EMBEDDED GENERATION IMPACTS TO MEDIUM VOLTAGE DISTRIBUTION NETWORK AND MITIGATION TECHNIQUES

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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 is also not being concurrently submitted for any other degree.

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Date : 30/01/2009

I endorse the declaration by the candidate.

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Abstract

As a result of increasing of electricity demand, the electrical transmission and distribution systems are continuously expanding. Connection of Distribution Generators (DG) to the distribution network and upgrading of the transmission lines are more frequent expansions. Connection of new mini hydro power plants (MHPs) in Sri Lanka is one good example. In most of the cases these DGs, which are mainly based renewable energy are located in remote areas. The main bottleneck barrier of connecting DG is violation of fault current ratings at some parts of the network. Some expansions may result in higher fault current level at some points of the power system and thus exceeding the short circuit ratings of equipment such as switchgears and expulsion switches. As upgrading of equipment is not feasible both economically and technically, introduction of fault current limiting devices has become an essential requirement.

Fault Current Limiter (FCL) is series device connected to the power system, which shows the high impedance to the current during a fault while showing a zero or low impedance during normal loading condition. Although several FCL topologies were introduced by researchers, there are some technical and economical problems to be solved before introducing them to the power system effectively. It demands the investigation of new FCL topologies which are more feasible or modifications of available topologies to increase feasibility. FCL introduces additional impedance to the system depending on the system operating conditions. It is not only reduces the fault current but also effects on a number of power system related phenomena such as power losses, protection coordination, interrupting duty of switchgears, transient stability and voltage sag.

This research work is mainly focus on application of Fault Current Limiter (FCL) to overcome this problem and facilitate the equipment safety.

Acknowledgement

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List of Abbreviations

AAAC	All Aluminium Alloy Conductor
ABS	Air Break Switch
ACSR	Aluminium Conductor Steel Reinforced
CB	Circuit Breaker
CEB	Ceylon Electricity Board
CSC	Consumer Service Centre
DDLO	Drop Down Lift Off
DG	Distributed Generator
FCL	Fault Current Limiter
GSS	Grid Substation
GTO	Gate Turn Off
HTS	High Temperature Superconducting
I	Current
I_c	Critical current
J_c	Critical Current density
LBS	Load Break Switch
LT	Low Tension
LV	Low Voltage
MFCL	Magnetic Fault Current Limiter
MHP	Mini Hydro Power
MOV	Metal
MV	Medium Voltage
PSS	Primary Substation
RGSS	Rathnapura Grid Substation
SC	Superconductor
SFCL	Superconducting Fault Current Limiter
SIN	System Identification Number
SPP	Small Power Producers
SPPA	Small Power Purchase Agreement

StFCL	Static Fault Current Limiter
T_c	Critical Temperature
TCSC	Thyristor Control Series Capacitor
TCR	Thyristor Controlled Reactor

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Chapter 01

Introduction

1.1 Background

As a national policy, the ministry of Power and Energy has taken a decision to promote generation of electricity using embedded generation since early nineties by giving the required assistance to the private sector, which includes training & capacity building, pre feasibility studies and resource assessments. Embedded generation could be defined as an electric power source connected directly to the distribution network of a power system and also known as distributed generation (DG). Capacity range for this embedded generation is defined from 100 kW to 10 MW and connected to the grids according to the CEB Guides for "Grid Interconnection of Embedded Generators" December 2000 or called as Grid Code.[1]

The government has identified the development of Renewable Energy Projects, as a matter of policy to diversify the electricity sector from high cost thermal power generation. Therefore, required incentives and assistance has to be provided for the renewable energy resource development (Mini Hydro, Bio Mass, Wind, etc.,). Further National Energy Policy 2006 has. identified to obtain fuel diversify and energy security in electricity generation as a strategic objective to development of renewable energy projects.

The procedure for electricity purchases from small power producers (SPPs) by the CEB was regularized beginning of 1997 with the publication of a standardized power purchase agreement (SPPA) which included a scheme for calculating the purchase price based on the avoided cost principle. This was offered to all sources of power plants of capacity less than 10 MW.

It is observed that renewable energy resources (Mini Hydro, Bio Mass, Wind, etc.,) are being used for embedded generation. Accordingly, CEB has extended the required assistance for the development of the renewable energy projects and up to now around 70 projects having total capacity of around 132 MW have been commissioned and connected to the national grid under the renewable energy promotional program. Out of them 68 projects are Mini Hydro Plants. (Refer Appendix - A)

There are advantages and disadvantages due to these embedded generations to the CEB. Majority of this embedded generators are Mini Hydropower Plants (MHPs) and they are running based on the water flow *(Hydro plants, capacity range from 100 kW to 10 MW defined as MHP s in CEB).* Thus the system control manages the balance. As the fuel is hydro it gives contribution to reduce the fuel burning plants indirectly saving the foreign currency flows. On the other way, basically this will be saving the national funds.

If we consider the network side as these power stations are far away from the grid substations during the peak time they contribute to improve the feeder end voltage profile and this would be a major advantage. When we consider disadvantages, during the off peak time there is no loads or light load flow to the grid substation, thereby increasing the voltage around the MHP s which in turn resulting high voltage to the consumers connected to the same line. Moreover in addition to above, there are several issues connected to the MHP s in Distribution Network

It is obviously understood that while referring the table of Grid vice connected MHP s in Sri Lanaka Rathnapura Grid Substation is one of a leading Grid Substation in Sri Lanka with many number DG s. Hence this study has been confined to the Rathnapura Grid Substation of Sabaragamuwa Province of CEB, taking as a sample and analysis for voltage variations and fault currents with DG s.

1.2 Motivation

Power system is continuously expanding and this may result in higher fault current level at some points of the power system. This can be clearly observed when introducing new DG in remote areas. In such cases the fault current at certain locations after connection of the new generator may be much greater than the short circuit capability of the existing switchgears and other equipments. This may demand upgrading of the existing switchgear short circuit rating. However, such upgrades are not easy due to: (a) high replacement cost; (b) system reliability would be greatly reduced during the necessary construction period, and (c) the short circuit ratings of the currently available circuit breakers would soon become inadequate. Other than replacing the existing switchgear, there are several methods that can be used to reduce the fault current in the power system to an acceptable level. These methods include (a) network splitting, (b) current limiting reactors, (c) sequential network tripping and (d) fault current limiters.

The out come of this fault current analysis is very important for system planning engineers and future planning work of CEB. Usually before connecting a DG to the power system fault current analysis is done by the system planning engineer of that province. Further tools available in SynerGEE software could be effectively used for load flow analysis. However introducing the Fault Current Limiters (FCL s) to distribution network is a new concept to the CEB and as an engineer in CEB, author motivated to select this topic for his study.

1.3 Objective

The objectives of this study are given below,

- Analyse the voltage variations of the feeders of Rathnapura Grid Substation with and without DG s using SynerGEE software package.
- Model the MHP s using MATLAB software connected to the feeders and calculate fault currents in sections with and without DG s.
- Introduction of Fault Current Limiter (FCL) to bring down the fault current to an acceptable level.

1.4 Scope of work

- Rathnapura Grid Substation is taken as the sample network for this study because it is rich from DGs and update the MV maps of the feeders by using SynerGEE software.
- Then it is easy to run the load flow and analysis to obtain line voltage variations of the feeders with and without DGs by considering peak and off-peak times. As results high voltage areas around MHP s could be investigated and discuss about the results.
- Model the feeders of Rathnapura Grid Substation with DGs by using MATLAB software.
- Obtain fault levels of feeders with DGs.
- Analyzing the fault levels, realize the unacceptable fault levels.
- Discuss the types of FCL s as mitigating technique of this high fault levels.
- A novel FCL topology is implemented by using MATLAB and propose bring down the fault current to acceptable level.
- Apply this implemented FCL to selected places of the modeled network and try to reduce high fault currents to acceptable level.
- Clearly arrange and prepare the documentation of above discussions with the results and conclusions.

Chapter 02

MV Distribution System of Sabaragamuwa Province of Sri Lanka

2.1 Sabaragamuwa Province

The province consists of Ratnapura district and part of Kegalle and Kandy districts in which Ruwanwella area and Nawalapitiya area located respectively. The total land area is 5386 sq. km. The total population in 2004 is 2.3 million. Traditionally, the province is based on plantation economy and geologically it comprises of hilly terrain. Gem industry is the major attraction of Ratnapura district. In addition to the Tea and Rubber factories industrial estate has been located in Kuruwita. Considerable number of garment factories, two ceramic factories and a sugar factory are located in different places of the province. The province does not have much attraction to the industries due to the inadequate infrastructure facilities.

The unique feature in the whole province is the fast development of Mini Hydro Power Projects. Large number of Mini Hydro Power plants are feeding the MV distribution system and further proposals are given and exploring for new projects by developers. As these energy input are in embedded nature, there is no control over the amount of power dispatched to the 33 kV network.[2]

2.2 Electricity distribution network of Sabaragamuwa Province

MV network of Sabaragamuwa province is fed by nine 132/33kV Grid Substatins located at Rathnapura, Balandoda, Deniyaya and Wimalasurendra. The MV distribution is mainly carried out at 33kV. Bare Aluminum conductors of ACSR or

AAAC is used for MV distribution. 33kV distribution is done with Lynx or ELM double circuit express lines from grid substation up to gantries and several Racoon, Weasel distributors are used from gantries to the distribution transformers. At gantries Auto reclosure are connected to avoid entire feeder tripping due to transient faults. There by Air Break Switches (ABS) improving reliability and Load Break Switches (LBS) used to sectionalize the MV network. Over current and earth fault protection is provided at Grid Substations and at the switching gantries for 33 kV feeders. At the sections of MV lines, DDLO switches are used to ensure the isolation of the exact section during the faults.

The LV distribution system is 400V, 3 phase, and 4-wire. Bare Aluminum conductors are commonly used for LT distribution, but insulated bundle conductors are also used in highly congested areas. Distribution transformer capacity is not allowed to exceed 160 kVA other than in city limits. Maximum LT feeder length is limited to 1.8km to ensure the stipulated voltage at the feeder end.

2.3 Rathnapura Grid Substation

Rathnapura Grid Substation is fed by double circuit 132kV line comes from Blangoda Grid Substation. Two numbers of 31.5 MVA power transformers are installed to step down 132kV to 33kV. There are eight numbers of out going 33kV feeders mainly illustrate Rathnapura town and surrounding areas. Single line diagram of the Rathnapura Grid Substation in Figure2.1 and the distribution facilities are presented in Table 2.1. Out of 08 numbers of feeders, MHPs are connected only three feeders, which are Feeder No. 06, 08 and 05. Names of the MHP s, capacities, power plant developers and feeder details are tabulated in Table 2.3. (Refer Table 2.2 for feeder lengths). The statistical data of Rathnapura Grid Substation and feeders were obtained from the system planning engineer of Sabaragamuwa Province.

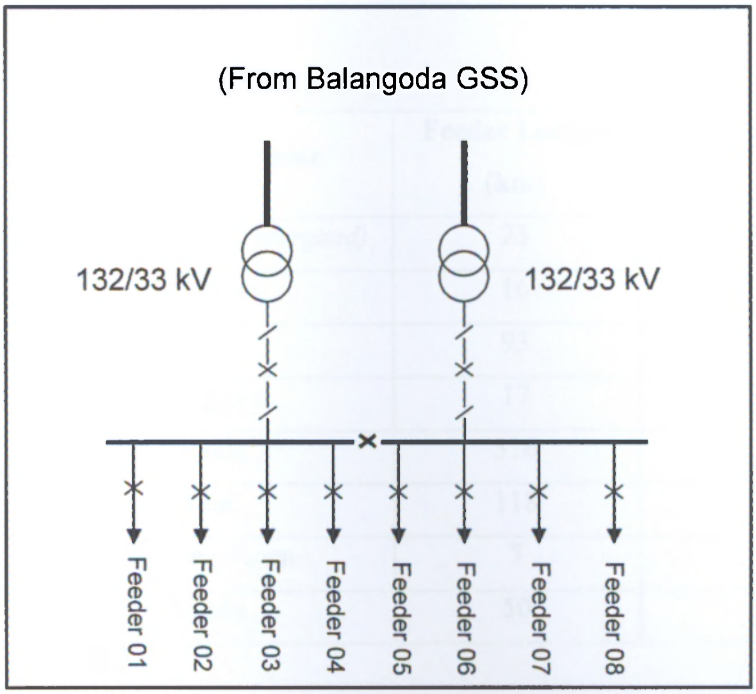


Figure :2.1 Single Line Diagram of Rathnapura Grid Substation

Item	Unit	Available Installed Quantity
LBS/ABS	Nos.	65
Auto Re-Closure	Nos.	05
Primary S/S Man/Unman	Nos.	01/15
Gantry	Nos.	08
Capacitor Bank	Nos.	0
33kV LT	Nos.	640
33kV O/H 1. Lynx	km	61
2. Racoon	km	244
3. ELM	km	27
4. Weasel	km	264
5. Copper	km	19

Table 2.1 : MV distribution facilities of Rathnapura Grid Substation

2.3.1 Feeder Data

Table 2.2: MV Feeder Data

Feeder No.	Feeder Name	Feeder Length (km)	No. of MHPs connected
01	Kiriella *(not energized)*	23	0
02	Ratnap. Town	16	0
03	Rathganga	93	0
04	*(not energized)*	17	0
05	Eheliyagoda	316	5
06	Nivithigala	118	2
07	Ratn. new Town	7	0
08	Durekkanda	50	5

2.3.2 Data of MHP s

Table 2.3: Data of connected MHP s

Name of MHP	Developer	Capacity (kW)	Feeder
Batatota	Vidullanka Ltd.	2,000	Feeder - 05
Erathna	Vallibel Power Erathna Ltd	9,900	Feeder - 05
Hemingford	Paulownia Plantations (Pvt) Ltd	180	Feeder - 05
Gomala Oya	Bhagya Hydro Power (Pvt) Ltd	800	Feeder - 05
Adawikanda	Alternate Power Systems (Pvt.) Ltd	6,500	Feeder - 05
Wayganga	Vidullanka Ltd.	8,930	Feeder - 06
Niriella	Weswin Power (Pvt.) Ltd	3,000	Feeder - 06
Rathganga	Paulownia Plantations (Pvt) Ltd	180	Feeder - 08
Guruluwana	Samangiri Hydroelectric Co (Pvt) Ltd	180	Feeder - 08
Labuwawa	Aqua Power (Pvt.) Ltd	800	Feeder - 08
Denawakganga	Country Energy (Pvt) Ltd	5,000	Feeder - 08
Guruluwana(Upgrade)	Samangiri Hydroelectric Co (Pvt) Ltd	3,600	Feeder - 08

2.4 Updating the map of MV distribution network

Hard copy maps are needed to be updated with the latest changes/additions to the network. This information was obtained from the System Planning Engineer of Sabaragamuwa Province. This is required to model the network in SynerGEE exactly like the existing system. It is also required to have the latest updated map of the area printed by the Surveyor Department to identify the correct locations of the MHPs and the routes of feeders more accurately.

Following data need to be recorded in the map updating process

- Recording of the line route on the map as accurate as possible.
- Type of conductor (Lynx, Raccoon), configuration of the circuit (vertical, horizontal, delta formation etc.), number of circuits (single or double line etc.) to be recorded. (Refer Appendix – B)
- All network switchgear items like Auto Reclosers, Sectionalizers (ABS, LBS and DDLO) need to be recorded with their reference numbers and status (whether open or closed).
- All distribution and bulk supply substations need to be recorded individually with their SIN.
- Network switching arrangements at Gantries, PSS need to be recorded.

2.5 Data Collection

To realize the present switching arrangements of feeders, correct feeder length were taken from relevant Consumer Service Centers (CSC). Peak and off peak time feeder demands were obtained from Ratnapura Grid Substation of Sabaragamuwa Province.

2.6 Modeling the network using SynerGEE

SynerGEE electric is a power full and comprehensive software, which perform number of useful power system studies like load flow, fault calculations and reliability analysis. While modeling the feeders and equipments, key points of the process are listed below [3].

2.6.1 Digitizing MV distribution network of Sabaragamuwa Province

a) Scan map sheet (1:50,000 or lower scale rectified map sheet) need to be kept in the background. (Latest map is required for more accuracy of digitizing the network)

b) Digitizing need to be initiated from the GSS and to be done outwards till the feeder comes across a provincial boundary or termination. All network switchgear items like, Auto Reclosures, ABS, LBS, DDLO & sectionalizes have to be installed in the digitized network model, in the way that they physically locate in the network. (Refer Appendix - C for SynerGEE maps of feeder No. 5, 8 and 6)

c) Each section (under description) with the relevant SIN of the substation attached. If more than one substation is available, multiple SIN numbers are to be entered separating each other with a comma. Indicate the feeder name under section ID of each section to identify the feeder to which the section belongs.

2.7 Assigning input data to the digitizing model

Input data can be divided into 3 categories

a) **Input data for the feeders**
   - i) Source impedance (Refer Appendix - D)
   - ii) Feeder demands

b) **Input data for substation transformers**
   - i) SIN for the substation.
   - ii) Bulk or Distribution

c) **Input data for DG s**
   - i) Select the suitable type of the generator
   - ii) Input sub transient reactance

a) **Input data for the equipment**

Equipment types and rated current capacities are assigned.

b) Input data for substation transformers

i) SIN for the substation

SIN for the transformers is allocated in such a way that it is easy to identify the area and the consumer service centre where the substation transformer is installed.

Example : SIN – MW -001

First letter gives the name of CSC, second letter gives the name of area.

ii) Load data for substations

There are two types of groups

1. Bulk Supply Substations
2. Distribution Supply Substations

In case of Bulk Supply, loads are taken from billing information and those loads are fed. Distribution substation loads are taken at peak time.

