Underground

Electric energy utilises overhead and underground means to deliver power. Overhead networks comprise relatively low-cost insulators and conductors mounted on poles made of various materials like wood, steel or concrete. Other overhead equipments are installed on some of these poles which make it more cost effective to repair and maintain. On the other hand, this direct exposure has a down side of being highly susceptible to malfunctioning due to environmental and man made breakdowns [29].

Undergrounding consists of maintenance holes which are commonly referred to as manholes which are tubes used to connect underground utilities to the surface. Manholes are widely used in sewer systems, electrical and communication systems. These manholes are situated at regular intervals along the utility path, to allow easy access to maintenance workers. Rubber and other insulated conductors (cables) are installed and sliced inside these underground cavities. Therefore, fault detection and repairs can be a very costly exercise [29].

Undergrounding used to be implemented in very few cases where it met strict regulatory conditions. This was primarily, due to the high cost involved in undergrounding, for example when utilities and the public dispute over private property for line easement. Over the years, various factors have played a significant role in increasing the deployment of undergrounding. Some of these core factors are: the demand for higher power consumption which has led to building more generation sites. Unfortunately, it became ultra difficult to obtain properties for such purposes. Another factor was the need for larger more economical generation units instead of local units. Finally, a more recent factor came into inception which is that health and environmental effects have been pushed quite heavily by industry lobby groups, regulators and more green governments [29].

The aforementioned emphasis on health and environmental effects was the major driver for increased undergrounding due to the perception that underground cables will emit less electromagnetic field. Furthermore, cities began to pay extra attention to the visual appearance of their urban areas and business districts to attract more tourists and investors, therefore more power lines started to disappear in well presented paved areas. Underground cables in general operate under lower voltage levels than their overhead counterparts. Therefore, it was necessary to implement step-up and step-down transformers to maintain a long overhead line route [29].

The biggest advantage of underground installation is that it is less exposed and susceptible to external factors than overhead. However, somehow or other, this advantage can be offset by the time and effort spent in locating and repairing faults should they take place. The nature of the installation design and the complexity will be determined by the obligatory standards used for the installation [29].

Chang et al. [14], argued that although underground cables have continued, up until the present, to be more expensive than overhead lines for the same capacity, a number of European countries like the Netherlands have had underground cables installed widely since the early 70’s. The reasons behind their ultimate decisions were based on:

- environmental nature of power network reliability;

- shortage of land and its utilisation;
- recent regulation changes and opposition to overhead lines among the public.

On the other hand development and reduction in the cost of cable technology enhanced with reliable and efficient cable installation have contributed considerably in reducing the overall cost of underground cables. Meanwhile the cost ratio is less prominent at lower voltages and the economic potential of operating and maintenance costs favour underground cables and make them a dominant alternative solution to overhead lines in many cases such as:

- highly congested or populated urban areas;
- areas with historic or environmental values;
- crucial sections of the network which have low reliability records; and
- areas with a need for extra capacity where constructing a new overhead transmission line is out of question.

Adopting underground power cables has been slow in Australia in the past mainly as a consequence of the high cost of the cable technology, the low density demographic of Australian cities and limited restrictions on the use of overhead lines. Major catastrophic events have normally acted as the mechanism which drives the undergrounding of power lines. In 1974, when Cyclone Tracey hit Darwin it provided the justification for undergrounding Darwin overhead lines so subsequently by 1980, more than 50% of that city was serviced by underground LV and MV cables. Although there was little effort to retrofit existing areas throughout Australian cities since 1980, a steady introduction of underground cables for new residential areas has been undertaken. The bush fire risks in Australia has turned out to be more apparent due to climate change, in many cases these bushfires were results of clashing of bare conductors. Besides, the consumer demand for a more reliable and safer power supply will highlight the necessity of undergrounding the existing power network [30]. The relevant aspects of different underground cables have been elaborated.

5.4 Reliability Issues

As reference [31] reported, the top predominate causes of outages which account for over 50% of all power outages were external and due to tree and conductor failure. Figure 5.2 shows the percentage of top causes for outages for SP AusNet Electricity Distribution, Australia in 2004.

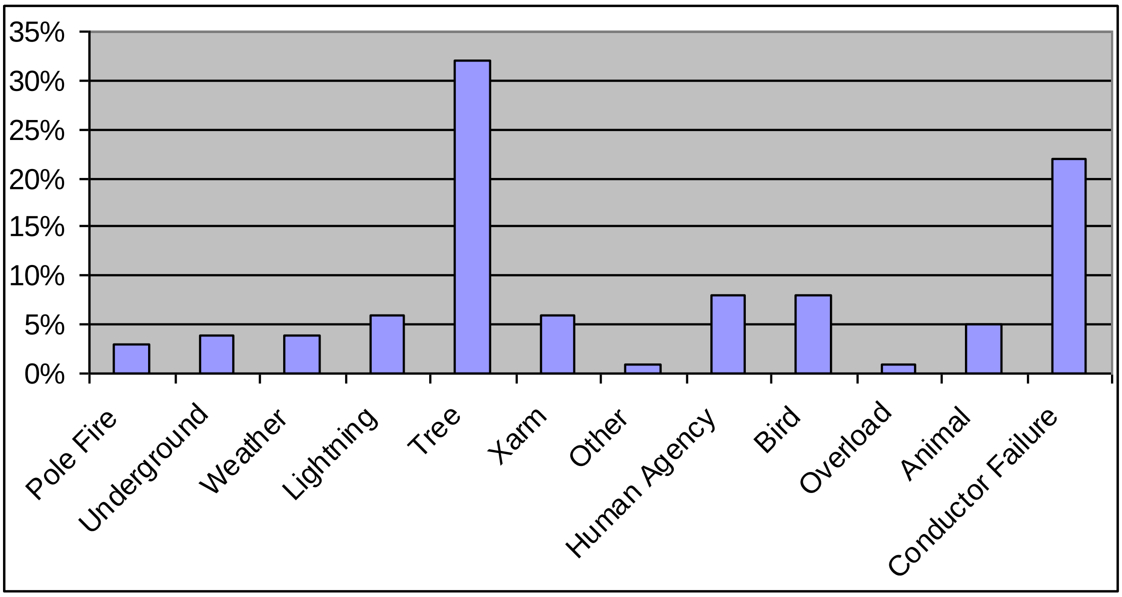


Figure 5.2: Unplanned SAIDI by Cause for 2004 [31]

This figure shows that there is a correlation between reliability and external factors. Progress in reliability is achievable by reducing the controllable unplanned outages such as trees, no cause identified outages and equipment failure. In other words, implementing underground cables will have the potential to reduce power outages throughout normal weather and limit the damage of severe ones, although if a fault occurs a longer time is needed to recover the power supply.

Another aspect of underground reliability is the potential for reduced network maintenance and losses caused by electricity outages and reduced transmission losses. As reference [9] suggested, maintenance costs are equal to the sum of preventive maintenance, vegetation management and reactive maintenance; in spite of that, the cost of overhead maintenance would approximately double provided replacement materials cost was included. Table 5.1 shows average maintenance in the Australian electricity network.

TABLE 5.1: AVERAGE MAINTENANCE COSTS OF AUSTRALIAN ELECTRICITY NETWORK [9]

Type of maintenance	**Expenditure on maintenance (Average of 1997 & 1998) ($ per km of line per year)**					
	Low *		**Medium**		**High**	
OH Overhead / UG Underground	**OH**	**UG**	**OH**	**UG**	**OH**	**UG**
Preventative	282	128	380	158	590	941
Vegetation Management	107	nil	194	nil	285	nil
Reactive	79	102	155	178	527	460
Total non capital	468	230	729	336	1 402	1 401
Total capital & non capital	936	460	1 458	672	2 804	2 802

* Represents the lower 25% quartile, medium and upper 25% quartile of maintenance expenditure from a database of thirteen utilities.
# Costs are for urban residential areas, excluding the central business district and lightly populated rural areas and the costs include, labour, contractors, vehicles and materials, but exclude capital costs such as transformers, poles and cable.

The figures indicate that maintenance costs of overhead network are about twice as much as underground. Nevertheless, the figures are a representation of the difference between the maintenance costs of existing overhead systems and new underground cables. However, $786 per kilometre of line per year for the medium avoided maintenance cost is expected to draw near the difference between the figures for overhead and underground shown in Table 5.1, as time progresses and the new underground system ages [9].

Based on the System Average Interruption Duration Index (SAIDI) of a local power distribution company in Melbourne SP AusNet [3], it is predicted that 70% of outages are encountered on the overhead network and 30% on the underground network, with an average duration for an overhead fault of 50 minutes and an average duration of approximately 65 minutes for an underground fault. The longer time it takes to repair an underground faulty cable, reflects a higher duration for the underground network fault. This is a reflection of the time it takes to effect repairs. On a per unit basis an underground fault will take about 10 times longer than an overhead lines fault to repair (with a similar cost ratio), hence the need for the interconnectivity on the underground system. For 2004 alone, SP AusNet experienced 84 outages on its overhead HV load power feeders and 54 on its underground feeders. The causes for outages on the overhead network were animals, vegetation, weather and third parties.

5.5 Power Network Fundamentals

As stated earlier, underground cables have the potential to reduce outages, maintenance cost and transmission losses. In general transmission losses are lower with underground cables compared to overhead lines. Additionally, new underground cable technology with its unique characteristics of low impedance and ohmic loss enables a massive increase in power transmission capacity. Underground cables can also deliver economic benefits where civil works are reduced by avoiding unnecessary digging; besides there is a big savings in tree pruning for local councils.

To make the decision of moving overhead distribution systems underground there are many issues, which need to be considered thoroughly. The technical and non-technical issues and their broad impact can be categorised as follows:

- design aspects;
- engineering aspects;
- innovation aspects.

5.5.1 Design aspects

Replacing of overhead lines networks by underground cables networks has many advantages and some disadvantages. There are several technical aspects that need to be considered when planning for such a move, especially in established residential areas, which can be a nightmare for network designers. Some of the challenging issues that designers normally face include:

- how to design undergrounpower network using existing zone and terminal substations due to land acquisition troubles;
- number and location of the new pad-mounted substations associated with an underground network need to be identified, as this is a very significant issue to the resident and electricity distributors;
- type of cable and cable technology to be used;

- the co-ordination time between different services has to be minimised to maximise overall efficiency of undergrounding cables.

On the other side, this conversion will provide network designers with a good opportunity to design a modern network to meet not only current load requirements but also the future anticipated load. Designers will be more confident in designing underground networks since many of the design parameters will be known to a certain extent [32].

The continuous development of underground cables and equipment technology has led to tightening the variation of price tag between overhead and underground systems. Moreover, traditionally, overhead lines have been associated with costing less to construct and maintain, and this is still the case, especially for transmission levels, but this can not be taken as a rule of thumb. In cases of regulatory demand, coastal view urban and residential areas, and new real estate, underground will have obvious advantages over overhead lines [29].

5.5.2 Engineering aspects

Cable selection is the main element in designing underground power systems. Selecting the best available and reliable underground cable technology has the potential of overcoming many of the cost, safety and environment related issues. This study will focus on three different types of cables.

- **Cross-linked polyethylene (XLPE) cable**

XLPE cable is the major developing technology and has wide industry acceptance at voltages up to 132-154kV. This type of cable uses vulcanised polyethylene insulation, which is solid insulation extruded onto the conductor during cable manufacture. For high quality insulating properties, the raw materials must be free of even minute contaminants and the extrusion and vulcanising process must ensure homogeneity and absence of voids and moisture in the insulation. Compared with oil-filled cable it is considered to be a simplified technology. According to Karlstrand et al. [12], During the last decade, no other power cables have had such a high rate of improvement as XPLE cable technology. Improvements were made possible due to the overall cost savings, along with environmental focus and de-regulation of electricity markets which makes XLPE cable systems more attractive solutions where they were not even an option in the past [9]. Figure 5.3 shows typical XLPE underground cable as manufactured by Olex in Melbourne.

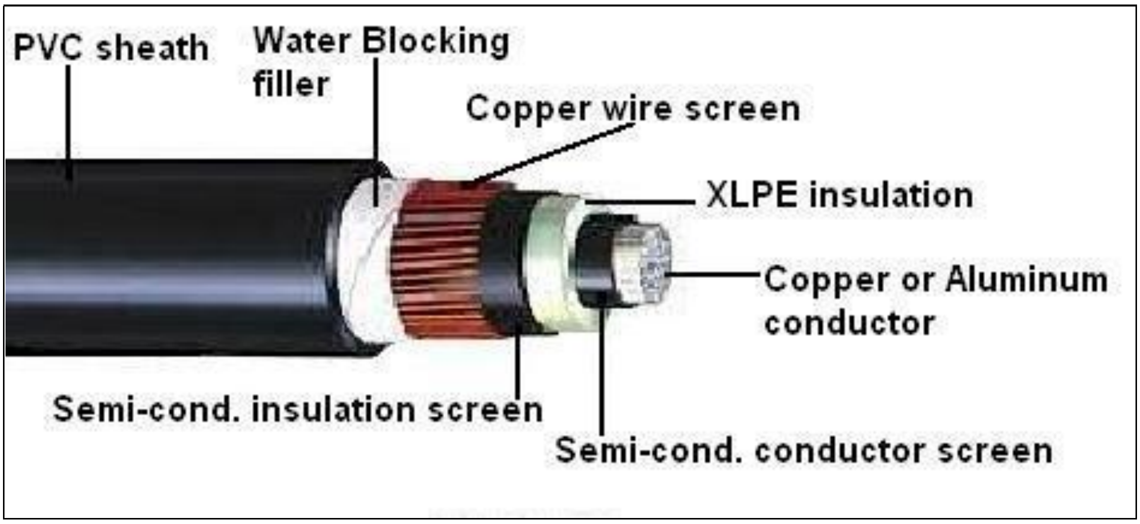


Figure 5.3: Typical XLPE underground cable [33]

- **Gas Insulated Lines (GIL) cable**

The GIL cable has achieved high system reliability by means of the austerity of its design. This design consists of an aluminium conductor supported by insulators and spacers with a pressurised gas compartment which is covered by an aluminium envelope. The technology has established its reliability in more than 3,000 km and 30 years of operation exclusive of main failures. Hitherto, GIL cables' advantages have been limited to special application. Nevertheless, they turn out to be an economical solution for long distance application with the introduction of site assemblage, standardization of its components and better design. Yet a major cost reduction could be accomplished through highly standardized GIL units, developing automated orbital welding machines and pipeline laying methods [7, 34]. Figure 5.4 shows GIL cable design.

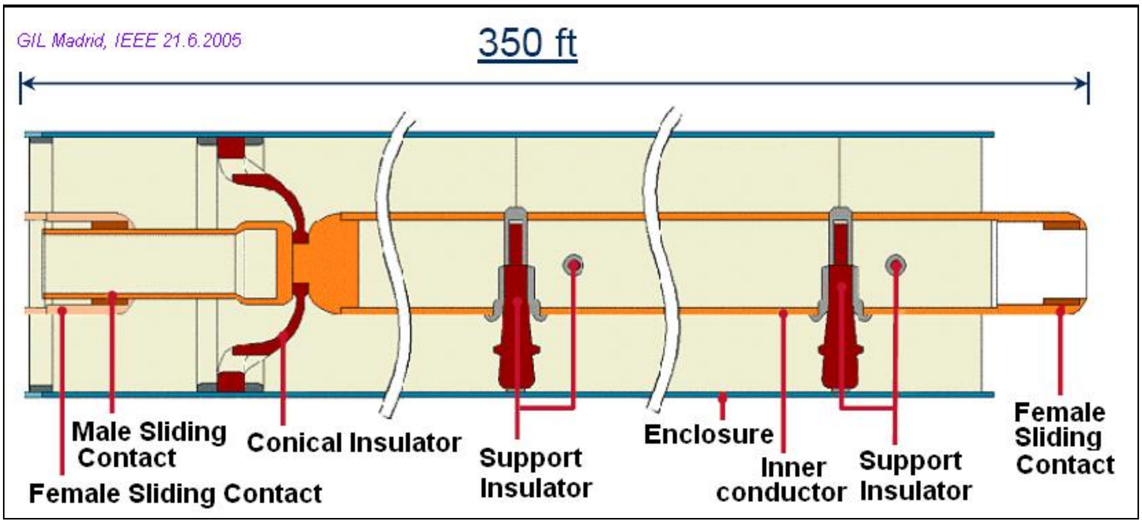


Figure 5.4: GIL cable design [34]

According to Koch et al. [34], the first US Gas Insulated Transmission line installed in 1972 still operates today at the Public Service Electric and Gas

Company (PSEG) Hudson Generating station in New Jersey, while in 1974 Europe installed the First Gas Insulated Transmission Line to connect the electrical generator of a hydro pump storage plant in Schluchsee, Germany. The GIL went into commission in 1975 and up to now it has been in service without interruption. A section of 700 meters of the line was installed in a tunnel in the mountain, nonetheless, this GIL is the longest application at 420 kV voltage level in the world, while the world's longest GIL installation with 20 km single phase length is the Shinmeika-Tokai Line in Chubu, Japan. Currently nearly 200 kilometers of GIL are installed worldwide at voltage levels from 135 to 800 kV. The GIL applications include high voltage substations, power generation plants and areas with severe environmental restrictions. Moreover, GIL has a flexible design, where circuit length can vary between 10 meters to kilometers in length, in addition to all different climate conditions from the low temperatures in Canada to the high ambient temperatures in Saudi Arabia or Singapore, or rough conditions in Europe or South Africa.

The importance of GIL in configurations is clearly represented by an idea of installing a double-circuit GIL in the pilot tunnel of the new planned railway galleries between Italy and Austria through the Brenner Pass. Another aspect of the GIL system is isolation from surroundings because the entire high voltage system including insulators is entirely sealed inside the aluminium field. The magnetic field effect in any GIL arrangement normally is tremendously low due to the shielding effect of the opposing currents flowing in the field, therefore, this feature is crucial when extremely low magnetic field levels are demanded, for example in countries with highly restrictive magnetic field regulations. Meanwhile the limitation of this technology may well include the high cost as well as the cable flexibility, where cable installation requires a direct route, therefore, to achieve bending of the cable a small number of straight sections or elbow sections can be used [34, 35].

- **High Temperature Superconductive (HTS) cable**

HTS cable has an exclusive feature: the ability to conduct electricity without resistive losses; this feature grants a potential for increasing the reliability of the cable, hence, the power system. As opposed to conventional power cables, HTS cable utilises high-tech underground cable technology; it presents not only advanced power transfer mechanism with minimum losses and more compact design of power applications, but also a better power flow absorption in the networks at the same voltage levels. A high current rate and higher capacity than conventional overhead lines or underground cables at similar voltage, is another unique characteristic of HTS cable which is an outcome of its low electric losses which are about < 1% compared with about 8% for conventional cables of low to medium voltage range. HTS cable technology allows an enormous growth in power transmission capacity, thus HTS cable has the potential of becoming a practicable solution to power transmission dilemmas. Other advantages are the ability to carry current of up to 5 times more than conventional underground power cables, power evaluation of up to 10 times more than the same thickness copper wire and the transmission of the power can be done at lower voltage. The delivery of an extra capability is vitally advantageous especially in highly congested cities. Meanwhile, transmissions at lower level voltages are more approachable; they have the potential to reduce supplementary generation by transmitting a larger portion of generated power and they provide, in commission, cost savings. In the same token, this technique may well decrease or even eliminate numbers of transformers and related equipment, savings also in building extra substations, consequently reduction in power systems costs and declining system vulnerability [36]. Figure 5.5 shows HTS cable as developed by Ultera, Denmark.

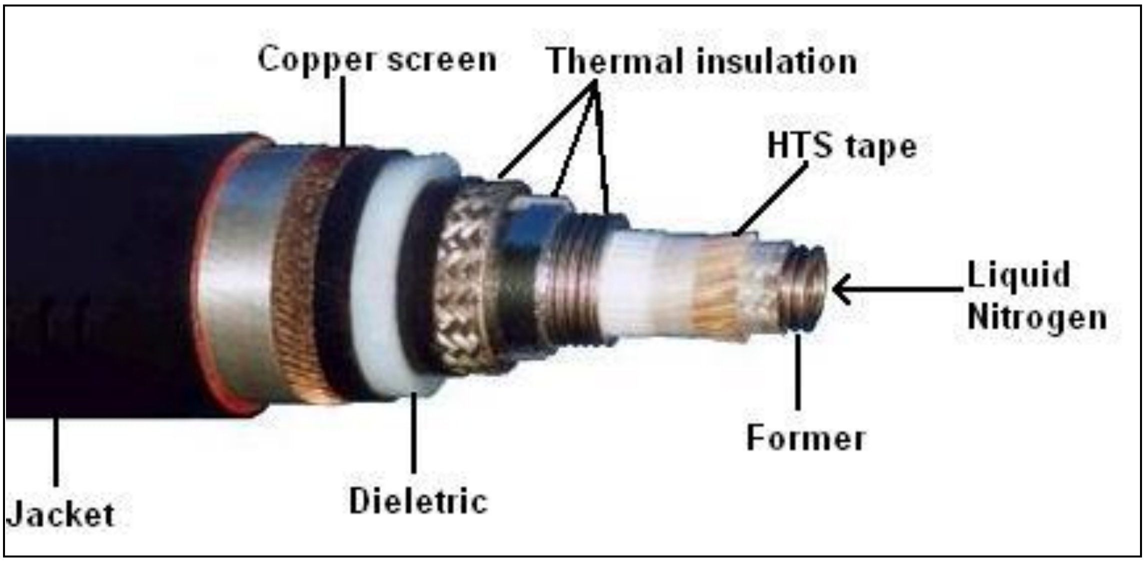


Figure 5.5: Typical HTS cable

A HTS cable does show a promising future. Nevertheless, the significant ordeal of this technology has always been the high cost associated with the cost of superconductive materials on top of the cable-cooling cost which is essential for its normal operation temperature (-208ºC for current HTS cables). In an attempt to reduce the second most expensive component of HTS cable system, a new cryogenic electrical insulator design has been developed to reduce costs by 40-50%, and it cuts the energy losses by 50%; the estimated cost of HTS conductor required to transmit 1 kA over 1 m length using HTS cables is approximately 11 EUR/kAm. In the meantime, highly reliable cable cooling technology has been developed aiming at longer service life for longer service intervals to reduce maintenance costs. All those incentives will make HTS cable technology more practically feasible, but industry scale production is necessary to bring the cost down considerably in the longer run [36]. The first commercial product in 2006 was presented at the Hannover Messe 24-28 April 2006.

Although HTS cable is still in the research and development phase, the forecast predicts a rational technical and economic alternative for power systems. The market expectation for superconductor products is anticipated to intensify to near US$5 billion by the year 2010 and to US$38 billion by 2020 [36].

5.5.3 Innovation aspects

New ideas which enhance reliability, efficiency and lower the cost of installation and maintenance are contributing significantly in the development of underground cable networks. These ideas cover various phases of the underground systems. A few ideas are identified as follows:

- **Cable tunnel**

Most urban underground cables run in congested streets, which require part of the traffic being diverted, often for a long time, causing disruption to traffic flow, parking and pedestrians in the area. Using a tunnel has several advantages over conventional cable burial technique:

- impact on traffic flow and other utilities would be minimal;
- shorter outages are required to connect;
- ease of access for maintenance and testing;
- secure cable environment for 100 years;
- direct tunnel route will results in reduction in cable length.

As an extra benefit, cable tunnel are naturally ventilated, where cables are laid in vertical snaking on saddles with spacing of 7.2 m in horizontal and 0.6 m in vertical direction; tunnel temperatures are permanently monitored using fibre optic Distributed Temperature Sensor (DTS) [18, 37].

- **Fibre optic sensing system**

Although some methods are already in use to locate a fault, the cable needs to be removed from service and connected to detection equipment, but locating a fault in underground system can take extensive time and effort. A new method is integrating Fibre Optic Distributed Temperature (FODT) sensor into the cable. This sensor can find the fault immediately by applying fault detection of XLPE installed underground cable in a resistance grounded system. The maximum detection distance, distance resolution and processing time for fault location are 10km, 1m and 30s respectively [38, 39].

Underground object radar

Underground assets maps, if they exist, are often inaccurate, incomplete or out of date, and the use of metal detectors to find these assets often proves disappointing. Researchers have developed a new Ground-Penetrating Image Radar (GPIR) system that creates sharp, three-dimensional (3-D) images of underground lines and objects. This system can be utilised to reduce operating and maintenance costs, by reducing unnecessary excavations and lowering the risk of damaging other assets [38, 40].

5.6 Underground Construction

To put cables underground, there are a couple of conventional practical options available, either using trenching technique or boring technique. The decision is based on the geology of the area that the underground cable will be routed through. Determining the best scenario for each individual site can minimise time and efforts and increase efficiency overall.

Trenching: This technique involves an open cut along the edges of the trench to avoid damaging the surrounding area and then excavation work will be carried out, in general, using a tracked excavator. In some cases where space is an issue, a site plan to redirect traffic or limiting time of work needs to be implemented. Utilising the site for traffic flow will be a big challenge itself, e.g. excavated materials should be moved to a temporary area. If rocks are present, a hydraulic breaker will be used. This is the most common tool used to break rock and it can be swapped with the excavators bucked in a short time with limited vibration impact operation. There are limited cases where explosives are used as an alternative to hydraulic tools. Precautions should be taken under engineering supervision to make sure that blasts will not produce overwhelming vibration [32, 41].

Boring: There are two types of boring technique, straight and directional. Straight boring uses a kind of rotating drill to make a direct hole through the ground. The direction of the boring is determined to a certain extent once the drilling starts. The operator cannot adjust the direction afterwards. The drilling machine is placed in a pit below the ground level and a similar pit dug some distance from the first pit, which becomes the ending point of the drilling. Directional boring involves drilling a straight or curved hole. Boring technique is commonly used in crossing roads which can be a tough and an expensive process, which depends on the size of the drilled hole and soil type [9].

Cable Laying: The cables can be delivered to the site on large drums, typically 4m in diameter. Due to height restrictions, these drums are transported by a low loader. Due to the cable’s high mass and large transport drum size the amount of cable that can be handled in a single length is limited. Therefore a joint is required at each interval along the route. Jointing employs highly skilled techniques to provide a high quality electrical connection. The insulation is then reconstructed across the joint. The joint is contained within an insulating and waterproofing casing for final protection. Joint bay excavations are wider than for a normal trench to provide a suitable working area; this bay should be kept clean and dry for jointing operations. It is usually lined with concrete. At joint positions, a link box is located within 10m and contains electrical equipment associated with earthing of cable sheaths [32].

Backfill and Surface Reinstatement: The trench can be backfilled with materials such as crushed rock or selected sand, which assist in conducting heat generated in the cable. Failure to meet such conditions will cause premature cable faults. Plastic protective slaps and plastic waring tapes are buried within the backfill to provide protection and permanent identification of buried cables. The surface can then be reinstated in a manner consistent with land use e.g. in the form of road pavement or regressed for open areas [32].

Retirement of Overhead Assets: All poles, cross-areas, insulators, switchgear and associated hardware and conductors, including old public lighting poles have to be removed safely and disposed of in an appropriate manner. All pole holes are to be filled with suitable materials to the final finished surface level [32].

Constructing underground cables can be determined by the nature of the route and type of cable installation. In general, for highly congested areas like shopping strips, the recommended method would be installing the cable in ducts where lengths of cables and equipment are installed in ducts and manholes to accommodate for future cable maintenance and replacement. In using this method there is less disturbance for the area which makes it relatively faster than other methods [29].

Other forms of installation can be used where direct burial in a trench is used. It enables long lengths of cable to be installed and offers saving in terms of building ducts and manholes; also there will be fewer joints in the route which increases the overall reliability of the cable. Sharing the ducts or trench with other utilities can reduce the overall cost of cable installation, but coordination issues can subdue such savings [29].

There are cases where installation can be done using boring technique especially in sandy areas; this will eliminate the cost of trenching and backfilling. This type of installation can be used in road crossing or under river [29].

5.7 Conclusion

It has become mandatory for most modern cities worldwide to use underground power cables. This demonstrates that undergrounding has become feasible economically and technologically. Various advantages have been presented about underground cables. However, there are significant challenges in the underground network as much as it has benefits, it is essential to carefully design and implement an underground power network. In line with this, the next chapter discusses the development and analysis of a Victorian hybrid underground power network, where although conventional XLPE cables are used, new cable technology in the form of HTS cables was visualised to be utilised.

CHAPTER 6

DEVELOPMENT AND ANALYSIS OF VICTORIAN UNDERGROUND POWER NETWORK MODEL

6.0 Introduction

The general overview of underground power networks and cable technologies was presented in Chapter 5. This chapter discusses about the proposed Victorian underground network model. Load flow analysis was used in analysing the Victorian network. Section 6.1 provides details about the Victorian underground power network model. This model is based on sub-models developed separately then combined together to form the overall underground model. A load flow analysis is carried out on the sub-models where the results obtained from this study are compared with results obtained from other models developed in pervious sections and to be developing in next chapter.

6.1 WMTS 2007 Underground Model

This model comprises multiple sub-models: these include the 66kV and 22kV WMTS terminal station loops which as indicated earlier in Figure 4.1. After obtaining the load flow analysis of the two voltage levels, a submission of all power losses, which basically represents the loading demand of WMTS for the year 2007, is identified to undergo further analysis.

6.1.1 EDSA WMTS 66kV underground sub-model

The configuration of this base sub-model is set to closely match the overhead sub-model presented in Section 4.2 with the exception that overhead lines are replaced with underground cables. The 66kV XLPE Olex underground cable parameters were used in this sub-model; full cable information is given in Appendix F.

It worth stating that the load demand of the year 2007 which was used in this sub-model was obtained from Citipower 2007 planning report [28].

The model shown in Figure 6.1 displays a summary of the load flow analysis results situated close to the bus, line or transformer. The summary includes an arrow that reveals the direction of power flow. Real and reactive power are also shown close to each bus, line or transformer in terms of positive values which denote when power flow direction is out from the bus and vice versa; in other words, negative values have been applied for power flow direction into the bus.

Accordingly, summing up of the four power flow values for each line or feeder will provide real and reactive power losses in the specific line.

The figure shows all feeders consist of a single circuit or single cable, as compared to the WMTS 66kV overhead sub-model in Section 4.2.1; the grounds for such a move is that the 66kV XLPE cable has a current rate of 1260A. This rating is considerably high and in some cases as much as twice the 66kV overhead lines rating. Therefore, instead of under utilising the cable to around 40% of its full capacity, a single cable with utilisation of over 80% is employed; bearing in mind the n-1 redundancy configuration is maintained.

Table 6.1 illustrates the bus results of load flow analysis performed on the WMTS 66kV sub-model. The table also lists bus parameters including name, real and reactive generated powers, real and reactive static loads and load flow results from which the real and reactive power losses are obtained with bus current rating and power factor incorporated.

Table 6.2, summarises load flow results obtained in Table 6.1. The table shows, in two different columns, the power delivered to and from the line, and in the last two columns it lists the power difference or power losses. The total real power losses are found to be 159.1 kW; in addition the total reactive power was found to be -45215 kVAR.

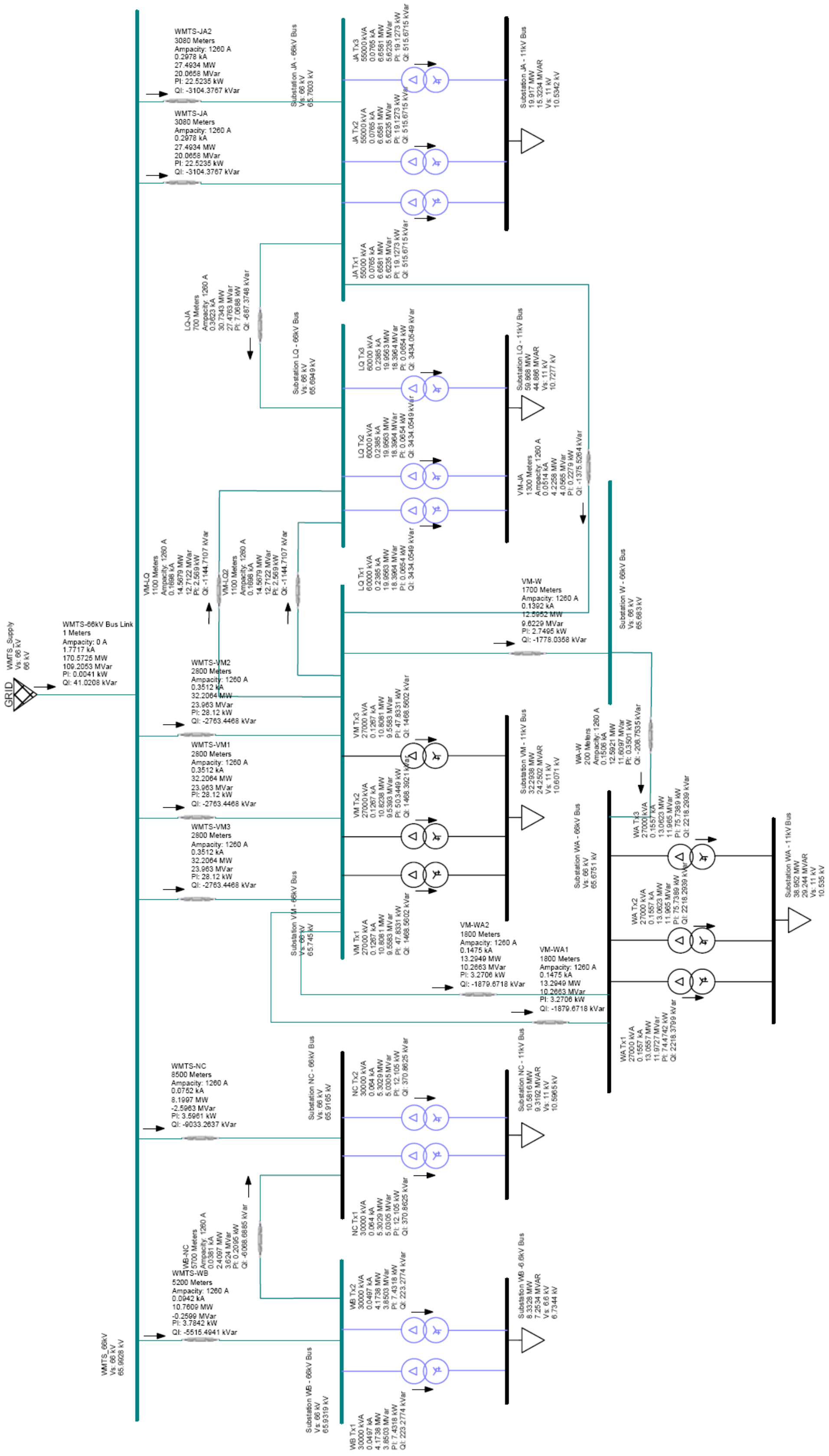


Figure 6.1: WMTS 66kV underground sub-model

Table 6.1: WMTS 66kV underground EDSA load flow bus results

Bus Info	Generation		Static Load		Load Flow Results				
Name	**MW**	**MVAR**	**MW**	**MVAR**	**To Bus Name**	**MW**	**MVAR**	**Amp**	**%pf**
Sub JA 66	0.00	0.00	0.00	0.00	Sub LQ	30.74	28.57	369	73.3
Sub JA 66	0.00	0.00	0.00	0.00	Sub LQ	30.74	26.79	362	75.4
					Sub VM 66	4.23	2.68	51	84.4
					WMTS 66	-27.47	-23.17	298	76.4
					WMTS 66	-27.47	-23.17	298	76.4
Sub LQ 66	0.00	0.00	0.00	0.00	Sub JA 66	-30.73	-27.48	362	74.6
					Sub VM 66	-14.57	-13.86	170	72.5
					Sub VM 66	-14.57	-13.86	170	72.5
Sub NC 66	0.00	0.00	0.00	0.00	Sub WB 66	-2.41	-3.62	38	55.4
					WMTS 66	-8.2	-6.44	75	78.6
Sub VM 66	0.00	0.00	0.00	0.00	Sub JA 66	-4.23	-4.06	51	72.1
					Sub LQ 66	14.57	12.71	170	75.3
					Sub LQ 66	14.57	12.71	170	75.3
					Sub W 66	12.6	9.62	139	79.5
					Sub WA 66	13.29	10.27	148	79.1
					Sub WA 66	13.29	10.27	148	79.1
					WMTS 66	-32.18	-26.73	351	76.9
					WMTS 66	-32.18	-26.73	351	76.9
					WMTS 66	-32.18	-26.73	351	76.9
Sub W	0.00	0.00	0.00	0.00	Sub VM 66	-12.59	-11.4	139	74.1
					Sub WA 66	12.59	11.4	151	74.1
Sub WA 66	0.00	0.00	0.00	0.00	Sub VM 66	-13.29	-12.15	148	73.8
					Sub VM 66	-13.29	-12.15	148	73.8
					Sub W 66	-12.59	-11.61	151	73.5
Sub WB 66	0.00	0.00	0.00	0.00	Sub NC 66	2.41	-2.44	38	70.2
					WMTS 66	-10.76	-5.26	94	89.8
WMTS 66	0.00	0.00	0.00	0.00	Sub JA 66	27.49	20.07	298	80.8
					Sub JA 66	27.49	20.07	298	80.8
					Sub NC 66	8.2	-2.6	75	95.3
					Sub VM 66	32.21	23.96	351	80.2
					Sub VM 66	32.21	23.96	351	80.2
					Sub VM 66	32.21	23.96	351	80.2
					Sub WB 66	10.76	-0.26	94	100
					Total losses	**0.15**	**-45.25**		

Table 6.2: WMTS 66kV underground losses

Branch	From -> To Flow		To -> From Flow		Losses	
Name	**MW**	**MVAR**	**MW**	**MVAR**	**kW**	**kVAR**
LQ-JA	-30.734	-27.476	30.741	26.789	7.1	-687.4
VM-JA	-4.226	-4.056	4.226	2.681	0.2	-1375.5
VM-LQ1	14.568	12.712	-14.565	-13.857	2.6	-1144.7
VM-LQ2	14.568	12.712	-14.565	-13.857	2.6	-1144.7
VM-W	12.595	9.623	-12.592	-11.401	2.7	-1778
VM-WA1	13.295	10.266	-13.292	-12.146	3.3	-1879.7
VM-WA2	13.295	10.266	-13.292	-12.146	3.3	-1879.7
WA-W	-12.592	-11.61	12.592	11.401	0.4	-208.8
WB-NC	-2.41	-3.624	2.41	-2.445	0.2	-6068.7
WMTS-JA1	27.493	20.066	-27.471	-23.17	22.5	-3104.4
WMTS-JA2	27.493	20.066	-27.471	-23.17	22.5	-3104.4
WMTS-NC	8.2	-2.596	-8.196	-6.437	3.6	-9033.3
WMTS-VM1	32.206	23.963	-32.178	-26.726	28.1	-2763.4
WMTS-VM2	32.206	23.963	-32.178	-26.726	28.1	-2763.4
WMTS-VM3	32.206	23.963	-32.178	-26.726	28.1	-2763.4
WMTS-WB	10.761	-0.26	-10.757	-5.256	3.8	-5515.5
			Total power losses		**159.1**	**-45215**

WMTS 66kV line's real and reactive power losses are shown in Figure 6.2. The figure demonstrates that the power losses are line impedance dependent. As can be observed, cable WMTS – JA1 is longer in length than its counterpart WMTS – VM1, therefore its real and reactive power losses are more; the clear reason for that is the higher impedance which in turn causes higher power losses.

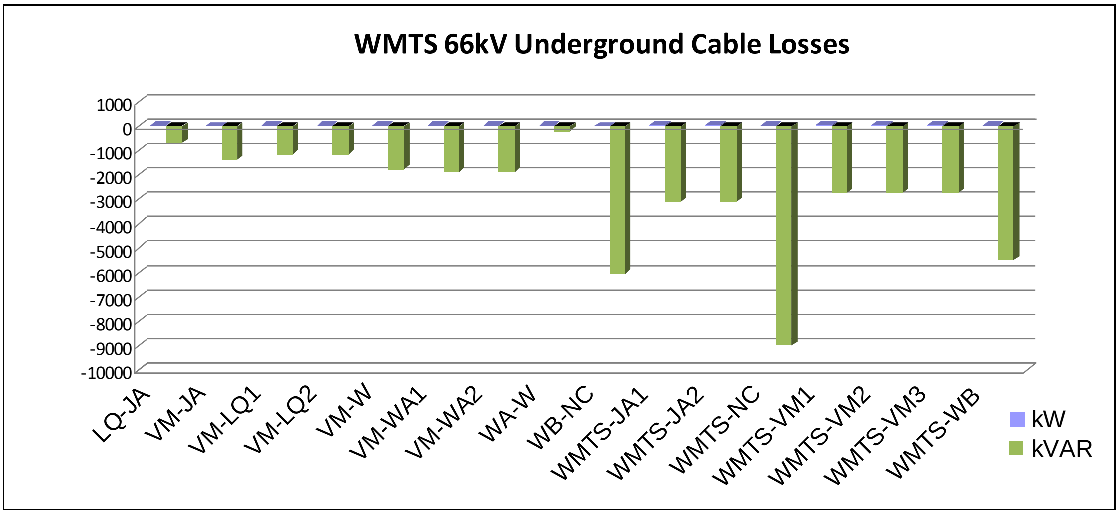


Figure 6.2: WMTS 66kV underground cables power losses

6.1.2 EDSA WMTS 22kV underground sub-model I

The configuration of this base sub-model has many similarities to the WMTS 22kV sub-model exhibited earlier in Section 4.2.3, which closely matched the existing Citipower section of the network with the exception that overhead lines are replaced with 22kV XLPE underground cables. Again the 2007 zone substation loading demand parameters were acquired from the company's 2007 planning report [28]. The 22kV XLPE Olex underground cable parameters were used in this sub-model. Full cable information is given in Appendix G.

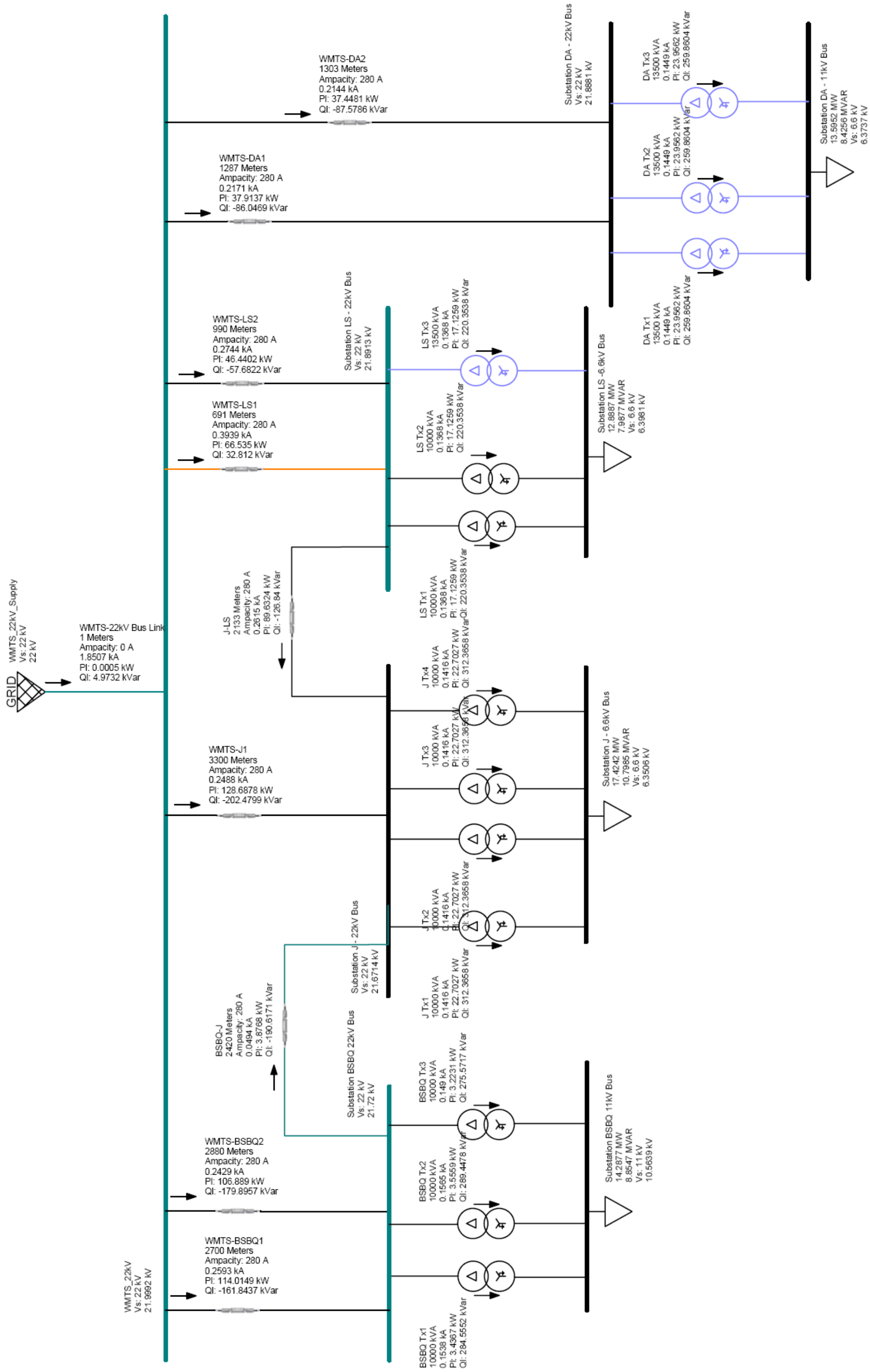


Figure 6.3: WMTS 22kV underground sub-model I

An expected, finding from Figure 6.3 reveals many cables in the sub-model will be operating over their 100% rating; these elements are identified by their colour coding and one particular cable WMTS – LS1 will exceed its 140% rating under normal operation condition. Additionally there are more elements identified when n-1 redundancy configuration is used. After identifying all the elements over stressed in this sub-model, single or double circuits are added to keep in line with the Citipower n-1 redundancy configuration. A 22kV XLPE cable with a current rate of 325A which is commonly used by power utilities in Melbourne is employed rather than the 22kV XLPE cable with 280A current rating to enhance the capacity of the feeders and minimise the number of parallel circuits required for normal and contingency operations. Figure 6.5 shows the updated WMTS 22kV underground sub-model where all elements are operating under their 100% rating and n-1 Citipower redundancy configuration is maintained.

The developed sub-model II in Figure 6.4 shows the WMTS terminal station 22kV section of the network base sub-model and a load flow analysis on the model was carried out to obtain power loss figures. Again Figure 6.5 shows the summary of the load flow analysis results situated close to the bus, line or transformer.

The lists of bus parameters in Table 6.3 of WMTS 22kV sub-model comprises name, real and reactive generated power, real and reactive static load and load flow results where real and reactive power losses can be obtained with bus current rating and power factor incorporated as well.

The load flow results obtained in Table 6.3 are summarised in Table 6.4. The table shows in two different columns the power delivered to and from the line and in the last two columns it lists the power difference or power losses. The total real power losses found to be 300.7 kW, in addition total reactive power was found to be -3334 kVAR.

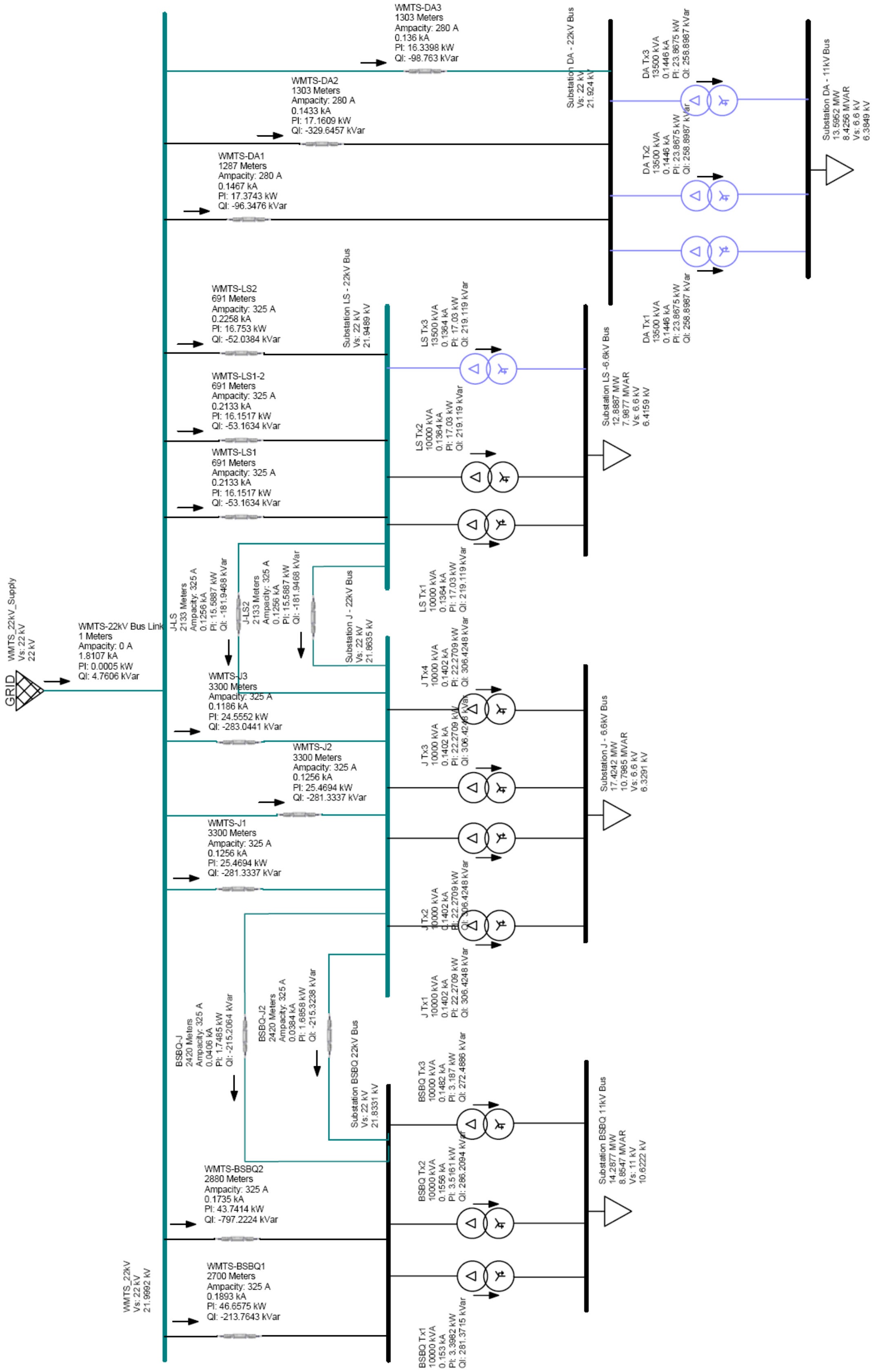


Figure 6.4: WMTS 22kV underground sub-model II

Table 6.3: WMTS 22kV underground sub-model II EDSA load flow bus results

Bus Info	Generation		Static Load		Load Flow Results				
Name	MW	MVAR	MW	MVAR	To Bus Name	MW	MVAR	Amp	%pf
Sub BSBQ 22	0.00	0.00	0.00	0.00	Sub J 22	-1.27	-0.87	41	82.6
					Sub J 22	-1.22	-0.78	38	84.2
					WMTS 22	-6.09	-4	189	83.6
					WMTS 22	-5.71	-4.05	173	81.6
Sub DA 22	0.00	0.00	0.00	0.00	WMTS 22	-4.66	-3.16	147	82.8
					WMTS 22	-4.6	-3.24	143	81.8
					WMTS 22	-4.4	-2.8	136	84.4
Sub J 22	0.00	0.00	0.00	0.00	Sub BSBQ 22	1.27	0.65	41	89
					Sub BSBQ 22	1.22	0.57	38	90.7
					Sub LS 22	-3.98	-2.6	126	83.7
					Sub LS 22	-3.98	-2.6	126	83.7
					WMTS 22	-4.06	-2.77	126	82.6
					WMTS 22	-4.06	-2.77	126	82.6
					WMTS 22	-3.92	-2.49	119	84.4
Sub LS 22	0.00	0.00	0.00	0.00	Sub J 22	4	2.42	126	85.5
					Sub J 22	4	2.42	126	85.5
					WMTS 22	-6.9	-4.33	213	84.7
					WMTS 22	-6.9	-4.33	213	84.7
					WMTS 22	-7.14	-4.83	226	82.8
WMTS 22	0.00	0.00	0.00	0.00	Sub BSBQ 22	6.14	3.79	189	85.1
					Sub BSBQ 22	5.76	3.25	173	87.1
					Sub DA 22	4.68	3.06	147	83.7
					Sub DA 22	4.62	2.91	143	84.6
					Sub DA 22	4.42	2.7	136	85.3
					Sub J 22	4.09	2.49	126	85.4
					Sub J 22	4.09	2.49	126	85.4
					Sub J 22	3.94	2.21	119	87.2
					Sub LS 22	6.91	4.28	213	85
					Sub LS 22	6.91	4.28	213	85
					Sub LS 22	7.16	4.78	226	83.2
					Total losses	**0.32**	**-3.32**		

Table 6.4: WMTS 22kV underground sub-model II power losses

Branch	From -> To Flow		To -> From Flow		Losses	
Name	**MW**	**MVAR**	**MW**	**MVAR**	**kW**	**kVAR**
BSBQ-J1	-1.268	-0.866	1.27	0.65	1.7	-215.2
BSBQ-J2	-1.222	-0.782	1.223	0.567	1.7	-215.3
J-LS1	-3.98	-2.604	3.996	2.422	15.6	-181.9
J-LS2	-3.98	-2.604	3.996	2.422	15.6	-181.9
WMTS-BSBQ1	6.141	3.786	-6.095	-4	46.7	-213.8
WMTS-BSBQ2	5.757	3.249	-5.714	-4.046	43.7	-797.2
WMTS-DA1	4.677	3.064	-4.66	-3.16	17.4	-96.3
WMTS-DA2	4.62	2.909	-4.603	-3.238	17.2	-329.6
WMTS-DA3	4.421	2.705	-4.405	-2.803	16.3	-98.8
WMTS-J1	4.087	2.489	-4.062	-2.77	25.5	-281.3
WMTS-J2	4.087	2.489	-4.062	-2.77	25.5	-281.3
WMTS-J3	3.944	2.209	-3.919	-2.492	24.6	-283
WMTS-LS1	6.912	4.277	-6.896	-4.33	16.2	-53.2
WMTS-LS2	6.912	4.277	-6.896	-4.33	16.2	-53.2
WMTS-LS3	7.157	4.777	-7.141	-4.829	16.8	-52
			Total power losses		**300.7**	**-3334**

Figure 6.5 shows WMTS 22kV underground cables' real and reactive power losses; the figure demonstrates that the power losses are line impedance dependent, as can be observed in that although line WMTS – DA2 is same in length as its counterpart WMTS – DA3 however its real and reactive power losses are much higher and the reason for that is the higher current passing through it.

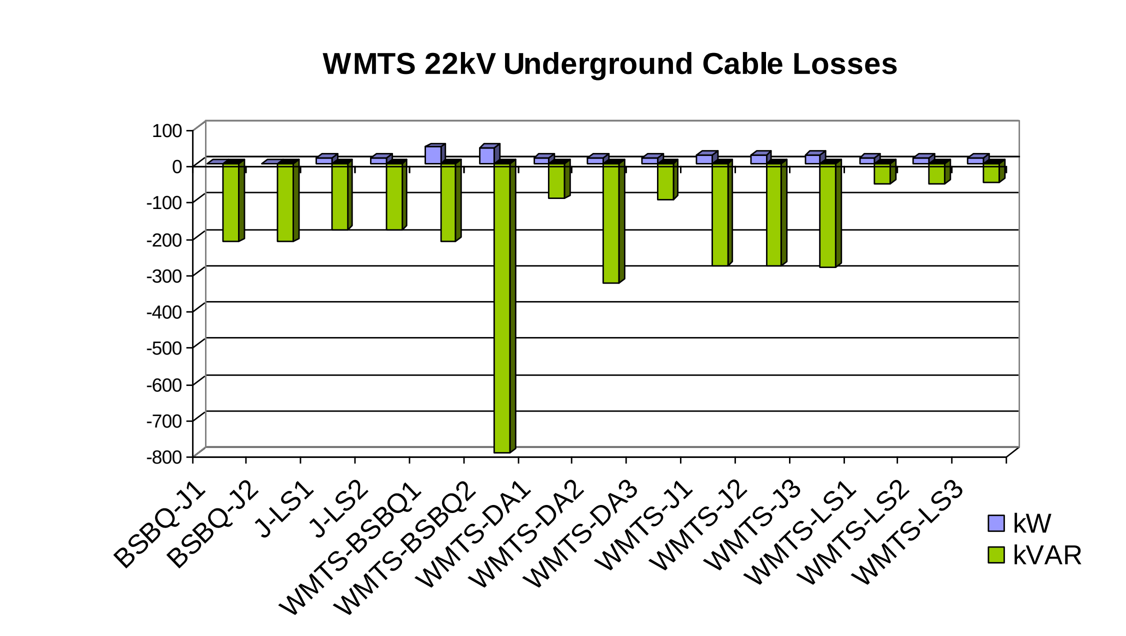


Figure 6.5: WMTS 22kV underground sub-model II power losses

As a conclusion for this section, the summation of power losses found in 22kV and 66kV loops are presented as the total power losses in the WMTS section of Citipower for the existing network configuration with 2007 loading demand.

Total real power losses = 300.7 + 159.1 = 459.8 kW

Total reactive power losses = -3334 + (-45215) = -48549 kVAR

6.1.3 EDSA WMTS 22kV underground sub-model III

The configuration of this base sub-model has many similarities to the WMTS 66kV sub-model exhibited earlier in Section 4.2.3, which closely matches the existing Citipower section of the network with the exception that overhead lines are replaced with 22kV XLPE underground cables. However, 66kV cables have been used in this model as one step forward towards upgrading the zone substations voltage level from 22kV to 66kV which is part of Citipower future planning. Again the 2007 zone substation loading demand parameters were acquired from the company's 2007 planning report. The 22kV XLPE Olex underground cable parameters were used in this sub-model; full cable information is given in Appendix F.

The developed sub-model III in Figure 6.6 shows the WMTS terminal station 22kV section of the network base sub-model; a load flow analysis on the model was carried out to obtain power loss figures. Again Figure 6.7 shows the summary of the load flow analysis results situated close to the bus, line or transformer.

The lists of bus parameters in Table 6.5 of the WMTS 22kV sub-model comprise name, real and reactive generated power, real and reactive static load and load flow results where real and reactive power losses can be obtained with the bus current rating and power factor incorporated as well.

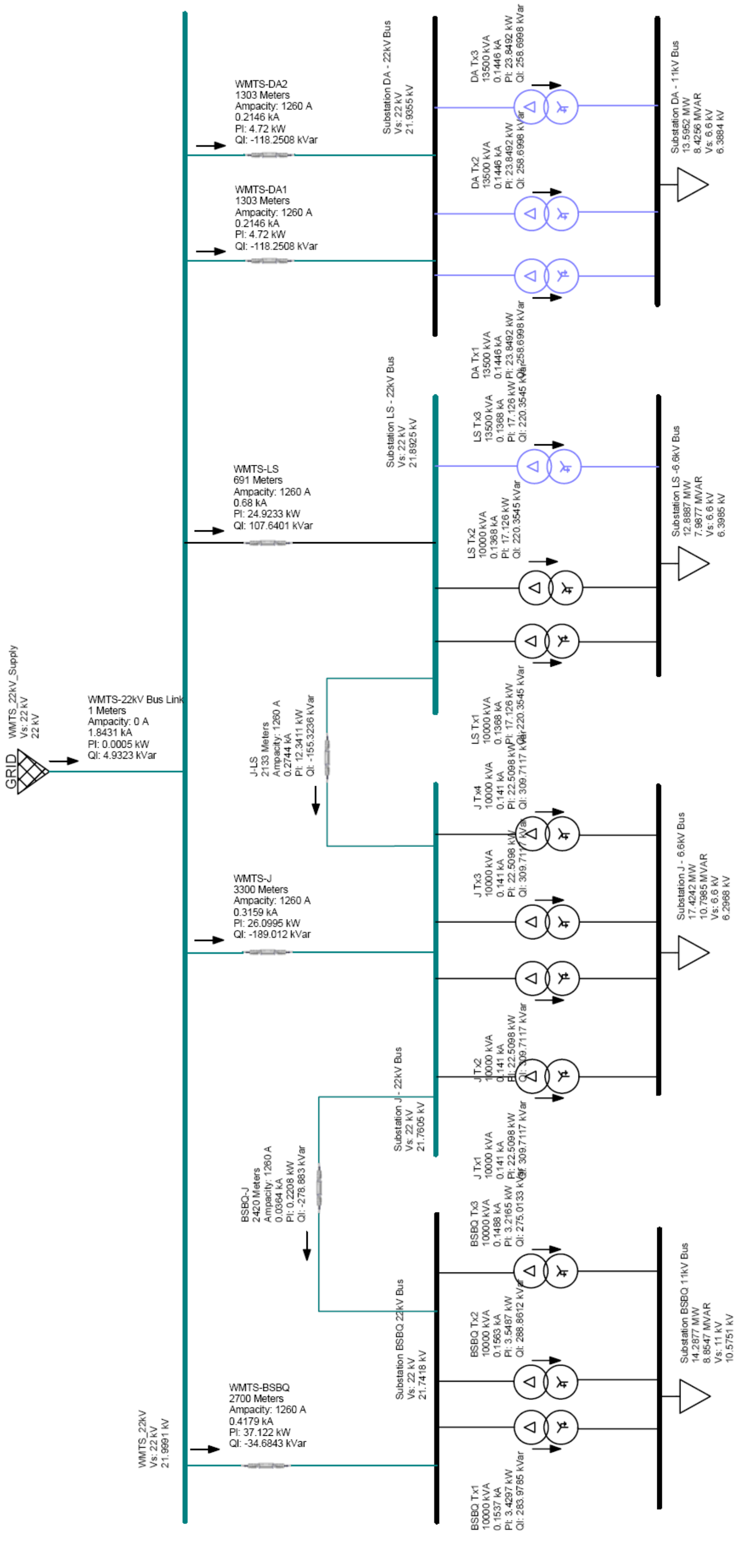


Figure 6.6: WMTS 22kV underground sub-model III

Table 6.5: WMTS 22kV underground sub-model III EDSA load flow bus results

Bus Info	Generation		Static Load		Load Flow Results				
Name	**MW**	**MVAR**	**MW**	**MVAR**	**To Bus Name**	**MW**	**MVAR**	**Amp**	**%pf**
Sub BSBQ 22	0	0	0	0	Sub J 22	-1.08	-0.85	36	78.5
					WMTS 22	-13.22	-8.85	418	83.1
Sub DA 22	0	0	0	0	WMTS 22	-6.83	-4.6	215	82.9
					WMTS 22	-6.83	-4.6	215	82.9
Sub J 22	0	0	0	0	Sub BSBQ 22	1.08	0.57	36	88.4
					Sub LS 22	-8.56	-5.81	274	82.8
					WMTS 22	-10.03	-6.8	316	82.8
Sub LS 22	0	0	0	0	Sub J 22	8.57	5.65	274	83.5
					WMTS 22	-21.51	-14.3	680	83.3
WMTS 22	0	0	0	0	Sub BSBQ 22	13.26	8.82	418	83.3
					Sub DA 22	6.84	4.48	215	83.6
					Sub DA 22	6.84	4.48	215	83.6
					Sub J 22	10.06	6.61	316	83.6
					Sub LS 22	21.54	14.41	680	83.1
					Total losses	**0.13**	**-0.79**		

The load flow results obtained in Table 6.5 are summarised in Table 6.6. The table shows, in two different columns, the power delivered to and from the line, and in the last two columns it lists the power difference or power losses. The total real power losses were found to be 110 kW; in addition the total reactive power was found to be -786.9 kVAR.

