TECHNICAL PRE-FEASIBILITY FOR DEVELOPING A TRANSMISSION SYSTEM INTERCONNECTION BETWEEN INDIA AND SRI LANKA – *A CASE STUDY FOR MADURAI – VEYANGODA INTERCONNECTION*

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the degree of Master of Science

by

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Declaration

The work submitted in this dissertation is the result of my own investigation, except where otherwise stated.

It has not already been accepted for any degree, and it also not being concurrently submitted for any other degree.

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Contents

Abstract

To cater to the growing demand of power in Sri Lanka, establishing a power transmission interconnection between India and Sri Lanka has become very important at present. The objective of this study is to do a technically pre-feasibility analysis of such an interconnection with the power system in 2008 and to propose a new interconnection option for the transmission of power.

Capability of the power transmission and the capacity of the link are decided by analyzing the present and future generation capacity in both countries. The locations for the potential terminus points for the interconnection are decided by examining the transmission systems. The most suitable power transmission method is selected by considering the technical and economic aspects. Finally the power transmission system of Sri Lanka is modeled with the selected interconnections and the power flow studies are carried out to analyze the performance of the system and to find the most suitable interconnection.

According to the present and future generation and transmission capacity in both countries there is enough opportunity to justify a transmission interconnection between India and Sri Lanka. The capacity of the link has been decided for 500MW in short term and for 1000MW in medium term. Since there are many advantages of using HVDC over HVAC, HVDC technology has been chosen and for the reliability the bipolar configuration was selected. And the selected voltage was HVDC 400kV. As for the forecasted loads of the grid substations and the locations (nearness to the major load centers) of them Veyangoda grid substation was taken as the terminus point for the power interconnection in Sri Lanka. The decided route for the interconnection is via Mannar.

Transmission system analyses were done for two cases as 500MW connected to Veyangoda and to New Anuradhapura. The observed low voltages at 220kV AC busses in both cases highlighted the requirement of reactive power addition to the system. The results of the studies confirmed that the transmission system around New Anuradhapura is fairly weak compared to the transmission system around Veyangoda. Also the losses of the system were high in New Anuradhapura case. Therefore Veyangoda grid substation was selected as the terminus point of the India – Sri Lanka power interconnection.

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Chapter 1

1.0 Background and Scope

1.1 Introduction

Electricity is a basic need for the economic growth of any country. Therefore the electricity demand grows at a higher rate with the rapid development of the economy. To meet the increasing demand of electricity the addition of new generation capacity to the system is required. There are two options for the addition of new generation, building new power plants or importing power from a neighboring country. Since the large scale hydro power additions are limited and the import of fuel is expensive, Sri Lanka has to go for the other options to increase its power generation, there the import of power from its neighboring country India comes in to the picture.

1.2 Background

Interconnections of large power systems are a worldwide phenomenon. This rapid development of transmission network interconnections between neighboring countries has taken place due to need of meeting growing power demand, concentration of various type of energy resources in different countries, economy of scale, decrease in operational cost through better resource management, usage of renewable energy resources and cutting investment cost by optimizing spinning reserve. There are several transnational interconnections existing in different parts of the world, such as America, Africa, North East Asia and South East Asia, which have provided considerable benefits to the parties concerned [1].

As the power systems of developing countries expand, and in particular when market reforms take place in the electric power sector, it becomes increasingly economical to interconnect with neighbouring countries to benefit from the pooling of resources. There are many political, economic, contractual and legal issues that need to be addressed when such international interconnections are established [1].

Establishing a new interconnection between two separated power systems involves much more than just a new transmission line between the two closest substations. There are several issues that have to be addressed;

- Amount of power that needs to be exchanged in each direction
- Availability of suitable terminus substations for the interconnection
- Reliability requirements to ensure all standards are met
- Compatibility of the frequencies of the two grids
- Appropriate method of transmission interconnection
- High voltage DC Vs. AC with back-to-back DC

The thought of establishing a power transmission interconnection between India and Sri Lanka was first considered in late 1970's [1}. In 2002 it was again considered and the viability of the interconnection and the technical options were considered by the United States Agency for International Development (USAID) with Nexant under the South Asia Regional Initiative for Energy (SARI/ENERGY) program and the pre-feasibility studies for the selected option (Madurai – New Anuradhapura) was done in 2006 [2].

1.3 Objective

The objective of this study is to find out the technical feasibility of a transmission system interconnection between India and Sri Lanka with the power system in 2008 and to propose a new interconnection option (Madurai – Veyangoda) for the transmission of power.

1.4 Methodology

The methodology followed in this pre-feasibility study is as follows;

- Capability of the power transmission and the capacity of the link were decided by analyzing the present and future generation capacity in both India and Sri Lanka.
- The most suitable power transmission method was selected by considering the technical and economic aspects.
- Identifying of the locations in Sri Lanka for the potential terminus point for the interconnection was done by examining the transmission system in Sri Lanka.
- The power transmission system of Sri Lanka was modeled with the selected interconnection and the power flow studies were carried out to analyze the performance of the system and to select the most suitable terminus point.

Chapter 2

2.0 Analyzing of the present power systems

2.1 Present Indian power system

The Indian Power System is demarcated into five electrical regions, namely – Northern, Southern, Western, Eastern and North-eastern Region. At present, all the regions except Southern Region are operating in synchronism. Southern Region is connected with Eastern and Western region through asynchronous links (HVDC back-to-back and bipolar) [2].

The present installed capacity of India is 141,080MW. The generation is mainly dominated by Coal-based power plants. About 64% of installed capacity is thermal based while 25% is hydro based. India has about 8% installed capacity from renewable sources. Each of the Northern, Western and Southern Regions share about 30% of the installed capacity while Eastern Region and North Eastern Regions share 14% and 2% of the installed capacity respectively. Out of the five regions, Northern (34%), Southern (27%) and North-Eastern (45%) have a substantial capacity of hydro –based generation plants. The same in Eastern (17%) and Western (17%) Regions are comparatively on lower side. The region-wise installed capacity for different fuel based generation is given in Table 2.1 [3].

The present peak demand of India is 111,198MW. Western (34%) and Northern (29%) Regions share the majority of the demand. Region-wise peak demand is given in Table 2.2 [3].

Table 2. 1: Region-wise installed capacity for different fuel based generation in India

Region /Islands	Hydro	Thermal				Renew-able	Nucl-ear	Grand Total
		Coal	Gas	Diesel	Total			
Northern	12,899	18,578	3,543	15	22,136	1,271	1,180	37,488
	34%				59%	3%	3%	27%
Western	7,199	23,753	6,601	17	30,371	3,011	1,840	42,420
	17%				72%	7%	4%	30%
Southern	10,646	16,683	3,586	939	21,208	6,221	1,100	39,175
	27%				54%	16%	3%	28%
Eastern	3,349	15,660	190	17	15,867	200	0	19,416
	17%				82%	1%		14%
North Eastern	1,116	330	772	143	1,244	146	0	2,506
	45%				50%	6%		2%
Islands*	0	0	0	70	70	6	0	76
	0%				92%	8%		0%
All India	35,209	75,002	14,692	1,202	90,896	10,855	4,120	141,080
	25%				64%	8%	3%	

*(Andaman & Nicobor, Lakshadweep)

Table 2. 2: Region-wise peak demand in India

Region	Peak Demand (MW)	Percentage
Northern Region	32,462	29%
Western Region	38,277	34%
Southern Region	26,777	24%
Eastern Region	11,940	11%
North Eastern Region	1,742	2%
TOTAL	**111,198**	

The transmission system of India comprises of 765kV, 400kV, 220kV and 132kV AC transmission lines as well as ±500kV HVDC back-to-back, mono-pole and bipolar system. In addition to the above, there are 220kV and 132kV lines in the state grid to draw and transmit power to different load centers in the state.

The inter-regional transmission capacity is 16,450 MW and inter-regional energy exchanges is more than 12 billion kWh in a year. Below Table 2.3 shows the inter-regional capacity of the transmission lines [3].

Table 2. 3: Inter-regional capacity of the transmission lines in India

Transmission line	Capacity (MW)
765kV	1,100
400kV	7,800
HVDC bi-pole	2,500
HVDC b-t-b	3,000
HVDC mono-pole	200
220kV	1,850
TOTAL	**16,450**

The power situation of five regions and of all India based on data from April 2007 to March 2008 is given in Table 2.4. At present, the total shortage of peak demand is 16.6% and that of peak energy is 9.8%.

Table 2. 4: The power situation of India from April 2007 to March 2008

Region	Energy Requirement (MU)	Deficit %	Peak Demand (MW)	Deficit %
Northern	217,589	-10.4	32,462	-9.1
Western	247,156	-15.8	38,277	-23.2
Southern	187,736	-3.2	26,777	-9.0
Eastern	75,772	-5.0	11,940	-10.4
North Eastern	8,799	-12.3	1,742	-22.7
All India	**737,052**	**-9.8**	**111,198**	**-16.6**

According to the "11th National Electricity Plan" of Central Electricity Authority of India, the future power supply scenario of each region for peak and off-peak condition of three prominent seasons i.e. Summer, Winter & Monsoon are given in Table 2.5 for 2011-12 condition [4].

Table 2. 5: Future power supply scenario of India for 2001-12 condition

Region	Peak Demand	Installed Capacity	Surplus/Deficit					
			Summer		Winter		Monsoon	
			Peak	Off-Peak	Peak	Off-Peak	Peak	Off-Peak
Northern	44,820	54,495	-2,598	-1,853	-8,768	-5,288	5,562	12,035
Western	51,770	58,602	-6,262	6,813	-5,458	9,386	-1,889	9,416
Southern	38,310	46,261	-762	5,170	-3,424	5,123	1,293	8,440
Eastern	13,240	35,958	12,445	14,680	12,513	14,832	13,700	15,852
North-eastern	2,160	8,213	4,410	3,748	2,445	581	5,853	5,738
All India	**150,300**	**203,529**	**7,233**	**28,558**	**-2,692**	**24,634**	**24,519**	**51,481**

During the 11th Plan, 20,700 MW of inter-regional transmission capacity is planned to be added. This would take the total inter-regional transmission capacity to be 37,150 MW by the end of 11th Plan period that is by 2011-12. The details of the capacity of interregional links between different regions expected to be added by 2011-12 are given Table 2.6 [4].

Table 2. 6: Future capacity of interregional links by 2011-12

Name of the link	Capacity(MW)
Eastern – Northern	3,500
Eastern – Western	5,700
Western – Northern	5,500
Southern – Western	1,000
Eastern - North eastern	1,000
North eastern – Northern	4,000
Total addition by 2012	**20,700**
GRAND TOTAL (up to 2012)	**37,150**

The frequency profile of the system remains within the desired band of 49Hz and 50.5Hz.

2.2 Present Sri Lankan power system

Ceylon Eelectricity Board (CEB) is responsible for Generation, Transmission and Distribution of the major parts of electricity in Sri Lanka. Presently, CEB has hydro and thermal power stations connected to the transmission system, which operates at 220 kV and 132 kV.

The total installed capacity of all hydro power stations owned and operated by CEB in year 2007 was 1,207 MW. The total installed capacity of all thermal power plants owned by CEB is 548 MW and there is a wind plant owned by CEB of 3 MW. In addition to this 567 MW (excluding emergency power plants) of private thermal power plants were connected to the system. Approximately 119 MW of embedded generation plants were connected to the system by year 2007. Further 15 MW of thermal generation is installed at Chunnakam and KKS to meet the demand in Jaffna peninsula [5]. The distribution of generation capacity of Sri Lanka in absolute terms and percentage ratio are given in Table 2.7 [6].

Table 2. 7: The distribution of generation capacity

Type of Generation	Capacity (MW)	Percentage
Hydro	**1,207**	**49%**
Thermal		
CEB Thermal	548	22%
IPP Thermal	567	23%
Subtotal(thermal)	**1,115**	**46%**
Small Power Producer	119	5%
CEB Wind	3	0.12%
TOTAL	**2,444**	

Based on the future requirements of power and energy the future generation of Sri Lanka has been planned. Out of total 3,675 MW of generation addition planned up to 2015 only 150MW of hydro and 600MW of thermal power plants (combined cycle at Kerawalapitiya and coal power at west coast) are committed till date. Due to the social and/or environmental factors as well as cost the future exploitation of hydro resources are becoming more and more difficult. Therefore all the future power plants other than 150MW of hydro power are planned as thermal generation. The list of the future power plants and the retirements of the existing plants up to 2015 are given in Table 2.8 [6].

Table 2. 8: List of future power plants up to 2015

	Plant Name	Total Capacity (MW)	Years of Commissioning
I	**Committed Power Plants**		
A	**Hydro**		
	1. Upper Kotmale	150	2011
B	**Thermal (IPP)**		
	1. Kerawalapitiya CCY (GT :200, ST: 100)	200	2008
		100	2009
	2. Coal-Steam (West Coast)	300	2011
	Subtotal (Committed Plants)	***750***	
II	**Other Power Plants (Thermal)**		
	1. Gas Turbine (4x105 MW)	420	2010
	2. Gas Turbine (3x35 MW)	105	2010
	3. Coal-Steam (West Coast)	600	2012
	4. Coal-Steam (East Coast)	300	2012
		600	2013
	5. Coal-Steam (Southern Coast)	300	2014
		600	2015
	Subtotal (Other Plants)	***2,925***	
	Total (addition of Generation)	***3,675***	
III	**Retirement of Plants**		
	1. Kelanitissa Gas Turbine	-68	2011
	2. ACE Power Matara	-20	2012
	3. 22.5 MW Lakdhanavi, 4x18 MW Sapugaskanda diesel Plant, 20 MW ACE Power Horana	-114.5	2013
	4. 60 MW Colombo Power Plant, 100 MW Heladhanavi Diesel Power Plant at Puttlam, 100 MW Diesel Power Plant at Embilipitiya	-260	2015
	Subtotal (Retired Plants)	***-462.5***	
	Total (net addition of Generation at 2015)	**3,212.5**	

The present peak demand of Sri Lanka is about 1,842 MW and the gross generation is 9,814 GWh. The demand for electricity has been increasing at a rate of 7-8% per annum for the last 20 years. At present the power system of Sri Lanka does not have any appreciable surplus or deficit of power. The present maximum demand is generally met by the existing generation.

The 220 kV and 132 kV voltage levels are used as the transmission voltages of the system. The System Control Centre located at Dematagoda manages the control and operation of the Sri Lanka's power system.

The 220 kV transmission network is mainly used to transmit power from Mahaweli hydro power generating stations namely Kotmale, Victoria, Randenigala and Rantembe to main load centers through Kotugoda, Pannipitiya and Biyagama grid substations. The 132kV transmission network is used to interconnect most of the grid substations and to transfer power from other power stations. 220/132kV inter-bus transformers are installed in the network to transfer power between the two voltage levels. The present transmission system has six 220/132 /33 kV grid substations. In addition, the system consists of thirty seven 132/33 kV grid substations, and four 132/11 kV indoor, Gas Insulated Switchgear (GIS) type substations. At present total route length of 220kV transmission line is 331 km and that of 132kV transmission line is 1,716 km [7].

According to the "Long term transmission development plan 2006-2015" prepared by CEB, by 2015 there will be new seventeen 132/33 kV grid substations, three 132/11 kV GIS substations, around 700 km 132 kV & 640 km 220 kV transmission lines. And also there will be fifteen 220 kV new and augmented grid substations.

Based on past data, rate of growth etc. the forecast of energy to be consumed along with losses up to 2026 has been estimated by CEB. The energy to be generated to meet the above requirement is thereafter calculated by adding loss with energy demand. Year-wise list of energy consumption and generation in terms of GWh as well as power demand at generation end in terms of MW from 2006 to 2026 is given in Table 2.9 [6]: (*National Power and Energy Forecast for 2006-2026 prepared by CEB)*

Table 2. 9: Power demand at generation end from 2006 to 2026

Year	Generation (GWh)	Losses %	Demand (GWh)	LF %	Generation peak (MW)
2006	9,426	17.1	7,811	56.8	1,894
2007	10,182	16.7	8,485	57.0	2,041
2008	11,058	16.1	9,280	57.1	2,211
2009	12,027	15.5	10,158	57.2	2,399
2010	13,122	15.0	11,153	57.4	2,611
2011	14,335	14.6	12,242	57.5	2,845
2012	15,692	14.4	13,432	57.7	3,107
2013	17,167	14.2	14,726	57.8	3,390
2014	18,781	14.1	16,130	57.9	3,700
2015	20,549	14.1	17,650	58.1	4,038
2016	22,461	14.1	19,295	58.2	4,404
2017	24,542	14.1	21,085	58.4	4,800
2018	26,797	14.1	23,025	58.5	5,228
2019	29,239	14.1	25,125	58.6	5,691
2020	31,883	14.1	27,398	58.8	6,191
2021	34,739	14.1	29,856	58.9	6,729
2022	37,844	14.0	32,528	59.1	7,313
2023	41,209	14.0	35,424	59.2	7,944
2024	44,850	14.0	38,559	59.4	8,626
2025	48,793	14.0	41,953	59.5	9,362
2026	53,058	14.0	45,626	59.6	10,156

The availability of generation has been calculated by comparing the installed capacity and the generation and this availability factor was used to find out the generation capacity available for dispatch.

Installed Capacity (MW) (excluding wind and embedded generation)	2,322
Maximum Gen (MW)	1,842
Availability Factor	**0.79**

For the future time frame the surplus-deficit of power of Sri Lanka can calculate by subtracting the demand at generating end from the availability of generation. Due to uncertainty in future generation addition, the surplus-deficit of power will calculate for the following conditions:

1. With all Proposed future Generation

1	Capacity(MW)							
	2008	2009	2010	2011	2012	2013	2014	2015
I. Hydro(Existing & Committed)	1,207	1,207	1,207	1,357	1,357	1,357	1,357	1,357
IIa. Thermal(Existing & Committed)	1,315	1,415	1,415	1,647	1,627	1,512.5	1,512.5	1,252.5
IIb. Other Thermal (Future)	0	0	525	525	1,425	2,025	2,325	2,925
II. Total Thermal	1,315	1,415	1,940	2,172	3,052	3,537.5	3,837.5	4,177.5
Total Annual Generation	**2,522**	**2,622**	**3,147**	**3,529**	**4,409**	**4,894.5**	**5,194.5**	**5,534.5**
Availability	**1,992**	**2,071**	**2,486**	**2,788**	**3,483**	**3,867**	**4,104**	**4,372**
Demand at Gen End	**2,211**	**2,399**	**2,611**	**2,845**	**3,107**	**3,390**	**3,700**	**4,038**
Surplus/Deficit	**-219**	**-328**	**-125**	**-57**	**376**	**477**	**404**	**334**

2. With only Committed future Generation

2								
	2008	2009	2010	2011	2012	2013	2014	2015
I. Hydro(Existing & Committed)	1,207	1,207	1,207	1,357	1,357	1,357	1,357	1,357
IIa. Thermal(Existing & Committed)	1,315	1,415	1,415	1,647	1,627	1,512.5	1,512.5	1,252.5
IIb. Other Thermal (Future)	0	0	0	0	0	0	0	0
II. Total Thermal	1,315	1,415	1,415	1,647	1,627	1,512.5	1,512.5	1,252.5
Total Annual Generation	**2,522**	**2,622**	**2,622**	**3,004**	**2,984**	**2,869.5**	**2,869.5**	**2,609.5**
Availability	**1,992**	**2,071**	**2,071**	**2,373**	**2,357**	**2,267**	**2,267**	**2,062**
Demand at Gen End	**2,211**	**2,399**	**2,611**	**2,845**	**3,107**	**3,390**	**3,700**	**4,038**
Surplus/Deficit	**-219**	**-328**	**-540**	**-472**	**-750**	**-1,123**	**-1,433**	**-1,976**

3. With committed generation and 50% of other Proposed future Generation

3								
	2008	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**
I. Hydro(Existing & Committed)	1,207	1,207	1,207	1,357	1,357	1,357	1,357	1,357
IIa. Thermal(Existing & Committed)	1,315	1,415	1,415	1,647	1,627	1,512.5	1,512.5	1,252.5
IIb. Other Thermal (Future)	0	0	262.5	262.5	712.5	1,012.5	1,162.5	1,462.5
II. Total Thermal	1,315	1,415	1,677.5	1,909.5	2,339.5	2,525	2,675	2,715
Total Annual Generation	**2,522**	**2,622**	**2,884.5**	**3,266.5**	**3,696.5**	**3,882**	**4,032**	**4,072**
Availability	**1,992**	**2,071**	**2,279**	**2,581**	**2,920**	**3,067**	**3,185**	**3,217**
Demand At Gen End	**2,211**	**2,399**	**2,611**	**2,845**	**3,107**	**3,390**	**3,700**	**4,038**
Surplus/Deficit	**-219**	**-328**	**-332**	**-264**	**-187**	**-323**	**-515**	**-821**

4. With committed generation and 25% of other Proposed future Generation

4								
	2008	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**
I. Hydro(Existing & Committed)	1,207	1,207	1,207	1,357	1,357	1,357	1,357	1,357
IIa. Thermal(Existing & Committed)	1,315	1,415	1,415	1,647	1,627	1,512.5	1,512.5	1,252.5
IIb. Other Thermal (Future)	0	0	131.25	131.25	356.25	506.25	581.25	731.25
II. Total Thermal	1,315	1,415	1,546.25	1,778.25	1,983.25	2,018.75	2,093.75	1,983.75
Total Annual Generation	**2,522**	**2,622**	**2,753.25**	**3,135.25**	**3,340.25**	**3,375.75**	**3,450.75**	**3,340.75**
Availability	**1,992**	**2,071**	**2,175**	**2,477**	**2,639**	**2,667**	**2,726**	**2,639**
Demand At Gen End	**2,211**	**2,399**	**2,611**	**2,845**	**3,107**	**3,390**	**3,700**	**4,038**
Surplus/Deficit	**-219**	**-328**	**-436**	**-368**	**-468**	**-723**	**-974**	**-1,399**

From the above analysis it can say that if all the proposed generation projects come out in time, there would be no significant surplus or deficit of power. But, if only the committed generation come out then there would be deficit of about 500MW in 2010, 750MW in 2012 and about 2,000MW in 2015 timeframe.

