SYSTEM IMPROVEMENT THROUGH CO-ORDINATED RING CIRCUIT IN MEDIUM VOLTAGE NETWORK IN COLOMBO CITY: A CASE STUDY

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Degree of Master of Science

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DECLARATION PAGE OF THE CANDIDATE & SUPERVISOR

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ABSTRACT

Power distribution systems feed in radial and ring feeding mechanisms. The radial feeding arrangement is used in rural networks where reliability is very low. In urban areas, ring feeding arrangements are likely to be used which provides an alternative feeding arrangement for load.

Colombo City uses an open loop feeding arrangement with a normally open point in the ring arrangement. It has an underground 11kV network where panel substations in a ring (partly meshed) manner are connected around the primary substation. Outgoing feeders from these panel substations are again connected in a ring manner through Ring Main Units.

By providing correct directional protection coordination these panel substations can be operated in a closed loop ring arrangement to improve reliability. It will also reduce distribution line losses and improve the system voltage profile.

In my dissertation, area fed by Primary Substation F was taken into consideration for analysis. Different time zones were recognized based on load changes for week days and weekends. The possible ring arrangements were identified and load flow analysis was carried out using SynerGEE for radial and closed loop ring arrangement to detail the power loss reduction, voltage improvement, excessive active power and reactive power absorbed by loads.

Reliability improvement was derived for SAIFI and SAIDI, using the rate of failure of cables based on the cable failure details of Colombo City. Voltage analysis and cost analysis were also carried out using SynerGEE.

Directional protection coordination was derived for two feeders operating in closed loop, two substations operating in closed loop and three substations operating in closed loop to cover the identified paralleling patterns in selected zones. Based on fault levels and the cable impedance data protection settings were calculated for actual field conditions for each pattern. Each pattern was simulated in Matlab to monitor the voltage and current variations for cable faults.

In conclusion, if the conditions prevail, the panel arrangement existing in Colombo City provides an easy approach to operate the system in a closed loop ring arrangement by replacing existing numerical relays with directional numerical relays, which improves the reliability, reduces the distribution losses and provides voltage improvements.

ACKNOWLEDGEMENT

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LIST OF ABBREVIATIONS

Abbreviation	**Description**
MV	Medium Voltage
NOP	Normal Open Point
LBS	Load Break Switch
RMU	Ring Main Unit
HV	High Voltage
CEB	Ceylon Electricity Board
SAIFI	System Average Interruption Frequency Index
SAIDI	System Average Interruption Duration Index
CC	Colombo City
PSSF	Primary Substation F
LV	Low Voltage
PILC	Paper Insulated Lead Covered
XLPE	Cross Linked Poly-Ethylene
CCCC	Colombo City Control Centre
IDMT	Inverse Definite Minimum Time
SCADA	Supervisory Control and Data Acquisition
CCDDP	Colombo City Electricity Distribution Project
AVR	Automatic Voltage Regulator
PSM	Pickup Setting Multiplier
TSM	Time Setting Multiplier
FL	Fault Level
OC	Over Current
EF	Earth Fault
SI	Source Impedance
P	Primary Substation
R	Radial/Ring Substation
F	Feeder
BS	Bus Section
Ld	Load feeder
z	Impedance of the cable
Z	Impedance

V	Medium Voltage Level (11kV)
I_{FL}	Fault Current
CB	Circuit Breaker
DT	Definite Time

Chapter 01

Introduction

1.1. Introduction to Power Systems

The electrical energy produced in generation station is conveyed to the consumer through a network of transmission and distribution lines. It is often difficult to draw a line between the transmission and distribution in power system merely by means of voltage. In general, distribution system is the part of power system which distributes power to the consumers for utilization. In Sri Lanka, 11 kV and 33 kV power systems are considered as the distribution systems.

The distribution system can be overhead or underground. Overhead lines are generally mounted on poles or towers while underground system uses conduits, cables and manholes under the surface of streets or sidewalks. The choice between overhead and underground system depend on the factors such as public safety, initial cost, flexibility, faults, appearance, fault location and repair, current carrying capacity, voltage drop, useful life, maintenance cost, interference with communication circuits etc[1].