Real and reactive power losses of WMTS 22kV underground cables are exhibited in Figure 6.7. The figure demonstrates that the power losses are line impedance dependent, as can be observed clearly in the fact that although line WMTS – BSBQ1 is shorter in length than its counterpart WMTS – BSBQ2, however, its real and reactive power losses are higher and the reason for that is the higher current passing through it, which in turn causes higher power losses.

Table 6.6: WMTS 22kV underground sub-model III power losses

Branch	From -> To Flow		To -> From Flow		Losses	
Name	**MW**	**MVAR**	**MW**	**MVAR**	**kW**	**kVAR**
BSBQ-J	-1.076	-0.85	1.076	0.571	0.2	-278.9
J-LS	-8.56	-5.807	8.572	5.652	12.3	-155.3
WMTS-BSBQ	13.259	8.818	-13.221	-8.853	37.1	-34.7
WMTS-DA1	6.838	4.483	-6.833	-4.601	4.7	-118.3
WMTS-DA2	6.838	4.483	-6.833	-4.601	4.7	-118.3
WMTS-J	10.056	6.613	-10.03	-6.802	26.1	-189
WMTS-LS	21.537	14.408	-21.512	-14.301	24.9	107.6
			Total power losses		**110.0**	**-786.9**

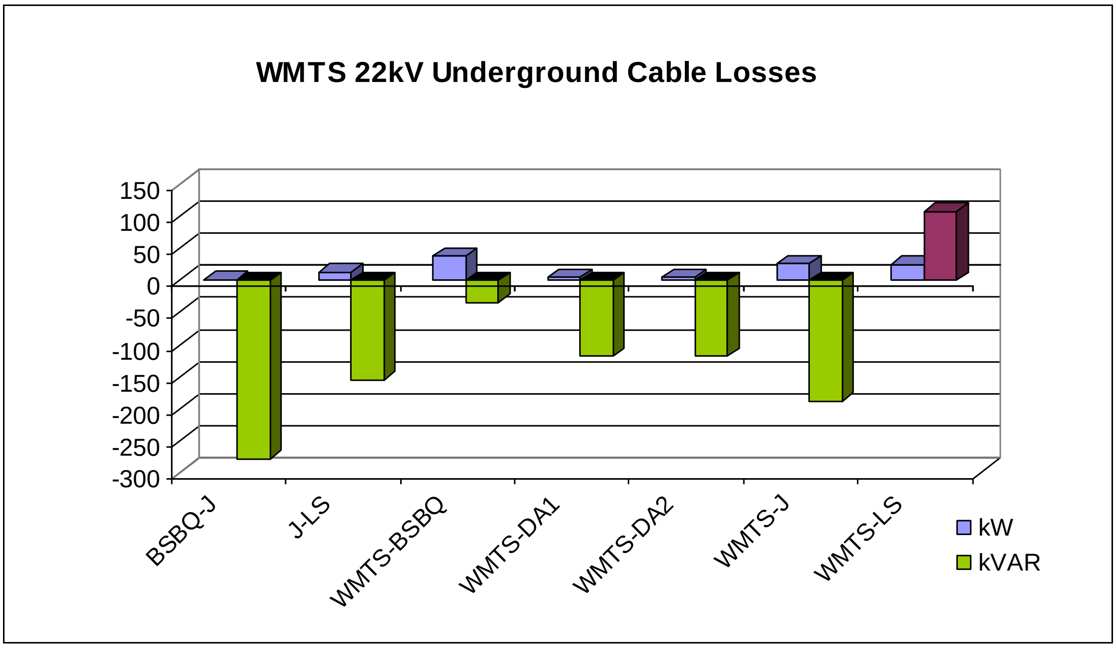


Figure 6.7: WMTS 22kV underground sub-model III power losses

In line with the Citipower future projects which are planned for the next 5 year period, an upgrade of existing 22kV stations to a high capacity 66kV CBD type station is due with ultimate firm capacity enhancement. This will assimilate the need for a new transmission network connection and the additional capacity to reinforce the loading of other Citipower stations. The result of this model confirms the prediction of low cable loading, where one cable recorded below 3%. Table 6.7 lists the WMTS 22kV underground sub-model III cable loading.

Table 6.7: WMTS 22kV underground sub-model III cable loading

Branch Name	Ampacity	Loading Amp	% Loading
BSBQ-J	1260	36.41	2.9
J-LS	1260	274.44	21.8
WMTS-BSBQ	1260	417.89	33.2
WMTS-DA1	1260	214.58	17
WMTS-DA2	1260	214.58	17
WMTS-J	1260	315.87	25.1
WMTS-LS	1260	680.04	54

A graphic representation of Table 6.7 is illustrated in Figure 6.8; it can be clearly noted that the cable loading off all branches of model III are very low. However, this low load rating is vital for future network expansion or load growth; in the coming subsections future demand will be examined on this model to identify the cable current utilisation and expected future capacity potential.

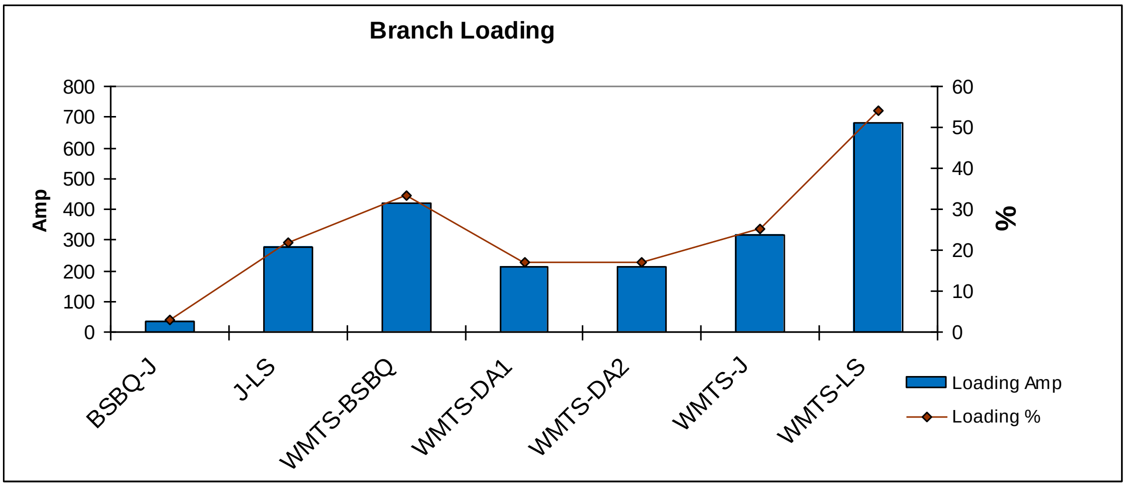


Figure 6.8: WMTS 22kV underground sub-model III branch loading

6.2 WMTS Underground 2011 Forecast Model

This model consists of a series of sub-models; these include the 66kV and 22kV WMTS terminal station loops as indicated earlier in Figure 4.1. Forecast load demands for the year 2011 are used in these sub-models. After obtaining the flow analysis of the two voltage levels, a submission of all power losses, which basically represents the loading demand forecast of the WMTS for the year 2011, is identified for further analysis.

6.2.1 WMTS 66kV underground 2011 forecast sub-model

In this sub model, a 2011 forecast load demand is used to determine the new overall load flow and identify the elements under stress in the network. After the first attempt to run the load flow analysis, the load flow analysis revealed no element of the network was over stressed or exceeds their 100% rating; also the percentage of loading is less compared to the WMTS overhead sub-model presented in Section 4.3.1. In other words the proposed increased load will not exceed the cable rating; therefore, the overall network capacity will be enhanced and can meet the expected growth without installing additional circuits. Nevertheless, compared to overhead sub-model in Section 4.3.1, fewer circuits have to be installed to meet expected load growth. Figure 6.9 shows the WMTS 66kV underground 2011 forecast demand sub-model.

Figure 6.9 reveals the expected finding that many elements in the sub-model will not be stressed or exceeds their 100% loading rating. The Citipower n-1 redundancy configuration has been met in this sub-model with fewer circuits installed; consequently, the overall cost of undergrounding will be reduced. Table 6.8 illustrates the bus results of flow analysis performed on the WMTS 66kV underground 2011 forecast sub-model. The table lists bus parameters including the current rating.

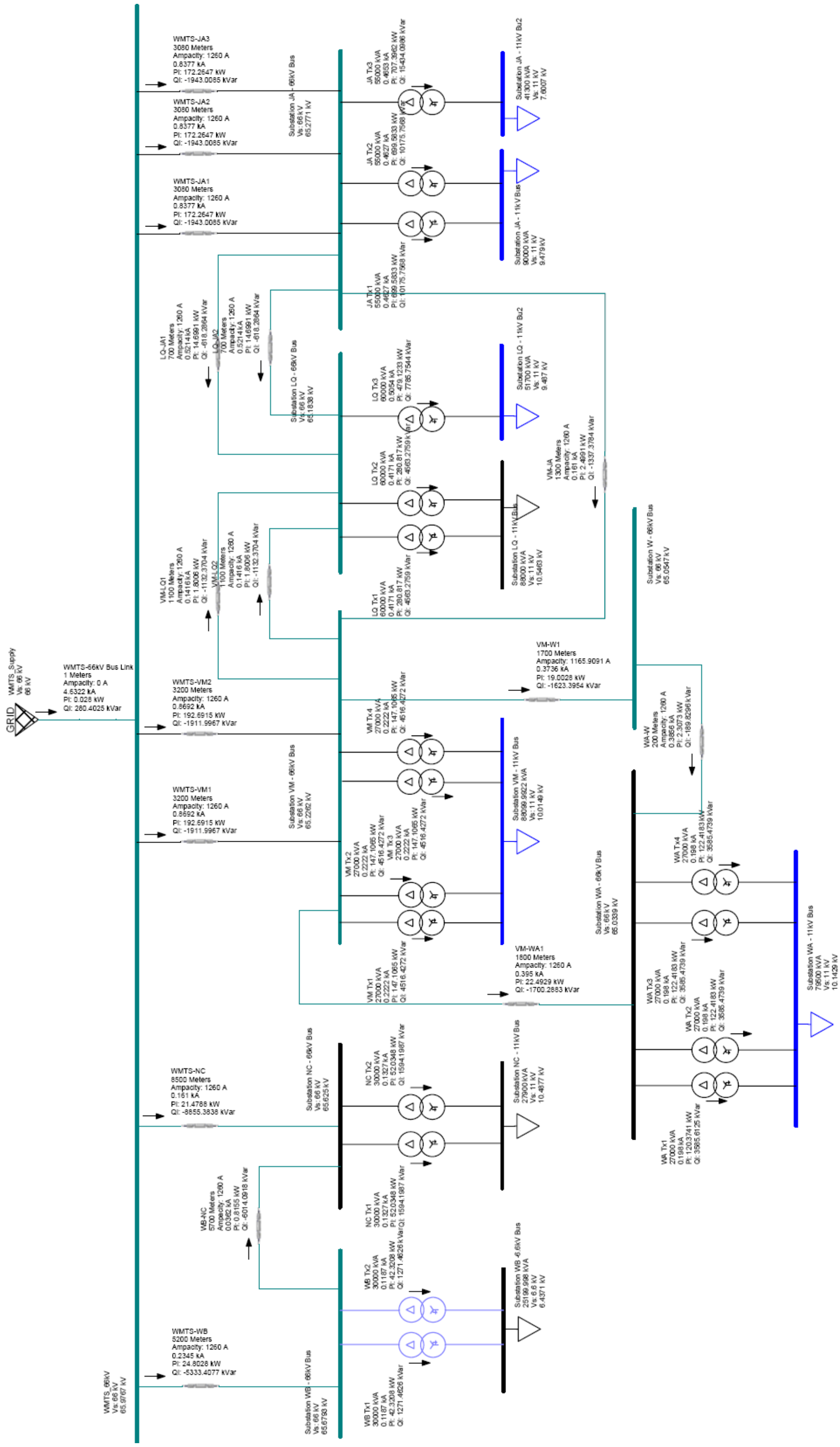


Figure 6.9: WMTS 66kV underground 2011 forecast sub-model

Table 6.8: WMTS 66kV underground 2011 updated forecast load flow results

Bus Info	Generation		Static Load		Load Flow Results				
Name	**MW**	**MVAR**	**MW**	**MVAR**	**To Bus Name**	**MW**	**MVAR**	**Amp**	**%pf**
Sub JA 66	0.00	0.00	0.00	0.00	Sub LQ 66	44.46	37.99	521	76
					Sub LQ 66	44.46	37.99	521	76
					Sub VM 66	13.81	10.49	161	79.6
					WMTS 66	-69.64	-67.44	838	71.8
					WMTS 66	-69.64	-67.44	838	71.8
					WMTS 66	-69.64	-67.44	838	71.8
Sub LQ 66	0.00	0.00	0.00	0.00	Sub JA 66	-44.44	-38.61	521	75.5
					Sub JA 66	-44.44	-38.61	521	75.5
					Sub VM 66	-11.96	-11.75	142	71.3
					Sub VM 66	-11.96	-11.75	142	71.3
Sub NC 66	0.00	0.00	0.00	0.00	Sub WB 66	-4.1	-5.64	36	58.8
					WMTS 66	-16.94	-15.99	161	72.7
Sub VM 66	0.00	0.00	0.00	0.00	Sub JA 66	-13.81	-11.83	161	75.9
					Sub LQ 66	11.96	10.62	142	74.8
					Sub LQ 66	11.96	10.62	142	74.8
					Sub W 66	31.19	28.44	374	73.9
					Sub WA 66	32.92	30.12	395	73.8
					WMTS 66	-72.63	-69.46	869	72.3
					WMTS 66	-72.63	-69.46	869	72.3
Sub W 66	0.00	0.00	0.00	0.00	Sub VM 66	-31.17	-30.06	374	72
					Sub WA 66	31.17	30.06	386	72
Sub WA 66	0.00	0.00	0.00	0.00	Sub VM 66	-32.9	-31.82	395	71.9
					Sub W 66	-31.17	-30.25	386	71.8
Sub WB 66	0.00	0.00	0.00	0.00	Sub NC 66	4.1	-0.38	36	99.6
					WMTS 66	-23.2	-18.71	235	77.8
WMTS 66	0.00	0.00	0.00	0.00	Sub JA 66	69.81	65.5	838	72.9
					Sub JA 66	69.81	65.5	838	72.9
					Sub JA 66	69.81	65.5	838	72.9
					Sub NC 66	16.96	7.14	161	92.2
					Sub VM 66	72.82	67.55	869	73.3
					Sub VM 66	72.82	67.55	869	73.3
					Sub WB 66	23.22	13.38	235	86.6
					Total losses	**1.01**	**-38.19**		

Table 6.9, summarises load flow results obtained in Table 6.8. The table shows, in two different columns, the power delivered to and from the line and in the last

two columns it lists the power difference or power losses. The total real power losses were found to be 1028.7 kW; in addition the total reactive power was found to be -38208.2 kVAR.

Table 6.9: WMTS 66kV underground 2011 updated forecast lines losses

Branch	From -> To Flow		To -> From Flow		Losses	
Name	**MW**	**MVAR**	**MW**	**MVAR**	**kW**	**kVAR**
LQ-JA1	-44.444	-38.61	44.459	37.991	14.7	-618.3
LQ-JA2	-44.444	-38.61	44.459	37.991	14.7	-618.3
VM-JA	-13.812	-11.83	13.815	10.493	2.5	-1337.4
VM-LQ1	11.965	10.615	-11.963	-11.748	1.8	-1132.4
VM-LQ2	11.965	10.615	-11.963	-11.748	1.8	-1132.4
VM-W	31.188	28.437	-31.169	-30.06	19	-1623.4
VM-WA	32.92	30.123	-32.898	-31.824	22.5	-1700.3
WA-W	-31.166	-30.25	31.169	30.06	2.3	-189.8
WB-NC	4.103	-0.377	-4.103	-5.637	0.8	-6014.1
WMTS-JA1	69.809	65.498	-69.637	-67.441	172.3	-1943
WMTS-JA2	69.809	65.498	-69.637	-67.441	172.3	-1943
WMTS-JA3	69.809	65.498	-69.637	-67.441	172.3	-1943
WMTS-NC	16.961	7.136	-16.939	-15.991	21.5	-8855.4
WMTS-VM1	72.824	67.552	-72.631	-69.464	192.7	-1912
WMTS-VM2	72.824	67.552	-72.631	-69.464	192.7	-1912
WMTS-WB	23.22	13.378	-23.196	-18.711	24.8	-5333.4
			Total power losses		**1028.7**	**-38208.2**

Figure 6.10 shows the WMTS 66kV line real and reactive power losses. The figure demonstrates that the power losses are line impedance dependent, as can be observed in the fact that although line WMTS – VM3 is shorter in length than its counterpart WMTS – VM2, however it's real and reactive power losses are much higher. The interpretation for this is due to its current rating which is less than WMTS – VM2 yet it carries almost double the amount of current

passing through as current always tends to pass through shorter paths; as a result it will produce higher losses.

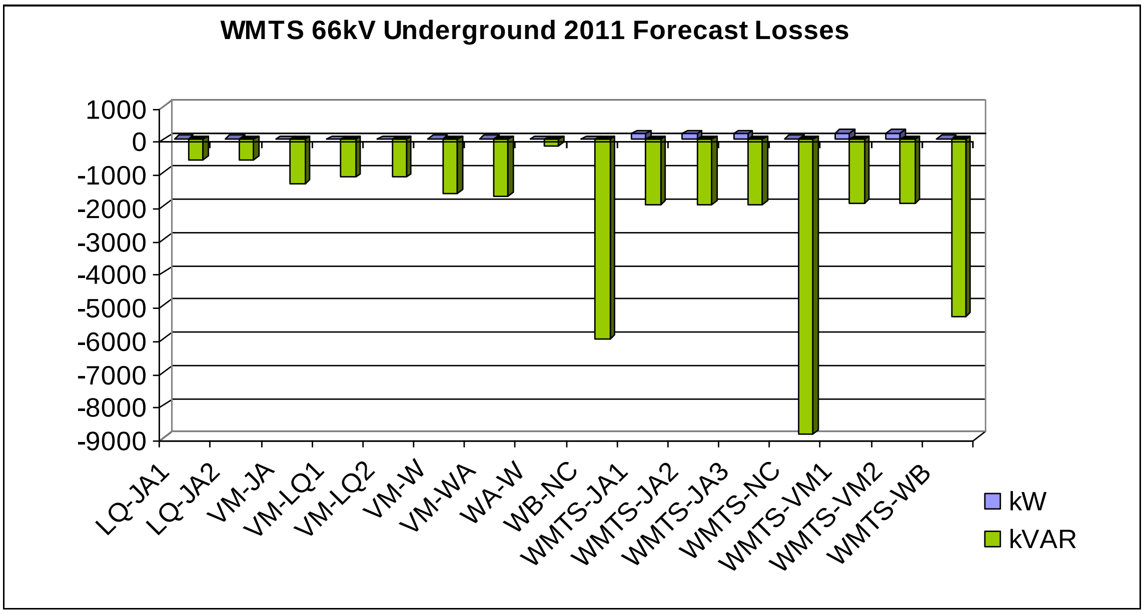


Figure 6.10: WMTS 66kV underground 2011 forecast power losses

6.2.2 WMTS 22kV underground 2011 forecast sub-model

Again the configuration of this base sub-model has many similarities to the configuration of the sub-model in Section 4.3.1 where a load demand of 2011 forecast load demand is used to determine the new overall load flow and identify the elements under stress in the network. After identifying all the elements under stress in this sub-model, single or double circuits are added to keep in line with Citipower n-1 redundancy configuration. Also new transformers have been added or upgraded to enable the load flow analysis to converge. Figure 6.11 shows the updated WMTS 22kV underground 2011 forecast sub-model.

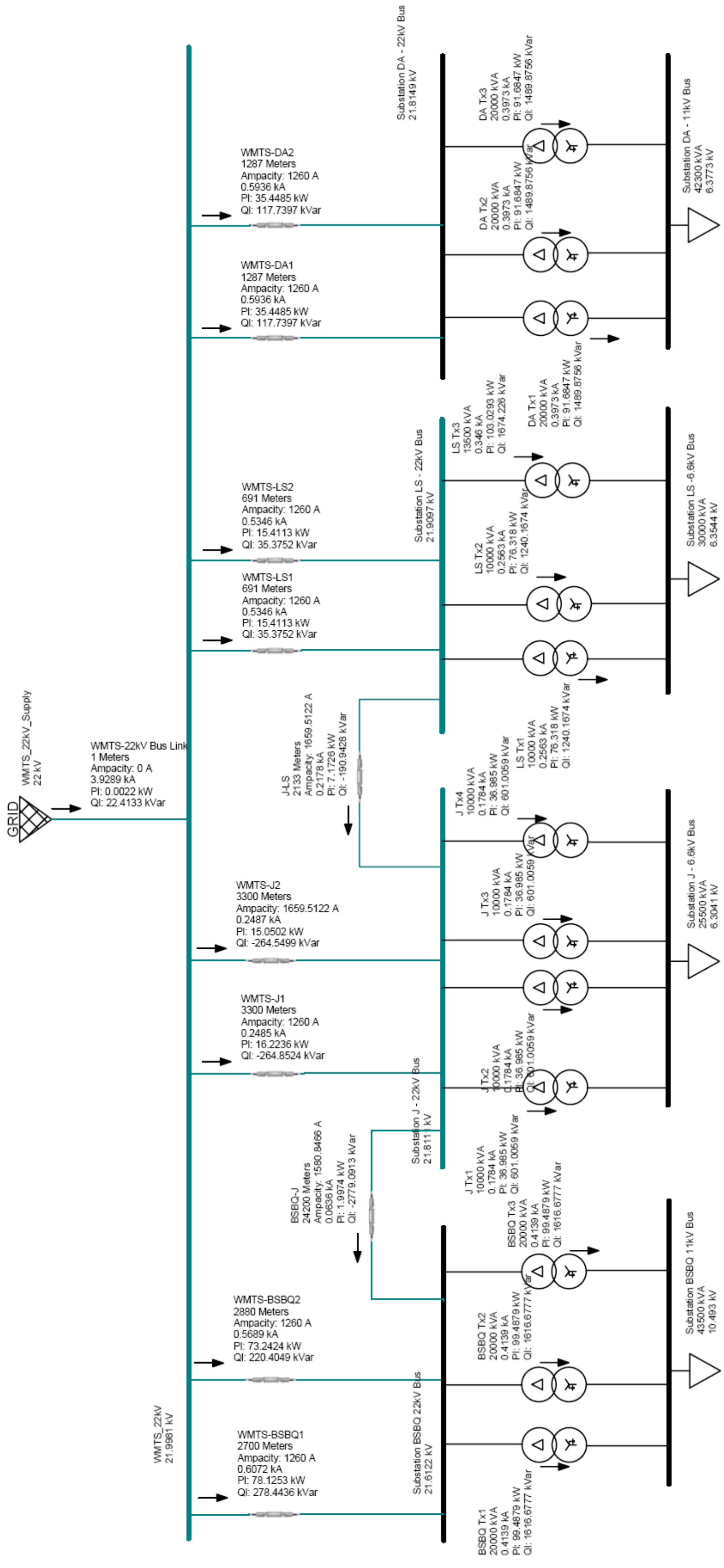


Figure 6.11: WMTS 22kV underground 2011 forecast sub-model

Table 6.10 shows the bus results of flow analysis performed on the WMTS 22kV underground 2011 forecast sub-model. The table lists bus parameters including the current rating.

Table 6.10: WMTS 22kV underground 2011 updated forecast load flow results

Bus Info	Generation		Static Load		Load Flow Results				
Name	**MW**	**MVAR**	**MW**	**MVAR**	**To Bus Name**	**MW**	**MVAR**	**Amp**	**%pf**
Sub BSBQ 22	0	0	0	0	Sub J 22	-1	-2.16	64	42.1
					WMTS 22	-18.72	-13.21	607	81.7
					WMTS 22	-17.55	-12.4	569	81.7
Sub DA 22	0	0	0	0	WMTS 22	-18.11	-13.38	594	80.4
					WMTS22	-18.11	-13.38	594	80.4
Sub J 22	0	0	0	0	Sub BSBQ 22	1	-0.62	64	85.1
					Sub LS 22	-6.97	-4.37	218	84.7
					WMTS 22	-7.95	-5.38	248	82.8
					WMTS 22	-7.91	-5.46	249	82.3
Sub LS 22	0	0	0	0	Sub J 22	6.97	4.18	218	85.8
					WMTS 22	-16.36	-12.07	535	80.5
					WMTS 22	-16.36	-12.07	535	80.5
WMTS 22	0	0	0	0	Sub BSBQ 22	18.8	13.48	607	81.3
					Sub BSBQ 22	17.62	12.62	569	81.3
					Sub DA 22	18.15	13.49	594	80.3
					Sub DA 22	18.15	13.49	594	80.3
					Sub J1 22	7.97	5.12	248	84.1
					Sub J2 22	7.92	5.2	249	83.6
					Sub LS1 22	16.38	12.11	535	80.4
					Sub LS2 22	16.38	12.11	535	80.4
					Total losses	**0.3**	**-2.7**		

Table 6.11 summarises load flow results obtained in Table 6.10. The table shows, in two different columns, the power delivered to and from the line and in the last two columns it lists the power difference or power losses. The total real

power losses were found to be 293.4 kW; in addition the total reactive power was found to be -2694.4 kVAR.

Table 6.11: WMTS 22kV underground 2011 updated forecast lines losses

Branch	From -> To Flow		To -> From Flow		Losses	
Name	MW	MVAR	MW	MVAR	kW	kVAR
BSBQ-J	-1.002	-2.16	1.004	-0.619	2	-2779.1
J-LS	-6.968	-4.374	6.975	4.183	7.2	-190.9
WMTS-BSBQ1	18.799	13.484	-18.721	-13.205	78.1	278.4
WMTS-BSBQ2	17.624	12.62	-17.551	-12.4	73.2	220.4
WMTS-DA1	18.15	13.494	-18.115	-13.376	35.4	117.7
WMTS-DA2	18.15	13.494	-18.115	-13.376	35.4	117.7
WMTS-J1	7.966	5.116	-7.95	-5.381	16.2	-264.9
WMTS-J2	7.924	5.199	-7.909	-5.464	15.1	-264.5
WMTS-LS1	16.38	12.107	-16.365	-12.071	15.4	35.4
WMTS-LS2	16.38	12.107	-16.365	-12.071	15.4	35.4
			Total power losses		**293.4**	**-2694.4**

Figure 6.12 shows the WMTS 22kV underground cables' real and reactive power losses. The figure demonstrates that the power losses are line impedance dependent, as it can be observed that although line WMTS – BSBQ1 is shorter in length than its counterpart WMTS – BSBQ2, however its real and reactive power losses are much higher, and the reason for that is the higher current passing through it causing higher losses.

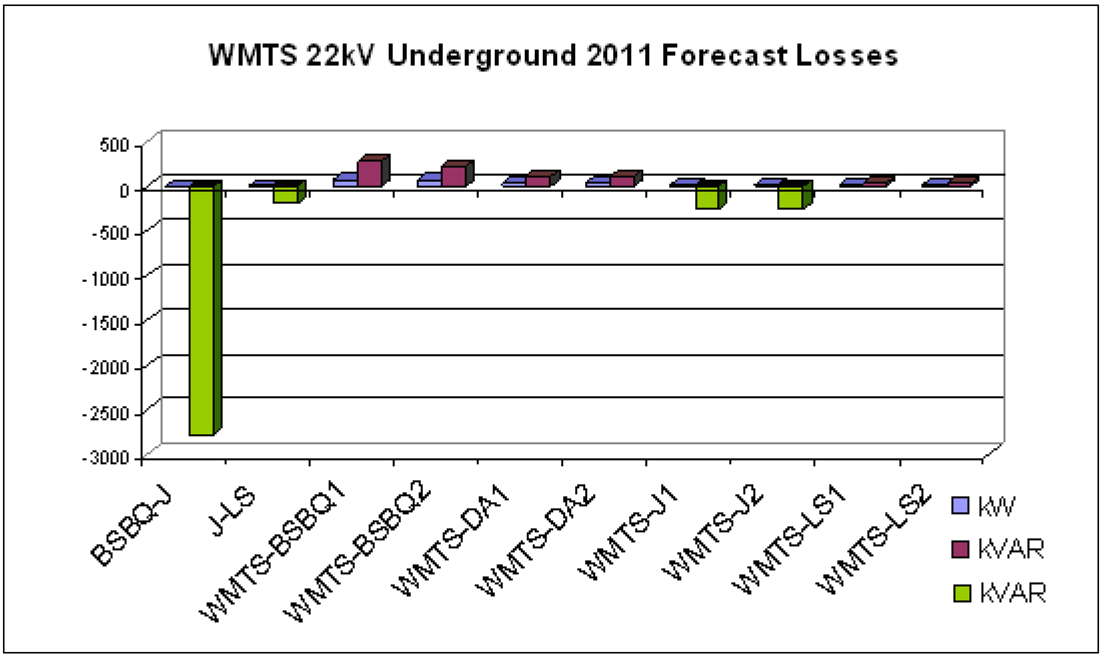


Figure 6.12: WMTS 22kV underground 2011 forecast power losses

To sum up this section, the summation of power losses found in 22kV and 66kV loops are presented as the total power losses in the WMTS section of Citipower for the network configuration with a forecast 2011 loading demand.

Total forecast 2011 real power losses = 293.4 + 1028.7 = 1322.1 kW

Total forecast 2011 reactive power losses = -2694.4 + (-38208.2)

= -40902.6 kVAR

Figure 6.13 shows the power loss comparison for the Citipower WMTS section of the underground network with power losses obtained from both 2007 and 2011 loading demand.

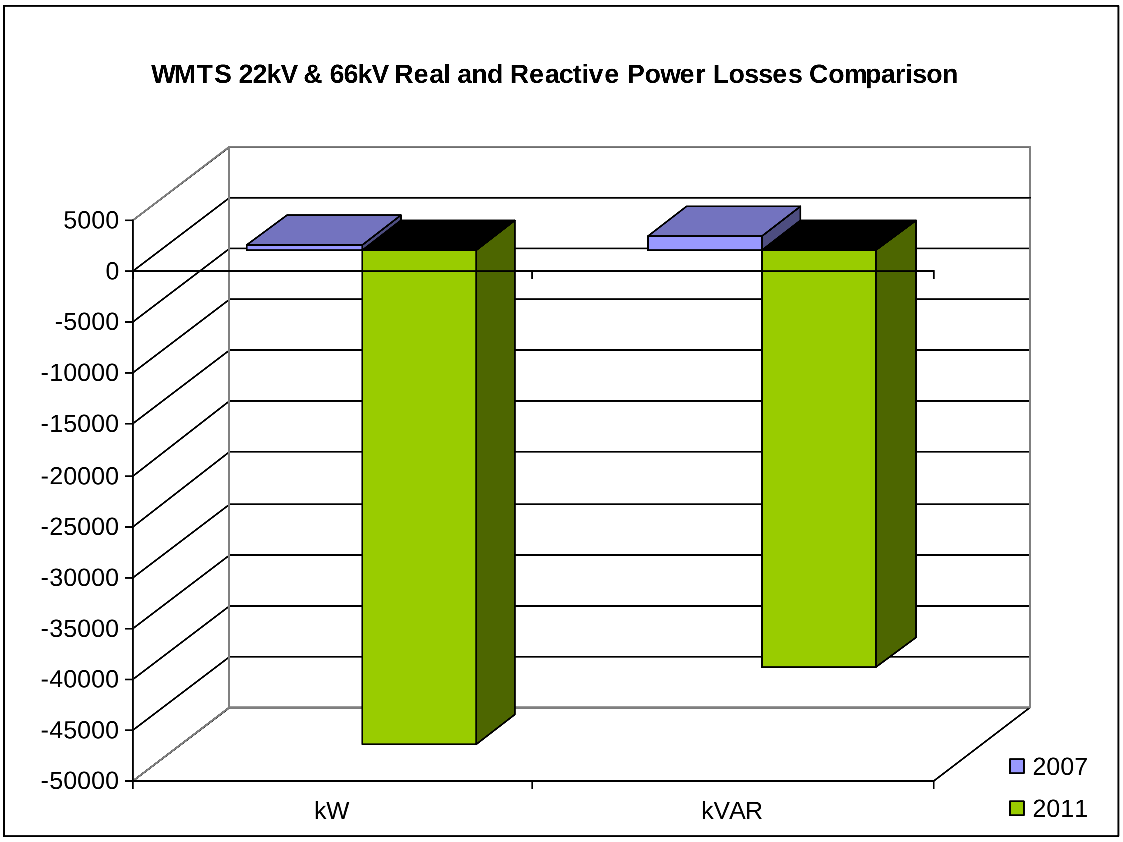


Figure 6.13: WMTS 22kV and 66kV underground power loss comparison

As can be seen from the figure, the real losses for the forecast year 2011 are almost 900 kW more than the losses for the year 2007. However, reactive losses are almost 8000 kVAR less than the losses for the year 2007. This observation can be interpreted as due to the high utilisation of cables expected for the forecasted year, hence the negative reactance will be changed to positive when cable current loading increased over approximately 50%. Also the losses are confirming the high demand on power expected for the year 2011; a matching proportional increase in the power loss is the conscience.

6.3 Citipower 2007 Underground Overall Power Losses

Data for the remaining terminal stations' loops of overhead network can be seen in Figure 4.1. Most of this data was obtained from Citipower and its publications from the public domain with the exception of the assumptions mentioned earlier in Section 4.1. Separate sub-models were developed individually for each terminal station with separate sections for 66kV and 22kV voltage levels. Appendix I lists Citipower Terminal stations underground sub-models.

Following the flow analysis of the two voltage levels, a submission of all power losses, which basically represents the loading demand of WMTS for the year 2007, is given in Tables 6.12 and 6.13 to undergo further analysis.

Table 6.12: Citipower 66kV underground overall lines losses

Branch Name	kW losses	kVAR losses
LQ-JA	7.1	-687.4
VM-JA	0.2	-1375.5
VM-LQ1	2.6	-1144.7
VM-LQ2	2.6	-1144.7
VM-W	2.7	-1778
VM-WA1	3.3	-1879.7
VM-WA2	3.3	-1879.7
WA-W	0.4	-208.8
WB-NC	0.2	-6068.7
WMTS-JA1	22.5	-3104.4
WMTS-JA2	22.5	-3104.4
WMTS-NC	3.6	-9033.3
WMTS-VM1	28.1	-2763.4
WMTS-VM2	28.1	-2763.4
WMTS-VM3	28.1	-2763.4

WMTS-WB	3.8	-5515.5
AR-BC	0.1	-3298.1
B-CW	0.1	-1479.1
BC-TK	2.4	-2642.8
CL-K	0.5	-2758.5
FR-MP	2.4	-721.2
FR-W	0.4	-736.5
NR-B	4.8	-1762.7
RTS-AR	5	-8381.3
RTS-CL	6.7	-7082.5
RTS-CW	12.8	-12224.5
RTS-EW	9.1	-7711.6
RTS-FR1	30.7	-4440.6
RTS-FR2	30.7	-4440.6
RTS-K	8	-3987.9
RTS-NR	33.2	-2300.1
RTS-SK	17	-5719.8
RTS-TK	7	-1759
SK-EW	1.2	-2217.8
W-MP	0.6	-946
E-PM	0	-1280
FBTS-AP	5.9	-4427.8
FBTS-E	0.7	-866.3
FBTS-FB	6.4	-2569.8
FBTS-MG	9.1	-2163.1
FBTS-PM	0.3	-1384.9
FBTS-SO1	4.7	-4117.7
FBTS-SO2	4	-4869.5
FBTS-WG	10.7	-896.3
MG-AP	0.3	-2126.4
WG-FB	0.7	-1238
L-Q	0.1	-4132
Q-HB	9.3	-8414.8
TSTS-HB	36.2	-10984.4
TSTS-L	39.6	-20098.9
EB-RD	0.4	-6388.5
SVTS-EB	14	-7346.1
SVTS-RD	7.1	-14665.7
Total overall power losses:	**481.30**	**-217795.80**

Both the real and reactive power losses of Citipower 66kV underground cables are shown in Figure 6.14. The figure demonstrates that the power losses are line impedance dependent and the higher current passing and longer length of line will result in higher power losses in that particular line.

The Citipower 22kV underground's real and reactive power losses are summarised in Table 6.13.

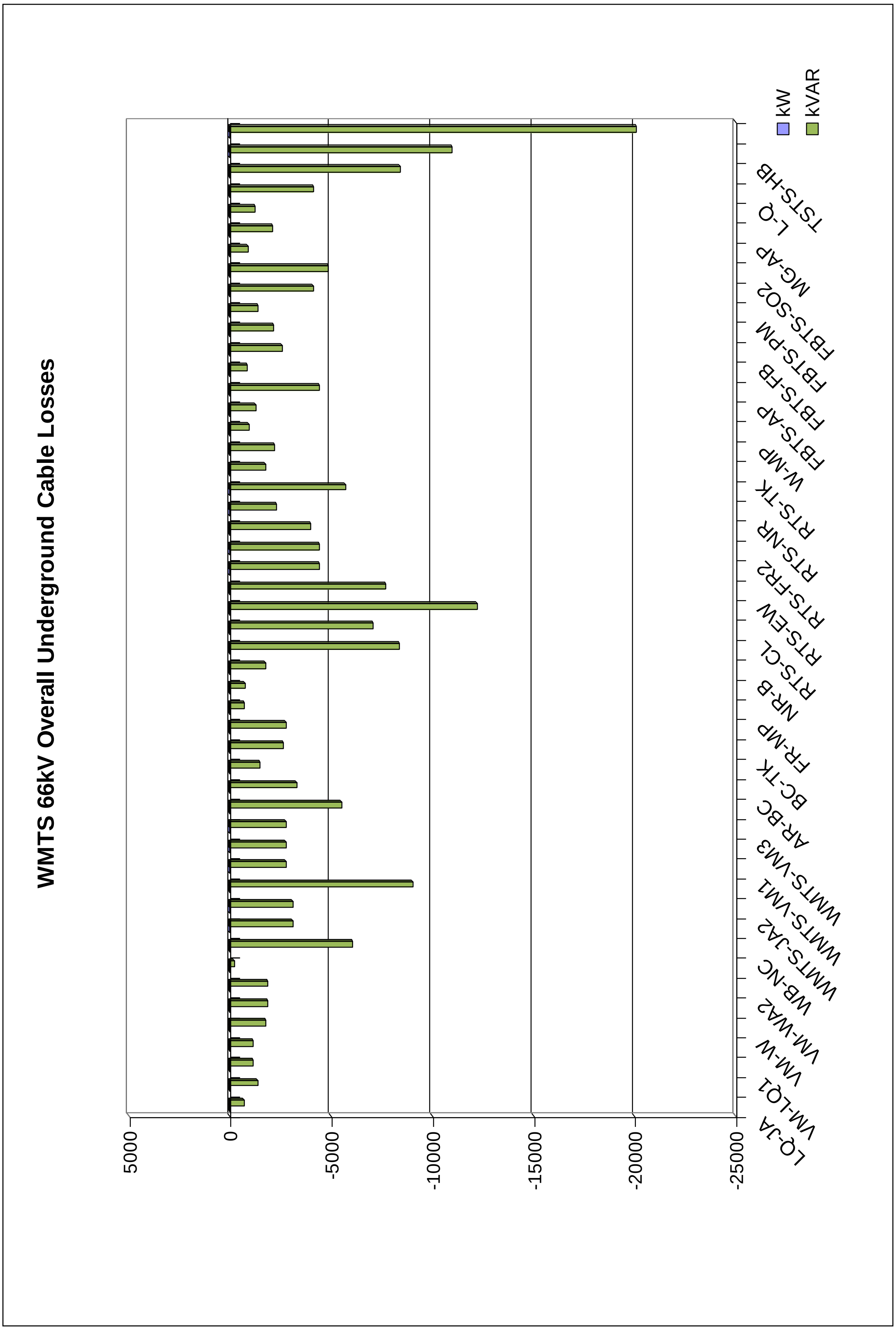


Figure 6.14: Citipower 66kV underground overall power losses

Table 6.13: Citipower 22kV underground overall lines losses

Branch Name	kW losses	kVAR losses
BSBQ-J1	1.7	-215.2
BSBQ-J2	1.7	-215.3
J-LS1	15.6	-181.9
J-LS2	15.6	-181.9
WMTS-BSBQ1	46.7	-213.8
WMTS-BSBQ2	43.7	-797.2
WMTS-DA1	17.4	-96.3
WMTS-DA2	17.2	-329.6
WMTS-DA3	16.3	-98.8
WMTS-J1	25.5	-281.3
WMTS-J2	25.5	-281.3
WMTS-J3	24.6	-283
WMTS-LS1	16.2	-53.2
WMTS-LS2	16.2	-53.2
WMTS-LS3	16.8	-52
PR-R1	4.2	-467.6
PR-R2	4.4	-467.3
R-SM	2.7	-387.7
R-SM2	2.5	-387.8
RTS-PR2	30.5	-236.8
RTS-PR3	30.5	-236.8
RTS-R1	19.6	-80
RTS-R2	19.6	-80
RTS-R3	19.6	-80
RTS-RP1	13.1	-513.6
RTS-RP2	14.9	-447.7
RTS-RP3	13.5	-497.2
RTS-SM1	14.4	-375.1
RTS-SM2	13.7	-375.9
BTS-BK1	4	-209.4
BTS-BK2	4	-211.1
BTS-BK3	4	-211.1
BTS-C2	11.7	-157.2
BTS-C3	11.7	-157.2
BTS-C4	11.7	-157.2
BTS-F1	9.5	-191
BTS-F2	9.1	-199.3
BTS-F3	9.5	-191
BTS-FF1	25.1	-272
BTS-FF2	27.5	-246.4
BTS-FF3	27.5	-246.4
BTS-NS1	100.4	-432.6
BTS-NS2	100.4	-432.6

BTS-NS3	100.4	-432.6
NT-TP1	29.4	-1465.8
NT-TP2	61.5	-676.9
Total overall power losses:	**1051.30**	**-13857.30**

Similarly, Citipower 22kV underground's real and reactive power losses are graphically represented in Figure 6.15. The figure demonstrates that power losses are line impedance dependent and the higher current passing and longer length of line will result in higher power losses in that particular line.

A combined summation of power losses is found in Tables 6.11 and 6.12 for 22kV and 66kV loops which illustrate the total power losses in the Citipower for the underground network configuration with a 2007 loading demand.

Total real power losses = 481.30 + 1051.30 = 1532.6 kW

Total reactive power losses = -217795.8 + (-13857.30) = -231653.10 kVAR

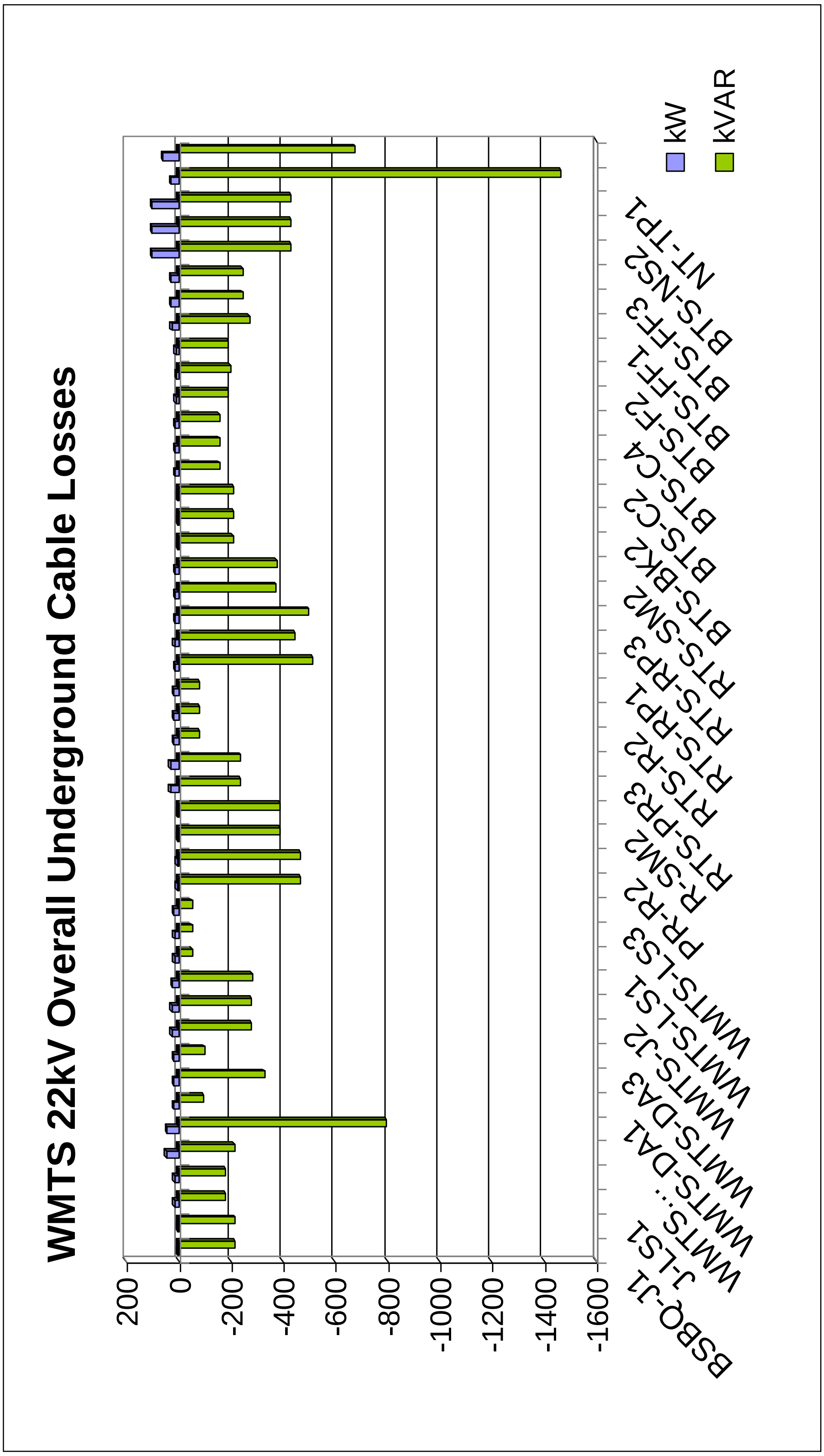


Figure 6.15: Citipower 22kV underground overall power losses

6.4 Citipower 2011 Forecast Underground Overall Power Losses

The sub-models in this section are sought to be aligned with Section 6.3. However, load demand data, for the year 2011, of all terminal stations loops as found earlier in Figure 4.1 were again obtained from Citipower publications and used in developing the sub-models of this section. Some of the network data were not available; therefore assumptions in Section 4.1 were used for the development of the network. Separate sub-models were developed individually for each terminal station with separate sections for 22kV and 66kV voltage levels.

Appendix J lists Citipower Terminal stations underground Forecast 2011 sub-models.

After obtaining the flow analysis of the two voltage levels, a submission of all power losses, which represents the loading demand of WMTS for the year 2011, is given in Tables 6.14 and 6.15 to undergo further analysis.

The Citipower 66kV underground's real and reactive power losses are in Figure 6.16. The figure demonstrates that the power losses are line impedance dependent and the higher current passing and longer length of line will result in higher power losses in that particular line.

Table 6.14: Citipower 66kV underground 2011 forecast overall lines losses

Branch Name	kW losses	kVAR losses
LQ-JA1	14.7	-618.3
LQ-JA2	14.7	-618.3
VM-JA	2.5	-1337.4
VM-LQ1	1.8	-1132.4
VM-LQ2	1.8	-1132.4
VM-W	19	-1623.4
VM-WA	22.5	-1700.3
WA-W	2.3	-189.8
WB-NC	0.8	-6014.1
WMTS-JA1	172.3	-1943
WMTS-JA2	172.3	-1943
WMTS-JA3	172.3	-1943
WMTS-NC	21.5	-8855.4
WMTS-VM1	192.7	-1912
WMTS-VM2	192.7	-1912
WMTS-WB	24.8	-5333.4
AR-BC	1.2	-3254.7
B-CW	0.3	-1460.3
BC-TK	16.8	-2511.6
CL-K	10.6	-2626.4
FR-MP	20.3	-580.7
FR-W	3.8	-706.2
NR-B	15.8	-1660.3
RTS-AR	44.1	-8036.2
RTS-CL	115.3	-6177.9
RTS-CW	49.7	-11870.1
RTS-EW	57	-7304.7
RTS-FR1	144.3	-3564.1
RTS-FR2	144.3	-3564.1
RTS-K	133.9	-2995.5
RTS-NR	137.5	-1496.2
RTS-SK	100.5	-5049.6
RTS-TK	63	-1327.7
SK-EW	4.7	-2165.4
W-MP	5	-906
E-PM	0.1	-1277.9
FBTS-E	3.4	-843.5
FBTS-FB	13	-2512.6
FBTS-MG1	23.6	-2040.3
FBTS-MG2	25.4	-2040.8
FBTS-PM	2.9	-1362

FBTS-SO1	46.6	-3753.2
FBTS-SO2	39.6	-4553.8
FBTS-WG1	11.1	-892.3
FBTS-WG2	12	-892.5
FPTS-AP1	18.8	-4323.2
FPTS-AP2	18.8	-4323.2
MG-AP	1.6	-2107.1
WG-FB	5.3	-1198.4
L-Q	0	-4051.2
Q-HB	55.6	-7919.5
TSTS-HB	58.6	-10756.7
TSTS-L	107.8	-19335.8
EB-RD	0.9	-6234.5
SVTS-EB	180.2	-5893.6
SVTS-RD	82.4	-13877.2
Total overall power losses:	**2804.50**	**-205655.20**

The Citipower 22kV underground's both real and reactive power losses are summarised in Table 6.15.

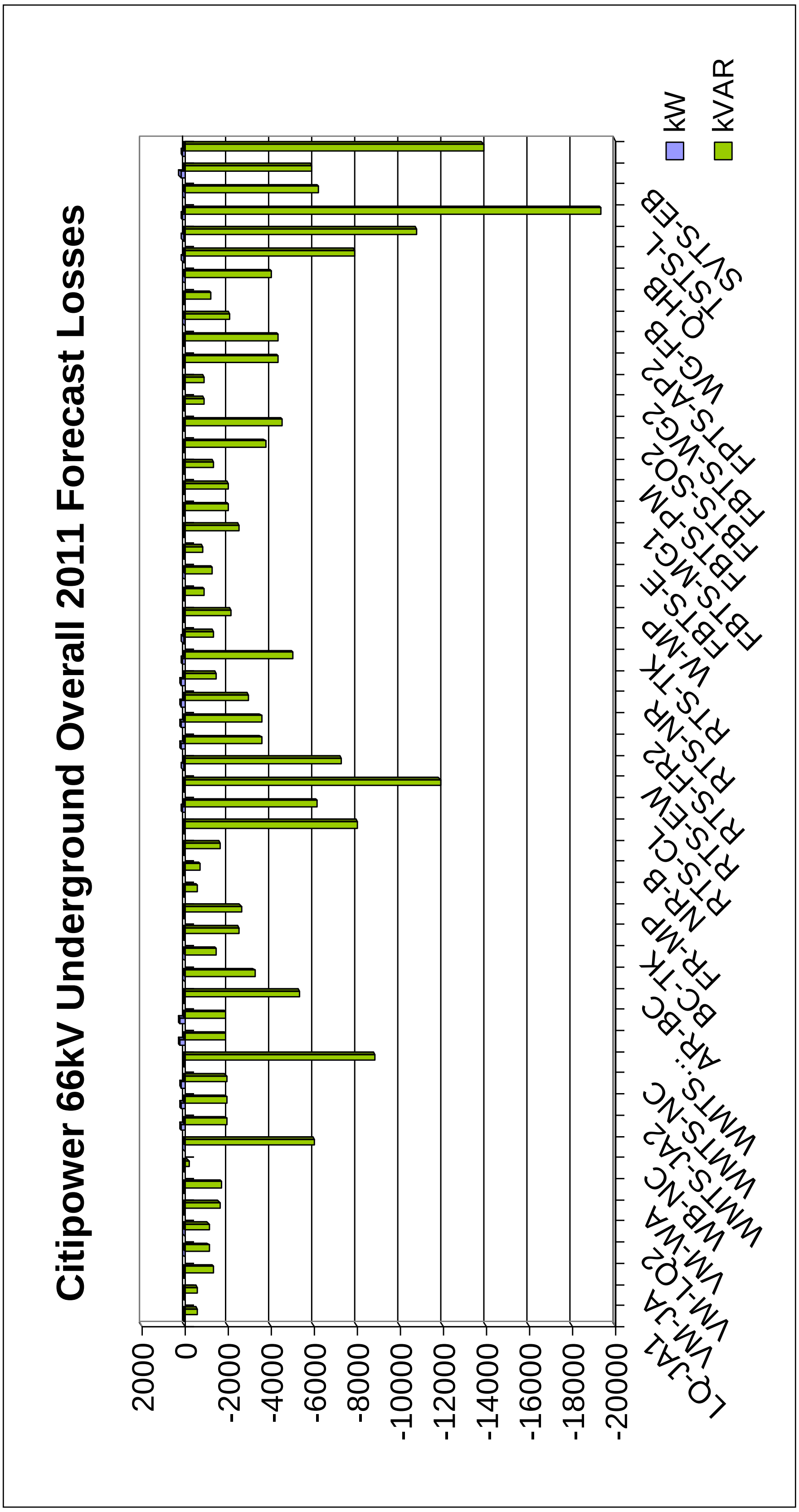


Figure 6.16: Citipower 66kV underground 2011 forecast overall power losses

Table 6.15: Citipower 22kV underground 2011 forecast overall power losses

Branch Name	kW losses	kVAR losses
BSBQ-J	2	-2779.1
J-LS	7.2	-190.9
WMTS-BSBQ1	78.1	278.4
WMTS-BSBQ2	73.2	220.4
WMTS-DA1	35.4	117.7
WMTS-DA2	35.4	117.7
WMTS-J1	16.2	-264.9
WMTS-J2	15.1	-264.5
WMTS-LS1	15.4	35.4
WMTS-LS2	15.4	35.4
PR-R1	0.4	-672.2
PR-R2	0.4	-672.2
R-SM1	107.1	268.9
R-SM2	107.1	268.9
RTS-PR1	21.6	-199.8
RTS-PR2	21.6	-199.8
RTS-R1	40	174.4
RTS-R2	40	174.4
RTS-R3	40	174.4
RTS-RP1	39.2	-621.9
RTS-RP2	20.6	-499
RTS-SM1	169.5	853.2
RTS-SM2	169.5	853.2
RTS-SM3	169.5	853.2
BTS-BK1	8.5	-241.1
BTS-BK2	8.4	-244
BTS-C2	4.3	-203.9
BTS-C3	4.3	-203.9
BTS-F1	9.7	-209.1
BTS-F2	9.3	-223.8
BTS-FF1	31.5	-135.4
BTS-FF2	31.5	-135.4
BTS-NS1	95.8	36.6
BTS-NS2	95.8	36.6
NT-TP1	14.3	-2027.3
NT-TP2	30	-778.8
Total overall power losses:	**1583.30**	**-6268.20**

The Citipower 22kV overall underground's real and reactive power losses are graphically represented in Figure 6.17. The figure demonstrates that power losses are line impedance dependent and the higher current passing and longer length of line will result in higher power losses in that particular line.

A combined summation of power losses is found in Table 6.13 and 6.14 for 22kV and 66kV loops which are presented as the total power losses in the Citipower for underground network configuration with a 2011 forecast loading demand.

Total real power losses = 1583.30 + 2804.50 = 4387.8 kW

Total reactive power losses = -6268.20 + (-205655.20) = -211923.4 kVAR

A clearer representation of the comparison of power losses for the overall Citipower underground network with power losses obtained from both 2007 and 2011 loading demand is shown in Figure 6.18.

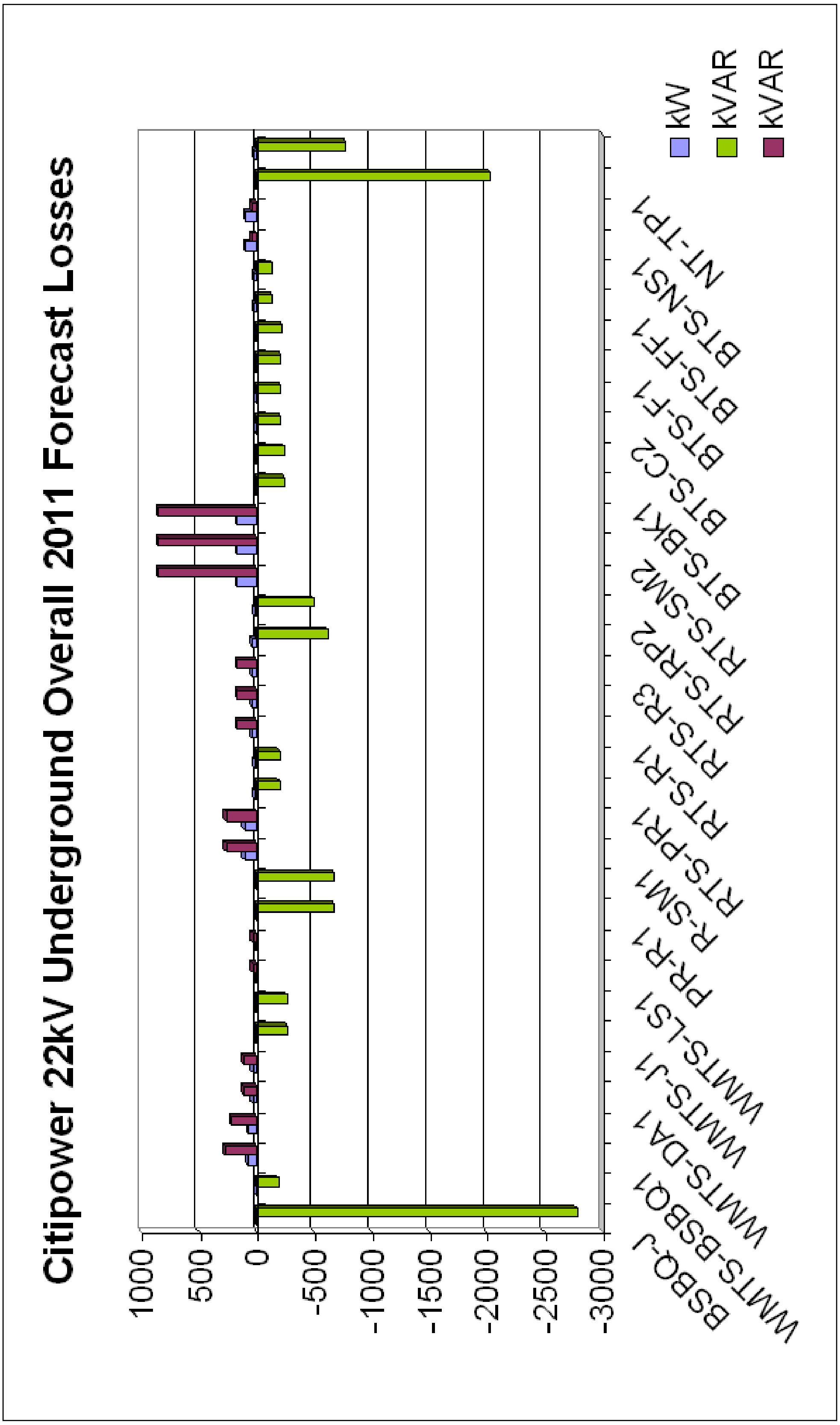


Figure 6.17: Citipower 22kV underground 2011 forecast overall power losses

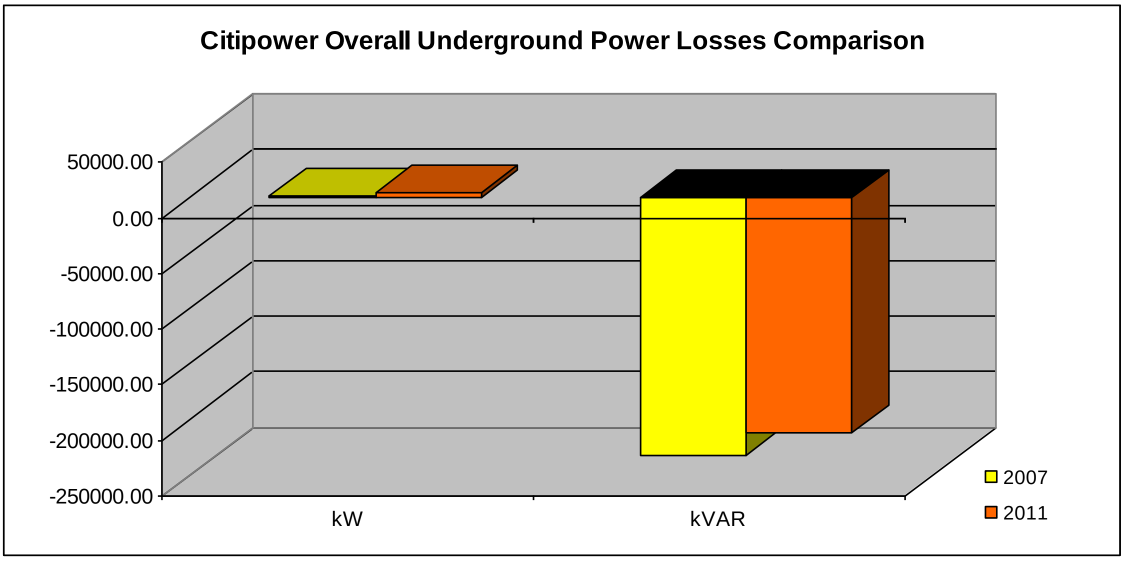


Figure 6.18: Citipower overall underground power loss comparison

As can be seen, the real losses for the forecast year 2011 are almost 3000 kW greater than the losses for the year 2007; on the other hand, the reactive losses for 2011 are almost 20000 less than the losses for 2007. Moreover there are many lines duplicated to keep the Citipower n-1 configuration; the added lines reduced the power losses due to the fact that less current will pass through the same lines and it will produce less power losses. Data in Figure 6.19 can be compared with the data in Figure 4.18 in Section 4.6, to highlight the Citipower overall power losses for the year 2007 and forecast losses of the year 2011. Figure 6.19 presents the comparison of Citipower overall power losses for overhead and the proposed underground models.