The load curves of Sri Lanka in general have two peaks, one during evening time and other during day time. The evening peak is very prominent and represents the maximum demand of the grid. It generally takes place at around 19:00pm. The day peak is not so sharp and occurs anytime during 6am to 12pm.

The fluctuations of voltage profile are allowed within a range of +5% and -10% in 220kV and +10% in 132kV. The voltages are generally maintained within the specified limits [7].

The nominal frequency of Sri Lanka grid is 50Hz and the allowable range of fluctuation is 50±0.5 Hz. The frequency profile is generally maintained in the band of 49.5-50.5Hz.

2.3 India - Sri Lanka Interconnection

Sri Lanka is an island in the Indian Ocean. The shortest distance between the end point of India and Sri Lanka is only 35km. Because of the nearness of the locations of the two countries the interconnections between these countries are feasible.

The interconnection between India and Sri Lanka has been planned to meet the requirement of economic power exchanges as well as emergency exchanges. Since hydro potentials of Sri Lanka have already been exploited the hydro dominance of the country would reduce gradually in future and the future generations are generally thermal based. India has a substantial amount of hydro based generation (overall 25%, 34% in Northern, 27% in Southern and 45% in North-Eastern Region). The interconnection between two countries would therefore provide much needed hydro support to Sri Lanka as well as thermal support to India during winter season. The two countries have mostly different festival holidays. This would also provide very good opportunity for transfer of power depending upon the availability and need of power.

As mentioned earlier Sri Lanka would not have appreciable surplus or deficit of power if the planned generations come up in time. But there will be a large deficit of power if only a 50% of the planned generation come up.

The future generation of Sri Lanka consists of mainly thermal and very little hydro. The hydro generation, which is at present about 49% of the installed capacity, is expected to reduce to 24% in the year 2015. In this process the hydro-thermal mix would decline year after year and Sri Lanka would be left with no other option than to meet its peak demand with thermal generation. This would lead to an expensive generation planning until strong interconnection is planned with India thereby taking the benefit of hydro power of India to meet peak load and finally have a better hydro-thermal mix.

The present power-supply scenario of India is facing peak deficit power. However depending on the implementation of future generation addition programme the situation is likely to improve in few years from now. The Southern Region itself is expected have surplus power except in the winter peak condition. Further, surplus power from Eastern Region and North Eastern Region of India would be transferred to other regions of India like Northern, Western and Southern Regions depending upon their need. Therefore India has potential for surplus power in major part of the year which could be sent to neighboring country like Sri Lanka.

The transfer of power from India to Sri Lanka can also reduce the use of expensive thermal generation based on liquid fuels. Thus a significant saving in cost can be achieved by importing cheaper power from India.

If the future generation comes up as per planning, Sri Lanka would be able to meet its peak demand. However this would lead to a significant amount of off-peak surplus power considering that the off-peak power is less than 50% of the peak power. Major part of this power can be utilized by exporting to India through transmission interconnection.

During winter period India faces problem due to low hydro generation. Sri Lanka does not have prominent winter season. Further in view of dominance of thermal generation in future, power from Sri Lanka can be transferred to India during low hydro condition of India. Therefore there is enough opportunity to transfer power to India during festival days as well as winter season.

Chapter 3

3.0 Selecting the most suitable power transmission method

3.1 Capacity of the connection

To decide the power transmission capacity between India and Sri Lanka it should consider the future power supply scenario of both the countries and the implementation time required for construction of transmission lines between two countries and the inverter/converter stations. In general the construction period can take as three years. Therefore the power supply scenario after three years (in 2011) should be considered.

To get the amount of surplus/deficit of power in Sri Lanka in future it will assume that 25% of proposed generation will implement other than committed generation. As mentioned earlier this condition will produce 368 MW of deficit in 2011 and 468 MW of deficit in 2012 and also around 1,000 MW of deficit in 2013 – 2015 periods.

On the other hand the Indian power scenario, even though facing peak deficit situation at present, is expected to produce surplus in peak power with implementation of future generation planned. Both Eastern and North-Eastern region would continue remain as surplus regions. The Southern region will remain in surplus situation except the peak condition of summer and winter periods. However, as a total in India the power situation gets worse considerably during winter period when availability of power reduces due to low hydro generation.

Depending on the implementation time and surplus/deficit of power, the requirement of power exchange between India and Sri Lanka can be analyzed for three types of time frames as;

Short term: First two years (2011-2012)

Medium term: Next three years (2013-2015)

Long term: After five years (After 2015)

The above power supply scenario suggests that in the short term period India and Sri Lanka can exchange power of about 500MW. The quantum of power exchange can be enhanced to about 1000MW in the medium time frame, then both the countries will have reasonable experience in exchange of power as well as comfortable power-supply scenario.

Depending upon the success of power exchange in short/medium term condition between India and Sri Lanka as well as the existing demand-supply scenario of both the countries, the quantum of power exchange for long term can be planned.

3.2 Connection across the Sea

India and Sri Lanka are separated by the Palk Strait. The distance across the sea between Dhanushkodi of India and Talaimanar of Sri Lanka is about 35km. There are two possibilities exist for the transmission interconnection across this sea portion. That is under sea cable or an overhead conductor using transmission towers.

Surveys and satellite pictures of Palk Strait show that the stretch of the sea between Dhanushkodi and Talaimanar is generally very shallow, and is dotted with many small islands every two or so kilometers. These features of the strait would facilitate construction of towers for overhead transmission lines, but it may be required 30m to 60m deep pile foundation for the building of towers [1]. Overhead transmission is beneficial if the technology for the power transmission is HVAC.

Under-sea or submarine cable is the most commonly used technology in the world for the cross border interconnections. Reduced environmental impacts, reduced transmission losses, elimination of potential health risks, increased security of supply with elimination of disruption due to extreme weather are among the advantages of submarine cables. Also the use of submarine cables has much more advantages over overhead lines if the transmission technology using is HVDC.

3.3 Transmission Technologies

There are two types of technologies for the transmission of power.

(1) High Voltage DC (HVDC)

Power is transferred in the form of direct current in this method. Generally HVDC is more expensive than AC. But since the losses in a DC transmission line is much less than in an AC transmission line, for the long distances of power transmission HVDC is the preferred choice.

In the HVDC technology it is needed a converter station (to convert AC to DC) at one connecting substation and an inverter station (to convert DC to AC) at the other connecting substation. The power is transmitted through a DC line. This method isolates one grid substation from the other as a result eliminating the requirement for frequency matching between the two grids.

The voltage of the HVDC line can be selected freely to provide the lowest overall cost, and it need not be coordinated with any of the AC system voltages. The highest DC voltage in use is ± 600 kV. A large number of HVDC transmissions in the 1200 – 3000 MW range operate at ± 500 kV. Most of the recent HVDC transmissions involving lines or cables have a rated capacity of 300 MW or higher because the cost per kW of the converter stations increases substantially at lower ratings [8].

The possibility to control the level of active power transmitted is one of the fundamental advantages with HVDC. This control is done electronically by the control systems included in the two converter stations. Often the main control mode is based on constant power transfer, i.e. the operator orders the link to transmit the amount of power to be exchanged. However in many cases the control systems of the link are designed to provide additional control action to improve the AC system performance.

One such control alternative often used in HVDC links interconnecting different power systems is to let the link automatically change the ordered power level to assist a network experiencing a problem, such as the loss of major generating unit.

Due to the fact that the power of the DC link is always controlled and limited so as not to exceed the link's capacity, there is never a risk that the interconnection will get overloaded and trip out when best needed. An HVDC link would also prevent disturbances occurring in one of the interconnected grids from spreading into the other. The worst that could happen is that the power flow on the HVDC interconnection would cease in case one of the grids gets so disturbed, that it is unable to deliver or receive power.

One of the fundamental properties of an HVDC transmission is its asynchronous nature. The networks connected to the rectifier and to the inverter stations need not to be in synchronism with each other. Interconnecting two grids by HVDC therefore allows them to retain individual frequency control. A disturbance in one of the AC systems that results in a frequency change will not affect the power transmitted the link, and there is no risk that the interconnection will become unstable.

(2) High voltage AC with back-to-back DC

An AC interconnection is the most commonly used technology. Generally AC interconnection is associated with the problem of matching the frequencies of two connecting grids, if the two grids either have widely different frequencies or if the frequencies fluctuate widely in one or both the grids. To overcome this problem an AC interconnection supplemented with DC is considered. This type of interconnection is called back-to-back DC. Here the power is transmitted over AC lines from one substation to another. Before delivering power to the other substation the AC power is first converted to DC and then immediately inverted to AC. This conversion and inversion process electrically isolates the two substations by this means eliminating the frequency fluctuation problem. Also the cost per kW of back-to-back AC station will remain low down to 100MW or below [8].

To select between HVAC and HVDC it has to compare the advantages and disadvantages of both.

Despite alternating current being the dominant mode for electric power transmission, in a number of applications, the advantages of HVDC makes it the preferred option over AC transmission. Examples include [9]:

- Undersea cables where high capacitance causes additional AC losses (e.g., the 250-km Baltic Cable between Sweden and Germany).
- Endpoint-to-endpoint long-haul bulk power transmission without intermediate taps, for example, in remote areas.
- Increasing the capacity of an existing power grid in situations where additional wires are difficult or expensive to install.

- Allowing power transmission between unsynchronized AC distribution systems.
- Reducing the profile of wiring and pylons for a given power transmission capacity, as HVDC can carry more power per conductor of a given size.
- Connecting a remote generating plant to the distribution grid; for example, the Nelson River Bipolar line in Canada (IEEE 2005).
- Stabilizing a predominantly AC power grid without increasing the maximum prospective short-circuit current.
- Reducing corona losses (due to higher voltage peaks) compared to HVAC transmission lines of similar power.
- Reducing line cost, since HVDC transmission requires fewer conductors; for example, two for a typical bipolar HVDC line compared to three for three-phase HVAC.

HVDC transmission is particularly advantageous in undersea power transmission. Long undersea AC cables have a high capacitance. Consequently, the current required to charge and discharge the capacitance of the cable causes additional power losses when the cable is carrying AC, while this has minimal effect for DC transmission. In addition, AC power is lost to dielectric losses.

In general applications, HVDC can carry more power per conductor than AC, because for a given power rating, the constant voltage in a DC line is lower than the peak voltage in an AC line. This voltage determines the insulation thickness and conductor spacing. This reduces the cost of HVDC transmission lines as compared to AC transmission and allows transmission line corridors to carry a higher power density.

A HVDC transmission line would not produce the same sort of extremely low frequency (ELF) electromagnetic field as would an equivalent AC line. While there has been some concern in the past regarding possible harmful effects of such fields, including the suspicion of increasing leukemia rates, the current scientific consensus does not consider ELF sources and their associated fields to be harmful. Deployment of HVDC equipment would not completely eliminate electric fields, as there would still be DC electric field gradients between the conductors and ground. Such fields are not associated with health effects.

Because HVDC allows power transmission between unsynchronized AC systems, it can help increase system stability. It does so by preventing cascading failures from propagating from one part of a wider power transmission grid to another, while still allowing power to be imported or exported in the event of smaller failures. This feature has encouraged wider use of HVDC technology for its stability benefits alone.

Power flow on an HVDC transmission line is set using the control systems of converter stations. Power flow does not depend on the operating mode of connected power systems. Thus, unlike HVAC ties, HVDC intersystem ties can be of arbitrarily low transfer capacity, eliminating the "weak tie problem," and lines can be designed on the basis of optimal power flows. Similarly, the difficulties of synchronizing different operational control systems at different power systems are eliminated.

Fast-acting emergency control systems on HVDC transmission lines can further increase the stability and reliability of the power system as a whole. Further, power flow regulation can be used for damping oscillations in power systems or in parallel HVAC lines.

The main disadvantages of HVDC transmission systems, including DC links connecting HVAC systems area, are as follows [10]:

- Converter stations needed to connect to AC power grids are expensive. Converter substations are more complex than HVAC substations, not only in additional converting equipment, but also in more complicated control and regulating systems. Costs of such stations may be offset by lower construction costs of DC transmission lines, but offsets require DC lines of considerable length.
- In contrast to AC systems, designing and operating multi-terminal HVDC systems is complex. Controlling power flow in such systems requires continuous communication between all terminals, as power flow must be actively regulated by the control system instead of by the inherent properties of the transmission line.
- Converter substations generate current and voltage harmonics, while the conversion process is accompanied by reactive power consumption. As a result, it is necessary to install expensive filter-compensation units and reactive power compensation units.
- During short-circuits in the AC power systems close to connected HVDC substations, power faults also occur in the HVDC transmission system for the duration of the short-circuit. Inverter substations are most affected. During

short-circuits on the inverter output side, a full HVDC transmission system power fault can be caused. Power faults due to short-circuits on the rectifier input side are usually proportional to the voltage decrease.

- The number of substations within a modern multi-terminal HVDC transmission system can be no larger than six to eight, and large differences in their capacities are not allowed. The larger the number of substations, the smaller may be the differences in their capacities. Thus, it is practically impossible to construct an HVDC transmission system with more than five substations.
- The high-frequency constituents found in direct current transmission systems can cause radio noise in communications lines that are situated near the HVDC transmission line. To prevent this, it is necessary to install expensive "active" filters on HVDC transmission lines.
- Grounding HVDC transmission involves a complex and difficult installation, as it is necessary to construct a reliable and permanent contact to the Earth for proper operation and to eliminate the possible creation of a dangerous "step voltage."
- The flow of current through the Earth in monopole systems can cause the electro-corrosion of underground metal installations, mainly pipelines.

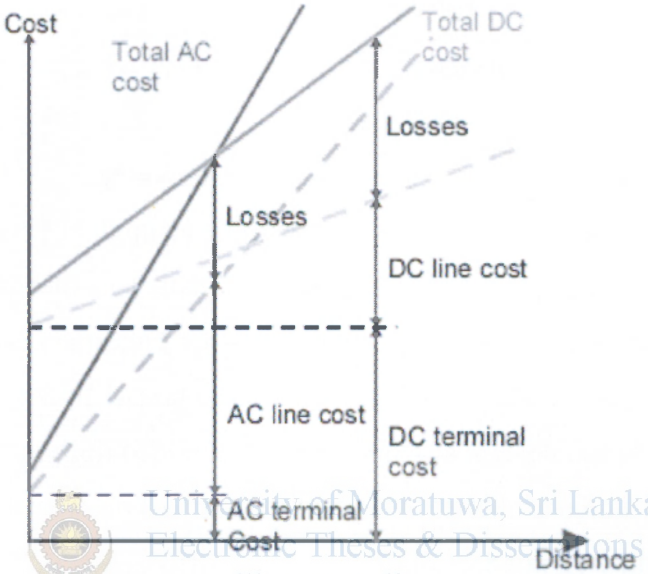
Some of the above-listed disadvantages can be eliminated with the use of new technologies. In particular, disadvantages such as a complete power fault of the HVDC transmission system during short-circuits in the AC power system and reactive power consumption can be eliminated completely, or mostly, with the use of turn-off thyristors. Several research centers are working on improving high-capacity turn-off thyristors and also on new types of converter devices for high capacity HVDC transmission [10].

Also, there are several new techniques for the perfection of grounding devices, providing for decreased electro-corrosion impacts and the formation of so-called "metal return," which precludes the working current from flowing through the ground. Other techniques aimed at perfecting HVDC technology are also being developed.

Comparing the costs of a thyristor-based HVDC system to an HVAC system, the investment costs for HVDC converter stations are higher than those for HVAC substations, but the costs of transmission lines and land acquisition are lower for

HVDC. Furthermore, the operation and maintenance costs are lower in the HVDC case. Initial loss levels are higher in the HVDC system, but they do not vary with distance. In contrast, loss levels increase with distance in a HVAC system. The following Figure 4.2 shows the cost breakdown (shown with and without considering losses) [11].

Figure 3. 1: Cost breakdown for HVAC & HVDC



DC converter station costs and system losses are a relatively high part of total cost, while transmission line costs are relatively low, compared to AC systems. Thus, at some transmission line length, costs are even. The breakeven distance depends on several factors, as transmission medium (cable or OH line), different local aspects (permits, cost of local labour etc.). When comparing high voltage AC with HVDC transmission, it is important to compare a bipolar HVDC transmission to a double-circuit high voltage AC transmission, especially when availability and reliability is considered. Comparing the costs for an HVAC transmission system with those of a 2,000-MW HVDC system indicates that HVDC becomes cheaper at distances greater than about 435 km [11]. However, since system prices for both HVAC and HVDC have varied widely even for a given level of power transfer, market conditions at the time a project is built could override these numerical comparisons between the costs of an AC versus a DC system.

HVDC transmission lines have reduced impacts compared to HVAC transmission lines for many environmental impact measures. These advantages may appear as lower costs for mitigating such impacts when installing HVDC lines compared to HVAC lines. If land use is taken as an overall measure of the comparative environmental impacts of HVAC and HVDC transmission lines of the same relative capacity, HVDC line impacts are roughly two-thirds of those of HVAC lines. Thus, a transmission system that incorporates HVDC power transmission will, as a whole, have reduced impacts compared to one that exclusively employs HVAC transmission lines [8].

The main requirements to select an AC interconnection are synchronization and stable operation of the two grids. It is desirable to go ahead with synchronous mode of interconnection only when the grids of the countries are strong, disciplined, operating in accordance with a uniform grid standard & under sound commercial principle. But the major problem is the frequency fluctuation of the India's Southern region, which is very large compared to that of Sri Lanka. This can affect badly on the Sri Lankan system if they were connected with AC lines. Therefore the use of an asynchronous mode of interconnection is required. That is it has to use HVDC technology. Also since there is a sea portion between the two countries and the use of submarine cables is beneficial, the use of HVDC will be the most suitable method. Therefore for the interconnection of Madurai – Veyangoda the HVDC technology will be selected.

The HVDC technology offers two configurations, i.e. monopole and bipolar. At a conceptual level, a monopole connection may be viewed as consisting of one path of power flow carrying full power, while a bipolar connection may be viewed as consisting of two parallel paths of power flows each carrying half of total power.