1.2. Connection Schemes of Distribution Systems

Different types of distribution circuits are available to improve the reliability at the consumer end. The choice depends on whether incremental cost is acceptable with the reliability improvement achieved.

1.2.1. Single end radial network arrangement

This is the simplest and cheapest distribution circuit and has the lowest reliability due to following drawbacks.

- The end of the distributor nearest to the feeding point will be heavily loaded[1].
- The consumers are dependent on a single feeder and single distributor. Therefore, any fault on the feeder or distributor cuts off supply to the consumers who are beyond the faulty point until the fault is corrected [1].
- The consumer at the distant end of the distributor would be subjected to serious voltage fluctuations when the load on the distributor changes[1].

1.2.2. Open end ring network arrangement

This is the most commonly used topology for Medium Voltage (MV) distribution networks and simple to operate. The ring provides at least two alternative paths to each substation fed from it. The substations are connected to the ring by load break switches (LBS), all of which are closed except one, which is referred to as the Normal Open Point (NOP). Each section of the ring can then be treated as a simple radial feeder, with the only protection being at the primary substation. An MV cable fault causes the feeder breaker to trip, disconnecting all distribution substations fed from it. Supply can be restored to the healthy part of the system by opening switches at each end of the faulted cable to isolate the fault, closing the primary feeder breaker and the NOP. Traditionally restoration has been achieved manually, a process that takes several hours [2].

Telecontrol systems enable the restoration of supplies to a large number of customers within minutes by monitoring and controlling a few strategically positioned MV switches. This improves availability by reducing the time taken to identify and isolate the faulty network section. However, telecontrol systems do not improve security because the primary feeder breaker trip still takes place [2].

1.2.3. Closed loop ring network arrangement

This is commonly used in High Voltage (HV) transmission networks in coordination with high cost distance and differential protection. In closed ring networks more than one source is permanently connected to each substation using a three circuit breaker arrangement (two cable feeder breakers with unit protection and a transformer feeder breaker with over current and earth fault). In the case of an MV cable fault, only the two breakers at each end of the faulty cable trip and no customers are disconnected[2].

This system requires greater protection coordination than above arrangements and has the lesser voltage fluctuations at the customer terminals and high reliability.

1.2.4. Interconnected network arrangement

In interconnected network the ring is energized by two or more generating stations. This requires very high protection coordination such as distance and differential protection due to distributed generation stations and complex power flow analysis. Pilot wire system is required for the communication and coordination between protection equipment. So the initial cost is very high.

1.3. Reliability

The main task of electric power systems and system operators is to provide their customers with a reliable and affordable supply of electricity [5]. Reliability is defined by the International Electrotechnical Commission (IEC) as "the ability to perform a required function under given conditions for a given time interval"[6]. Reliability of the electric power system (EPS) can be increased by either shortening the duration of the interruptions of the power supply or by lowering the frequency by which interruptions occur [7]. The probability that a component in the system will fail is generally increased when the number of components rises. By introducing alternative paths and reserve capacity, reliability can be increased [5].

Ceylon Electricity Board (CEB) uses the SAIFI (System Average Interruption Frequency Index) and SAIDI (System Average Interruption Duration Index) to measure the reliability of the EPS.

For n load points N being the number of customers connected to a load point and F being the number of supply interruptions per year for the load

$$\mathrm{SAIFI} = \frac{\sum_{i=1}^{n} N_i}{N_T} \text{per year}$$

For n load points N being the number of customers connected to a load point and U being the duration of supply unavailability for the load in minutes per year.

$$\mathrm{SAIDI} = \frac{\sum_{i=1}^{n} U_i N_i}{N_T} \text{minutes/year}$$

1.4. Scope and Aim

This thesis is focused on analyzing closed loop operation to NOP ring operation in panel substations and its impact on reliability improvement, energy saving, voltage improvement and extra energy served in the Colombo City (CC) distribution system. The results are used to propose development that can be used in the general case of the MV distribution system in Colombo City.