2.8 Modeling the network using MATLAB

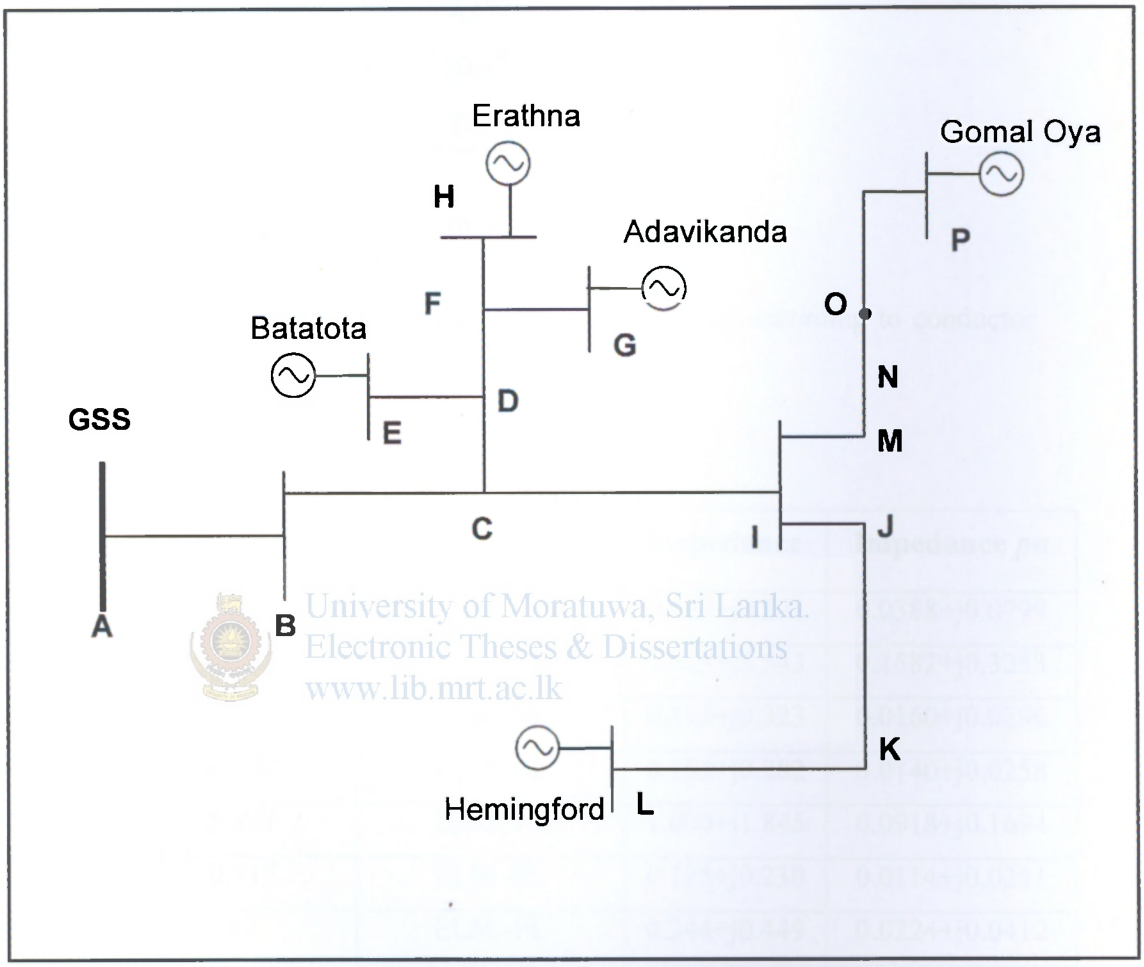
According to Thevenin's theorem any linear network containing any number of voltage sources and impedances can be replaced by a single emf and an impedance. The emf is the open circuit voltage as seen from the terminals (under consideration) and the impedance is the network impedance as seen from these terminals. This circuit consisting of a single emf and impedance is known as Thevenin's equivalent circuit.

The calculation of the fault current can be very easily done by applying this theorem. It is only necessary to find the open circuit emf and network impedance as seen from the fault point. In most of the calculations, the open circuit emf can be assumed to be 1 *pu*. Let Base MVA = 100MVA, Base voltage = 33kV and line impedances were calculated according to Base impedence (Z_b). Per unit values of feeder impedances were calculated and modeled the circuit. After that generators were modeled as voltage sources with their sub transient reactances. (Refer Appendix - E)

2.8.1 Modeling the feeders with DGs

a) Feeder No : 05

Figure 2.2: Single line Diagram of Feeder No: 05



Single Line diagram of Feeder No: 05 is shown in Figure No. 2.2. This feeder starts from Ratnapura Grid Substation (A) as 33kV double circuit (with feeder No: 03) Lynx tower Line(TL) and run around 2.392 km till Rathnapura Gantry(B). After that Single Circuit Lynx Tower Line starts and continues to Eheliyagoda Gantry(I), with the total distance of 22.7 km. Pathagama ABS(C) is located at a mid point of this Lynx TL. ELM Pole Line (PL) is started from Pathagama ABS to Erathna MHP (H) to connect Batatota(E) and Adavikanda(G) MHP s at the points of D & F respectively in the figure. Section vice impedances were calculated and tabulated in Table 2.4.

For example calculating per unit impedance of section AB,

$$Z_{AB}\ \text{pu} = \frac{Z_{AB}}{Z_b}$$

$$Z_{AB} = 2.392(0.177 + j\ 0.364)\ \Omega$$

$$= (0.423 + j\ 0.871)\ \Omega$$

$$= \frac{(0.423 + j\ 0.871)}{10.89}$$

$$\therefore\ Z_{AB} = \underline{\underline{(0.0388 + j\ 0.0799)}}\ \text{pu}$$

Refer Appendix – B to find out resistances and reactances, according to conductor types.

Table 2.4: Conductor Data of Feeder No: 05

Section	**Distance (km)**	**Conductor Type**	**Impedance**	**Impedance *pu***
AB	2.392	Lynx - TL	0.423+j0.871	0.0388+j0.0799
BC	9.733	Lynx - TL	1.723+j3.543	0.1582+j0.3253
CD	1.006	ELM -PL	0.175+j0.323	0.0160+j0.0296
DE	0.878	ELM -PL	0.153+j0.282	0.0140+j0.0258
DF	5.747	ELM -PL	1.000+j1.845	0.0918+j0.1694
FG	0.717	ELM -PL	0.125+j0.230	0.0114+j0.0211
FH	1.4	ELM -PL	0.244+j0.449	0.0224+j0.0412
CI	12.98	Lynx - TL	2.297+j4.725	0.2109+j0.4338
IM	7.608	Copper	5.767+j5.425	0.5295+j0.4981
MN	2.917	Racoon - PL	1.257+j1.094	0.1154+0.1004
NO	2.966	Weasel - PL	3.263+j1.195	0.2996+j0.1097
OP	6.773	Weasel - PL	7.45+j2.73	0.6841+j0.2506
IJ	5.438	Copper	4.122+j3.877	0.3785+j0.3560
JK	2.528	Weasel - PL	2.781+j1.019	0.2553+j0.0935
KL	1.012	Racoon - PL	0.436+j0.380	0.0400+j0.0348

a) Feeder No : 06

Single line diagram of feeder No: 06 is shown in Figure 2.3. Feeder starts from Ratnapura Grid Substation(A) as 33kV double circuit Lynx TL and run until Watapotha ABS (B). Way Ganga MHP (C) is connected to Watapotha ABS through ELM PL around 4.7 km long. Same as Niriella MHP (F) is connected to the same ABS combination of weasel PL & Racoon PL, around 12.5 km long line. Section vice line impedances are tabulated in Table 2.5

Figure 2.3: Single line Diagram of Feeder No: 06

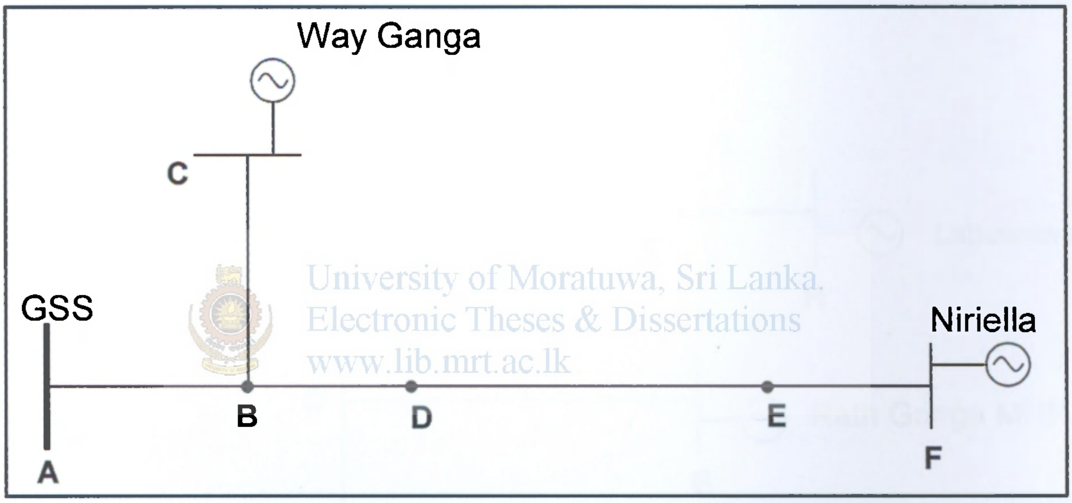


Table 2.5: Conductor Data of Feeder No: 06

Section	Distance (km)	Conductor Type	Impedance	Impedance *pu*
AB	16.853	Lynx - TL	2.983+j6.134	0.2739+j0.5632
BC	4.767	ELM -PL	0.829+j1.530	0.0761+j0.1404
BD	4.24	Racoon - PL	1.827+j1.806	0.1677+j0.1658
DE	10.161	Weasel - PL	10.177+j4.095	1.0262+j0.3760
EF	2.319	Racoon - PL	0.999+j0.870	0.0917+j0.0798

c) Feeder No : 08

Single line diagram of feeder No: 08 is shown in Figure 2.4. Feeder starts from RGSS as 33 kV Racoon TL and run until Durekanda Gantry. Malwala DDLO (B) is located from GSS around 4.3 km distance. Rath Ganga (E), Labiwewa (H) & Guruluwewa (I) MHPs are connected to the same place through Racoon PL. Denawak Ganga (C) MHP is also connected to the main line through another DDLO set. Calculated line impedances of described sections in Figure 2.4, are tabulated in Table 2.6.

Figure 2.4: Single line Diagram of Feeder No: 08

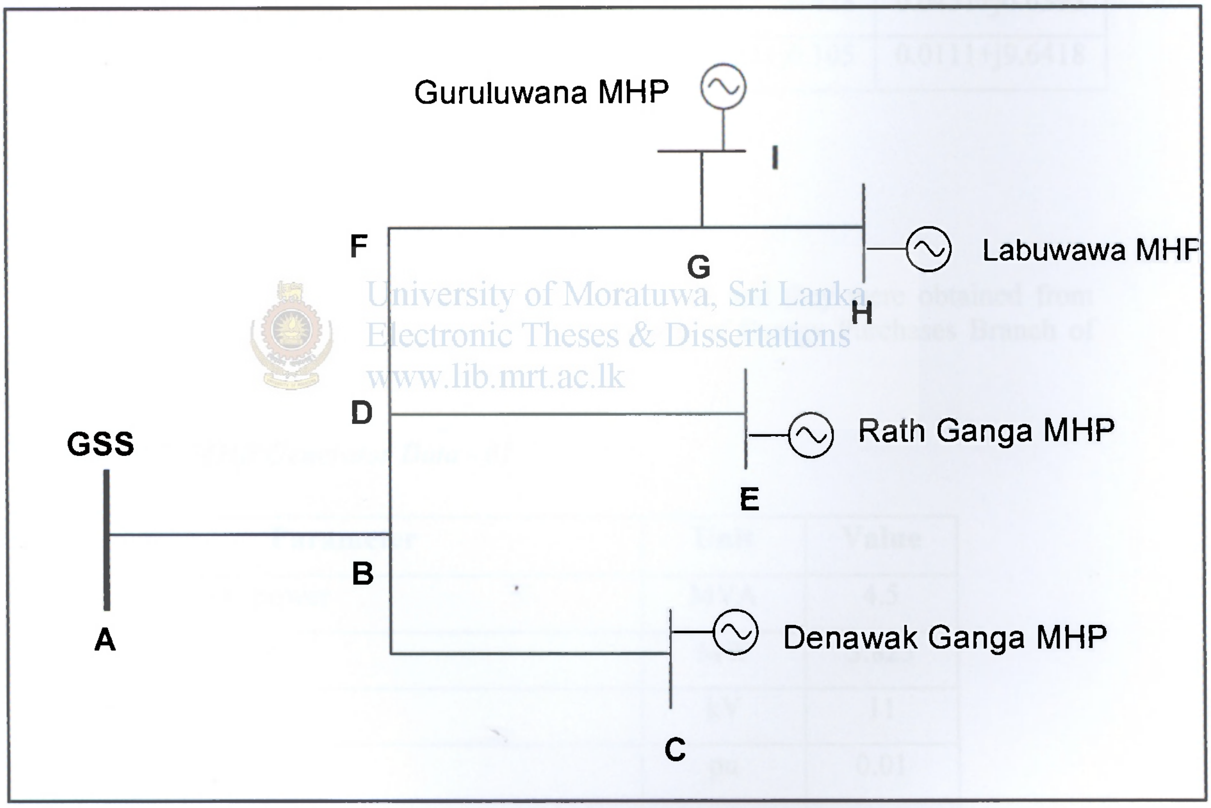


Table 2.6: Conductor Data of Feeder No: 08

Section	Distance (km)	Conductor Type	Impedance	Impedance *pu*
AB	4.086	Racoon - TL	1.761+j1.74	0.1617+j0.1597
BC	3.007	Racoon - PL	1.296+j1.127	0.1190+j0.1034
BD	3.27	Racoon - PL	1.409+j1.226	0.1293+j0.1125
DE	4.193	Racoon - PL	1.807+j1.572	0.1659+j0.1443
DF	4.274	Racoon - PL	1.842+j1.602	0.1691+j0.1471
FG	2.13	Racoon - PL	0.918+j0.798	0.0842+j0.0732
GH	1.142	Racoon - PL	0.492+j0.428	0.0451+j0.0393
GI	0.282	Racoon - PL	0.121+j0.105	0.0111+j9.6418

2.9 MHP Data

Data of DG s are given in Tables from 2.7 to 2.10 and they were obtained from relevant power plant developers with the guidance of Energy Purchases Branch of CEB.

Table 2.7: MHP Generator Data - 01

Parameter	Unit	Value
Rated Apparent power	MVA	4.5
Rated active power	MW	3.825
Rated Voltage	kV	11
Resistance (R_a)	pu	0.01
Sub transient Reactance (X''_d)	pu	0.17
Transient Reactance (X'_d)	pu	0.25
Synchronous Reactance (X_d)	pu	2.95

Table 2.8: MHP Generator Data – 02

Parameter	Unit	Value
Rated Apparent power	MVA	1300
Rated active power	MW	1040
Rated Voltage	V	400
Resistance (R_a)	pu	0.01
Sub transient Reactance (X''_d)	pu	0.15
Transient Reactance (X'_d)	pu	0.19
Synchronous Reactance (X_d)	pu	2.23

Table 2.9: MHP Generator Data - 03

Parameter	Unit	Value
Rated Apparent power	MVA	1200
Rated active power	MW	960
Rated Voltage	V	415
Resistance (R_a)	pu	0.01
Sub transient Reactance (X''_d)	pu	0.12
Transient Reactance (X'_d)	pu	0.23
Synchronous Reactance (X_d)	pu	1.36

Table 2.10: MHP Generator Data - 04

Parameter	Unit	Value
Rated Apparent power	MVA	5600
Rated active power	MW	4760
Rated Voltage	kV	6.3
Resistance (R_a)	pu	0.01
Sub transient Reactance (X_d'')	pu	0.2241
Transient Reactance (X_d')	pu	0.386
Synchronous Reactance (X_d)	pu	2.21

Chapter 03

Analysis and Results

By considering the MV distribution network of Rathnapura Grid Substation some feeder ends are weak due to the long length and experiencing low voltages at the ends. Hence analyzing the network without DGs feeder ends show very low voltages. But fortunately MHPs are connected to the feeders in remote areas and these MHPs support to voltage improvements. But these MHPs also creat problems. In off peak times when the grid loads are very low MHPs feeds to the Grid, trending over volategs around MHP areas. This over voltages may harmfull to equipments of CEB and consumer appliances. Another problem is islanding of MHPs, would risk to staff of CEB unless strictly follow the proper safety procedures.

3.1 Voltage Regulation

The statutory in Sri Lanka require that the voltage at a consumer's supply terminal shall be maintained within limits of ± 6%. In order to comply with this, the voltage drops occurring through the system under full load conditions must be carefully matched with any voltage regulating equipment installed. In the MV distribution development plan, the analysis is carried out assuming the voltage at 33 kV bus of the grid substation is 100% (33 kV) all the time and the maximum allowable voltage drop in the feeder is ± 6%. However, it is found that it was difficult to maintain consumer end voltage especially in rural feeders running to long distance, setting maximum voltage drop at MV feeder to ± 6%. Moreover, relaxing this limit below this level needs larger investment for reinforcements.

The load analysis has been carried out to see the performances of the existing network by setting the exception for voltage ± 6%. Based on the network analysis studies, the voltage levels at different locations of the 33kV network are obtained. These voltage levels have been computed assuming 100% level at the 33 kV bus. Voltage analysis of the feeders are indicated according to the sections at the table. (Refer Annexure-C)

3.1.1 Feeder 05

This is the longest feeder in the Rathnapura grid substation, which is around 195km long. Mainly this feeder covers Ehaliyagoda, Ayagama, Kuruwita, Madola areas. When analyzing the voltages of far ends of the feeder, when MHP s are not connected it is observed that, near Siripada area voltage is 83.6% (E-106), which is very low (about 38km to the GSS). But Erathna and Adawikanda MHPs are operate around 10km distance to Sri Pada hence while they operate, voltage will be rise to 98.1%. But in night peak time it decrease to 91.7%.

Pahala Maniyangama (G - 052) is another far end, which experiences low voltage 85.4% and this voltages would be rise up to 94.2% in night peak also, with the contribution of MHPs. (which is around 35km far from RGSS). Ehaliyagoda gantry (G - 037), without DG s, voltage is 88.3% (29.2 km) and this voltage will be rise up to 100.0%. Nileagoda (around 68km from GSS) is another far end, experiences low voltage around 85.9% without DG s and this voltage rises up to 93.8% while operating MHP s. (L – 043). Bodhimaluwa (G – 070) is the mid point of the feeder, without DG voltage would be 85.9% and this has been raised up to 93.9% at night peak and 99% in other times, while operating DGs.