In a common configuration, called monopole, one of the terminals of the rectifier is connected to earth ground. The other terminal, at a potential high above, or below, ground, is connected to a transmission line. The earthed terminal may or may not be connected to the corresponding connection at the inverting station by means of a second conductor. If no metallic conductor is installed, current flows in the earth between the earth electrodes at the two stations [12]. Therefore it is a type of Single wire earth return. The issues surrounding earth-return current include,

- Electrochemical corrosion of long buried metal objects such as pipelines
- Underwater earth-return electrodes in seawater may produce chlorine or otherwise affect water chemistry.

- An unbalanced current path may result in a net magnetic field, which can affect magnetic navigational compasses for ships passing over an underwater cable.

These effects can be eliminated with installation of a metallic return conductor between the two ends of the monopole transmission line. Since one terminal of the converters is connected to earth, the return conductor need not be insulated for the full transmission voltage which makes it less costly than the high-voltage conductor. Use of a metallic return conductor is decided based on economic, technical and environmental factors.

Modern monopole systems for pure overhead lines carry typically 1500 MW. If underground or underwater cables are used the typical value is 600 MW.

Most monopole systems are designed for future bipolar expansion. Transmission line towers may be designed to carry two conductors, even if only one is used initially for the monopole transmission system. The second conductor is unused, used as electrode line or connected in parallel with the other.

In bipolar transmission a pair of conductors is used, each at a high potential with respect to ground, in opposite polarity. Since these conductors must be insulated for the full voltage, transmission line cost is higher than a monopole with a return conductor. However, there are a number of advantages to bipolar transmission which can make it the attractive option [12].

- Under normal load, negligible earth-current flows, as in the case of monopole transmission with a metallic earth-return. This reduces earth return loss and environmental effects.
- When a fault develops in a line, with earth return electrodes installed at each end of the line, approximately half the rated power can continue to flow using the earth as a return path, operating in monopole mode.
- Since for a given total power rating each conductor of a bipolar line carries only half the current of monopole lines, the cost of the second conductor is reduced compared to a monopole line of the same rating.
- In very adverse terrain, the second conductor may be carried on an independent set of transmission towers, so that some power may continue to be transmitted even if one line is damaged.

A bipolar system may also be installed with a metallic earth return conductor.

Bipolar systems may carry as much as 3,000 MW at voltages of +/-533 kV. Submarine cable installations initially commissioned as a monopole may be upgraded with additional cables and operated as a bipolar.

A major disadvantage of the monopole configuration is that in case of a fault with any of the converter/inverter or conductor/cable, the full power is lost, and this may adversely affect the operation of the Sri Lankan system which is much smaller than the Indian system. A bipolar system on the other hand provides a greater reliability as it is essentially two independent systems operating in parallel.

When considering the reliability of the system the use of a bipolar HVDC connection can be selected. But for the initial stage (short term) of transferring 500 MW it can have a monopole connection of 500 MW and for the medium term of transferring 1,000 MW it can put up the second line of 500 MW with the first line to make it a 1,000 MW bipolar connection.

3.4 Voltage of the connection

In selection of the voltage both the technical and economical factors has to be considered. The voltage selected has to be economical and depends on the cost of the lines, cost of the apparatus such as transformers, circuit breakers, insulators, etc. This cost increases very rapidly for voltages in the range of 230kV and above. With increase in the power to be transmitted over long distances use of high voltages for power transmission is considered.

The selected technology for the interconnection is HVDC and the amount of power to be transmitted is 1000MW. In general to transmit 1000MW of power over a distance of 450km or higher, it should use the voltages in the range of ±300kV, ±400kV or ±500kV. However a choice could be made out of the standard voltages which are used on the two countries.

The highest transmission voltage use in Sri Lanka is 220kV (there are proposals for the use of 400kV for the transmission but it has not studied up to now). And also the grid substation at Veyangoda will be upgraded to 220kV by 2011. Generally for the 220kV transmission the maximum length of the line is about 300km. Since the length of the interconnection between Madurai and Veyangoda is about 480km it has to go for a voltage higher than 220kV.

In India the transmission voltages are 765kV, 400kV, 200kV and 132kV and it has experiences of ±500kV and ±400kV of HVDC transmission [3]. At present the Madurai substation of India is a 400/220kV substation. Since there is a 400kV bus at Madurai and the maximum length of the line for the 400kV transmission is above 600km, it will be beneficial to select the 400kV as the voltage for the interconnection. By selecting 400kV for the interconnection is can eliminate the cost of the transformers at the Indian end, and also it will be an advantage for Sri Lanka when they are upgrading to 400kV transmission system.

Chapter 4

4.0 Selecting the most suitable location based on load forecast

4.1 Suitable locations in Sri Lanka

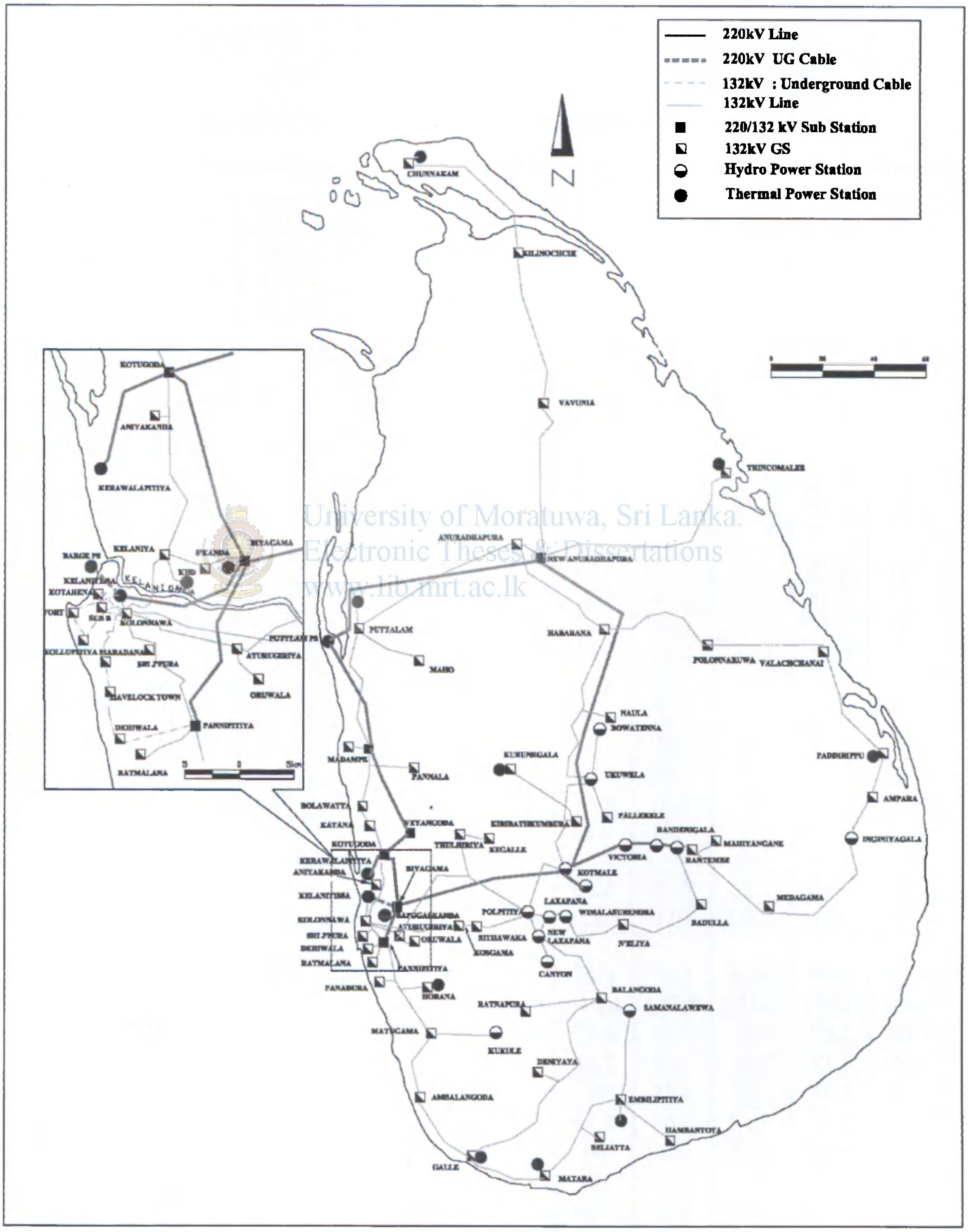
To connect a large generation to the system the connecting point should be a strong point in the system. In Sri Lanka 220kV and 132kV voltage levels are used as the transmission voltages of the system. 220kV transmission system is mainly used to transmit power from Mahaweli complex hydro plants to main load centers around Colombo through Kotougoda, Pannipitiya and Biyagama grid substations. 132kV transmission network is used to interconnect most of the grid substations and to transfer power from other power stations. The transmission system of Sri Lanka by 2011 is as Figure 3.1 [7].

By 2011 the coal plants of Puttalam connects to the 220kV system by a 100km long transmission line to New Anuradhapura and a 70km long transmission line to New Chilaw grid substations. The 220kV transmission lines of Biyagama – Kotugoda, Kotugoda – Veyangoda, Veyangoda – New Chilaw, New Chilaw – Puttalam Coal, Puttalam Coal – New Anuradhapura, New Anuradhapura – Kotmale and Kotmale – Biyagama create the 220kV ring and act as the backbone of the system [7]. Also by that time there will be around 2400MW connected to the 220kV and around 1400MW connected to 132kV network. Therefore for the selection of the suitable connecting point the 220kV grid substations were selected as the strong points.

When selecting a terminus point for the India – Sri Lanka interconnection, the access of the transmission line to the existing transmission network should be considered. Therefore the 220kV grid substations towards the Indian side were taken into consideration.

According to the transmission plan 2006 – 2015 New Anuradhapura, Puttalam power station, Veyangoda, Biyagama and Kotugoda grid substations can be selected as the suitable points of the transmission system to connect the India – Sri Lanka power interconnection. Since the grid substations such as Biyagama and Kotugoda are located in highly populated and industrialized areas the access of the interconnection to those grid substations are not practical. Also the location of the Puttalam power plant is not a good place for such an interconnection. Therefore Veyangoda and New Anuradhapura grid substations are considered for the study.

Figure 4. 1: Transmission system of Sri Lanka by 2011



In Sri Lanka the major load centers are located around Colombo. According to the "Grid Substation Peak Demand Forecast from 2006 to 2015" prepared by the transmission planning branch of the Ceylon Electricity Board[7], it is clear that the loads of the grid substations connected to the Veyangoda grid substation are very much higher than the loads of the grid substations connected to the New Anuradhapura grid substation.

Table 4. 1: Grid Substation Peak Demand Forecast from 2006 to 2015

Grid Substations	**LOAD [MW]**									
	2006	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**
Colombo E	42.3	45.4	48.7	52.3	56.1	60.3	63.4	58	60.3	62.8
Colombo-F	43.6	47.6	51.9	55.6	59.5	63.7	58.9	58.8	61.2	63.6
Kelanitissa	38.6	41.4	44.3	27.5	29.5	31.6	20.9	22.4	24	25.8
Kolonnawa – Col.	36	38.7	46.6	50.2	54	58	50.4	54.2	58.3	62.7
Colombo-A	25	27.1	29.3	31.7	34.3	37.1	40.2	51.4	55.6	60.1
Colombo-I	30	32.1	29.3	31.4	33.6	36	46.5	49.7	53.2	56.9
Colombo – C				20	21.6	23.3	25.2	27.2	29.4	31.7
Colombo-B							25	27	29.2	31.5
Pannipitiya	42	44.6	47.1	50.3	54	58.6	63.6	69.1	75.3	79.1
Kolonnawa _New	46.4	50.1	43.9	47.8	52.2	47.7	52.7	47.1	51.2	50.7
Kosgama	41.3	44.2	47.9	51.6	35.8	39.1	42.8	46.9	51.5	74.6
Sithawakapura	26.1	28.2	29.9	32.2	54.8	59.8	65.3	71.5	78.5	76.1
Athurugiriya	10.2	11.5	12.4	13.6	14.8	16.4	18.2	20.2	22.2	39.3
Ratmalana	51.5	56.4	60.9	66.5	72.9	70.8	78.5	72.2	78.5	75.4
Matugama	69.5	74.2	64.9	69.9	77	74.2	71.2	78.1	85.8	84.3
Panadura	58.9	55.5	54.6	59.4	64.7	71.3	78.6	75.3	81.8	86.1
Horana	33.5	44.2	53	57.9	63.1	69.6	76.7	83.2	80.4	78.6
Sri Ja'pura	23	24.8	26.4	28.4	30.7	33.5	36.6	50	54.9	68.2
Dehiwala	22	23.5	35	37.7	40.7	64.4	70.3	77	74.5	78.8
Moratuwa								25	47.4	52.1
# Kelaniya	**15.9**	**27**	**26.7**	**28.7**	**31**	**43.8**	**47.7**	**52.1**	**47.1**	**61.6**
# Kotugoda	**99.8**	**103.5**	**96.3**	**100.8**	**105.8**	**112.2**	**119**	**126.6**	**145**	**151.6**
# Sapugaskanda	**77.4**	**72.7**	**80**	**78.1**	**74.4**	**70.4**	**76.2**	**82.6**	**99.8**	**98.5**
# Biyagama	**66.4**	**71**	**82.4**	**88.7**	**105.8**	**114.4**	**123.8**	**134.2**	**145.8**	**158.6**
# Veyangoda	**41.8**	**46.3**	**51.4**	**57.4**	**64.4**	**71.6**	**79.7**	**78.9**	**78.2**	**80.4**
# Aniyakanda			**27**	**36.8**	**39.4**	**42.2**	**45.2**	**48.5**	**52.2**	**56.3**
# Katana						**20**	**21.6**	**33.5**	**36.4**	**49.5**
Kurunegala	46.4	51.2	55.7	61.3	61.8	67.7	74.1	81.4	79.5	87.5
Puttalam	29.3	31.6	33.9	36.9	40.3	44	48	52.6	57.8	63.4
Bolawatte	61.6	65.4	69.1	73.9	79.3	66	71.7	78	85	82.6
Madampe	45	49.9	36.2	40.6	45.6	50.8	56.6	63.2	70.8	79.3
Pannala			20	21.9	24.1	26.6	29.3	32.4	35.9	49.8
Maho					6	6.4	6.9	7.4	18	19.3
*** Old Anuradhapura**	**27.8**	**29.4**	**30.8**	**32.8**	**34.9**	**37.6**	**40.5**	**43.7**	**47.2**	**43.1**

*** New Anuradhapura**	**11.9**	**12.5**	**13.1**	**13.9**	**14.8**	**15.9**	**17.1**	**18.4**	**19.9**	**29.5**
*** Habarana**	**47.3**	**50.5**	**53.7**	**49.2**	**49.4**	**53.7**	**58.3**	**63.5**	**69.3**	**75.6**
*** Polonnaruwa**				**10**	**10.8**	**11.8**	**12.9**	**14.1**	**15.5**	**27**
Trincomalee	35.1	39	43.2	48.3	54.3	60.5	67.4	75.3	84.2	84.2
Ingiya./Ampara	60.9	67	73.3	81.2	65.3	72	69.4	76.7	84.9	84.1
Valachchanai	15.6	17.2	18.9	20.9	23.2	25.6	28.2	31.2	34.5	38.2
Paddirippu					25	27.5	40.4	44.6	49.4	64.7
Kiribathkumbura	67.3	73.2	77.7	67.5	73.1	69.7	59.7	65.4	71.6	78.6
Ukuwela	41	43.8	46.6	50.5	49.6	54.1	59	64.6	70.7	77.5
NuwaraEliya	44.1	47.2	49.9	53.1	56.4	60.5	64.9	69.8	75.1	80.9
Wimalasurendra	33	35.9	38.8	42.6	46.9	51.2	55.9	61.2	67.1	73.7
Pallekele				16	17.3	28.9	41.5	45.5	49.9	54.7
Naula					9	9.8	10.7	11.7	12.9	14.1
Thulhiriya	47.4	49.6	51.8	54.6	57.8	61.9	51.1	54.7	58.7	62.9
Balangoda	37.6	40.4	43	46.4	50.1	54.2	58.7	63.7	69.2	75.3
Embilipitiya	24.9	26.3	28	29.8	31.8	34.3	37	40.1	43.5	47.2
Ratnapura	17.2	19.1	22	23.9	26.1	28.5	31	33.9	37.1	40.6
Kegalle							21.4	23	24.7	26.6
Rantembe	6.4	6.9	7.2	7.6	8	8.5	9	9.6	10.2	10.9
Badulla	43.4	48.3	53.5	59.4	58.3	63.7	69.4	75.9	75.7	82.5
Medagama					8	8.7	9.5	10.4	18.5	20.3
Galle	58.8	62.3	57.8	61.8	66.2	71.8	67.8	73.7	80.2	82.3
Deniyaya	25.7	28.3	37.9	42	46.6	51.4	56.6	62.6	68	74
Matara	58.5	59.2	57.8	54	59.9	66	61.8	68.3	74.2	75.7
Hambantota	11.2	17.4	19.2	16.4	19.1	21.3	23.8	26.6	29.3	32.2
Ambalangoda			22	23.5	25.1	37.1	50.2	54.4	59.1	74.3
Beliatta				15	16.7	18.4	20.2	22.4	24.3	31.4
Weligama							21	22.8	24.7	31.9
Chunnakam	28.1	30.6	33.1	36.3	40	43.7	47.7	52.2	57.3	62.9
Kilinochchi				5.1	5.5	6	6.5	7.2	7.9	8.6
*** Vavunia**	**12.1**	**12.9**	**13.7**	**14.8**	**16**	**17.4**	**19**	**20.8**	**22.8**	**25.1**

Substations around Veyangoda

* Substations around New Anuradhapura

If the new generation added to the New Anuradhapura grid substation, it has to transmit power from Anuradhapura to the major load centers by 220kV AC over head lines over a long distance. This leads to a higher power loss. But since Veyangoda Grid substation is located near Colombo it is easier to transmit power to the major load centers.

When consider the future loads and the locations of the two grid substations it can select Veyangoda grid substation as the suitable connecting point. But to have a strong decision about the terminus point of the India – Sri Lanka power interconnection it should carryout the power system studies for both grid substations.

Chapter 5

5.0 Transmission system analysis for the interconnection

In general transmission system analysis comprises load flow studies, reliability studies and stability studies. To identify planning criteria violations and required mitigating measures these studies are required. Load flow studies are required to determine the power system performance in the steady state. Contingency analysis is required to identify network bottlenecks during equipment failure or unavailability.

The planning criteria which need to ensure a quality and reliable supply under normal operating conditions as well as under contingencies are as follows [7].

Voltage criteria:

The voltage criterion defines the permitted voltage deviation at any live bus bar of the network under normal operating conditions as given in Table 5.1.

Table 5. 1: Allowable voltage variations

Bus bar voltage	Allowable voltage variation (%)	
	Normal operating condition	Single contingency condition
220 kV	± 5%	- 10% to + 5%
132 kV	± 10%.	± 10%

Thermal criteria:

The design thermal criterion limits the loading of any transmission network element, in order to avoid overheating due to overload.

The loading of elements should not exceed their rated thermal loading values for steady state conditions.

Security criteria:

The performance of the transmission system under contingency situation is taken into consideration in the security criteria. The adopted contingency level for the planning purposes is N-1, i.e. outage of any one element of the transmission system at a time.

After outage of any one element (i.e. any one circuit of a transmission line or a transformer and without any adjustment or corrective measure), the system should be able to meet the distribution demand while maintaining the bus bar voltage levels as given in Table 5.1 and loading of all the remaining elements should not exceed their emergency ratings specified. After system readjustment following a disturbance described above, the voltage and loading of elements should return to their corresponding normal limits.

Since Sri Lanka has a mix of hydro and thermal generation, dispatching of generation to the system is done for two cases as hydro maximum and thermal maximum. Also there are two different peak demand times as day peak and night peak where the night peak is nearly double the day peak. The detailed system studies are performed under hydro maximum and thermal maximum generation dispatch scenarios and day peak (11.00 hours) and night peak (19.30 hours) load scenarios.

The system studies are carried out using the Power System Simulator for Engineering (PSS/E) software.

The transmission system analysis for the interconnection carried out with the new generation added to the system in year 2011 for the two cases as; 500 MW connected to Veyangoda grid substation and 500 MW connected to New Anuradhapura grid substation.