Available statistics from CC Planning & Development branch and Operations branch are used as inputs in the models to provide a high correlation between the models and reality. In considering the consistent nature of the CC distribution system, ring system Primary Substation F (PSSF) was considered for simulations and evaluation for closed loop and open loop operation.

Three arrangements used in closed loop operation were paralleling of feeders of same substation, paralleling of two substations and paralleling of three substations. These criteria are presented for different cases that are applicable in the ring system. The simulations were carried out on Matlab for normal load flow and faulty conditions for distribution system. The costs of the investments as well as the resulting implications were compared.

Chapter 02

Background

2.1. Colombo City Distribution Network

Power distribution of Colombo 1 to Colombo 15 is carried out by Colombo City Office. Open loop ring network arrangement is used in the distribution network to improve the system reliability. It consists of the 11kV MV distribution network and 400V Low Voltage (LV) distribution network. LV distribution network is governed by the four areas defined as Colombo North, Colombo West, Colombo East and Colombo South. Most of the LV distribution network is covered through underground cables except some areas under Colombo North.

MV distribution network of the Colombo City is totally covered through underground cables of PILC or XLPE. MV operations are monitored and controlled by the Operation Engineer at Colombo City Control Centre (CCCC) and the work orders are forwarded to field units. It mainly consists of nine primary substations, 300 radial and ring substations and around 1400 satellite substations.

2.1.1. Primary substation

Primary substations are fed with 132kV or 33 kV lines from Kolonnawa Grid Substation, Kelanithissa Grid Substation and Pannipitiya Grid Substation through Dehiwala primary substation. Primary substations A, C, E, F and I transform 132kV to 11 kV, while primary substations B, D, G and H transform 33kV to 11kV. Line protection is used for HV lines and busbar protection and transformer protection are used in Primary substations. IDMT overcurrent, IDMT earth fault, instantaneous over current and earth fault protection are implemented for the outgoing 11kV feeders of primary substations. Active power usage, reactive power usage and current are measured in these feeders and radial substations are fed with these feeders.

2.1.2. Radial & ring substations

All the radial substations consist of distribution panels to feed the consumers or to redistribute the supply to ring substations and satellite substations. Ring substations are mainly panel substations completing the ring network around the primary in between the radial substations. These MV distribution panels consist of IDMT over current, earth fault, instantaneous over current and earth fault protection for tripping. Voltage and current of the incoming feeders are measured while current is measured in the remaining feeders.

2.1.3. Satellite substation

Satellite substations mainly consist of RMUs which provide a T-off for the distribution transformers. These satellite substations generate a ring extending from one panel substation to another through a series of connected RMUs. LBSs are available on both sides of the ring and the load side of the RMU.

There are no specific rules for the differentiation between ring substation and satellite substation as there are occasions where RMUs are used for the completion of the ring connecting the radial substations as well as occasions where panel substations are used in satellites locations to cater the increasing demand needs of the consumers.

2.2. SCADA System

Supervisory Control and Data Acquisition (SCADA) system was introduced to Colombo City under CCEDDP and handed over for operation on July 2012. This has greatly eased monitoring and controlling of the MV distribution system.

Remote terminal units are placed to acquire the required data from primary, radial, ring and satellite substations. Fiber optic network was established for the communication between CCCC, primary, radial, ring and some satellite substations. Some satellite substations use a lease line connection for the communication with SCADA system through primary substation.

Operator of the SCADA system can monitor the status of circuit breakers, isolators and earth switches of distribution panels and LBS of RMUs. It also indicates available protection alarms, active power, reactive power, current, voltage of distribution panels and transformer tap positions and operation mode. It also provides the capability to remotely operate the breaker, isolator and tap positions.