3.1.2 Feeder 06

This feeder mainly runs to Nivithigala area, Watapotha gantry Horangala, Kahawatta, Niriella to Kalawana area. Far end of the feeder are Nivithigala & Kalawana area around 39km distance from the grid substation. Two MHP s are connected called Way Ganga at Poronuwa & Niriella MHP at Niriella. Due to these MHP s even in night peak time those far ends of the feeder, voltages would be maintained around 100%. (D-072, D-089).

3.1.3 Feeder 08 (Durekkanda)

This feeder runs from Rathnapura grid substation to Godigamuwa, Malwana Durekkanda gantry then Ambuldeniya via Pagoda, Guruluwana to Sri pada area (C- 106). At the far end of the feeder is Sripada area. Five numbers of MHP s are connected to the feeder. When those MPS s are absent, about 90% of voltage experience around Sripada area, which is around 23km from the grid substation. But with the operation of MHP s that voltage level will be rise up to 95.2% which goes to the acceptable level. Guruluwana & Labuwawa MHP s are situated around 10.7km to the Sripada area. But without MHP s the voltage level of Durekkanda gantry is 99.3%, (DURK-09) which is acceptable. Table 3.1 indicates the voltage levels with relevant sections.

Table 3.1 : Voltage variation of feeder sections at day peak time

Feeder	**Section**	**Base Case Voltage (%)**	**With DGS Voltage (%)**
05	G - 019	85.2	100.2
	G - 037	88.3	100.6
	G - 051	85.4	99.4
	G - 052	85.4	99.6
	G - 070	87.5	100.1
	E - 067	86.2	99.5
	E - 106	83.6	98.1
	L - 005	85.8	99.1
	L - 043	85.9	99.2
	EHE 5-12-18	94.3	111.5
	5-KL-29	86.0	99.3
06	NIV 6-06	97.8	102.7
	D-022	93.9	104.4
	D-069	96.3	104.1
	D-072	93.3	106.4
	D-089	91.8	103.5
08	C - 106	90.6	99.4
	DUREK - 09	99.3	101.2

3.2 Fault Level Analysis

The steady state operating mode of a power system is balanced 3-phase ac. However, due to sudden external or internal changes in the system, this condition is disrupted. When the insulation of the system fails at one or more points or a conducting object comes in contact with a live point, a short circuit or fault occurs. The causes of faults are numerous, e.g., lightning, heavy winds, trees falling, across lines, vehicles colliding with tower or poles, birds, line breaks, etc. A fault involving all the three phases is known as symmetrical (balanced) fault while involving only one or two phases is known as unsymmetrical fault. Single lines to ground, line to line and two-line to ground faults are unsymmetrical (unbalanced) faults. Majority of the faults are unsymmetrical. Fault calculations involve finding the voltage and current distribution throughout the system during the fault. It is important to determine the values of system voltages and currents during fault conditions so that the protective devices may be set to detect the fault and isolate the faulty portion of the system so as to minimize the harmful effects of such contingencies.

When fault occurs at a point in a power system, the corresponding MVA is referred to as the fault level at that point.

3.2.1 Symmetrical Fault

This type of fault occurs infrequently, as for example, when a line, which has been made safe for maintenance by clamping all the three phases to earth, is accidentally made alive or when, due to slow fault clearance, an earth fault spreads across to the other two phases or when a mechanical excavator cuts quickly through a whole cable. It is an important type of fault, it is easy for calculation and generally, a pessimistic answer. The circuit breaker rated MVA breaking capacity is based on 3-phase fault MVA. Since circuit breakers are manufactured in preferred standard sizes, e.g., 250,500,750 MVA high precision is not necessary when calculating the 3-phase fault level at a point in a power system. Moreover the system impedances are also never known accurately. In view of this, the following assumptions are made in fault calculations.[4]

- The emfs of all generators are $1\angle 0$ per unit. This means that the system voltage is at its nominal value and the system is operating on no load at the time of fault. The effect of this is that all generators can be replaced by a single generator since all emfs are equal and in phase. When desirable the load current can be taken into account, at a later stage, by superposition.

- Shunt elements in the transformer model that account for magnetizing current and core loss were neglected.
- Shunt capacitances of the transmission line were neglected.
- System resistance was neglected and only inductive reactance of the system was taken into account. This assumption was generally made only for hand calculations and educational purposes. For computer solution this approximation was not necessary. The sub-transient reactances of the generators were generally used in calculations. However, if transient current was to be determined, then transient reactance should be used.

The calculations for a symmetrical fault are easy because the circuit is a completely symmetrical circuit and calculations can be made only for one phase. The steps in the calculations are as under:

- Draw a single line diagram of the system.
- Select a common base and find out the per unit reactance of all generators, transformers, lines, etc., as referred to common base.
- From the single line diagram draw a single line reactance diagram showing one phase and neutral. Indicate all the reactance, etc., on the reactance diagram as seen from the fault point (Thevenin's reactance).
- Find the fault current and fault MVA in per unit. Convert these per unit values to actual values.
- Retrace the steps of calculation to find the current and voltage distribution throughout the network.

3.3 Obtaining maximum fault currents

The maximum fault currents through some selected points of the network were calculated by using the MATLAB software. Results are tabulated in the Table 3.2 and fault currents without DG s, considered as base case. It is clearly observed that after introducing DG s to the network fault currents at some points, specially the points of H, J and S increased. Few important observations derived from the results given in Table 3.2 are listed below.

Table 3.2 : Comparing fault currents with and without DG s

Feeder	**Location**	**Fault Current**				**Current contribution from MHP s** in pu
		Base Case		**With DG**		
		pu	kA	pu	kA	
05	B	3.00	5.25			
	C	1.46	2.55	5.00	8.75	I- 1.5, K- 0.5, L- 0.4
	D	0.86	1.50	2.55	4.46	G- 0.5, E- 0.85
	E	0.55	0.96			
	F	0.73	1.27	5.80	10.15	I- 2.5, K- 0.8, L- 0.7
	G	0.35	0.61			
	H	1.40	2.45	11.4	19.95	I- 6.5, K- 2.0, L-2.6
	I	1.00	1.75			
	J	0.86	1.505	14.00	24.5	L- 5.0, K- 6.0, 1- 2.5
	K	0.84	1.47			
	L	0.83	1.40			
06	M	1.20	1.89	7.20	12.6	N- 5.3, O- 0.7
	N	0.985	1.65			
	O	0.47	0.87			
08	P	1.15	1.98	10.00	17.5	V- 4.2, R- 2.0, U- 1.0
	Q	1.65	2.88	9.50	16.6	U- 1.8, T- 0.6, R- 4.0, V- 2.0
	R	1.55	1.98			
	S	0.55	0.96	11.00	19.25	U- 7.0, T- 2.3, R- 1.2
	T	1.075	1.80			
	U	1.025	1.76			
	V	1. 25	1.98			
Grid Bus	A	4.00	7.00	9.00	15.75	

- The maximum fault current observed from the point of J, which is around 24.5kA. Very high value and maximum fault current of 10.5kA comes from Adavikanda MHP.
- Fault level of point H is19.95kA, high value for the network. Maximum current contribution from Batatota MHP around 11.75kA to the fault.
- Next high fault level observed at Point S, which is 19.25kA. Maximum current contribution from Labuwawa MHP around 12.25kA to the fault.
- Other points of Q, P and M show much higher fault levels, but fault currents contribution from DG s are less.

These high fault currents could be definitely risk for electrical equipments like LBS, ABS units and expulsion switches because their short circuit current capacity is 10kA. It is observed that most of the places and paths this fault level have been increased. Insulation levels of those electrical equipments could be weaken gradually and jumper connections may be burnt most of the times. Hence maintenance staff of this power network and power utility face great problem while maintaining the reliable service.

Chapter 04

Proposed Solutions

By considering the embedded generation impacts to MV distribution network number of issues could be discussed, out of them mainly highlighted in this thesis, voltage variation and increasing of fault currents only.

4.1 Voltage Regulation

It is observed that most of the feeder ends experience low voltages with the absence of DGs. Hence increasing embedded generation in MV distribution network, feeder end voltage will be rice up and this would be a great advantage for CEB. But in off-peak times, it is observed that high voltages around MHP areas. For example the area of Adavikanda, Erathna and Batatota (EHE-5-12-18) shows high voltage around 111.5% in off-peak time. This voltage may harmful to the consumers, who are connected to the network around this area. It could be suggested that design change of the network, as a mitigating technique for this problem. This solution could not be implemented easily because it is costly.

4.2 Increasing the Fault Level

As a result of continuously expanding the power networks fault current level at some points may increase. For instance MHPs connected in remote areas. In such cases the fault current at certain locations after connection of the new generator may be much greater than the short circuit capability of the existing switchgears. This may demands upgrading of the existing switchgear short circuit rating. However, such upgrades are not easy due to: (a) high replacement cost; (b) system reliability would be greatly reduced during the necessary construction period, and (c) the short circuit ratings of the currently available circuit breakers would soon become inadequate. Other than replacing the existing switchgear, there are several methods that can be used to reduce the fault current in the power system to an acceptable level.

These methods include (a) network splitting, (b) current limiting reactors, (c) sequential network tripping and (d) Fault Current Limiters

4.2.1 Network splitting

In the case of network splitting, sources will be separated thus effectively reducing the number of sources that are contributing to fault. This in turn reduces the fault current. When whole system is operating as a single grid, due to availability of a number of parallel paths for power flow, the power system reliability is high. The network splitting will reduce the possible parallel paths that are supplying the normal load, thus reducing the system reliability.

4.2.2 Current Limiting Reactors

The current limiting reactor is reactive impedance, which is placed in series with the power line. This new impedance effectively increases the fault impedance to the fault and reduces the fault current. However current limiting reactors have a voltage drop across its terminals during the normal operation and present as a constant source of losses. They can interact with the other system component and cause instability [4]. However current limiting reactors are still in practice due to their relatively low cost in implementation and maintenance.

4.2.3 Sequential Network trapping

A sequential network tripping schemes prevents operation of circuit breakers due to excessive current larger than breaker rating. After detecting a fault by a circuit breaker, sequentially trip one or more upstream circuit breakers to limit the fault current within the zone of protection. The delay of final fault clearing, the opening of circuit breakers that are not originally affected from fault and complexity of the method are major disadvantages of the sequential network tripping.

4.2.4 Fault Current Limiters

Fault current Limiter (FCL) is a device, which is connected in series with power line to limit the fault current to an acceptable level by introducing high impedance during a fault, while showing low impedance and power loss under normal operating conditions. As a result of its superior operational characteristic from power system operation point of view, it is considered as a good approach for limiting of fault current. However this has some technical and economical problems to be solved before introducing to the power system effectively.

4.3 Fault Current Limiters

FCL prevents fault current reaching damageable high levels. This is achieved by introducing impedance, which is increasing with the fault current, in series with the line. Under normal operating conditions to minimize the voltage drop and the power loss, the FCL device should shows very low impedance to the system. To get this current dependent impedance characteristic, the FCL device should be operated using the line current. According to the technologies used to obtain the required impedance characteristic, FCL can be categorized into three main groups:

- Superconducting Fault Current Limiters (SFCL) [5],
- Magnetic Fault Current Limiters (MFCL) [6]and
- Static Fault Current Limiters (StFCL).

In addition to that there are FCL s, which can be identified as a combination of two of these types. (Refer Appendix – F for more details)

There are several operational characteristics to be considered in order to select a best FCL scheme among different FCL types for a particular application. Some of the key factors related to the operational characteristics are [5];

a) Under the normal operating condition of the system, voltage drop across the FCL should be zero or very low. This can be achieved by an FCL which has zero or very low impedance at normal loading currents.
b) Under the normal operating condition of the system, power loss due to the FCL should be zero or very low. This can be achieved by an FCL which has zero or very low resistance under load currents.
c) During a fault, FCL should response to a fault by moving from its low impedance state to high impedance state thus limiting the fault current. In

order to minimize the stress on equipment this transition should be very fast. In the most rigorous conditions, fault current reaches peak value in less than time correspond to the quarter of power frequency cycle. Therefore the transition time of the FCL should be less than that time 5 ms for 50 Hz systems.

d) After clearing the fault, for the proper operation of the power system FCL should move from limiting state to the normal state. This process is called as recovery of the FCL and time taken for the recovery should be low.
e) FCL should show a high reliability with minimum maintenance.
f) It can be observed that the physical size and the cost are highly depending on the type of FCL. It is important to minimize the volume, weight and cost by proper selecting an FCL.
g) As FCL is limiting the fault current, some of the power system protection schemes such as over current protection will see less current than that of without the FCL. This may change the existing protection coordination. It is desirable to select an FCL which has a minimum effect on the system protection.
h) In the power system, it can be observed that under over load conditions high currents may be present in the system for a short period of time. As FCL is operated with the line current, it may transit to the limiting mode unnecessarily under the over load conditions. It is important to make sure that the FCL is insensitive to normal overloads, transformer inrush current, discharging of capacitor banks and motor starting.

It is unlikely that all of the above characteristics and achievable performance through cost effective design. In addition to limiting the fault current, in the power system point of view FCL has several other advantages: (a) improvement of system stability (b) reduction of voltage sag during and after a fault and (c) reduction of cost in the case of new installations. However it is recognized that application of an FCL may have negative effects on protection coordination. Therefore comprehensive studies are required before applying an FCL to the utility network.[7]

4.4 Applications of Fault Current Limiters

FCL is introducing current dependent series impedance to the power line which limits the current during a fault. Even though ideally it is preferred to have zero impedance across the line under normal operation conditions, depending on the type of FCL, nature of the impedance, size of impedance and impedance transition characteristics varies. Further location of the FCL also changes the effective impedance. The change in the line impedance modifies the surge impedance, power flows and load angles of the system. Therefore comprehensive studies are requires to analyse the system under different phenomena such as voltage sags, protection coordination, transient stability and operational losses.

It was found that the location of an FCL is the most dominant factor for application considerations. Therefore an FCL located (a) at a Feeder, (b) in a transformer circuit, (c) at bus section, (d) at connection point of Distributed Generator and (e) in a transmission line was considered [6].

FCL schemes such as thyristor switched FCLs can limit and interrupt the fault current. There are other FCL s where complete current interruption can not be achieved under those conditions, the current interruption by downstream device is compulsory to clear the fault.

4.4.1 Fault Current Limiter at primary distribution feeder

Grid substation, where voltage transformation is taking place, is an essential power system component. At a grid substation, the electricity is converted from transmission level voltage to a distribution level voltage and distributed to the consumers. In practice, a grid substation supplies more than one primary radial distribution feeder. During a fault at a downstream location of the feeder, the circuit breaker (CB) at the starting point of the faulty feeder should operate to clear the fault. Also this fault is detected by all the CB s in the upstream. It is possible to install an FCL at the primary distribution feeder as shown in Figure 4.1 to limit the fault current during a fault in that feeder.

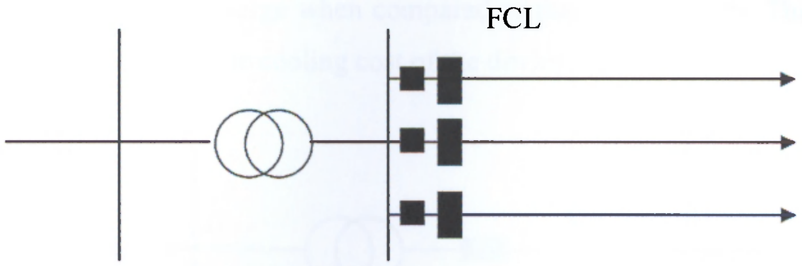


Figure 4.1: FCL at primary distribution feeder

When FCL is installed at the primary distribution feeder, FCL is operating only for a fault in the distribution feeder where FCL is installed. Since most of the distribution feeders are radial, it is required to use separate FCL for each feeder. As system has several distribution feeders and each feeder required an FCL, a number of FCL s required becomes high. When whole system is considered overall power loss is considerably high as a result of having a large number of FCL units in the system.

Although several FCL s are needed to limit the current in a distribution system, this location is attractive as the rating of the FCL is relatively low. When an FCL is located at the distribution feeder voltage sag experienced by the bus will be greatly reduced depending on the system parameters, type of the fault and impedance of the FCL. Thus improving the voltage profile and minimizing the voltage sags due to the fault.

4.4.2 Fault Current Limiter at Transformer circuit

To limit the distribution level fault current an FCL also can be installed at transformer circuit as shown in Figure 4.2. An FCL located at this location limits the current during a fault in any feeder. Therefore it is possible to reduce the number of FCL s required for a system. This resulted in relatively low installation capital. In the transformer circuit, it is possible to install FCL either in high voltage side or in low voltage side. Application of an FCL at low voltage side reduces the required installation level. The continuous current rating of an FCL can be selected as the total current taken by all feeders connected to the transformer. Therefore the continuous current rating is relatively large when compared to that at the feeder. This increases the operational losses and the cooling cost of the device.

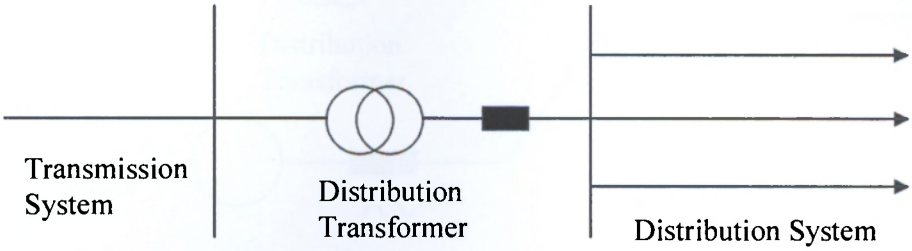


Figure 4.2: FCL at distribution transformer circuit

In voltage sag point of view an FCL at the distribution transformer can not improve the voltage profile at downstream distribution bus as in the case of FCL connected to a feeder. This scheme allows replacing a number of FCL s in feeders by one FCL at bus tie. An FCL connected to a bus coupler at the distribution system minimizes the insulation problems and reduces the size and the weight.