5.1 Assumptions for the analysis

1. The reactive power consumption at the converters will be taken as 50% of the active power rating of the DC link [13, 14].
2. The DC link will be modeled as a generator which delivers 500 MW of active power and consumes 250 Mvar of reactive power.
3. Since Sri Lanka needs the support of imported power in 2011 to recover its peak load (night peak around 19.30 hours), the study will limited to load scenario of night peak. Therefore the two scenarios selected for the study are;
    - Thermal Maximum Night Peak (TMNP)
    - Hydro Maximum Night Peak (HMNP)
4. In modeling of the power system, the improvements of the power system planned up to 2011 by “Long term transmission development plan” but not committed yet will be taken as implemented.

5.2 Transmission system analysis for the interconnection of 500MW to Veyangoda grid substation

Single line diagram of the Sri Lankan transmission system in year 2011 with 500 MW additions to Veyangoda grid substation is shown in Annex A-1. System studies were carried out for TMNP and HMNP scenarios considering normal and single contingency conditions.

5.2.1 Normal operating conditions

There was no overloaded equipment in the system. But a large number of voltage criteria violations were observed in the 220kV and 132kV systems in the power flow simulations. The under voltage 220 kV and 132kV buses at TMNP and HMNP were as follows.

Table 5. 2: Voltage criteria violations at 132kV & 220kV level for Veyangoda interconnection

Equipment	Voltage (p.u.)	
	HMNP	TMNP
Veyangoda 220 kV bus	0.922	0.939
Kotugoda 220 kV bus	0.903	0.923
Kerawalapitiya 220 kV bus	0.901	0.925
Biyagama 220 kV bus	0.900	0.924
Kelaniya 220 kV bus	0.902	0.923
Pannipitiya 220 kV bus	0.905	0.924
Veyangoda 132 kV bus	0.912	0.917
Thulhiriya 132 kV bus	-	0.923

Load flow diagram for night peak thermal maximum condition and night peak hydro maximum condition are shown in Annex A-2 and Annex A-3 respectively.

To overcome the problem of under voltage of 220kV buses the capacitor banks were added to the system as; 125 Mvar at Veyangoda 220kV bus, 125 Mvar at Kotugoda 220kV bus, 100 Mvar at Biyagama 220kV bus in TMNP and 125 Mvar at Veyangoda 220kV bus, 125 Mvar at Kotugoda 220kV bus, 100 Mvar at Biyagama 220kV bus and 50 Mvar at Kelaniya 220kV bus in HMNP. The load flow diagrams for night peak thermal maximum condition and night peak hydro maximum condition with the addition of capacitor banks to the system are shown in Annex A-4 and Annex A-5 respectively. The single contingency analyses were done with the capacitors added to the system.

5.2.2 Single contingency operating conditions

Other than the outage of one Biyagama – Kotugoda 220kV transmission line there were no voltage criteria violations were observed in 132kV and 220kV systems in the power flow simulations of the transmission system under single contingency operating conditions. The outage of one Biyagama – Kotugoda 220kV transmission line resulted in the voltage drops of 220kV system as follows.

Table 5. 3: Voltage criteria violations in single contingency for Veyangoda interconnection

Equipment	Voltage (p.u.)	
	HMNP	TMNP
Biyagama 220 kV bus	-	0.950
Kelaniya 220 kV bus	-	0.948
Pannipitiya 220 kV bus	-	0.949

The outage of one 220/132/33 kV transformer at Kotugoda GS resulted in the loadings of 116%, 99%, 112% in TMNP and 115%, 98%, 112% in HMNP of the 220kV, 132kV, 33 kV windings of remaining transformer. The outage of one 220/132/33 kV transformer at Biyagama GS resulted in the loadings of 111% in TMNP and 112% in HMNP of the remaining two transformers. The outage of one 220/132/33 kV transformer at Pannipitiya GS resulted in the loadings of 188 % in TMNP and HMNP of the 33 kV winding of remaining transformer. The outage of one 220/132/33 kV transformer at New Anuradhapura GS resulted in the loadings of 127% and 116% in TMNP and 121% and 109% in HMNP of the 220kV and 132kV windings of the remaining transformer. The outage of one 220/132 kV inter bus transformer at Rantambe GS resulted in the loadings of 118% in TMNP and 105% in HMNP of the remaining transformer.

Furthermore, during the outage of Pannipitiya – Panadura T 132 kV line the loading of the remaining line was 104% during TMNP. Outage of Kolonnawa – Kelaniya 132 kV transmission line in TMNP causes the load of the remaining two circuits to be 130%. The outage of one New Anuradhapura – Anuradhapura 132kV line resulted in the loadings of 114% in TMNP and 101% in HMNP of the remaining transmission line. The outage of Randenigala – Rantambe 220 kV transmission line causes the load of two 132/33 kV transformers of Rantambe GS to be 105% during TMNP. Also the outage of one Biyagama - Kotugoda 220kV line resulted in the loadings of 101% in TMNP of the remaining 220kV transmission line.

5.2.3 Transmission Losses

The transmission losses (the system losses from the high voltage side of the generator transformers up to the 33/11kV load busses of the network) as a percentage of total loads at 33/11 kV busses of the system are as follows;

TMNP - 2.06%
HMNP - 1.69%

5.3 *Transmission system analysis for the interconnection of 500MW to New Anuradhapura grid substation*

Single line diagram of the Sri Lankan transmission system in year 2011 with 500 MW additions to New Anuradhapura grid substation is shown in Annex A-6. System studies were carried out for TMNP and HMNP scenarios considering normal and single contingency conditions.

5.3.1 Normal operating conditions

The 220kV and 132kV windings of New Anuradhapura 220/132/33 kV transformer were loaded to 107% and 102% during TMNP and 104% and 99% during HMNP. Also there were a large number of voltage criteria violations were observed in the 220kV and 132kV systems in the power flow simulations. The under voltage 220 kV and 132kV buses at TMNP and HMNP were as follows.

Table 5. 4: Voltage criteria violations at 132kV & 220kV level for New Anuradhapura interconnection

Equipment	Voltage (p.u.)	
	HMNP	TMNP
Veyangoda 220 kV bus	0.929	-
Kotugoda 220 kV bus	0.908	0.937
Kerawalapitiya 220 kV bus	0.908	0.940
Biyagama 220 kV bus	0.905	0.934
Kelaniya 220 kV bus	0.905	0.933
Pannipitiya 220 kV bus	0.908	0.934
Thulhiriya 132 kV bus	-	0.930

Load flow diagram for night peak thermal maximum condition and night peak hydro maximum condition are shown in Annex A-7 and Annex A-8 respectively.

To overcome the problem of under voltage of 220kV buses the capacitor banks were added to the system as; 50 Mvar at New Anuradhapura 220kV bus, 150 Mvar at Kotugoda 220kV bus, 125 Mvar at Biyagama 220kV bus in TMNP and 50 Mvar at New Anuradhapura 220kV bus, 150 Mvar at Kotugoda 220kV bus, 125 Mvar at Biyagama 220kV bus and 50 Mvar at Kelaniya 220kV bus in HMNP. The load flow diagrams for night peak thermal maximum condition and night peak hydro maximum condition with the addition of capacitor banks to the system are shown in Annex A-9 and annex A-10 respectively. The single contingency analyses were done with the capacitors added to the system.

5.3.2 Single contingency operating conditions

Other than the outage of one Puttalam PS – New Chilaw 220kV transmission line there were no voltage criteria violations were observed in 132kV and 220kV systems in the power flow simulations of the transmission system under single contingency operating conditions. The outage of one Puttalam PS – New Chilaw 220kV transmission line resulted in the voltage drops of 220kV system as follows.

Table 5. 5: Voltage criteria violations in single contingency for New Anuradhapura interconnection

Equipment	Voltage (p.u.)	
	HMNP	TMNP
Kotugoda 220 kV bus	0.944	-
Kerawalapitiya 220 kV bus	0.945	-
Biyagama 220 kV bus	0.941	0.941
Kelaniya 220 kV bus	0.941	0.944
Pannipitiya 220 kV bus	0.942	0.945

The outage of one 220/132/33 kV transformer at Kotugoda GS resulted in the loadings of 126% in TMNP of the 33 kV winding and 115%, 97%, 112% in HMNP of the 220kV, 132kV, 33kV windings of remaining transformer. The outage of one 220/132/33 kV transformer at Biyagama GS resulted in the loadings of 117% in TMNP of the 33kV winding and 111% and 107% in HMNP of the 220kV and 33kV windings of the remaining two transformers. The outage of one 220/132/33 kV transformer at Pannipitiya GS resulted in the loadings of 188% in TMNP and 190% in HMNP of the 33 kV winding of remaining transformer. The outage of one 220/132/33 kV transformer at New Anuradhapura GS resulted in the loadings of 174%, 163% in TMNP and 171%, 158% in HMNP of the 220kV and 132kV windings of the remaining transformer. The outage of one 220/132 kV inter bus transformer at Rantambe GS resulted in the loadings of 117% in TMNP and 106% in HMNP of the remaining transformer.

Furthermore, during the outage of Pannipitiya – Panadura T 132 kV line the loading of the remaining line was 102% during TMNP. Outage of Kolonnawa – Kelaniya 132 kV transmission line in TMNP causes the load of the remaining two circuits to be 117%. The outage of one New Anuradhapura – Anuradhapura 132kV line resulted in the loadings of 177% in TMNP and 170% in HMNP of the remaining transmission line. The outage of Randenigala – Rantambe 220 kV transmission line causes the load of two 132/33 kV transformers of Rantambe GS to be 104% and Anuradhapura – New Anuradhapura 132kV two transmission lines to be 104% and two transformers of New Anuradhapura GS to be 122% during TMNP and the load of two transformers of New Anuradhapura GS to be 103% during HMNP. Also the outage of one Puttalam PS – New Chilaw 220kV line resulted in the loadings of Anuradhapura – New Anuradhapura 132kV two transmission lines to be 103% in TMNP and 101% in HMNP and the two transformers of New Anuradhapura GS to be 119% during TMNP and 120% during HMNP.

5.3.3 Transmission Losses

The transmission losses (the system losses from the high voltage side of the generator transformers up to the 33/11kV load busses of the network) as a percentage of total loads at 33/11 kV busses of the system are as follows;

TMNP - 2.41%
HMNP - 2.34%

5.4 Evaluation of the Results

In both cases under normal operating conditions it can observe a large number of voltage criteria violations in 220kV system. Therefore it should add a large amount of reactive power sources to the transmission system in order to keep an acceptable voltage profile during normal operating condition.

In New Anuradhapura case the 220/132/33kV transformers at New Anuradhapura grid substation were overloaded at normal operating condition, therefore the New Anuradhapura grid should be augmented from 2 x 220/132/33kV transformers to 3 x 220/132/33kV transformers. But in Veyangoda case there was no overloaded equipment in the system. This condition shows that the power of the DC link flows on 220kV system to the load centers in Veyangoda case and the power flows on 132kV system to the load centers in New Anuradhapura case. Since the load centers are far away from the connecting point in New Anuradhapura case the losses of the power flows through 132kV system is very much higher than the losses of the 220kV system power flows to near load centers in Veyangoda case.

Under single contingency operating conditions, the outage of Biyagama – Kotugoda 220kV line in Veyangoda case and the outage of Puttalam PS – New Chilaw 220kV line in New Anuradhapura case resulted in the voltage drops in the 220kV system. There also the case at New Anuradhapura is not as good as the case at Veyangoda, because the numbers of low voltage 220kV buses are higher and the reactive power addition is large in New Anuradhapura case. Also the lowering level of voltage is very much smaller in the Veyangoda case than in the New Anuradhapura case.

Some single contingency conditions such as, outage of one 220/132/33kV transformer at Kotugoda GS, outage of one 220/132/33kV transformer at Biyagama GS, outage of one 220/132/33kV transformer at Pannipitiya GS, outage of one 220/132kV inter bus transformer at Rantambe GS, outage of one Pannipitiya – Panadura T 132kV transmission line, outage of one Kolonnawa – Kelaniya 132kV transmission line, outage of one New Anuradhapura – Anuradhapura 132kV transmission line, are common in both cases and they can be attributed to the problems of the existing transmission system. However it is also important that these problems attributed to the existing transmission system be rectified as well by necessary reinforcement wherever required if the proposed interconnection is going to be implemented.

The outage of one Randenigala – Rantambe 220kV transmission line causes only the overloading of two 132/33kV transformers of Rantambe GS at TMNP in Veyangoda case. But that outage causes several problems in New Anuradhapura case such as, overloading of two 132/33kV transformers of Rantambe GS, overloading of two 220/132/33kV transformers of New Anuradhapura GS and overloading of New Anuradhapura – Anuradhapura 132kV two transmission lines. Also in the New Anuradhapura case, the outage of one Puttalam PS – New Chilaw 220kV transmission line resulted the over loadings of two New Anuradhapura – Anuradhapura 132kV transmission lines and the two 220/132/33kV transformers at New Anuradhapura GS other than creating low voltages at 220kV buses.

These contingency conditions around New Anuradhapura grid substation also establish the fact that the transmission system around New Anuradhapura is fairly weak compared to the transmission system around Veyangoda. It is also difficult to strengthen the New Anuradhapura grid substation at present or near future owing to the lack of supporting strong 220kV substations in the nearby areas. But since Veyangoda grid substation is surrounded by many 220kV grid substations such as Kotugoda, Biyagama and Kerawalapitiya, it is a strong point in the system. Therefore according to the transmission system analysis it can select Veyangoda grid substation as terminus point of the India – Sri Lanka power interconnection.

5.5 Interconnection Routes

The suitable locations for the terminus points of the interconnection are Madurai in India [1, 2] and Veyangoda in Sri Lanka. There is an existing 400/220 kV substation in Madurai while the transmission expansion plan of Sri Lanka plans a 220kV substation at Veyangoda with 220kV transmission lines connecting with the major load centers of the country by 2011.

There are two line routes for the Madurai – Veyangoda interconnection, which are connecting via Mannar and via Puttalam. The two routes are shown in Figure 4.1.

The lengths of the lines for these connections are as follows;

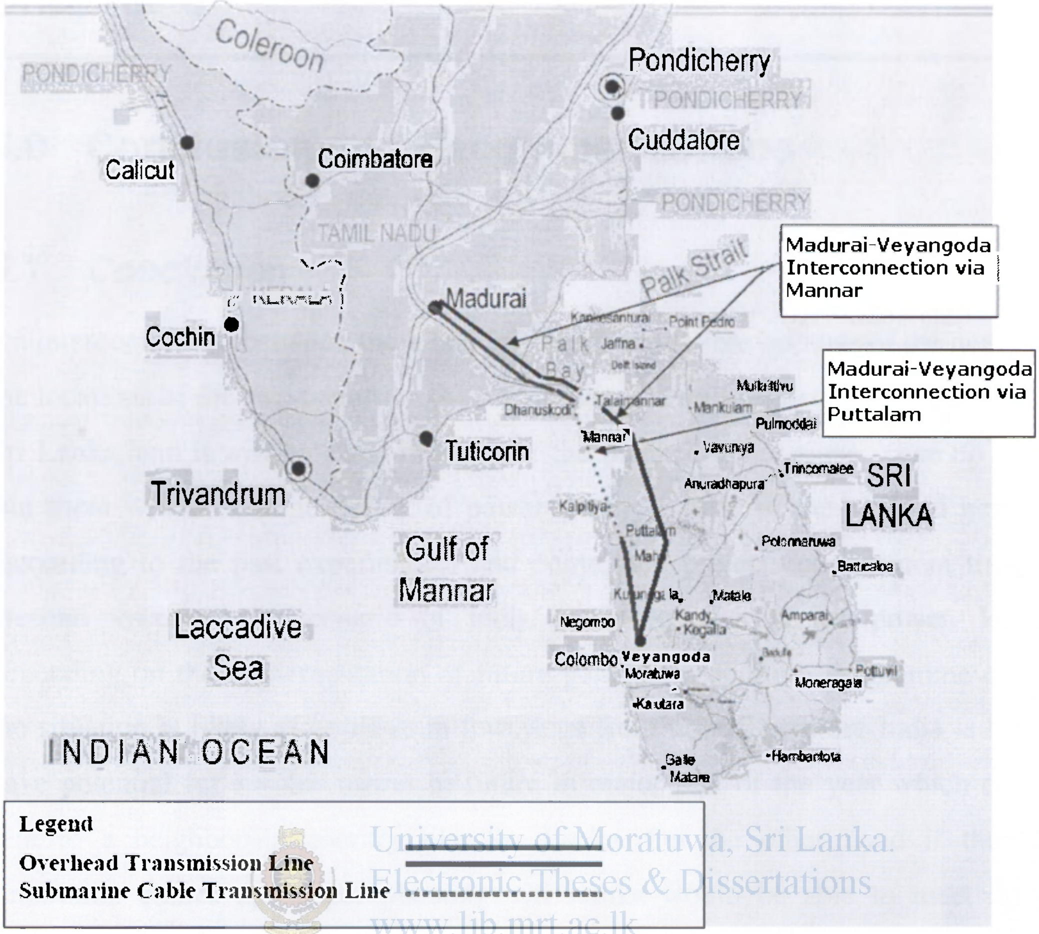
(1) Connecting via Mannar

- Overhead line from Madurai to Dhanushkodi - 200 km
- Distance across sea from Dhanushkodi to Talaimanar - 30 km
- Overhead line from Talaimanar to Veyangoda - 250 km

(2) Connecting via Puttalam

- Overhead line from Madurai to Dhanushkodi - 200 km
- Distance across sea from Dhanushkodi to Puttalam - 100 km
- Overhead line from Puttalam to Veyangoda - 100 km

Figure 5. 2: Line routes for the Madurai – Veyangoda interconnection



Interconnection via Mannar has a long length over land and a very short sea length while the connection via Puttalam has a short length over land and a long sea length. The cost for the connections (submarine cables or overhead lines) across the sea is very much higher than the cost for the connections over land. Thus the connection via Puttalam will be unfeasible when considering the cost of the project. Therefore the interconnection of Madurai and Veyangoda via Mannar will be selected as the best option.

Chapter 6

6.0 Conclusion and Recommendations

6.1 Conclusion

An interconnection between India and Sri Lanka is possible because of the nearness of the locations of the two countries. At present there is no surplus or deficit of power in Sri Lanka, and it will be same in future if the planned generations come up in time. But there will be a large deficit of power if only a 50% of the planned generation (according to the past experiences) and committed projects come up in time. The present power-supply scenario of India is facing peak deficit power. However depending on the implementation of future generation addition programme of India, the situation is likely to improve in few years from now. Therefore India is likely to have potential for surplus power in future in major part of the year which could be sent to a neighboring country like Sri Lanka. On the other hand if the future generation comes up as per planning, Sri Lanka would be able to meet its peak demand. However this would lead to a significant amount of off-peak surplus power and major part of this power can be utilized by exporting to India. Because of this it can say that there is enough opportunity for a transmission interconnection between India and Sri Lanka.

According to the surplus/deficit of power in both countries and the time taken to implement an interconnection the capacity of the interconnection was decided for three periods. Therefore in the short term period India and Sri Lanka can exchange power of about 500MW, and the quantum of power exchange can be enhanced to about 1000MW in the medium time frame. Depending upon the success of power exchange in short/medium term condition between India and Sri Lanka as well as the existing demand-supply scenario of both the countries, the quantum of power exchange for long term can be planned.

The power transmission technology of the interconnection was selected between HVDC and HVAC with back-to-back DC. There were many advantages of using HVDC over HVAC in technically, and when considering the distance of the interconnection the usage of HVDC is less costly than HVAC. Since the interconnection needs to cross the sea between India and Sri Lanka, to lower the losses of the submarine cables HVDC was the most suitable method. Also HVDC provide the solution for the major problem of frequency fluctuation in southern part of India. Therefore for the interconnection between India and Sri Lanka the HVDC technology was selected. When considering the reliability of the system the use of a bipolar HVDC connection was selected over monopole HVDC connection. But for the initial stage (short term) of transferring 500 MW it can have a monopole connection of 500 MW and for the medium term of transferring 1000 MW it can put up the second line of 500 MW with the first line to make it a 1000 MW bipolar connection. By considering both the economic and technical factors the voltage of the interconnection was selected. It was decided to use ±400kV as the transmission voltage.