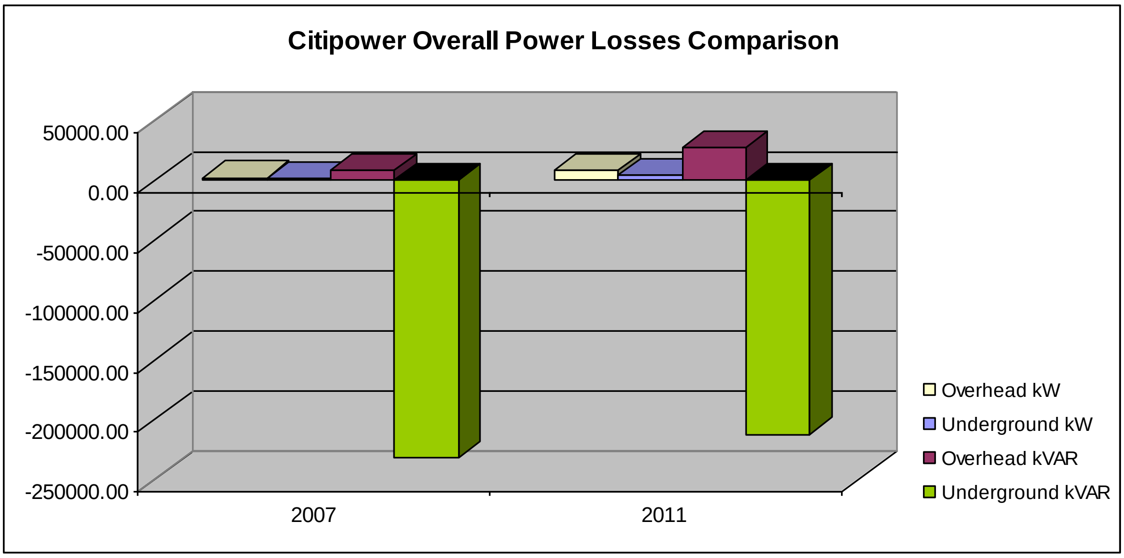


Figure 6.19: Citipower overall underground power loss comparison

As predicted, the real power losses comparison in Figure 6.20 shows almost 50% reduction between the losses in the year 2007 and the projected loss for the year 2011. However, the reactive power losses for the year 2007 were less than the anticipated reduction in losses. More interestingly, losses in reactive power for the year 2011 have exhibited a higher figure in underground than overhead losses. The obvious reasons for both scenarios is that less feeders have been used in the 2007 underground model than those used in the overhead model; furthermore, the same number of feeders have been used for 2011.

In Figure 6.20 there is a clear indication of the previously mentioned finding, that is, the number of circuits or number of cables in the underground forecast model is 25% less than the overhead forecast model.

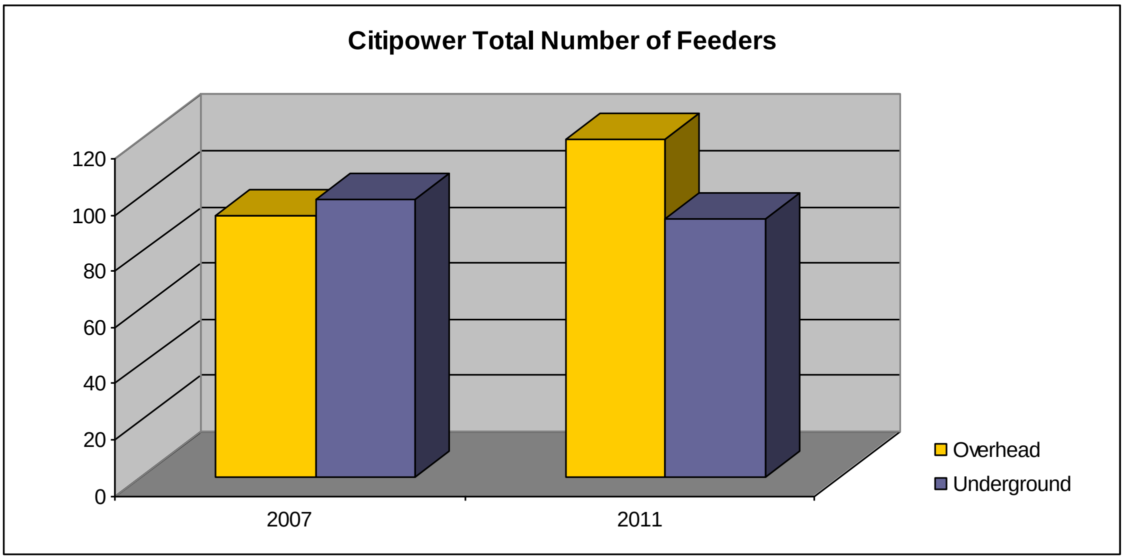


Figure 6.20: Citipower total number of lines compared to cables

6.5 Conclusion

A thorough analysis and development of Victorian underground power network sub-models were presented in detail in this chapter. In addition, an elaboration on overall underground network sub-models was discussed in chapter 5. These analyses are of great significance for the future growth and safe operation of the Victorian power network. Various forecasted models were analysed in order to determine the need for additional lines and transformers to cope with the additional forecasted load.

Load flow analysis and other industrial based specialised software were used to investigate and develop various sub-transmission network models. The results obtained from the load flow analyses provided crucial information about all buses in the network. Some buses were exceeding their normal operation values or nominal values so an action was made to rectify the problem associated with any abnormality in the network; again the Citipower n-1 redundancy configurations were met in all sub-models developed in this work.

Another outcome of the load flow analysis was the discovery of real and reactive power losses at each line and the effect of forecasted loading on the losses were identified as well.

The next chapter looks at the Victorian hybrid power network in an attempt to efficiently design an underground network for Victoria.

CHAPTER 7

DEVELOPMENT AND ANALYSIS OF VICTORIAN HYBRID POWER NETWORK MODEL

7.0 Introduction

HTS cable has a unique characteristic of low impedance to current flow. Unlike conventional power cables, HTS cable offers higher power transfer with minimum losses and more compact design of power applications yet better power flow absorption in the networks at the same voltage levels.

In attempts to closely study the effect of HTS cable on power networks, several pilot projects were carried out around the world. Promising results were achieved in terms of cable capacity and reliability. However, the big challenge of this technology is the high cost of superconductive materials in addition to the cost associated with cable-cooling, which is required at its normal operation temperature (-208ºC for present HTS cables). A new cable design which utilises the cryogenic electrical insulator has been developed, in parallel with developing highly reliable cable cooling technology with a long service life aiming for longer service intervals. These are expected to reduce the cost of HTS cable technology significantly in the short term; and in the midterm industry scale production will certainly further reduce the cost of HTS cable. This chapter will present the technology involved in HTS cable and its anticipated effects on power transmission networks.

For the last few decades power transmission for long distance was only possible with extra high voltage. However the transmission network required huge investment in high voltage equipment and switch gears, yet it came with big electrical transmission losses. Fast growing cities and deregulation of the electrical sector in many countries around the world resulted in overwhelming demand for more power [42]. So far, the focus of the electricity market has been narrowed onto the generation part of the power network, directing much of power investment into the new way of generation and renewable energy technology. This leaves the transmission part of the network with the burden of ageing and overloading to face reliability challenges. HTS cables, with their unique characteristics of low impedance and high current rate, have the potential for increasing power transmission capacity. Therefore by transferring a larger amount of generated power that normally is lost in conventional power transmission cables, less generation is then required for the existing load [17].

Further on in this chapter, Section 7.2 will explain in detail the obtained results from the load flow analysis performed on the hybrid sub-model, where four lengths of HTS cable were employed in conjunction with the conventional XLPE cable. The employment enabled a comparison to be drawn on the performance and impact of the HTS cable on the Citipower power network. WMTS loop was identified to be a potential site for future proposed HTS cable due to the predicted high load demand, current and scheduled zone substations upgrades from 22kV to 66kV like BSBQ.

7.1 General Overview of HTS Cable Technology

Superconductivity occurs in some materials at very low temperatures; it is often recognised to have exactly Zero electrical resistance with no interior magnetic field. The hunt for superconductive material has always played a vital role in continuous research and development which has led to great discoveries especially in the past couple of decades. Materials, such as ceramics, copper oxides and barium along with many others, were discovered in the late 1980s. The key benefits of such materials are the relatively low cost of refrigeration compared with that of conventional metallic superconductors. Examples, of potential applications of such superconductors, would be such as, utilising them in transmission cables to gain a huge reduction in high voltage transmission losses. In addition, the very low or no EMF leaves the doors widely open for applications such as fast trains and other applications that are within close proximity to users [43].

7.1.1 Superconducting cables

During the late 1980s many studies explored developing and designing the most cost effective superconducting cable. The outcome of these studies resulted in the design of low-loss dielectric insulators. In addition, other forms of insulators have also been considered in the literature [29, 33–35] such as liquid air impregnated paper as well as glass-epoxy tapes. As noted earlier, the discovery of ceramics superconductors has significantly contributed towards eliminating many of the problems associated with superconducting at high temperatures [42].

7.1.2 HTS triaxial cables design

Ultera - A Southwire Company of Carrollton, GA. and nkt cables of Denmark Joint Venture, of two leading wire and cable manufacture around the world, has successfully built and tested a new HTS cable design. It offers a thrilling new conductor design with the focus of reducing the technology cost and enhancing its reliability through reducing material cost, cooling areas and requirements, and thermal and electrical losses. The concept was to reduce the quantity of HTS wire needed, and reduce cooling requirements by means of using a common cold surface area. Thereby, the triaxial conductor design which placed all three phase conductors concentrically around a common central core was implemented. Electrical field cancellation was also achieved by the three concentric phases being 120º (electrical) apart. Thus one common copper shield was used to carry neutral currents. The first full-scale prototype of the Triax design was built and tested at Ultera's development partner Oak Ridge National Lab (ORNL) in 2002. The triaxial conductor design is shown in Figure 7.1 [44].

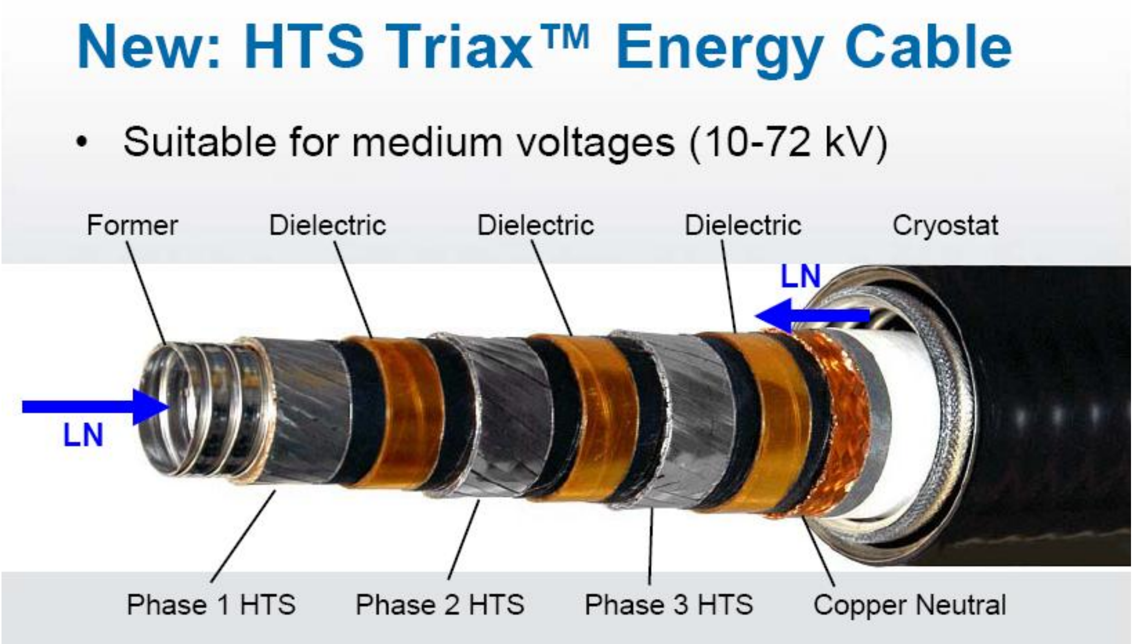


Figure 7.1: Triaxial superconducting cable design [44]

This design was a big milestone towards reducing HTS cables system costs and achieving a commercially viable product. The major breakthrough of the Triax design was tackling specifically the two major cost components in a superconducting cable system: HTS wires and refrigeration.

The Triax cable design termination provides ambient temperature transition to the three phases and the shield, which is typically at ground potential, as shown in Figure 7.2. The three concentric phases are connected to copper leads that continue throughout the length of the termination. The three phase connections are shown at the right side of the termination while the neutral bushing is hidden on the back side of the termination body. Another interesting feature of the Triax termination, is the slim design in which the body of the termination is no larger in diameter than the cable cryostat [44].

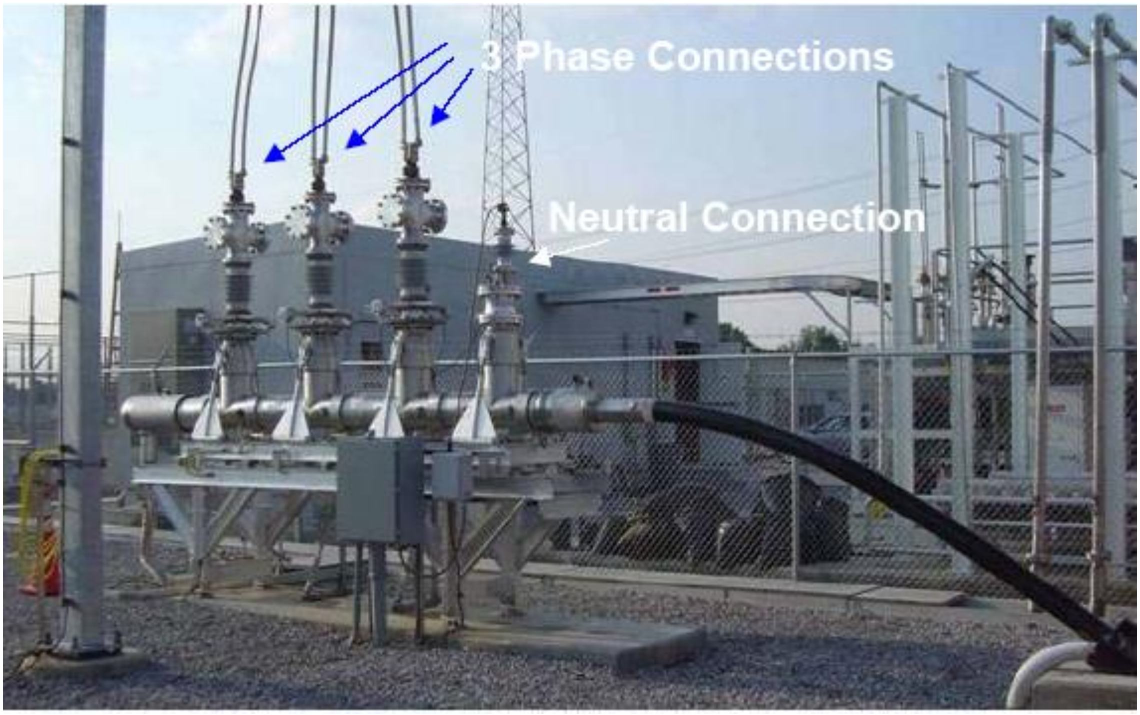


Figure 7.2: Full scale Triax termination [45]

7.1.3 Potential benefits of HTS cables

HTS cable is more expensive than any of the conventional cables (MV and HV). However, there can be economic benefits in short connections (1-3 km) where one or several HV stations (110-220 kV) can be converted to /replaced by MV stations (10-72 kV).

The biggest advantage is however that connection into city centres becomes possible without building new HV substations, as has been demonstrated with the 1.7 km project in New Orleans, US.

7.1.4 High capacity

HTS cables have the potential to improve the efficiency and stability of the power networks with their capacity to carry current up to 5 times more than conventional underground power cables. Therefore, more flexible power transmission or power flow within the power networks will be possible. Yet due to their compact design, they provide the best real life solution, for retrofitting conventional cables to increase capacity in highly congested cities where existing conduits have been utilised to the maximum. This will enhance the future expansion of the power network and give power designers more flexibility in designing the network. Masuda et al. [46], states that the cost of constructing HTS cables is likely to be much less than the cost of constructing a new conduit for conventional underground cables; this assumption is calculated based on current construction techniques and assuming the cooling system interval is every 5 km apart. In this aspect HTS cables will be more economic to construct than upgrading the conventional cables rating, which in some cases is not an option given that conduits have limited diameters. For these reasons, HTS cables become a more competitive and attractive solution where there was not an option before [17, 46].

7.1.5 Low ohmic resistance

Low ohmic resistance is the nature of superconductivity. In HTS cables, the ohmic resistance is almost zero at the critical temperature, which reduces transmission losses to very small amounts. According to Masuda et al. [46], a superconducting shield is constructed not only to eliminate the electromagnetic field leakage outside the cable, but also to eliminate eddy current loss from the electromagnetic field. These losses are normally generated by the alternating current and are similar to the magnetization loss of the superconductor itself. Additional losses are the dielectric loss of the insulation and the heat incursion through the thermal insulation pipe. The resulting heat has to be removed and HTS cables temperature needs to be maintained at the cable operating temperature. Coolant from a cooling unit is required to balance this heat gain. In addition, electric power is required for running the cooling unit. In summary, the loss of the superconducting cable is approximately half that of a conventional cable [46].

7.1.6 Low impedance

The low inductance in HTS cables is due to the high performing cryogenic dielectric, which permits a thin electrical layer and a screened cable design with zero external magnetic fields. This results in a small volume of magnetic field surrounding the conductor and therefore a low induction.

7.1.7 Limitation of HTS cables

HTS cable has many advantages and some limitations. Like any other new technology under development it faces some hurdles. As has been pointed out in some of the early work, these hurdles include:

(1) the high cost of the technology that can make the feasibility of installing HTS cable uneconomical;

(2) high power ratings requirement, meaning that unless there is an enormous amount of power that needs to be shifted for a short distance the use of HTS cables can hardly be justified e.g Detroit project [8];

(3) break-even energy losses due to the high maintenance cost, especially for the refrigeration part of the system.

7.1.8 Energy losses - a comparison between HTS and XLPE cables -

It is very well known that HTS cables ohmic losses are much lower than those with XLPE cables as mentioned in Section 7.1.5. For the purpose of this comparison, reference [46] has chosen three phase HTS and insulated copper conductor XLPE cables, the HTS cable's capacity rated at 3,000 A at 132 kV while the XLPE's capacity parameters where 1,080 A at 138kV. The negligible difference in voltage levels were highlighted merely to distinguish between the standards used in the US and Europe and will have no affects on the analysis results.

The ac losses in a particular conductor are proportional to its length and the amount of current passing through the conductor. In XLPE cables the heat is absorbed by the surrounding insulators while in HTS it must be explicitly eliminated in order to maintain its efficiency within regular operating temperatures. HTS cables heat load includes thermal losses from heat leakage in addition to another requirement which dictates that HTS cables must connect to system elements at ambient temperature.

What's more, the lack of experience in HTS cable technology has added to the fear, of power utilities, of adopting it. These hurdles can outweigh any benefits of HTS cable unless it proves commercially reliable. Until then it will not be a widely accepted technology. So far, the HTS cable has been successfully demonstrated in laboratory prototypes and to certain extents in the real life grid. The next phase should be a commercial scale introduction of this technology with larger HTS cable systems engineered to operate on the utility network [47].

7.1.9 Development of HTS cables

Bearing in mind all the challenges faced during the early development of HTS cables, Ultera is currently addressing these issues by developing a new cable design. it uses one thermally insulating envelope “Cryostat” for all three phases, and eliminates the need for a return screen for each of the phases. This reduces cost by 40-50%, and it cuts the energy losses by 50%. In this way Ultera achieves usefulness at smaller rated power. It has been estimated that the cost of the materials required to transmit 1 kA over 1 m length using HTS cables is approximately 11 EUR/kAm [47].

Nkt cables had 200 m HTS cable on pilot installation running for 2 years with American Electric Power. The cable was type tested in 2005 then installed and commissioned in 2006. The first generation of this cooling system was used at the time. The availability of cable reached 99.95% with only one scheduled outage. Overall nkt cables has more than 9 years of operation experience [45]. Figure 7.3 shows the 200 m pilot installation in the utility grid in Columbus, in the United States.

Figure 7.3: Triaxial superconducting cable termination [45]

The latest results obtained are approved type tests at 13 kV for a cable system with a power rating of 69 MVA. This is still a lot of power, but not as large as the 1-5 GVA that is mentioned by earlier work [45]. The cable has an inductance in the order of 16 µH/km. This allows it to absorb the load flow from other parts of the network at the same voltage. In order to reduce the operation costs, Ultera have partnered with Praxair, one of the three largest gas manufacturers. They develop cooling technology with long service life; the goal is longer service intervals than three years. The operation costs are then dominated by the losses and the electricity cost of running the cooler. This is similar to a conventional cable. The breakeven is around 3000 h of usage, which is an ordinary load level in most systems. For higher loading, the HTS cables are more efficient, for example in industrial systems, with 5000 h load per year [47].

Although developing and manufacturing HTS cable sounds intimidating, Shahidehpour [47], predicts the outlook for HTS cable to be a realistic technical and economic alternative for power delivery. Figure 7.4 shows the growth in U.S.-manufactured superconducting wires. Meanwhile, it is expected that the market for superconductor products is projected to grow to near US$5 billion by the year 2010 and to US$38 billion by 2020 [47].

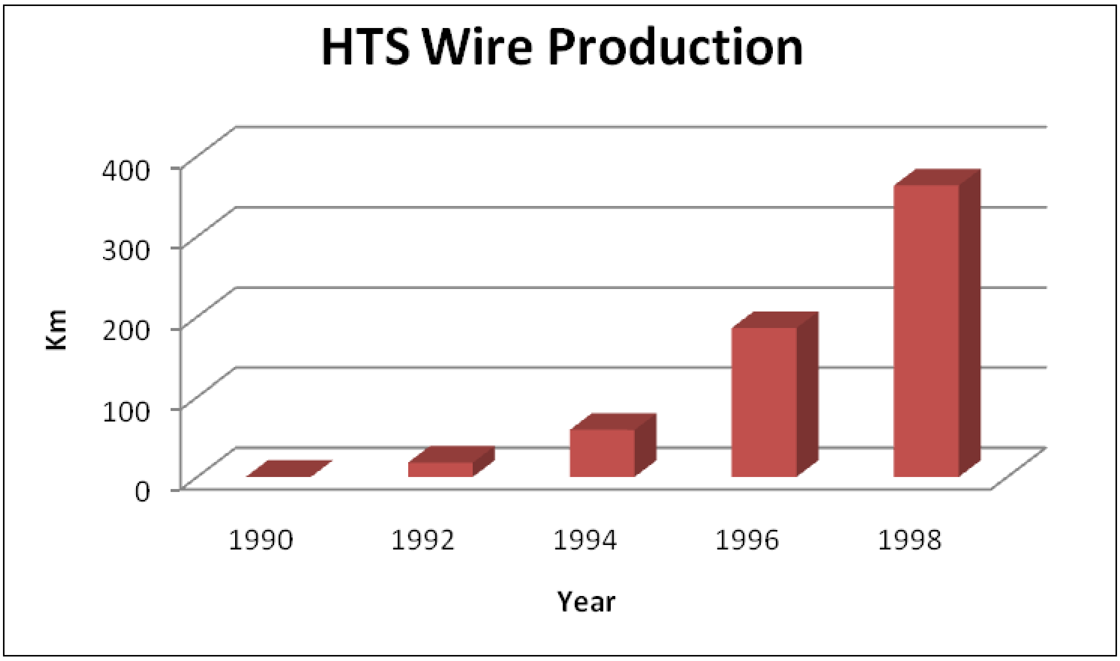


Figure 7.4: Growth in U.S.-manufactured superconducting wires [47]

In relation to the price of HTS, there are delays in the reduction in the price due to the slow adoption and slow growth in volume, and also due to the transit to second generation conductors. Figure 7.5 is an indicator of second generation tape price fall. The price-volume curve was developed by the German industry association IV Supra. This will eventually translate to second generation tapes being cheaper than copper. The tape industry is fighting to reach approximately 40 k$/kAm. The very long-term (large-volume) forecast is still 10-20 $/kAm. [45]

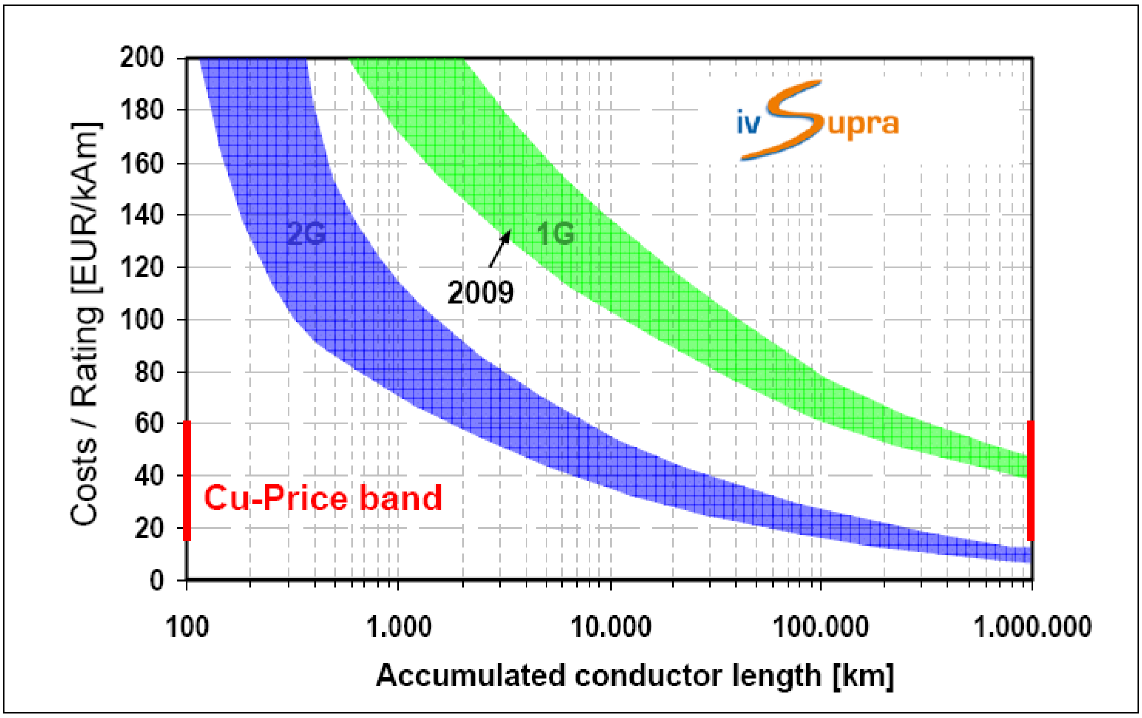


Figure 7.5: Price-volume curve developed by the German industry association IV Supra [45]

Today, several HTS cable projects are underway in the United States and around the world. One of these projects was the first to supply electricity to 50,000 customers in Copenhagen, Denmark, and another example was in Carrollton, Georgia [47], where more than 26,000 hours of fault-free operation were recorded while powering three manufacturing plants. Studies by major corporations and organizations, have suggested that principle investments in the HTS cables technology are needed. They will play a significant role to meet the necessary need for reliable and affordable electric power in the United States. Now it is obvious, the technology will progressively play a big role in the power applications for large markets in terms of cost as well as efficiency and performance [47].

7.2 Feasibility Studies

7.2.1 Power to city centre 6 km in Amsterdam

The technological advancement over the years has brought HTS cables a long way in terms of length as they have increased from cables a few hundred meters long to cables kilometres in length. In this case study [48], two Dutch utilities have come together to replace a 150kV Gas Pressure cable with a 50kV HTS cable which will be retrofitted into the existing steel pipe that was accommodating the old Gas Pressure cable. The new HTS cable will be utilising a new generation of modern and efficient cooling systems which are also known as “Pulse Tube Coolers” [48].

Figure 7.6 shows the length of the Netherlands’ High Voltage circuits in kilometres. These long distance networks have necessitated the need for the long HTS cable which was developed for this case study in order to retrofit into a steel pipe that was occupied by an old gas pressure cable [48].

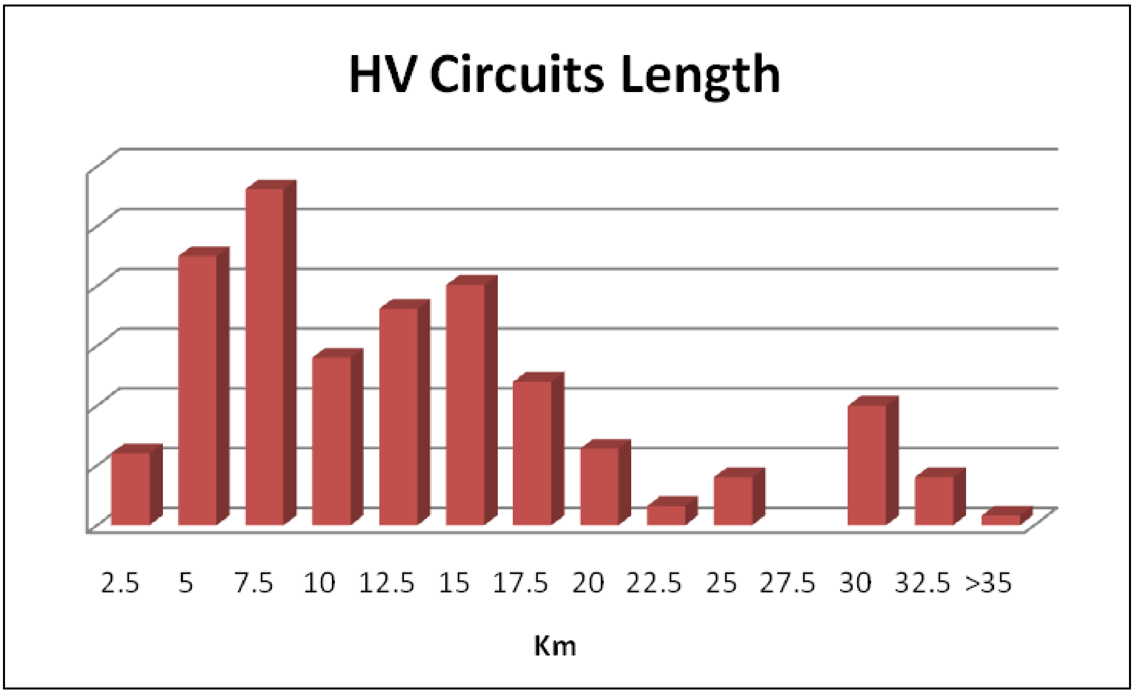


Figure 7.6: The Netherlands HV circuits length [48]

The advantages gained from this case study:

- zero electro-magnetic emissions;
- eliminating the need for alternating voltage level;
- substantially lower energy losses;
- eliminating negative thermal influence on other infrastructure;
- huge reduction in civil cost.

The case study has applied the newly developed HTS cable in a pilot project. This extra-long HTS cable was retrofitted into the aforementioned steel pipe. The location of this pilot project was carefully selected in the Dutch capital where three GP cables – 6km long with 100MVA capacity – fed the 150kV substation with 200 MVA connected load [48].

As illustrated in Figure 7.7, the three 100MVA gas pressure cables were replaced with two 200MVA XLPE cables connected to 150kV busbar, in addition to one 250MVA HTS cable connected to a 50kV busbar of the zone substation [48].

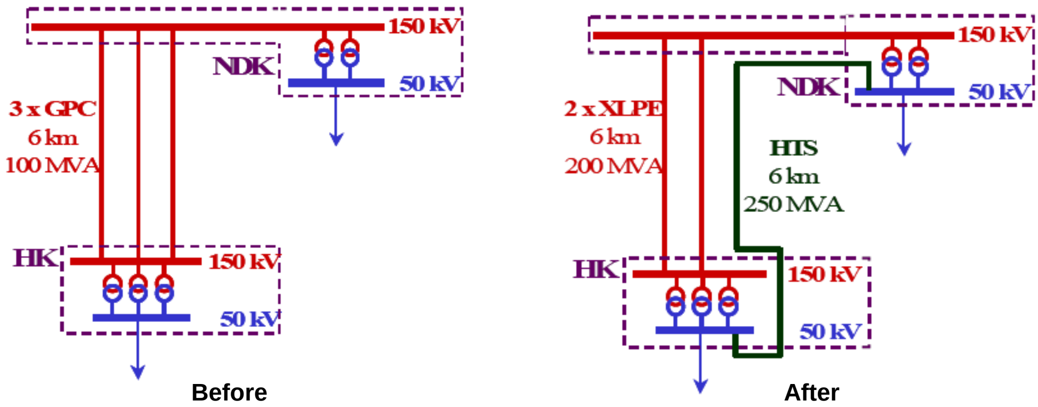


Figure 7.7: HV-network before and after installation HTS cable [48]

Since the operating temperature of the HTS cable should be kept below 75K and in order to obtain low-loss superconductivity, the HTS cable temperature will be controlled by a liquid nitrogen cooling station installed at each end. As shown in Figure 7.8, the motor utilises oscillations that are produced by a magnetic field which makes it free of moving parts and oil to eliminate wear and tear as well as the need for any ongoing maintenance. In turn this motor is attached to a cold-head Crycooler. These Crycoolers are very versatile and reliable for distributed refrigeration applications [48].

Figure 7.8: Cryocooler pulse with tube design [48]

A stack of cryocoolers or cryogenic pumps can be located where needed along the length of the cable as shown in Figure 7.9.

The advantage of installing a stack of these crycoolers would be the redundancy required for maintenance purposes in case of faults, as well as load balancing on the cooling system. Perhaps it is worth mentioning that some assumptions were made in this study, such as, modifying the grid's impedances to allow a large part of the power flow through the HTS cable instead of the other two XLPE cables. If the impedances were left without alterations the HTS cable would not be used to its full potential. Moreover, coupling between two 50kV substations was another predicament that needed to be addressed, as coupling should be carried out in a way to ensure that short circuit currents will hinder the substation's busbar and other components [48].

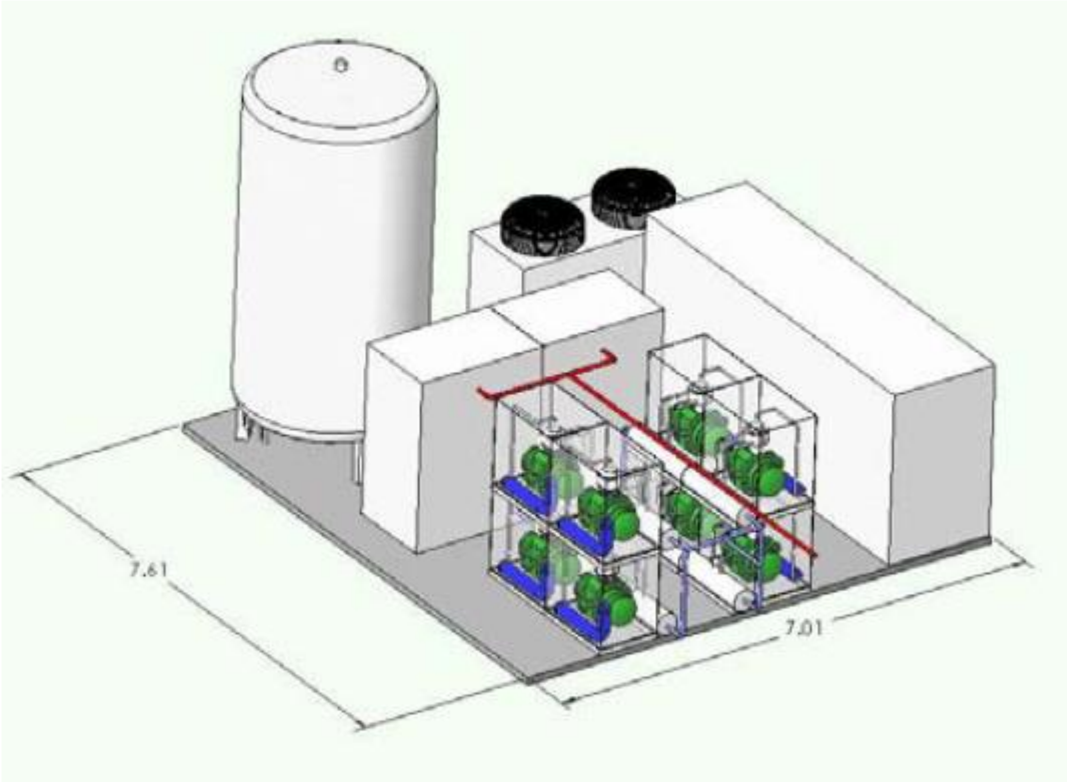


Figure 7.9: Cooling system for long length superconducting cables - an array of pulse tube cryocoolers and reserve liquid nitrogen tank - [48]

Further to the issues above, phase shifting of the three phases in the cable may prove necessary to regulate the asymmetry effect of the current and the voltage which may take place due to the very concentric design of the HTS cable. The asymmetrical effect can result in a large voltage on transformers that will damage equipment [48].

In summary, this study has explored the possibility of installing a long distance HTS cable in an existing HV-network. Preliminary studies during the project's feasibility stage showed that most plausible technical problems can be resolved. The full potential of the HTS cable will be harnessed thanks to the new and efficient crycoolers. This Dutch case study has certainly paved the way for a commercial scale application of HTS cables around the world [48].

7.2.2 22.9kV HTS cable in metropolitan city of South Korea

This case study details the planning and deployment aspects of a 22kV HTS cable in big congested cities like Seoul. The aim of the project described in this study was to replace existing 154kV or 22.9kV conventional cable. As is the trend around major cities in the world, Seoul has an ever increasing energy demand coupled with poor investment in power infrastructure. The route length per MW demand is likely to diminish from the current 0.6 to 0.53 C-km/MW in 2010 [49]. Figure 7.10 illustrates the anticipated decline of route length per unit demand in the future.

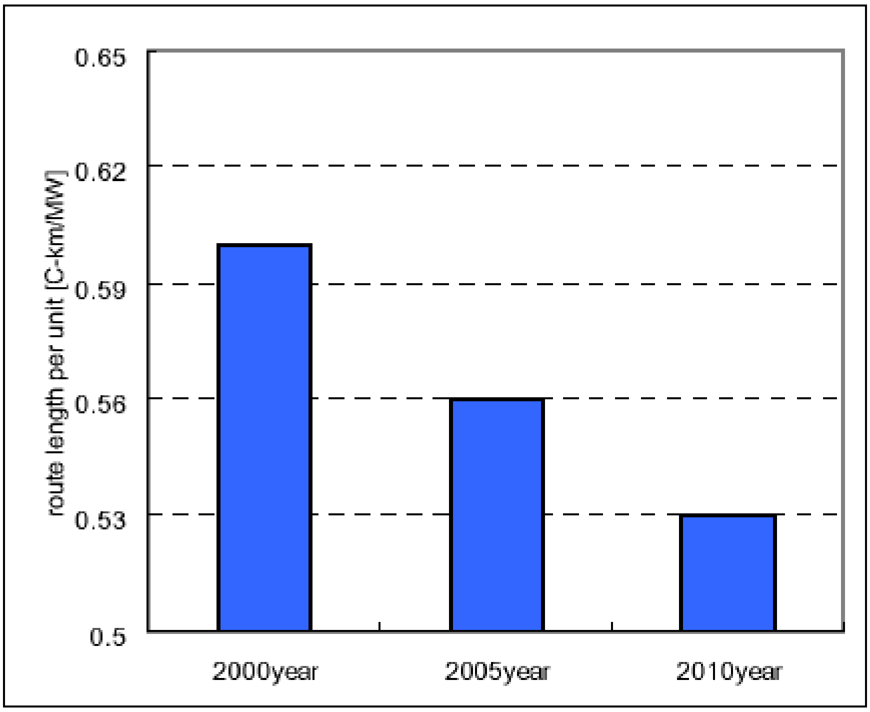


Figure 7.10: Expected route length per unit demand [49]

The increased demand and shrinking route lengths have instigated a complex dilemma in transmission and distribution networks. New improvements in the HTS cable design that provide massive power transfer for short distances may be the answer for power network system planning and operating predicaments [49].

Yoon et al. [49] predicted a rise in the order of 4 to 5% annually in power demand. This demand will be experienced by South Koreans in the year 2010 where the maximum demand is predicted to exceed 67 GW. A large percentage of this predicted growth will take place in the metropolitan areas. Therefore, a robust and reliable power network is essential to keep up with such a demanding environment, where the HTS cable can play a vital role.

Figure 7.11 demonstrates the country's 154kV underground cable route length versus procession rate; notably the rate will increase dramatically from 6.8% to 11.6% and Yoon et al. [49] expected the rate to hit 13.4% by 2020.

Other issues that affect the need for deploying HTS cable include: limited transmission capacity of existing distribution lines; the congested underground easement with many utilities assets; the burden of constructing new cable in the jam-packed cities which mean disruption to traffic and public areas, and rapid increase in general power supply's cost to accommodate for laying new cable [49].

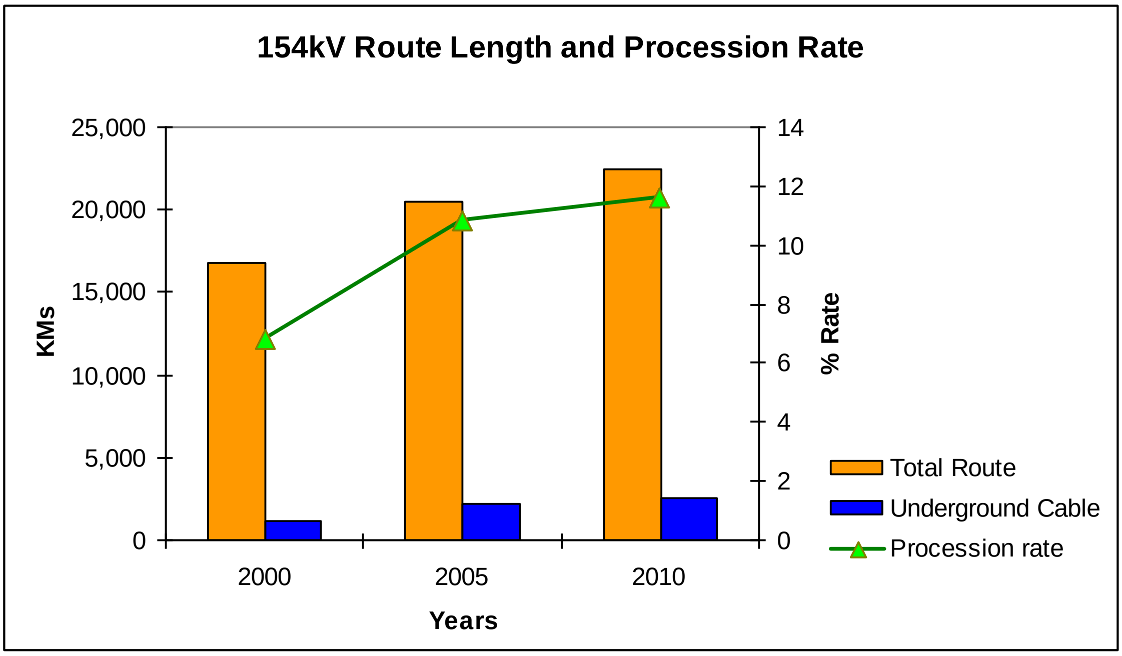


Figure 7.11: Route length verses 154kV underground cable procession rate – circuit to km – [49]

This case study has identified some general benefits of utilising HTS cable in the city centre for the overall power network [49].

- savings in transmission losses;
- reduction in civil work with less site disturbance;
- saving in overall cost of laying underground cable;
- gaining more space by converting large 145kV to smaller 22kV substations;
- eliminating the need for new 154kV substation;
- gaining better investment yields;
- environmental benefits.

Figure 7.12 shows the deployment steps of 22kV HTS cable in city centre. The following steps summarise the phases in which the HTS cable has been deployed when migrating from 154kV to 22.9kV substation [49].

(1) replace 154kV conventional cable linking suburban to city centre substations;
(2) convert city centre 154kV to 22.9kV substations;
(3) replace 154kV conventional cable linking city centre substations with 22kV HTS cable;
(4) replace 154kV conventional cable linking substation to city centre loads with 22kV HTS cable.

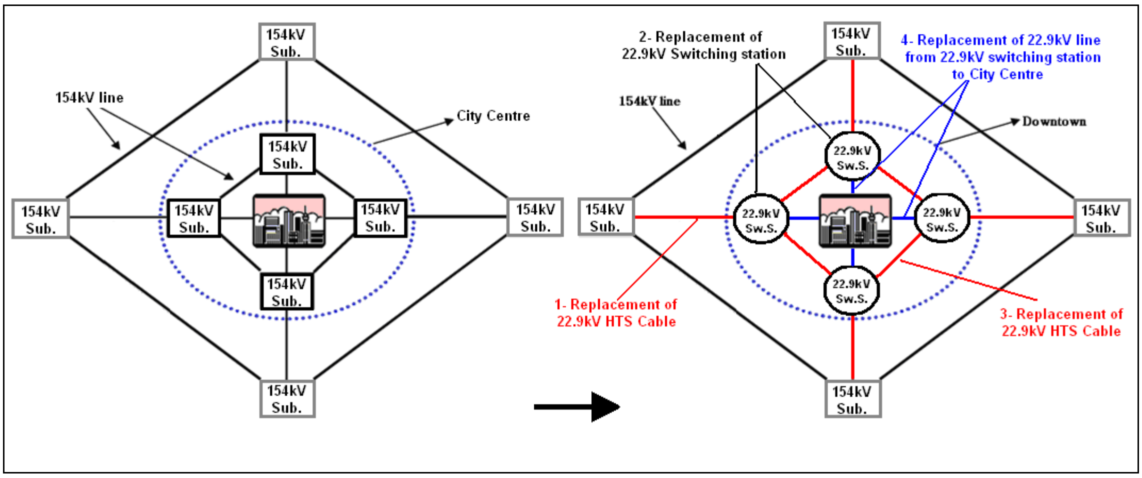


Figure 7.12: Deployment of 22kV HTS cable in city centre [49]

In conclusion, this case study highlighted the benefits of retrofitting 154kV conventional cable with the lower voltage level 22kV HTS cable, with potential advantages such as:

- higher transmission capacity with lower voltage level on top of minimum power losses, can be the answer of congested cities power networks;
- retaining spaces in the city substations by converting them from 154kV to 22.9kV substations where big transformers and other equipment will be removed, also eliminating the need for new 154kV substation;
- savings in the civil works by retrofitting 22kV HTS cable in existing ducts;
- gaining the experience of installing, testing and operating the HTS cable, together with solving any problems that might arise in each stage;
- aiming for developing higher rate HTS cable;
- comprehensive research on the proposed site should be done first in order to find the practicality of the HTS cable application is recommended.

7.3 The 66kV - 300 MVA HTS Triaxial Cable for Melbourne

A 66kV, 300 MVA HTS cable has been designed by Ultera for the purpose of this research. The configuration of this Triax™ design cable is basically sharing a common centre, where the three electrical phases are concentrically assembled around a common central core. The three phases are insulated with thermal and electrical insulators. Although there are two void spaces in addition to the three electrical phases and insulators, the overall diameter of the cable is 170 mm. However the diameter can be changed by reconfiguring the number of HTS tapes. Figure 7.13 shows the 66kV, 300 MVA HTS cable.

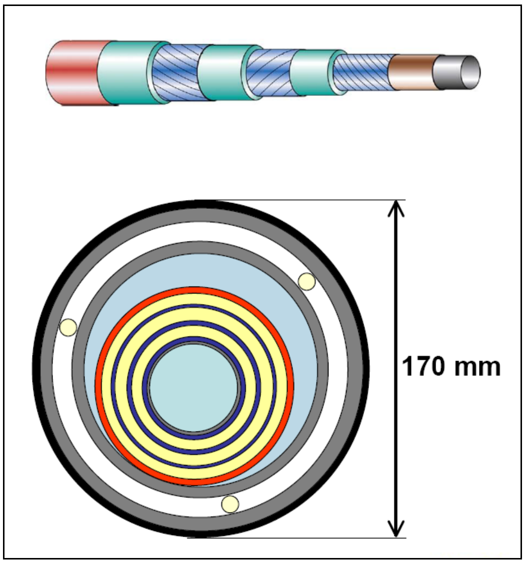


Figure 7.13: 66kV, 300 MVA HTS triaxial cable [50]

Ultera's electrical data for the HTS cables was obtained and used in the design and verification development stages of the hybrid sub-model. As it can be noted the cable resistance is almost zero, meanwhile the cable's inductance and capacitance are much lower than its XLPE counterpart or any rival conventional cable. The lower values of the cable electrical elements give the cable the competitive advantage of high current rating allowing a great amount of power to be shifted through the cable, so it would take an enormous amount of current to overload the HTS cable. Table 7.1 provides comprehensive details on the 66kV HTS cable physical and technical data.

Table 7.1: 66kV 300 MVA HTS cable for Melbourne data

HTS cable	Technical Data	
Type of Cable:66kV Triax three-phase		
Construction / Conductor	kA	3x2.6
Conductor Diameter	mm	84
Insulation	-	Cryoflex™
Cable diameter	mm	170
Weight	kg/m	14
Pulling force (max)	tons	2
Electrical Data		
dc resistance	μΩ/km	< 10
acresistance (eqv.)	μΩ/km	110
Nominal voltage	kV	66
BIL	kV	350
Capacitance (transposed)	μF/km	1.8
Inductance	μH/km	30
Surge Impedance	Ω	4.1
SIL/natural load	MVA	1070
Critical length (cap.)	km	99
30 deg length limit (ind.)	km	643
Thermal Data, full load		
Heat released to soil	W/m	-2
Internal temp. increase	K	1
Cooling requirement	kW/km	2

7.4 Hybrid Power Network Sub-Model

In this study, a hybrid sub-model is developed to emulate Melbourne's CBD network. This network is currently over loaded due to the vast expansion of the CBD with many residential towers built in the city's central district. Additional HTS cables maybe the answer to the necessity concerning the required load growth. This hybrid model replaces the conventional underground cables with limited excavation and construction work, as it utilises the existing conduits that were originally housing the old oil-filled cables. This replacement will allow for enhanced capacity of power transfer as opposed to installing a new 220kV transmission line going through the city of Melbourne, like the Richmond to Brunswick cable [51].

7.4.1 Citipower 66kV hybrid sub-model I

To enable the comparison of HTS cable to conventional XLPE, hybrid sub-model will initially use WMTS 2011 forecasted model in Section 6.2 with the addition of BSBQ zone substation. Despite the obtained convergence when running the load flow analysis, WMTS-JA and WMTS-BSBQ cables were stretched to 200% of their normal load rating. Figure 7.14 shows the Citipower 66kV hybrid Sub-Model I with 2011 forecasted demand and BSBQ zone substation added; it can be noted that to meet the n-1 configuration, there are a few cables have been duplicated up to five times, consequently no element in the sub-model was stressed or exceeded its 100% rating.

The figure displays a summary of the load flow analysis results situated close to the bus, line or transformer. The summary includes an arrow that reveals the direction of power flow.

Table 7.2, illustrates the bus results of flow analysis performed on the WMTS 66kV hybrid sub-model. The table also lists bus parameters including name, real and reactive generated powers.

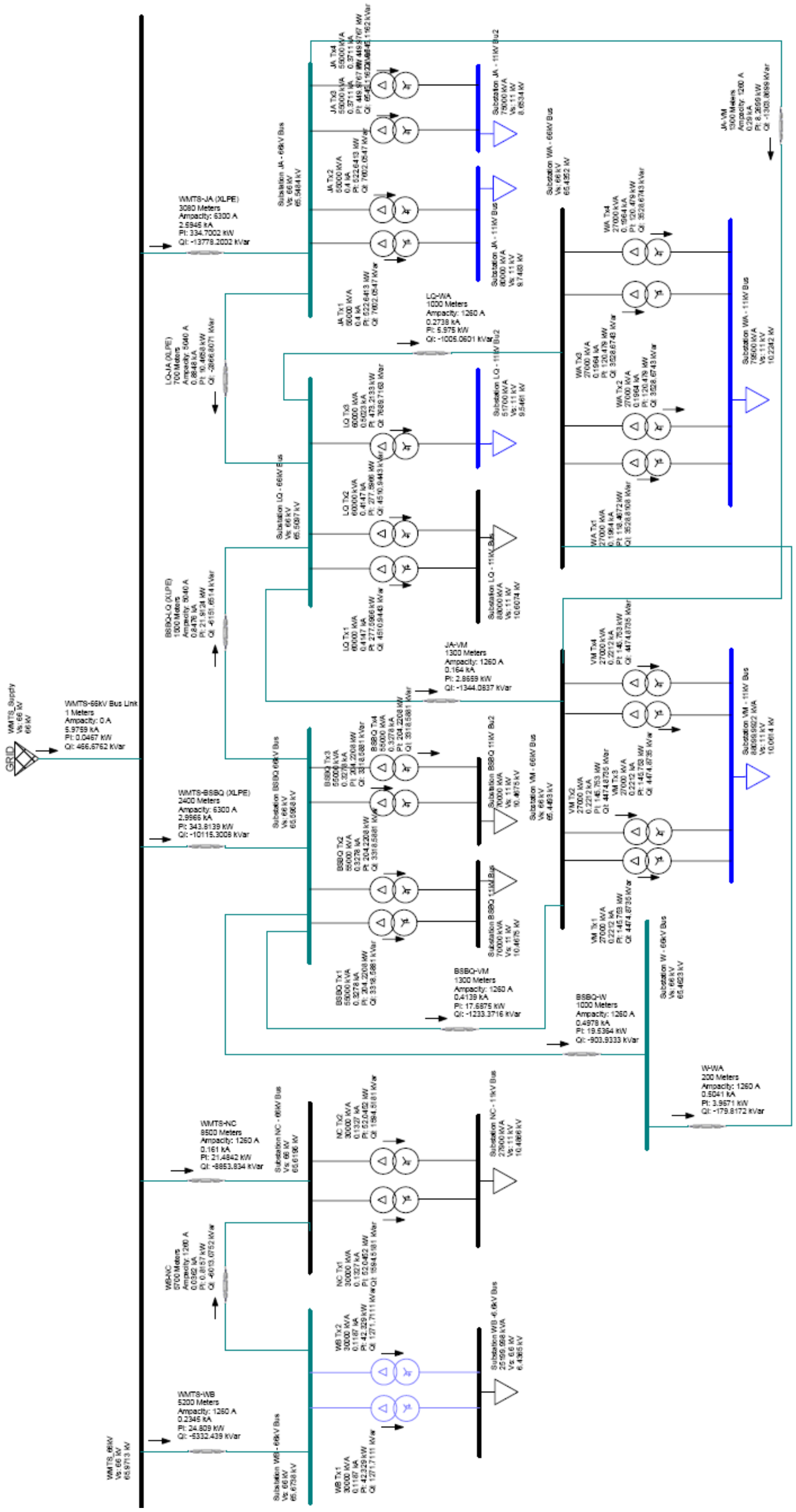


Figure 7.14: Citipower 66kV hybrid sub-model I

Table 7.2: Citipower 66kV hybrid sub-model I power losses

Branch	**From -> To Flow**		**To -> From Flow**		**Losses**	
Name	**MW**	**MVAR**	**MW**	**MVAR**	**kW**	**kVAR**
WMTS-BSBQ (XLPE)	260.856	221.801	-260.513	-231.916	343.8	-10115.3
WMTS-JA (XLPE)	225.411	192.562	-225.076	-206.34	334.7	-13778.2
BSBQ-LQ (XLPE)	72.143	63.796	-72.121	-69.947	21.9	-6151.7
LQ-JA (XLPE)	-76.646	-64.836	76.656	61.969	10.5	-2866.8
WMTS-NC	16.961	7.138	-16.939	-15.992	21.5	-8853.8
WMTS-WB	23.22	13.38	-23.196	-18.712	24.8	-5332.4
BSBQ-VM	34.122	32.352	-34.105	-33.585	17.7	-1233.4
BSBQ-W	41.43	38.494	-41.41	-39.398	19.5	-903.9
JA-VM	-23.62	-22.865	23.629	21.561	8.3	-1303.9
JA-VM	13.309	13.006	-13.306	-14.35	2.9	-1344.1
LQ-WA	22.656	21.263	-22.65	-22.268	6	-1005.1
W-WA	41.41	39.398	-41.406	-39.578	4	-179.8
WB-NC	4.103	-0.376	-4.103	-5.637	0.8	-6013.1
			Total power losses		816.4	-59081.5

The table exhibits, in two different columns, the power delivered to and from the line and in the last two columns it lists the power losses. The total real power losses were found to be 816.4 kW; in addition the total reactive power was found to be -59081.5 kVAR.

A graphical representation of the load flow analysis of hybrid sub-model I is presented in Figure 7.15.