4.4.3 FCL at connection point of Distributed Generator

Most of the fault current increment problems are associated with connection of distributed generators at remote areas. In most of the cases contribution to the fault current from DG increases the fault current and resulted in exceeding of switchgear short circuit current ratings. The installation of an FCL in series with the DG as shown in Figure 4.3, limits the fault current contribution from DG, thus reducing the increment of fault current in the original network. During a fault in the main grid, FCL only limits the fault current contribution from the DG. As this current contribution is relatively low with respect to the current coming from the Grid in feed, the percentage reduction of total fault current experienced by devices is low. This means that the connection of DG has minimal effect to the original network during the fault condition.

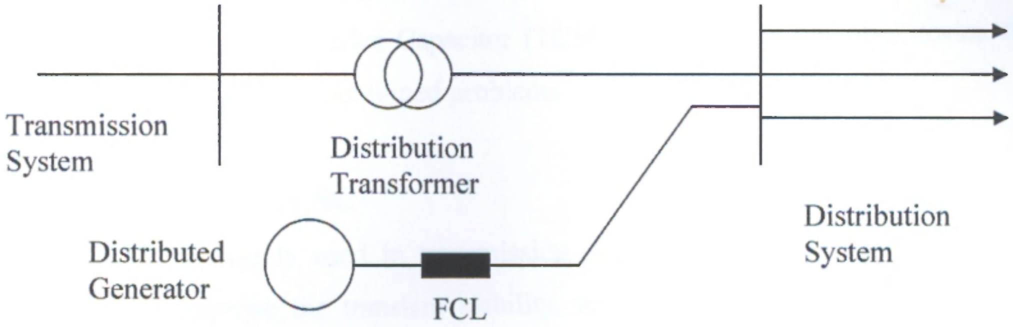


Figure 4.3: FCL at connection point of DG

FCL can not improve the voltage of the distribution network during a fault when compared to other application locations.

Effect of nature of the FCL impedance

Impedance of an FCL is resistive or inductive or combination of both. The resistive type FCL offers resistive impedance to the fault current while inductive type is showing an inductive reactance to the fault. Two types of FCL s with the same impedance are giving two different current limiting capabilities depend on the application. In most cases fault impedance is inductive. Inductive type FCL limits the fault current to a greater extend than that provides by a resistive type FCL. However, resistive type has an advantage of enhancing the transient stability.

4.5 Thyristor Control Series Capacitor as FCL

Due to potential threat for the environment, depletion of the resource and difficulty of finding right of way for new transmission facilities, there is a recent trend towards connecting Distributed Generation (DG) mainly based on renewable energy sources. In many instances these sources are available in locations where utility grid is very weak. The weak networks impose many operational constraints when connecting DG and therefore utilities tends to impose large safety margins when allowing DG interconnection. Some of the operational issues of DG interconnection include violation of voltage and line flow limits, fault current exceeding switchgear rating and stability issues. Due to the controllable impedance characteristic and simple structure of the Thyristor Control Series Capacitor (TCSC), it will be a potential device for solving most of the above mentioned problems.

4.6 Introduction to TCSC

So far TCSC is widely used in transmission networks to increase power transfer capability, to improve the transient stability, to reduce transmission losses and to damp power system oscillations [9]. Among various TCSC configurations available, the basic configuration shown in Figure 4.14 was selected for this study. TCSC is simply a variable reactance connected in series with power lines. It consists of a fixed capacitor and a Thyristor Controlled Reactor (TCR) connected in parallel with the capacitor.

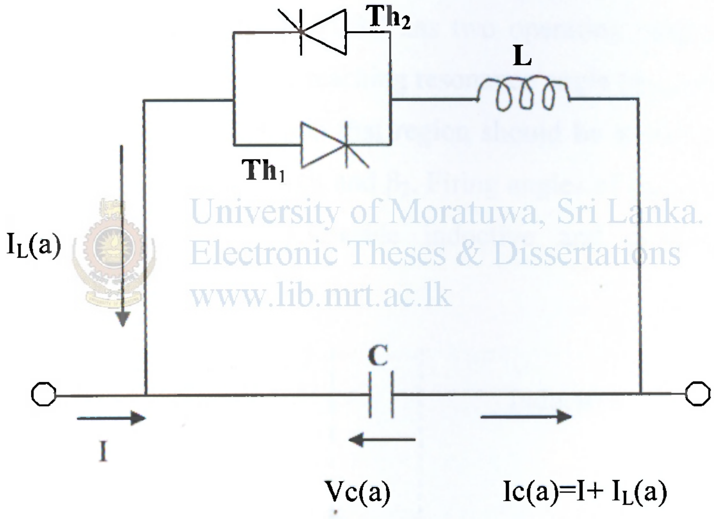


Figure 4.4: Basic Structure of TCSC

The TCR is offering a variable inductive reactance, which is controlled by firing delay angle α of thyristor Th1 and Th2. The steady state impedance of the TCSC is the parallel combination of the fixed capacitive impedance X_C and the TCR variable inductive impedance $X_L(\alpha)$. The steady state effective impedance of the TCSC, X_{TCSC} (α) can be expressed as in equation 4.1[8]. Magnitude of the TCR impedance is given by equation 4.2 in terms of firing angle and reactor impedance $X_L(=\omega L)$. Where L is inductance of the reactor and α is the delay angle measured from zero crossing of the capacitor voltage.

$$X_{TCSC}(\alpha) = \frac{X_C . X_L(\alpha)}{X_C - X_L(\alpha)} \quad \text{-----------------------} \quad 4.1$$

Where;

$$X_L(\alpha) = X_L \frac{\pi}{2\pi - 2\alpha + \mathrm{Sin}(2\alpha)} \quad \text{-----------------} \quad 4.2$$

The typical variation of the TCSC impedance with the delay angle α is shown in Figure 4.5. As the firing angle (α) decreases from 180° to α_{res}, TCSC impedance ($X_{TCSC}(\alpha)$) is varying in the capacitive region from its minimum value of $1/\omega C$ up to parallel resonance. When α is increasing from 90° to α_{res} impedance $X_{TCSC}(\alpha)$ varies in the inductive region from its minimum value of $X_L.X_C$ / (X_C-X_L) up to parallel resonance. Therefore provided that the impedance of the TCR reactor (X_L) is smaller than that of the capacitor (X_C) the TCSC has two operating ranges: inductive and capacitive. When the firing angle is reaching resonance angle (α_{res}) the impedance of the TCSC can be infinitely large and that region should be avoided. The allowable operating regions are defined using β_1 and β_2. Firing angles of (α_{res} -β_1) and (α_{res} + β_2) are corresponds to maximum allowable inductive and capacitive impedance respectively.

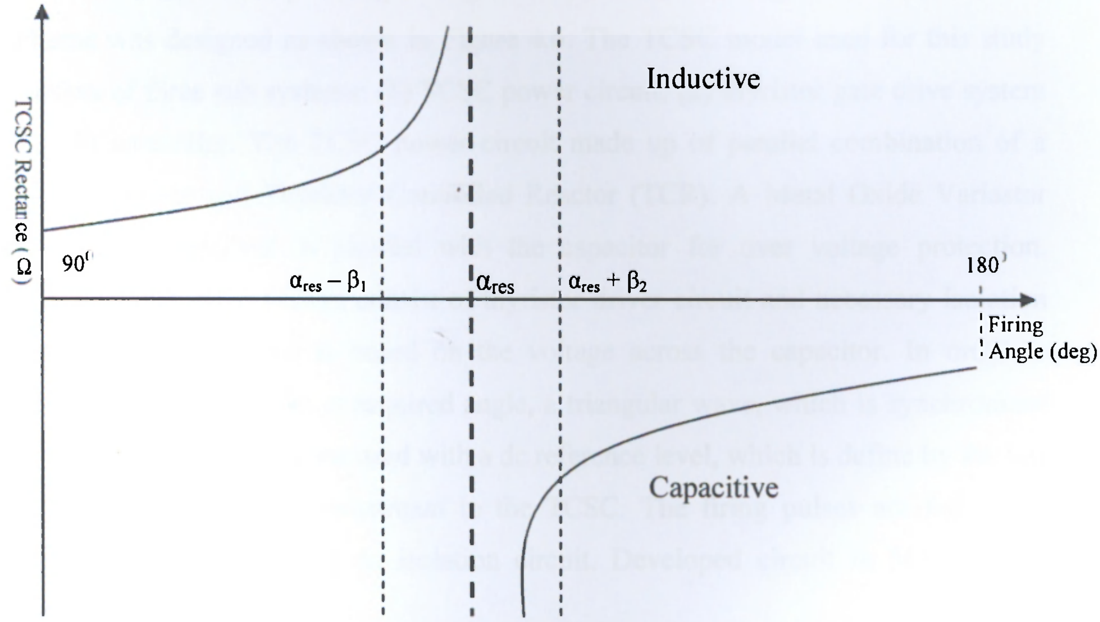


Figure 4.5: Impedance characteristic of TCSC

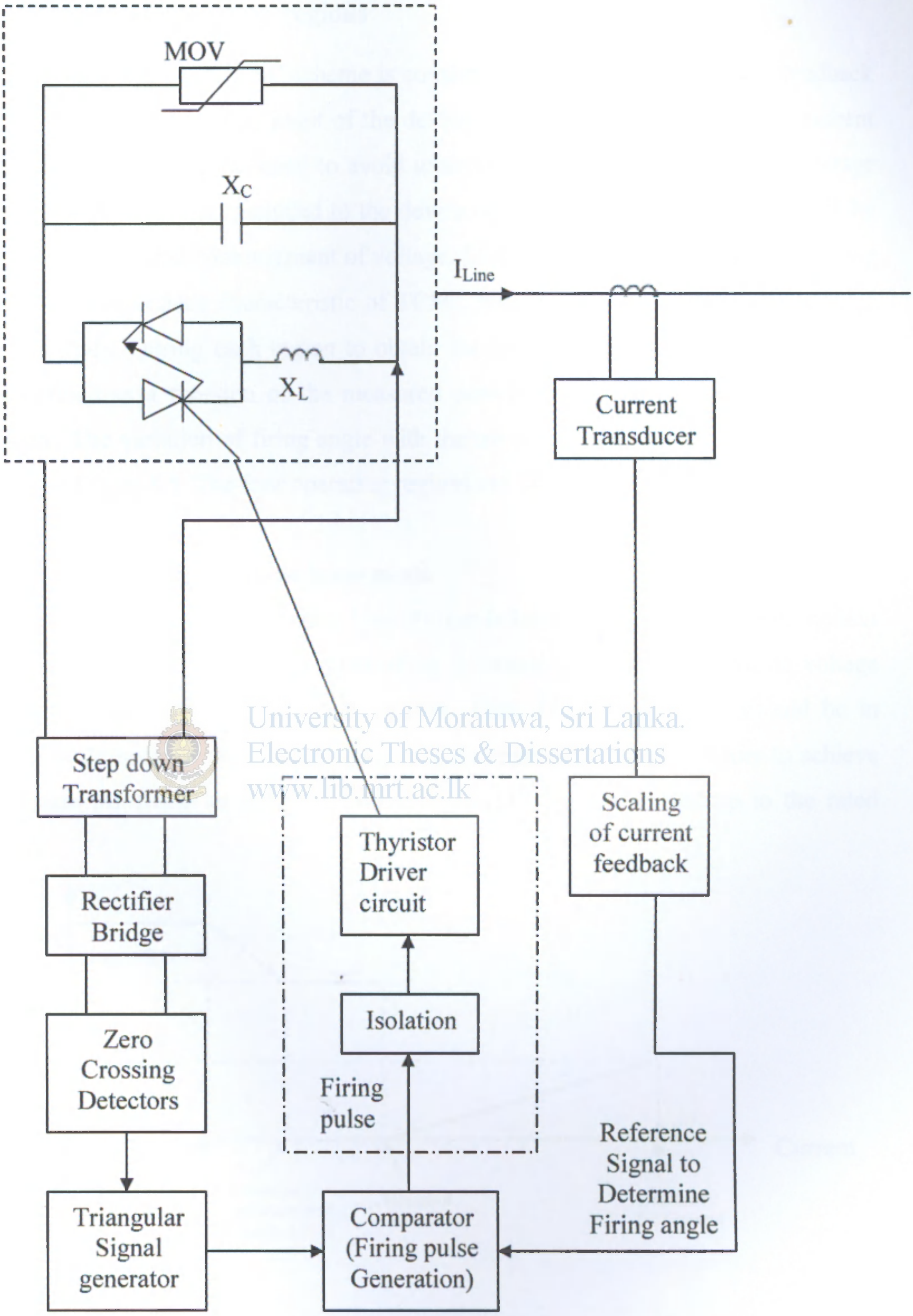
4.7 Proposed TCSC for distribution network applications

4.7.1 Operation modes

According to the impedance characteristic of TCSC shown in Figure 8.2, two impedance regions can be identified: inductive and capacitive [6]. With the help of variable nature of the impedance different operating modes can be defined according to the application. As this study is focusing on issues related to the connection of DGs to existing distribution network, two operating modes namely, (a) voltage compensation mode and (b) fault current limiting mode were considered. The voltage controller was designed such that when the voltage is less than the set level, the TCSC is switched to variable capacitive impedance mode, where as when the voltage is higher than the set level, the TCSC is switched to variable inductive impedance mode. When ever there is a fault the TCSC was taken into high inductive impedance region thus limiting the fault current. The amount of current limiting can be controlled by adjusting the firing angle.

4.7.2 Configuration and operation of TCSC model

By considering the required operating modes, the basic configuration of the TCSC scheme was designed as shown in Figure 4.6. The TCSC model used for this study consists of three sub systems: (1) TCSC power circuit, (2) thyristor gate drive system and (3) controller. The TCSC power circuit made up of parallel combination of a fixed capacitor and Thyristor Controlled Reactor (TCR). A Metal Oxide Variastor (MOV) is connected in parallel with the capacitor for over voltage protection. Thyristor gate drive system consist of thyristor driver circuit and necessary isolation devices. The controller is based on the voltage across the capacitor. In order to produce the firing pulses at required angle, a triangular wave, which is synchronized to the TCSC voltage is compared with a dc reference level, which is define by the line current or the voltage downstream to the TCSC. The firing pulses are fed to the thyristor driver circuit via an isolation circuit. Developed circuit in MATLAB is shown in Appendix – E.



4.6 Configuration of TCSC and control system

4.8 Selection of operation regions

Although the proposed TCSC scheme is consist of both voltage and current feedback to manipulate the operating point of the device, in the prototype TCSC, only current feedback signal was considered to avoid unnecessary complexity. However, voltage control feature was also included to the device with the help of the current signal by using it as as indirect measurement of voltage. Considering the two required operating modes and impedance characteristic of TCSC, four impedance modes were selected for this study. During each region to obtain the required impedance the firing angle was defined as a function of the measured current, which defines the state of the network. The variation of firing angle with the measured line current was selected as shown in Figure 8.5. The four operating regions are briefly explained below.

(a) Minimum capacitive impedance mode

Under light load conditions, where load current is less than the rated current, neither current limiting nor the voltage controlling is required for this network as voltage increment under light loading is acceptable. Then TCSC impedance should be in capacitive impedance region with the minimum impedance value. In order to achieve this mode the firing angle was maintained at 180^0 for the current up to the rated current.

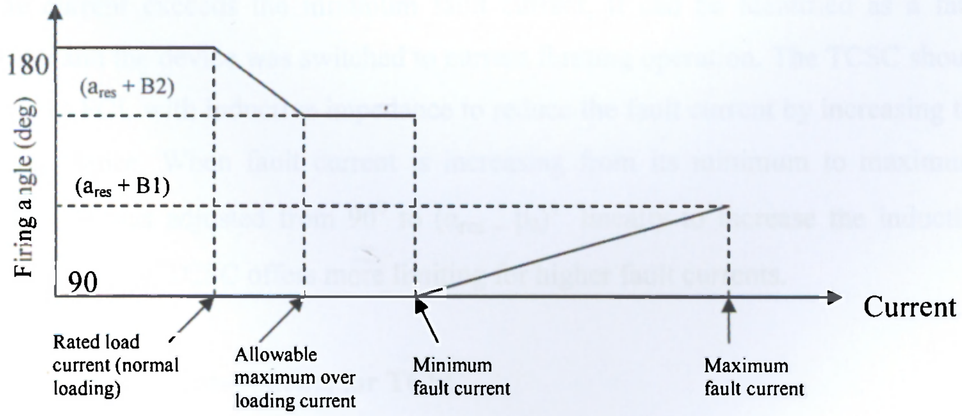


Figure 4.7: Expected firing angle variation with line current

(b) Variable capacitive impedance mode

In the case of over loading conditions, as the voltage could reduce below the lower limit of the statutory limits, voltage compensation is required. Then TCSC should introduce capacitive impedance to the line. As the amount of compensation required depends on the over loading current, the capacitive impedance should be increased with the line current. To obtain this characteristics firing angle was decreased from 180^0 to $(\alpha_{res}+\beta_2)^0$, when the line current is increasing from rated to maximum allowable load current. Then capacitive impedance is increasing from minimum to allowable maximum.

(c) Maximum capacitive impedance

In order to differentiate between the over load condition and the fault condition, a minimum fault current for the network was defined. When current is in between the allowable over load limit and the minimum fault, the model was designed to operate with maximum capacitive impedance. The firing angle was kept constant at $(\alpha_{res}+\beta_2)^0$ for entire current range.

(d) Variable inductive impedance mode

If line current exceeds the minimum fault current, it can be identified as a fault situation and the device was switched to current limiting operation. The TCSC should operate as FCL with inductive impedance to reduce the fault current by increasing the line impedance. When fault current is increasing from its minimum to maximum, firing angle was adjusted from 90^0 to $(\alpha_{res} - \beta_2)^0$ lineally to increase the inductive impedance. Thus TCSC offers more limiting for higher fault currents.

4.8.1 Selection of components for TCSC

The selection of TCSC power circuitry components: capacitor, reactor and thyristor basically depend on the network parameters and the required performance of the TCSC. During the light loading condition as the TCSC is operated at the minimum capacitive impedance mode, the TCSC impedance is same as capacitor impedance.