When selecting the terminus point for the interconnection in Sri Lankan side the strong points of the system and access of the interconnection to the system were considered. Since the 220kV transmission line ring acts as the backbone of the system, the 220kV grid substations were selected as the strong points of the Sri Lankan system and the substations towards the Indian side of the country were chosen. Also the grid substations which are located in highly populated and industrialized areas were not considered. Therefore Veyangoda and New Anuradhapura substations were selected for the analysis. According to the forecasted loads (2006 - 2015) of the grid substations and the locations (nearness to the major load centers) of them Veyangoda grid substation was chosen as the suitable terminus point for the India – Sri Lanka power interconnection. But to have a strong decision about the terminus point the load flow studies were carried for both substations.

The DC link was modeled as a generator which delivers 500MW of active power and consumes 250Mvar of reactive power. Transmission system analysis (power flow studies and single contingency analysis) were done for two cases as, 500MW connected to Veyangoda and 500MW connected to New Anuradhapura. In both cases it could observe low voltages at 220kV busses which highlight the requirement of reactive power addition to the system. The load flow studies under normal operating conditions showed the necessity of augmentation of New Anuradhapura grid substation. Also the transmission system losses in 220kV and 132kV system showed that the losses in Veyangoda case are smaller than New Anuradhapura case. The results of the single contingency analysis established the fact that the transmission system around New Anuradhapura is fairly weak compared to the transmission system around Veyangoda. Since it is difficult to strengthen the New Anuradhapura grid substation in near future it cannot select New Anuradhapura as a suitable point to interconnect the DC link. Therefore Veyangoda grid substation was selected as the terminus point of the India – Sri Lanka power interconnection.

When selecting the interconnection routes, the lengths and the costs of the line across land and across sea were considered. And the route via Mannar was selected as the best option over the route via Puttalam.

6.2 Recommendations

When selecting the capacity of the interconnection it was assumed that the future generation and transmission plans of India will implement 100% on time. Therefore it should carry out a study of the implementation pattern of the Indian plans in detail before taking a decision of the capacity of the link.

During the system studies it was observed some contingency conditions which could attribute to the problems of the existing transmission system, and those problems should correct by required reinforcement wherever necessary if the proposed interconnection is going to be implemented.

Because the interconnection of the DC link affect badly on the voltage profile of the existing system, it is important that a thorough voltage stability analysis be carried out to the system.

Also since there were several approximations done in modeling of the DC link interconnection, it is very important that the above link, its converter and inverter stations and there controllers be modeled in detail prior to the implementation.

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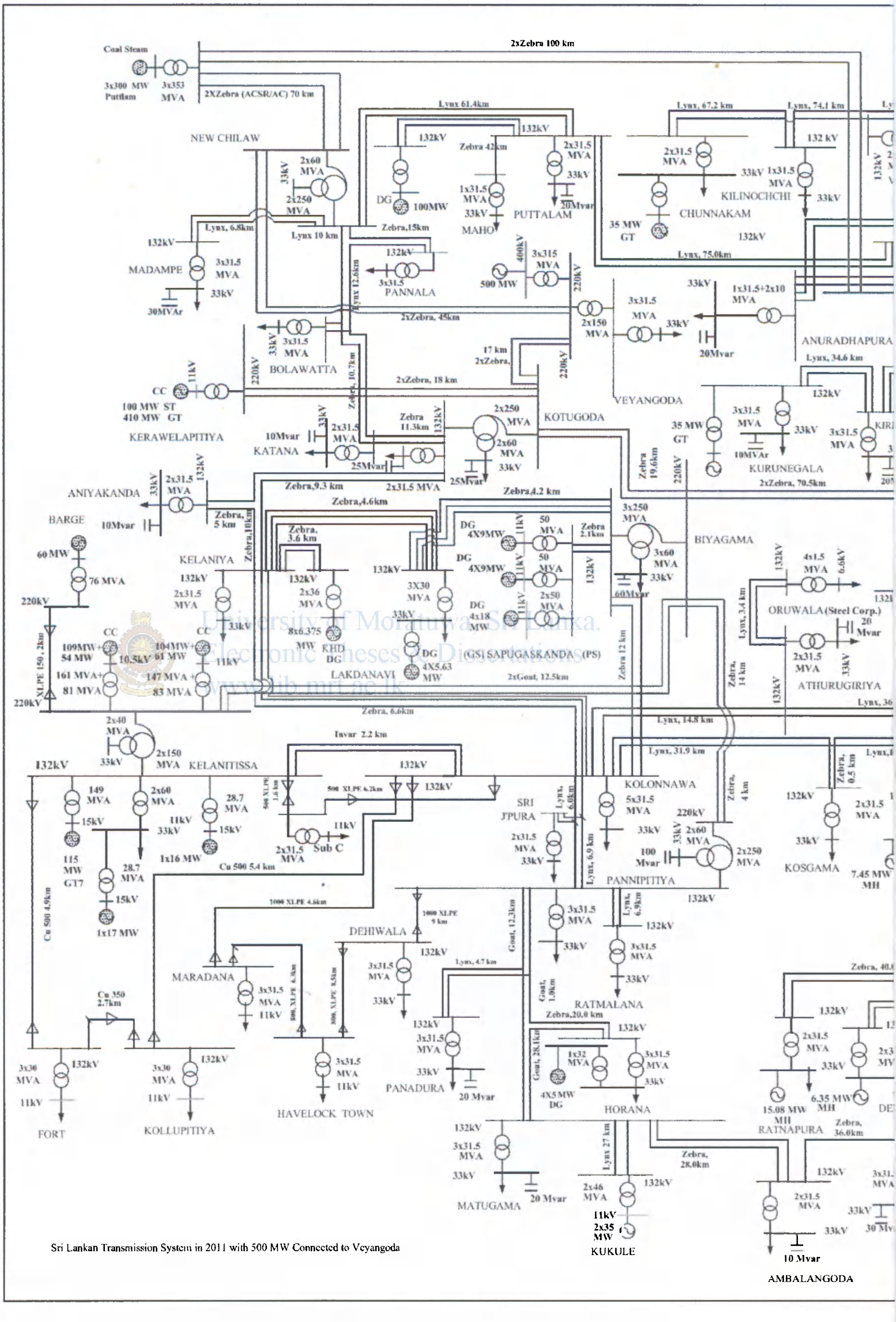
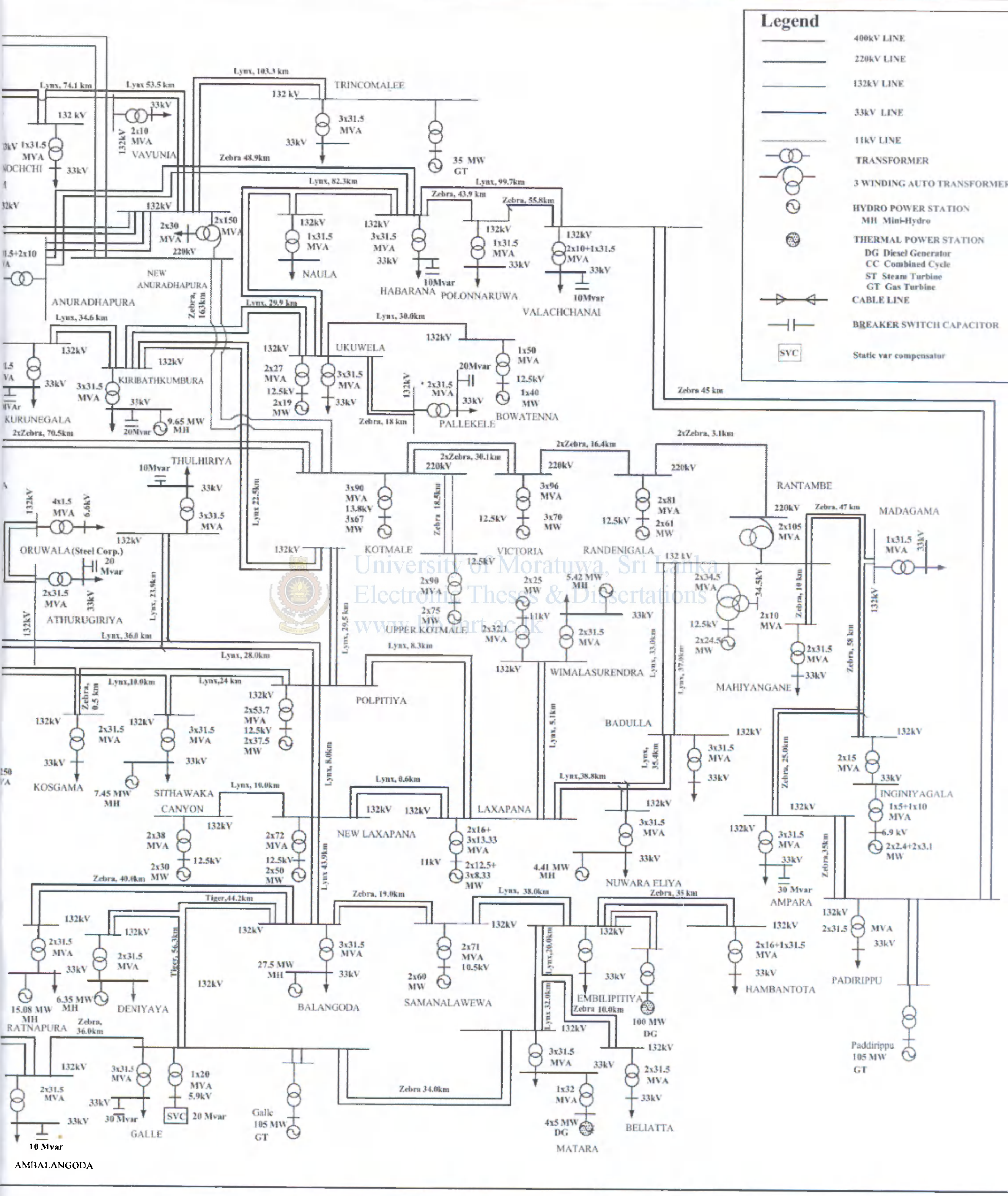
Annexes

Annex A - 1: Single line diagram of the Sri Lankan transmission system in year 2011 with 500

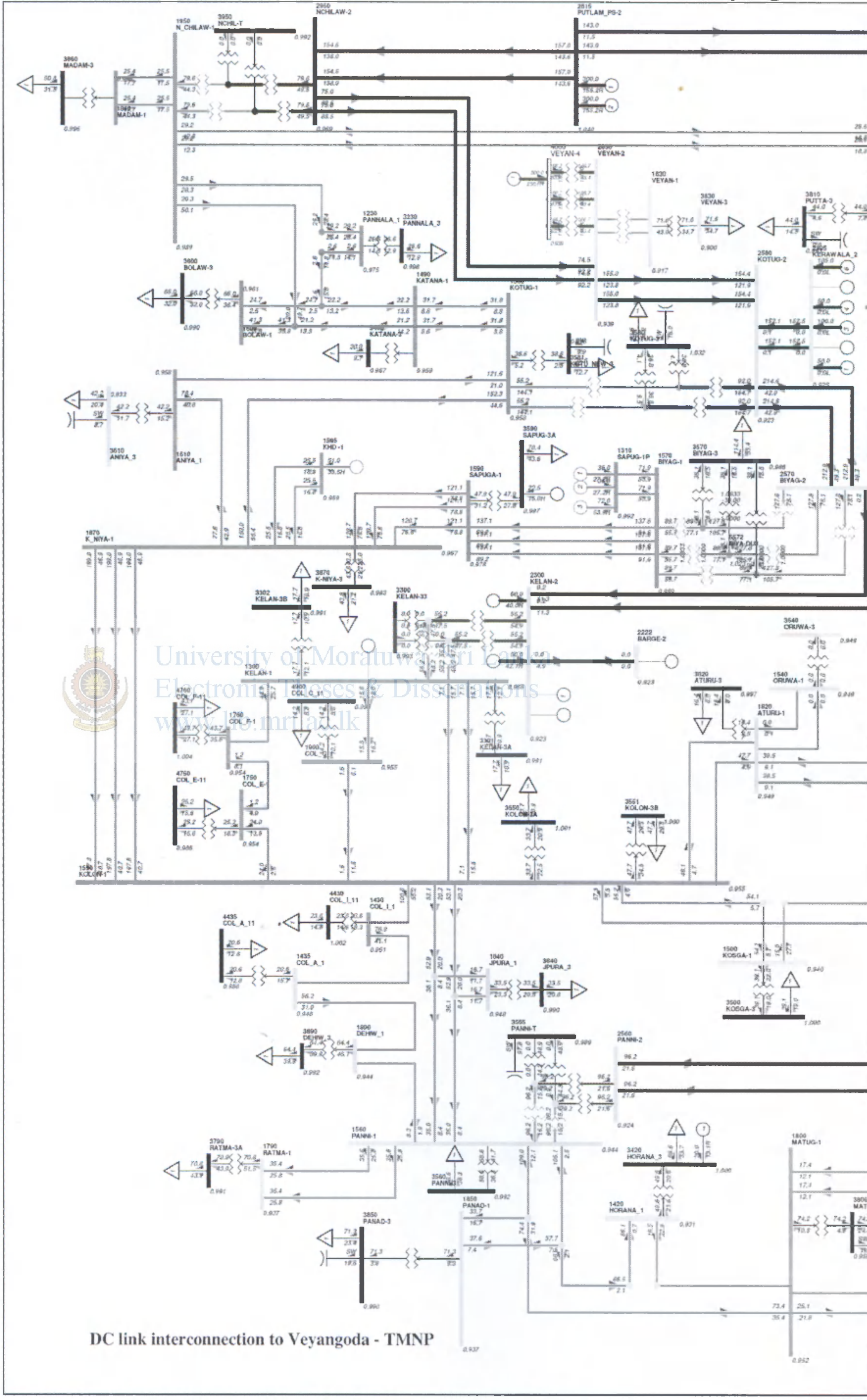


Sri Lankan Transmission System in 2011 with 500 MW Connected to Veyangoda

2011 with 500 MW additions to Veyangoda grid substation.

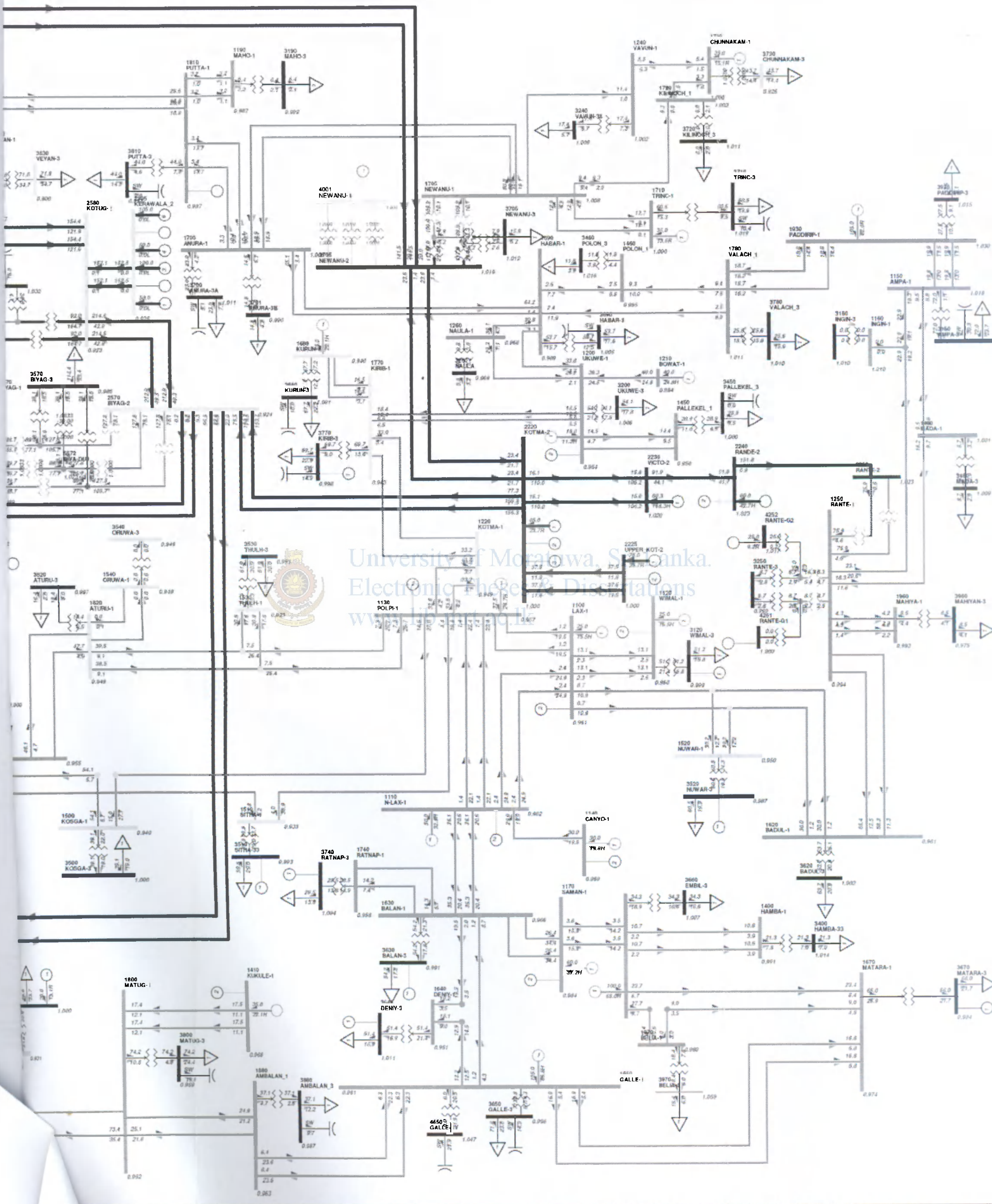


Annex A - 2: Load flow diagram for night peak thermal maximum condition – Veyangoda