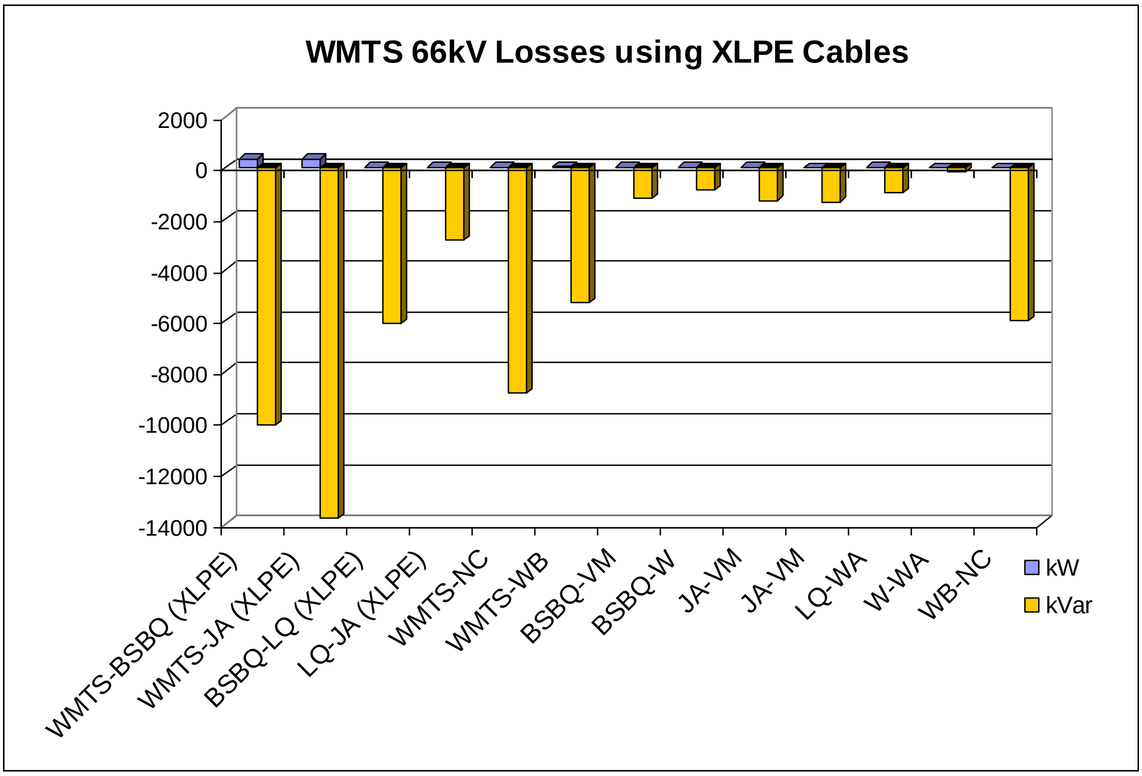


Figure 7.15: Citipower 66kV hybrid sub-model I losses

7.4.2 Citipower 66kV hybrid sub-model II

The configuration of this sub-model has many similarities to the WMTS 66kV underground 2011 forecasted sub-model exhibited earlier in Section 6.2.1. The exception was that four 66kV XLPE cables identified as WMTS-JA, WMTS-VM, LQ-JA and VM-LQ routes with five or four circuits were replaced with single cable of 66kV HTS cable. Again the 2011 zone substation loading demand parameters were acquired from the company's 2007 planning report. The 66kV HTS cable parameters presented in Section 7.2 were used in this sub-model.

Figure 7.16 illustrates the Citipower WMTS loops, indicating the proposed location of HTS cables; also the figure shows some of the Citipower zone substations. It is worth mentioning that this map is not intended for the exact distance between zone substations; rather approximate lengths were used.

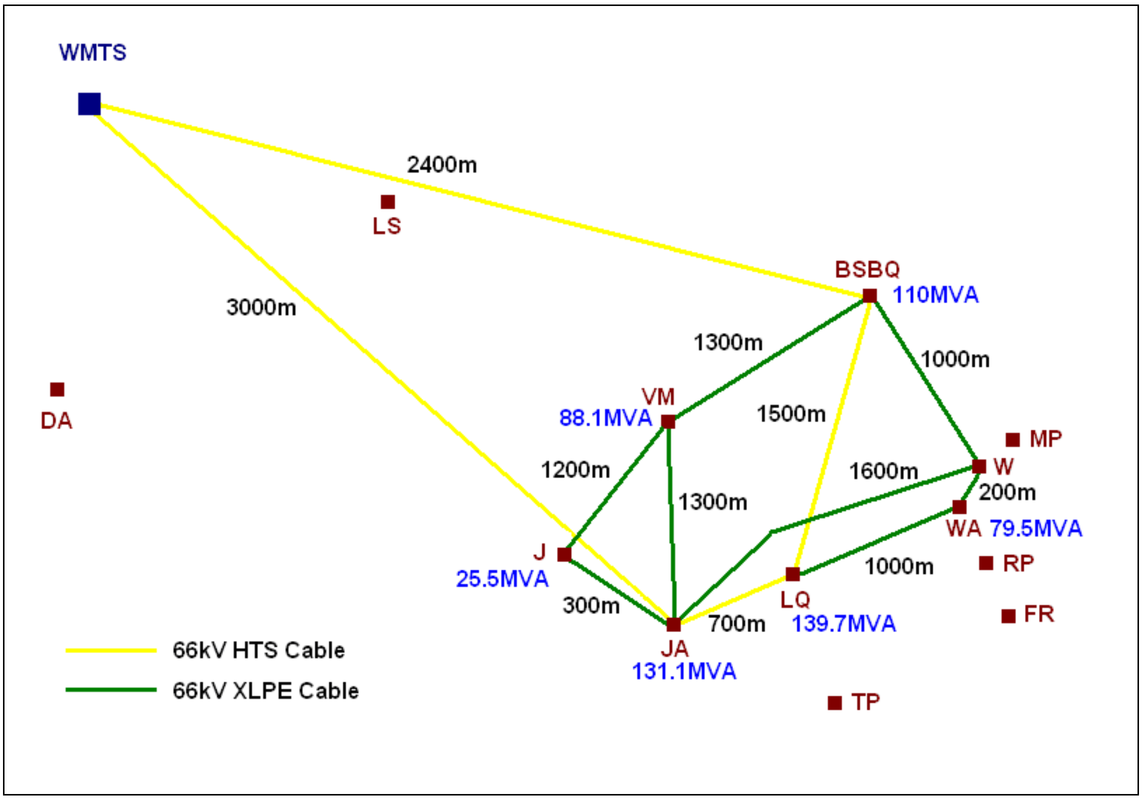


Figure 7.16: Citipower – WMTS zone substations and sub-transmission underground cables [28]

The deployment of HTS cable has the potential of eliminating some of the small zone substations in the area where the cables run, as the load of those small substations can be transferred to the upgraded bigger once like JA, LQ and BSBQ, hence small substations can be converted to switching stations or decommissioned and the revenues generated from properties sale can significantly contribute towards funding the HTS cable replacement.

In this sub-model, XLPE cables of WMTS-BSBQ, WMTS-JA, BSBQ-LQ and LQ-JA were replaced with the Melbourne 66kV HTS cables. Other network parameters are kept the same as the hybrid sub-model I to lay the ground for cable comparison. The obvious observation was only one HTS cable per route was required to meet n-1 Citipower configuration. Figure 7.17 presents the updated hybrid sub-model with selected lengths of the HTS cable.

The figure shows all feeders consist of a single circuit or single cable, as compared to the Citipower 66kV hybrid Sub-Model I in Section 7.2.1, bearing in mind that the n-1 redundancy configuration is maintained. The result of this sub-model confirms the prediction of low cable loading, where one HTS cable is recorded below 12%. Table 7.3 lists the WMTS 66kV hybrid sub-model II cable loading.

Table 7.3: Citipower 66kV hybrid sub-model II cable loading

Branch Name	Ampacity	Loading Amp	% Loading
WMTS-BSBQ (HTS cable)	7800	2813.00	36.1
WMTS-JA (HTS cable)	7800	2738.31	35.1
BSBQ-LQ (HTS cable)	7800	931.94	11.9
LQ-JA (HTS cable)	7800	1028.31	13.2
BSBQ-VM	1260	289.09	22.9
BSBQ-W	1260	356.69	28.3
JA-VM	1260	298.36	23.7
JA-VM	1260	273.07	21.7
LQ-WA	1260	408.59	32.4
W-WA	1260	363.07	28.8
WB-NC	1260	36.22	2.9
WMTS-NC	1260	161.04	12.8
WMTS-WB	1260	234.53	18.6

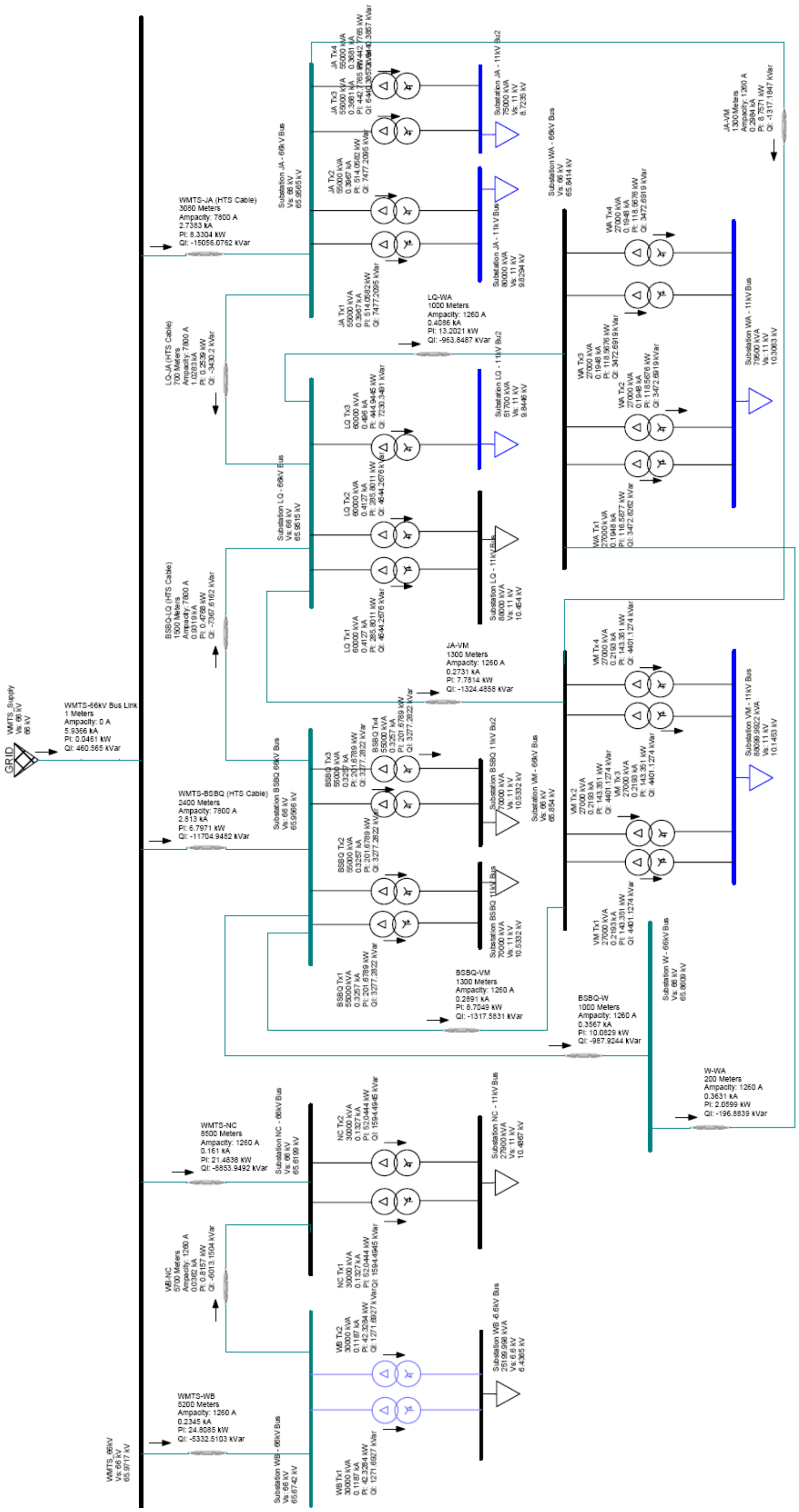


Figure 7.17: Citipower 66kV hybrid sub-model II

A graphic representation of Table 7.4 is illustrated in Figure 7.18; it can be clearly noted that the cable loading off all branches of model III is very low. In particular, the HTS cables have a low load rating which is vital for future network expansion or load growth, to utilise the high capacity potential of the cables.

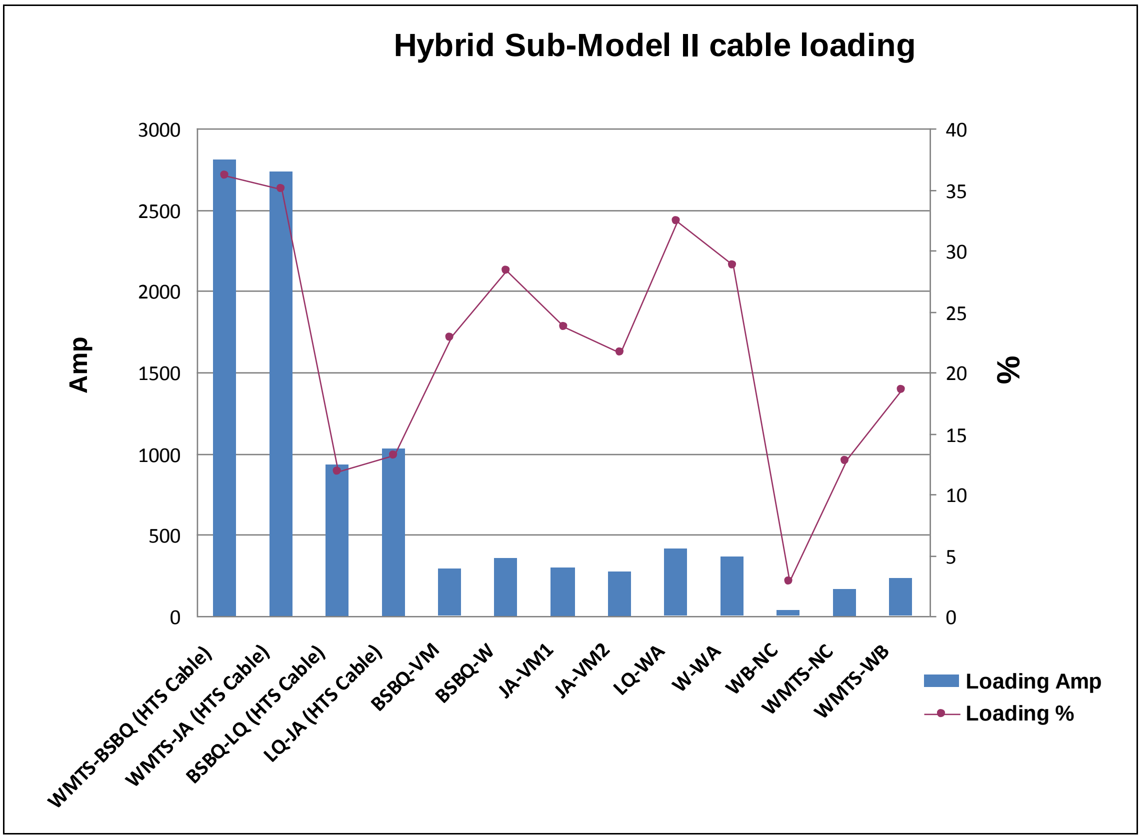


Figure 7.18: Hybrid sub-model II cable loading

The maximum loading utilised by WMTS-JA HTS cable was found to be 72% when WMTS-BSBQ HTS cable disconnected or taken out of service. This means there is a margin of 28% for extra loading that can be utilised in future growth or should the need for extra capacity be raised due to unforeseen circumstances. In addition, the corrective measurements such as opening or closing circuit breakers or regulating phase shifters, which are normally taken by Citipower for n-1 redundancy configuration, have not been adopted in the simulation of this sub-model, owing to the lack of information regarding the Citipower n-1 contingences, as it is considered confidential. However, the results from the simulation identified the influence that HTS cable can have on overall power network.

Table 7.4 illustrates the bus results of flow analysis performed on the hybrid sub-model II. The table also lists bus parameters including name, real and reactive generated powers, real and reactive static loads and load flow results from which the real and reactive power losses are obtained with bus current rating and power factor incorporated.

Table 7.4: Hybrid sub-model II power losses

Branch	From -> To Flow		To -> From Flow		Losses	
Name	**MW**	**MVAR**	**MW**	**MVAR**	**kW**	**kVAR**
BSBQ-LQ (HTS)	79.742	77.761	-79.741	-77.749	0.5	-7367.6
LQ-JA (HTS)	-89.782	-78.385	89.782	78.4	0.3	-3430.2
WMTS-BSBQ (HTS)	246.648	227.768	-246.641	-227.655	6.8	-11704.9
WMTS-JA (HTS)	238.85	224.803	-238.841	-224.695	8.3	-15056.1
BSBQ-VM	24.105	23.979	-24.096	-23.911	8.7	-1317.6
BSBQ-W	29.987	28.804	-29.977	-28.725	10.1	-987.9
JA-VM	-24.289	-23.871	24.298	23.939	8.8	-1317.2
JA-VM	22.645	22.791	-22.637	-22.73	7.8	-1324.5
LQ-WA	34.087	33.019	-34.074	-32.917	13.2	-963.8
W-WA	29.977	28.725	-29.975	-28.71	2.1	-196.9
WB-NC	4.105	4.385	-4.104	-4.376	0.8	-6013.2
WMTS-NC	16.969	17.499	-16.939	-17.27	21.5	-8853.9
WMTS-WB	23.232	23.745	-23.198	-23.485	24.8	-5332.5
			Total power losses		**113.7**	**-63866.3**

The total real power losses were found to be 113.7 kW; in addition the total reactive power was found to be -63866.3 kVAR.

The HTS cable capacitance influence reduction in the compensating reactor of the cable by its smaller charging current as compared with XLPE or oil filled cables. Magnetic shield of HTS cable reduces its reactance by utilising an outer HTS conductor. This results in a more stable power network and voltage levels [52].

A graphical representation of the load flow analysis of hybrid sub-model I is presented in Figure 7.19.

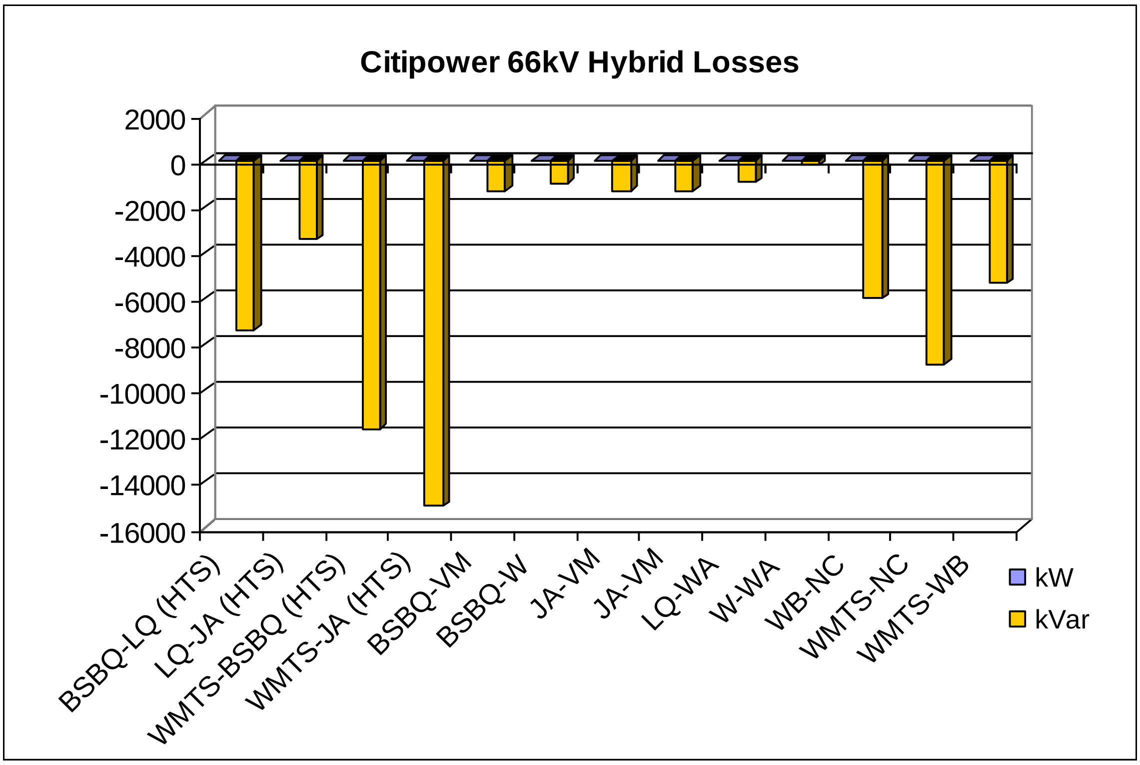


Figure 7.19: Citipower 66kV hybrid sub-model II losses

Figure 7.19 reveals the potential capacity gain to the citipower network and WMTS section in particular. The current WMTS 66kV overhead sub-model presented in Section 4.2.1 had double and triple lines connecting the WMTS to the zone substation JA and VM. Meanwhile the WMTS hybrid sub-model I, which includes the upgraded substation BSBQ, had four cables for WMTS-BSBQ and five cables for WMTS-JA; the cables were XLPE type rated at 1260A. It has been found that maximum loading of the cables reached up to 48% at normal operation and less than 100% at n-1 configuration. An interesting finding was uncovered in Figure 7.18, where a single cable of HTS rated at 7800A was able to meet and exceed the forecasted load demand for the year 2011, what’s more, the maximum cable loading was found to be 36% at normal operation and about 80% at n-1 configuration. This is a clear indication of what extra capacity HTS cable can provide for the network adding to that the big savings in eliminating the need for constructing new cable ducts in the city, should the HTS cable the one to be chosen rather than XPLE.

7.5 HTS Cable and Fault Current

A fault can occur in a power network due to various reasons. The effects of this fault can alter the network behaviour, so predicting these effects are of critical importance to determine the overall network response to the fault. Here is where fault current calculation plays a big role in ascertaining the consequence for network voltages and currents. Furthermore, a reliable network can only be designed when a comprehensive analysis of the system behaviour is carried out during all types of operation conditions [53].

There are two main circumstances that any particular power network operates under, the first of which is a normal operation, under normal conditions, while the second operation is spread over the network when abnormalities occur or when the network is under the effect of a range of faults. By simulating these faults it is possible then to: configure the network in a way which minimizes the effects of faults; rate the network elements to accommodate for the fault currents; estimate the rating break point so that switchgears and fuses within the network operate safely; validate the suitability of network protection; determine the reliability and security of the network and investigate any poor performance in the network [53].

Like any other power cable in a particular power network, HTS cable can be struck with fault current [54]. Normally fault current can be as high as ten to thirty times the normal operating current. The period of which the fault current can last is determined by the protection equipment and the load of the cable, in any circumstance the fault current will constrain the HTS conductor to operate as a normal conductor. In other words, it loses its superconductivity properties for the fault duration; this means heat will build up in the conductor in that period and the real concern is whether or not the generated heat can damage the HTS cable. In an attempt to investigate the effects of fault current on HTS cables, Lue et al. [54] presented an interesting finding from a few tests carried out on a

HTS prototype cable. The finding stated that a negligible degrading was observed. In addition, limitations of both thermal and high current magnitude were found in these tests.

Fault current testing of HTS cables was performed by Southwire on a 30 meter cable. According to Lue et al. [55], the aim of the test was to verify that HTS cables can withstand a high fault current. The results of the testing indicate a rise in the cable voltage, meaning that the cable conductor temperature had risen during the fault. In addition, not only was the temperature of the cable raised but also the resistive properties of the cable conductor have rose throughout the fault, yet when the fault disappeared, the cable voltage returned almost to its normal level. However, the resistive properties of the cable conductor did fall to its normal value at slower rate, in comparison to the voltage drop rate.

Verily, extra high currents cause high magnetic fields and superconductivity will be interrupted for a few milliseconds. The resulting high resistance of the conductor limits the fault current in HTS cables. In light of this cable behaviour at the fault current, HTS cable inherits a current limitation property, so by knowing the amount of receptivity rise, the limitation of HTS cables' current can be set. Figure 7.20 which was provided by nkt cables [56], shows cable resistance as a function of current. It can be clearly observed that the cable resistance has risen immediately at the fault current then it reached a finite limit even when the current kept rising.

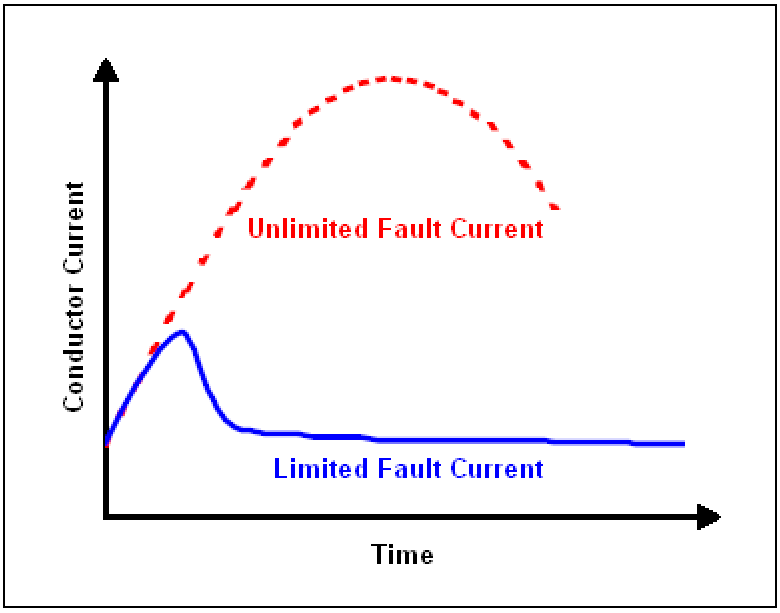


Figure 7.20: HTS cable ability to limit a fault current [56]

7.6 HTS Cable and Short Circuit Analysis Sub-Model

In this sub-model a short circuit analysis using EDSA software has been performed on Citipower 66kV hybrid Sub-Model II which was presented in Section 7.4.2. This analysis brings to light anticipated current levels of HTS cables during short circuit event. Knowing the magnitude of the short circuit current can be vital in designing the power network elements, especially protection equipment. What would be of a great concern to this study is whether or not current protection schemes and switchgears are to be replaced? Moreover, the short circuit analysis will highlight areas where protection is inadequate and if there are any requirements for changes to network elements settings change to bring down short circuit fault to acceptable levels. Figure

7.21 shows the HTS cable and Short Circuit Analysis Sub-Model. The figure clearly illustrates the analysed sub-model for short circuit event and the results are noted close to each bus bar in the network.

The results obtained from short circuit analysis of Citipower 66kV hybrid sub-model II are presented in Table 7.5 The table lists bus parameters including the current rating.

Table 7.5: Citipower 66kV hybrid v short circuit analysis results

Bus Name	I P A	3P Fault A	LL Fault A	LG Fault A	LLG Fault A
BSBQ 66kV Bus	2216	875	758	735	846
JA 66kV Bus	2216	875	758	735	846
LQ 66kV Bus	2216	875	758	735	846
NC 66kV Bus	2173	856	741	722	836
VM 66kV Bus	2212	873	756	733	845
W 66kV Bus	2211	873	756	733	845
WA 66kV Bus	2211	873	756	733	845
WB 66kV Bus	2182	860	745	725	838

Meanwhile the fault level at HTS cable was found to be matching the bus fault. A fault occurred 35 Meters away from a bus in LQ-JA HTS cable was: 875A for three phase, line-ground and double line-ground faults; 758A for line-line fault.

The results presented in Table 7.6 confirm the expected outcome of the analysis. As mentioned earlier, insignificant increases in the fault currents have been found on the buses that HTS cables were attached to. This indicates that normal protection schemes should be sufficient to handle any fault currents that might occur in the network.

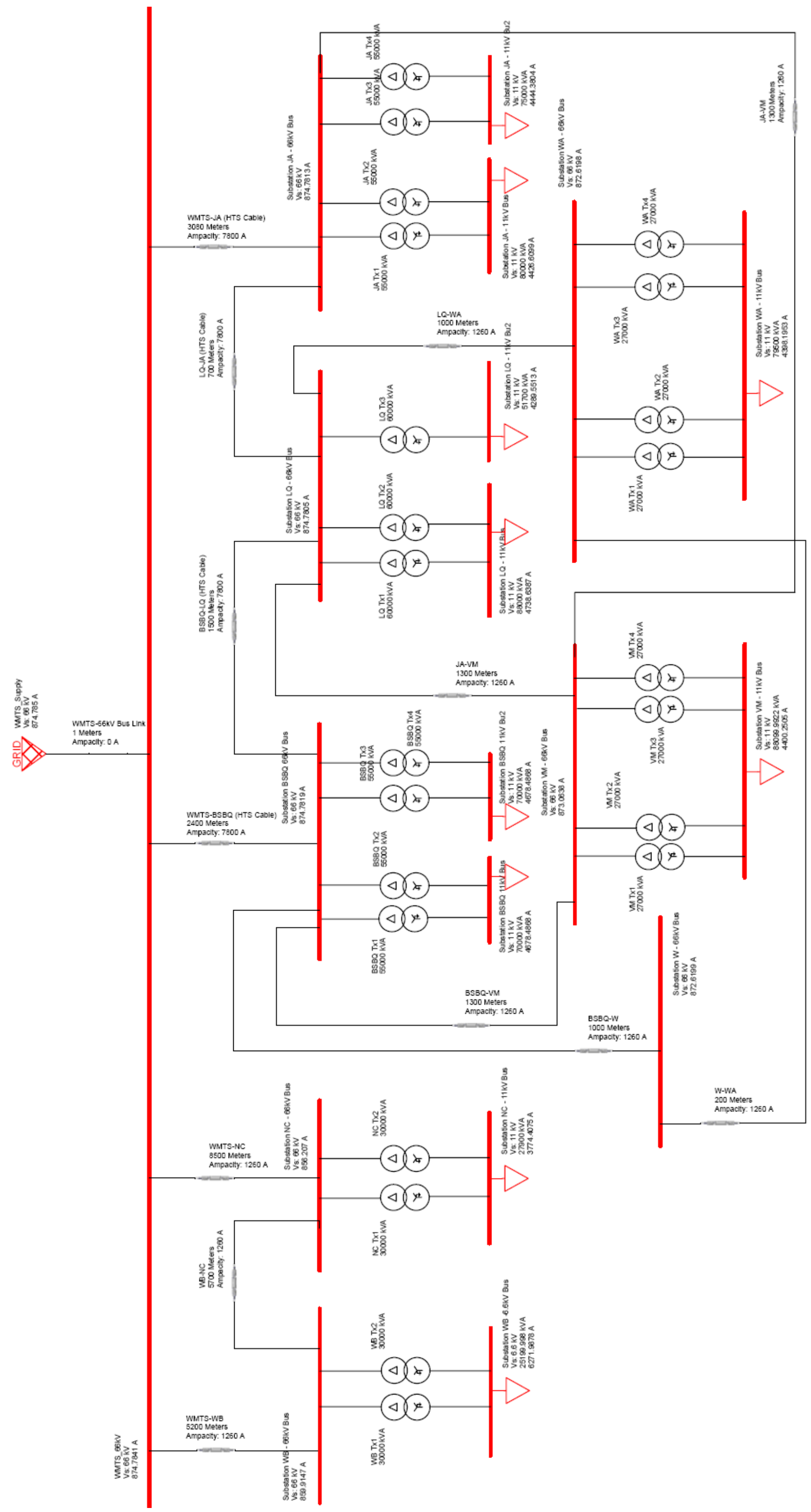


Figure 7.21: Citipower 66kV hybrid short circuit analysis sub-model

7.7 Conclusion

HTS cable technology enables a massive increase in power transmission capacity, with its unique characteristics of low impedance and low ohmic loss. HTS cable has the potential of becoming a feasible new solution to power transmission problems. This incorporates environmental benefits of no thermal or magnetic field emission and no visual impact on the aesthetic surroundings. Economic benefits can also be achieved in situations where civil works are reduced by avoiding unnecessary excavation works.

The Triax design facilitates economic benefits through the substitution of HV by MV attributable to reduced transmission losses. It will be essential to demonstrate the reliability and efficiency of this technology commercially in order to gain wide acceptance.

This chapter has established that utilising HTS cables will enhance the reliability and improve power networks' loading capacity. A hybrid sub-model has been simulated for load flow as well as short circuit analysis. All results revealed that HTS cables can be employed along with conventional cables like XLPE, and in some circumstances the HTS cables may prove a more technically and economically efficient solution than any other counterparts.

CHAPTER 8

CONCLUSION AND RECOMMENDATIONS

8.0 Introduction

In most countries around the world, energy and power sectors have been liberalised, which has forced the electricity utilities to operate under more competitive retail markets. Hence, utilities were put under pressure to develop greater flexibility, environmental-friendliness and security for supplying, transmitting and distributing electricity.

Chapter 1 highlighted the increasing global trend of overhead lines replacement with underground cables over the last decade. Emerging new cable technology, combined with improved production processes and specifications of international testing, has led to increased usage of underground cables.

8.1 Appraise

Chapter 2 established the necessary background in the transition of overhead lines to underground for both, distribution and transmission power networks. Benefits and limitations have been closely examined in underground and overhead technologies. Various cable technologies have also been extensively questioned and scrutinised.

This field of study was exposed to methodical and thorough research; there is a common perspective which is shared amongst multinational power engineers and researchers, that underground transmission cabling bestows mammoth improvements & benefits when compared to its predecessor technology of overhead lines. Nonetheless, the overhead technology is still dominating and is in use all over the world.

A comprehensive overview of the overhead power network along with its structure was dedicatedly elaborated in Chapter 3. For decades, power has been transmitted via a relatively low cost medium, commonly known as overhead lines. Since then, substantial transformations have been occurring to improve the reliability of overhead networks. A load flow technique is often employed to analyse and design an improved overhead power network. Chapter 4 has provided an overview of overhead power networks. This chapter has also extensively explored overhead power networks' various aspects as well as the major factors that form the core requirements of a reliable power network. Various conductors used in overhead lines have also been discussed. As power loss is a major concern for transmission systems, an elaborative study on power losses in overhead lines has also been included.

The Victorian overhead power network was researched in an attempt to efficiently design an underground network for Victoria, which is covered in Chapter 5. Comprehensive analyses and the development of Victorian overhead power network sub-models were presented in detail in this chapter. In addition, a great deal of emphasis was placed on overall overhead network sub-models, which were discussed in Chapter 4. These analytical studies are of a great significance for the future growth and the safe operation of the Victorian power network. Various forecast models were analysed and critically analysed in order to determine future network needs of additional lines and transformers to cope and cater for the extra load which was predicted in forecast studies.

Load flow analysis and other industrial based specialised software applications were utilised to investigate and develop various sub-transmission network models. The results obtained from the load flow analysis provided crucial information about all buses in the network. Some buses were exceeding their normal operation values or nominal values so an action was made to rectify the problem associated with any abnormality in the network. It is worth mentioning that Citipower n-1 redundancy configurations were met in all of the developed sub-models. Another outcome of the load flow analysis was the uncovering of the real and reactive power losses at each line and the effect of forecasted loading on the losses was also identified.

Chapter 6 examined the Victorian overhead power network in an attempt to efficiently design an underground network for Victoria. It has become mandatory for most modern cities worldwide to use underground power cables. This demonstrates that undergrounding has become economically and technologically feasible. Various advantages have been presented about underground cables in this chapter. However, there are significant challenges in the underground network as much as it has benefits. It is essential to carefully design and implement an underground power network.

A thorough analysis and development of Victorian underground power network sub-models were presented in detail in this chapter. In addition, an elaboration of overall underground network sub-models was discussed in chapter 6. This analytical study was again of great significance for the future growth and safe operation of the Victorian power network. Various forecasted models were analysed to determine the future need for additional lines and transformers in order to enable the handling of the forecasted extra load.

Load flow analysis and other industrial based specialised software applications were used to investigate and develop various sub-transmission network models. The results obtained from the load flow analysis provided crucial information about all buses in the network. Some buses were exceeding their normal operation values or nominal values so an action was made to rectify the problem associated with any abnormality in the network, Citipower n-1 redundancy configurations were met in all sub-models developed in this chapter.

Another outcome of the load flow analysis was the determination of real and reactive power losses at each line, also the effect of the forecasted loading on the losses were identified.

Chapter 7 discussed the development and analysis of a Victorian hybrid underground power network, where, in addition to conventional XLPE cables a new generation of cable technology was used in the form of HTS cables. HTS cable technology enables a massive increase in power transmission capacity with its unique characteristics of low impedance and ohmic loss. HTS cable has the potential of becoming a feasibly new solution to power transmission problems. This incorporates environmental benefits of no thermal or magnetic field emission and no visual impact on the surroundings. Economic benefits can also be achieved in situations where civil works are reduced by avoiding unnecessary excavation.

The Triax design facilitates economic benefit through the substitution of HV with MV, attributable to reduced transmission losses. It will be essential to demonstrate the reliability and efficiency of this technology commercially in order to gain wide acceptance.

Chapter 7 has also established that utilising HTS cables will enhance reliability and improve the loading capacity of power networks. A hybrid sub-model has been simulated for load flow analysis purposes as well as for short circuit analysis; all results revealed that HTS cables can be employed alongside conventional cables like XLPE, and in some circumstances the HTS cables may prove to be a more economical solution than any other counterpart cables.

This research contributed directly to the body of knowledge of power transmission and distribution systems. More specifically, it contributes to the overhead transmission lines undergrounding framework. The research produced reference guidelines for Victorian underground sub-transmission and distribution networks. The research made a unique technical contribution to the processes and procedures of undergrounding overhead power lines in Victoria as well as laid emphasis on portability aspects for potential adoption by other Australian states.

This research contributes to the knowledge framework in the following areas:

(1) identifies the requirements of the technical aspects of undergrounding overhead power lines in Victoria, this work is of immense benefit to the Victorian overhead sub-transmission and distribution networks as it provides a technical solution with appropriate processes and measures for migrating to underground network;

(2) investigates the implementation of a new cable technology and its effects on the electricity supply from efficiency point of view as well as reliability and economics;

(3) presents a unique simulated models that produce a new voltage level of the new underground cable technology, HTS, to be used in a small section of the Victorian power network;

(4) demonstrates the hybrid implementation of the new cable technology, HTS, combined with the traditional underground cable technology, XLPE, and their simulated performance;

(5) it signifies a remarkable reduction in the environmental impact of power networks, which includes EMF and pollution in addition to the improved public safety.

8.2 Recommendations

Large scale applications of HTS cables are crucial when making a strategic decision for the viability of HTS in comparison to its conventional XLPE counterparts. [57]. Market acceptance of HTS cable technology needs an extensive and a proven field illustration, which covers both, the system's capabilities and appropriateness for installation within commercial utilities [58].

The following works are recommended in extension to this research; a pilot project with HTS cable runs approximately 700 m between two 66kV zone substations LQ and JA of WMTS loop in Citipower network. The location for this pilot project was selected because it mingles performance specifications suitable for the application of HTS cables in addition to other advantages. The chosen route offers many of the challenges that will be faced in other field installations

Figure 8.1 presents the Citipower 66kV LQ-JA pilot sub-model with the selected length of the HTS cable. A load flow analysis on the model was carried out to obtain power loss figures. The figure shows the summary of the load flow analysis results situated close to the bus, line or transformer.

Power capacity can be increased up to three folds when existing ducts are retrofitted with HTS cables. Given the ever increasing cost of rights-of-way with highly congested pathways with other utility assets such as gas and telephony, all of these factors make the cost of construction new ducts for underground power cables unrealistic.

The objective of the proposed pilot is to demonstrate HTS cables in an operational grid. The cable design and its accessories were presented in Section 7.3. However, this cable will need to be tested for a period of time to verify the installation in order to establish a benchmark for the cable's attributes and behaviour in the Australian environment. Altera recommends minimum of two years testing prior to commission the cable to portray an accurate reading of cable behaviour.

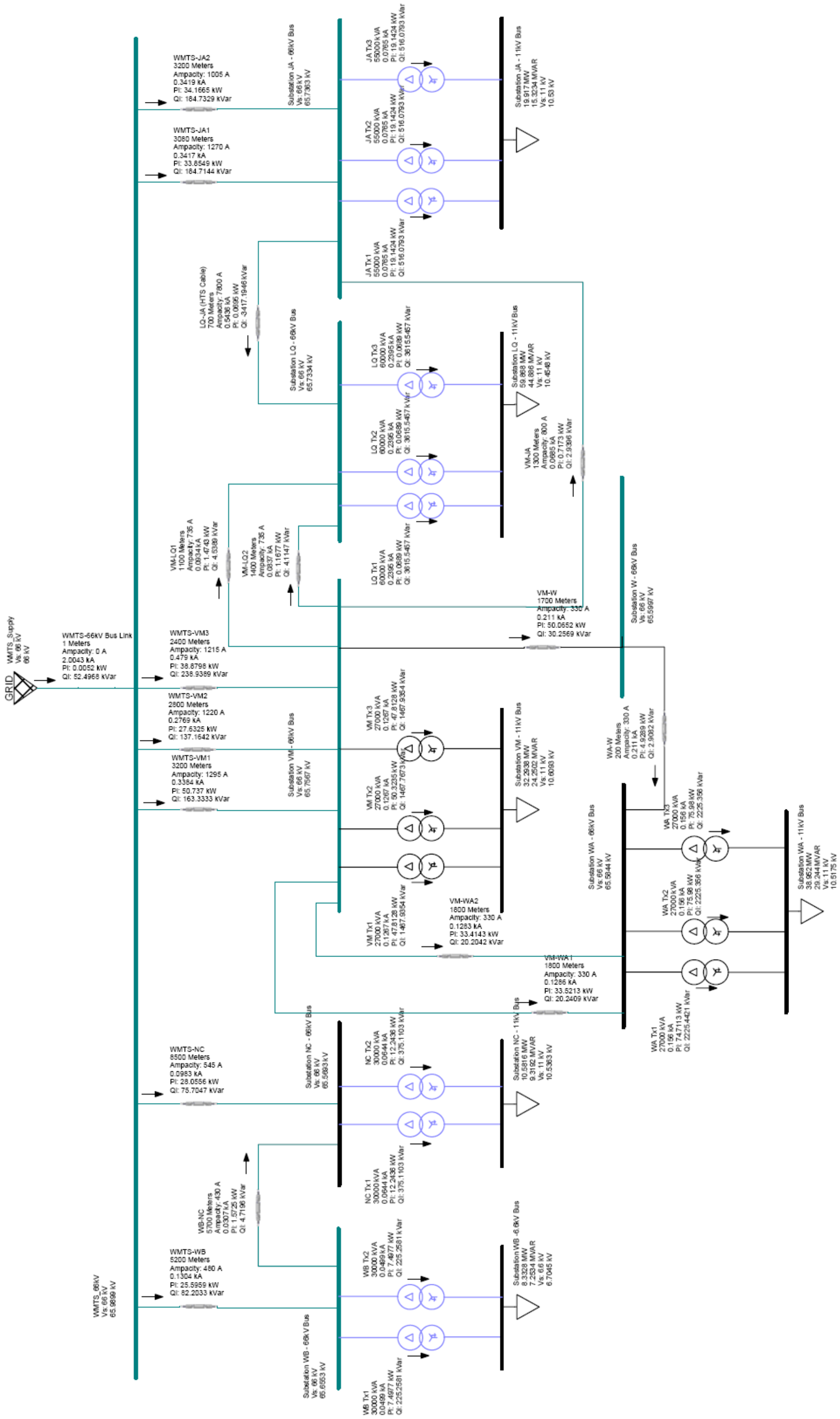


Figure 8.1: Citipower 66kV LQ-JA pilot sub-model

As this will be the first installation of an underground HTS cable in Australia, particular attention has to be paid to the installation site. Comprehensive surveys need to be carried out for site's manholes, ducts and mounting locations so that no unexpected dilemmas are experiencing during the cable installation.

A major milestone would be the evaluation phase, in which determining the cable performance capability to cater for the forecasted load without requiring regular maintenance or attention. To obtain accurate data on the cable's behaviour, key parameters of the cable and cooling system must be utilised in addition to constantly measuring the cable's temperature at different points in the route, this temperature reading must be captured before and after the termination points. All of these readings must be collated and stored in a central location to be further processed and analysed for verification purposes.

HTS cable pilot project can demonstrate the potential superconductivity which plays a vital role in the modernisation of electrical power networks. It also showcases the reliability, security and potential benefits that they would bring to the Victorian aging electrical infrastructure. This pilot also leads one step closer to full commercialisation and utilisation of HTS cable technology.

REFERENCES

1. Christensen, P. and Roes, T., '*Underground EHV System In Copenhagen'*, Transmission and Distribution World: NESA. 2000.

2. Barber, K., '*Undergrounding transmission and distribution lines in Australia'*, Australian Power Transmission & Distribution magazine. 2004.

3. Mutton, S., Tebbs, J., Simpson, S., and Mann, R., '*Investigation of Low Reliability Urban and Rural Feeders Phase Two of Two TXU Networks'*. 2000.

4. U.S. Department of Labor, O.S.H.A., '*Electric Power, Generation Transmission Distribution eTool'*. 2005.

5. Brown, R., '*Undergrounding Assessment Phase 1 Final Report Literature Review and Analysis of Electric Distribution Overhead to Underground Conversion'*: Raleigh. 2007.

6. Cowell, R., '*The Scope for Undergrounding Overhead Electricity Lines'*. 2003.

7. ICF Consulting Ltd, '*Overview of the Potential for Undergrounding the Electricity Networks in Europe'*: London. 2003.

8. Kelley, N. and Jipping, J. '*HTS cable system demonstration at Detroit Edison'*. *Power Engineering Society Winter Meeting, 2002. IEEE*. 2002.

9. Putting Cables Underground Working Group, '*Putting Cables Underground Report*'. 1998.

10. Wales, I.P.a.R.T.o.N.S., '*Electricity Undergrounding in New South Wales*'. 2002.

11. Citipower, '*DISTRIBUTION SYSTEM PLANNING REPORT*'. 2006.

12. Karlstrand, J., Bergman, G., and Jonsson, H.-A. '*Cost-efficient XLPE cable system solutions*'. *AC-DC Power Transmission, 2001. Seventh International Conference on (Conf. Publ. No. 485)*. 2001.

13. Communities, C.o.t.E., '*Background Paper Undergrounding of electricity lines in europe*': Brussels. 2003.

14. Chang, G.W., Huang, H.M., and Lai, G.G. '*A study on controlling electrical stress of underground cable by semi-conductive shielding*'. *Transmission and Distribution Conference and Exhibition 2002: Asia Pacific. IEEE/PES*. 2002.

15. Johnson, B., '*Out of Sight, Out of Mind?*' Washington. 2006.

16. Commission, J.L.A.a.R., '*Evaluation of Underground Electric Transmission Lines in Virginia*'. 2006.

17. Ettedgui, E., Grijalva, S., Silberglitt, R., and Wakefield, C.A.-W., C. '*Potential impact of high temperature superconducting cables on grid reliability and available transfer capacity: power flow simulation results*'.

Power Engineering Society Winter Meeting, 2002. IEEE Power Engineering Society Winter Meeting, 2002. IEEE VO - 1. 2002.

18. West, R. and Larsen, S. '*Kentish town project [power cable laying]*'. *Cables in Tunnels (Ref. No. 2000/070), IEE Seminar*. 2000.

19. Jey, K. and Jeyapalan, P.E., '*Creative Ways to Build Broadband Networks And Underground Power Cables Through StrategicPartnerships Among Utilities'.* 2003.

20. Maney, C.T., '*Benefits of urban underground power delivery'.* Technology and Society Magazine, IEEE. 15(1): p. 12-22. 1996.

21. '*Back-to-back hurricanes cripple US network Back-to-back hurricanes cripple US network'.* Power Engineer (see also Power Engineering Journal). 19(5): p. 4-4. 2005.

22. Lakervi, E. and Holmes, E.J., '*Electricity distribution network design*', ed. A.T. Johns and Platts, J.R. Vol. 9, London: Peter Peregrinus Ltd. on behalf of the Institution of Electrical Engineers, London, United Kingdom. 1988.

23. Bayliss, C., '*Transmission And Distribution Electrical Engineering (Book Review)'.* Power Engineering Journal [see also Power Engineer]. 11(3): p. 99-99. 1997.

24. Cable, G., '*General Cables, Electric Utility Cables*'. 2004.

25. Kyoung-Soo, R. '*An approach to allocate real power losses of transmission lines to individual loads'*. *TENCON 99. Proceedings of the IEEE Region 10 Conference*. 1999.

26. Nagrath, I.J. and Kothari, D.P., '*Power System Engineering'*: TATA McGraw Hill Publishing Company Limited. 1994.

27. Rabinowitz, M., '*Power systems of the future. I'.* Power Engineering Review, IEEE. 20(1): p. 5-16. 2000.

28. Citipower, '*Distribution System Planning Report'*: Melbourne. 2007.

29. Pansini, A.J. and Smalling, K.D., '*Undergrounding Electric Lines'*. Second ed, Lilburn: The Fairmont Press, Inc. 1993.

30. Marazzato, H. and Barber, K.W., '*The Challenge for Undergrounding Electricity Supply*', Australian Power Transmission & Distribution magazine

31. Ausnet, S., '*SP AusNet Electricity Distribution Price Review 2006'*. 2005.

32. Peter, W., Wally, S., Graham, K., Kelvin, G., David, S., and Dieter, H., '*Environment Effects Statement'*: Melbourne. 1989.

33. Olex, '*High Voltage catalogue'*,

34. Koch, H. and Hopkins, M. '*Overview of gas insulated lines (GIL)'*. *Power Engineering Society General Meeting, 2005. IEEE*. 2005.

35. Benato, R., Di Mario, C., and Koch, H. '*High Capability Applications of Long Gas-Insulated Lines in Structures*'. *PES TD 2005/2006*. 2006.

36. Kalam, A., Al-Khalidi, H., and Willen, D. '*HTS cable and its anticipated effects on power transmission networks*'. *AC and DC Power Transmission, 2006. ACDC 2006. The 8th IEE International Conference on*. 2006.

37. Schroth, R.G. and Obst, D. '*Long distance tunnels for the installation of 400 kV XLPE cables*'. *Cables in Tunnels (Ref. No. 2000/070), IEE Seminar*. 2000.

38. Zhang, X., Jiang, X., and Xie, H. '*The application of fiber optic distributed temperature sensor to fault detection of XLPE insulated underground cable*'. *Properties and Applications of Dielectric Materials, 2000. Proceedings of the 6th International Conference on*. 2000.

39. Mendez, S.J.M. and Monteys, J. '*Design of power and communication cable installations to minimise interference in tunnels*'. *Cables in Tunnels (Ref. No. 2000/070), IEE Seminar*. 2000.

40. Bernstein, R., Oristaglio, M., Miller, D.E., and Haldorsen, J., '*Imaging radar maps underground objects in 3-D'.* Computer Applications in Power, IEEE. 13(3): p. 20-24. 2000.

41. Orton, H.E. and Samm, R., '*Worldwide underground transmission cable practices'.* Power Delivery, IEEE Transactions on. 12(2): p. 533-541. 1997.

42. Rahman, M.M. and Nassi, M., '*High capacity cable's role in once and future grids'.* Spectrum, IEEE. 34(7): p. 31-35. 1997.

43. Abdel-Salam, M., Anis, H., El-Morshedy, A., and Radwan, R., '*High-Voltage Engineering Theory and Practice'*. Second ed, New York: Macel Dekker, Inc. 725. 2000.

44. Gouge, M.J., Lindsay, D.T., Demko, J.A., Duckworth, R.C., Ellis, A.R., Fisher, P.W., James, D.R., Lue, J.W., Roden, M.L., Sauers, I., Tolbert, J.C., Traeholt, C., and Willen, D., '*Tests of tri-axial HTS cables'.* Applied Superconductivity, IEEE Transactions on. 15(2): p. 1827-1830. 2005.

45. Willén, D., '*Experience Shapes the Future Superconducting Cables'*. p. 26. 2009.

46. Masuda, T., Yumura, H., Watanabe, M., Takigawa, H., Ashibe, Y., Suzawa, C., Kato, T., Okura, K., Yamada, Y., Hirose, M., Yatsuka, K., Sato, K., and Isojima, S., '*High-temperature Superconducting Cable Technology and Development Trends'.* 2005.

47. Shahidehpour, M., '*Cool currents: superconductors' evolution for power transmission'.* Power and Energy Magazine, IEEE. 3(2): p. 17-19. 2005.

48. GESCHIERE, A., WILLÉN, D., PIGA, E., BARENDREGT, P., ROYAL, J., and LYNCH, N. '*LONG DISTANCE TRIAX HTS CABLE'*. *19th International Conference on Electricity Distribution*. Vienna. 2007.

49. Jae-young, Y., Seung Ryul, L., and Jong Yul, K., '*Application Methodology for 22.9 kV HTS Cable in Metropolitan City of South Korea'.* Applied Superconductivity, IEEE Transactions on. 17(2): p. 1656-1659. 2007.

50. Willén, D., '*66 kV, 300 MVA HTS Triax Cable for Melbourne'*. p. 8. 2007.

51. Citipower, '*Melbourne CBD Security of Supply Enhancement Project Submission to the Essential Service Commission'*: Melbourne. p. 188. 2006.

52. Kimura, A. and Yasuda, K., '*R & D of superconductive cable in Japan'.* Applied Superconductivity, IEEE Transactions on. 15(2): p. 1818-1822. 2005.

53. Naylor, J.H., '*Fault Calculation'*, *Power System Protection*, T.E.T. Association, Editor, The Institution of Electrical Engineers: London. 1995.

54. Lue, J.W., Gouge, M.J., and Duckworth, R.C., '*Over-current testing of HTS tapes'.* Applied Superconductivity, IEEE Transactions on. 15(2): p. 1835-1838. 2005.

55. Lue, J.W., Barber, G.C., Demko, J.A., Gouge, M.J., Stovall, J.P., Hughey, R.L., and Sinha, U.K., '*Fault current tests of a 5-m HTS cable'.*

Applied Superconductivity, IEEE Transactions on. 11(1): p. 1785-1788. 2001.

56. nkt cables, G., '*HTS Triax™ Energy Cable Systems HTS Cables and Accessories'*. p. 12. 2009.

57. Matheus, C., Haubrich, H.J., and Willen, D. '*Superconducting cables as a new option in network planning'*. *Power Tech, 2005 IEEE Russia*. 2005.

58. Kelley, N.J., Wakefield, C., Nassi, M., Corsaro, P., Spreafico, S., Von Dollen, D.W., and Jipping, J., '*Field demonstration of a 24-kV warm dielectric HTS cable'.* Applied Superconductivity, IEEE Transactions on. 11(1): p. 2461-2466. 2001.

Appendix A

Lakervi [51] presented the power loss as the maximum current or real and reactive power flows have been determined, the series active and reactive power losses in a 3-phase circuit or any item of equipment, P1 and Qj can be calculated from the following equations:

$$Pl = 3I^2 Rl \qquad (3.4)$$

or $$Pl = \left[\frac{P}{V}\right]^2 Rl + \left[\frac{Q}{V}\right]^2 Rl \qquad (3.5)$$

and $$Q = 3I^2 Xl$$

$$= \left[\frac{P}{V}\right]^2 Xl + \left[\frac{Q}{V}\right]^2 Xl \qquad (3.6)$$

where R1 and X1 refer to the circuit series resistance and reactance as shown in Figure 3.2.

Given that the circuit shunt impedance is (Rs +jXs), as indicated in Figure 3.2, the shunt losses can be calculated using the shunt current I instead of I:

$$Is = \frac{V/\sqrt{3}}{\sqrt{Rs^2 + Xs^2}} \qquad (3.7)$$

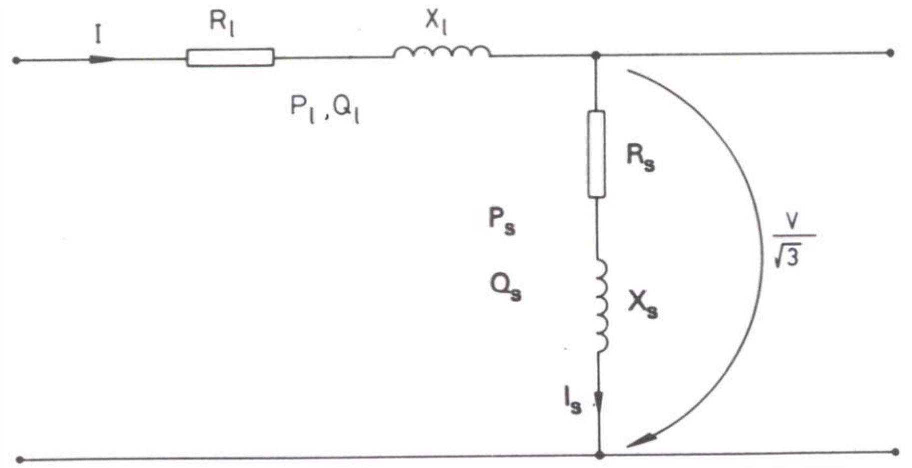


Figure 3.2 Calculation of circuit series and shunt losses

This circuit and method are most relevant for transformers and shunt capacitors, while parallel connection of the susceptance of the capacitance B and leakage conductance G is used when cables or high-voltage lines are concerned. Their shunt losses can be calculated using:

$$Ps = 3G\left[\frac{V}{\sqrt{3}}\right]^2 = GV^2$$
$$Qs = 3B\left[\frac{V}{\sqrt{3}}\right]^2 = BV^2 \qquad (3.8)$$

The shunt resistive losses P for lines are usually very low while the reactive losses

Q are negative; e.g. the shunt capacitance feeds reactive power to the system. Here V is the phase—phase voltage.

In the previous calculations it has been assumed that the system voltage was 3-phase. However, particularly at low voltage, single- or double-phase systems are sometimes used instead of the conventional 3-phase system because of their lower construction costs, even though the losses are higher.

Example

The ratio of losses between a single-phase and a symmetrical 3-phase line is derived. It is assumed that the same total real power P is delivered by both circuits, that all conductors are similar and have resistance R, and also that the phase—earth voltages are equal.

Single-phase line: The load P represents a certain current I. The current flows through the phase line, load and neutral conductor, and thus the system losses are

$Pl1 = I^2(2R) = 2I^2R$ Pl (3.10)

3-phase system: The load P is divided between three phases and the current in all of these is 1/3. Because the load is symmetrical the phasor sum of these 3-phase currents is zero, and thus no current flows in the neutral conductor:

$Pl3 = \left(\frac{I}{3}\right)^2(3R) = \frac{I^2R}{3} = \frac{1}{6}Pl1$ (3.11)

Thus, when the same real power is being delivered, the losses in a single-phase line are six times the losses in a balanced 3-phase line. In practice not all loads will be balanced 3-phase loads and the resulting imbalance will reduce this ratio.

When making economic comparisons, it is not sufficient just to compare the losses. In the above example the investment required for the 3-phase system is larger than that for the alternative single-phase arrangement. If the alternative of a four-conductor 3-phase line operating at single phase is considered, this would result in two wires in parallel being used for the phase and also the neutral conductors. Under this mode of single-phase operation the losses would be

$P'l1 = 2I^2(R/2) = I^2R$

which is three times the losses at 3-phase operation of the same line.

3.3.3 Load and loss load factors

In economic comparisons it is often necessary to take account of the recurring annual system losses. System losses can be separated into so-called fixed losses and variable losses. The fixed losses are those due to the magnetisation currents of such items as transformers and reactors, which are often referred to as iron losses. For simplicity it is assumed that these losses occur for the full 8760 hours per annum, neglecting outages owing to maintenance or faults. Where more accuracy is required, the effect of the variation of voltage on the losses may need to be taken into account.

The variable losses are those caused by the flow of current through the different items of equipment on the network, and are also termed copper losses. Power losses in a component having resistance R are proportional to the square of the current flowing through it, i.e. P1 = 12R. For example, in Figure 3.3, the ratio P1/P is much higher for high values of P than for low P values. The annual energy losses Wl can be determined by integrating the squared time function or duration curve of the current or of the power flow:

$$Wl = R\int_0^T I^2(t)dt = \int_0^T Pl(t)dt\mathrm{T} \qquad (3.12)$$

This integration can be applied alternatively to the load curve shown in Figure 3.3a or to the duration curve in Figure 3.3b.

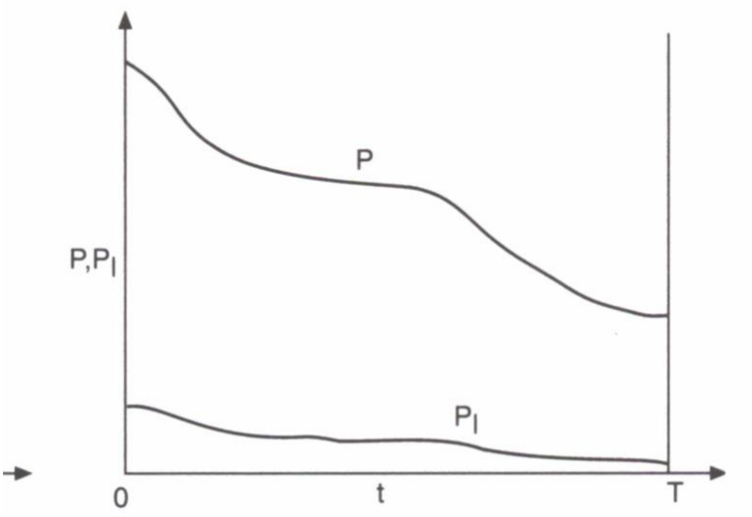


Figure 3.3 Load and load-duration curves

a Load curve

b Duration curves for power (P) and power losses (P1)

The load factor F is defined as the ratio of the average power divided by the maximum demand, and can be expressed as W/Pmax T. The loss load factor is defined as the ratio of the average power loss divided by the losses at the time of peak load, expressed by (Wi/Pimax T). The load factor can be determined by integrating the duration curve for F, and the loss load factor by integrating the P1(t) curve. The quadratic relationship between P1 and P is shown in Figure 3.3b.

Where only the load factor F is available, various formulas have been developed to obtain a quick approximation of loss load factor (LLF), generally based on the expression LLF = aF + (1 — a)F2. Two examples are given below:

Loss load factor $\cong 0.1F + 0.9F^2$ (3.13)

$\cong 0.3F + 0.7F^2$ (3.14)

Appendix B

The following section presents a high level description of the risk assessment of all CitiPower zone substations. It should be noted that the energy at risk calculations are based on excluding any planned responses to mitigate the risk.

AP Zone Substation, Albert Park

Station Rating & supply area

Albert Park Zone substation has a summer n-1 rating of 61.6MVA comprised of three 20/27MVA transformers operating at 66/11kV. The Zone Substation supplies the Albert Park, South Melbourne and Port Melbourne areas.

Although expected demand for the next five years will exceed the station's n-1 rating, there is sufficient load transfer capability via 11kV links to adjacent zone substations to cover this shortfall. Thus no customer load is at risk for the outage of a major plant item.