Under this condition TCSC impedance should be small enough to maintain the voltage within the allowable voltage range of 94% to 106% of rated. On the other hand when system operates under the minimum over loading, the maximum possible impedance of the TCSC should be higher enough to maintain the voltage within the allowable voltage range. By considering both conditions with the studies carried out in MATLAB simulation package a 1200 uF capacitor was selected for this application. Inductor need to be selected by considering both the required current limiting capability and resonance angle (α_{res}). From the simulation studies, a 3 mH inductor was selected to achieve 10-15% current limiting and resonance angle of 123^0.

4.8.2 Design the circuit of TCSC

As explain in section 4.7.2 and shown in Fig.4.6 available components of MATLAB simulation package was used to design TCSC [10]. It is essential to create a triangular signal, which is synchronized with TCSC capacitor voltage. Full wave bridge rectifier was connected to detected voltage across the capacitor. The full wave rectified signal is shifted by adding a small dc voltage and zero crossing detectors also used to get accurate triangular signal from the module. In order to maintain required firing angle, the correct firing pulses needed to be generated. Hence the comparator compares the line current with the triangular signal was used to generate firing pulses.

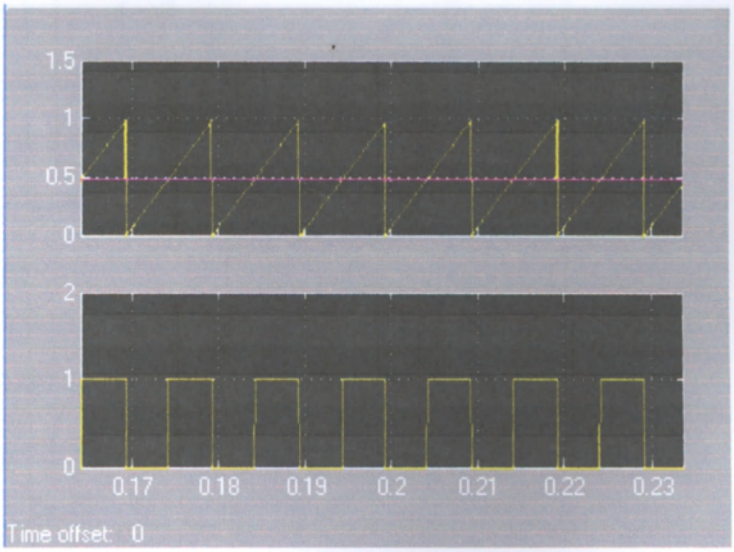


Figure 4.8: Wave forms of the firing pulses

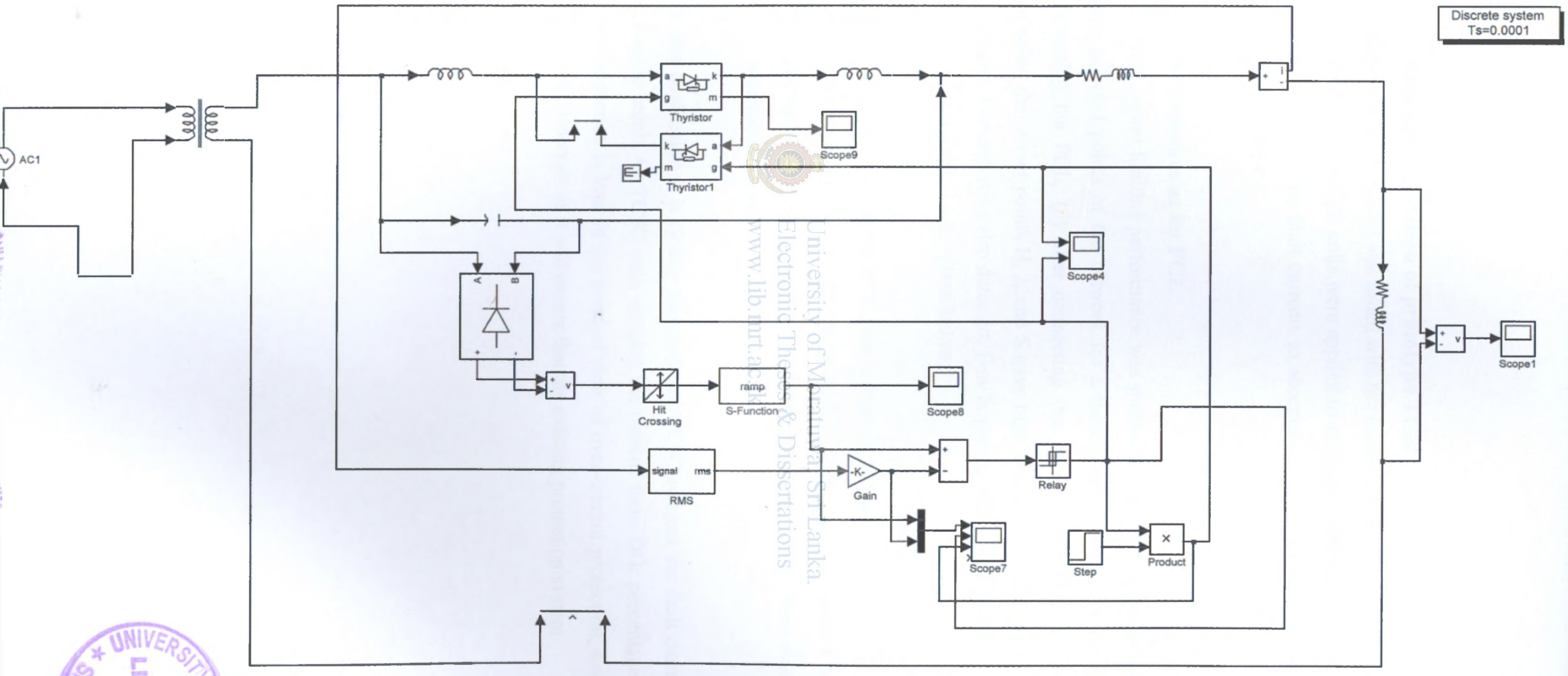


Figure 4.9 : Circuit Diagram of TCSC

4.9 Testing and simulation of prototype TCSC

The designed TCSC model was tested with the network and investigated the expected performances. Three FCL units were applied to different branches of sample network and tried to reduce the fault currents to acceptable level. Test results are tabulated below in the Table 4.1

4.9.1 Performance as an FCL

The fault current limiting performance was studied by considering the fault current at same selected points of the network for a three phase balanced faults: (a) before connecting the FCL, (b) after connecting the TCSC in series with line. While analyzing the circuit points H, J, and S gave high fault currents. Same as maximum fault current contribution also detected. Few important observations derived from the results given in Table 4.1 are given below.

- Before connecting the FCL fault current at H was 19.95kA and it has been reduced to 14kA while performing the FCL connected to Batatota MHP line.
- Giving same results, fault levels of point of J and S have been decreased to acceptable levels.

For this application it is clearly observed that TCSC reduces the fault current to an acceptable level. As TCSC only limiting the current from DG, percentage of total current reduction is less. In the point of view of over-current protection, low current reduction is important as it will ensure that the existing protection system.

Table 4.1 : Performance Data for FCL

Feeder	**Location**	**Fault Current**				**Current contribution from MHP s** in pu
		without FCL		**with FCL**		
		pu	kA	pu	kA	
05	B					
	C	5.00	8.75	4.2	7.35	I- 0.5, K- 0.2, L- 0.4
	D	2.55	4.46	2.55	4.46	G- 0.5, E- 0.85
	E					
	F	5.8	10.15	4.2	7.35	I- 1.5, K- 0.3, L- 0.7
	G					
	H	11.4	19.95	8.25	14.43	1- 3.5, K- 2.0, L-2.6
	I					
	J	14.00	24.5	9.00	15.75	L- 5.0, K- 3.0, 1- 2.5
	K					
	L					
06	M	7.2	12.6	7.1	12.4	N- 5.3, O- 0.7
	N					
	O					
08	P	10.00	17.5	8.65	15.13	V- 2.8, R- 2.0, U- 1.0
	Q	9.5	16.6	8.7	15.22	U- 0.8, T- 0.6, R- 4.0, V- 0.8
	R					
	S	11.00	19.25	7.75	13.56	U- 7.0, T- 2.3, R- 1.2
	T					
	U					
	V					
Grid Bus	A	9.00	15.75	7.85	13.73	

Chapter 05

Conclusions

5.1 Conclusions

It is clearly observed that with increasing the connection of embedded generation to the distribution network mainly increases the fault levels at some points and experience high voltages at off peak times. Within sample network it is observed high voltage feeder sections. Fortunately these two areas are not populated much, but one day this problem arises. Hence as mitigating technique for this high voltage problem, system planning engineers can rethink about the design changes of the network.

Analyzing the sample network three points were selected, which was given high fault currents. After that designed FCL was applied to the network and performance observed. FCL was able to reduce the high fault current to acceptable level. Otherwise the electrical equipments like ABS s, LBS s and expulsion switches should be replaced to withstand such high fault levels. Hence by introducing the FCL s to the network would be a great advantage without much spending for the above equipments. Not only for these fault currents but also FCL could effect the line voltage variations. But that topic has not discussed in this thesis and remains as future work.

The application of an FCL at the connection point of the DG solves problems associated with increasing in fault current due to embedded generation. The current limiting capability is depending on both the location and the FCL impedance. However this study of selected distribution network in Sri Lanka clearly showed that application and advantages of FCL s. This study revealed that the FCL and one directional relay was enabled to use the same switchgear without disturbing the existing protection coordination relay settings. Although this study was based on a particular network, the methodology used in this study could be directly applied for any network.

5.2 Suggestions for future works

Detail modeling of the FCL enables to carry out full application studies, where to investigate the effect of FCL on over current protection coordination, transient stability and voltage quality related issues could be addressed, more accurately. For these types of analysis it is convenient to use PSCAD/EMTDC, IPSA software packages which are specially designed for power system stability and transient analysis.

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APPENDIX – A : Grid vice connected MHP s in Sri Lanka

Table A.1 : Grid vice connected MHP s in Sri Lanka

No.	Grid Substation	No. of MHP s Connected		SPPA Signed Projects	
		Nos.	Total Capacity (MW)	Nos.	Total Capacity (MW)
1	Badulla	02	5	04	12.840
2	Balangoda	09	30.3	08	17.8
3	Deniyaya	06	7.868	03	3.35
4	Kiribathkumbura	08	13.696	01	2.2
5	Mathugama	01	0.150	01	0.5
6	Nuwara Eliya	08	11.138	06	16.920
7	Rantambe	01	2.4	01	1.6
8	Rathnapura	09	22.88	02	11.5
9	Seethawaka	09	9.432	06	14.53
10	Thulhiriya	01	4.480	-	-
11	Ukuwela	01	6.5	01	1.5
12	Wimalasurendra	13	21.630	05	9.85
Total		**68**	**135.474**	**38**	**92.59**

(Grid substations of Sabaragamuwa Province are highlighted)

APPENDIX – B : Conductor Data

Table B.1 : Resistances and reactances of conductor types

Conductor Type	**Resistance (ohm/km)**	**Reactance (ohm/km)**		**Current (A)**
		Pole line	**Tower Line**	
Lynx (37/2.79)	0.177	0.313	0.364	400
ELM (19/3.76)	0.174	0.321	0.372	400
Racoon (7/4.09)	0.431	0.375	0.426	220
Weasel (7/2.59)	1.1	0.403	0.454	100
Copper (19/7.38)	0.758	0.7135	-	300

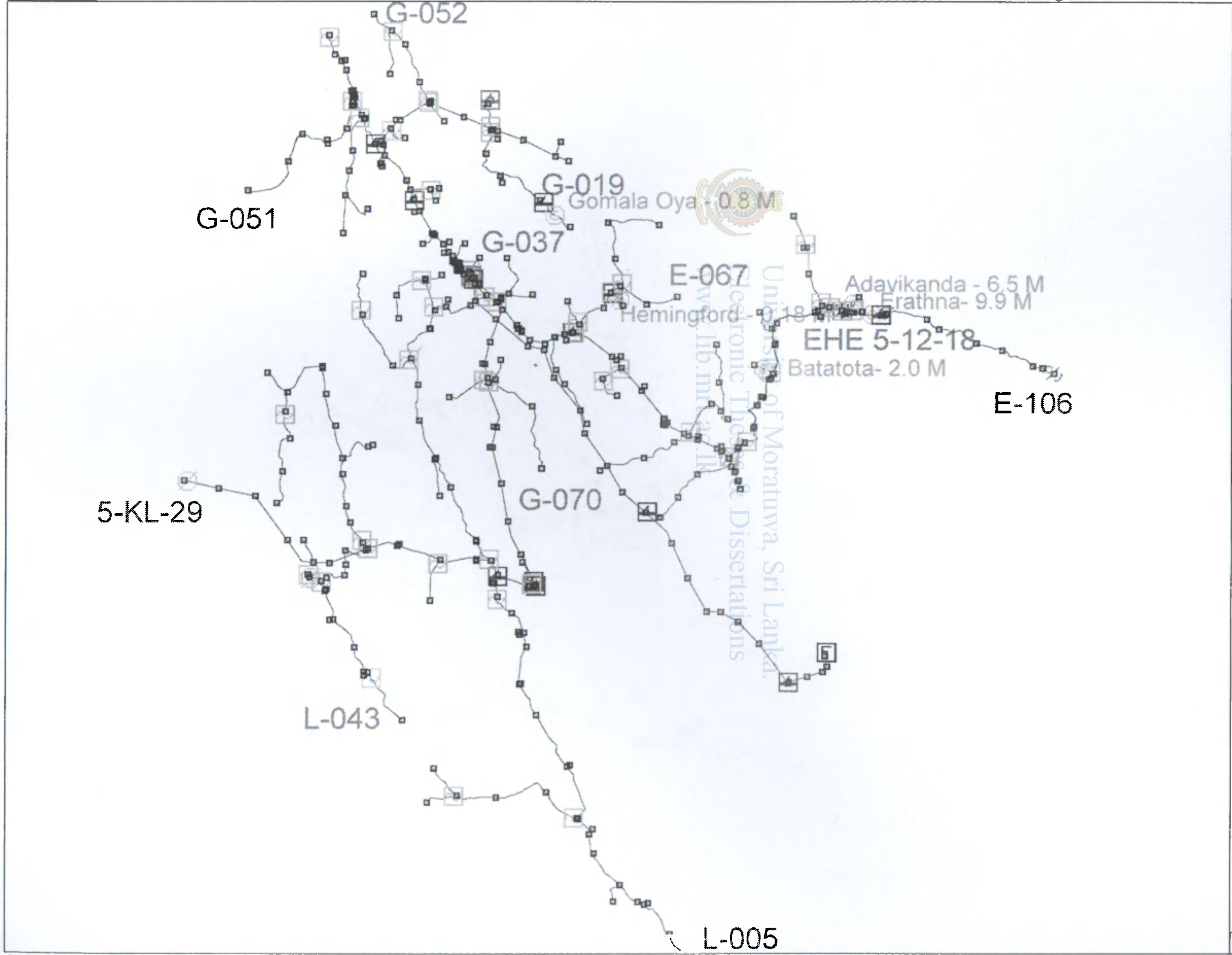
APPENDIX - C : SynerGEE Table and Maps

Table : C.1 Voltage analysis of feeders

Feeder No.	Section Name	Distance	11.30 a.m. Base Case *(Day Peak)*			11.30 a.m. with DGs *(Day Peak)*			7.30 p.m. with DGs *(Night Peak)*			1.00 a.m. with DGs *(Night Off Peak)*		
			Volts (%)			Volts (%)			Volts (%)			Volts (%)		
		(km)	A/AB	B/BC	C/CA	A/AB	B/BC	C/CA	A/AB	B/BC	C/CA	A/AB	B/BC	C/CA
5	G-019	43.6	85.2	85.2	85.2	100.2	100.2	100.2	94.8	94.8	94.8	107.2	107.2	107.2
	G-037	25.5	88.3	88.3	88.3	100.6	100.6	100.6	96.2	96.2	96.2	106.1	106.1	106.1
	G-051	42.6	85.4	85.4	85.4	99.4	99.4	99.4	94.0	94.0	94.0	106.4	106.4	106.4
	G-052	40.4	85.4	85.4	85.4	99.6	99.6	99.6	94.2	94.2	94.2	106.5	106.5	106.5
	G-070	35.6	87.5	87.5	87.5	100.1	100.1	100.1	95.4	95.4	95.4	106.0	106.0	106.0
	E-106	59.3	83.6	83.6	83.6	98.1	98.1	98.1	91.7	91.7	91.7	105.7	105.7	105.7
	E-067	36.4	86.2	86.2	86.2	99.5	99.5	99.5	94.3	94.3	94.3	106.0	106.0	106.0
	L-005	61.8	85.8	85.8	85.8	99.1	99.1	99.1	93.7	93.7	93.7	105.8	105.8	105.8
	L-043	57.9	85.9	85.9	85.9	99.2	99.2	99.2	93.9	93.9	93.9	105.8	105.8	105.8
	F-RAT-EHE 5-12-18	27.9	94.3	94.3	94.3	111.5	111.5	111.5	109.7	109.7	109.7	113.9	113.9	113.9
	F-RAT-EHE 5-KL-29	56.4	86	86	86	99.3	99.3	99.3	94.0	94.0	94.0	105.8	105.8	105.8
6	F-RAT-NIV 6-06	10.7	97.8	97.8	97.8	102.7	102.7	102.7	102.0	102.0	102.0	103.8	103.8	103.8
	D-022	25.1	93.9	93.9	93.9	104.4	104.4	104.4	102.4	102.4	102.4	107.5	107.5	107.5
	D-069	24.3	96.3	96.3	96.3	104.1	104.1	104.1	102.9	102.9	102.9	105.9	105.9	105.9
	D-072	33.6	93.3	93.3	93.3	106.4	106.4	106.4	104.2	104.2	104.2	109.7	109.7	109.7
	D-089	39.0	91.8	91.8	91.8	103.5	103.5	103.5	100.9	100.9	100.9	107.8	107.8	107.8
8	C-106	23.3	90.6	90.6	90.6	99.4	99.4	99.4	94.8	94.8	94.8	103.1	103.1	103.1
	F-RAT-DUREK-09	5.5	99.3	99.3	99.3	101.2	101.2	101.2	100.9	100.9	100.9	101.5	101.5	101.5