DC link interconnection to Veyangoda - TMNP

n – Veyangoda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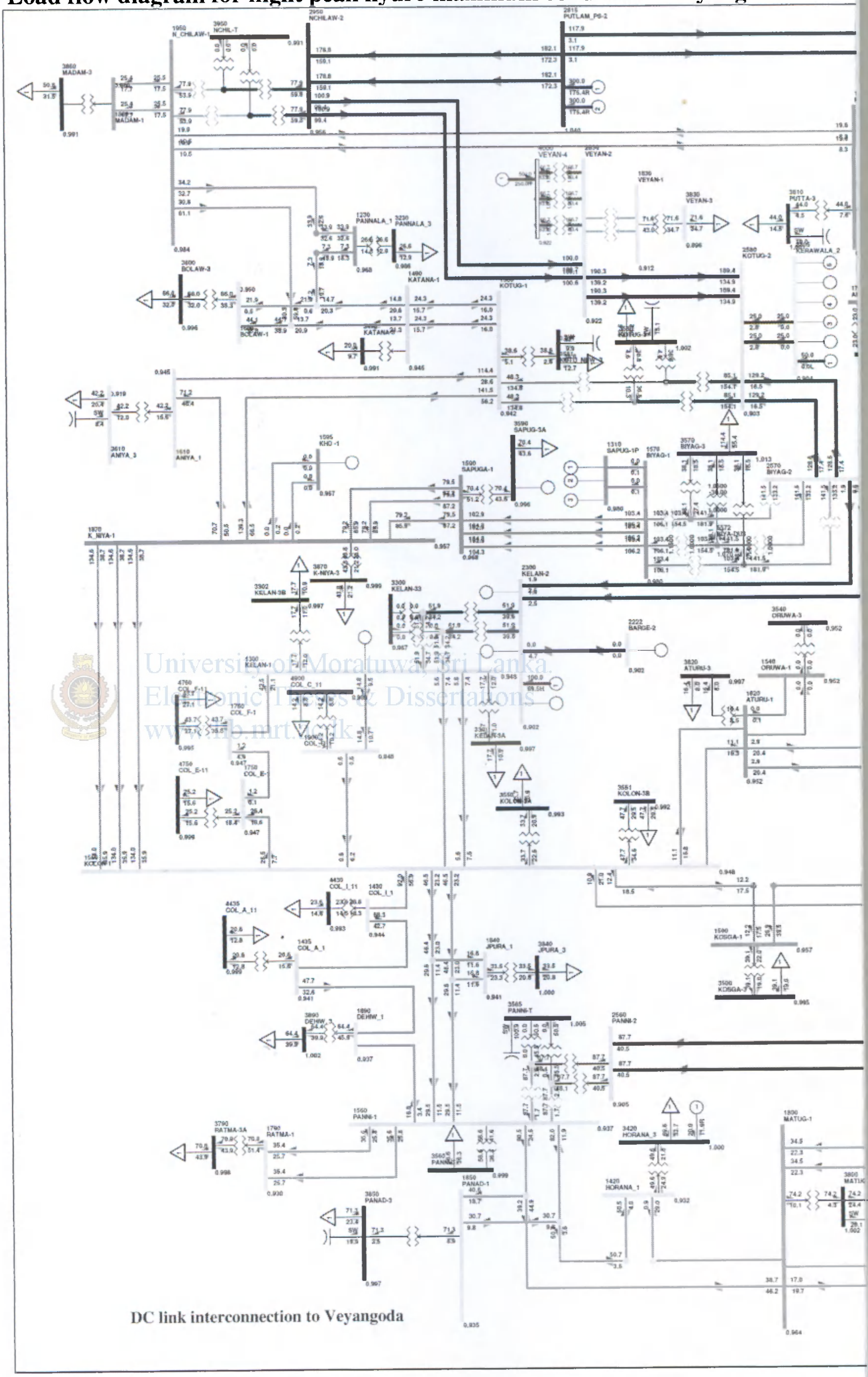
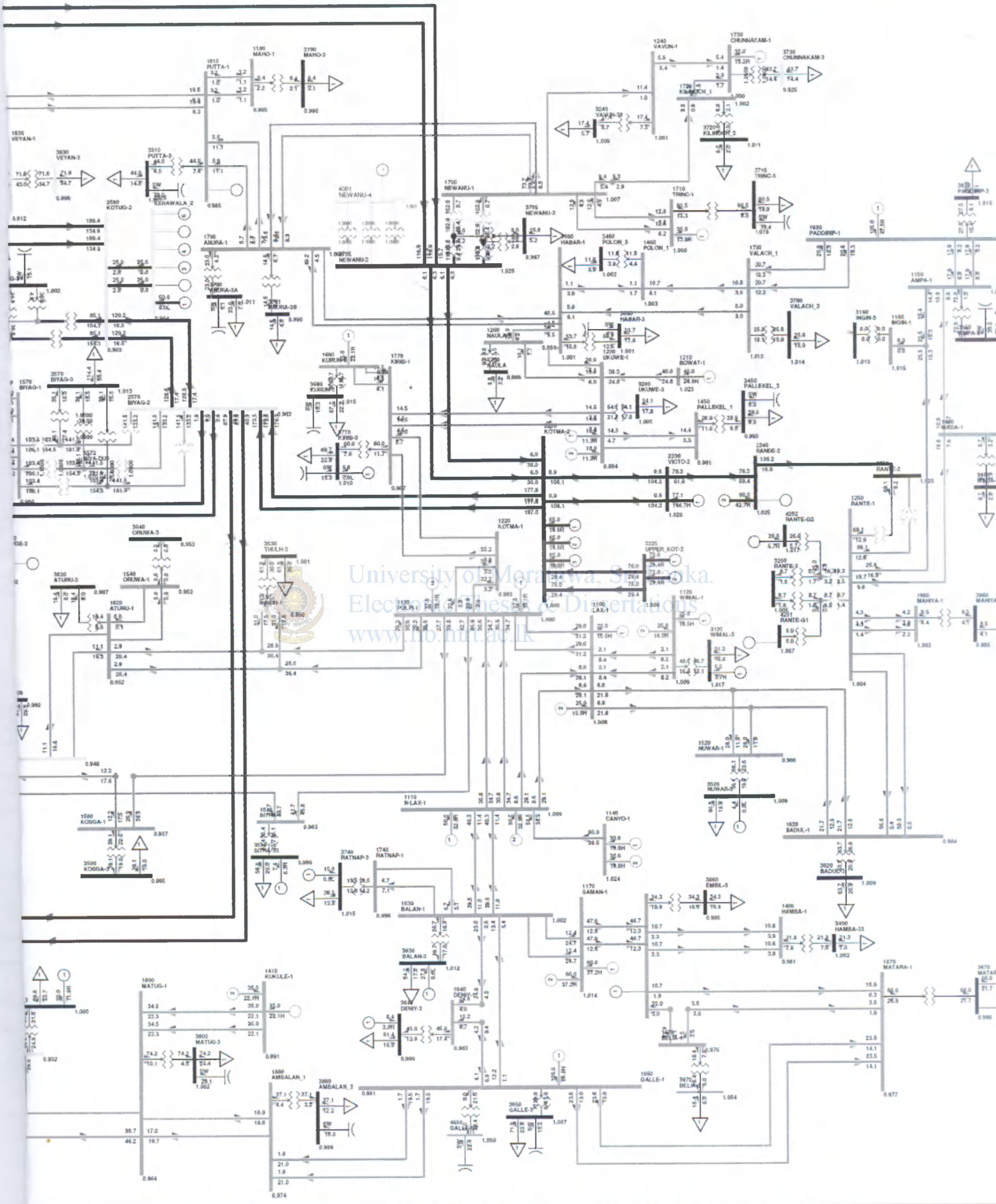
3190 MAHO-3
1810 PUTTA-1
3810 PUTTA-3
3630 VEYAN-3
2580 KOTUG-1
KERAWALA_2
1700 ANURA-1
3700 ANURA-3A
3701 ANURA-3B
4001 NEWANU-1
1705 NEWANU-1
3705 NEWANU-3
3706 NEWANU-2
1240 VAVUN-1
3240 VAVUN-3
CHUNNAKAM-1
3730 CHUNNAKAM-3
1720 KILINOCH_1
3720 KILINOCH_3
1710 TRINC-1
3710 TRINC-3
1930 PADDIRIP-1
3930 PADDIRIP-3
1690 HABAR-1
3690 HABAR-3
3460 POLON_3
1460 POLON_1
1780 VALACH_1
3780 VALACH_3
1150 AMPA-1
3150 AMPA-3
3160 INGIN-3
1160 INGIN-1
1260 NAULA-1
3260 NAULA
1680 KURUN-1
3680 KURUN-3
1770 KIRIB-1
3770 KIRIB-3
1200 UKUWE-1
3200 UKUWE-3
1210 BOWAT-1
1450 PALLEKEL_1
3450 PALLEKEL_3
BADA-1
3570 BIYAG-3
2570 BIYAG-2
2220 KOTMA-2
2230 VICTO-2
2240 RANDE-2
RANTE-2
1250 RANTE-1
4252 RANTE-G2
3250 RANTE-3
4251 RANTE-G1
1220 KOTMA-1
2225 UPPER_KOT-2
3540 ORUWA-3
1540 ORUWA-1
3530 THULH-3
1530 THULH-1
3520 ATURU-3
1520 ATURU-1
1130 POLPI-1
1100 LAX-1
1120 WIMAL-1
3120 WIMAL-3
1960 MAHIYA-1
3960 MAHIYAN-3
1520 NUWAR-1
3520 NUWAR-3
1620 BADUL-1
3620 BADUL-3
1500 KOSGA-1
3500 KOSGA-3
1510 SITHA-1
3510 SITHA-33
1110 N-LAX-1
1140 CANYO-1
3740 RATNAP-3
1740 RATNAP-1
1630 BALAN-1
3630 BALAN-3
1170 SAMAN-1
3660 EMBIL-3
1400 HAMBA-1
3400 HAMBA-33
1670 MATARA-1
3670 MATARA-3
1640 DENIY-1
DENIY-3
1970 BELIA-1
3970 BELIA-3
1800 MATUG-1
3800 MATUG-3
1410 KUKULE-1
1880 AMBALAN_1
3880 AMBALAN_3
1650 GALLE-1
3650 GALLE-3
4650 GALLE

Annex A - 3: Load flow diagram for night peak hydro maximum condition – Veyangoda



DC link interconnection to Veyangoda

n – Veyangoda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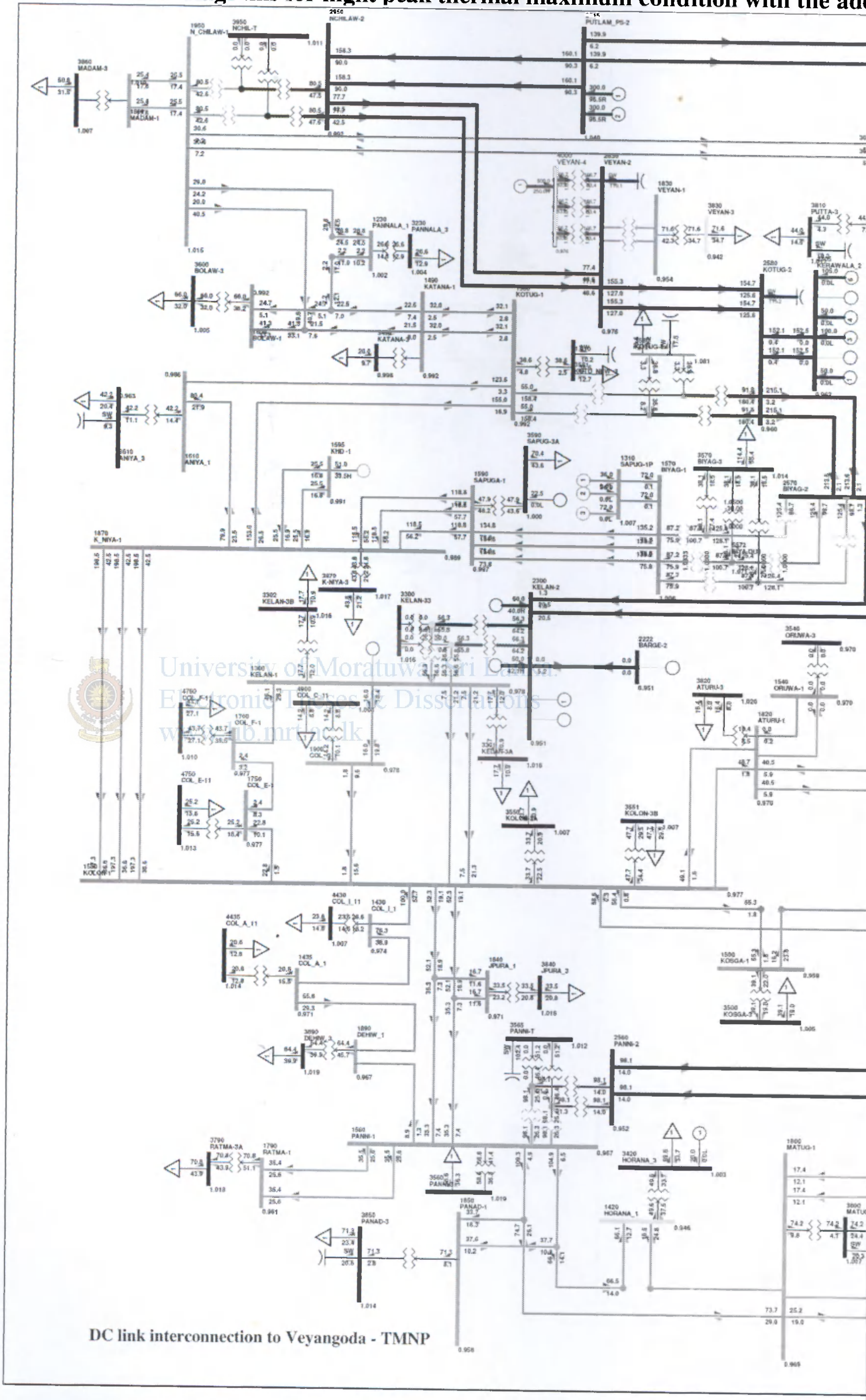
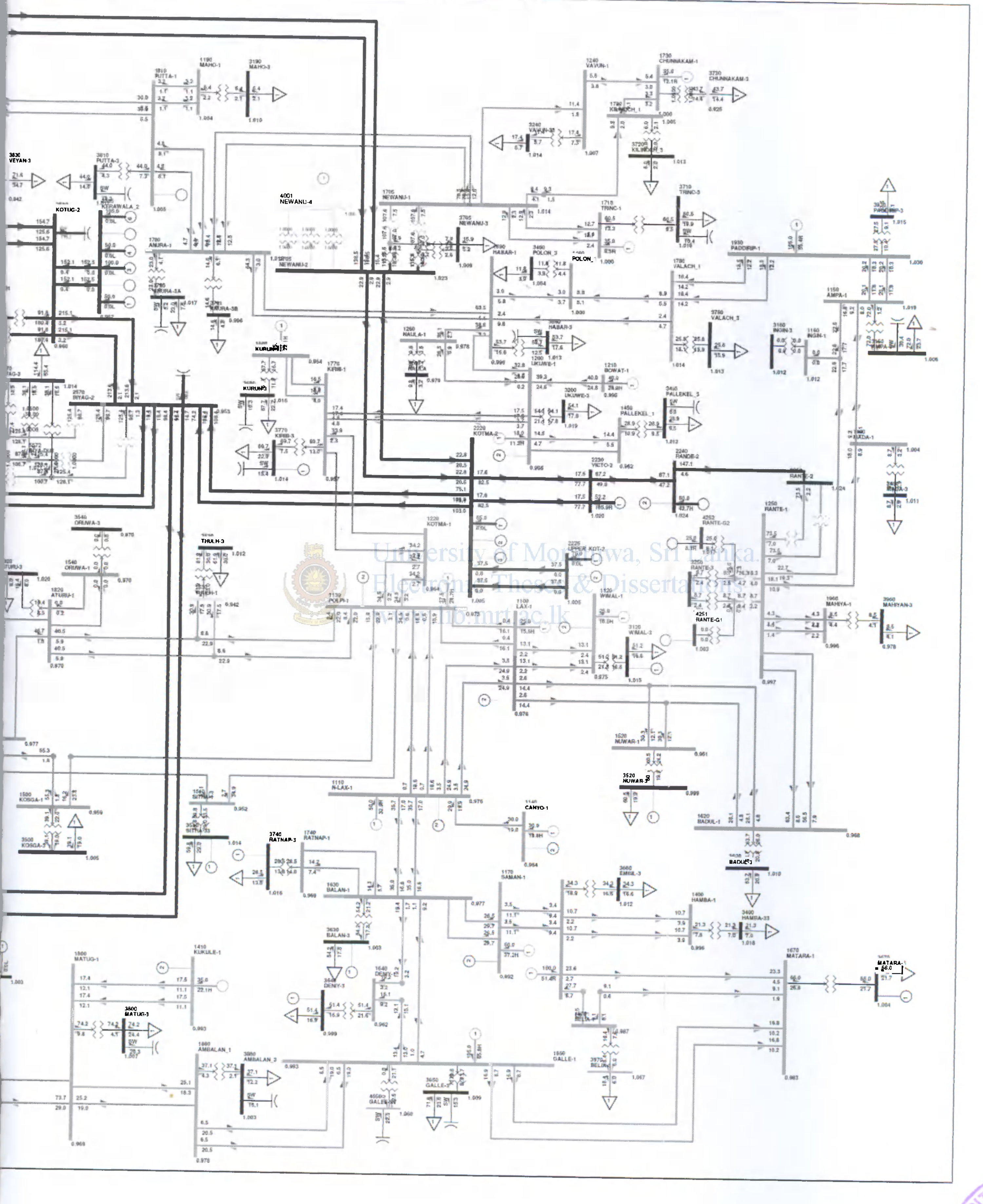
1190 MAHO-1
3190 MAHO-3
1240 VAVUN-1
1730 CHUNNAKAM-1
3730 CHUNNAKAM-3
1720 KILINOCH_1
3240 VAVUN-33
3720 KILINOCH_3
3710 TRINC-3
1710 TRINC-1
1830 VEYAN-1
3830 VEYAN-3
2510 PUTTA-3
2580 KOTUG-2
KERAWALA_2
4001 NEWANU-4
1700 NEWANU-1
3705 NEWANU-3
2700 NEWANU-2
1790 ANURA-1
3790 ANURA-3A
3791 ANURA-3B
1660 HABAR-1
3460 POLON_3
1460 POLON_1
1780 VALACH_1
3780 VALACH_3
1930 PADDIRIP-1
3930 PADDIRIP-3
1150 AMPA-1
3150 INGIN-3
1160 INGIN-1
1260 NAULA
3260 NAULA
3660 HABAR-3
1200 UKUWE-1
3200 UKUWE-3
1210 BOWAT-1
3450 PALLEKEL_3
1450 PALLEKEL_1
1680 KURUN-1
3680 KURUN-3
1770 KIRIB-1
3770 KIRIB-3
3570 BIYAG-3
1570 BIYAG-1
2570 BIYAG-2
2220 KOTMA-2
2230 VICTO-2
2240 RANDE-2
RANTE-2
1250 RANTE-1
4252 RANTE-G2
3250 RANTE-3
4251 RANTE-G1
1960 MAHIYA-1
1960 MADA-1
3640 ORUWA-3
1640 ORUWA-1
3620 ATURU-3
1620 ATURU-1
3530 THULH-3
1220 KOTMA-1
2225 UPPER_KOT-2
1120 WIMAL-1
3120 WIMAL-3
1130 POLPI-1
1100 LAX-1
1520 NUWAR-1
3520 NUWAR-3
1110 N-LAX-1
1140 CANYO-1
1620 BADUL-1
3620 BADUL-3
1590 KOSGA-1
3590 KOSGA-3
3740 RATNAP-3
1740 RATNAP-1
1630 BALAN-1
3630 BALAN-3
1170 SAMAN-1
3660 EMBIL-3
1400 HAMBA-1
3400 HAMBA-33
1670 MATARA-1
1800 MATUG-1
3800 MATUG-3
1410 KUKULE-1
3640 DENIY-3
1640 DENIY-1
1880 AMBALAN_1
3880 AMBALAN_3
1650 GALLE-1
3650 GALLE-3
3970 BELIA-3

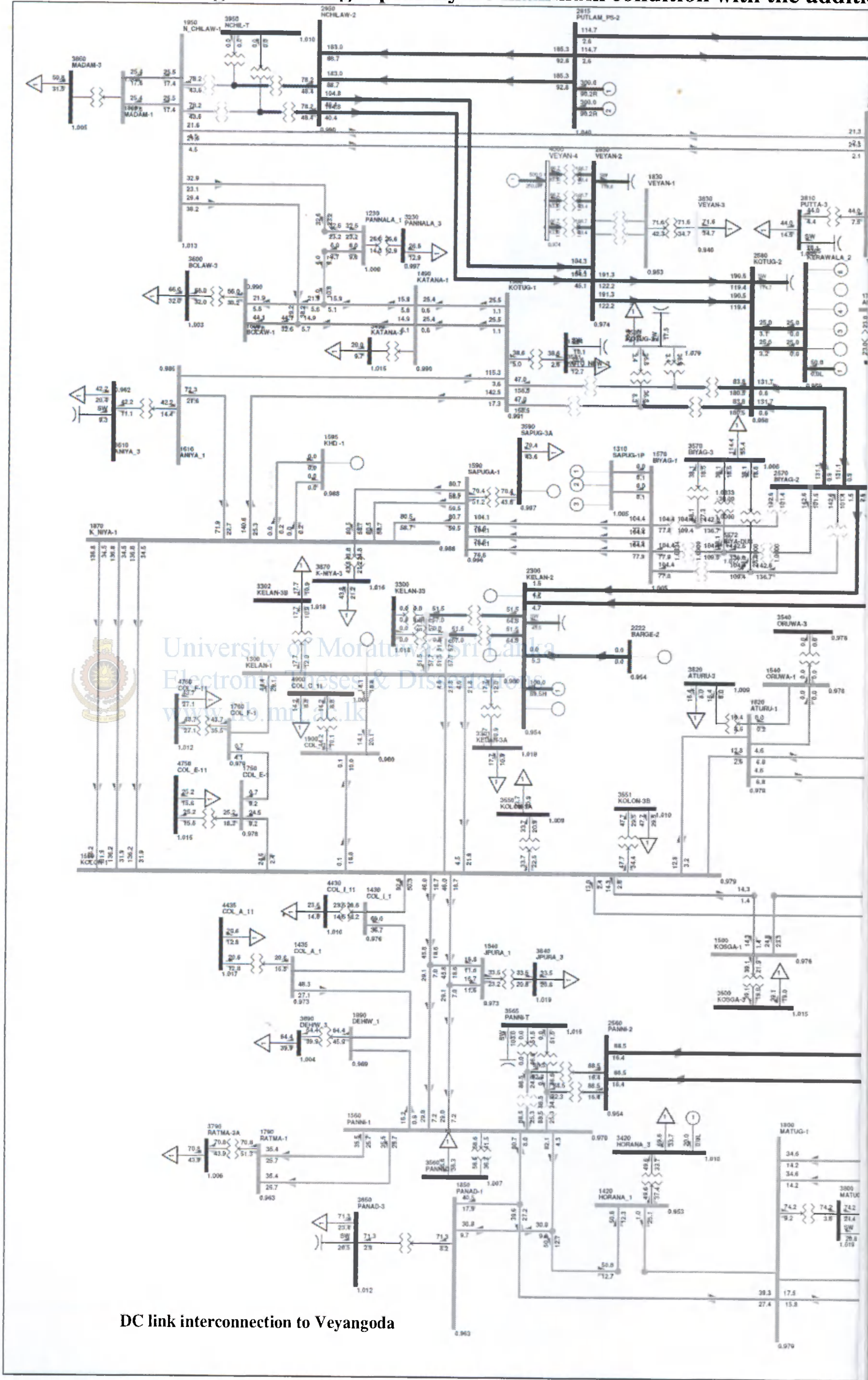
Annex A - 4: The load flow diagrams for night peak thermal maximum condition with the ade