AR Zone Substation, Armadale

Station Rating & supply area

Armadale Zone substation has a summer n-1 rating of 33.7MVA comprised of two 20/30MVA transformers operating at 66/11kV. The Zone Substation supplies the Armadale and Malvern areas.

Although expected demand for the next five years will exceed the station's n-1 rating, there is sufficient load transfer capability via 11kV links to adjacent zone substations to cover this shortfall. Thus no customer load is at risk for the outage of a major plant item.

B Zone Substation, Collingwood

Station Rating & supply area

B Zone substation has a summer n-1 rating of 29.0MVA comprised of two 20/27MVA transformers operating at 66/11kV. The Zone Substation supplies the Collingwood and Abbotsford areas.

Although expected demand for the next five years will exceed the station's n-1 rating, there is sufficient load transfer capability via 11kV links to adjacent zone substations and 7.4MVA cogeneration capacity to cover this shortfall. Thus no customer load is at risk for the outage of a major plant item.

BC Zone Substation, Balaclava

Station Rating & supply area

Balaclava Zone substation has a summer n-1 rating of 32.1MVA comprised of two 30MVA transformers operating at 66/11kV. The Zone Substation supplies the Balaclava, St.Kilda East and Caulfield North areas.

The expected demand for the next five years is less than the station's n-1 rating, thus no customer load is at risk for the outage of a major plant item.

BK Zone Substation, Brunswick

Station Rating & supply area

Brunswick Zone substation has a summer n-1 rating of 27.4MVA comprised of three 10MVA transformers operating at 22/6.6kV. The Zone Substation supplies the Brunswick area.

The expected demand for the next five years is less than the station's n-1 rating, thus no customer load is at risk for the outage of a major plant item.

BSBQ Zone Substation, Bouverie St

Station Rating & supply area

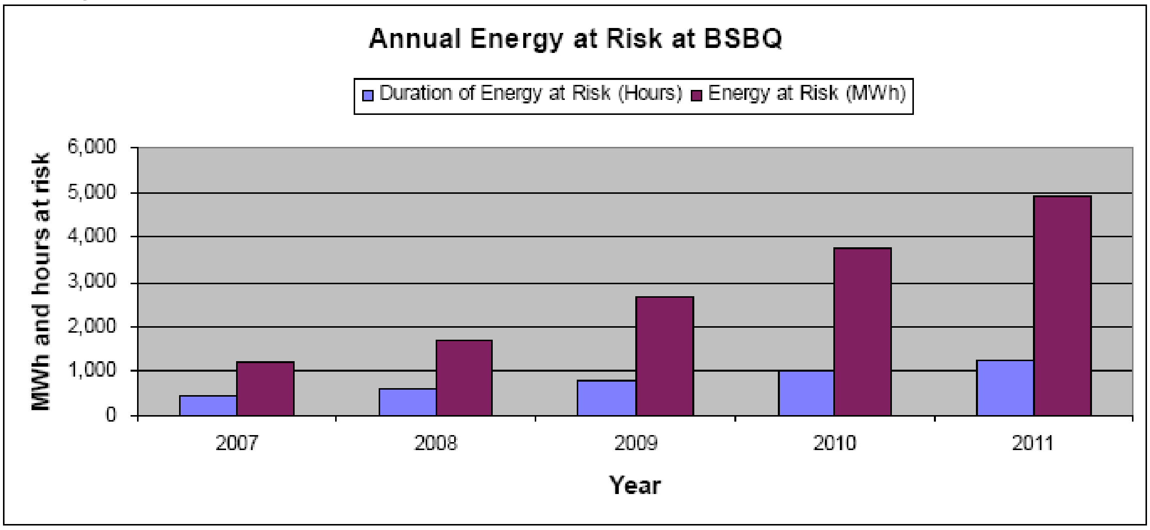
Bouverie St Zone substation has a summer n-1 rating of 25.8MVA comprised of three 10MVA transformers operating at 22/11kV. The Zone Substation supplies the Carlton, Melbourne and Parkville areas.

In the 2006/2007 summer period the station's n-1 rating will be exceeded by 10.6MVA with 1202.3MWh at risk. By 2008/2009 summer, the station's N rating will be exceeded by 1.2MVA with 2,684.3MWh at risk.

BSBQ SUMMER LOAD PROJECTION 2007-2011

Year	2007	2008	2009	2010	2011
Station Load (MVA)	36.4	37.7	39.9	41.7	43.5
n-1 Rating	25.8	25.8	25.8	25.8	25.8
n Rating	38.7	38.7	38.7	38.7	38.7

BSBQ ANNUAL ENERGY & HOURS AT RISK



Network solutions to manage load at risk under n-1 conditions

_ Use of co-generation capacity of up to 14.8MVA.

_ Transfer of load via 11kV links to adjacent zone substations.

_ Upgrade of existing station to a high capacity CBD type station by 2009/10 with ultimate firm capacity of 110 MVA. This will incorporate a new transmission network connection at BTS 66kV (Brunswick Terminal Station) and the additional capacity will support existing CBD stations (Refer BTS 66kV report in Transmission Connection Planning Report 2006).

The load at risk as shown above is before implementation of any network risk mitigation strategies.

Prior to completion of the BSBQ upgrade, it is expected that the customer load at risk is manageable by available load transfer capabilities to adjacent stations. Following completion of the BSBQ upgrade, it is expected that the customer load at risk will be minimal.

C Zone Substation, Brunswick

Station Rating & supply area

C Zone substation has a summer n-1 rating of 17.0MVA comprised of three 7.5MVA transformers operating at 22/6.6kV. The Zone Substation supplies the Brunswick area.

The expected demand for the next five years is less than the station's n-1 rating, thus no customer load is at risk for the outage of a major plant item.

CL Zone Substation, Camberwell

Station Rating & supply area

Camberwell Zone substation has a summer n-1 rating of 65.8MVA comprised of two 20/30MVA transformers and one 20/27MVA transformer operating at 66/11kV. The Zone Substation supplies the Camberwell and Hawthorn areas.

The expected demand for the next five years is less than the station's n-1 rating, thus no customer load is at risk for the outage of a major plant item.

CW Zone Substation, Collingwood

Station Rating & supply area

Collingwood Zone substation has a summer n-1 rating of 32.2MVA comprised of two 20/27MVA transformers operating at 66/11kV. The Zone Substation supplies the Collingwood, Fitzroy and Abbotsford areas.

Although expected demand for the next five years will exceed the station's n-1 rating, there is sufficient load transfer capability via 11kV links to adjacent zone substations to cover this shortfall. Thus no customer load is at risk for the outage of a major plant item.

DA Zone Substation, Docklands Area

Station Rating & supply area

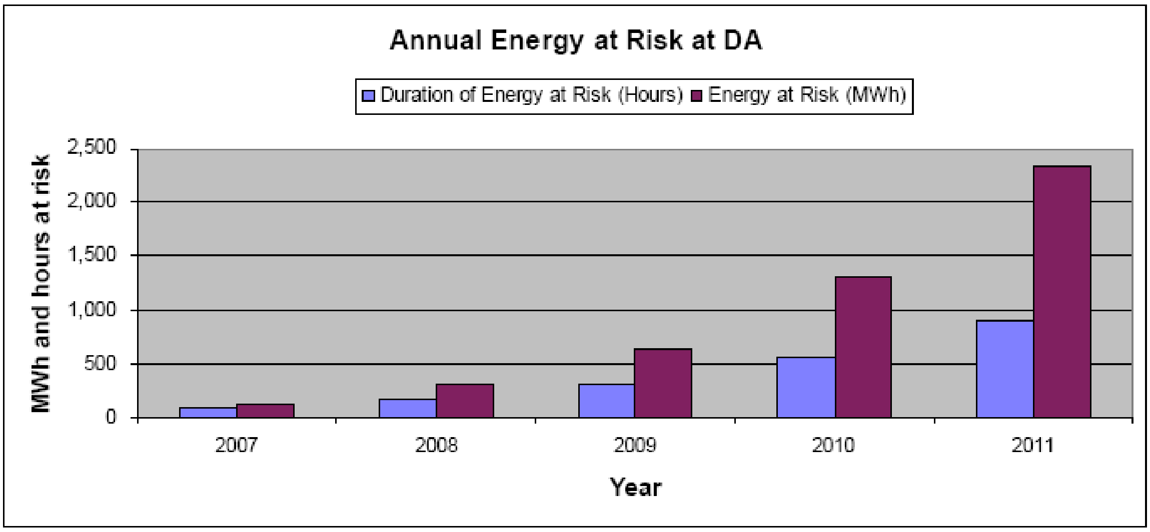
Docklands Zone substation has a summer n-1 rating of 28.8MVA comprised of three 10/13.5MVA transformers operating at 22/11kV. The Zone Substation supplies the Docklands and North Melbourne areas.

In the 2006/2007 summer period the station's n-1 rating will be exceeded by 5.0MVA with 116.7MWh at risk.

DA SUMMER LOAD PROJECTION 2007-2011

Year	2007	2008	2009	2010	2011
Station Load (MVA)	33.8	35.8	37.8	40.0	42.3
n-1 Rating	28.8	28.8	28.8	28.8	28.8
n Rating	42.9	42.9	42.9	42.9	42.9

DA ANNUAL ENERGY & HOURS AT RISK



Network solutions to manage load at risk under n-1 conditions

_ Use of Co-generation capacity of up to 2 MVA

_ A planned new 11kV link between DA and WG in 2007/08 to increase load transfer capability.

_ Following installation of a 3rd 27MVA 66/11kV transformer at WG by 2007/08, new 11kV feeders will be installed from WG to Docklands area for load transfer.

The load at risk shown above is before implementation of any network risk mitigation strategies.

Although the expected demand over the next five years is higher than the station's n-1 rating, it is expected that the customer load at risk is manageable by available load transfer capabilities to adjacent stations.

E Zone Substation, Port Melbourne

Station Rating & supply area

E Zone substation has a summer n-1 rating of 24.3MVA comprised of one 10/13.5MVA transformer and one 20MVA transformer operating at 66/6.6kV. The Zone Substation supplies the Port Melbourne and Fishermans Bend areas.

The expected demand for the next five years is less than the station's n-1 rating, thus no customer load is at risk for the outage of a major plant item.

F Zone Substation, Fitzroy

Station Rating & supply area

Fitzroy Zone substation has a summer n-1 rating of 22.9MVA comprised of three 10MVA transformers operating at 22/6.6kV. The Zone Substation supplies the Fitzroy north area.

The expected demand for the next five years is less than the station's n-1 rating, thus no customer load is at risk for the outage of a major plant item.

FB Zone Substation, Fisherman's Bend

Station Rating & supply area

Fishermans Bend Zone substation has a summer n-1 rating of 63.7MVA comprised of three 20/30MVA transformers operating at 66/11kV. The Zone Substation supplies the Fishermen's Bend and Port Melbourne areas.

The expected demand for the next five years is less than the station's n-1 rating, thus no customer load is at risk for the outage of a major plant item.

FR Zone Substation, Flinders & Ramsden Place

Station Rating & supply area

FR Zone substation has a summer n-1 rating of 61.4MVA comprised of three 30MVA transformers operating at 66/11kV. The Zone Substation supplies the Melbourne CBD and Jolimont areas.

Although expected demand for the next five years will exceed the station's n-1 rating, there is sufficient load transfer capability via 11kV links to adjacent zone substations to cover this shortfall. Thus no customer load is at risk for the outage of a major plant item.

J Zone Substation, Spencer Street

Station Rating & supply area

J Zone substation has a summer n-1 rating of 38.4MVA comprised of four 10MVA transformers operating at 22/6.6kV. The Zone Substation supplies the Melbourne CBD and Dockland areas.

The expected demand for the next five years is less than the station's n-1 rating, thus no customer load is at risk for the outage of a major plant item.

JA Zone Substation, Little Bourke Street

Station Rating & supply area

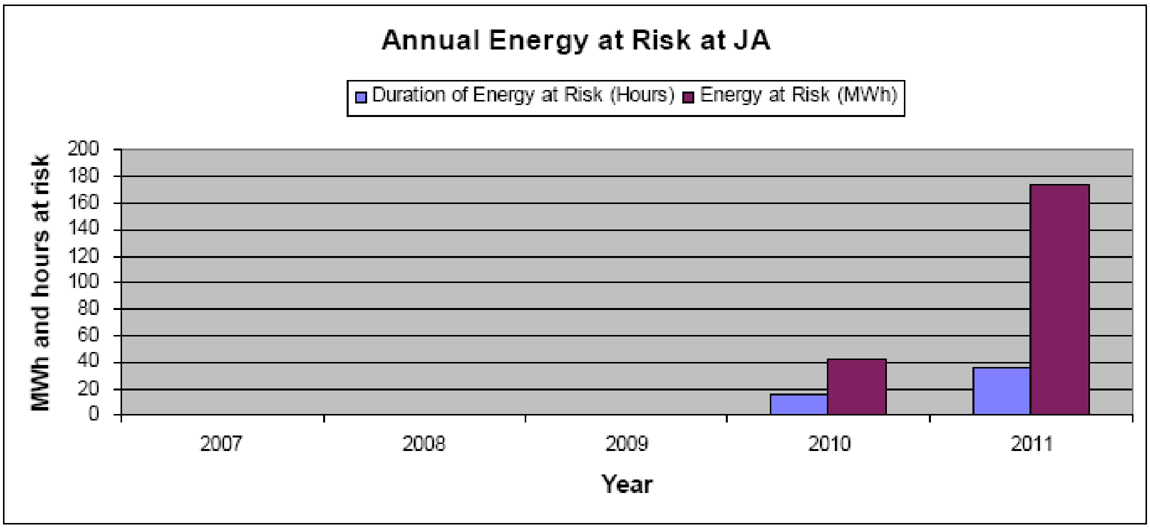
JA Zone substation has a summer n-1 rating of 118MVA comprised of three 55MVA transformers operating at 66/11kV. The Zone Substation supplies the Melbourne CBD and Docklands areas.

In the 2009/2010 summer period the station's n-1 rating will be exceeded by 6.5MVA with 42.0MWh at risk.

JA SUMMER LOAD PROJECTION 2007-2011

Year	2007	2008	2009	2010	2011
Station Load (MVA)	94.9	109.1	115.7	124.5	131.3
n-1 Rating	118.0	118.0	118.0	118.0	118.0
n Rating	172.5	172.5	172.5	172.5	172.5

JA ANNUAL ENERGY & HOURS AT RISK



Network solutions to manage load at risk under n-1 conditions

_ Load reduction involving transfer of load via 11kV links to adjacent stations.

_ Installation of 2 x 12MVAr 11kV capacitor banks by 2008/09 to improve transformer and subtransmission line loading under plant outage contingency.

The load at risk shown above is before implementation of any network risk mitigation strategies.

Although the expected demand over the next five years is higher than the station's n-1 rating, it is expected that the customer load at risk is manageable by available load transfer capabilities to adjacent stations.

L Zone Substation, Deepdene

Station Rating & supply area

L Zone substation has a summer n-1 rating of 32.1MVA comprised of two 20/30MVA transformers operating at 66/11kV. The Zone Substation supplies the Balwyn, Canterbury and Kew areas.

Although expected demand for the next five years will exceed the station's n-1 rating, there is sufficient load transfer capability via 11kV links to adjacent zone substations to cover this shortfall. Thus no customer load is at risk for the outage of a major plant item.

LQ Zone Substation, Little Queen Street

Station Rating & supply area

Little Queen Zone substation has a summer n-1 rating of 131.6MVA comprised of three 60MVA transformers operating at 66/11kV. The Zone Substation supplies the Melbourne CBD area.

A total of additional 12MVAr capacitor bank capacity has been installed at LQ in 2006 to improve the transformer loading.

Although expected demand for the next five years will exceed the station's n-1 rating, there is sufficient load transfer capability via 11kV links to adjacent zone substations to cover this shortfall. Thus no customer load is at risk for the outage of a major plant item.

LS Zone Substation, Laurens Street

Station Rating & supply area

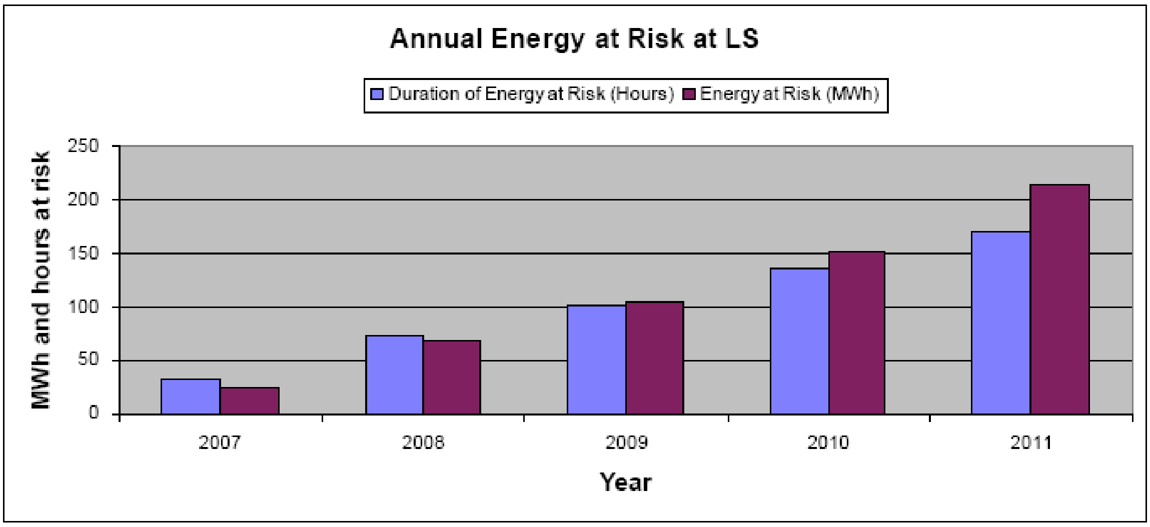
Laurens St Zone substation has a summer n-1 rating of 23.6MVA comprised of two 10MVA transformers and one 13.5MVA transformer operating at 22/6.6kV. The Zone Substation supplies the North Melbourne and Parkville areas.

In the 2006/2007 summer period the station's n-1 rating will be exceeded by 3.5MVA with 24.3MWh at risk.

LS SUMMER LOAD PROJECTION 2007-2011

Year	2007	2008	2009	2010	2011
Station Load (MVA)	27.1	28.3	28.8	29.4	30.0
n-1 Rating	23.6	23.6	23.6	23.6	23.6
n Rating	35.5	35.5	35.5	35.5	35.5

LS ANNUAL ENERGY & HOURS AT RISK



Network solutions to manage load at risk under n-1 conditions

_ Load reduction involving transfer of load via 11kV links to VM via auto-transformers.

_ A new HV link is planned to be installed between LS and adjacent zone substation in 2008/09 to increase load transfer capability.

The load at risk shown above is before implementation of any network risk mitigation strategies.

Although the expected demand over the next five years is higher than the station's n-1 rating, it is expected that the customer load at risk is manageable by available load transfer capabilities to adjacent stations.

MG Zone Substation, Montague Street, Port Melbourne

Station Rating & supply area

Montague Zone substation has a summer n-1 rating of 61.7MVA comprised of two 20/30MVA transformers and one 20/27MVA transformer operating at

66/11kV. The Zone Substation supplies the South Melbourne and Melbourne CBD areas.

Although expected demand for the next five years will exceed the station's n-1 rating, there is sufficient load transfer capability via 11kV links to adjacent zone substations to cover this shortfall. Thus no customer load is at risk for the outage of a major plant item.

MP Zone Substation, McIlwraith Place, Melbourne

Station Rating & supply area

Myers Place Zone substation has a summer n-1 rating of 116.3MVA comprised of three 55MVA transformers operating at 66/11kV. The Zone Substation supplies the Melbourne CBD area.

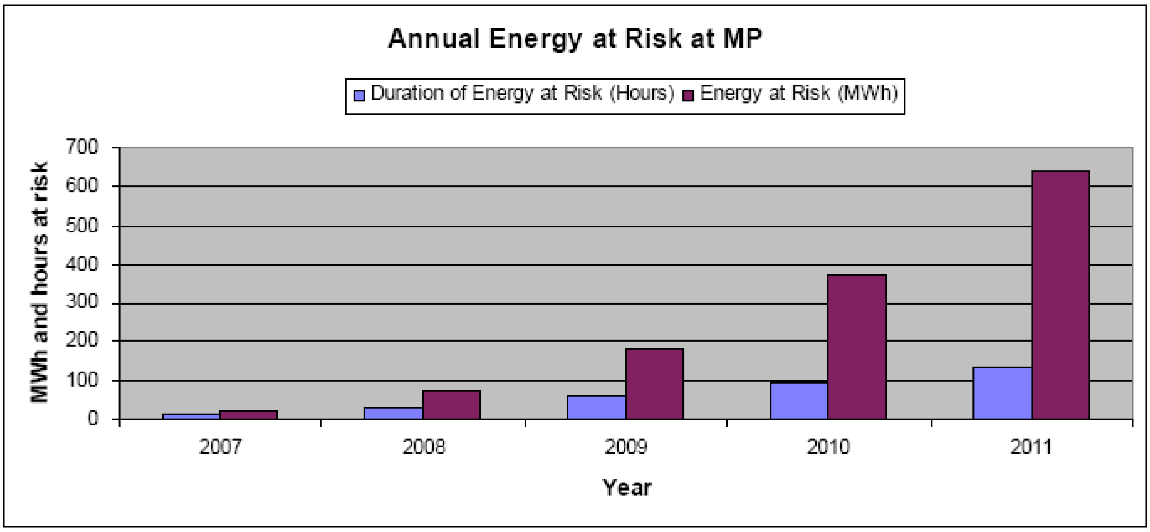
A total of additional 24MVAr capacitor bank capacity is being installed at MP for completion in 2006/07 summer to improve the transformer loading.

In the 2006/2007 summer period the station's n-1 rating will be exceeded by 4.2MVA with 18.4MWh at risk.

MP SUMMER LOAD PROJECTION 2007-2011

Year	2007	2008	2009	2010	2011
Station Load (MVA)	120.5	123.2	125.9	128.6	131.4
n-1 Rating	116.3	116.3	116.3	116.3	116.3
n Rating	169.5	169.5	169.5	169.5	169.5

MP ANNUAL ENERGY & HOURS AT RISK



Network solutions to manage load at risk under n-1 conditions

_ Load reduction involving transfer of load via 11kV links to adjacent stations.

_ The planned upgrade of BSBQ in around 2009/10 will allow load to be permanently transferred from MP to BSBQ.

The load at risk shown above is before implementation of any network risk mitigation strategies.

Although the expected demand over the next five years is higher than the station's n-1 rating, it is expected that the customer load at risk is manageable by available load transfer capabilities to adjacent stations.

NC Zone Substation, Northcote

Station Rating & supply area

Northcote Zone substation has a summer n-1 rating of 28.5MVA comprised of two 20/30MVA transformers operating at 66/11kV. The Zone Substation supplies the Northcote area.

The expected demand for the next five years is less than the station's n-1 rating, thus no customer load is at risk for the outage of a major plant item.

NR Zone Substation, North Richmond

Station Rating & supply area

North Richmond Zone substation has a summer n-1 rating of 57.4MVA comprised of two 23/28MVA transformers and one 20/27MVA transformer operating at 66/11kV. The Zone
Substation supplies the Richmond and Abbotsford areas.

The expected demand for the next five years is less than the station's n-1 rating, thus no customer load is at risk for the outage of a major plant item.

PM Zone Substation, Port Melbourne

Station Rating & supply area

Port Melbourne Zone substation has a summer n-1 rating of 28.0MVA comprised of three 10/13.5MVA transformers operating at 66/6.6kV. The Zone Substation supplies the Port Melbourne area.

The expected demand for the next five years is less than the station's n-1 rating, thus no customer load is at risk for the outage of a major plant item.

PR Zone Substation, Prahran

Station Rating & supply area

Prahran Zone substation has a summer n-1 rating of 27.5MVA comprised of two 9.3/11.7MVA transformers and one 10/13.5MVA transformer operating at 22/11kV. The Zone Substation supplies the Prahran area.

The expected demand for the next five years is less than the station's n-1 rating, thus no customer load is at risk for the outage of a major plant item.

Q Zone Substation, Kew

Station Rating & supply area

Q Zone substation has a summer n-1 rating of 30.7MVA comprised of two 20/30MVA transformers operating at 66/11kV. The Zone Substation supplies the Kew area.

Although expected demand for the next five years will exceed the station's n-1 rating, there is sufficient load transfer capability via 11kV links to adjacent zone substations to cover this shortfall. Thus no customer load is at risk for the outage of a major plant item.

R Zone Substation, Richmond

Station Rating & supply area

Richmond Zone substation has a summer n-1 rating of 31.4MVA comprised of three 10/14MVA transformers operating at 22/6.6kV. The Zone Substation supplies the Richmond area.

Following the installation of additional capacity at TK in 2006/07 permanent load transfers from R to TK at 11kV will be carried out.

Although expected demand for the next five years will exceed the station’s n-1 rating, there is sufficient load transfer capability via 11kV links to adjacent zone substations to cover this shortfall. Thus no customer load is at risk for the outage of a major plant item.

RD Zone Substation, Riversdale

Station Rating & supply area

Riversdale Zone substation has a summer n-1 rating of 30.6MVA comprised of two 20/30MVA transformers operating at 66/11kV. The Zone Substation supplies the Camberwell area.

Although expected demand for the next five years will exceed the station’s n-1 rating, there is sufficient load transfer capability via 11kV links to adjacent zone substations to cover this shortfall. Thus no customer load is at risk for the outage of a major plant item.

RP Zone Substation, Russell Place

Station Rating & supply area

Russel Place Zone substation has a summer n-1 rating of 18.7MVA comprised of three 10/13.5MVA transformers operating at 22/6.6kV. The Zone Substation supplies the Melbourne CBD area.

The expected demand for the next five years is less than the station's n-1 rating, thus no customer load is at risk for the outage of a major plant item.

SK Zone Substation, St Kilda

Station Rating & supply area

St.Kilda Zone substation has a summer n-1 rating of 62.6MVA comprised of three 20/30MVA transformers operating at 66/11kV. The Zone Substation supplies the St.Kilda area.

Although expected demand for the next five years will exceed the station's n-1 rating, there is sufficient load transfer capability via 11kV links to adjacent zone substations and 7.4MVA cogeneration capacity to cover this shortfall. Thus no customer load is at risk for the outage of a major plant item.

SM Zone Substation, South Melbourne

Station Rating & supply area

South Melbourne Zone substation has a summer n-1 rating of 26.7MVA comprised of three 10/13.5MVA transformers operating at 22/11kV. The Zone Substation supplies the Southbank and South Melbourne areas.

SM will be reconstructed and upgraded to 66kV with 55MVA transformer firm capacity for completion by 2009/10.

The reconstruction program has been started and all the SM loads will be temporarily transferred away to facilitate the reconstruction. A significant amount of SM loads has already been transferred away prior to the 2006/07 summer and the remaining station demand in 2006/07 summer is expected to be within the existing zone substation n-1 rating.

SO Zone Substation, South Melbourne

Station Rating & supply area

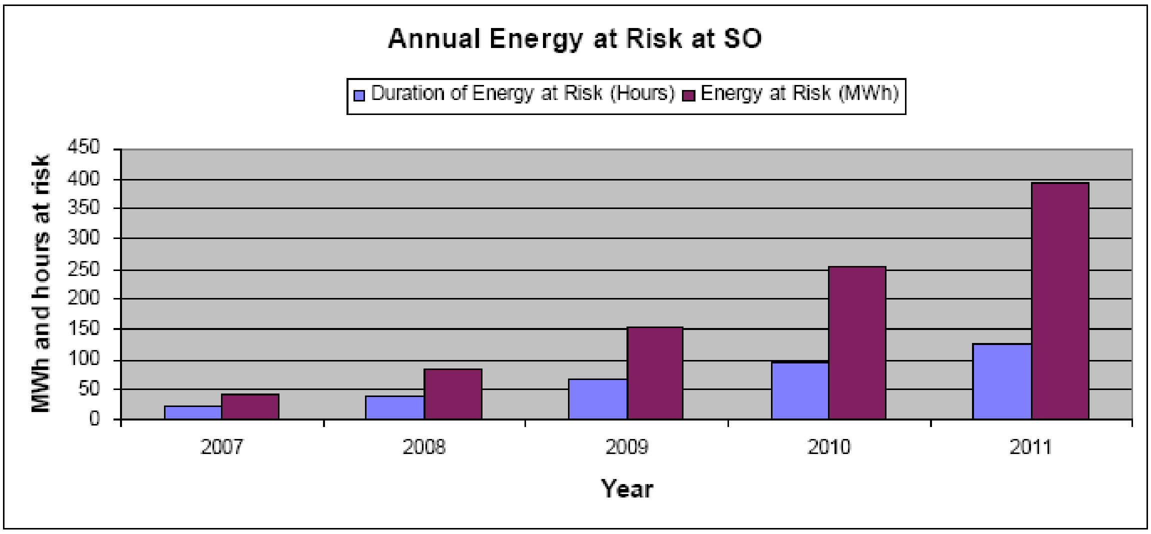
SO Zone substation has a summer n-1 rating of 63.7MVA comprised of three 20/30MVA transformers operating at 66/11kV. The Zone Substation supplies the Southbank and South Melbourne areas.

In the 2006/2007 summer period the station's n-1 rating will be exceeded by 6.4MVA with 43.5MWh at risk.

SO SUMMER LOAD PROJECTION 2007-2011

Year	2007	2008	2009	2010	2011
Station Load (MVA)	70.1	71.6	73.2	74.7	76.3
n-1 Rating	63.7	63.7	63.7	63.7	63.7
n Rating	93.5	93.5	93.5	93.5	93.5

SO ANNUAL ENERGY & HOURS AT RISK



Network solutions to manage load at risk under n-1 conditions

_ Load reduction involving transfer of load via 11kV links to adjacent stations.

_ The reconstruction of SM zone substation, due for completion in 2009/10, will allow a permanent load transfer from SO.

The load at risk as shown above is before implementation of any network risk mitigation strategies.

Prior to completion of the SM upgrade, it is expected that the customer load at risk is manageable by available load transfer capabilities to adjacent stations. Following completion of the SM upgrade, it is expected that the customer load at risk will be minimal.

TK Zone Substation, Toorak

Station Rating & supply area

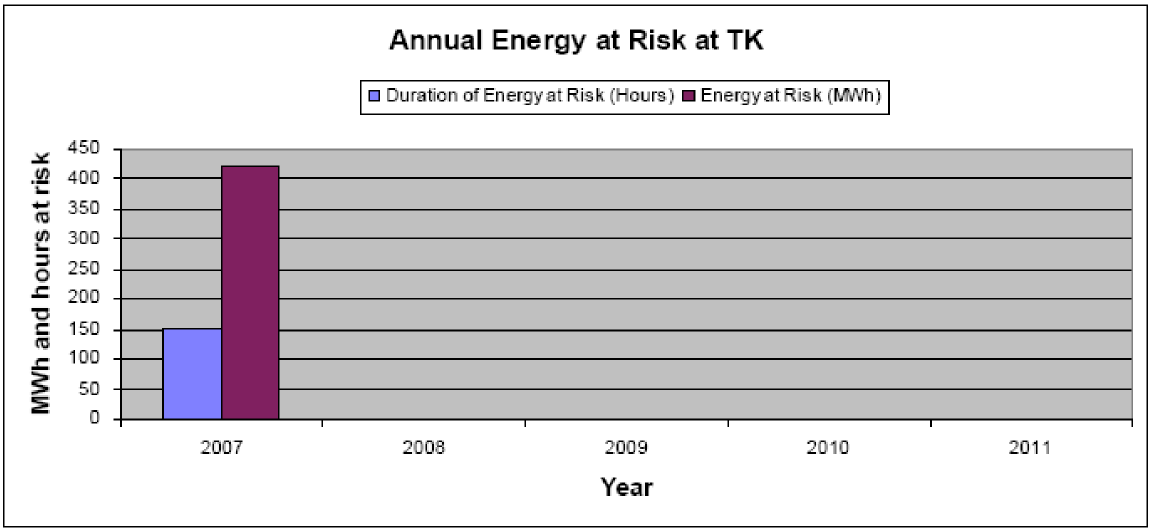
Toorak Zone substation has a summer n-1 rating of 28.7MVA comprised of two 20/30MVA transformers operating at 66/11kV. The Zone Substation supplies the Toorak area.

In the 2006/2007 summer period the station's n-1 rating will be exceeded by 10.3MVA with 420.7MWh at risk.

TK SUMMER LOAD PROJECTION 2007-2011

Year	2007	2008	2009	2010	2011
Station Load (MVA)	39.0	39.7	40.4	41.1	41.8
n-1 Rating	28.7	54.1	54.1	54.1	54.1
n Rating	54.1	78.1	78.1	78.1	78.1

TK ANNUAL ENERGY & HOURS AT RISK



Network solutions to manage load at risk under n-1 conditions

_ Load reduction involving transfer of load via 11kV links to adjacent stations.

_ Installation of a 3rd transformer at TK is in progress and is available as an emergency spare for the 2006/07 summer. Following full commissioning of the 3rd transformer, the expected demand for the next five years is less than the station's n-1 rating, thus no customer load is at risk for the outage of a major plant item.

Following installation of the 3rd transformer at TK, there will be sufficient capacity to meet the station demand over next 5 years, and thus no customer load at risk for outage of a major plant.

TP Zone Substation, Tavistock Place

Station Rating & supply area

Tavistock Place Zone substation has a summer n-1 rating of 11.6MVA comprised of two 10MVA transformers operating at 22/6.6kV. The Zone Substation supplies the Melbourne CBD area.

Although expected demand for the next five years will exceed the station's n-1 rating, there is sufficient load transfer capability via 11kV links to adjacent zone substations to cover this shortfall. Thus no customer load is at risk for the outage of a major plant item.

VM Zone Substation, Victoria Market

Station Rating & supply area

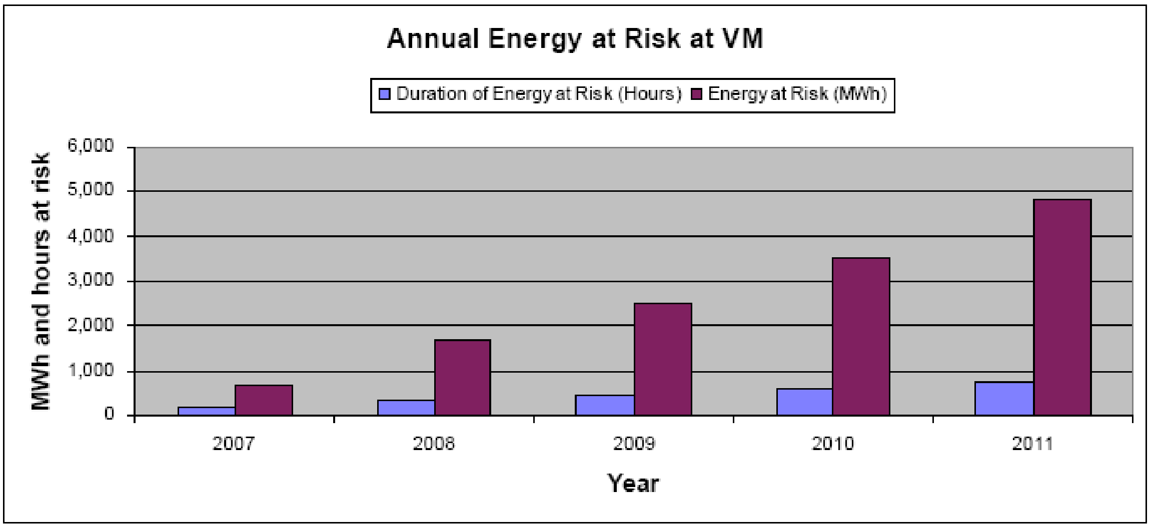
Victoria Market Zone substation has a summer n-1 rating of 63.2MVA comprised of three 20/27MVA transformers operating at 66/11kV. The Zone Substation supplies the Melbourne, North Melbourne and Parkville areas.

In the 2005/2006 summer period the station's n-1 rating will be exceeded by 11.7MVA with 681.0MWh at risk.

VM SUMMER LOAD PROJECTION 2007-2011

Year	2007	2008	2009	2010	2011
Station Load (MVA)	74.9	79.7	82.5	85.2	88.1
n-1 Rating	63.2	63.2	63.2	63.2	63.2
n Rating	94.8	94.8	94.8	94.8	94.8

VM ANNUAL ENERGY & HOURS AT RISK



Network solutions to manage load at risk under n-1 conditions

_ Load reduction involves transfer of load via 11kV links to adjacent stations.

_ The planned upgrade of BSBQ around 2009/10 will allow load to be permanently transferred from VM to BSBQ.

The load at risk shown above is before implementation of any network risk mitigation strategies.

Although the expected demand over the next five years is higher than the station's n-1 rating, it is expected that the customer load at risk is manageable by available load transfer capabilities to adjacent stations.

WA Zone Substation, Waratah Place Melbourne

Station Rating & supply area

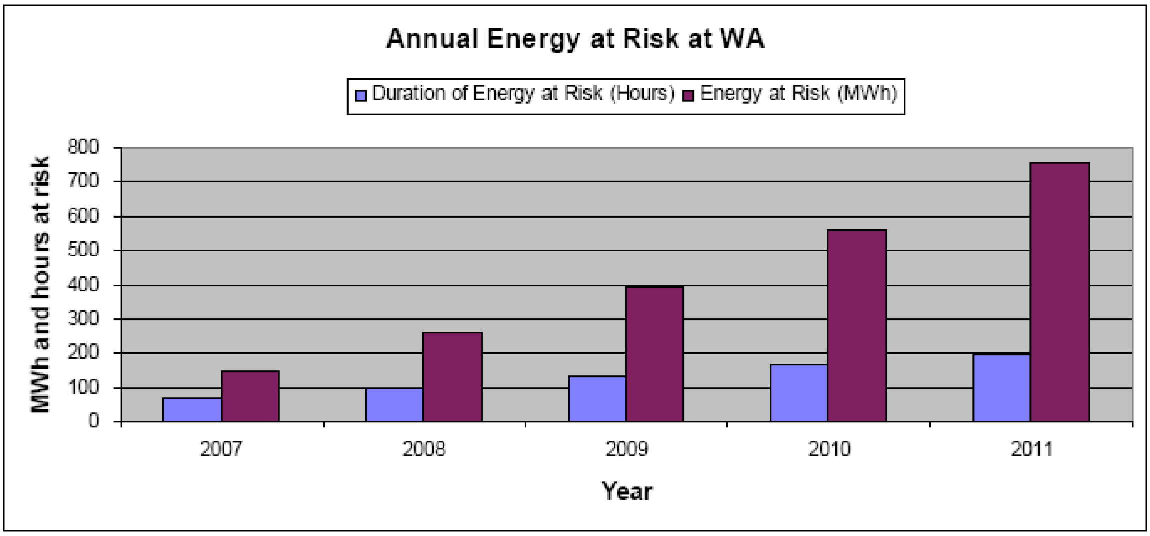
WA Zone substation has a summer n-1 rating of 67.0MVA comprised of three 20/27MVA transformers operating at 66/11kV. The Zone Substation supplies the Melbourne CBD area.

In the 2006/2007 summer period the station's n-1 rating will be exceeded by 6.7MVA with 147.8MWh at risk.

WA SUMMER LOAD PROJECTION 2007-2011

Year	2007	2008	2009	2010	2011
Station Load (MVA)	73.7	75.4	76.7	78.1	79.5
n-1 Rating	67.0	67.0	67.0	67.0	67.0
n Rating	103.5	103.5	103.5	103.5	103.5

WA ANNUAL ENERGY & HOURS AT RISK



Network solutions to manage load at risk under n-1 conditions

_ Load reduction involves transfer of load via 11kV links to adjacent stations

_ Planned new 11kV links between WA and JA in 2007/08 to increase load transfer capability.

_ The planned upgrade of BSBQ in 2009/2010 will allow load to be permanently transferred from WA to BSBQ. Additional new 11kV links will be established for permanent load transfers.

The load at risk shown above is before implementation of any network risk mitigation strategies.

Although the expected demand over the next five years is higher than the station's n-1 rating, it is expected that the customer load at risk is manageable by available load transfer capabilities to adjacent stations.

WB Zone Substation, West Brunswick

Station Rating & supply area

West Brunswick Zone substation has a summer n-1 rating of 26.4MVA comprised of two 20/30MVA transformers operating at 66/6.6kV. The Zone Substation supplies the West Brunswick area.

The expected demand for the next five years is less than the station's n-1 rating, thus no customer load is at risk for the outage of a major plant item.

WG Zone Substation, Westgate

Station Rating & supply area

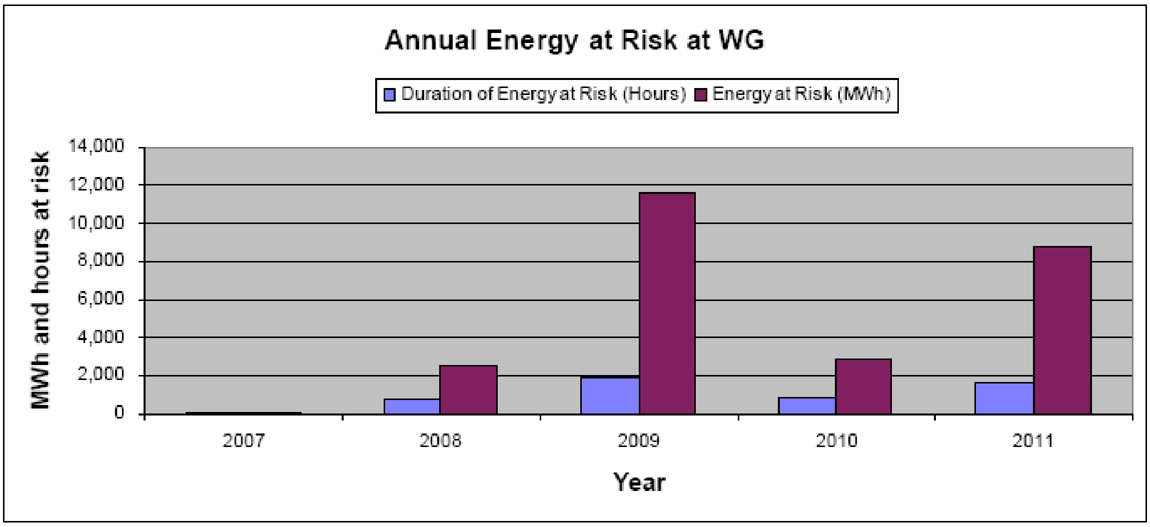
WG Zone substation has a summer n-1 rating of 36.1MVA comprised of two 20/27MVA transformers operating at 66/11kV. The Zone Substation supplies the Port Melbourne and Fishermans Bend areas.

In the 2007/2008 summer period the station's n-1 rating will be exceeded by 14.1MVA with 2,591.6MWh at risk.

WG SUMMER LOAD PROJECTION 2007-2011

Year	2007	2008	2009	2010	2011
Station Load (MVA)	34.2	50.2	62.5	52.1	59.6
n-1 Rating	36.1	36.1	36.1	36.1	36.1
n Rating	72.2	72.2	72.2	72.2	72.2

WG ANNUAL ENERGY & HOURS AT RISK



Network solutions to manage load at risk under n-1 conditions

_ Load reduction involves transfer of load via 11kV links to adjacent stations.

_ Installation of a 3rd 27MVA 66/11kV transformer at WG is presently in progress and due for commissioning in the 4th quarter of 2007.

_ The reconstruction of SM zone substation, due for completion in 2009/10, will allow a permanent load transfer from WG.

With the above network solutions implemented, zone substation WG will have sufficient capacity to meet the station demand, and thus no customer load at risk for outage of a major plant.

Appendix C

WMTS SUB-TRANSMISSION LINES

Where the expected demand over the next five years is higher than the n-1 rating of the lines, it is expected that the customer load at risk is manageable by available load transfer capabilities to adjacent loops.

WMTS-DA 22kV SUBTRANSMISSION LINES

Supply points & line loading

The WMTS-DA subtransmission lines supplies Docklands (DA) zone substation fed from West Melbourne Terminal Station (WMTS) at 22kV.

In the event of an outage of any one of WMTS-DA213 or WMTS-DA222 lines, the remaining WMTS-DA line will be loaded up to 17.1% in 2006/07 summer and up to 51% in 2010/11 summer

Network solutions to manage load at risk

_ Use of Co-generation capacity of up to 2 MVA.

_ Load reduction involving transfer of load via 11kV links to adjacent stations.

_ A planned new 11kV link from WG in 2007/08 to increase load transfer capability.

_ Following installation of a 3rd 27MVA 66/11kV transformer at WG by 2007/08, new 11kV feeders will be installed from WG to Docklands area for load transfer.

WMTS-J-LS-BSBQ-WMTS 22kV INTERCONNECTED SUBTRANSMISSION LOOP

Supply points & line loading

The WMTS-J-LS-BSBQ-WMTS interconnected subtransmission lines supply the J (Spencer Street), Laurens St (LS) and Bouverie St (BSBQ) zone substations fed from West Melbourne Terminal Station (WMTS) at 22kV.

Network solutions to manage load at risk

_ Use of Co-generation capacity (14.8 MVA) to meet load at risk.

_ Transfer of load via 11kV links to adjacent zone substations.

_ Establish new 66kV connection point at Brunswick Terminal Station (BTS) and new 66kV feeders from new connection point in around 2009/10 to support CBD substations (Refer BTS 66kV report in Transmission Connection Planning Report 2006). Two new 66kV underground cables have been estimated for this option and will enable the existing 22kV cables to be retired. This proposal to be in conjunction with the re-development of station BSBQ from 22kV to 66kV.

_ Establishment of additional transfer capacity between LS and adjacent zone substations by 2008/09.

WMTS-VM-LQ/WA 66kV SUBTRANSMISSION LINES

Supply points & line loading

The WMTS-VM-LQ/WA subtransmission lines supply the Victoria Market (VM), Little Queen (LQ) and Warratah Place (WA) zone substations fed from West Melbourne Terminal Station (WMTS) at 66kV.

A total of additional 12MVAr capacitor bank capacity has installed at LQ prior 2006/07 summer to improve the subtransmission line under line outage contingency.

In the event of an outage of any one of the WMTS-VM1-LQ1/WA1, WMTS-VM2-LQ2/WA2 or WMTS-VM3-LQ3/WA3 lines, the remaining lines will be loaded above their n-1 rating up to 4.3% in 2007/08 summer and up to 17.1% in 2010/11 summer.

Network solutions to manage load at risk

_ Load reduction involves transfer of load via 11kV links to adjacent stations

_ The planned upgrade of BSBQ in 2009/2010 will allow load to be permanently transferred from VM and WA to BSBQ. New 11kV links will be established for permanent load transfers.

WMTS-JA 66kV SUBTRANSMISSION LINES

Supply points & line loading

The WMTS-JA subtransmission lines supply the Little Bourke (JA) zone substation fed from West Melbourne Terminal Station (WMTS) at 66kV.

In the event of an outage of any one of the WMTS-JA1 lines, the remaining WMTS-JA2 line will be loaded above their n-1 rating by 7.7% in 2007/08 summer and by 30.6% in 2010/11 summer.

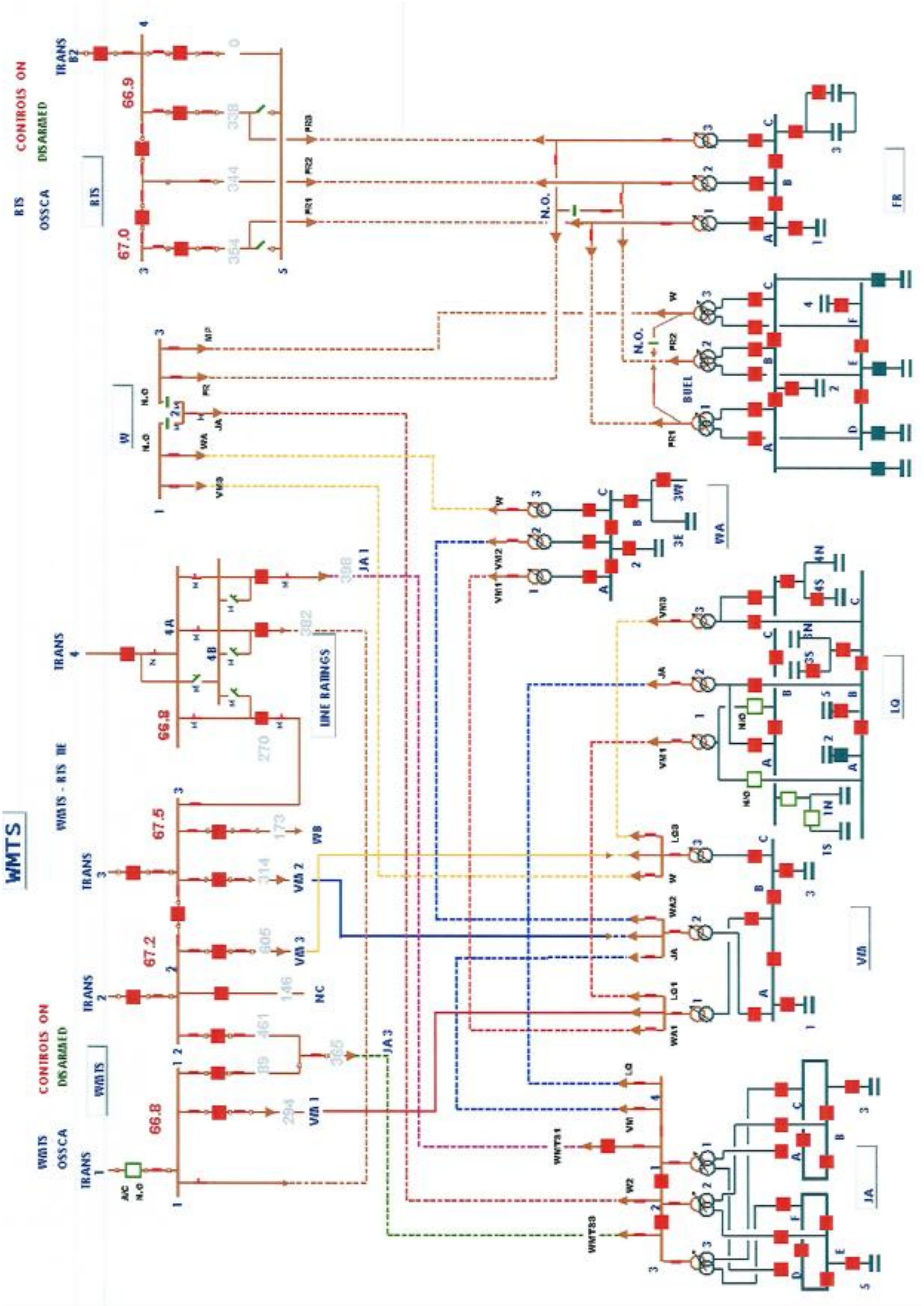
In the event of an outage of any one of the WMTS-JA2 lines, the remaining WMTS-JA1 line will be loaded above their n-1 rating by 6.4% in 2009/10 summer and by 12.1% in 2010/11 summer.

Network solutions to manage load at risk

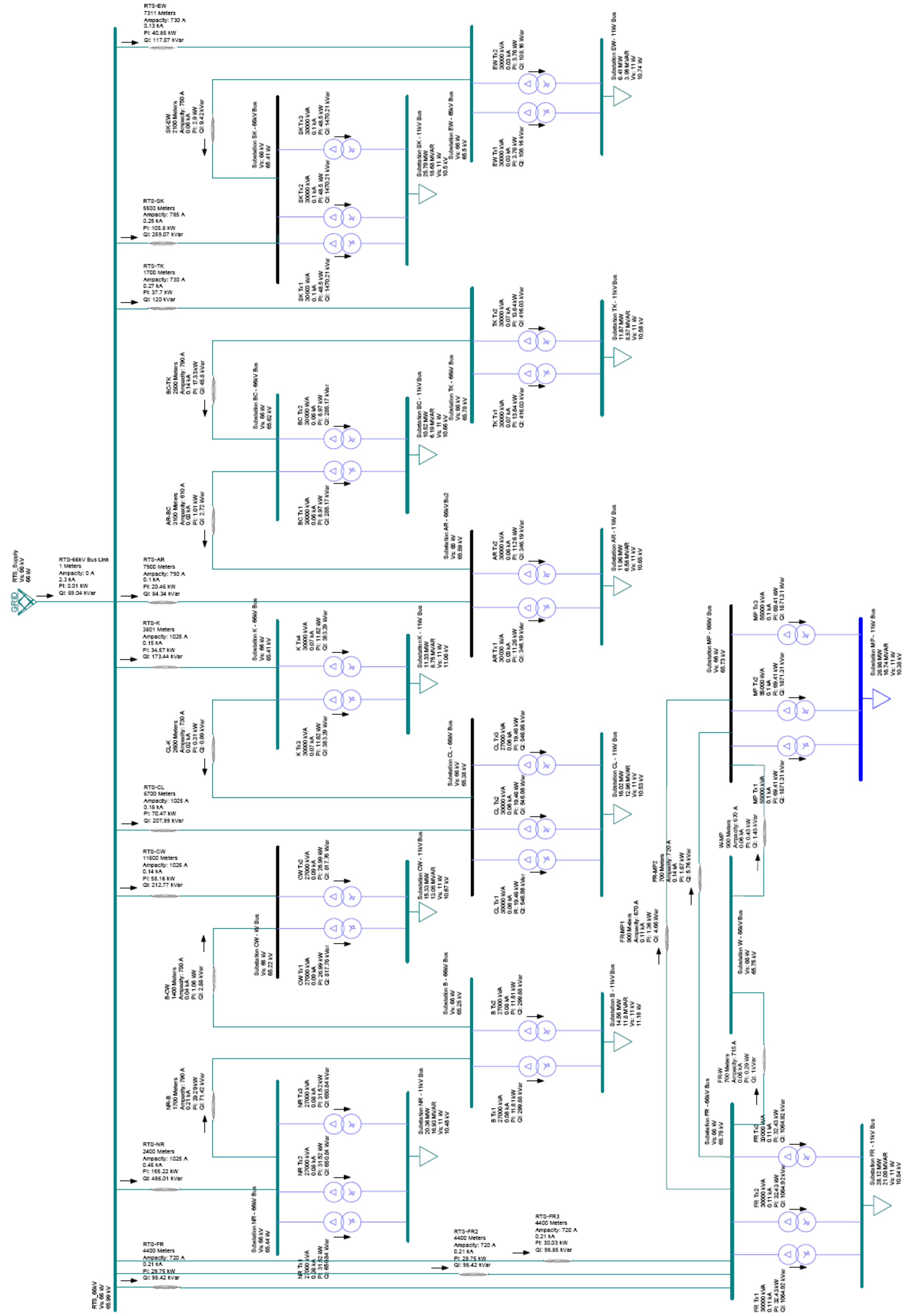
_ Load reduction involving transfer of load via 11kV links to adjacent stations.

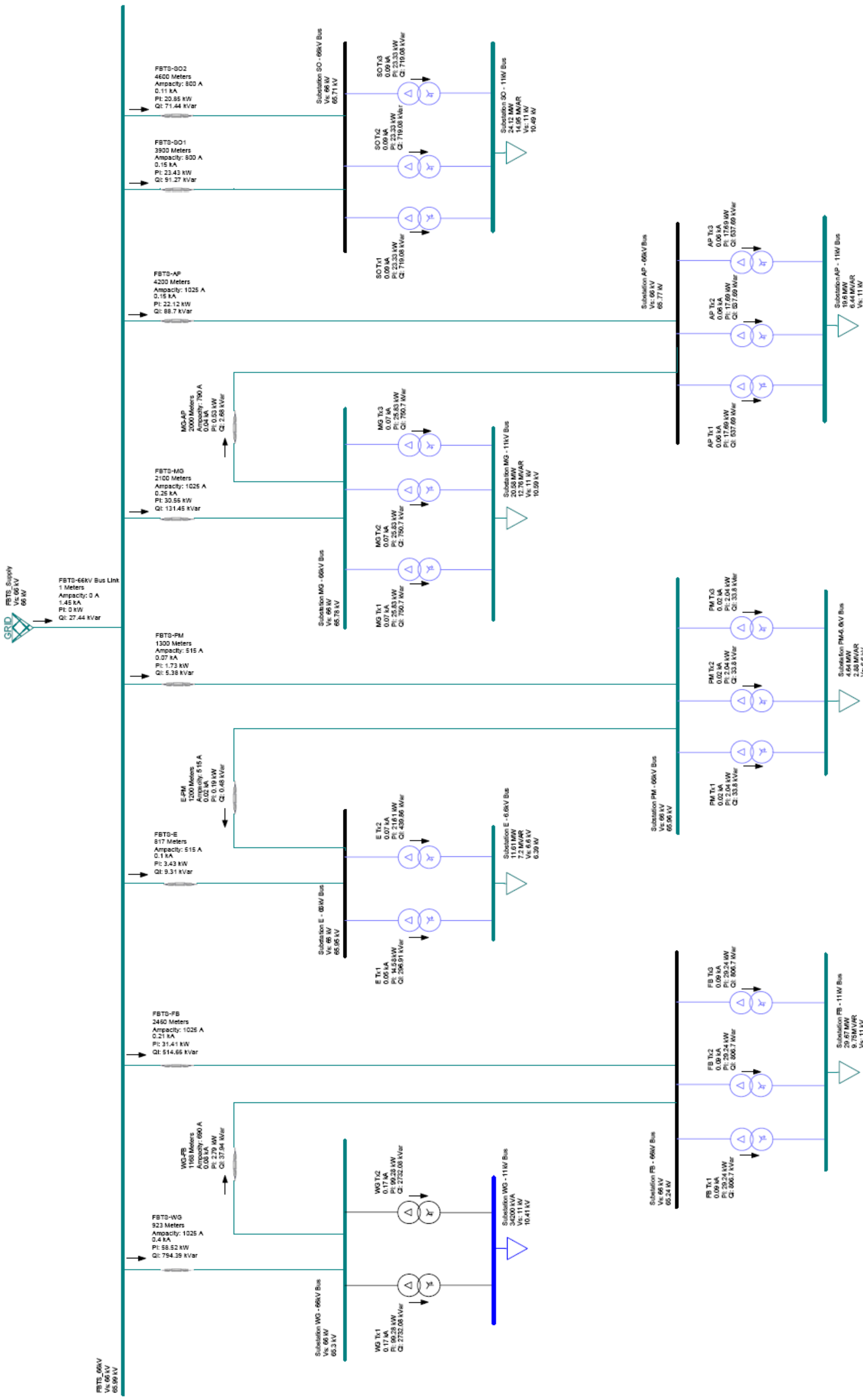
_ Installation of 2 x 12MVAr 11kV capacitor banks by 2008/09 to improve subtransmission line loading under line outage contingency.