SynerGEE Electric Printout
Stoner Associates, Inc.
Carlisle, PA 17013

Figure C.1 : Feeder - 05



Section Color By: Feeders

Color Scheme:
▇ F-RAT-EHE 5
▇ Unknown

Line Type By: Phases
1 Phase:
2 Phase: — — — —
3 Phase: ————

Equipment:
Capacitors
Generators
Motors
Fuses
Breakers
Reclosers
Sectionalizers
Protective Devices
Regulators
Open Switches
Closed Switches
Tie Switches
Transformers
Feeders
Substation Transformers
Pad-Mounted Gear

Map Display Coordinates:
Southwest:
(467590.265,552545.157)
Northeast:
(518932.691,592560.593)

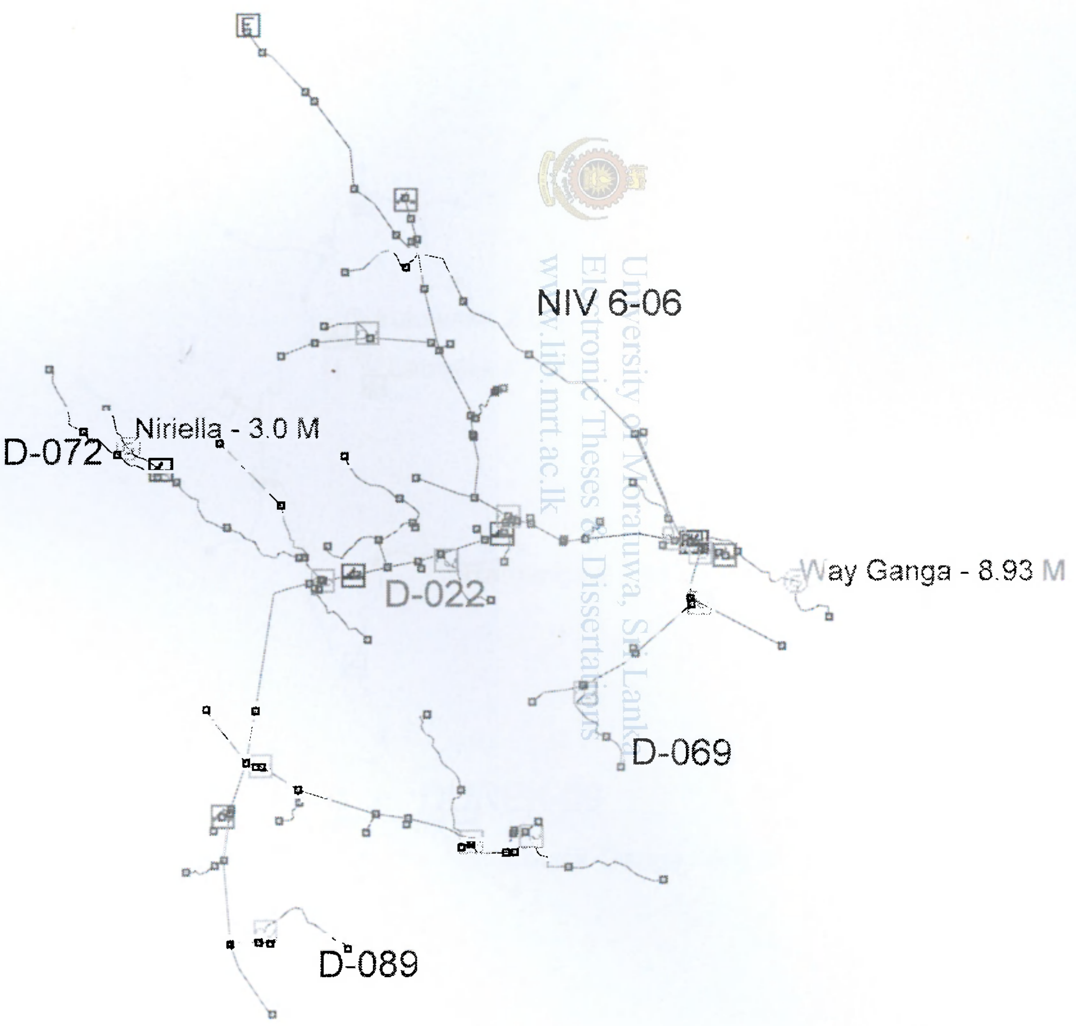
Rathnapura GSS
SAI In house (Carlisle)

SynerGEE Electric Version 3.52 1May2003

Scale: (1 cm = 2551.3 Meters)

SynerGEE Electric Printout
Stoner Associates, Inc.
Carlisle, PA 17013

Figure C.2 : Feeder - 06



Section Color By: Feeders

Color Scheme:
F-RAT-NIV 6
Unknown

Line Type By: Phases
1 Phase:
2 Phase:
3 Phase:

Equipment:
Capacitors
Generators
Motors
Fuses
Breakers
Reclosers
Sectionalizers
Protective Devices
Regulators
Open Switches
Closed Switches
Tie Switches
Transformers
Feeders
Substation Transformers
Pad-Mounted Gear

Map Display Coordinates:
Southwest:
(518936.811,495711.662)
Northeast:
(554548.940,523467.165)

Rathnapura GSS

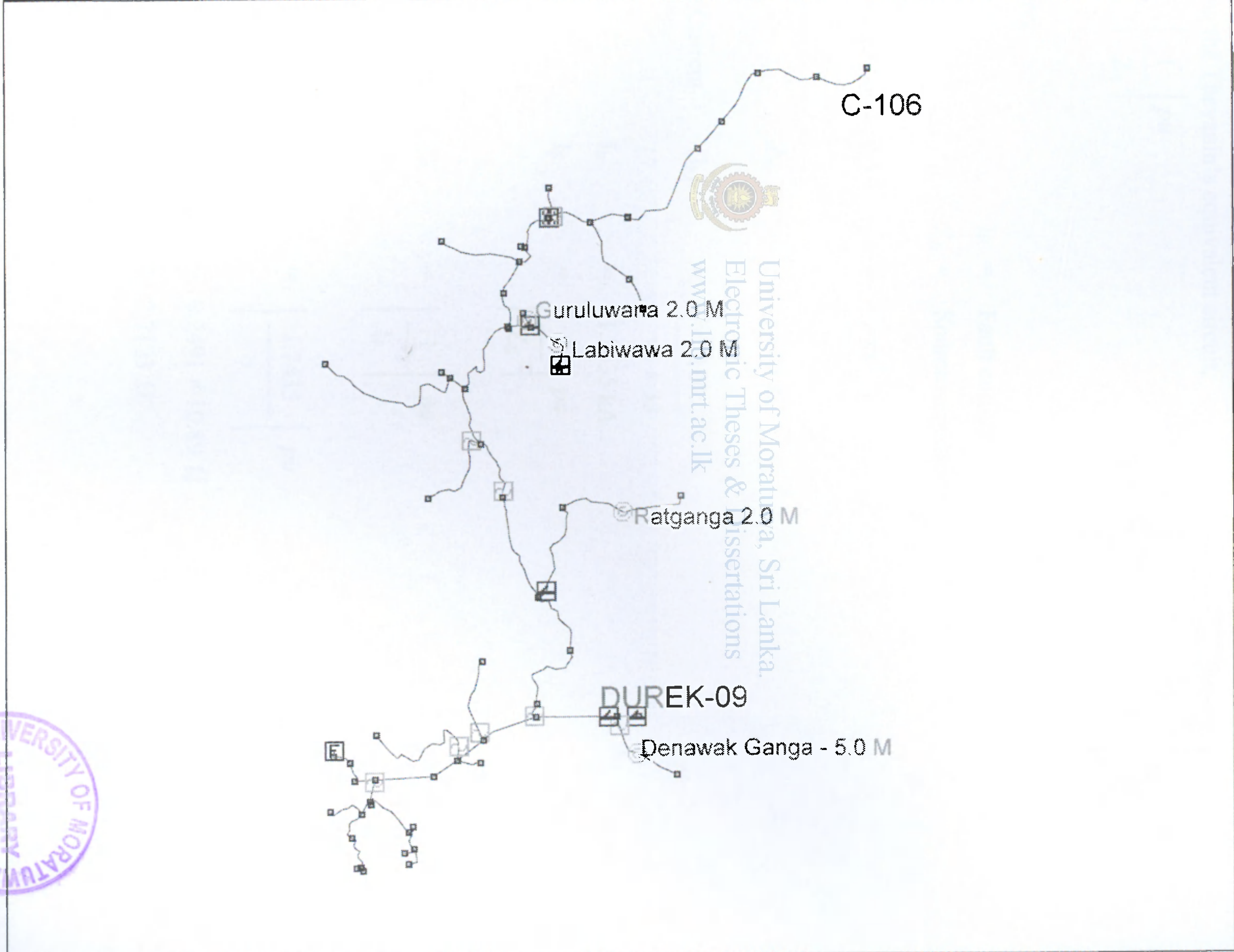
SynerGEE Electric Version 3.52 1May2003

Scale: (1 cm = 1769.6 Meters)

SAI In house (Carlisle)

SynerGEE Electric Printout
Stoner Associates, Inc.
Carlisle, PA 17013

Figure C.3 : Feeder - 08



Section Color By: Feeders

Color Scheme:
F-RAT-DUREK
Unknown

Line Type By: Phases
1 Phase:
2 Phase:
3 Phase:

Equipment:
Capacitors
Generators
Motors
Fuses
Breakers
Reclosers
Sectionalizers
Protective Devices
Regulators
Open Switches
Closed Switches
Tie Switches
Transformers
Feeders
Substation Transformers
Pad-Mounted Gear

Map Display Coordinates:
Southwest:
(527936.325,555102.853)
Northeast:
(549491.767,571902.807)

Rathnapura GSS
SAI In house (Carlisle)

SynerGEE Electric Version 3.52 1May2003

Scale: (1 cm = 1071.1 Meters)

APPENDIX – D : Calculations

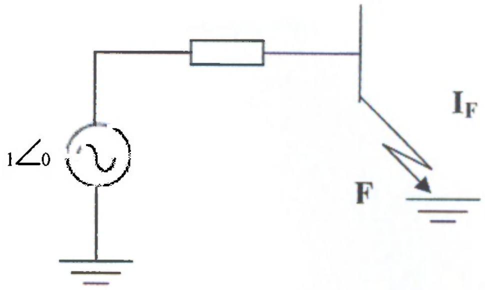
D.1 : Calculating the source impedance (Z_S)

Taking the initial fault level (without DGs) of RGSS in 7 kA.

Let taken, Base MVA = 100 MVA

Base kV = 33 kV

`Using the Thevanin's equivalent circuit,



$$I_F = \left|\frac{1}{Z_S}\right| pu$$

Where,

I_F = Fault current

Z_S = Source impedance

$$\text{Base Impedance } (Z_b) = \frac{33^2}{100}$$

$$Z_b = 10.89\ \Omega$$

$$\text{Base Current } (I_b) = \frac{100}{\sqrt{3} \times 33}$$

$$I_b = 1.7435 \text{ kA}$$

$$I_F = \left|\frac{1}{Z_S}\right| pu$$

$$Z_S = \left|\frac{1}{I_F}\right| pu$$

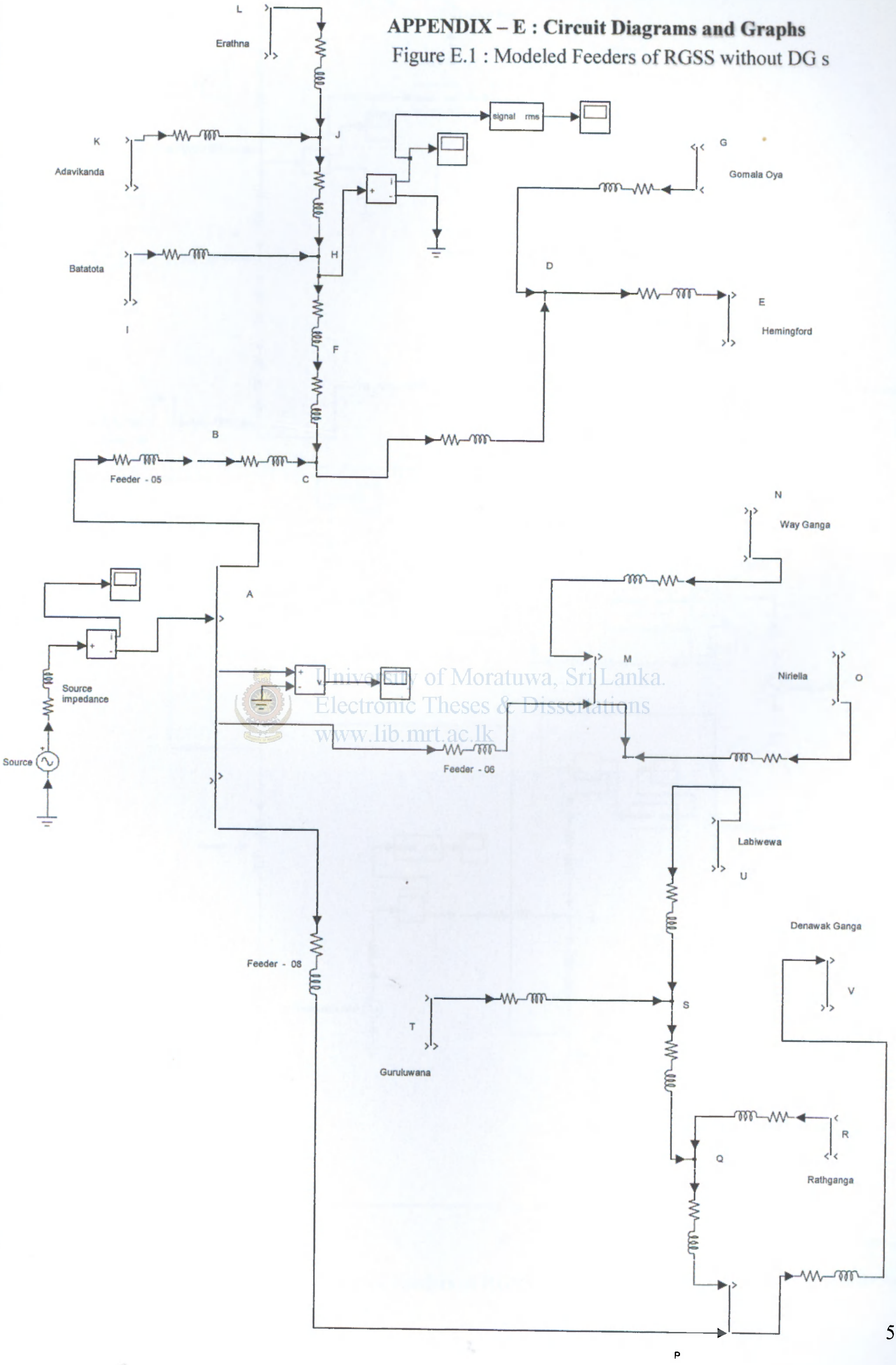
$$\therefore Z_S = \left|\frac{1.7435}{7}\right| pu$$