DC link interconnection to Veyangoda - TMNP ion with the addition of capacitor banks to the system – Veyangoda

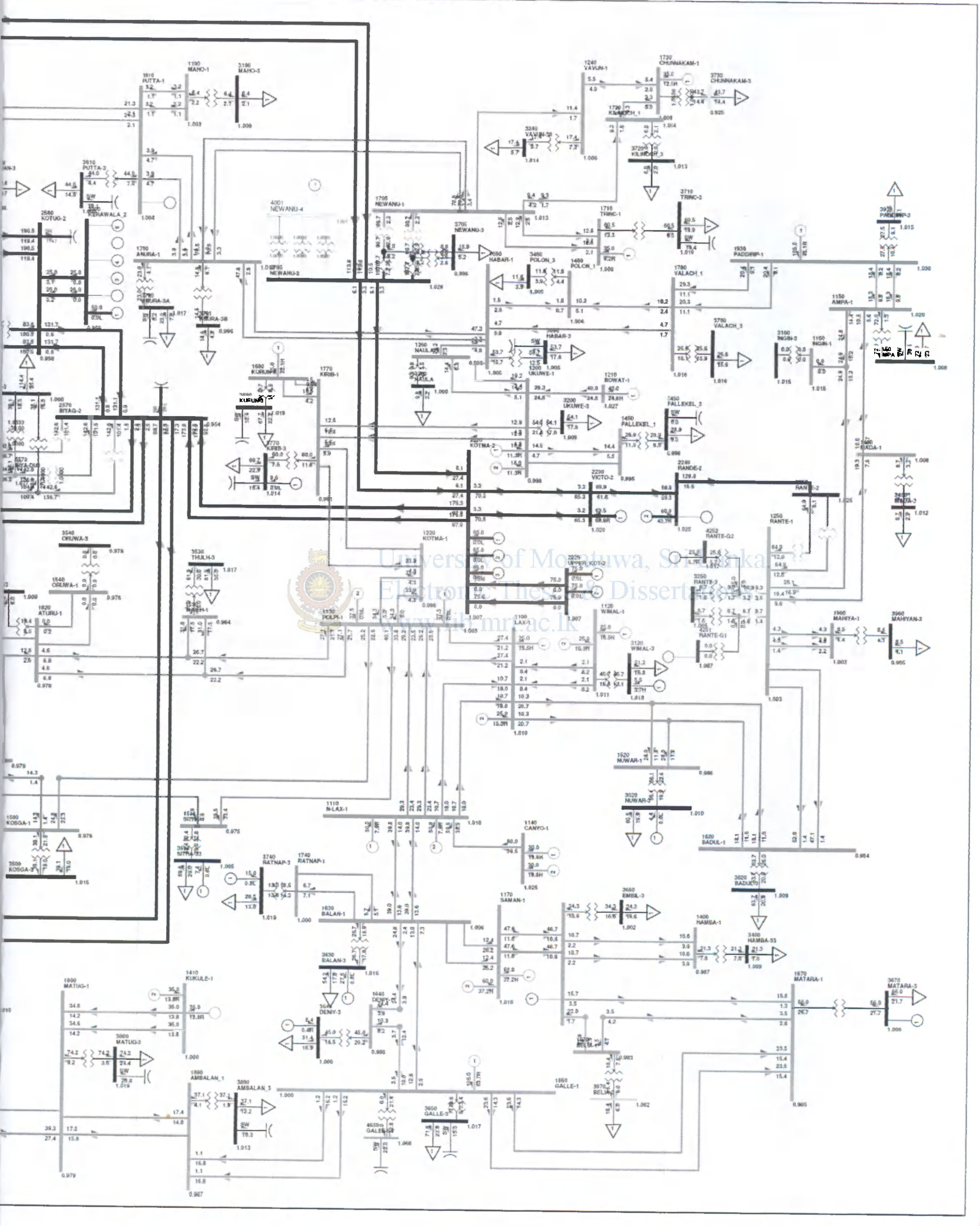


Annex A - 5: The load flow diagrams for night peak hydro maximum condition with the additi



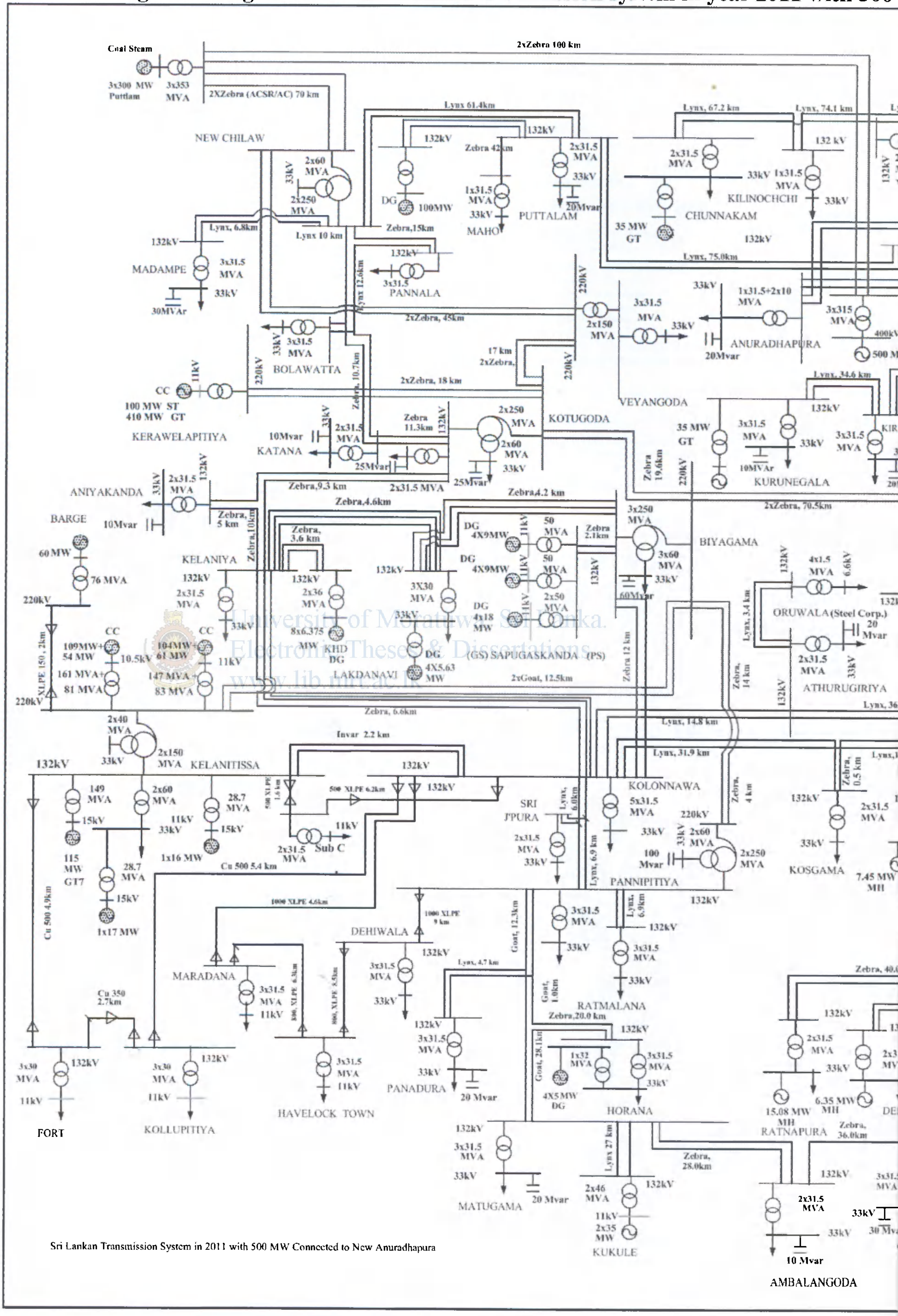
DC link interconnection to Veyangoda

with the addition of capacitor banks to the system – Veyangoda



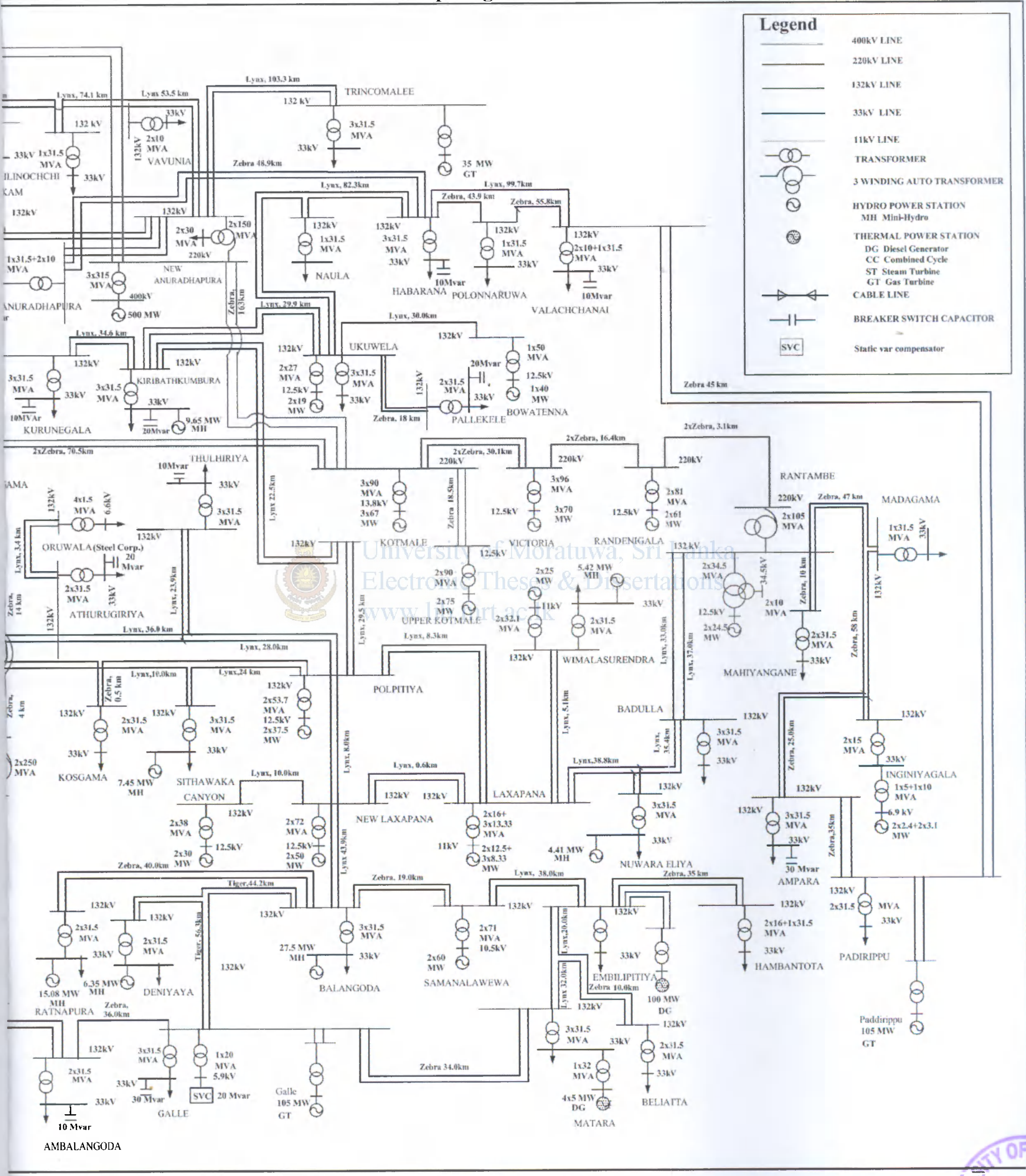
M.Sc. in Electrical Engineering

Annex A - 6: Single line diagram of the Sri Lankan transmission system in year 2011 with 500

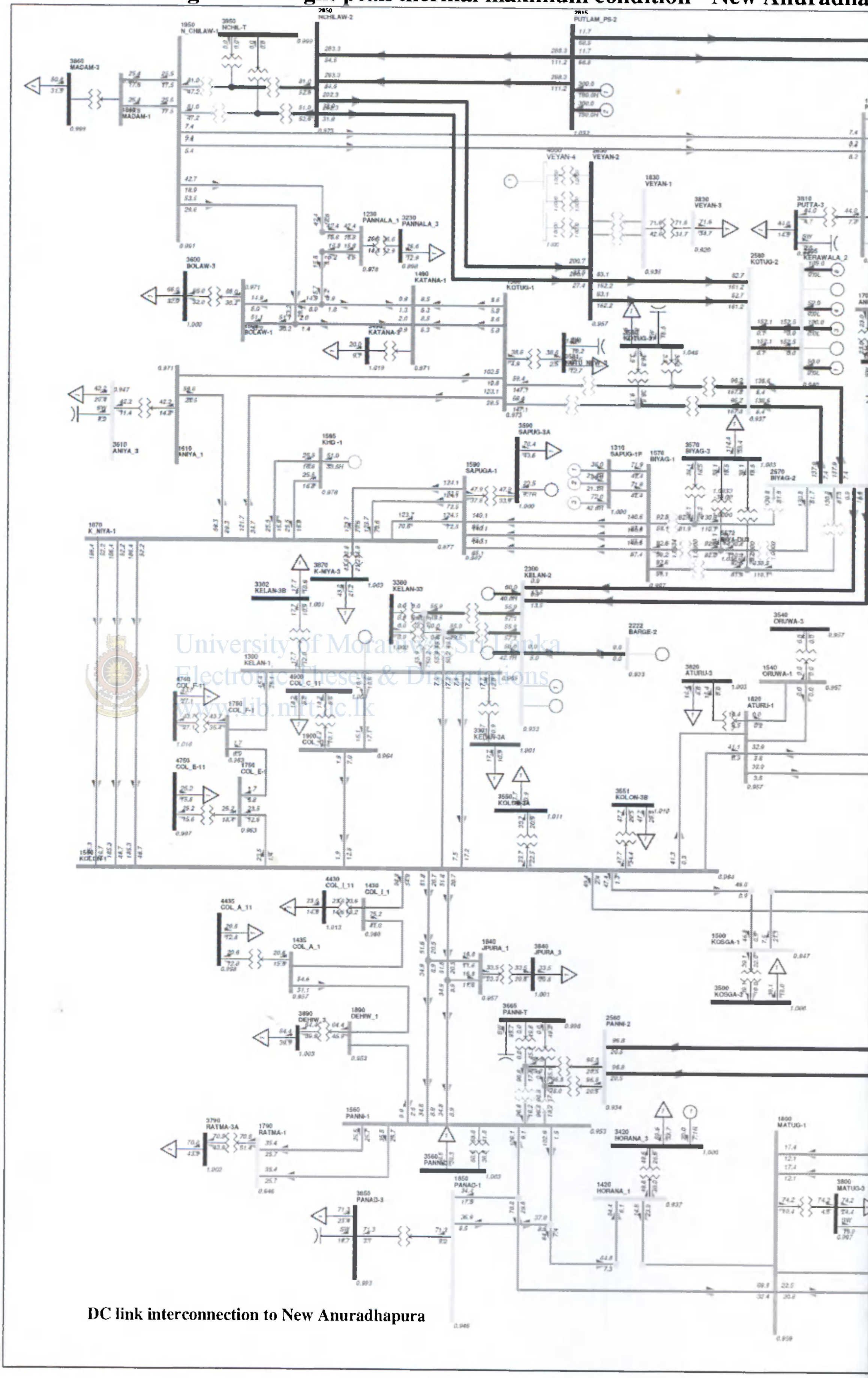


Sri Lankan Transmission System in 2011 with 500 MW Connected to New Anuradhapura

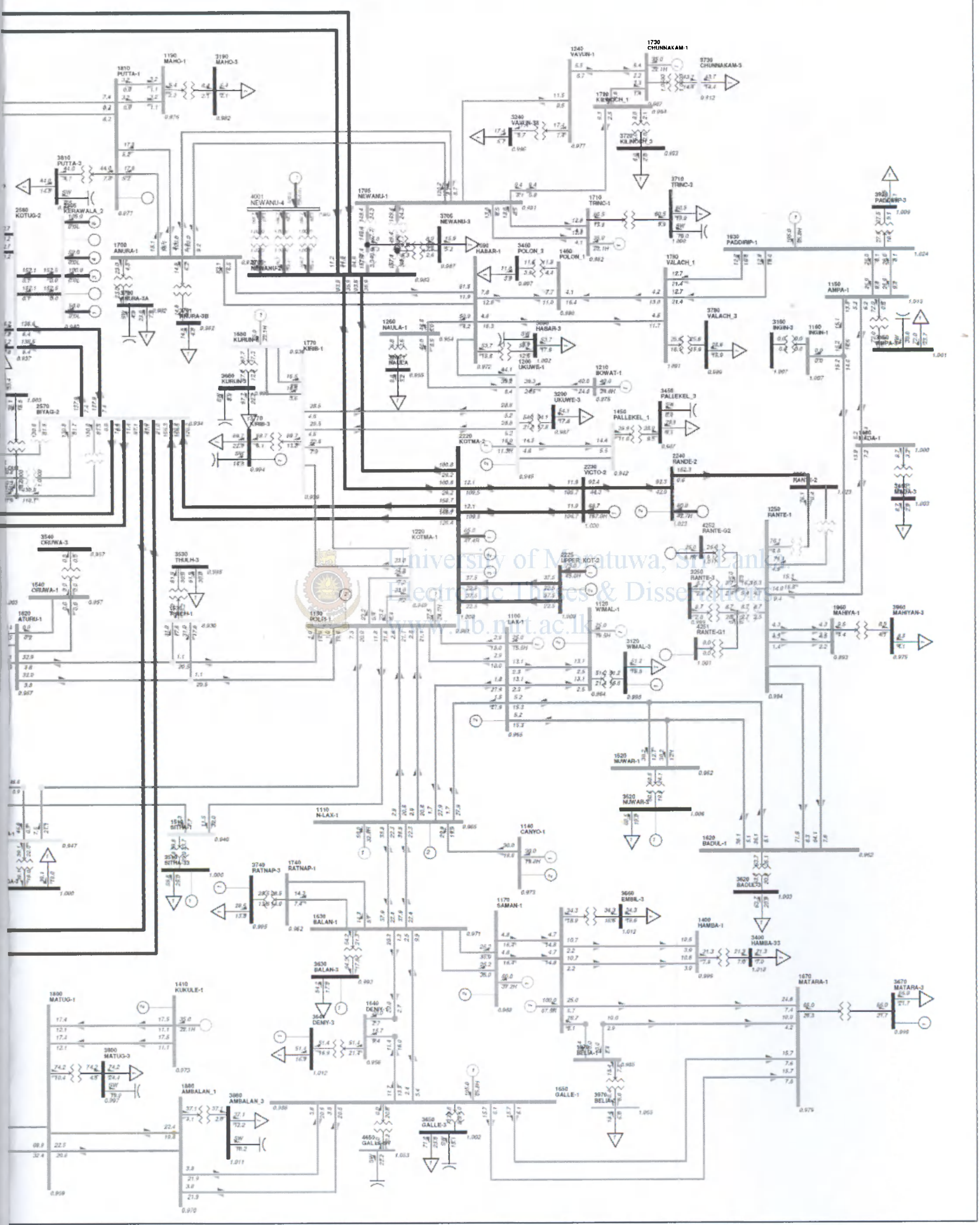
r 2011 with 500 MW additions to New Anuradhapura grid substation