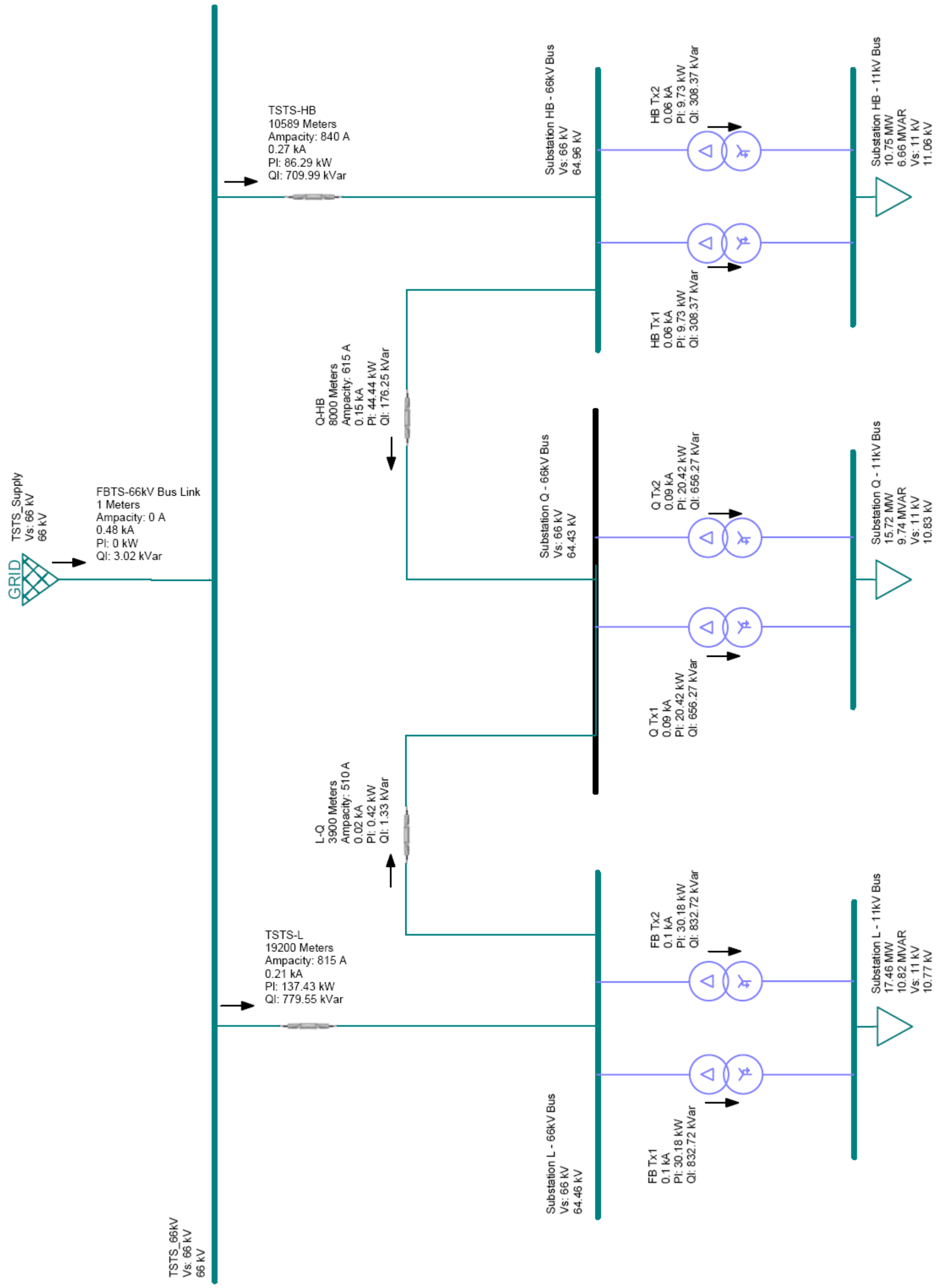
Appendix D

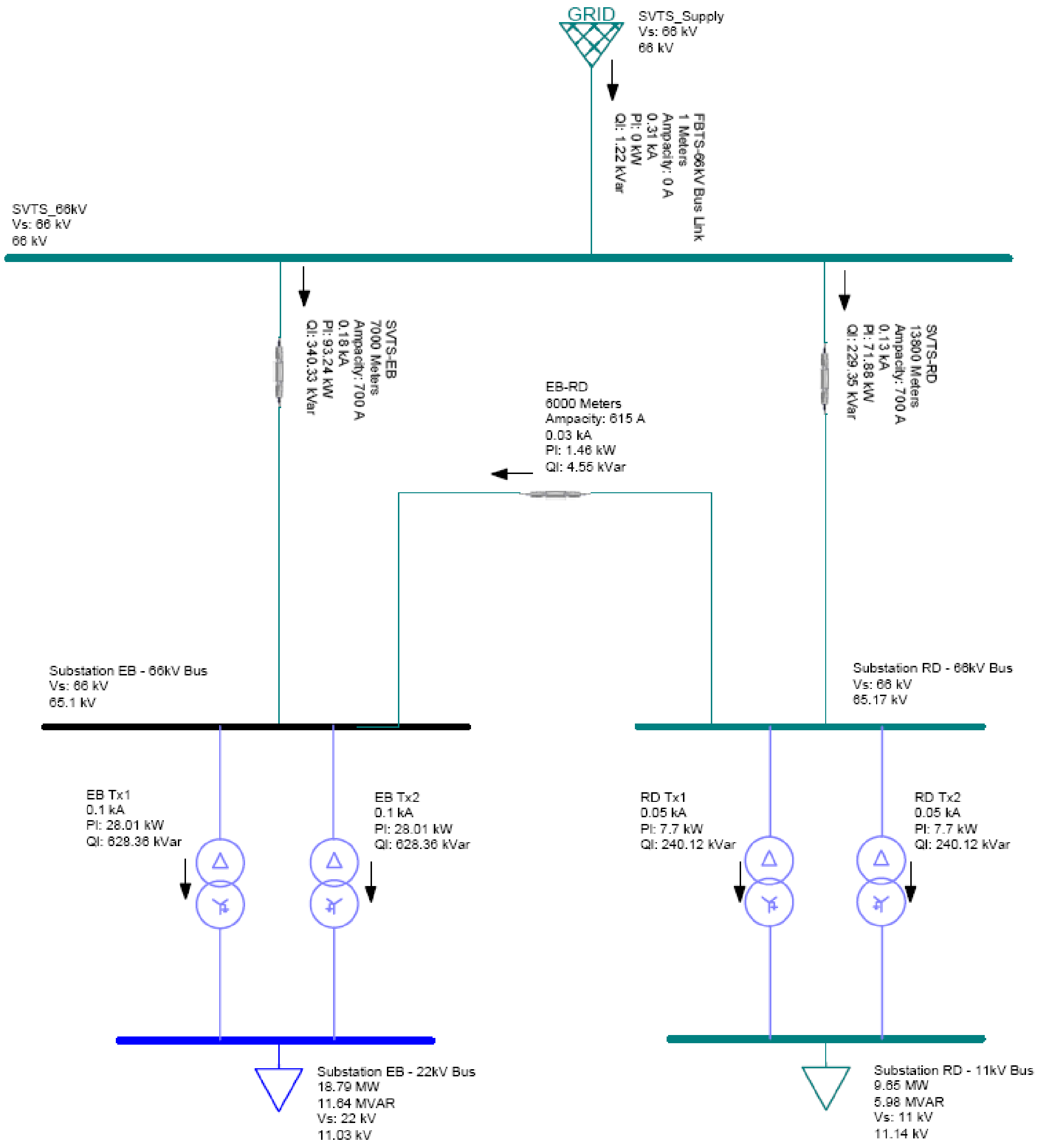

WMTS
WMTS
OSSCA
CONTROLS ON
DISARMED
WMTS - RTS TIE
LINE RATINGS
RTS
OSSCA
CONTROLS ON
DISARMED
TRANS 1
TRANS 2
TRANS 3
TRANS 4
TRANS 82
66.8
67.2
67.5
66.8
67.0
66.9
BUEL
FR
WA
LQ
VM
JA

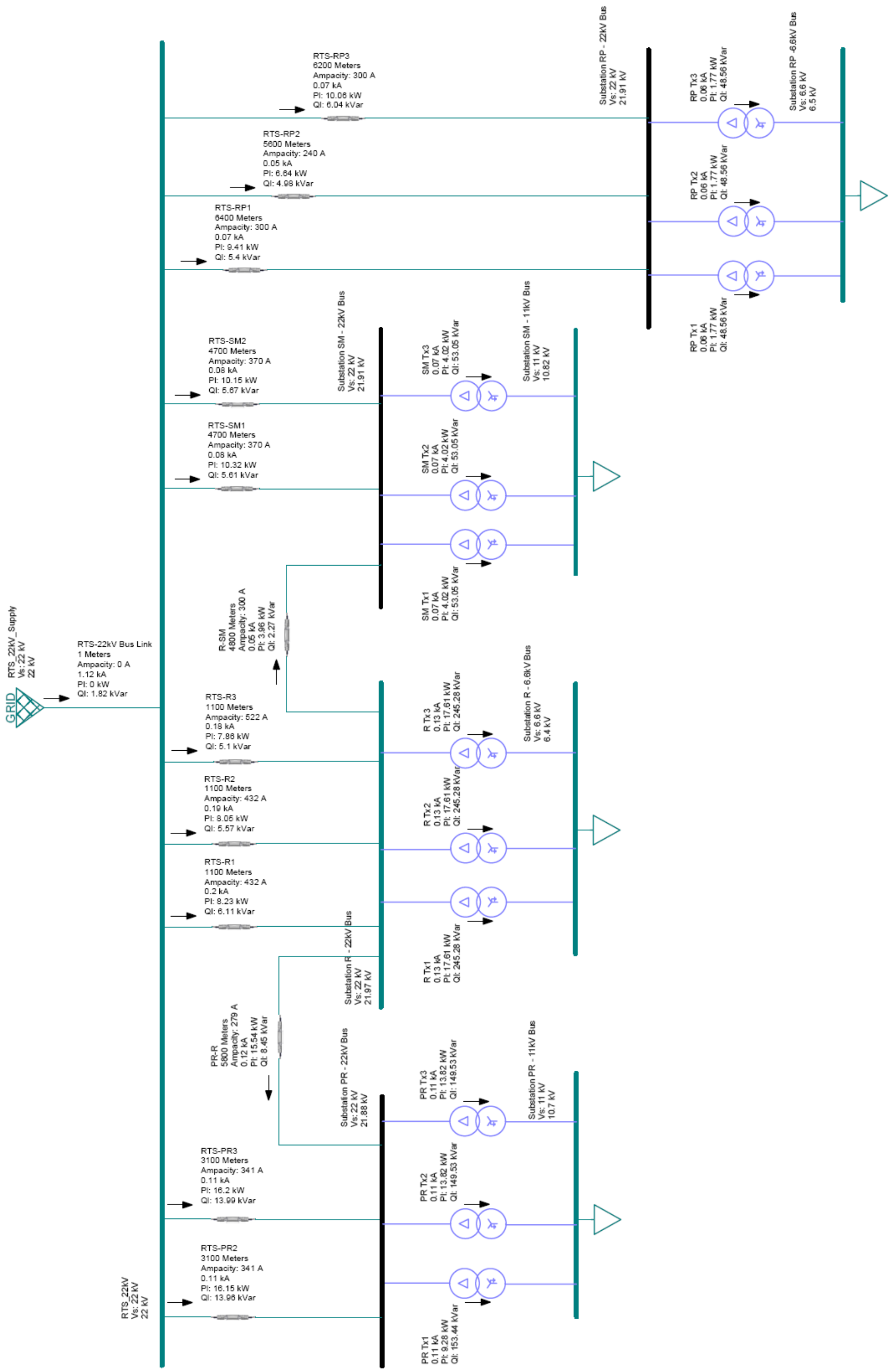
Appendix E

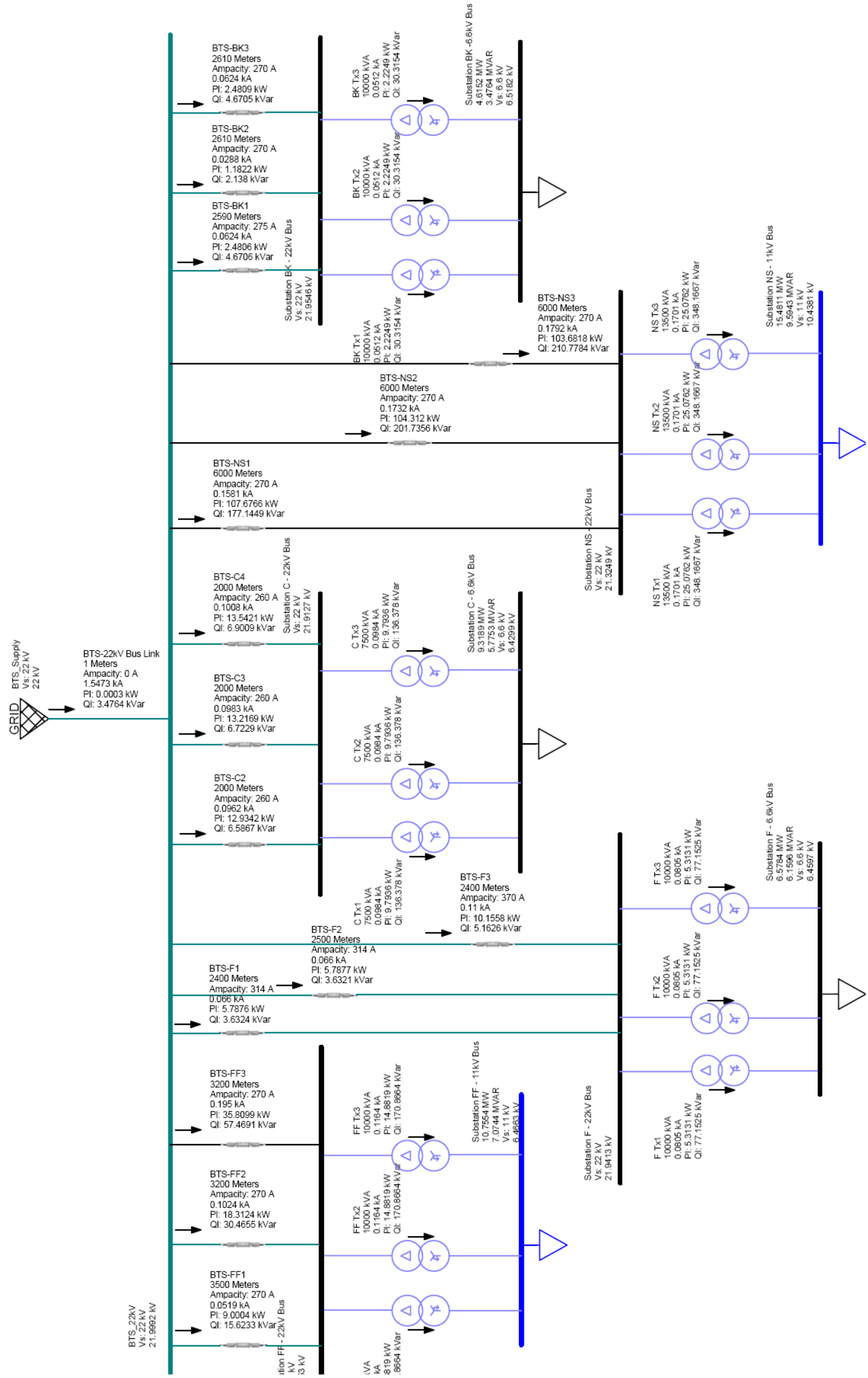




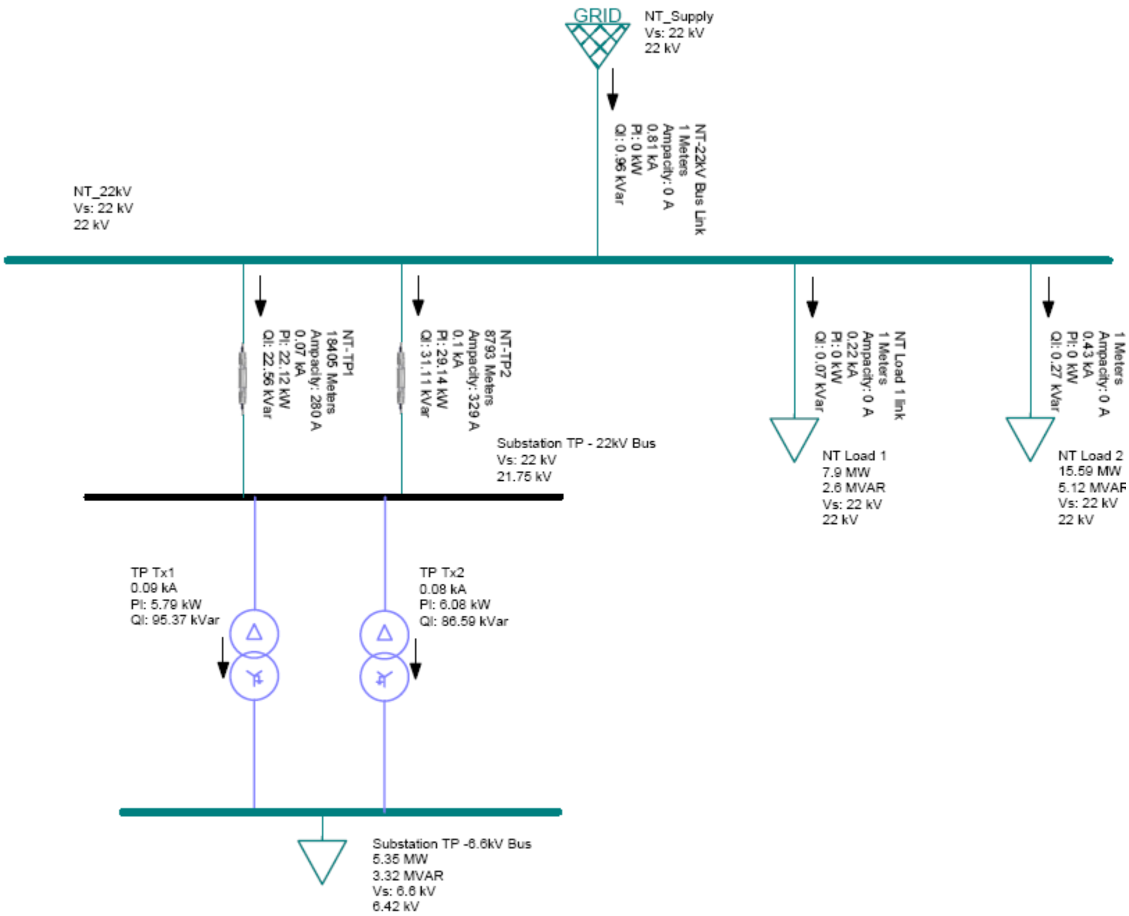

TSTS-HB
10589 Meters
Ampacity: 840 A
0.27 kA
Pl: 86.29 kW
Ql: 709.99 kVar
Substation HB - 66kV Bus
Vs: 66 kV
64.96 kV
HB Tx2
0.06 kA
Pl: 9.73 kW
Ql: 308.37 kVar
HB Tx1
0.06 kA
Pl: 9.73 kW
Ql: 308.37 kVar
Substation HB - 11kV Bus
10.75 MW
6.66 MVAR
Vs: 11 kV
11.06 kV
Q-HB
8000 Meters
Ampacity: 615 A
0.15 kA
Pl: 44.44 kW
Ql: 176.25 kVar
TSTS_Supply
Vs: 66 kV
66 kV
GRID
FBTS-66kV Bus Link
1 Meters
Ampacity: 0 A
0.48 kA
Pl: 0 kW
Ql: 3.02 kVar
Substation Q - 66kV Bus
Vs: 66 kV
64.43 kV
Q Tx2
0.09 kA
Pl: 20.42 kW
Ql: 656.27 kVar
Q Tx1
0.09 kA
Pl: 20.42 kW
Ql: 656.27 kVar
Substation Q - 11kV Bus
15.72 MW
9.74 MVAR
Vs: 11 kV
10.83 kV
L-Q
3900 Meters
Ampacity: 510 A
0.02 kA
Pl: 0.42 kW
Ql: 1.33 kVar
TSTS-L
19200 Meters
Ampacity: 815 A
0.21 kA
Pl: 137.43 kW
Ql: 779.55 kVar
FB Tx2
0.1 kA
Pl: 30.18 kW
Ql: 832.72 kVar
FB Tx1
0.1 kA
Pl: 30.18 kW
Ql: 832.72 kVar
Substation L - 11kV Bus
17.46 MW
10.82 MVAR
Vs: 11 kV
10.77 kV
Substation L - 66kV Bus
Vs: 66 kV
64.46 kV
TSTS_66kV
Vs: 66 kV
66 kV


GRID
SVTS_Supply
Vs: 66 kV
66 kV
FBTS-66kV Bus Link
1 Meters
Ampacity: 0 A
0.31 kA
Pl: 0 kW
Ql: 1.22 kVar
SVTS_66kV
Vs: 66 kV
66 kV
SVTS-EB
7000 Meters
Ampacity: 700 A
0.18 kA
Pl: 93.24 kW
Ql: 340.33 kVar
EB-RD
6000 Meters
Ampacity: 615 A
0.03 kA
Pl: 1.46 kW
Ql: 4.56 kVar
SVTS-RD
13800 Meters
Ampacity: 700 A
0.13 kA
Pl: 71.88 kW
Ql: 229.35 kVar
Substation EB - 66kV Bus
Vs: 66 kV
65.1 kV
Substation RD - 66kV Bus
Vs: 66 kV
65.17 kV
EB Tx1
0.1 kA
Pl: 28.01 kW
Ql: 628.36 kVar
EB Tx2
0.1 kA
Pl: 28.01 kW
Ql: 628.36 kVar
RD Tx1
0.05 kA
Pl: 7.7 kW
Ql: 240.12 kVar
RD Tx2
0.05 kA
Pl: 7.7 kW
Ql: 240.12 kVar
Substation EB - 22kV Bus
18.79 MW
11.64 MVAR
Vs: 22 kV
11.03 kV
Substation RD - 11kV Bus
9.65 MW
5.98 MVAR
Vs: 11 kV
11.14 kV


RTS-RP3
6200 Meters
Ampacity: 300 A
0.07 kA
Pl: 10.06 kW
Ql: 6.04 kVar
RTS-RP2
5600 Meters
Ampacity: 240 A
0.05 kA
Pl: 6.64 kW
Ql: 4.98 kVar
RTS-RP1
6400 Meters
Ampacity: 300 A
0.07 kA
Pl: 9.41 kW
Ql: 5.4 kVar
Substation RP - 22kV Bus
Vs: 22 kV
21.91 kV
Substation RP -6.6kV Bus
Vs: 6.6 kV
6.5 kV
RTS-SM2
4700 Meters
Ampacity: 370 A
0.08 kA
Pl: 10.15 kW
Ql: 5.67 kVar
RTS-SM1
4700 Meters
Ampacity: 370 A
0.08 kA
Pl: 10.32 kW
Ql: 5.61 kVar
Substation SM - 22kV Bus
Vs: 22 kV
21.91 kV
Substation SM - 11kV Bus
Vs: 11 kV
10.82 kV
RTS_22kV_Supply
Vs: 22 kV
22 kV
GRID
RTS-22kV Bus Link
1 Meters
Ampacity: 0 A
1.12 kA
Pl: 0 kW
Ql: 1.82 kVar
RTS-R3
1100 Meters
Ampacity: 522 A
0.18 kA
Pl: 7.86 kW
Ql: 5.1 kVar
RTS-R2
1100 Meters
Ampacity: 432 A
0.19 kA
Pl: 8.05 kW
Ql: 5.57 kVar
RTS-R1
1100 Meters
Ampacity: 432 A
0.2 kA
Pl: 8.23 kW
Ql: 6.11 kVar
Substation R - 22kV Bus
Vs: 22 kV
21.97 kV
Substation R - 6.6kV Bus
Vs: 6.6 kV
6.4 kV
Substation PR - 22kV Bus
Vs: 22 kV
21.88 kV
Substation PR - 11kV Bus
Vs: 11 kV
10.7 kV
RTS-PR3
3100 Meters
Ampacity: 341 A
0.11 kA
Pl: 16.2 kW
Ql: 13.99 kVar
RTS-PR2
3100 Meters
Ampacity: 341 A
0.11 kA
Pl: 16.15 kW
Ql: 13.96 kVar
RTS_22kV
Vs: 22 kV
22 kV



GRID
BTS_Supply
Vs: 22 kV
22 kV
BTS-22kV Bus Link
1 Meters
Ampacity: 0 A
1.5473 kA
Pl: 0.0003 kW
Ql: 3.4764 kVar
BTS-BK3
2610 Meters
Ampacity: 270 A
0.0624 kA
Pl: 2.4809 kW
Ql: 4.6705 kVar
BTS-BK2
2610 Meters
Ampacity: 270 A
0.0288 kA
Pl: 1.1822 kW
Ql: 2.138 kVar
BTS-BK1
2590 Meters
Ampacity: 275 A
0.0624 kA
Pl: 2.4806 kW
Ql: 4.6706 kVar
Substation BK - 22kV Bus
Vs: 22 kV
21.9546 kV
BK Tx3
10000 kVA
0.0512 kA
Pl: 2.2249 kW
Ql: 30.3154 kVar
BK Tx2
10000 kVA
0.0512 kA
Pl: 2.2249 kW
Ql: 30.3154 kVar
BK Tx1
10000 kVA
0.0512 kA
Pl: 2.2249 kW
Ql: 30.3154 kVar
Substation BK - 6.6kV Bus
4.6152 MW
3.4764 MVAR
Vs: 6.6 kV
6.5182 kV
BTS-NS3
6000 Meters
Ampacity: 270 A
0.1792 kA
Pl: 103.6818 kW
Ql: 210.7784 kVar
BTS-NS2
6000 Meters
Ampacity: 270 A
0.1732 kA
Pl: 104.312 kW
Ql: 201.7356 kVar
BTS-NS1
6000 Meters
Ampacity: 270 A
0.1581 kA
Pl: 107.6766 kW
Ql: 177.1449 kVar
Substation NS - 22kV Bus
Vs: 22 kV
21.3249 kV
NS Tx3
13500 kVA
0.1701 kA
Pl: 25.0762 kW
Ql: 348.1667 kVar
NS Tx2
13500 kVA
0.1701 kA
Pl: 25.0762 kW
Ql: 348.1667 kVar
NS Tx1
13500 kVA
0.1701 kA
Pl: 25.0762 kW
Ql: 348.1667 kVar
Substation NS - 11kV Bus
15.4811 MW
9.5943 MVAR
Vs: 11 kV
10.4381 kV
BTS-C4
2000 Meters
Ampacity: 260 A
0.1008 kA
Pl: 13.5421 kW
Ql: 6.9009 kVar
BTS-C3
2000 Meters
Ampacity: 260 A
0.0983 kA
Pl: 13.2169 kW
Ql: 6.7229 kVar
BTS-C2
2000 Meters
Ampacity: 260 A
0.0962 kA
Pl: 12.9342 kW
Ql: 6.5867 kVar
Substation C - 22kV Bus
Vs: 22 kV
21.9127 kV
C Tx3
7500 kVA
0.0984 kA
Pl: 9.7936 kW
Ql: 136.378 kVar
C Tx2
7500 kVA
0.0984 kA
Pl: 9.7936 kW
Ql: 136.378 kVar
C Tx1
7500 kVA
0.0984 kA
Pl: 9.7936 kW
Ql: 136.378 kVar
Substation C - 6.6kV Bus
9.3189 MW
5.7753 MVAR
Vs: 6.6 kV
6.4299 kV
BTS-F3
2400 Meters
Ampacity: 370 A
0.11 kA
Pl: 10.1558 kW
Ql: 5.1626 kVar
BTS-F2
2500 Meters
Ampacity: 314 A
0.066 kA
Pl: 5.7877 kW
Ql: 3.6321 kVar
BTS-F1
2400 Meters
Ampacity: 314 A
0.066 kA
Pl: 5.7876 kW
Ql: 3.6324 kVar
Substation F - 22kV Bus
Vs: 22 kV
21.9413 kV
F Tx3
10000 kVA
0.0805 kA
Pl: 5.3131 kW
Ql: 77.1525 kVar
F Tx2
10000 kVA
0.0805 kA
Pl: 5.3131 kW
Ql: 77.1525 kVar
F Tx1
10000 kVA
0.0805 kA
Pl: 5.3131 kW
Ql: 77.1525 kVar
Substation F - 6.6kV Bus
6.5784 MW
6.1596 MVAR
Vs: 6.6 kV
6.4597 kV
BTS-FF3
3200 Meters
Ampacity: 270 A
0.195 kA
Pl: 35.8099 kW
Ql: 57.4691 kVar
BTS-FF2
3200 Meters
Ampacity: 270 A
0.1024 kA
Pl: 18.3124 kW
Ql: 30.4655 kVar
BTS-FF1
3500 Meters
Ampacity: 270 A
0.0519 kA
Pl: 9.0004 kW
Ql: 15.6233 kVar
FF Tx3
10000 kVA
0.1164 kA
Pl: 14.8819 kW
Ql: 170.8664 kVar
FF Tx2
10000 kVA
0.1164 kA
Pl: 14.8819 kW
Ql: 170.8664 kVar
Substation FF - 11kV Bus
10.7554 MW
7.0744 MVAR
Vs: 11 kV
BTS_22kV
Vs: 22 kV
21.9992 kV


GRID
NT_Supply
Vs: 22 kV
22 kV
NT-22kV Bus Link
1 Meters
Ampacity: 0 A
0.81 kA
Pl: 0 kW
Ql: 0.96 kVar
NT_22kV
Vs: 22 kV
22 kV
NT-TP1
18405 Meters
Ampacity: 280 A
0.07 kA
Pl: 22.12 kW
Ql: 22.56 kVar
NT-TP2
8793 Meters
Ampacity: 329 A
0.1 kA
Pl: 29.14 kW
Ql: 31.11 kVar
NT Load 1 link
1 Meters
Ampacity: 0 A
0.22 kA
Pl: 0 kW
Ql: 0.07 kVar
1 Meters
Ampacity: 0 A
0.43 kA
Pl: 0 kW
Ql: 0.27 kVar
Substation TP - 22kV Bus
Vs: 22 kV
21.75 kV
NT Load 1
7.9 MW
2.6 MVAR
Vs: 22 kV
22 kV
NT Load 2
15.59 MW
5.12 MVAF
Vs: 22 kV
22 kV
TP Tx1
0.09 kA
Pl: 5.79 kW
Ql: 95.37 kVar
TP Tx2
0.08 kA
Pl: 6.08 kW
Ql: 86.59 kVar
Substation TP -6.6kV Bus
5.35 MW
3.32 MVAR
Vs: 6.6 kV
6.42 kV

Appendix F

CABLE DATA SUPPLIED BY OLEX CABLES

Conductor	
Material:	Aluminium
Design:	Miliken
Diameter:	48.2 mm
Conductor screen	
Material	Semi-conductive XLPE
Construction	Extruded
Nominal thickness	1.6 mm

Maximum dielectric stress at the conductor screen (assumed smooth) -4.4 kV/mm

Minimum radial thickness of insulation between Conductor screen and insulation screen. 10.0 mm

Insulation	
Material	XLPE
Type of Extruder	VCV
Type of curing process	Dry
Diameter over insulation	72.4 mm
Max	73.4 mm
Minimum	71.4 mm
Insulation screen	
Material	Semi-conductive XLPE
Thickness	1.0 mm

Electrical data

Rated voltage	66kV
Highest system voltage	72.5 kV
Impulse voltage level	325 kV peak
Maximum conductor dc-resistance at 20 ºC	0.0186 mΩ/m
Nominal operating capacitance	0.39 µF/km
Maximum permissible short circuit for 0.5 second	
Phase conductor (from 90 ºC up to 250 ºC)	215 kA
Metallic screen (from 80 ºC up to 250 200 ºC) (adiabatic)	23.1 kA
Metallic screen (from 80 ºC up to 250 200 ºC) (non-adiabatic)	25.0 kA
Zero sequence impedance at 90 deg C R0 + jX0 Ohms/km	0.457 + j0.046
Positive sequence impedance at 90 deg C R1 + jX1 Ohms/km	0.0245 + j0.197
Capacitance Pico Farads / m	390
Continuous current rating Summer at 20 deg C, soil thermal	

receptivity 1.2 k-m/W, single point bonded, 1m deep Cables @300mm centre direct buried Cables @300mm centre in 125mm diameter, (Heavy Duty) HD, UPVC conduit of AS 2053	 1260 A 1150 A
Continuous current rating Winter at 10 deg C, soil thermal receptivity 1.2 k-m/W, single point bonded, 1m deep Cables @300mm centre direct buried Cables @300mm centre in 125mm diameter, (Heavy Duty) HD, UPVC conduit of AS 2053	 1350 A 1230 A

The following are the standard 66kV XLPE insulated cables that have been used in the sub transmission system:

CABLE TYPE 66Kv XLPE	CABLE CONSTRUCTION
OLEX 1000 sq mm Cu 1/c	**LEAD SHEATH/COPPER WIRE SCREEN/HDPE OUTERSHEATH**
OLEX 1200 sq MM Al 1/c	**LEAD SHEATH/COPPER WIRE SCREEN/HDPE OUTERSHEATH**
OLEX 1200 sq MM Al 1/c	**LEAD SHEATH/HDPE OUTERSHEATH**
BICC 1200 sq mm Al 1/c	**LEAD SHEATH/HDPE OUTERSHEATH**
PIRELLI 16sq mm Al 1/c	**COPPER WIRE SCREEN/ALUMINIUM LAMINATED POLYETHELENE SHEATH**
OLEX 1600 sq mm Al 1/c	**LEAD SHEATH/PVC/HDPE OUTERSHEATH**

For all new installations 1600mm² Al 1/core cable is used.

CABLE DESCRIPTION

38/66(72.5) kV, 1/core, 1600mm² Aluminium Miliken construction conductor, Semi conductive XLPE conductor screen, XLPE insulated using the CDCC-Process (Completely Dry Curing and Cooling Process), Semi conductive XLPE insulation screen, semi conductive water blocking tape, Lead sheath with or without plain annealed copper wire screen (Equivalent Copper Area of 105mm²) rated for 22.0kA for 0.5 second phase to earth fault level, Termite protected, Graphite coated, Black polyethylene Outer Sheath, Cable confirming to AS/NZS 1429.2

Appendix G

12.7/22kV Three Core Ind. Screened & PVC Sheathed

Aluminium Conductors, 10kA Fault Level

Nominal conductor area	Nominal conductor diameter	Average insulation thickness	Nominal diameter over insulation	Nominal screen area on each core	Number and nominal diameter of screen wires	Nominal diameter over wire screen	Nominal overall diameter	Approximate mass	Product code
mm²	mm	mm	mm	mm²	no/mm	mm	mm	kg/100m	
35	6.9	5.5	19.2	7.9	14/0.85	22.5	54.6	225	XLHA18AA003
50	8.1	5.5	20.3	10.8	19/0.85	23.6	57.3	255	XLHA19AA003
70	9.6	5.5	21.9	15.3	27/0.85	25.2	60.9	310	XLHA20AA003
95	11.4	5.5	23.6	20.4	36/0.85	26.9	64.8	370	XLHA22AA003
120	12.8	5.5	25.0	22.7	40/0.85	28.3	68.0	415	XLHA23AA003
150	14.2	5.5	26.4	22.7	40/0.85	29.7	71.3	460	XLHA24AA003
185	15.7	5.5	27.9	22.7	40/0.85	31.2	74.7	505	XLHA25AA003
240	18.0	5.5	30.3	22.7	40/0.85	33.6	80.1	585	XLHA26AA003
300	20.1	5.5	32.6	22.7	40/0.85	36.1	85.9	685	XLHA27AA003
400	23.0	5.5	35.4	22.7	40/0.85	38.9	92.5	800	XLHA28AA003
500	26.5	5.5	39.0	22.7	40/0.85	42.5	100.5	960	XLHA30AA003

Current Ratings

Nominal conductor area	Continuous current-carrying capacity, A In air			In ground		Fault current carrying capacity for 1 second	
		D/2, D				Conductor	Screen
mm²						kA	kA
35	130	140	97	135	110	3.31	3.53
50	155	165	120	160	130	4.73	4.80
70	190	205	145	195	160	6.62	6.82
95	235	250	175	230	190	8.99	9.09
120	270	290	200	265	215	11.4	10.1
150	305	325	230	295	250	14.2	10.1
185	345	375	265	335	280	17.5	10.1
240	410	440	305	390	325	22.7	10.1
300	465	505	350	440	370	28.4	10.1
400	545	590	405	500	425	37.8	10.1
500	630	685	480	570	495	47.3	10.1

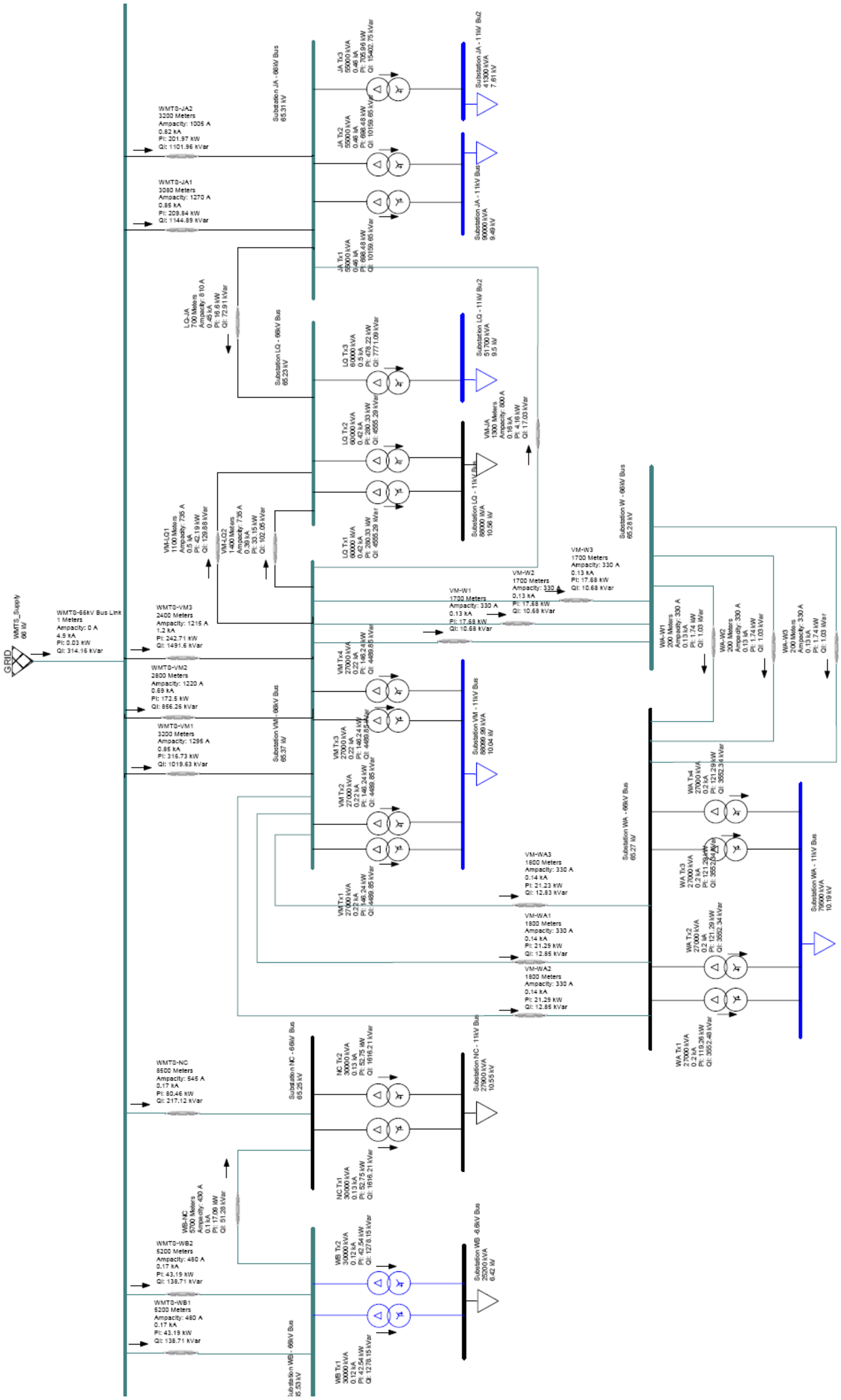
Installation

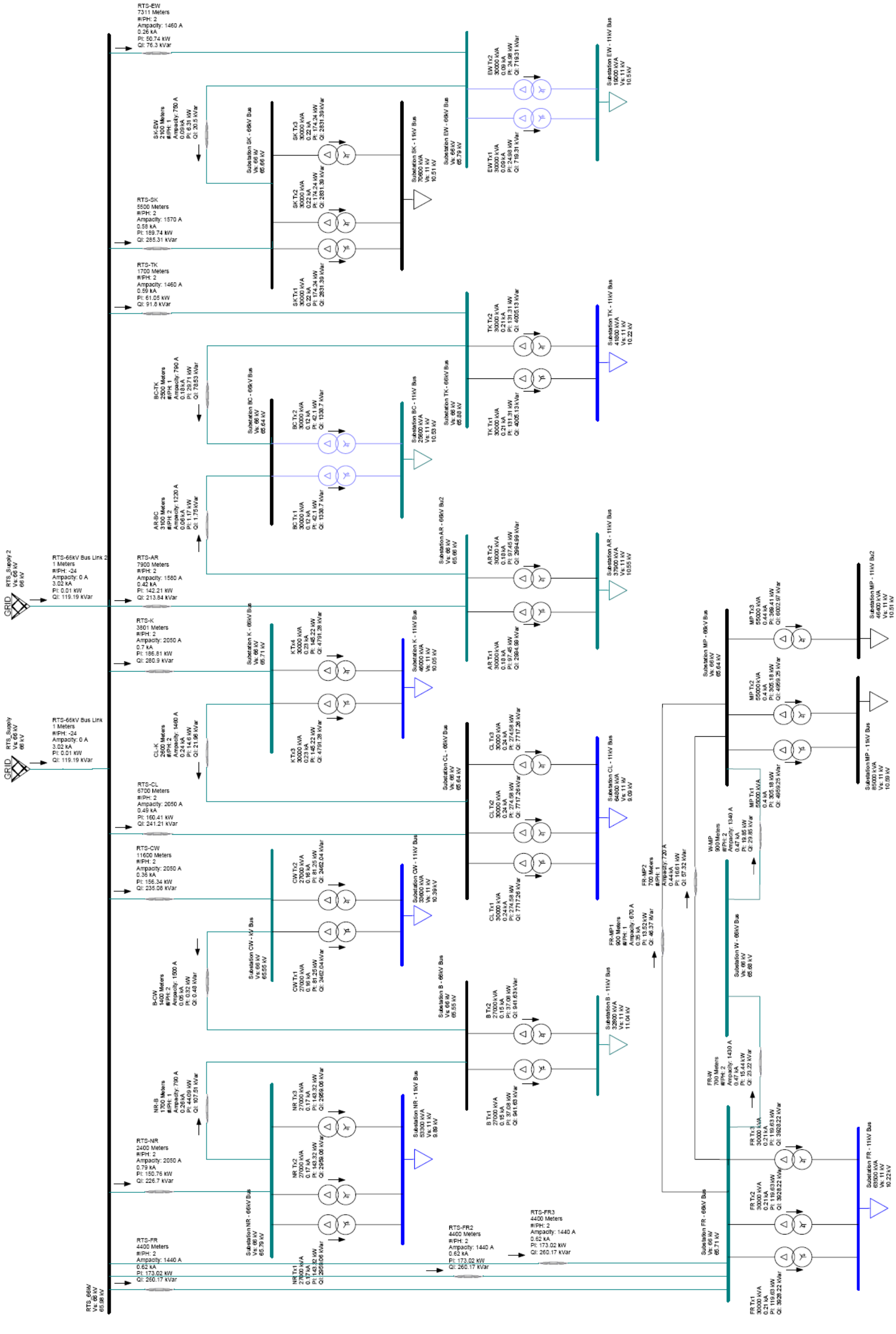
Maximum pulling tension	Minimum bending radius		Nominal duct dia
	During pulling	Set in position	
kN	mm	mm	mm
5.3	980	660	80
7.5	1030	690	100
11	1100	730	100
14	1170	780	100
18	1220	820	100
23	1280	860	150
28	1340	900	150
36	1440	960	150
45	1550	1030	150
60	1660	1110	150
75	1810	1210	200

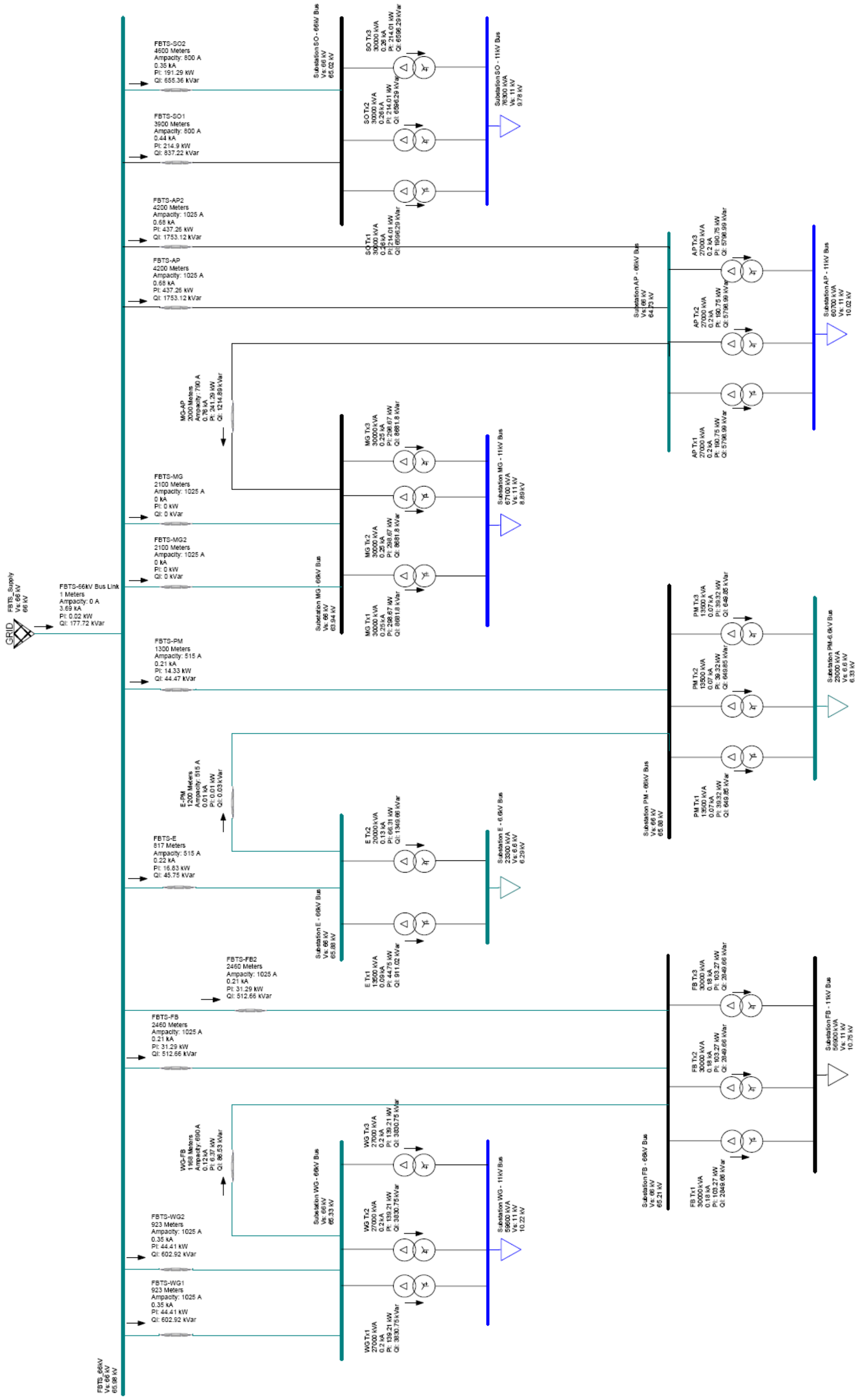
Electrical Characteristics

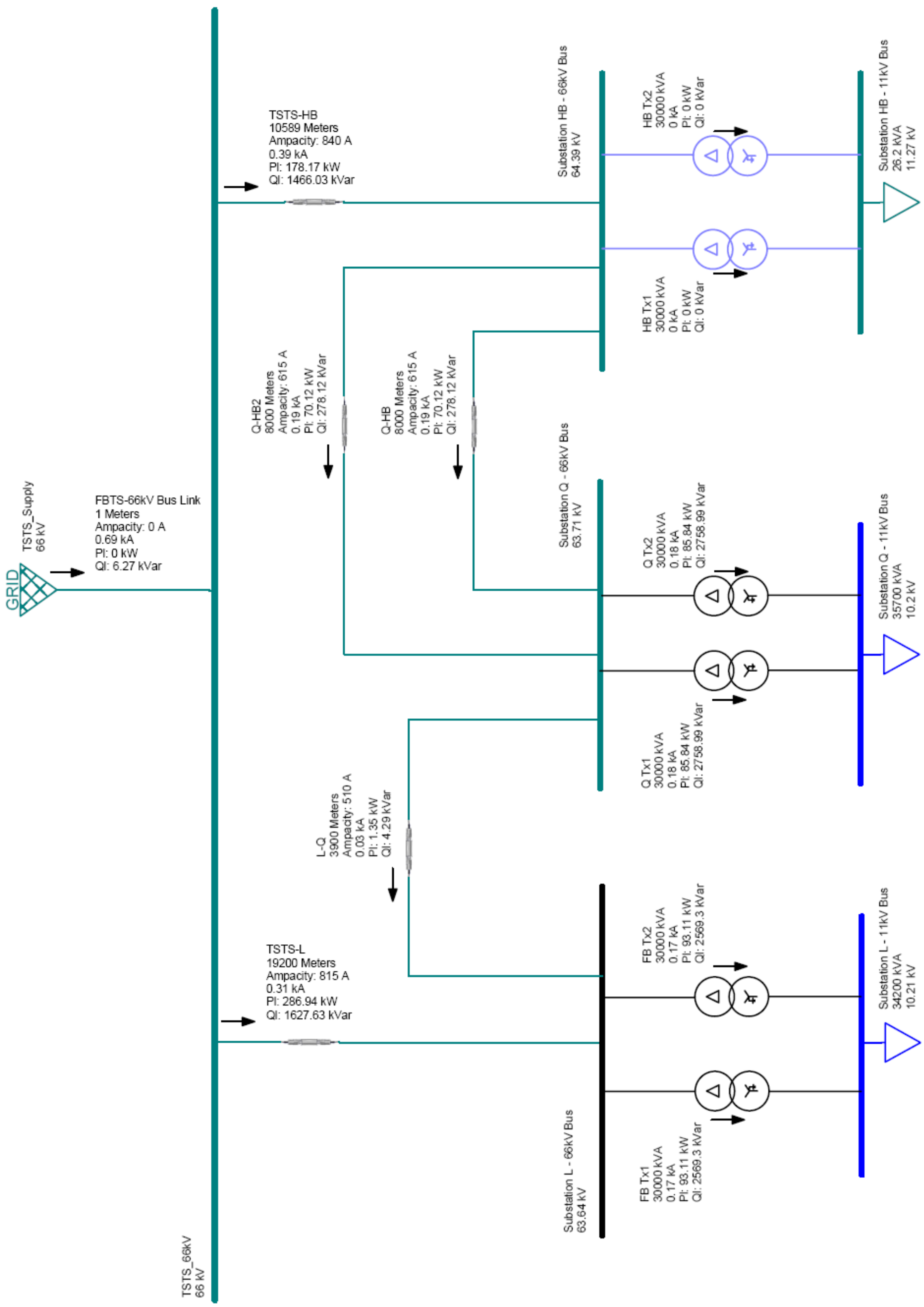
Nominal conductor area	Conductor DC resistance at 20°C	Conductor AC resistance at 50Hz and 90°C	Inductive reactance at 50Hz	Insulation resistance at 20°C	Conductor to screen capacitance	Charging current per phase	Dielectric loss per phase	Maximum dielectric stress	DC resistance of screens at 20°C	Zero sequence resistance at 20°C	Zero seq. react. at 50Hz
mm²	Ohm/km	Ohm/km	Ohm/km	MegOhm.km	μF/km	A/km	W/km	kV/mm	Ohm/km	Ohm/km	Ohm/km
35	0.868	1.11	0.134	15000	0.157	0.626	31.8	3.62	0.759	3.15	0.0919
50	0.641	0.821	0.128	14000	0.172	0.685	34.8	3.47	0.559	2.32	0.0855
70	0.443	0.568	0.118	13000	0.192	0.768	39.0	3.30	0.394	1.62	0.0756
95	0.320	0.410	0.112	11000	0.214	0.855	43.4	3.17	0.303	1.23	0.0696
120	0.253	0.325	0.108	10000	0.232	0.926	47.0	3.08	0.272	1.07	0.0656
150	0.206	0.265	0.105	9700	0.250	0.997	50.7	3.01	0.272	1.02	0.0622
185	0.164	0.211	0.102	9000	0.269	1.07	54.5	2.95	0.272	0.982	0.0582
240	0.125	0.161	0.0983	8100	0.298	1.19	60.4	2.87	0.272	0.941	0.0542
300	0.100	0.130	0.0958	7400	0.327	1.30	66.3	2.81	0.272	0.918	0.0519
400	0.0778	0.102	0.0917	6700	0.363	1.45	73.5	2.75	0.272	0.894	0.0480
500	0.0617	0.0819	0.0885	5900	0.407	1.62	82.4	2.69	0.272	0.879	0.0446

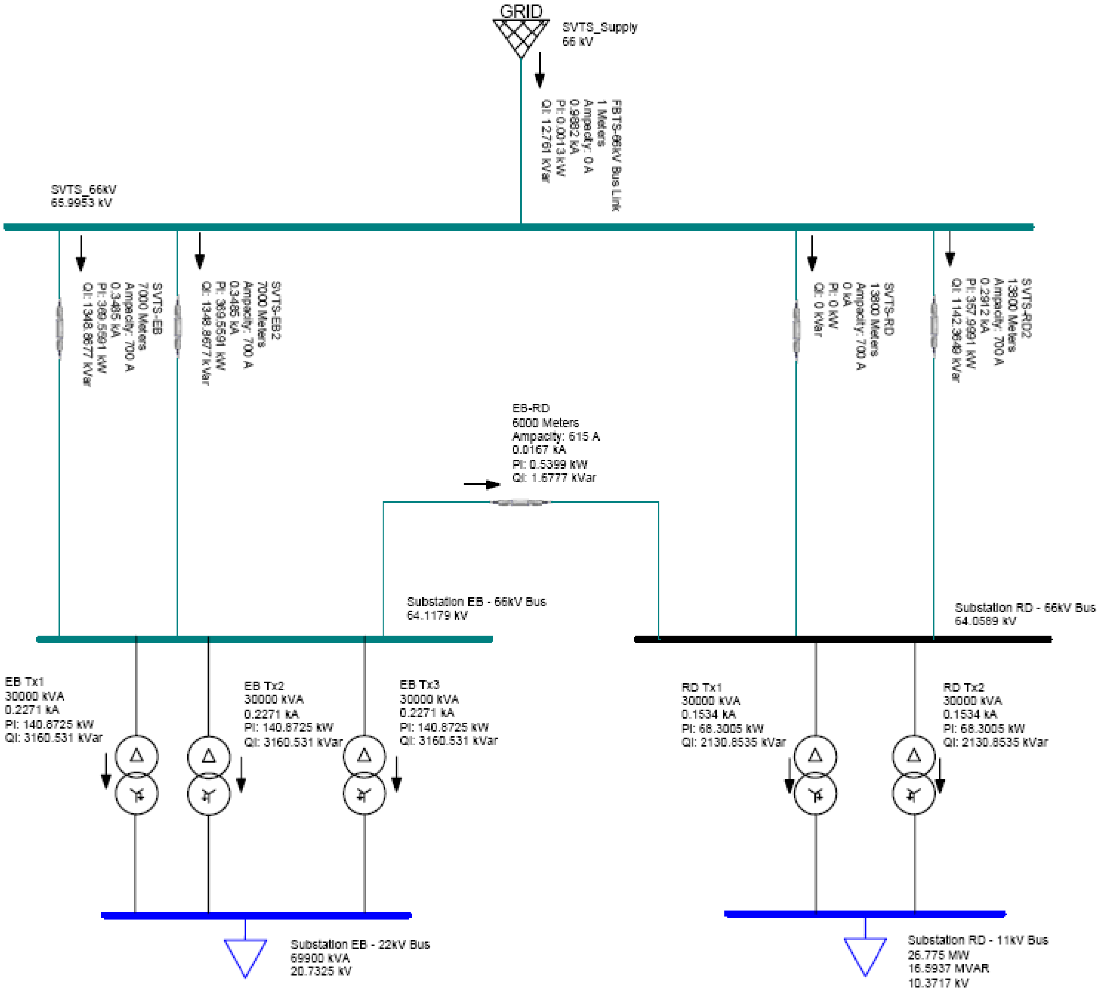
Appendix H



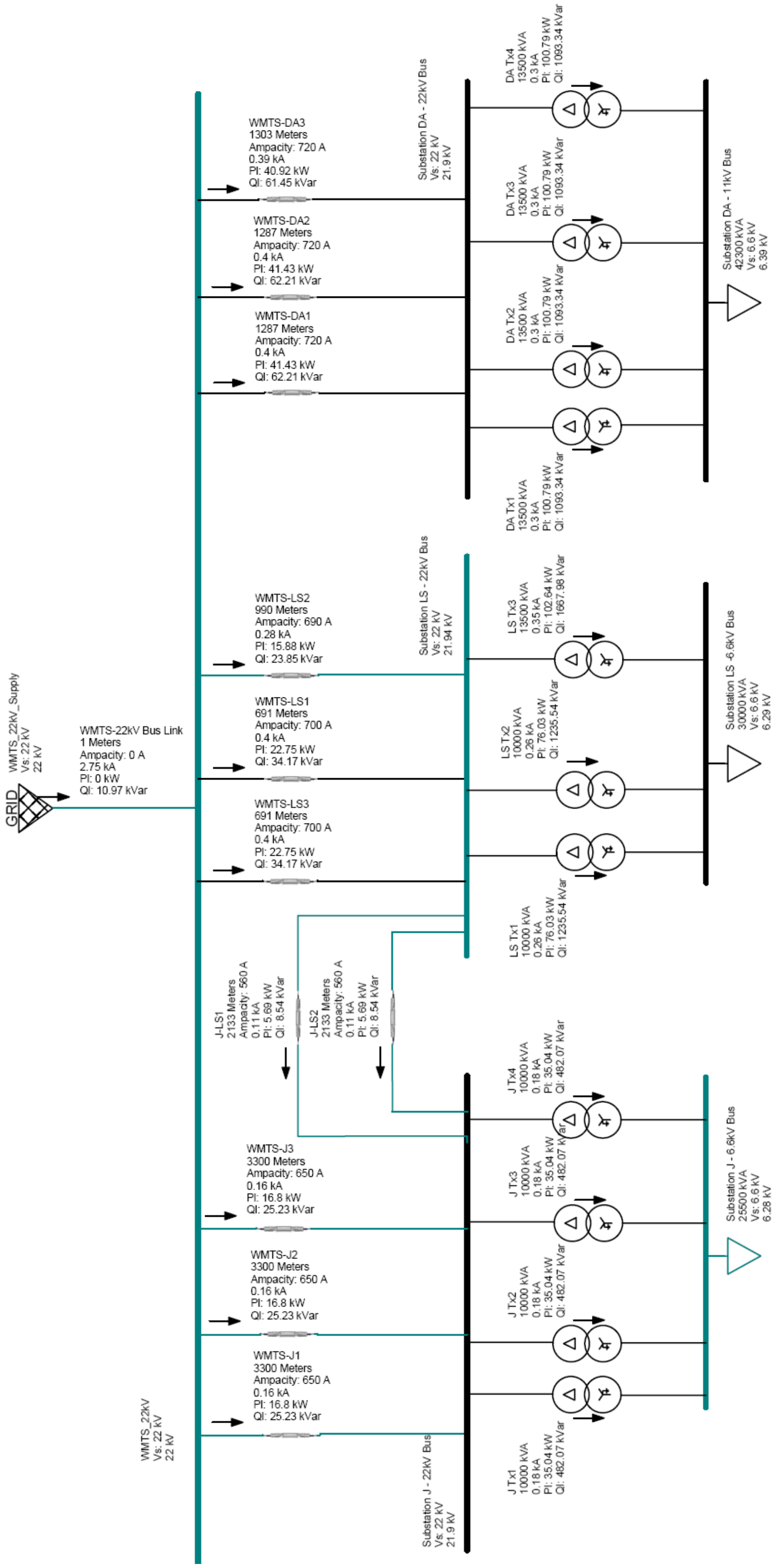


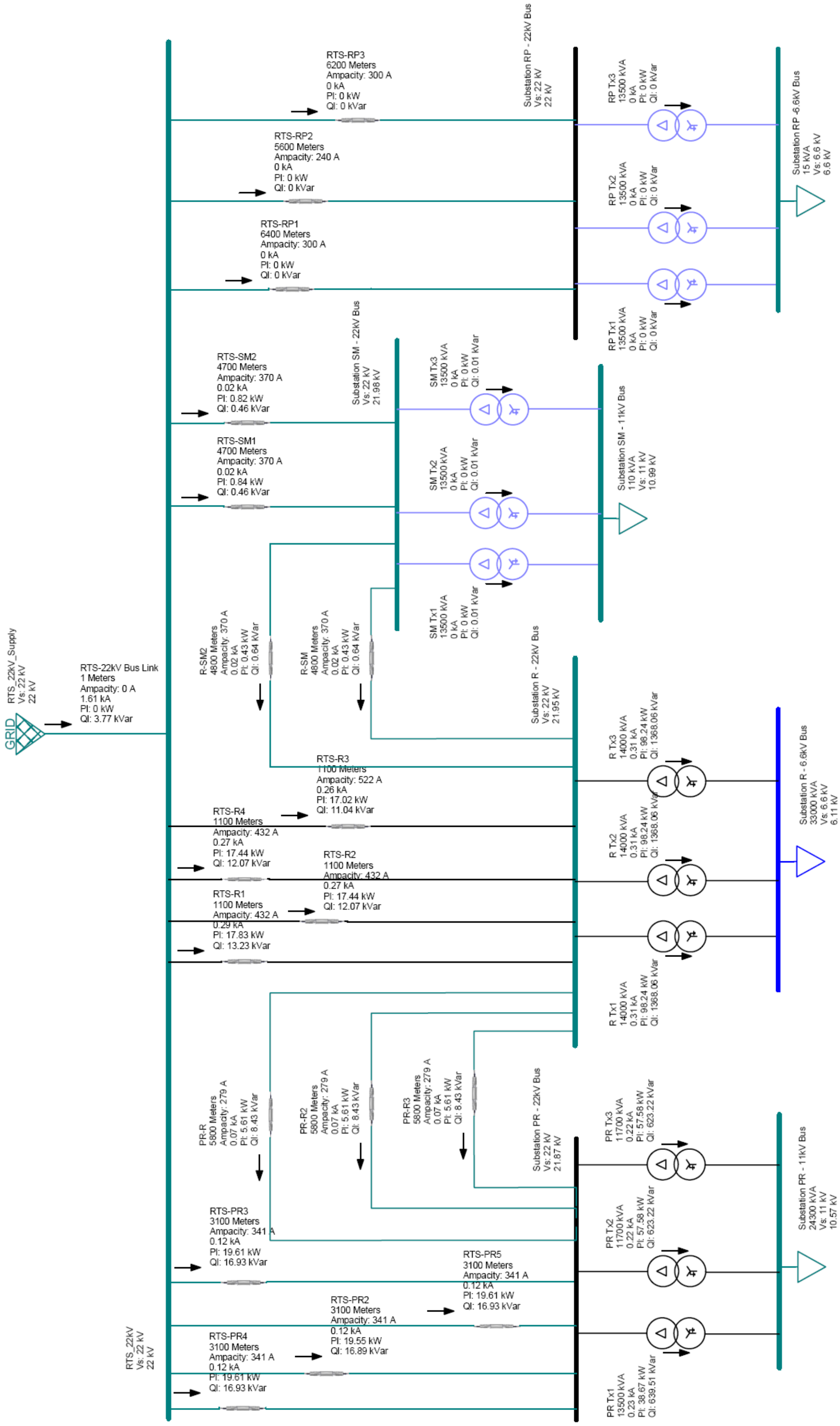


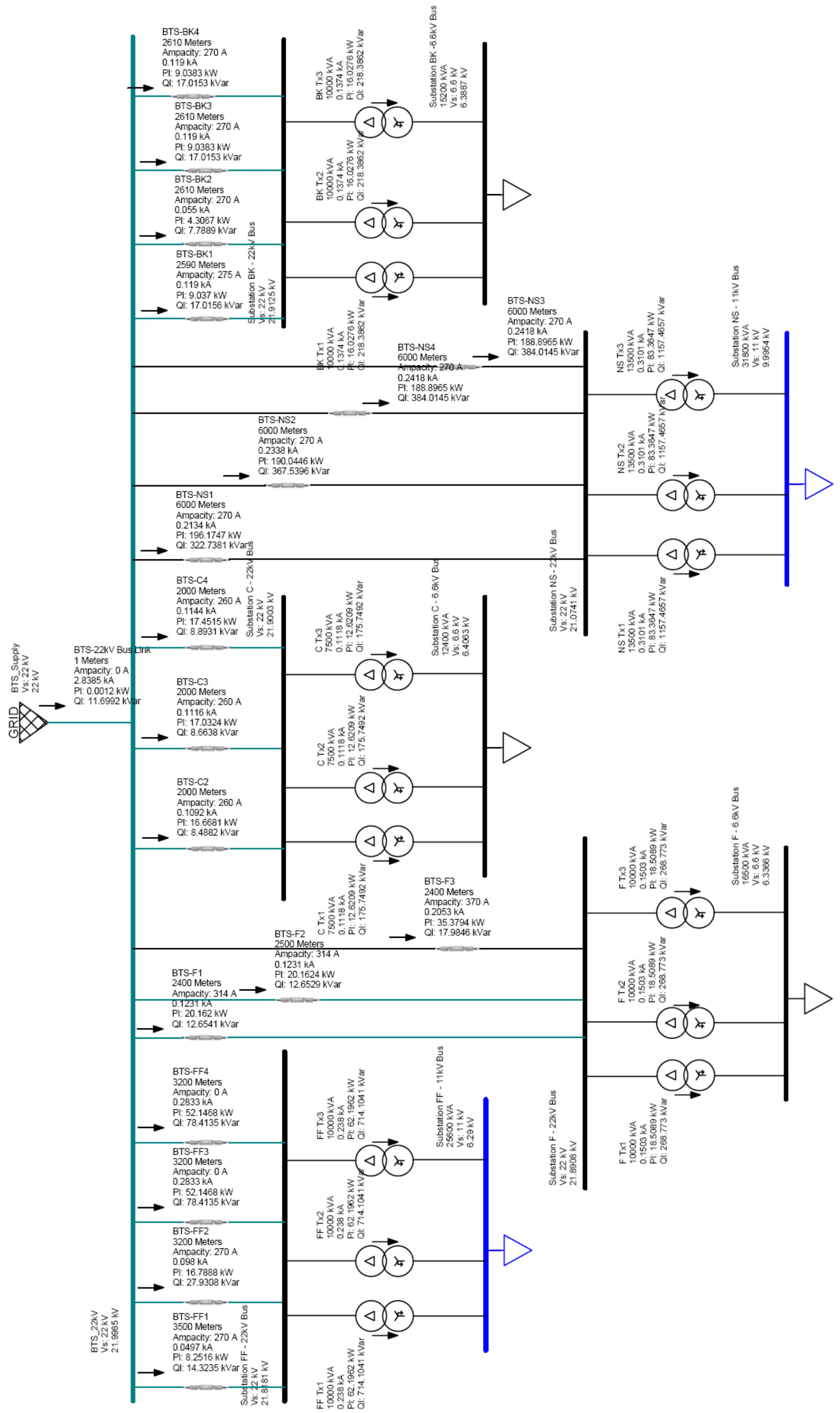

TSTS_Supply
66 kV
GRID
FBTS-66kV Bus Link
1 Meters
Ampacity: 0 A
0.69 kA
Pl: 0 kW
Ql: 6.27 kVar
TSTS_66kV
66 kV
TSTS-HB
10589 Meters
Ampacity: 840 A
0.39 kA
Pl: 178.17 kW
Ql: 1466.03 kVar
Q-HB2
8000 Meters
Ampacity: 615 A
0.19 kA
Pl: 70.12 kW
Ql: 278.12 kVar
Q-HB
8000 Meters
Ampacity: 615 A
0.19 kA
Pl: 70.12 kW
Ql: 278.12 kVar
L-Q
3900 Meters
Ampacity: 510 A
0.03 kA
Pl: 1.35 kW
Ql: 4.29 kVar
TSTS-L
19200 Meters
Ampacity: 815 A
0.31 kA
Pl: 286.94 kW
Ql: 1627.63 kVar
Substation HB - 66kV Bus
64.39 kV
Substation Q - 66kV Bus
63.71 kV
Substation L - 66kV Bus
63.64 kV
HB Tx2
30000 kVA
0 kA
Pl: 0 kW
Ql: 0 kVar
HB Tx1
30000 kVA
0 kA
Pl: 0 kW
Ql: 0 kVar
Q Tx2
30000 kVA
0.18 kA
Pl: 85.84 kW
Ql: 2758.99 kVar
Q Tx1
30000 kVA
0.18 kA
Pl: 85.84 kW
Ql: 2758.99 kVar
FB Tx2
30000 kVA
0.17 kA
Pl: 93.11 kW
Ql: 2569.3 kVar
FB Tx1
30000 kVA
0.17 kA
Pl: 93.11 kW
Ql: 2569.3 kVar
Substation HB - 11kV Bus
26.2 kVA
11.27 kV
Substation Q - 11kV Bus
35700 kVA
10.2 kV
Substation L - 11kV Bus
34200 kVA
10.21 kV