$$Z_S = 0.2491 \times 10.89\ \Omega$$

$$= 2.7123\ \Omega$$

APPENDIX – E : Circuit Diagrams and Graphs

Figure E.1 : Modeled Feeders of RGSS without DG s



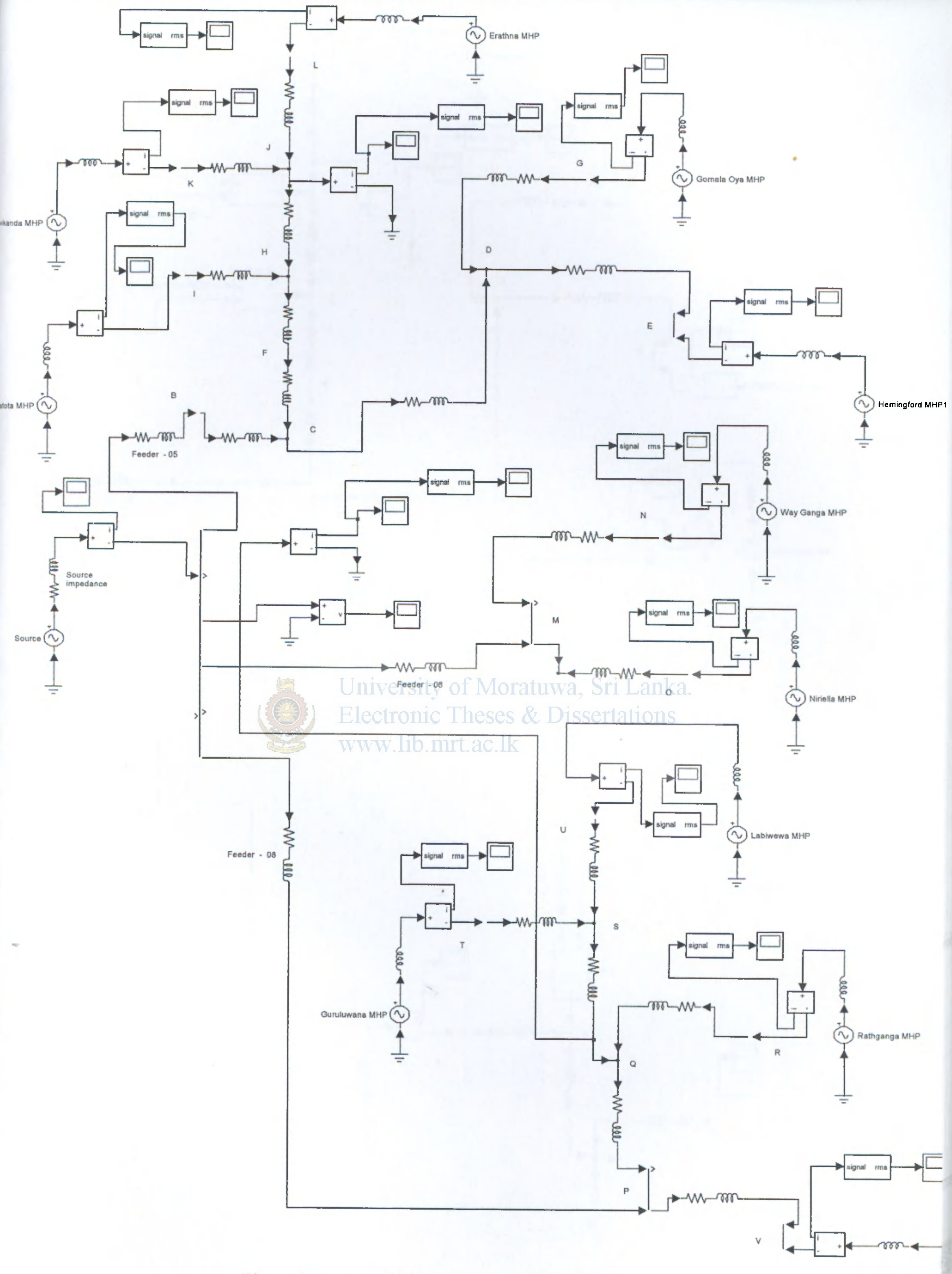


Figure E.2 : Modeled Feeders of RGSS with DG s

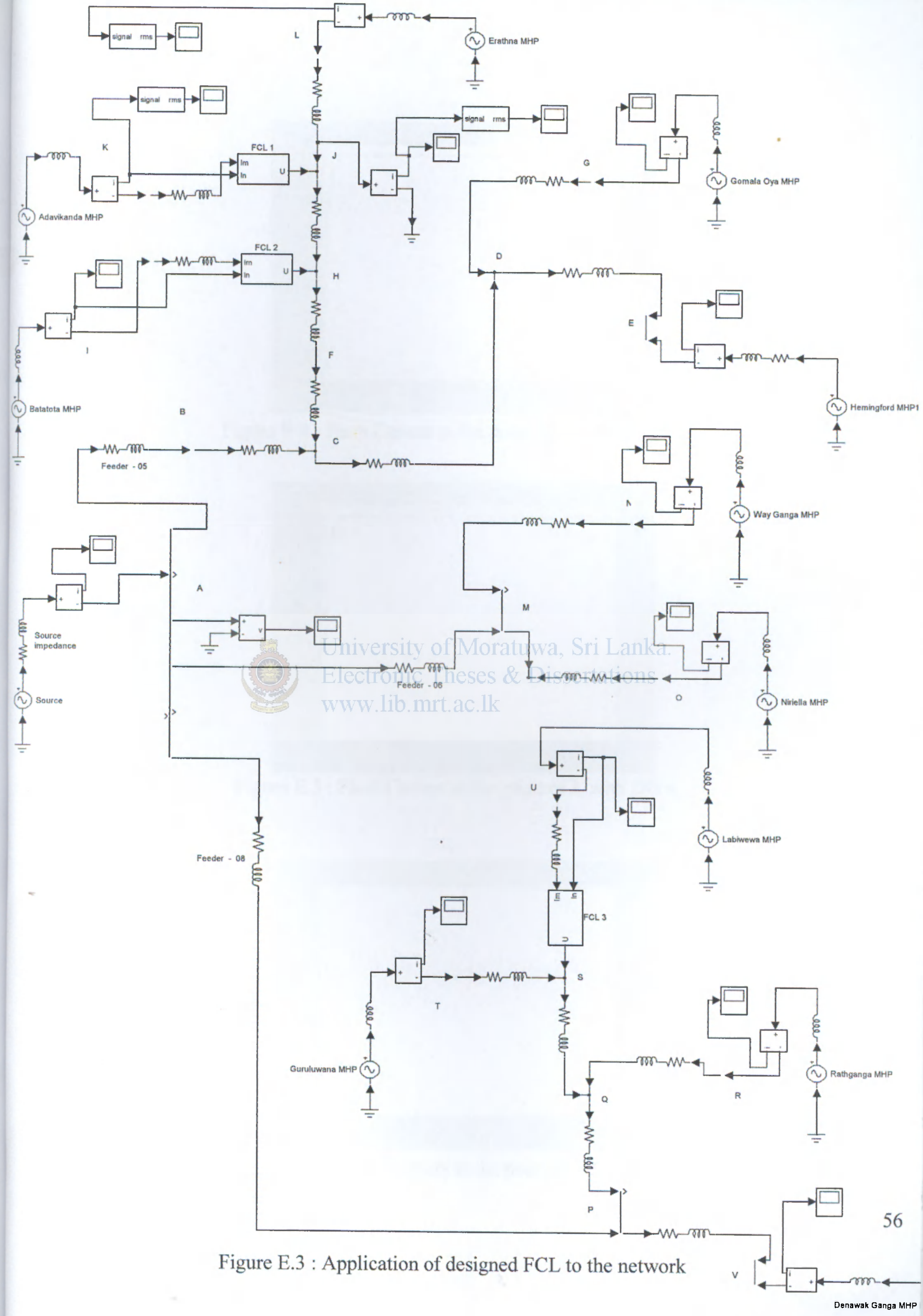


Figure E.3 : Application of designed FCL to the network

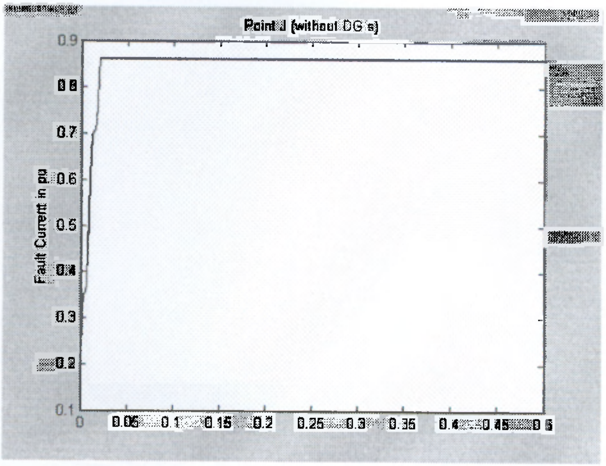


Figure E.4 : Fault Current at the point of J, without DG s

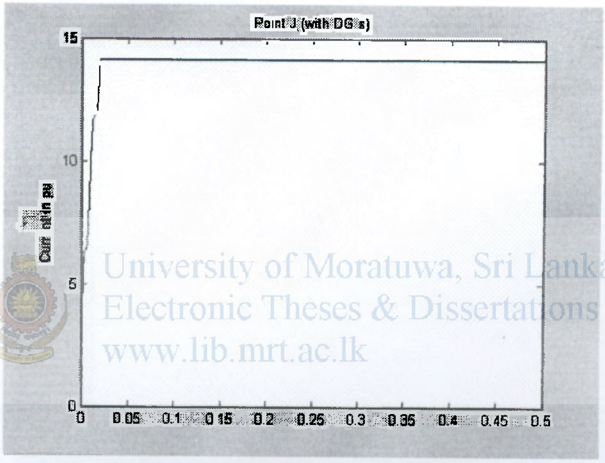


Figure E.5 : Fault Current at the point of J, with DG s

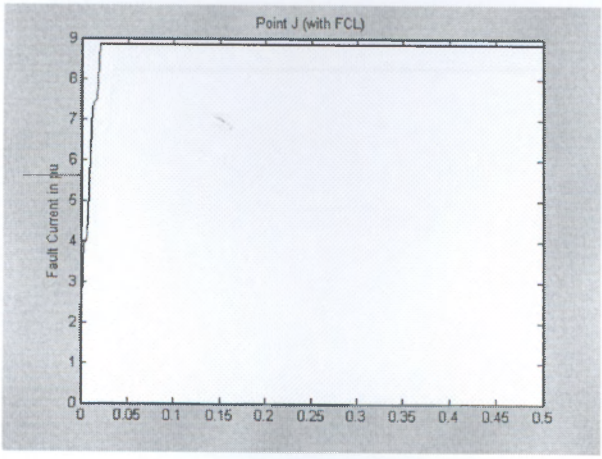


Figure E.6 : Fault Current at the point of J, with FCL

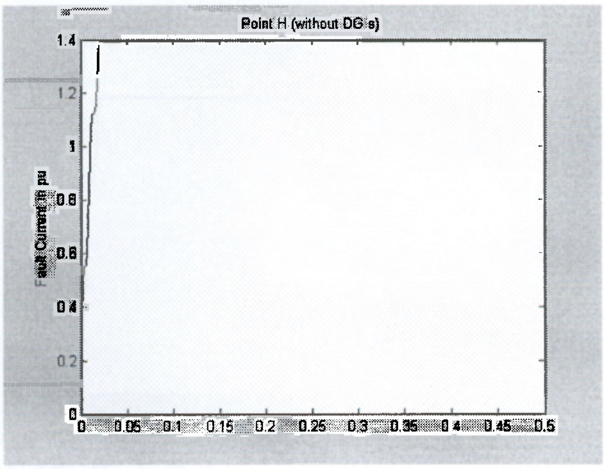


Figure E.7 : Fault Current at the point of H, without DG s

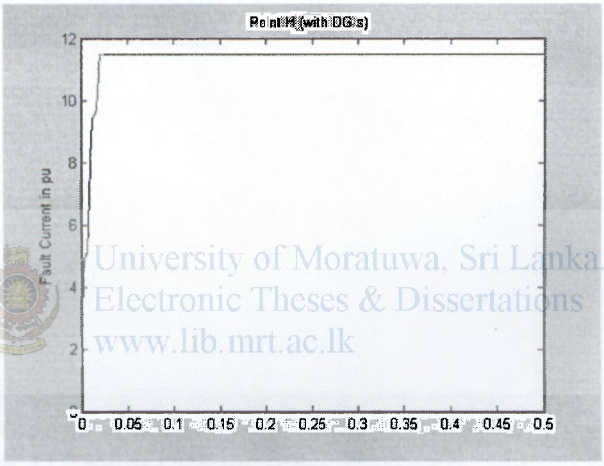


Figure E.8 : Fault Current at the point of H, with DG s

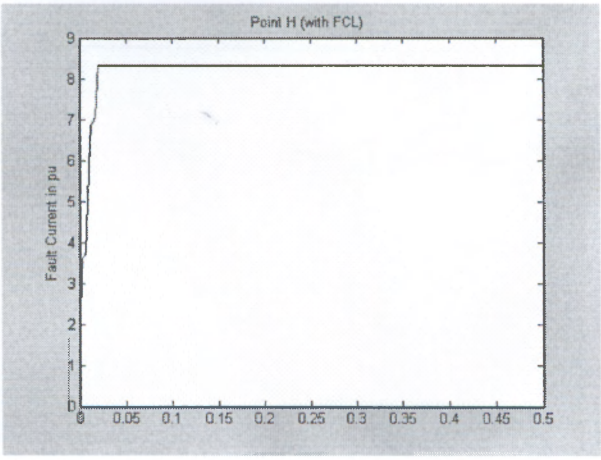


Figure E.9 : Fault Current at the point of J, with FCL

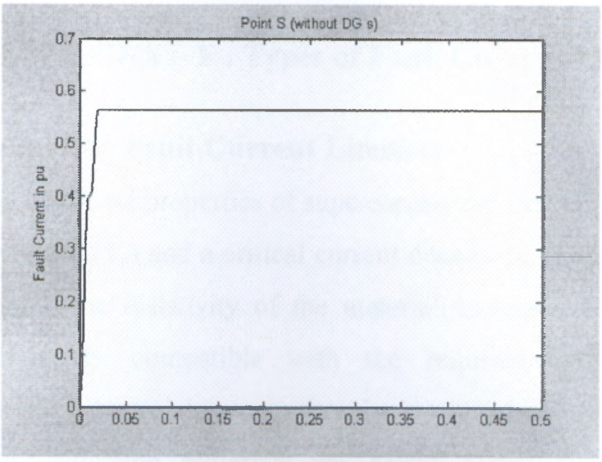


Figure E.10 : Fault Current at the point of S, without DG s

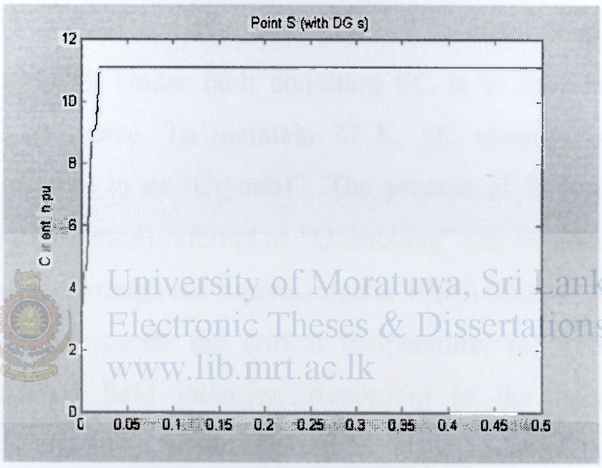


Figure E.11 : Fault Current at the point of S, without DG s

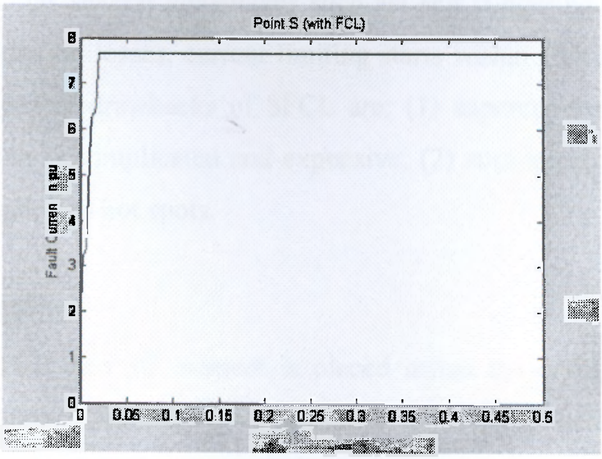


Figure E.12 : Fault Current at the point of S, with FCL

APPENDIX – F : Types of Fault Current Limiters

F.1 Superconducting Fault Current Limiters

The outstanding electrical properties of superconductors are: (1) zero resistivity below a critical temperature (T_c) and a critical current density (J_c) and (2) as soon as T_c and Jc are surpassed, the resistivity of the material increases very rapidly. As these properties are highly compatible with the required properties of an FCL, Superconductor (SC) materials were extensively considered for FCL s. The FCL s based on superconducting materials are called Superconducting Fault Current Limiters (SFCL). With the availability of High Temperature Superconducting (HTS) materials, several types of SFCL s were introduced and tested. During the normal operation of the system and if the temperature is maintained at 77K SC is in its superconducting state. Under fault condition SC is in its normal state and shows relatively high resistance. To maintain 77 K, SC element is located in a liquid nitrogen bath referred to as "Cryostat". The process of Superconducting to normal transition (S-N transaction) referred as "Quenching" can be a result of application of: (a) transport current through the superconductor which exceeds the critical current, (b) heat energy which exceeds the critical temperature, (c) a magnetic field which exceeds the critical field intensity. According to the operating principle and configuration, SFCL s can be categorized as: resistive, shielded inductive, saturated inductive, flux lock type, transformer type, dc reactor type and rectifier type. In this thesis only a few main types are briefly discussed. With respect to the other FCL schemes SFCL has several advantages such as: self triggering by line current, very low normal operation losses, current limiting starts within first half cycle and simple structure. The major drawbacks of SFCL are: (1) superconductor has to be cooled below T_c, which is complicated and expensive; (2) superconductor tends to thermal instabilities, leading to hot spots.

Resistive type SFCL

In Resistive SFCL, the SC element is placed inside the cryostat and connected in series with the power line as shown in Figure 4.1. During the normal operation, the load current (I) is lower than the Critical Current (I_c) of the SC element thus giving a zero resistance across the FCL. During a fault, I exceed I_c and transition from superconducting to normal will take place. This process brings the FCL resistance to relatively high value thus limiting the fault current.

During the limiting operation, all the fault current flow through the SC element and Energy of the fault current directly absorbed by it. This in turn is overheating the element. The quick interruption of fault current or diversion of fault current into a parallel path will solve this problem. The shunt impedance shown in Figure F.1 provides a parallel path to divert the fault current at limiting operation. Heat ingress into cryostat due to I^2R losses lead to a significant refrigeration cost, even under normal operation. In homogeneities in SC, which may take place during manufacturing, may result in localized normal zones during quenching which leads overheating. In order to overcome this situation, normal zone propagation needs to be very quick. In some applications, both load current and external magnetic field is used to achieve a uniform quenching. Due to temperature rise in SC, it takes few seconds to come back to superconducting mode thus showing a high recovery time.

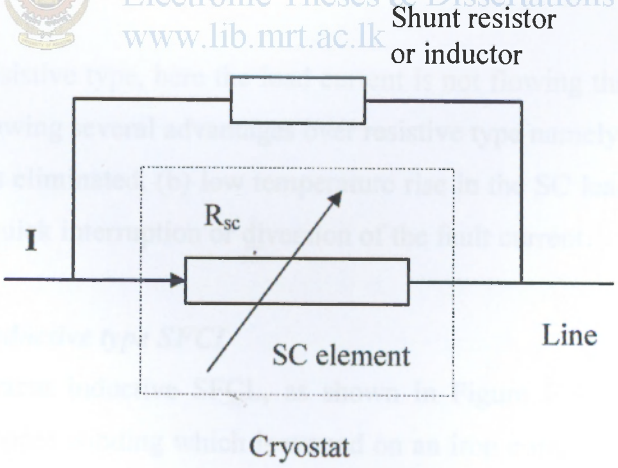


Figure F.1: Layout of Resistive type SFCL

Magnetic Shielding type SFCL

The Magnetic Shielding type SFCL consists of an iron core, copper winding in series with the protected power line and an SC cylinder placed around an iron core as shown in Figure F.2 [5]. The operation can be visualized as a transformer with short circuited single secondary turn. During the normal operation, the current induced in the SC tube balances the ampere-turn produced by the primary winding therefore the device shows low impedance. For fault condition, the induced current in SC exceeds the critical current, Ic, and flux balance is destroyed. The flux enters the iron core and the device shows relatively high impedance. The line current at which the FCL trigger can be varied by changing the number of turns in the primary coil.