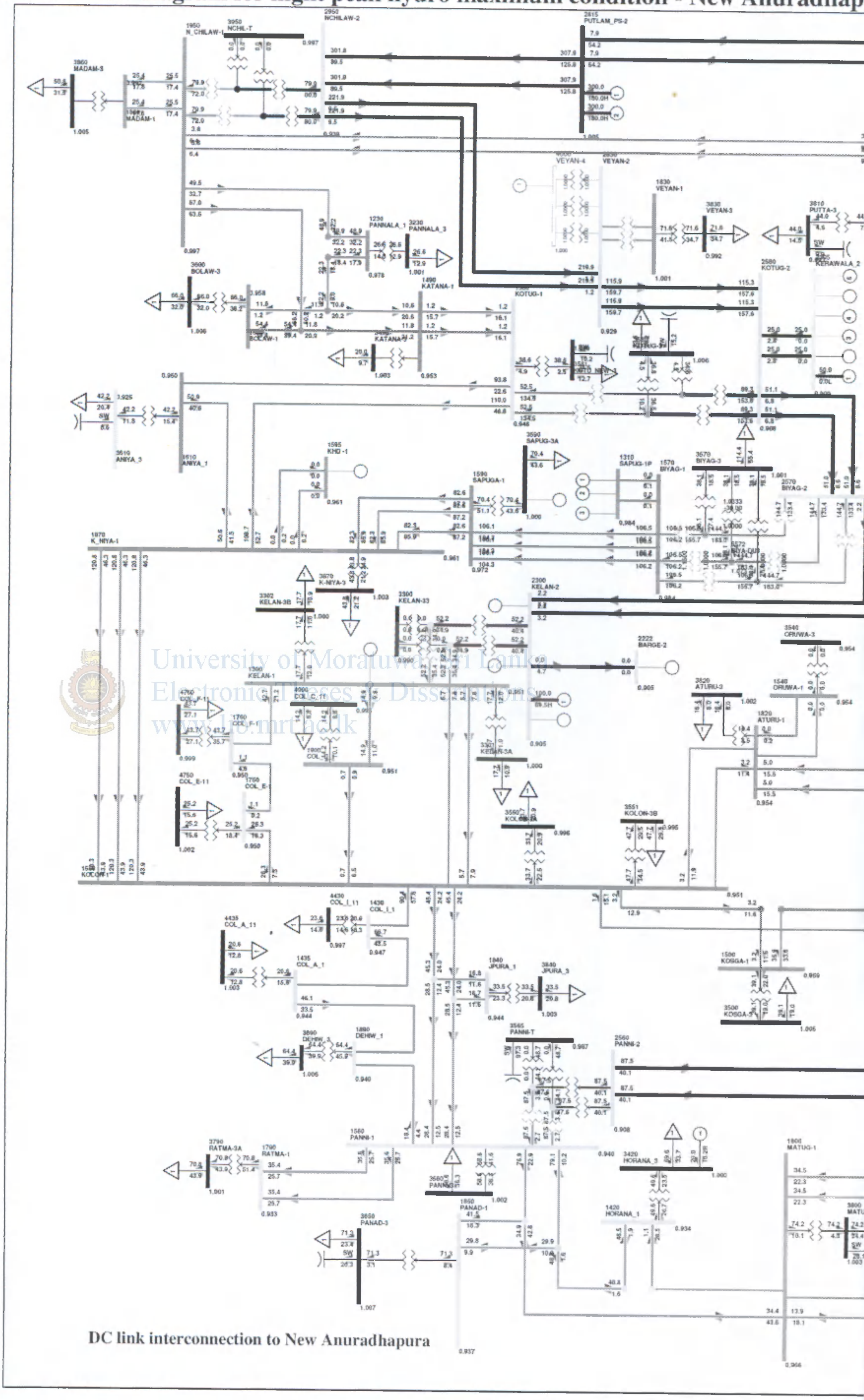
Annex A - 7: Load flow diagram for night peak thermal maximum condition - New Anuradha



w Anuradhapura

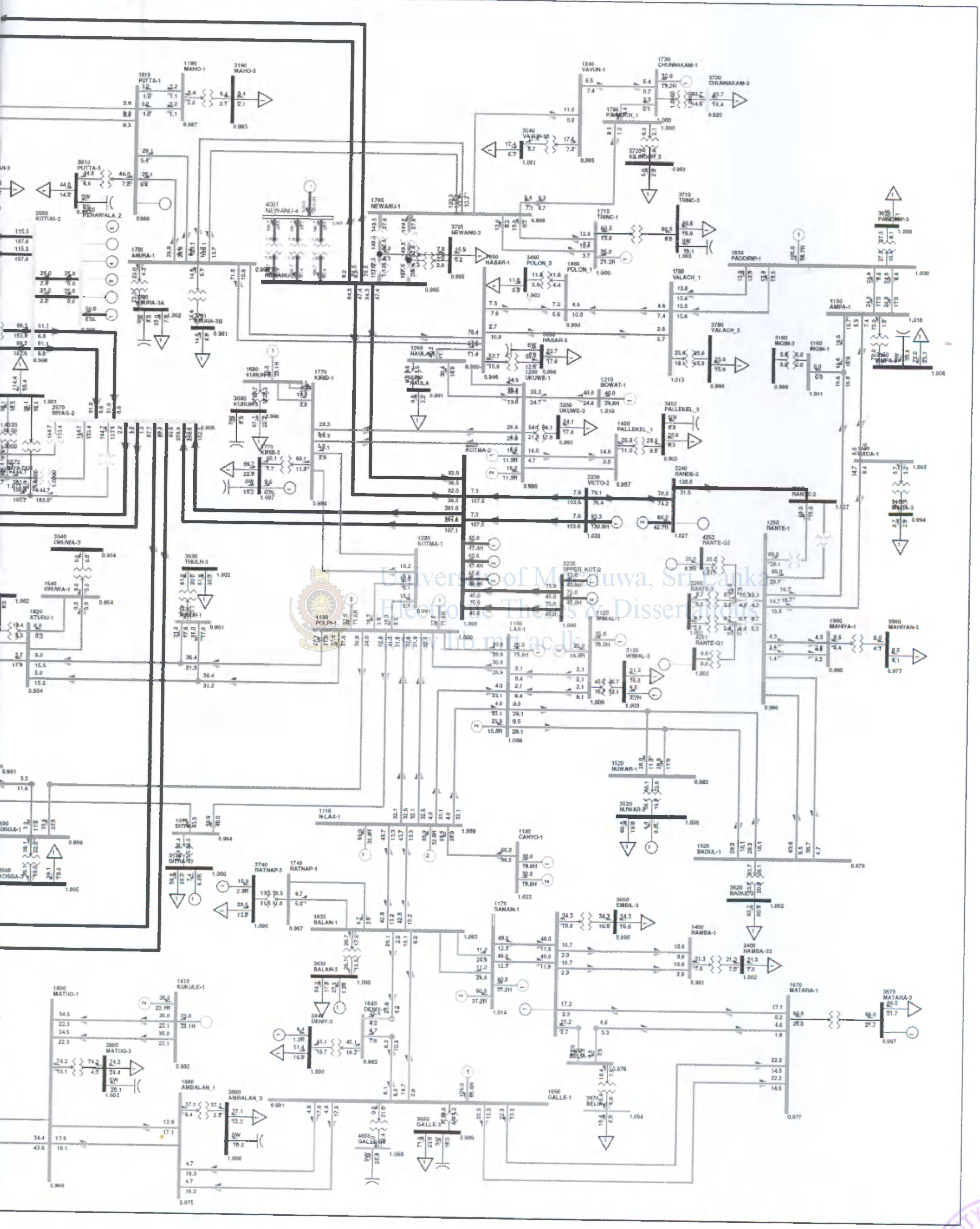


Annex A - 8: Load flow diagram for night peak hydro maximum condition - New Anuradhap

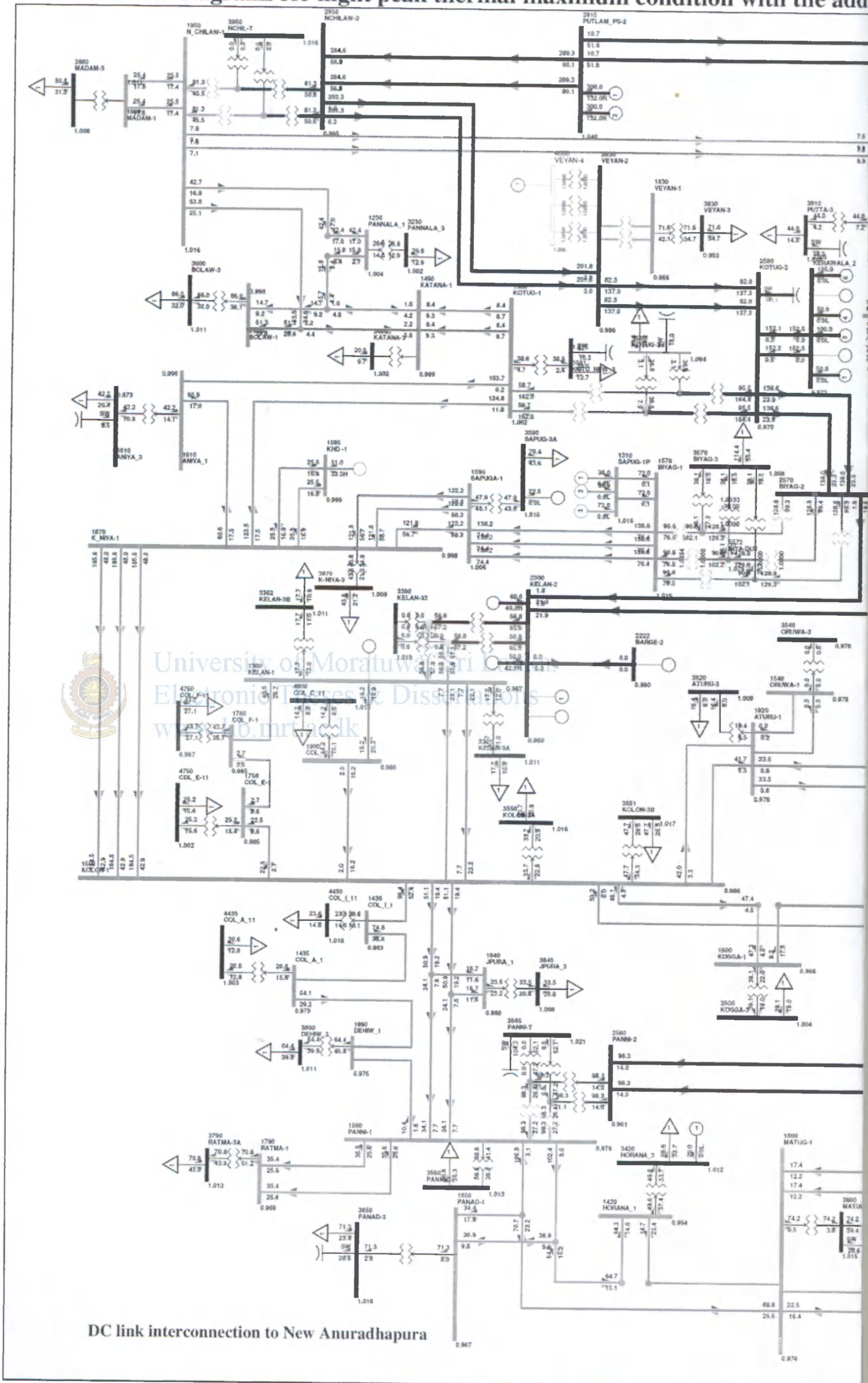


DC link interconnection to New Anuradhapura

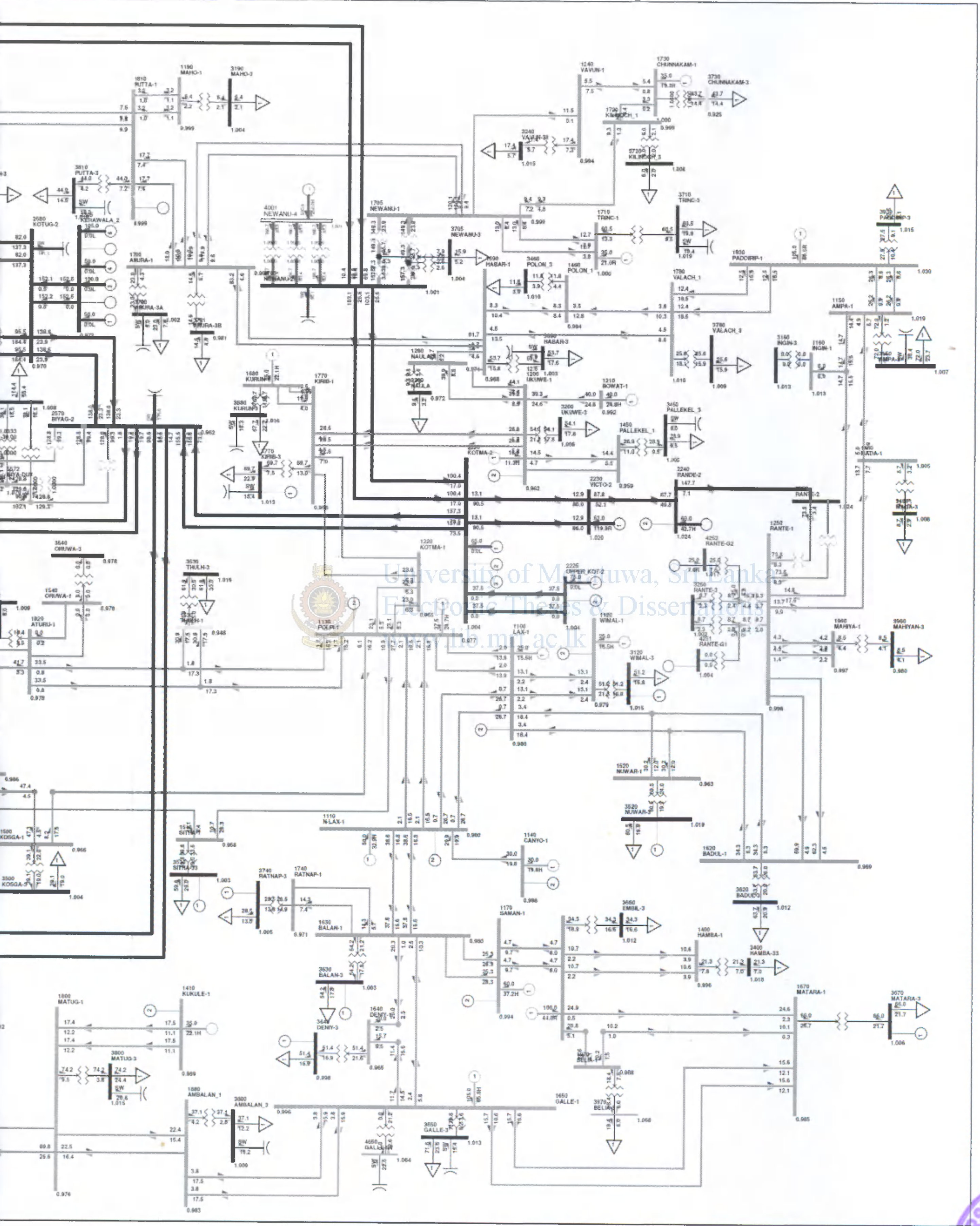
w Anuradhapura



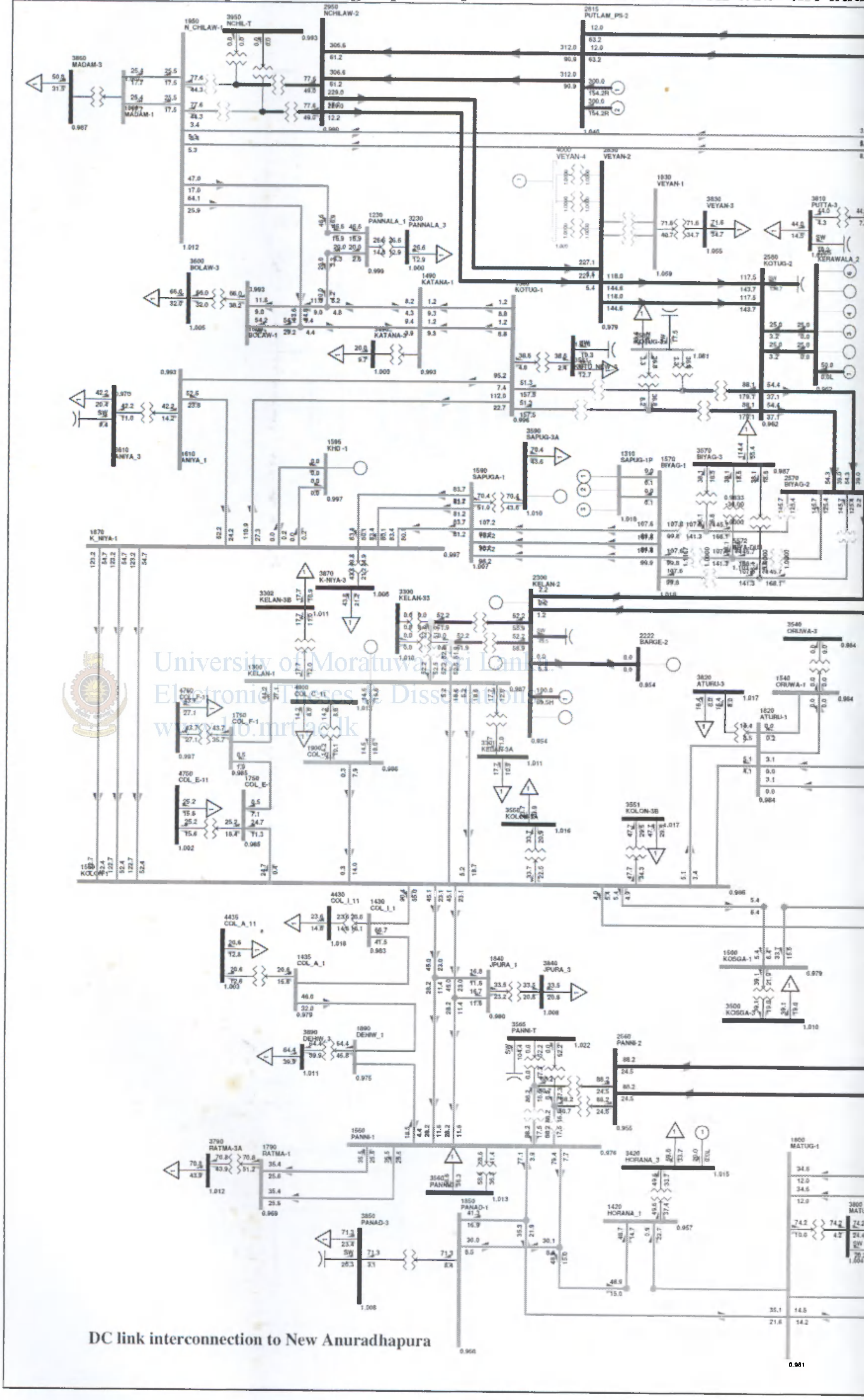
Annex A - 9: The load flow diagrams for night peak thermal maximum condition with the add



n with the addition of capacitor banks to the system - New Anuradhapura



Annex A - 10: The load flow diagrams for night peak hydro maximum condition with the add



DC link interconnection to New Anuradhapura

th the addition of capacitor banks to the system - New Anuradhapura