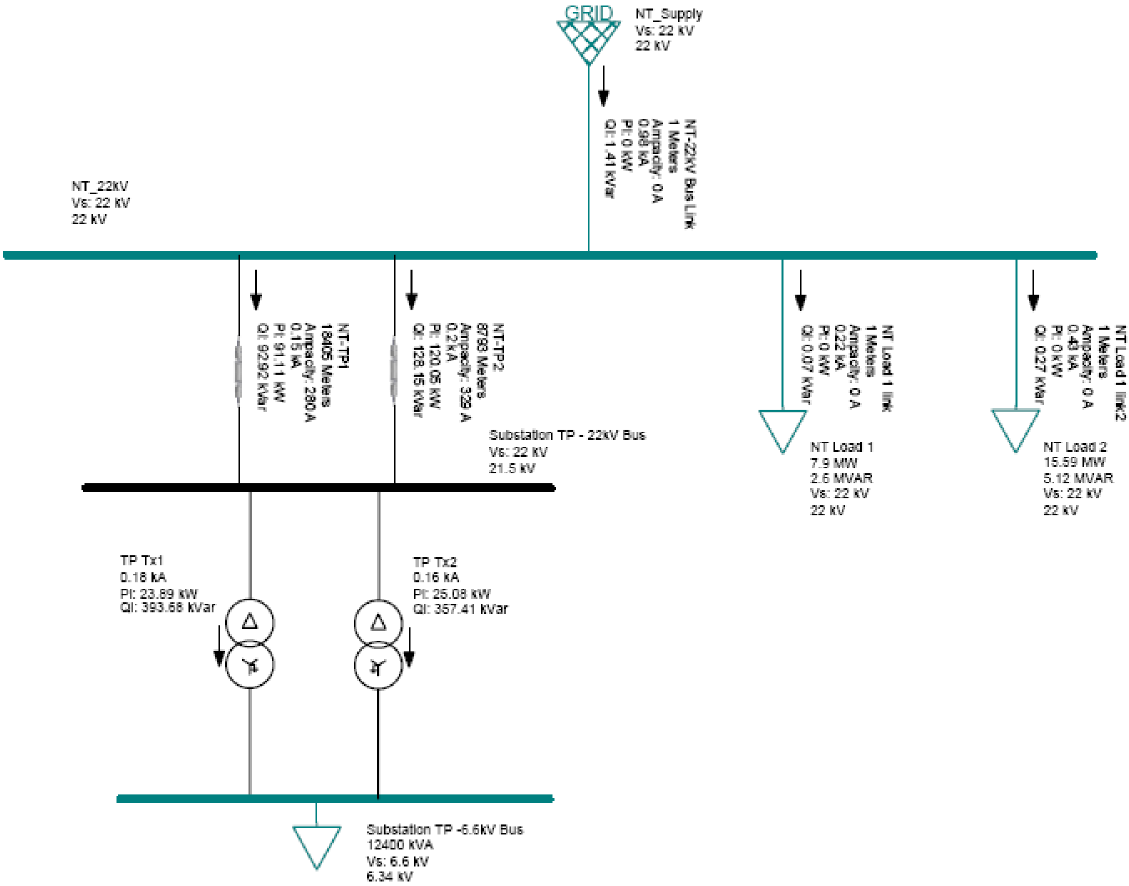


GRID
SVTS_Supply
66 kV
FBTS-66kV Bus Link
1 Meters
Ampacity: 0 A
0.9882 kA
Pl: 0.0013 kW
Ql: 12761 kVar
SVTS_66kV
65.9953 kV
SVTS-EB
7000 Meters
Ampacity: 700 A
0.3485 kA
Pl: 369.5591 kW
Ql: 1348.8677 kVar
SVTS-EB2
7000 Meters
Ampacity: 700 A
0.3485 kA
Pl: 369.5591 kW
Ql: 1348.8677 kVar
SVTS-RD
13800 Meters
Ampacity: 700 A
0 kA
Pl: 0 kW
Ql: 0 kVar
SVTS-RD2
13800 Meters
Ampacity: 700 A
0.2912 kA
Pl: 357.9991 kW
Ql: 1142.3649 kVar
EB-RD
6000 Meters
Ampacity: 615 A
0.0167 kA
Pl: 0.5399 kW
Ql: 1.6777 kVar
Substation EB - 66kV Bus
64.1179 kV
Substation RD - 66kV Bus
64.0569 kV
EB Tx1
30000 kVA
0.2271 kA
Pl: 140.8725 kW
Ql: 3160.531 kVar
EB Tx2
30000 kVA
0.2271 kA
Pl: 140.8725 kW
Ql: 3160.531 kVar
EB Tx3
30000 kVA
0.2271 kA
Pl: 140.8725 kW
Ql: 3160.531 kVar
RD Tx1
30000 kVA
0.1534 kA
Pl: 68.3005 kW
Ql: 2130.8535 kVar
RD Tx2
30000 kVA
0.1534 kA
Pl: 68.3005 kW
Ql: 2130.8535 kVar
Substation EB - 22kV Bus
69900 kVA
20.7325 kV
Substation RD - 11kV Bus
26.775 MW
16.5937 MVAR
10.3717 kV

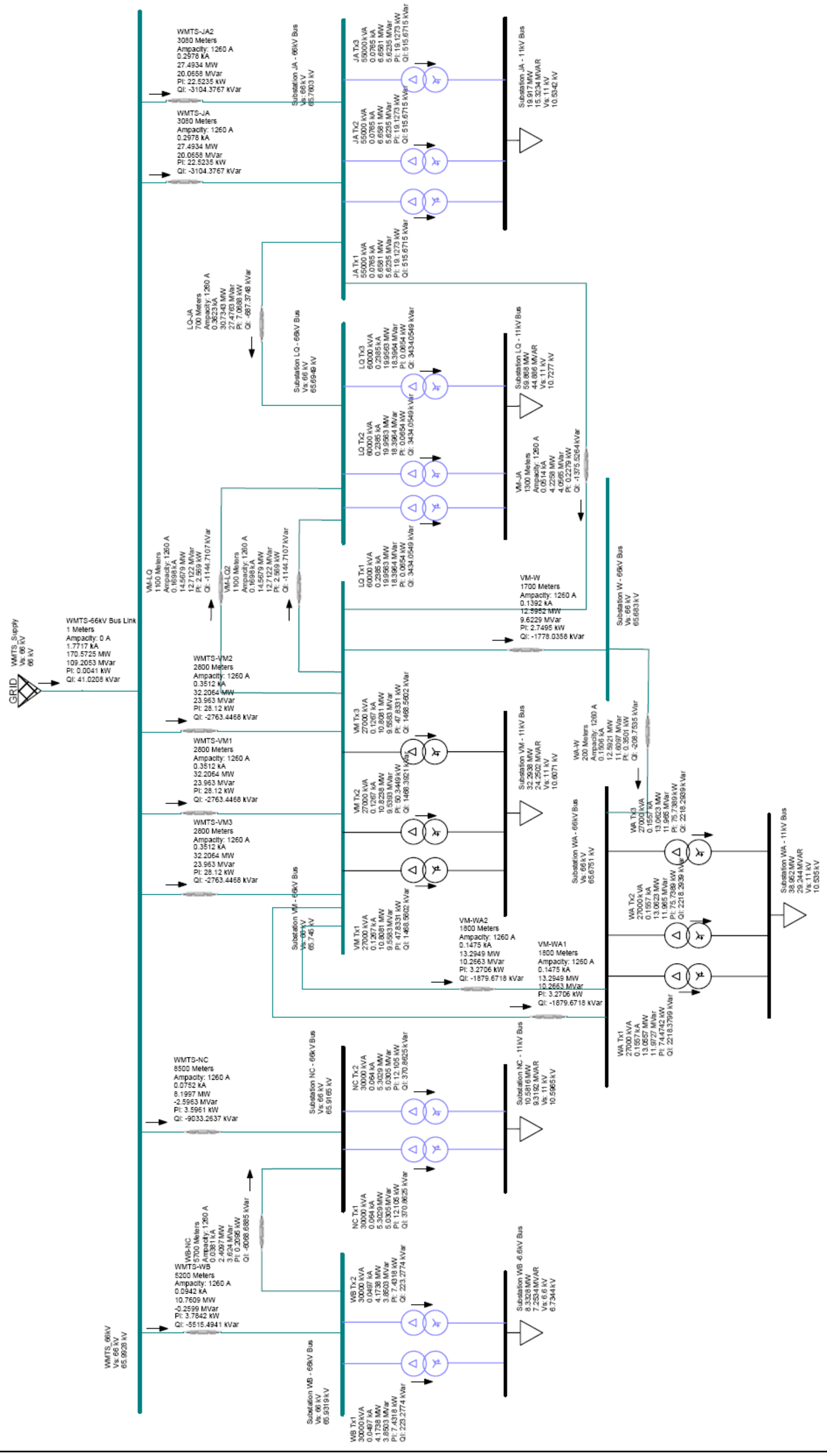

WMTS-DA3
1303 Meters
Ampacity: 720 A
0.39 kA
Pl: 40.92 kW
Ql: 61.45 kVar
WMTS-DA2
1287 Meters
Ampacity: 720 A
0.4 kA
Pl: 41.43 kW
Ql: 62.21 kVar
WMTS-DA1
1287 Meters
Ampacity: 720 A
0.4 kA
Pl: 41.43 kW
Ql: 62.21 kVar
Substation DA - 22kV Bus
Vs: 22 kV
21.9 kV
DA Tx4
13500 kVA
0.3 kA
Pl: 100.79 kW
Ql: 1093.34 kVar
DA Tx3
13500 kVA
0.3 kA
Pl: 100.79 kW
Ql: 1093.34 kVar
DA Tx2
13500 kVA
0.3 kA
Pl: 100.79 kW
Ql: 1093.34 kVar
DA Tx1
13500 kVA
0.3 kA
Pl: 100.79 kW
Ql: 1093.34 kVar
Substation DA - 11kV Bus
42300 kVA
Vs: 6.6 kV
6.39 kV
WMTS-LS2
990 Meters
Ampacity: 690 A
0.28 kA
Pl: 15.88 kW
Ql: 23.85 kVar
WMTS-LS1
691 Meters
Ampacity: 700 A
0.4 kA
Pl: 22.75 kW
Ql: 34.17 kVar
WMTS-LS3
691 Meters
Ampacity: 700 A
0.4 kA
Pl: 22.75 kW
Ql: 34.17 kVar
Substation LS - 22kV Bus
Vs: 22 kV
21.94 kV
LS Tx3
13500 kVA
0.35 kA
Pl: 102.64 kW
Ql: 1667.98 kVar
LS Tx2
10000 kVA
0.26 kA
Pl: 76.03 kW
Ql: 1235.54 kVar
LS Tx1
10000 kVA
0.26 kA
Pl: 76.03 kW
Ql: 1235.54 kVar
Substation LS -6.6kV Bus
30000 kVA
Vs: 6.6 kV
6.29 kV
WMTS_22kV_Supply
Vs: 22 kV
22 kV
GRID
WMTS-22kV Bus Link
1 Meters
Ampacity: 0 A
2.75 kA
Pl: 0 kW
Ql: 10.97 kVar
J-LS1
2133 Meters
Ampacity: 560 A
0.11 kA
Pl: 5.69 kW
Ql: 8.54 kVar
J-LS2
2133 Meters
Ampacity: 560 A
0.11 kA
Pl: 5.69 kW
Ql: 8.54 kVar
WMTS-J3
3300 Meters
Ampacity: 650 A
0.16 kA
Pl: 16.8 kW
Ql: 25.23 kVar
WMTS-J2
3300 Meters
Ampacity: 650 A
0.16 kA
Pl: 16.8 kW
Ql: 25.23 kVar
WMTS-J1
3300 Meters
Ampacity: 650 A
0.16 kA
Pl: 16.8 kW
Ql: 25.23 kVar
WMTS_22kV
Vs: 22 kV
22 kV
Substation J - 22kV Bus
Vs: 22 kV
21.9 kV
J Tx4
10000 kVA
0.18 kA
Pl: 35.04 kW
Ql: 482.07 kVar
J Tx3
10000 kVA
0.18 kA
Pl: 35.04 kW
Ql: 482.07 kVar
J Tx2
10000 kVA
0.18 kA
Pl: 35.04 kW
Ql: 482.07 kVar
J Tx1
10000 kVA
0.18 kA
Pl: 35.04 kW
Ql: 482.07 kVar
Substation J - 6.6kV Bus
25500 kVA
Vs: 6.6 kV
6.28 kV

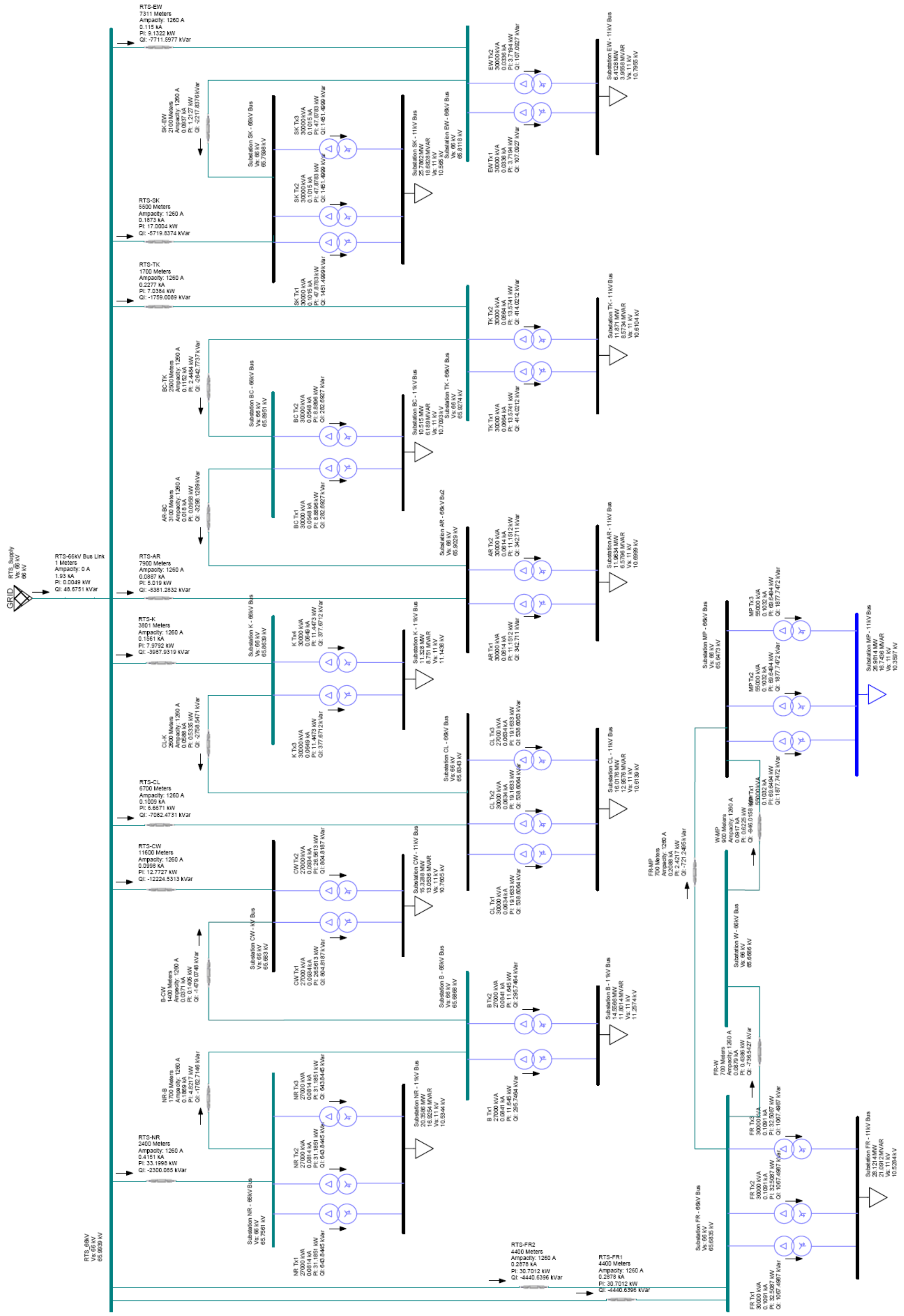

RTS-RP3
6200 Meters
Ampacity: 300 A
0 kA
Pl: 0 kW
Ql: 0 kVar
RTS-RP2
5600 Meters
Ampacity: 240 A
0 kA
Pl: 0 kW
Ql: 0 kVar
RTS-RP1
6400 Meters
Ampacity: 300 A
0 kA
Pl: 0 kW
Ql: 0 kVar
RTS-SM2
4700 Meters
Ampacity: 370 A
0.02 kA
Pl: 0.82 kW
Ql: 0.46 kVar
RTS-SM1
4700 Meters
Ampacity: 370 A
0.02 kA
Pl: 0.84 kW
Ql: 0.46 kVar
RTS-22kV Bus Link
1 Meters
Ampacity: 0 A
1.61 kA
Pl: 0 kW
Ql: 3.77 kVar
GRID
RTS-R3
1100 Meters
Ampacity: 522 A
0.26 kA
Pl: 17.02 kW
Ql: 11.04 kVar
RTS-R4
1100 Meters
Ampacity: 432 A
0.27 kA
Pl: 17.44 kW
Ql: 12.07 kVar
RTS-R2
1100 Meters
Ampacity: 432 A
0.27 kA
Pl: 17.44 kW
Ql: 12.07 kVar
RTS-R1
1100 Meters
Ampacity: 432 A
0.29 kA
Pl: 17.83 kW
Ql: 13.23 kVar
RTS-PR3
3100 Meters
Ampacity: 341 A
0.12 kA
Pl: 19.61 kW
Ql: 16.93 kVar
RTS-PR5
3100 Meters
Ampacity: 341 A
0.12 kA
Pl: 19.61 kW
Ql: 16.93 kVar
RTS-PR2
3100 Meters
Ampacity: 341 A
0.12 kA
Pl: 19.55 kW
Ql: 16.89 kVar
RTS-PR4
3100 Meters
Ampacity: 341 A
0.12 kA
Pl: 19.61 kW
Ql: 16.93 kVar

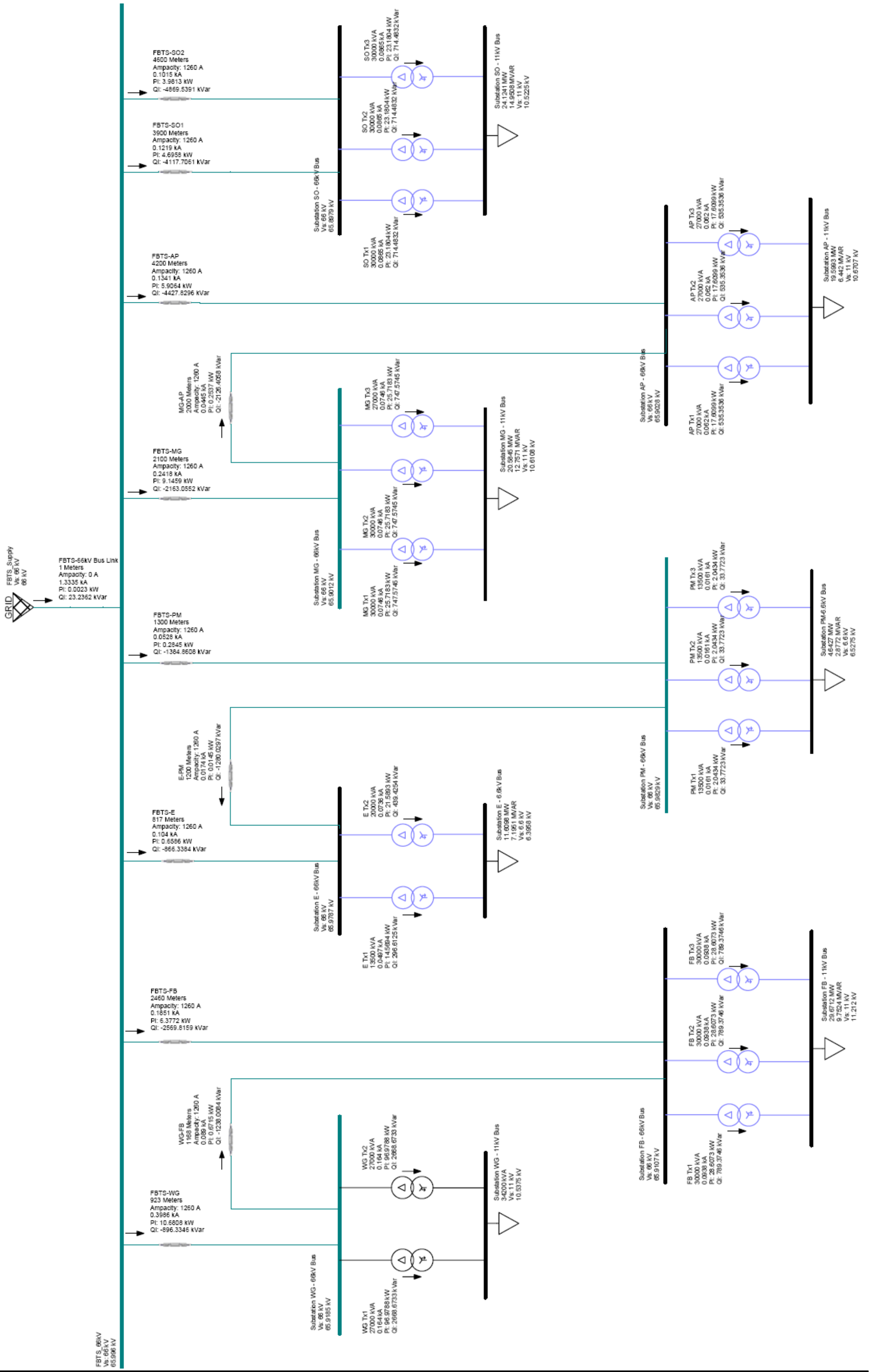


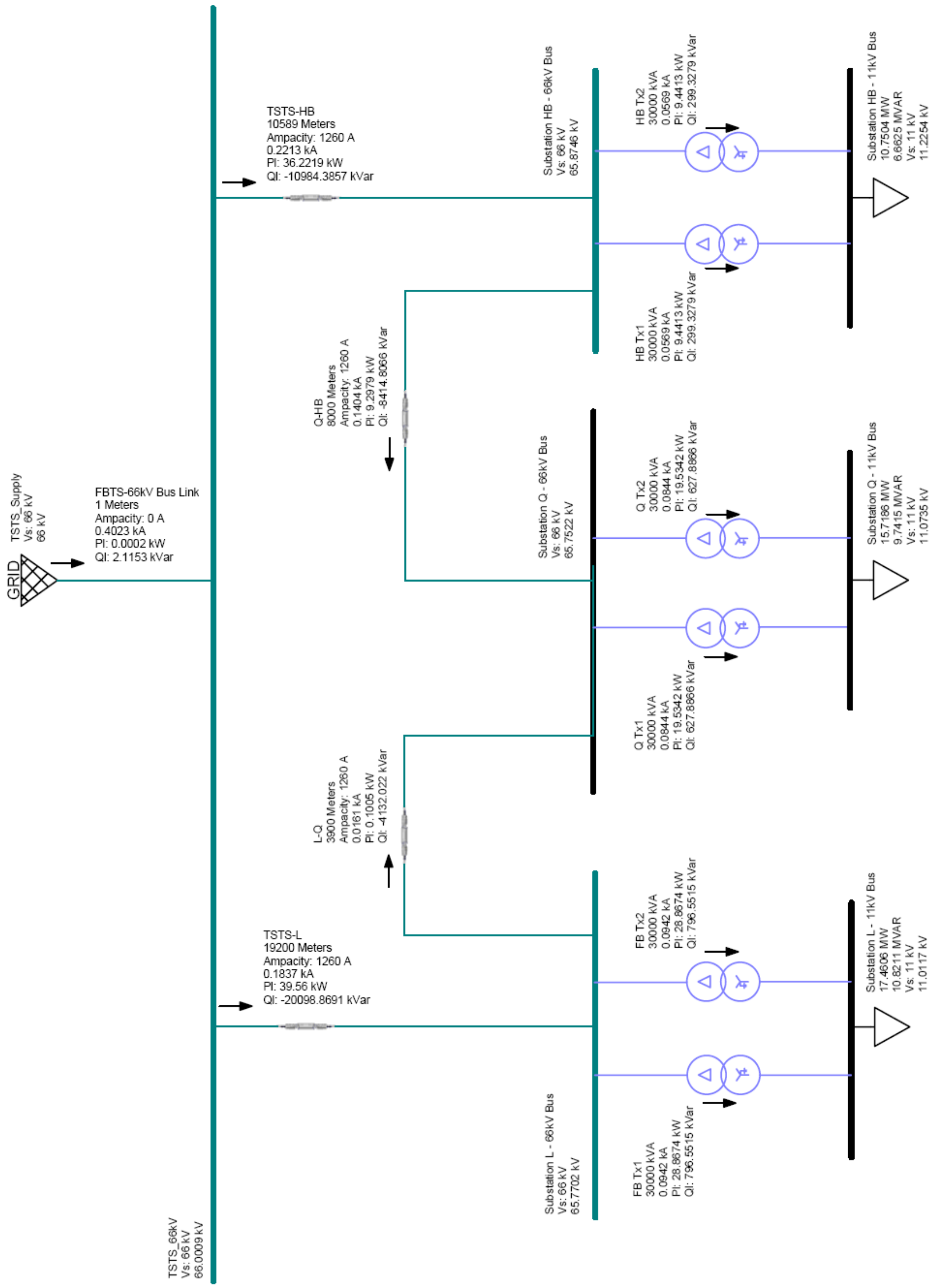

GRID
NT_Supply
Vs: 22 kV
22 kV
NT-22kV Bus Link
1 Meters
Ampacity: 0 A
0.98 kA
Pl: 0 kW
Ql: 1.41 kVar
NT_22kV
Vs: 22 kV
22 kV
NT-TP1
18405 Meters
Ampacity: 280 A
0.15 kA
Pl: 91.11 kW
Ql: 92.92 kVar
NT-TP2
8788 Meters
Ampacity: 329 A
0.2 kA
Pl: 120.05 kW
Ql: 128.15 kVar
NT Load 1 link
1 Meters
Ampacity: 0 A
0.22 kA
Pl: 0 kW
Ql: 0.07 kVar
NT Load1 link2
1 Meters
Ampacity: 0 A
0.43 kA
Pl: 0 kW
Ql: 0.27 kVar
Substation TP - 22kV Bus
Vs: 22 kV
21.5 kV
NT Load 1
7.9 MW
2.6 MVAR
Vs: 22 kV
22 kV
NT Load 2
15.59 MW
5.12 MVAR
Vs: 22 kV
22 kV
TP Tx1
0.18 kA
Pl: 23.89 kW
Ql: 393.68 kVar
TP Tx2
0.16 kA
Pl: 25.08 kW
Ql: 357.41 kVar
Substation TP -6.6kV Bus
12400 kVA
Vs: 6.6 kV
6.34 kV

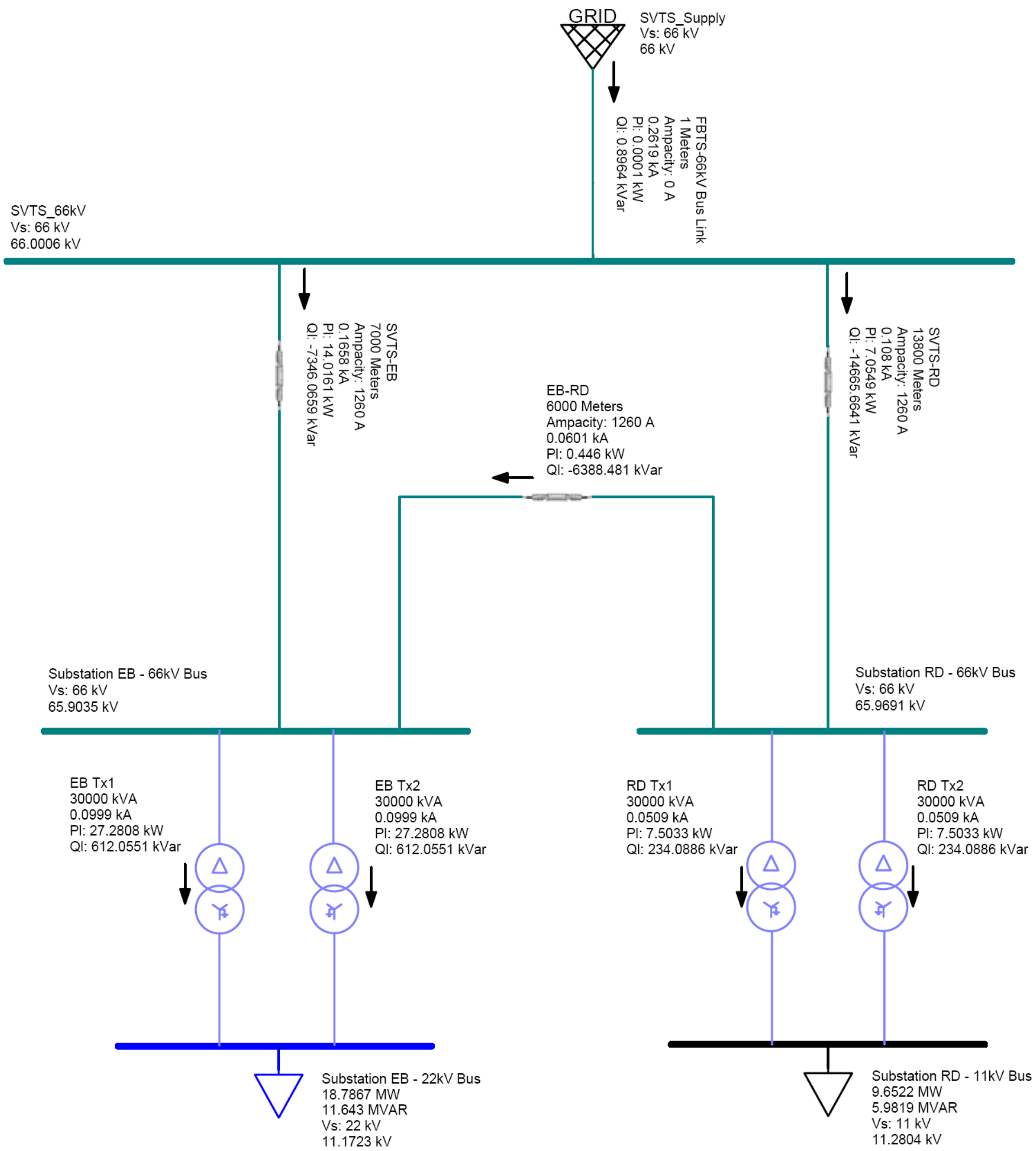
Appendix I



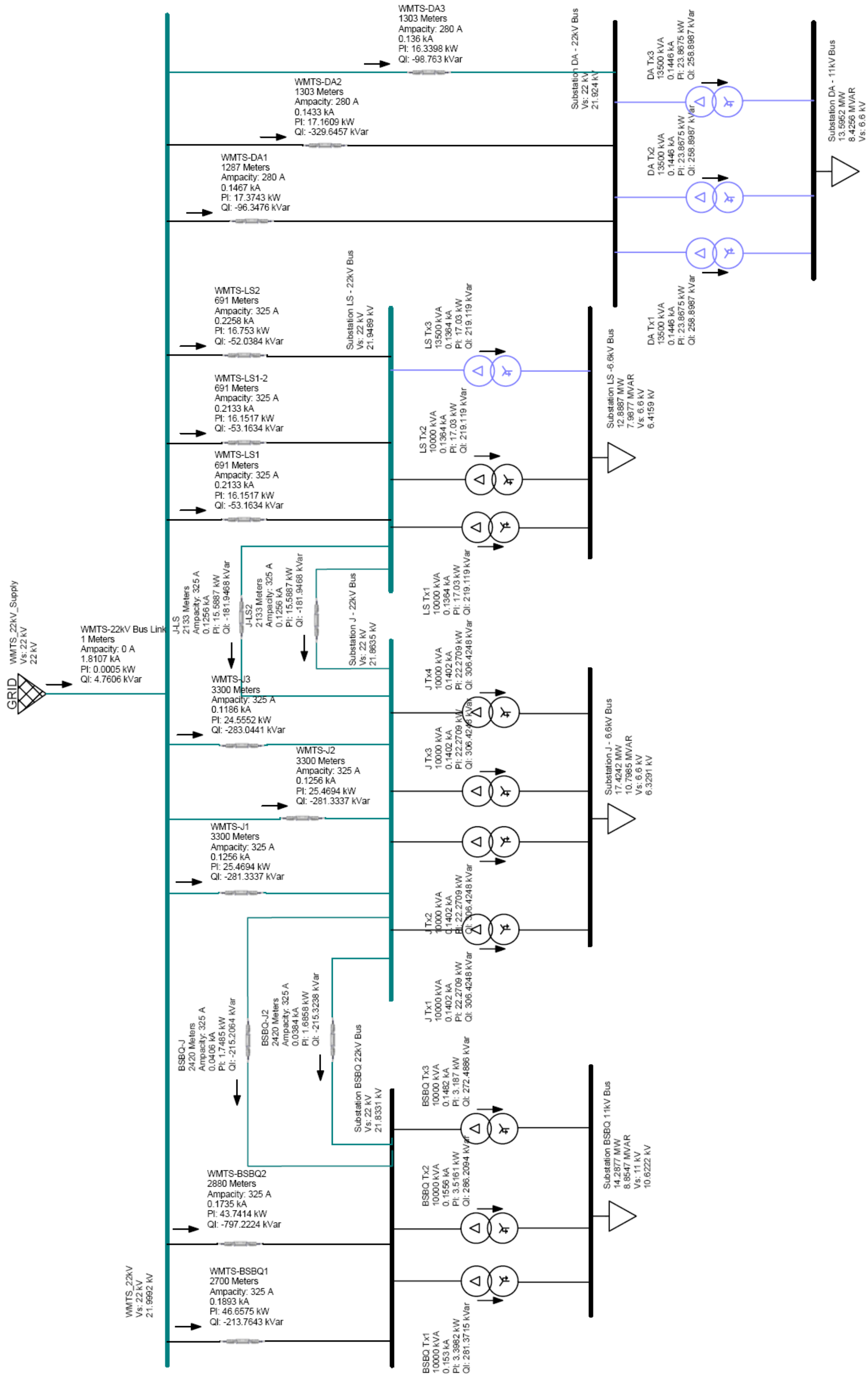


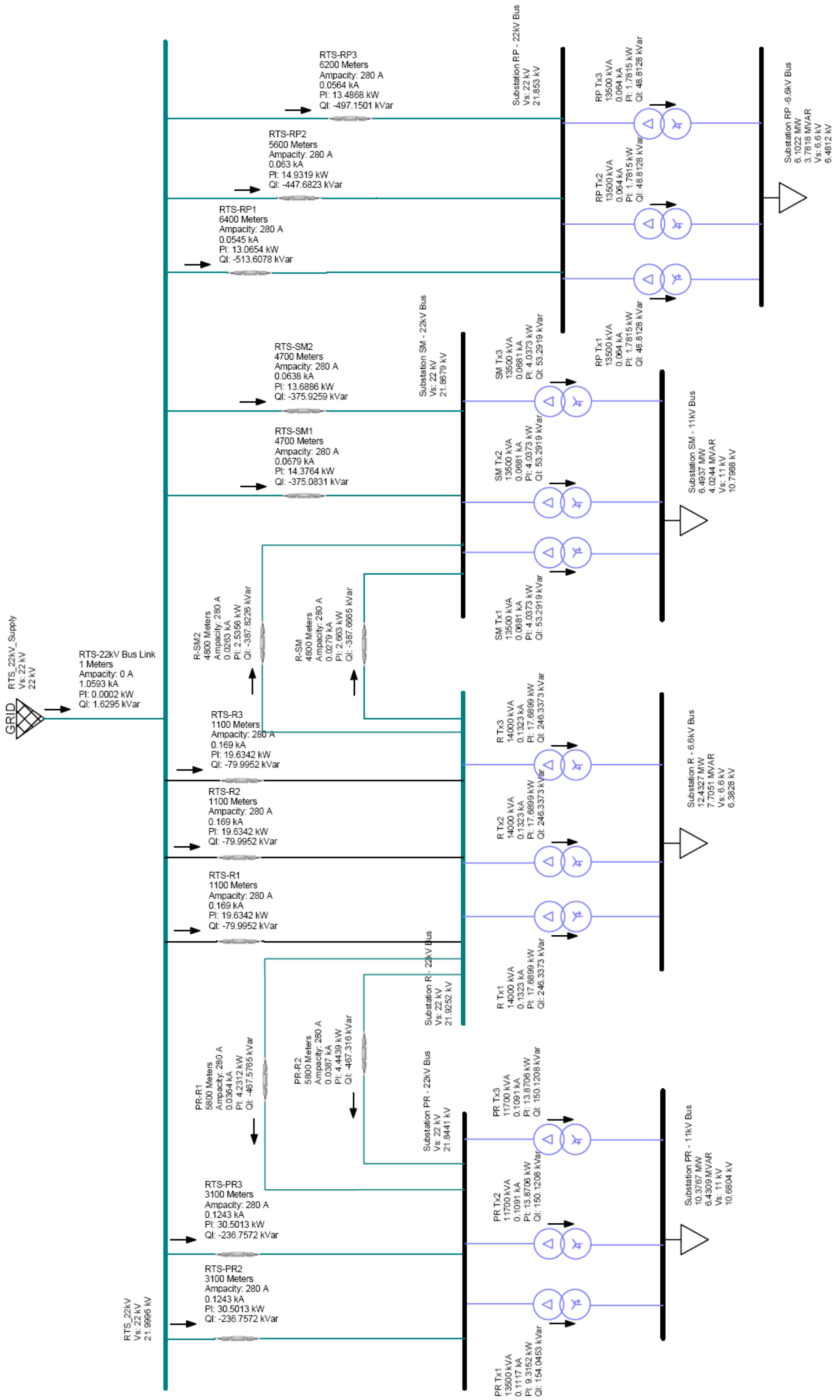

FBTS-SO2
4600 Meters
Ampacity: 1260 A
0.1015 kA
Pl: 3.9613 kW
Ql: -4869.5391 kVar
FBTS-SO1
3900 Meters
Ampacity: 1260 A
0.1219 kA
Pl: 4.6958 kW
Ql: -4117.7061 kVar
FBTS-AP
4200 Meters
Ampacity: 1260 A
0.1341 kA
Pl: 5.9064 kW
Ql: -4427.8296 kVar
FBTS-MG
2100 Meters
Ampacity: 1260 A
0.2418 kA
Pl: 9.1459 kW
Ql: -2163.0552 kVar
FBTS-66kV Bus Link
1 Meters
Ampacity: 0 A
1.3335 kA
Pl: 0.0023 kW
Ql: 23.2362 kVar
GRID
FBTS-PM
1300 Meters
Ampacity: 1260 A
0.0528 kA
Pl: 0.2845 kW
Ql: -1384.8608 kVar
FBTS-E
817 Meters
Ampacity: 1260 A
0.104 kA
Pl: 0.6586 kW
Ql: -865.3384 kVar
FBTS-FB
2460 Meters
Ampacity: 1260 A
0.1851 kA
Pl: 6.3772 kW
Ql: -2569.8159 kVar
FBTS-WG
923 Meters
Ampacity: 1260 A
0.3986 kA
Pl: 10.6608 kW
Ql: -896.3346 kVar


TSTS_Supply
Vs: 66 kV
66 kV
GRID
FBTS-66kV Bus Link
1 Meters
Ampacity: 0 A
0.4023 kA
Pl: 0.0002 kW
Ql: 2.1153 kVar
TSTS_66kV
Vs: 66 kV
66.0009 kV
TSTS-HB
10589 Meters
Ampacity: 1260 A
0.2213 kA
Pl: 36.2219 kW
Ql: -10984.3857 kVar
Q-HB
8000 Meters
Ampacity: 1260 A
0.1404 kA
Pl: 9.2979 kW
Ql: -8414.8066 kVar
L-Q
3900 Meters
Ampacity: 1260 A
0.0161 kA
Pl: 0.1005 kW
Ql: -4132.022 kVar
TSTS-L
19200 Meters
Ampacity: 1260 A
0.1837 kA
Pl: 39.56 kW
Ql: -20098.8691 kVar
Substation HB - 66kV Bus
Vs: 66 kV
65.8746 kV
HB Tx2
30000 kVA
0.0569 kA
Pl: 9.4413 kW
Ql: 299.3279 kVar
HB Tx1
30000 kVA
0.0569 kA
Pl: 9.4413 kW
Ql: 299.3279 kVar
Substation HB - 11kV Bus
10.7504 MW
6.6625 MVAR
Vs: 11 kV
11.2254 kV
Substation Q - 66kV Bus
Vs: 66 kV
65.7522 kV
Q Tx2
30000 kVA
0.0844 kA
Pl: 19.5342 kW
Ql: 627.8866 kVar
Q Tx1
30000 kVA
0.0844 kA
Pl: 19.5342 kW
Ql: 627.8866 kVar
Substation Q - 11kV Bus
15.7186 MW
9.7415 MVAR
Vs: 11 kV
11.0735 kV
Substation L - 66kV Bus
Vs: 66 kV
65.7702 kV
FB Tx2
30000 kVA
0.0942 kA
Pl: 28.8674 kW
Ql: 796.5515 kVar
FB Tx1
30000 kVA
0.0942 kA
Pl: 28.8674 kW
Ql: 796.5515 kVar
Substation L - 11kV Bus
17.4606 MW
10.8211 MVAR
Vs: 11 kV
11.0117 kV

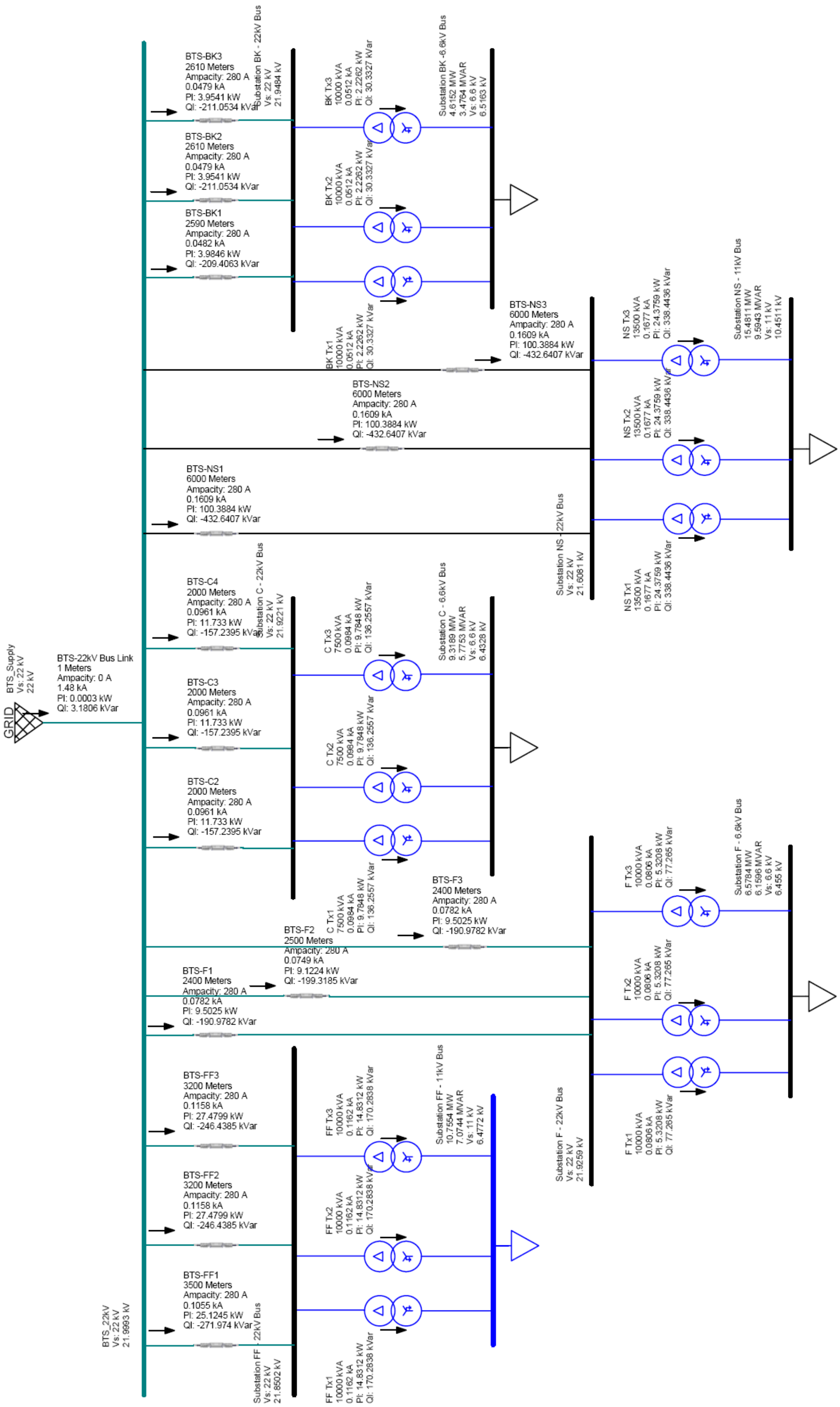


GRID
SVTS_Supply
Vs: 66 kV
66 kV
FBTS-66kV Bus Link
1 Meters
Ampacity: 0 A
0.2619 kA
Pl: 0.0001 kW
Ql: 0.8964 kVar
SVTS_66kV
Vs: 66 kV
66.0006 kV
SVTS-EB
7000 Meters
Ampacity: 1260 A
0.1658 kA
Pl: 14.0161 kW
Ql: -7346.0659 kVar
SVTS-RD
13800 Meters
Ampacity: 1260 A
0.108 kA
Pl: 7.0549 kW
Ql: -14665.6641 kVar
EB-RD
6000 Meters
Ampacity: 1260 A
0.0601 kA
Pl: 0.446 kW
Ql: -6388.481 kVar
Substation EB - 66kV Bus
Vs: 66 kV
65.9035 kV
Substation RD - 66kV Bus
Vs: 66 kV
65.9691 kV
EB Tx1
30000 kVA
0.0999 kA
Pl: 27.2808 kW
Ql: 612.0551 kVar
EB Tx2
30000 kVA
0.0999 kA
Pl: 27.2808 kW
Ql: 612.0551 kVar
RD Tx1
30000 kVA
0.0509 kA
Pl: 7.5033 kW
Ql: 234.0886 kVar
RD Tx2
30000 kVA
0.0509 kA
Pl: 7.5033 kW
Ql: 234.0886 kVar
Substation EB - 22kV Bus
18.7867 MW
11.643 MVAR
Vs: 22 kV
11.1723 kV
Substation RD - 11kV Bus
9.6522 MW
5.9819 MVAR
Vs: 11 kV
11.2804 kV

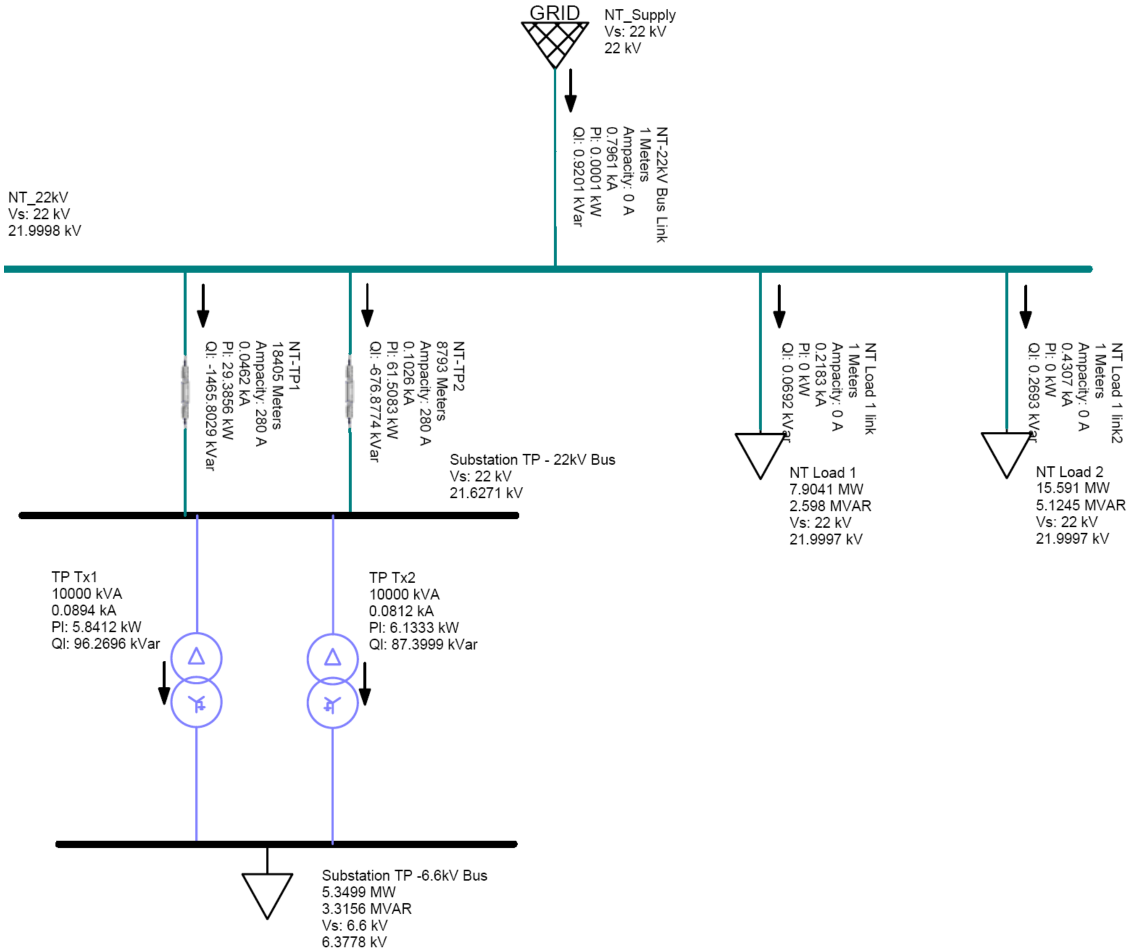

WMTS-DA3
1303 Meters
Ampacity: 280 A
0.136 kA
Pl: 16.3398 kW
Ql: -98.763 kVar
WMTS-DA2
1303 Meters
Ampacity: 280 A
0.1433 kA
Pl: 17.1609 kW
Ql: -329.6457 kVar
WMTS-DA1
1287 Meters
Ampacity: 280 A
0.1467 kA
Pl: 17.3743 kW
Ql: -96.3476 kVar
WMTS-LS2
691 Meters
Ampacity: 325 A
0.2258 kA
Pl: 16.753 kW
Ql: -52.0384 kVar
WMTS-LS1-2
691 Meters
Ampacity: 325 A
0.2133 kA
Pl: 16.1517 kW
Ql: -53.1634 kVar
WMTS-LS1
691 Meters
Ampacity: 325 A
0.2133 kA
Pl: 16.1517 kW
Ql: -53.1634 kVar
WMTS-22kV Bus Link
1 Meters
Ampacity: 0 A
1.8107 kA
Pl: 0.0005 kW
Ql: 4.7606 kVar
GRID
WMTS-J3
3300 Meters
Ampacity: 325 A
0.1186 kA
Pl: 24.5552 kW
Ql: -283.0441 kVar
WMTS-J2
3300 Meters
Ampacity: 325 A
0.1256 kA
Pl: 25.4694 kW
Ql: -281.3337 kVar
WMTS-J1
3300 Meters
Ampacity: 325 A
0.1256 kA
Pl: 25.4694 kW
Ql: -281.3337 kVar
WMTS-BSBQ2
2880 Meters
Ampacity: 325 A
0.1735 kA
Pl: 43.7414 kW
Ql: -797.2224 kVar
WMTS-BSBQ1
2700 Meters
Ampacity: 325 A
0.1893 kA
Pl: 46.6575 kW
Ql: -213.7643 kVar



RTS-RP3
6200 Meters
Ampacity: 280 A
0.0564 kA
Pl: 13.4868 kW
Ql: -497.1501 kVar
RTS-RP2
5600 Meters
Ampacity: 280 A
0.063 kA
Pl: 14.9319 kW
Ql: -447.6823 kVar
RTS-RP1
6400 Meters
Ampacity: 280 A
0.0545 kA
Pl: 13.0654 kW
Ql: -513.6078 kVar
Substation RP - 22kV Bus
Vs: 22 kV
21.853 kV
RP Tx3
13500 kVA
0.064 kA
Pl: 1.7815 kW
Ql: 48.8128 kVar
RP Tx2
13500 kVA
0.064 kA
Pl: 1.7815 kW
Ql: 48.8128 kVar
RP Tx1
13500 kVA
0.064 kA
Pl: 1.7815 kW
Ql: 48.8128 kVar
Substation RP -6.6kV Bus
6.1022 MW
3.7818 MVAR
Vs: 6.6 kV
6.4812 kV
RTS-SM2
4700 Meters
Ampacity: 280 A
0.0638 kA
Pl: 13.6886 kW
Ql: -375.9259 kVar
RTS-SM1
4700 Meters
Ampacity: 280 A
0.0679 kA
Pl: 14.3764 kW
Ql: -375.0831 kVar
Substation SM - 22kV Bus
Vs: 22 kV
21.8679 kV
SM Tx3
13500 kVA
0.0681 kA
Pl: 4.0373 kW
Ql: 53.2919 kVar
SM Tx2
13500 kVA
0.0681 kA
Pl: 4.0373 kW
Ql: 53.2919 kVar
SM Tx1
13500 kVA
0.0681 kA
Pl: 4.0373 kW
Ql: 53.2919 kVar
Substation SM - 11kV Bus
6.4937 MW
4.0244 MVAR
Vs: 11 kV
10.7988 kV
R-SM2
4800 Meters
Ampacity: 280 A
0.0263 kA
Pl: 2.5356 kW
Ql: -387.8226 kVar
R-SM
4800 Meters
Ampacity: 280 A
0.0279 kA
Pl: 2.663 kW
Ql: -387.6665 kVar
GRID
RTS_22kV_Supply
Vs: 22 kV
22 kV
RTS-22kV Bus Link
1 Meters
Ampacity: 0 A
1.0593 kA
Pl: 0.0002 kW
Ql: 1.6295 kVar
RTS-R3
1100 Meters
Ampacity: 280 A
0.169 kA
Pl: 19.6342 kW
Ql: -79.9952 kVar
RTS-R2
1100 Meters
Ampacity: 280 A
0.169 kA
Pl: 19.6342 kW
Ql: -79.9952 kVar
RTS-R1
1100 Meters
Ampacity: 280 A
0.169 kA
Pl: 19.6342 kW
Ql: -79.9952 kVar
R Tx3
14000 kVA
0.1323 kA
Pl: 17.6899 kW
Ql: 246.3373 kVar
R Tx2
14000 kVA
0.1323 kA
Pl: 17.6899 kW
Ql: 246.3373 kVar
R Tx1
14000 kVA
0.1323 kA
Pl: 17.6899 kW
Ql: 246.3373 kVar
Substation R - 6.6kV Bus
12.4327 MW
7.7051 MVAR
Vs: 6.6 kV
6.3828 kV
Substation R - 22kV Bus
Vs: 22 kV
21.9252 kV
PR-R1
5800 Meters
Ampacity: 280 A
0.0364 kA
Pl: 4.2312 kW
Ql: -467.5765 kVar
PR-R2
5800 Meters
Ampacity: 280 A
0.0387 kA
Pl: 4.4439 kW
Ql: -467.316 kVar
Substation PR - 22kV Bus
Vs: 22 kV
21.8441 kV
PR Tx3
11700 kVA
0.1091 kA
Pl: 13.8706 kW
Ql: 150.1208 kVar
PR Tx2
11700 kVA
0.1091 kA
Pl: 13.8706 kW
Ql: 150.1208 kVar
PR Tx1
13500 kVA
0.1117 kA
Pl: 9.3152 kW
Ql: 154.0453 kVar
Substation PR - 11kV Bus
10.3767 MW
6.4309 MVAR
Vs: 11 kV
10.6804 kV
RTS-PR3
3100 Meters
Ampacity: 280 A
0.1243 kA
Pl: 30.5013 kW
Ql: -236.7572 kVar
RTS-PR2
3100 Meters
Ampacity: 280 A
0.1243 kA
Pl: 30.5013 kW
Ql: -236.7572 kVar
RTS_22kV
Vs: 22 kV
21.9996 kV