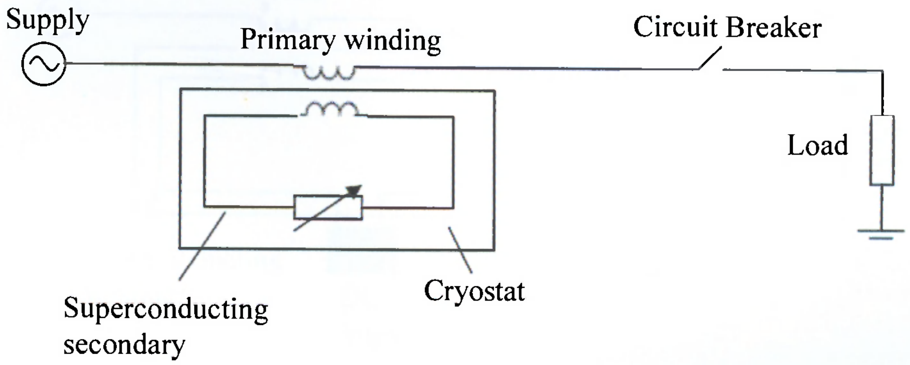


Figure F.2: Layout of Magnetic Shielding type SFCL

Unlike in resistive type, here the load current is not flowing through the SC Cylinder and thus showing several advantages over resistive type namely: (a) heat loss from the line to SC is eliminated, (b) low temperature rise in the SC leads to fast recovery, (c) no need of quick interruption or diversion of the fault current.

Saturated inductive type SFCL

In the Saturated inductive SFCL, as shown in Figure F.3, the line current passes through a copper winding which is wound on an iron core. The iron core is saturated using de biased superconducting winding. For normal load current, the core is in saturation and shows zero impedance across the device. During a fault, large ac current brings the core out of saturation and introduces relatively large impedance to the system. In order to achieve current limiting in both positive and negative half cycles of current, two such units are connected in series to make a single-phase unit.

In normal operation, it shows relatively high operating losses and voltage drop as a result of two units in series. Since SC element is always in superconducting state, fast recovery can be achieved with saturated inductive design. This FCL needs large amount of iron and copper with respect to the shielded inductive type, thus leading to higher installation cost.

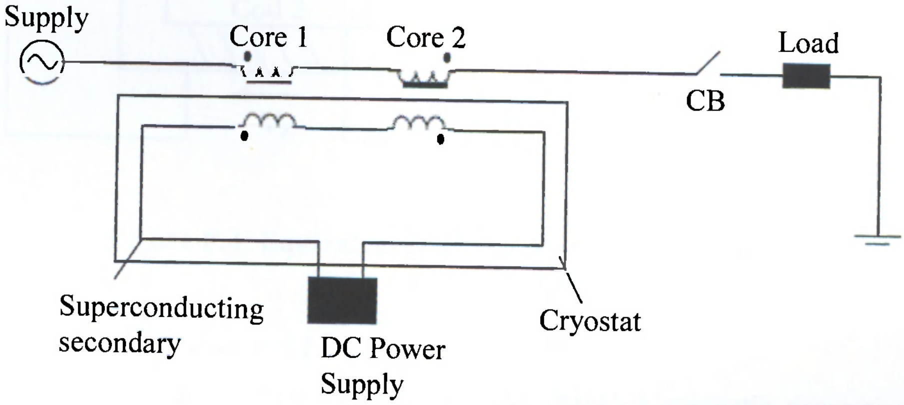


Figure F.3: Layout on Saturated Inductive type SFCL

Flux Lock Type SFCL

The Flux Lock type SFCL device consists of two similar coils wound on iron core to produce fluxes in opposite directions and a HTS element, which is connected in series with a coil. The two coils are connected in series with the power line as shown in Figure F.4. During the normal operation the load current equally distribute in two paths and current through HTS element (I_{sc}) will not exceed I_c. Since HTS element is in superconducting state V_1, V_2 and V_3 become zero. Thus introduces zero impedance across the device. Under fault conditions I_{sc} exceeds Ic and HTS element become resistive. As a result V_1, V_2 and V_3 become non-zero. This means device introduce a series impedance to the power line. Different topologies of Flux Lock type SFCL with slight modifications can be found in literature [12].

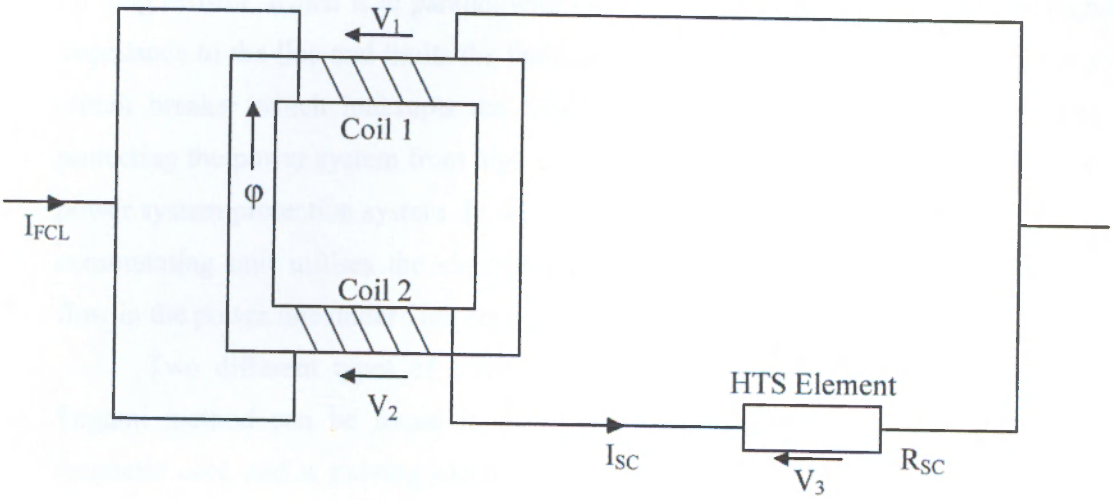


Figure F.4: Equivalent circuit of Flux Lock type SFCL

F.2 Magnetic Fault Current Limiters

In the case of Magnetic Fault Current Limiter (MFCL) magnetic properties of a device or a circuit is used to introduce current dependent impedance to the power line. When compared with an SFCL, this type shows very low operational cost and low power loss under normal operating condition. As superconductors are expensive, MFCL is more economical than SFCL. The size and the weight may be higher than other types due to usage of magnetic cores. MFCLs can broadly be categories into two types: (a) Magnetic switch based MFCL [13] and (b) Saturated core based MFCL[10]

Magnetic switch based MFCL [9]

Basic components of magnetic switch based MFCL and there arrangements are shown in Figure F.5. The MFCL consists of commutating unit, load disconnecting switch and a current limiting resistor. The device is connected in series with the power line. Under normal loading conditions both load disconnecting switch and the contactor in commutating unit are closed, thus introducing low impedance to the power line. Heat loss and voltage drop across the device is negligible as the impedance of the contactor is very small. During a fault due to high current flow commutating unit quickly opens its contactor. The opening of the contactor results in current flow through the current limiting resistor, which is in parallel with the commutating unit. This introduces high impedance to the line and limits the fault current. The load disconnecting switch is a circuit breaker which interrupts the limited fault current within certain time thus protecting the power system from high current flow. Normally this unit links with the power system protection system. In order to achieve a rapid opening of the contactor, commutating unit utilises the electromagnetic force generated by the high current flow in the power line under fault condition.

Two different types of commutating methods namely Lorentz method and Togami method can be found in literature[13]. In Lorentz method, an U shape magnetic core and a moving electrode are used to open the contact as shown in Figure F.6. Magnetic flux density created by the fault current flowing through the electrode produces the Lorentz force, which then open the contact. The Togami method uses to coil disks, one movable and other fixed as shown in Figure F.7. High current flowing through each coil disk in a direction opposite to that of the compounding disk produces a repulsive force and drives the movable disk and moving electrode. This causes rapid opening of the contact.

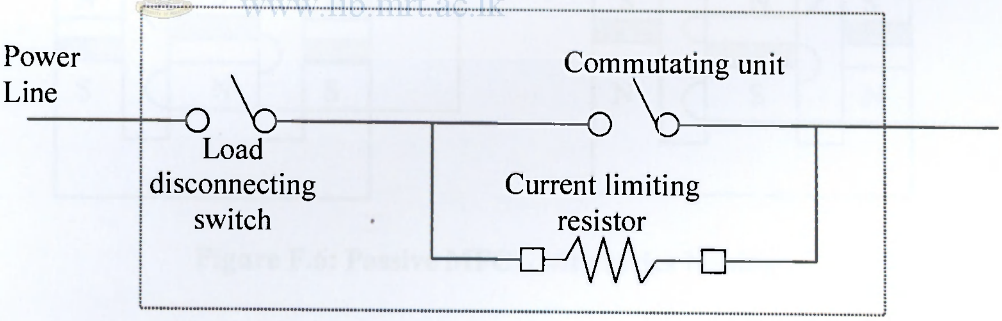


Figure F.5: Equivalent circuit of Magnetic switch based MFCL

Saturated core based MFCL

Saturated core based MFCL uses a magnetic core which is kept in the saturation region during normal loading conditions using a suitable biasing arrangement. When current flow is higher than the predetermined critical level, core comes out from saturation. This current dependent magnetic characteristic is utilized in different ways to design MFCL s. Different biasing mechanisms which utilise a magnetic core in combination of a semiconductors or a static circuit can be found in literature [7]

(1) Passive MFCL *in series biasing mode*

A permanent magnet is used to bias the core and forced it into saturation under normal operating conditions. A winding wound on the middle limb is serially connected to the power line. The assembly of core permanent magnet behaves like an inductor and during low value of operating current; it offers saturated inductance to the circuit which is normally low. Under a fault due to large current, core comes out of saturation and offer unsaturated inductance which is comparably larger than saturated inductance. Since one core has ability to limit the current in one half cycles, two cores are required to build the complete unit. Two cores with opposite biasing arrangements are connected as shown in Figure F.6 to make complete unit which can limit the fault current in both positive and negative half cycles.

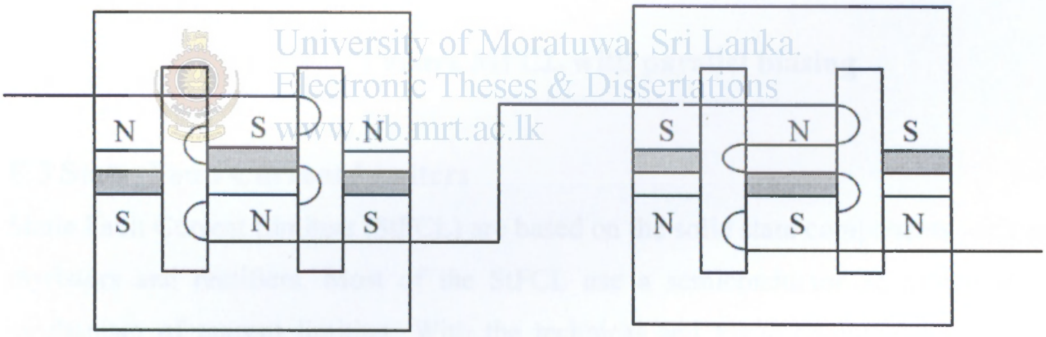


Figure F.6: Passive MFCL with series biasing

In this arrangement flux due to the line current flows through the permanent magnet and Magneto Motive Force (MMF) due to line current will act in series with MMF force of permanent magnet. For each core, during a full cycle of line current two MMF components act in opposite directions. This causes reduction of the next flux and thus completely demagnetizing the permanent management. This disadvantage was rectified with the parallel biasing arrangement.

(2) Passive MFCL in parallel biasing mode

In parallel biasing arrangement permanent magnet is located at the middle limb and coil is wound in order two limbs in magnetically opposite direction as shown in figure F.7. Although operational mechanisms of both series and parallel biasing are very similar, demagnetization effect in series biasing techniques can be minimized with parallel biasing. Other advantage is that a single core is sufficient to achieve current limiting in both positive and negative half cycles as both windings are in the same core.

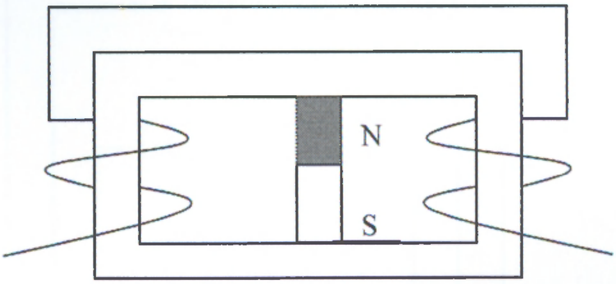


Figure F.7: Passive MFCL with parallel biasing

F.3 Static Fault Current Limiters

Static Fault Current Limiters (StFCL) are based on the solid state components such as thyristors and rectifiers. Most of the StFCL use a semiconductor ac switch as a mechanism of current limiting. With the technical and the economical limitations associated with the SFCL and MFCL, StFCL is a good candidate for fault current limiting [14]. There are varies types of StFCL some of which are based completely on solid state devices while some other types are combination of solid state devices with superconducting or magnetic devices. According to the basic structure and the operating mechanism, mainly two types of StFCL can mainly be identified: (a) GTO thyristor switch based StFCL, and (b) thyristor controlled series turned circuit based StFCL

GTO thyristor switch based StFCL

In the case of GTO thyristor based FCLs, a semiconductor switch consist of two GTO thyristor connected in inverse parallel, is connected in parallel with a current limiting impedance as shown in Figure F.8 [8].

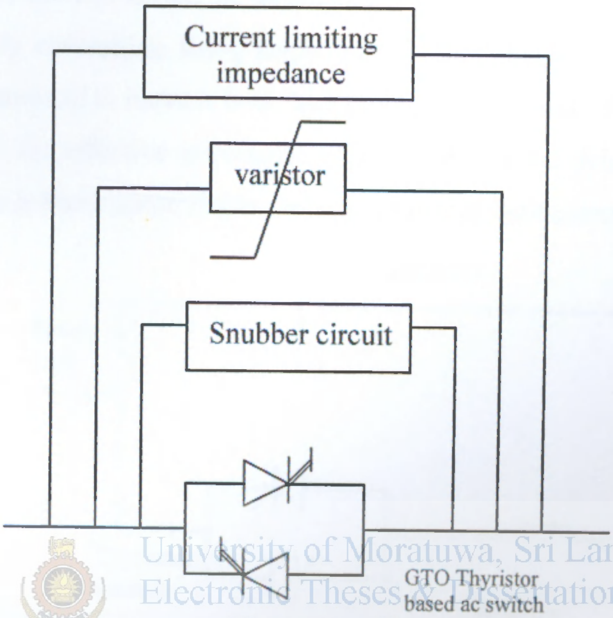


Figure F.8: GTO thyristor switch based

During normal loading conditions, GTO thyristor switch shown low impedance to the current flow. When a high current is detected the normally conducting ac switch is turned off and current is diverted into the parallel limiting impedance. This will introduce relatively high impedance to current flow and reduces the current to an acceptable level. Purpose of the varistor and snubber circuit connected in parallel with the thyristor switch is to limit the level and the rate of rise of transient voltage across the switch.

Thyristor Controlled series tuned circuit based StFCL

Thyristor controlled Reactor (TCR) is a back to back thyristor ac switch connected in series with a reactor and when a connected in parallel with the TCR as shown in figure 4.9, it is called as a Thyristor Controlled Series Compensator (TCSC). Impedance characteristic of the TCSC is illustrated in Figure F.10. At the firing angle of 90^0, it shows inductive impedance to the line and the inductive impedance increases with the firing angle. If the firing angle exceeds a certain value, impedance becomes capacitive and the capacitive impedance decreases, with the increase in the firing angle. The transient region from inductive to capacitive is depending on the value of the capacitor and inductor impedances. Although TCSC is commonly used as power flow control device, its impedance characteristics allow it to be used as an FCL by properly controlling firing angle. Rather than using TCSC only as an FCL, it is more economical to harness both fault current limiting and compensation capability of the TCSC. As effective impedance of an TCSC can be dynamically controlled, it is possible to achieve controllable compensation and fault current limiting.

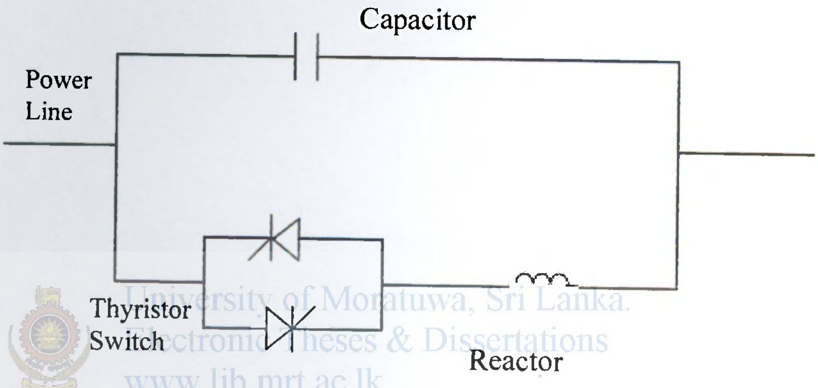


Figure F.9: Thyristor controlled series tune circuit based StFC

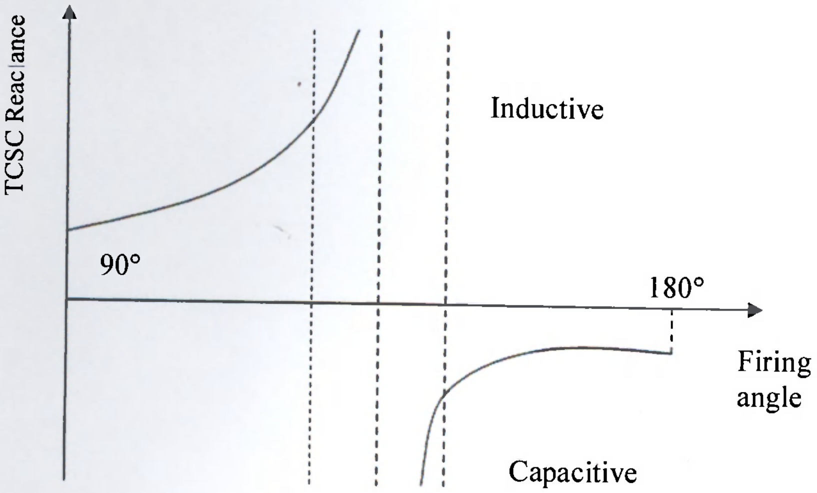


Figure F.10: Impedance characteristics of TCSC