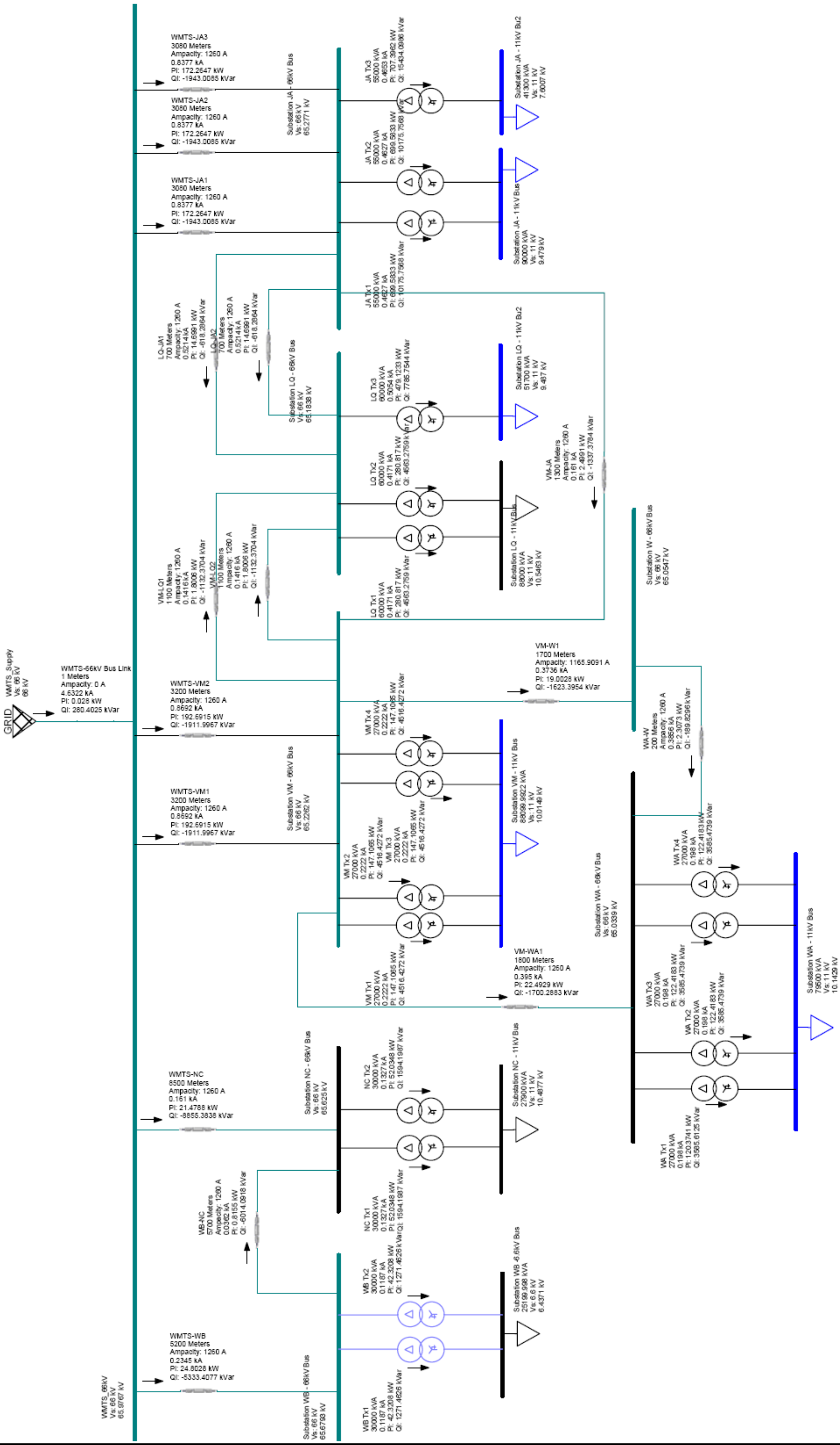


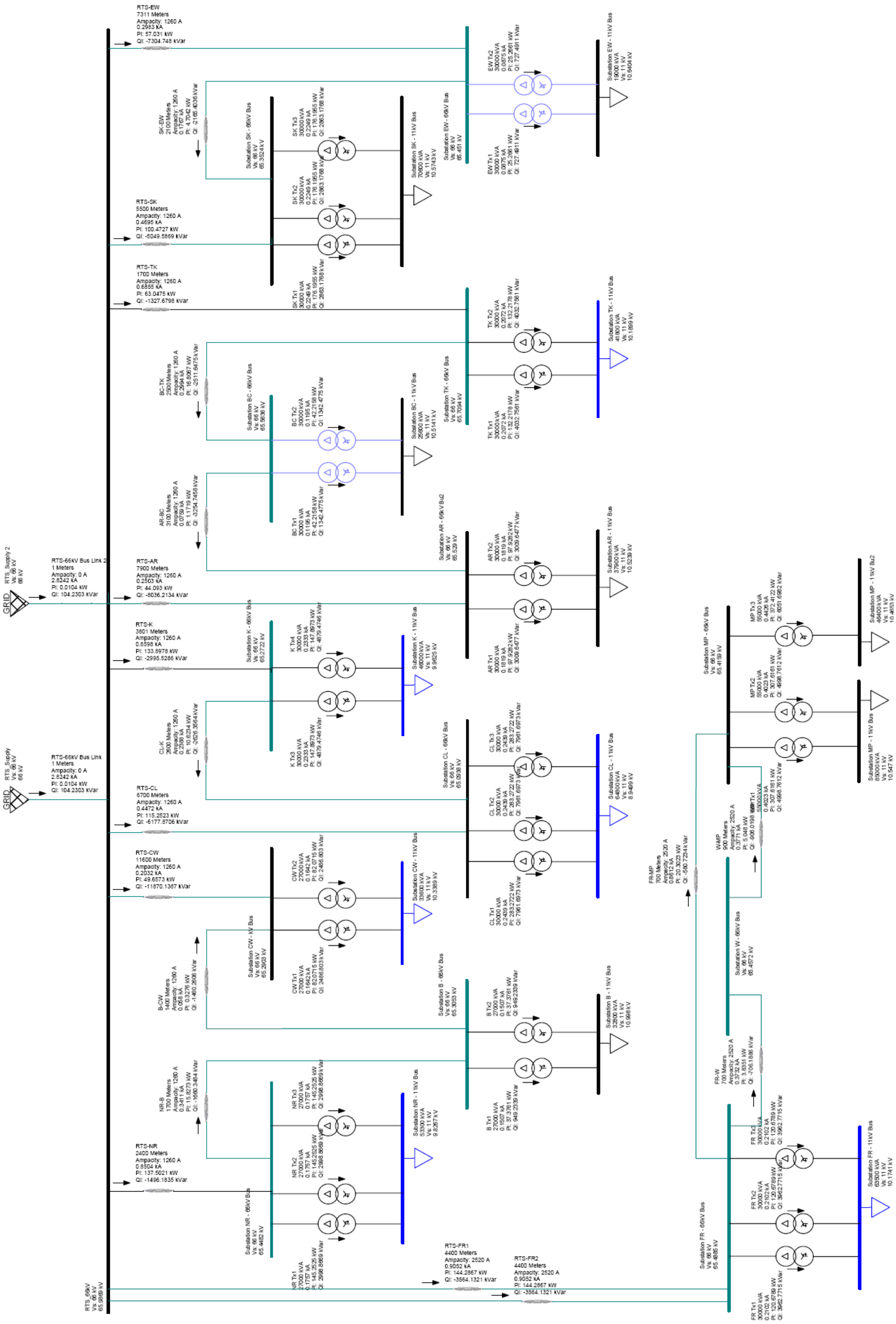
GRID
BTS_Supply
Vs: 22 kV
22 kV
BTS-22kV Bus Link
1 Meters
Ampacity: 0 A
1.48 kA
Pl: 0.0003 kW
Ql: 3.1806 kVar
BTS-BK3
2610 Meters
Ampacity: 280 A
0.0479 kA
Pl: 3.9541 kW
Ql: -211.0534 kVar
BTS-BK2
2610 Meters
Ampacity: 280 A
0.0479 kA
Pl: 3.9541 kW
Ql: -211.0534 kVar
BTS-BK1
2590 Meters
Ampacity: 280 A
0.0482 kA
Pl: 3.9846 kW
Ql: -209.4063 kVar
BTS-NS3
6000 Meters
Ampacity: 280 A
0.1609 kA
Pl: 100.3884 kW
Ql: -432.6407 kVar
BTS-NS2
6000 Meters
Ampacity: 280 A
0.1609 kA
Pl: 100.3884 kW
Ql: -432.6407 kVar
BTS-NS1
6000 Meters
Ampacity: 280 A
0.1609 kA
Pl: 100.3884 kW
Ql: -432.6407 kVar
BTS-C4
2000 Meters
Ampacity: 280 A
0.0961 kA
Pl: 11.733 kW
Ql: -157.2395 kVar
BTS-C3
2000 Meters
Ampacity: 280 A
0.0961 kA
Pl: 11.733 kW
Ql: -157.2395 kVar
BTS-C2
2000 Meters
Ampacity: 280 A
0.0961 kA
Pl: 11.733 kW
Ql: -157.2395 kVar
BTS-F3
2400 Meters
Ampacity: 280 A
0.0782 kA
Pl: 9.5025 kW
Ql: -190.9782 kVar
BTS-F2
2500 Meters
Ampacity: 280 A
0.0749 kA
Pl: 9.1224 kW
Ql: -199.3185 kVar
BTS-F1
2400 Meters
Ampacity: 280 A
0.0782 kA
Pl: 9.5025 kW
Ql: -190.9782 kVar
BTS-FF3
3200 Meters
Ampacity: 280 A
0.1158 kA
Pl: 27.4799 kW
Ql: -246.4385 kVar
BTS-FF2
3200 Meters
Ampacity: 280 A
0.1158 kA
Pl: 27.4799 kW
Ql: -246.4385 kVar
BTS-FF1
3500 Meters
Ampacity: 280 A
0.1055 kA
Pl: 25.1245 kW
Ql: -271.974 kVar
BTS_22kV
Vs: 22 kV
21.9993 kV
Substation BK - 22kV Bus
Vs: 22 kV
21.9484 kV
BK Tx3
10000 kVA
0.0512 kA
Pl: 2.2262 kW
Ql: 30.3327 kVar
BK Tx2
10000 kVA
0.0512 kA
Pl: 2.2262 kW
Ql: 30.3327 kVar
BK Tx1
10000 kVA
0.0512 kA
Pl: 2.2262 kW
Ql: 30.3327 kVar
Substation BK -6.6kV Bus
4.6152 MW
3.4764 MVAR
Vs: 6.6 kV
6.5163 kV
Substation NS -22kV Bus
Vs: 22 kV
21.6081 kV
NS Tx3
13500 kVA
0.1677 kA
Pl: 24.3759 kW
Ql: 338.4436 kVar
NS Tx2
13500 kVA
0.1677 kA
Pl: 24.3759 kW
Ql: 338.4436 kVar
NS Tx1
13500 kVA
0.1677 kA
Pl: 24.3759 kW
Ql: 338.4436 kVar
Substation NS - 11kV Bus
15.4811 MW
9.5943 MVAR
Vs: 11 kV
10.4511 kV
Substation C - 22kV Bus
Vs: 22 kV
21.9221 kV
C Tx3
7500 kVA
0.0984 kA
Pl: 9.7848 kW
Ql: 136.2557 kVar
C Tx2
7500 kVA
0.0984 kA
Pl: 9.7848 kW
Ql: 136.2557 kVar
C Tx1
7500 kVA
0.0984 kA
Pl: 9.7848 kW
Ql: 136.2557 kVar
Substation C - 6.6kV Bus
9.3189 MW
5.7753 MVAR
Vs: 6.6 kV
6.4328 kV
Substation F - 22kV Bus
Vs: 22 kV
21.9259 kV
F Tx3
10000 kVA
0.0806 kA
Pl: 5.3208 kW
Ql: 77.265 kVar
F Tx2
10000 kVA
0.0806 kA
Pl: 5.3208 kW
Ql: 77.265 kVar
F Tx1
10000 kVA
0.0806 kA
Pl: 5.3208 kW
Ql: 77.265 kVar
Substation F - 6.6kV Bus
6.5784 MW
6.1596 MVAR
Vs: 6.6 kV
6.455 kV
Substation FF - 22kV Bus
Vs: 22 kV
21.8502 kV
FF Tx3
10000 kVA
0.1162 kA
Pl: 14.8312 kW
Ql: 170.2838 kVar
FF Tx2
10000 kVA
0.1162 kA
Pl: 14.8312 kW
Ql: 170.2838 kVar
FF Tx1
10000 kVA
0.1162 kA
Pl: 14.8312 kW
Ql: 170.2838 kVar
Substation FF - 11kV Bus
10.7554 MW
7.0744 MVAR
Vs: 11 kV
6.4772 kV

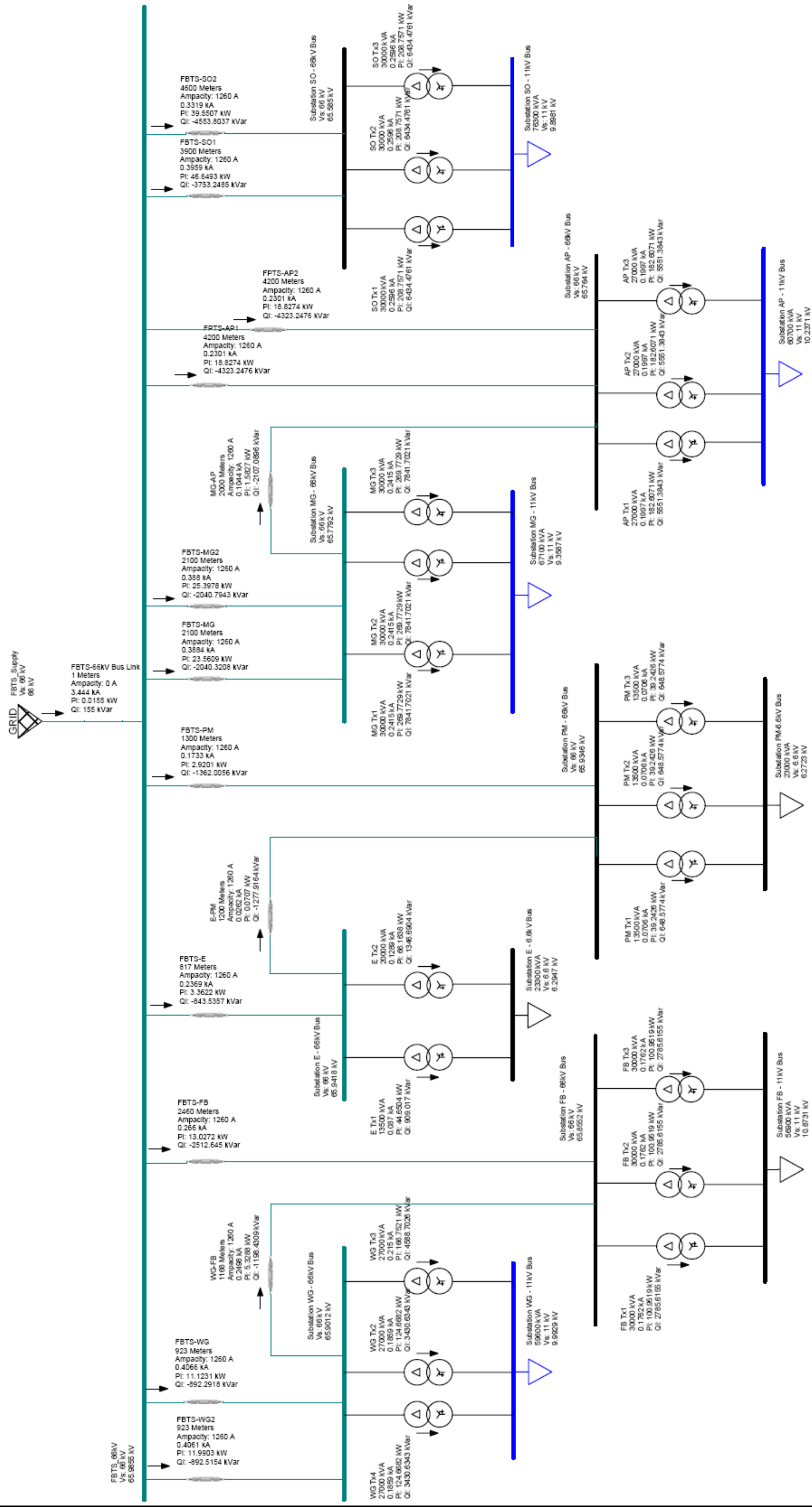


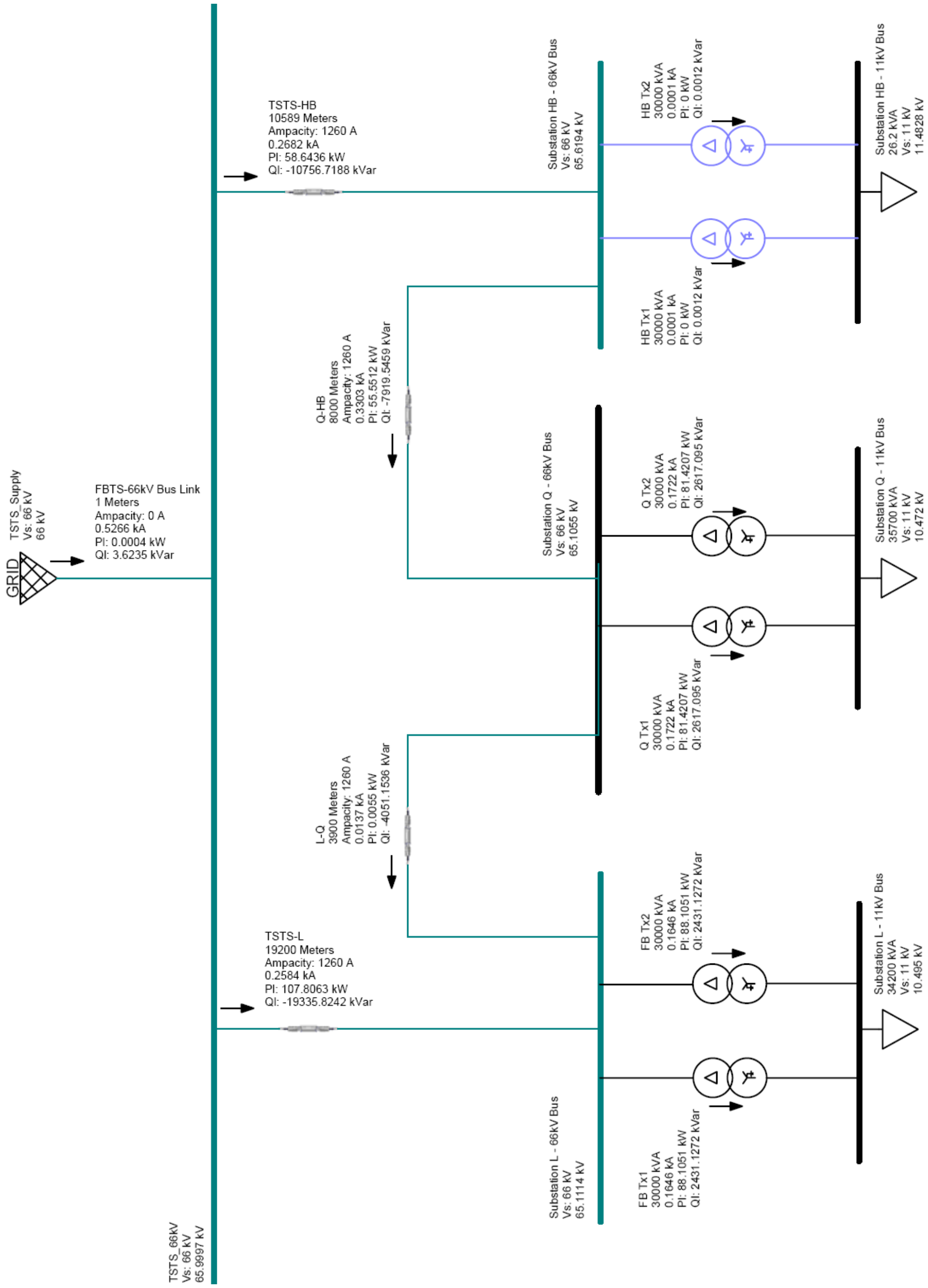
GRID
NT_Supply
Vs: 22 kV
22 kV
NT-22kV Bus Link
1 Meters
Ampacity: 0 A
0.7961 kA
Pl: 0.0001 kW
Ql: 0.9201 kVar
NT_22kV
Vs: 22 kV
21.9998 kV
NT-TP1
18405 Meters
Ampacity: 280 A
0.0462 kA
Pl: 29.3856 kW
Ql: -1465.8029 kVar
NT-TP2
8793 Meters
Ampacity: 280 A
0.1026 kA
Pl: 61.5083 kW
Ql: -676.8774 kVar
Substation TP - 22kV Bus
Vs: 22 kV
21.6271 kV
NT Load 1 link
1 Meters
Ampacity: 0 A
0.2183 kA
Pl: 0 kW
Ql: 0.0692 kVar
NT Load 1
7.9041 MW
2.598 MVAR
Vs: 22 kV
21.9997 kV
NT Load 1 link2
1 Meters
Ampacity: 0 A
0.4307 kA
Pl: 0 kW
Ql: 0.2693 kVar
NT Load 2
15.591 MW
5.1245 MVAR
Vs: 22 kV
21.9997 kV
TP Tx1
10000 kVA
0.0894 kA
Pl: 5.8412 kW
Ql: 96.2696 kVar
TP Tx2
10000 kVA
0.0812 kA
Pl: 6.1333 kW
Ql: 87.3999 kVar
Substation TP -6.6kV Bus
5.3499 MW
3.3156 MVAR
Vs: 6.6 kV
6.3778 kV

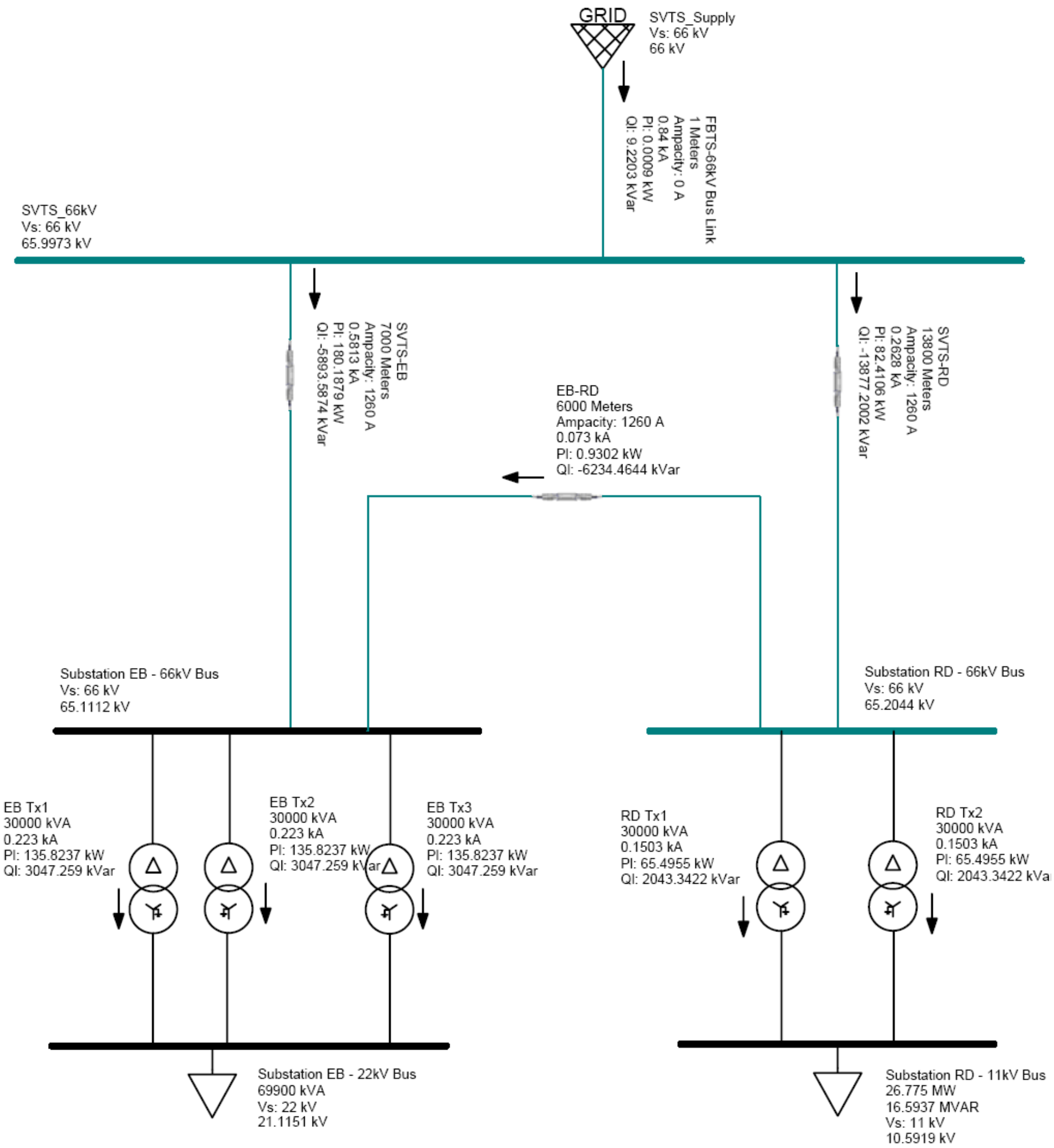
Appendix J



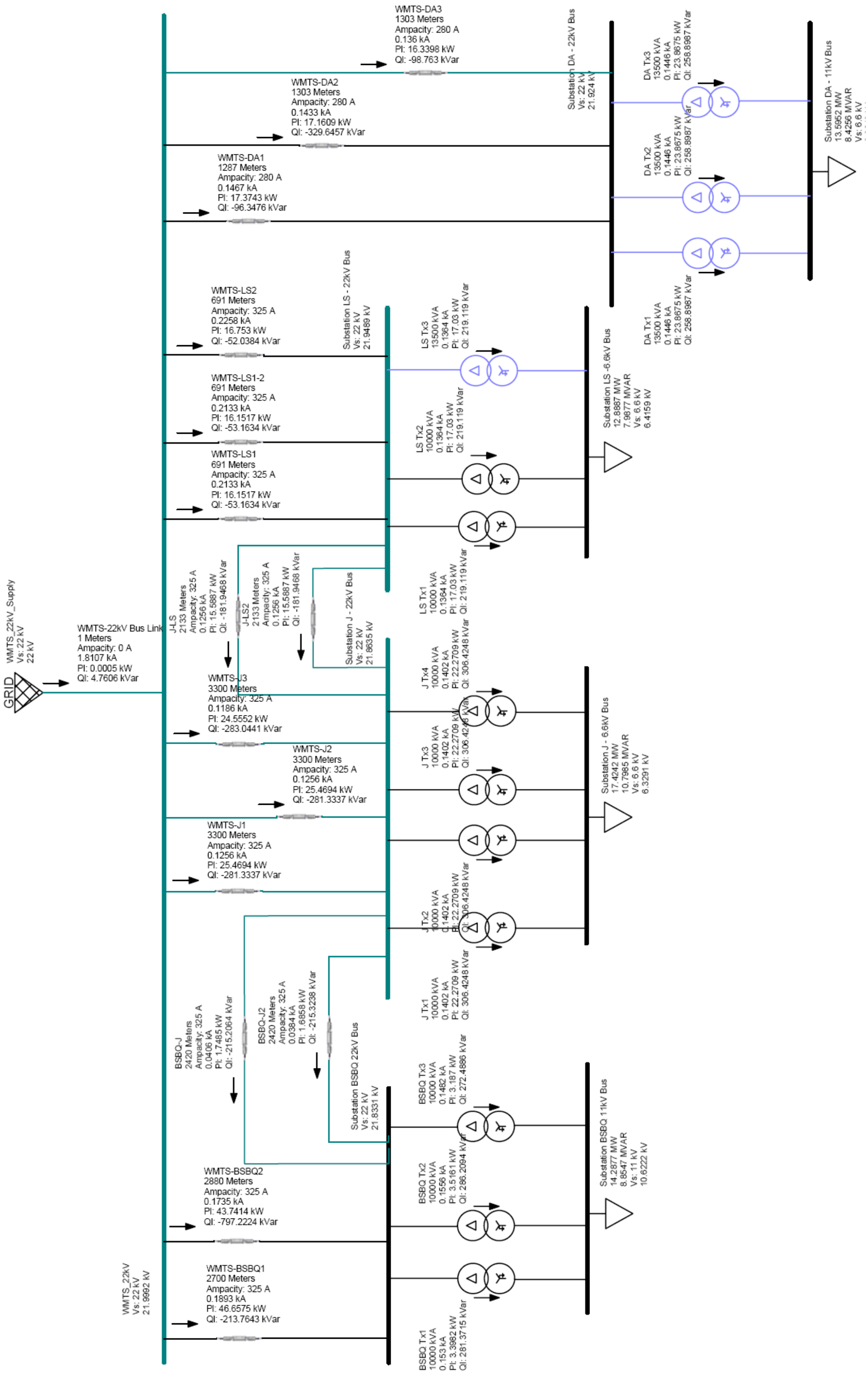



GRID
FBTS_Supply
Vs: 66 kV
66 kV
FBTS-66kV Bus Link
1 Meters
Ampacity: 0 A
3.444 kA
Pl: 0.0155 kW
Ql: 155 kVar
FBTS-SO2
4500 Meters
Ampacity: 1260 A
0.3319 kA
Pl: 39.5507 kW
Ql: -4553.8037 kVar
FBTS-SO1
3900 Meters
Ampacity: 1260 A
0.3959 kA
Pl: 46.6493 kW
Ql: -3753.2485 kVar
FPTS-AP2
4200 Meters
Ampacity: 1260 A
0.2301 kA
Pl: 18.8274 kW
Ql: -4323.2476 kVar
FBTS-AP1
4200 Meters
Ampacity: 1260 A
0.2301 kA
Pl: 18.8274 kW
Ql: -4323.2476 kVar
FBTS-MG2
2100 Meters
Ampacity: 1260 A
0.388 kA
Pl: 25.3978 kW
Ql: -2040.7943 kVar
FBTS-MG
2100 Meters
Ampacity: 1260 A
0.3884 kA
Pl: 23.5609 kW
Ql: -2040.3208 kVar
FBTS-PM
1300 Meters
Ampacity: 1260 A
0.1733 kA
Pl: 2.9201 kW
Ql: -1362.0056 kVar
FBTS-E
817 Meters
Ampacity: 1260 A
0.2369 kA
Pl: 3.3622 kW
Ql: -843.5357 kVar
FBTS-FB
2460 Meters
Ampacity: 1260 A
0.266 kA
Pl: 13.0272 kW
Ql: -2512.645 kVar
FBTS-WG
923 Meters
Ampacity: 1260 A
0.4066 kA
Pl: 11.1231 kW
Ql: -892.2918 kVar
FBTS-WG2
923 Meters
Ampacity: 1260 A
0.4061 kA
Pl: 11.9903 kW
Ql: -892.5154 kVar
FBTS_66kV
Vs: 66 kV
65.9855 kV

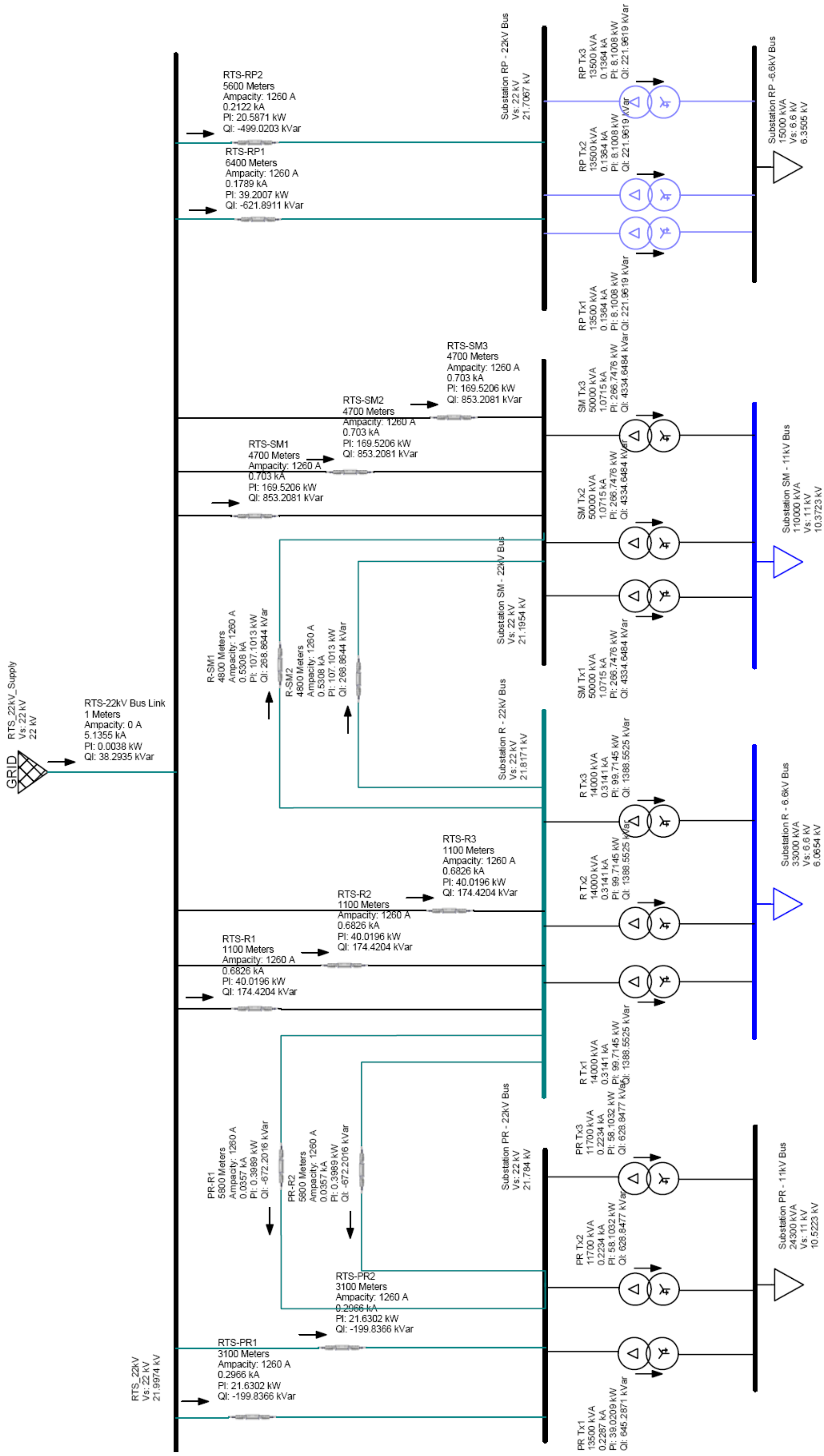

TSTS_Supply
Vs: 66 kV
66 kV
GRID
FBTS-66kV Bus Link
1 Meters
Ampacity: 0 A
0.5266 kA
Pl: 0.0004 kW
Ql: 3.6235 kVar
TSTS-HB
10589 Meters
Ampacity: 1260 A
0.2682 kA
Pl: 58.6436 kW
Ql: -10756.7188 kVar
Substation HB - 66kV Bus
Vs: 66 kV
65.6194 kV
HB Tx2
30000 kVA
0.0001 kA
Pl: 0 kW
Ql: 0.0012 kVar
HB Tx1
30000 kVA
0.0001 kA
Pl: 0 kW
Ql: 0.0012 kVar
Substation HB - 11kV Bus
26.2 kVA
Vs: 11 kV
11.4828 kV
Q-HB
8000 Meters
Ampacity: 1260 A
0.3303 kA
Pl: 55.5512 kW
Ql: -7919.5459 kVar
Substation Q - 66kV Bus
Vs: 66 kV
65.1055 kV
Q Tx2
30000 kVA
0.1722 kA
Pl: 81.4207 kW
Ql: 2617.095 kVar
Q Tx1
30000 kVA
0.1722 kA
Pl: 81.4207 kW
Ql: 2617.095 kVar
Substation Q - 11kV Bus
35700 kVA
Vs: 11 kV
10.472 kV
L-Q
3900 Meters
Ampacity: 1260 A
0.0137 kA
Pl: 0.0055 kW
Ql: -4051.1536 kVar
TSTS-L
19200 Meters
Ampacity: 1260 A
0.2584 kA
Pl: 107.8063 kW
Ql: -19335.8242 kVar
FB Tx2
30000 kVA
0.1646 kA
Pl: 88.1051 kW
Ql: 2431.1272 kVar
FB Tx1
30000 kVA
0.1646 kA
Pl: 88.1051 kW
Ql: 2431.1272 kVar
Substation L - 11kV Bus
34200 kVA
Vs: 11 kV
10.495 kV
Substation L - 66kV Bus
Vs: 66 kV
65.1114 kV
TSTS_66kV
Vs: 66 kV
65.9997 kV

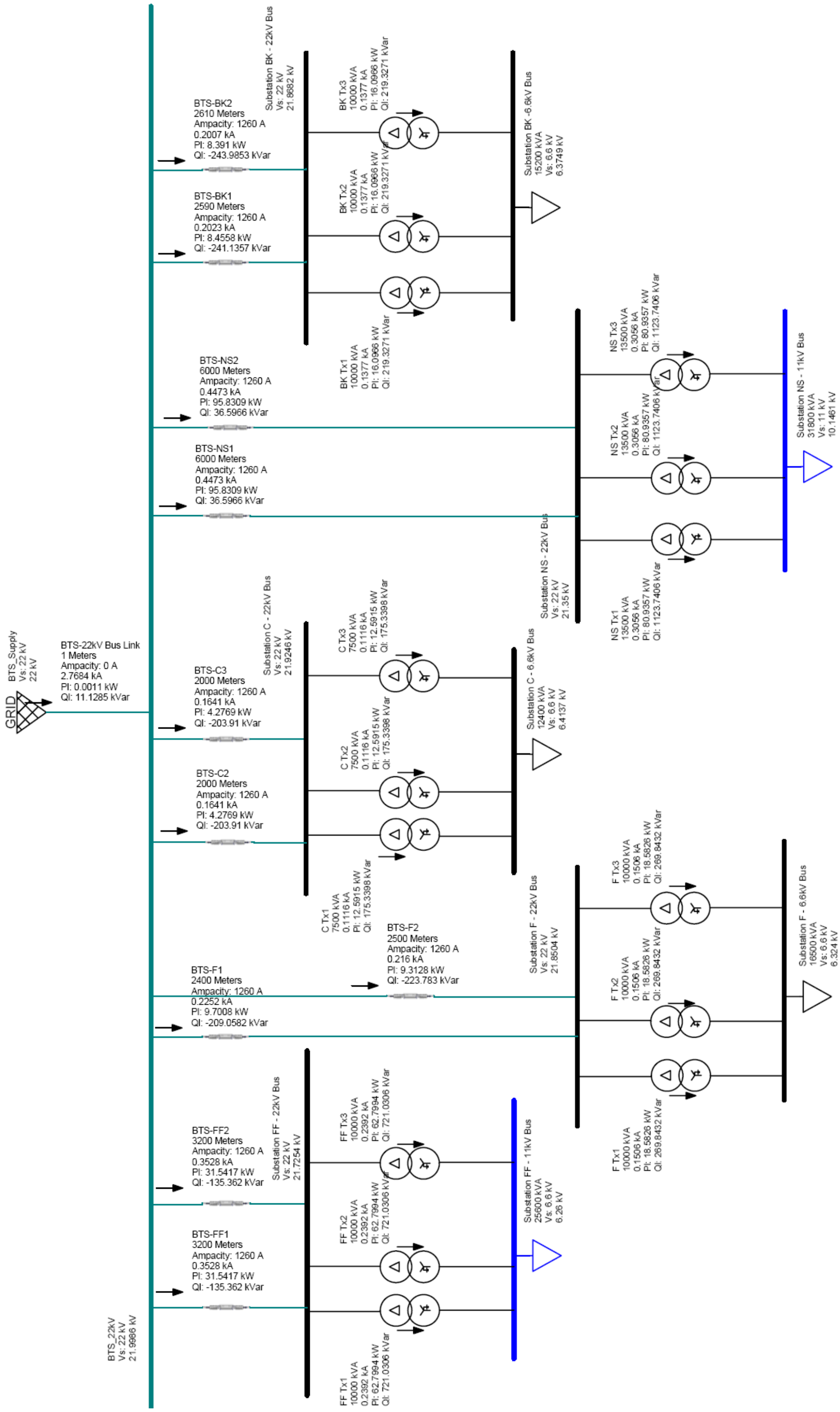


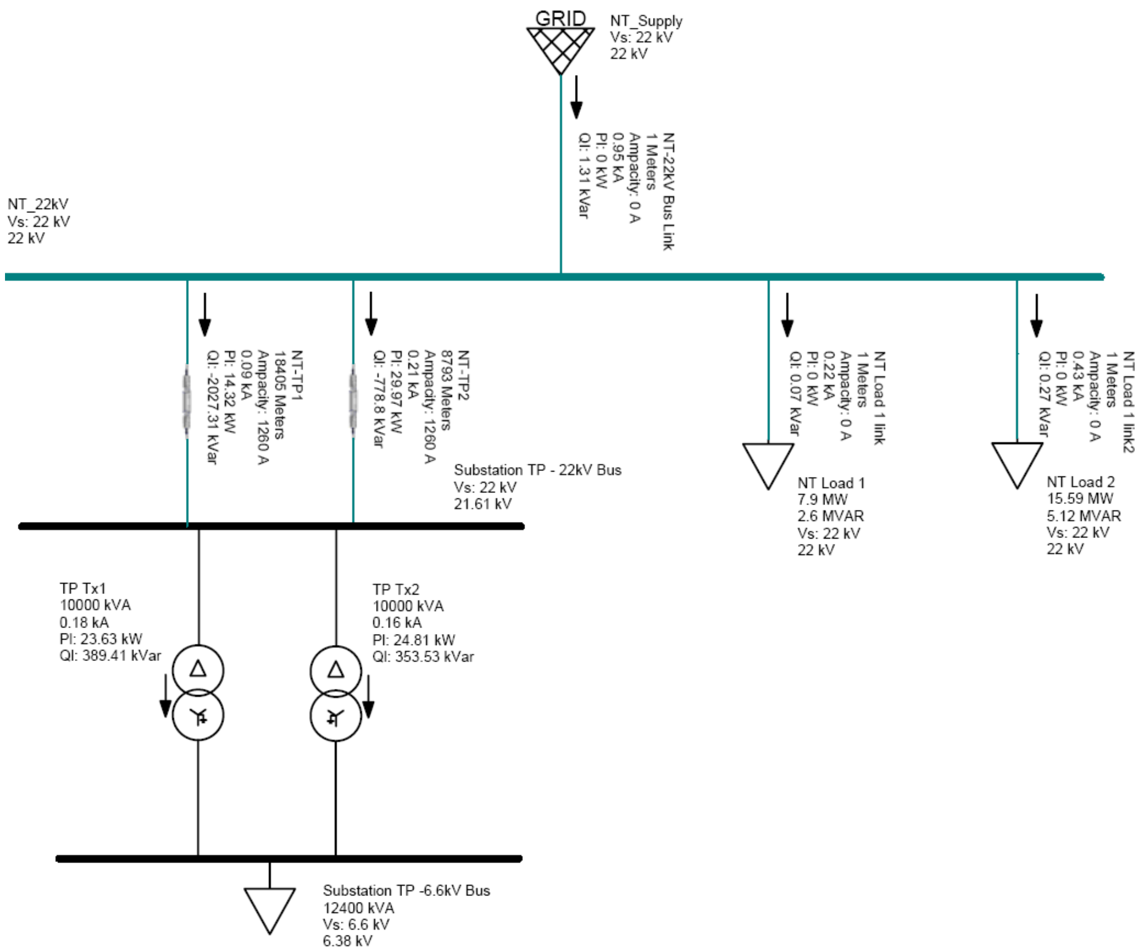
GRID
SVTS_Supply
Vs: 66 kV
66 kV
FBTS-66kV Bus Link
1 Meters
Ampacity: 0 A
0.84 kA
Pl: 0.0009 kW
Ql: 9.2203 kVar
SVTS_66kV
Vs: 66 kV
65.9973 kV
SVTS-EB
7000 Meters
Ampacity: 1260 A
0.5813 kA
Pl: 180.1879 kW
Ql: -5893.5874 kVar
SVTS-RD
13800 Meters
Ampacity: 1260 A
0.2628 kA
Pl: 82.4106 kW
Ql: -13877.2002 kVar
EB-RD
6000 Meters
Ampacity: 1260 A
0.073 kA
Pl: 0.9302 kW
Ql: -6234.4644 kVar
Substation EB - 66kV Bus
Vs: 66 kV
65.1112 kV
Substation RD - 66kV Bus
Vs: 66 kV
65.2044 kV
EB Tx1
30000 kVA
0.223 kA
Pl: 135.8237 kW
Ql: 3047.259 kVar
EB Tx2
30000 kVA
0.223 kA
Pl: 135.8237 kW
Ql: 3047.259 kVar
EB Tx3
30000 kVA
0.223 kA
Pl: 135.8237 kW
Ql: 3047.259 kVar
RD Tx1
30000 kVA
0.1503 kA
Pl: 65.4955 kW
Ql: 2043.3422 kVar
RD Tx2
30000 kVA
0.1503 kA
Pl: 65.4955 kW
Ql: 2043.3422 kVa
Substation EB - 22kV Bus
69900 kVA
Vs: 22 kV
21.1151 kV
Substation RD - 11kV Bus
26.775 MW
16.5937 MVAR
Vs: 11 kV
10.5919 kV



WMTS-DA3
1303 Meters
Ampacity: 280 A
0.136 kA
Pl: 16.3398 kW
Ql: -98.763 kVar
WMTS-DA2
1303 Meters
Ampacity: 280 A
0.1433 kA
Pl: 17.1609 kW
Ql: -329.6457 kVar
WMTS-DA1
1287 Meters
Ampacity: 280 A
0.1467 kA
Pl: 17.3743 kW
Ql: -96.3476 kVar
Substation DA - 22kV Bus
Vs: 22 kV
21.924 kV
DA Tx3
13500 kVA
0.1446 kA
Pl: 23.8675 kW
Ql: 258.8987 kVar
DA Tx2
13500 kVA
0.1446 kA
Pl: 23.8675 kW
Ql: 258.8987 kVar
DA Tx1
13500 kVA
0.1446 kA
Pl: 23.8675 kW
Ql: 258.8987 kVar
Substation DA - 11kV Bus
13.5952 MW
8.4256 MVAR
Vs: 6.6 kV
WMTS-LS2
691 Meters
Ampacity: 325 A
0.2258 kA
Pl: 16.753 kW
Ql: -52.0384 kVar
WMTS-LS1-2
691 Meters
Ampacity: 325 A
0.2133 kA
Pl: 16.1517 kW
Ql: -53.1634 kVar
WMTS-LS1
691 Meters
Ampacity: 325 A
0.2133 kA
Pl: 16.1517 kW
Ql: -53.1634 kVar
Substation LS - 22kV Bus
Vs: 22 kV
21.9489 kV
LS Tx3
13500 kVA
0.1364 kA
Pl: 17.03 kW
Ql: 219.119 kVar
LS Tx2
10000 kVA
0.1364 kA
Pl: 17.03 kW
Ql: 219.119 kVar
LS Tx1
10000 kVA
0.1364 kA
Pl: 17.03 kW
Ql: 219.119 kVar
Substation LS -6.6kV Bus
12.8887 MW
7.9877 MVAR
Vs: 6.6 kV
6.4159 kV
GRID
WMTS_22kV_Supply
Vs: 22 kV
22 kV
WMTS-22kV Bus Link
1 Meters
Ampacity: 0 A
1.8107 kA
Pl: 0.0005 kW
Ql: 4.7606 kVar
J-LS
2133 Meters
Ampacity: 325 A
0.1256 kA
Pl: 15.5887 kW
Ql: -181.9468 kVar
J-LS2
2133 Meters
Ampacity: 325 A
0.1256 kA
Pl: 15.5887 kW
Ql: -181.9468 kVar
Substation J - 22kV Bus
Vs: 22 kV
21.8635 kV
WMTS-J3
3300 Meters
Ampacity: 325 A
0.1186 kA
Pl: 24.5552 kW
Ql: -283.0441 kVar
WMTS-J2
3300 Meters
Ampacity: 325 A
0.1256 kA
Pl: 25.4694 kW
Ql: -281.3337 kVar
WMTS-J1
3300 Meters
Ampacity: 325 A
0.1256 kA
Pl: 25.4694 kW
Ql: -281.3337 kVar
J Tx4
10000 kVA
0.1402 kA
Pl: 22.2709 kW
Ql: 306.4248 kVar
J Tx3
10000 kVA
0.1402 kA
Pl: 22.2709 kW
Ql: 306.4248 kVar
J Tx2
10000 kVA
0.1402 kA
Pl: 22.2709 kW
Ql: 306.4248 kVar
J Tx1
10000 kVA
0.1402 kA
Pl: 22.2709 kW
Ql: 306.4248 kVar
Substation J - 6.6kV Bus
17.4242 MW
10.7985 MVAR
Vs: 6.6 kV
6.3291 kV
BSBQ-J
2420 Meters
Ampacity: 325 A
0.0406 kA
Pl: 1.7485 kW
Ql: -215.2064 kVar
BSBQ-J2
2420 Meters
Ampacity: 325 A
0.0384 kA
Pl: 1.6858 kW
Ql: -215.3238 kVar
Substation BSBQ 22kV Bus
Vs: 22 kV
21.8331 kV
BSBQ Tx3
10000 kVA
0.1482 kA
Pl: 3.187 kW
Ql: 272.4886 kVar
BSBQ Tx2
10000 kVA
0.1556 kA
Pl: 3.5161 kW
Ql: 286.2094 kVar
BSBQ Tx1
10000 kVA
0.153 kA
Pl: 3.3962 kW
Ql: 281.3715 kVar
Substation BSBQ 11kV Bus
14.2877 MW
8.8547 MVAR
Vs: 11 kV
10.6222 kV
WMTS-BSBQ2
2880 Meters
Ampacity: 325 A
0.1735 kA
Pl: 43.7414 kW
Ql: -797.2224 kVar
WMTS-BSBQ1
2700 Meters
Ampacity: 325 A
0.1893 kA
Pl: 46.6575 kW
Ql: -213.7643 kVar
WMTS_22kV
Vs: 22 kV
21.9992 kV


Substation RP - 22kV Bus
Vs: 22 kV
21.7067 kV
RP Tx3
13500 kVA
0.1364 kA
Pl: 8.1008 kW
Ql: 221.9619 kVar
RP Tx2
13500 kVA
0.1364 kA
Pl: 8.1008 kW
Ql: 221.9619 kVar
RP Tx1
13500 kVA
0.1364 kA
Pl: 8.1008 kW
Ql: 221.9619 kVar
Substation RP -6.6kV Bus
15000 kVA
Vs: 6.6 kV
6.3505 kV
RTS-RP2
5600 Meters
Ampacity: 1260 A
0.2122 kA
Pl: 20.5871 kW
Ql: -499.0203 kVar
RTS-RP1
6400 Meters
Ampacity: 1260 A
0.1789 kA
Pl: 39.2007 kW
Ql: -621.8911 kVar
RTS-SM3
4700 Meters
Ampacity: 1260 A
0.703 kA
Pl: 169.5206 kW
Ql: 853.2081 kVar
RTS-SM2
4700 Meters
Ampacity: 1260 A
0.703 kA
Pl: 169.5206 kW
Ql: 853.2081 kVar
RTS-SM1
4700 Meters
Ampacity: 1260 A
0.703 kA
Pl: 169.5206 kW
Ql: 853.2081 kVar
SM Tx3
50000 kVA
1.0715 kA
Pl: 266.7476 kW
Ql: 4334.6484 kVar
SM Tx2
50000 kVA
1.0715 kA
Pl: 266.7476 kW
Ql: 4334.6484 kVar
SM Tx1
50000 kVA
1.0715 kA
Pl: 266.7476 kW
Ql: 4334.6484 kVar
Substation SM - 11kV Bus
110000 kVA
Vs: 11 kV
10.3723 kV
Substation SM - 22kV Bus
Vs: 22 kV
21.1954 kV
R-SM1
4800 Meters
Ampacity: 1260 A
0.5308 kA
Pl: 107.1013 kW
Ql: 268.8644 kVar
R-SM2
4800 Meters
Ampacity: 1260 A
0.5308 kA
Pl: 107.1013 kW
Ql: 268.8644 kVar
RTS_22kV_Supply
Vs: 22 kV
22 kV
GRID
RTS-22kV Bus Link
1 Meters
Ampacity: 0 A
5.1355 kA
Pl: 0.0038 kW
Ql: 38.2935 kVar
Substation R - 22kV Bus
Vs: 22 kV
21.8171 kV
R Tx3
14000 kVA
0.3141 kA
Pl: 99.7145 kW
Ql: 1388.5525 kVar
R Tx2
14000 kVA
0.3141 kA
Pl: 99.7145 kW
Ql: 1388.5525 kVar
R Tx1
14000 kVA
0.3141 kA
Pl: 99.7145 kW
Ql: 1388.5525 kVar
Substation R - 6.6kV Bus
33000 kVA
Vs: 6.6 kV
6.0654 kV
RTS-R3
1100 Meters
Ampacity: 1260 A
0.6826 kA
Pl: 40.0196 kW
Ql: 174.4204 kVar
RTS-R2
1100 Meters
Ampacity: 1260 A
0.6826 kA
Pl: 40.0196 kW
Ql: 174.4204 kVar
RTS-R1
1100 Meters
Ampacity: 1260 A
0.6826 kA
Pl: 40.0196 kW
Ql: 174.4204 kVar
PR-R1
5800 Meters
Ampacity: 1260 A
0.0357 kA
Pl: 0.3989 kW
Ql: -672.2016 kVar
PR-R2
5800 Meters
Ampacity: 1260 A
0.0357 kA
Pl: 0.3989 kW
Ql: -672.2016 kVar
Substation PR - 22kV Bus
Vs: 22 kV
21.784 kV
PR Tx3
11700 kVA
0.2234 kA
Pl: 58.1032 kW
Ql: 628.8477 kVar
PR Tx2
11700 kVA
0.2234 kA
Pl: 58.1032 kW
Ql: 628.8477 kVar
PR Tx1
13500 kVA
0.2287 kA
Pl: 39.0209 kW
Ql: 645.2871 kVar
Substation PR - 11kV Bus
24300 kVA
Vs: 11 kV
10.5223 kV
RTS-PR2
3100 Meters
Ampacity: 1260 A
0.2966 kA
Pl: 21.6302 kW
Ql: -199.8366 kVar
RTS-PR1
3100 Meters
Ampacity: 1260 A
0.2966 kA
Pl: 21.6302 kW
Ql: -199.8366 kVar
RTS_22kV
Vs: 22 kV
21.9974 kV


GRID
BTS_Supply
Vs: 22 kV
22 kV
BTS-22kV Bus Link
1 Meters
Ampacity: 0 A
2.7684 kA
Pl: 0.0011 kW
Ql: 11.1285 kVar
BTS_22kV
Vs: 22 kV
21.9986 kV
BTS-BK2
2610 Meters
Ampacity: 1260 A
0.2007 kA
Pl: 8.391 kW
Ql: -243.9853 kVar
BTS-BK1
2590 Meters
Ampacity: 1260 A
0.2023 kA
Pl: 8.4558 kW
Ql: -241.1357 kVar
Substation BK - 22kV Bus
Vs: 22 kV
21.8682 kV
BK Tx3
10000 kVA
0.1377 kA
Pl: 16.0966 kW
Ql: 219.3271 kVar
BK Tx2
10000 kVA
0.1377 kA
Pl: 16.0966 kW
Ql: 219.3271 kVar
BK Tx1
10000 kVA
0.1377 kA
Pl: 16.0966 kW
Ql: 219.3271 kVar
Substation BK -6.6kV Bus
15200 kVA
Vs: 6.6 kV
6.3749 kV
BTS-NS2
6000 Meters
Ampacity: 1260 A
0.4473 kA
Pl: 95.8309 kW
Ql: 36.5966 kVar
BTS-NS1
6000 Meters
Ampacity: 1260 A
0.4473 kA
Pl: 95.8309 kW
Ql: 36.5966 kVar
Substation NS - 22kV Bus
Vs: 22 kV
21.35 kV
NS Tx3
13500 kVA
0.3056 kA
Pl: 80.9357 kW
Ql: 1123.7406 kVar
NS Tx2
13500 kVA
0.3056 kA
Pl: 80.9357 kW
Ql: 1123.7406 kVar
NS Tx1
13500 kVA
0.3056 kA
Pl: 80.9357 kW
Ql: 1123.7406 kVar
Substation NS - 11kV Bus
31800 kVA
Vs: 11 kV
10.1461 kV
BTS-C3
2000 Meters
Ampacity: 1260 A
0.1641 kA
Pl: 4.2769 kW
Ql: -203.91 kVar
BTS-C2
2000 Meters
Ampacity: 1260 A
0.1641 kA
Pl: 4.2769 kW
Ql: -203.91 kVar
Substation C - 22kV Bus
Vs: 22 kV
21.9246 kV
C Tx3
7500 kVA
0.1116 kA
Pl: 12.5915 kW
Ql: 175.3398 kVar
C Tx2
7500 kVA
0.1116 kA
Pl: 12.5915 kW
Ql: 175.3398 kVar
C Tx1
7500 kVA
0.1116 kA
Pl: 12.5915 kW
Ql: 175.3398 kVar
Substation C - 6.6kV Bus
12400 kVA
Vs: 6.6 kV
6.4137 kV
BTS-F2
2500 Meters
Ampacity: 1260 A
0.216 kA
Pl: 9.3128 kW
Ql: -223.783 kVar
BTS-F1
2400 Meters
Ampacity: 1260 A
0.2252 kA
Pl: 9.7008 kW
Ql: -209.0582 kVar
Substation F - 22kV Bus
Vs: 22 kV
21.8504 kV
F Tx3
10000 kVA
0.1506 kA
Pl: 18.5826 kW
Ql: 269.8432 kVar
F Tx2
10000 kVA
0.1506 kA
Pl: 18.5826 kW
Ql: 269.8432 kVar
F Tx1
10000 kVA
0.1506 kA
Pl: 18.5826 kW
Ql: 269.8432 kVar
Substation F - 6.6kV Bus
16500 kVA
Vs: 6.6 kV
6.324 kV
BTS-FF2
3200 Meters
Ampacity: 1260 A
0.3528 kA
Pl: 31.5417 kW
Ql: -135.362 kVar
BTS-FF1
3200 Meters
Ampacity: 1260 A
0.3528 kA
Pl: 31.5417 kW
Ql: -135.362 kVar
Substation FF - 22kV Bus
Vs: 22 kV
21.7254 kV
FF Tx3
10000 kVA
0.2392 kA
Pl: 62.7994 kW
Ql: 721.0306 kVar
FF Tx2
10000 kVA
0.2392 kA
Pl: 62.7994 kW
Ql: 721.0306 kVar
FF Tx1
10000 kVA
0.2392 kA
Pl: 62.7994 kW
Ql: 721.0306 kVar
Substation FF - 11kV Bus
25600 kVA
Vs: 6.6 kV
6.26 kV


GRID
NT_Supply
Vs: 22 kV
22 kV
NT-22kV Bus Link
1 Meters
Ampacity: 0 A
0.95 kA
Pl: 0 kW
Ql: 1.31 kVar
NT_22kV
Vs: 22 kV
22 kV
NT-TP1
18405 Meters
Ampacity: 1260 A
0.09 kA
Pl: 14.32 kW
Ql: -2027.31 kVar
NT-TP2
8793 Meters
Ampacity: 1260 A
0.21 kA
Pl: 29.97 kW
Ql: -778.8 kVar
NT Load 1 link
1 Meters
Ampacity: 0 A
0.22 kA
Pl: 0 kW
Ql: 0.07 kVar
NT Load 1 link2
1 Meters
Ampacity: 0 A
0.43 kA
Pl: 0 kW
Ql: 0.27 kVar
Substation TP - 22kV Bus
Vs: 22 kV
21.61 kV
NT Load 1
7.9 MW
2.6 MVAR
Vs: 22 kV
22 kV
NT Load 2
15.59 MW
5.12 MVAR
Vs: 22 kV
22 kV
TP Tx1
10000 kVA
0.18 kA
Pl: 23.63 kW
Ql: 389.41 kVar
TP Tx2
10000 kVA
0.16 kA
Pl: 24.81 kW
Ql: 353.53 kVar
Substation TP -6.6kV Bus
12400 kVA
Vs: 6.6 kV
6.38 kV