2.3. SynerGEE Electric 3.7

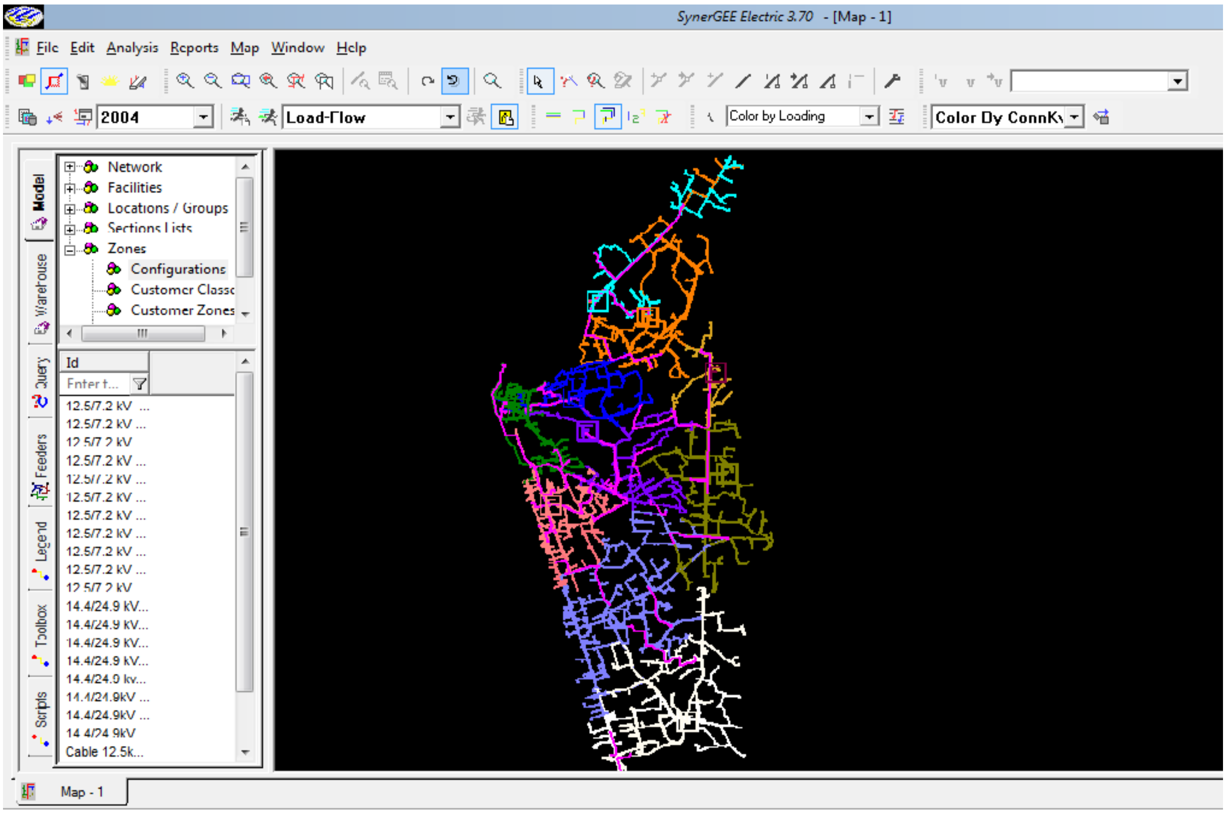


Figure 2.1: Overview of SynerGEE with ColomboCity distribution network

SynerGEE is a tool used for modeling and analyzing of the distribution networks. SynerGEE® Electric is a software package developed by Advantica that simulates, analyzes, and plans power distribution feeders, networks, and substations. The package is a modular collection of tools built on a by-phase simulation engine. The simulation engine is an object-oriented design that consists of highly detailed models for power system devices such as lines, transformer banks, regulator banks, switched capacitors, active generators, and others. The models are built to reflect the actual construction of real power system equipment [3].

2.3.1. Growth factor

SynerGEE can simulate load growth over time for analysis purposes. When this type of simulation is used no permanent changes are made to the load values in your model. The growth is merely simulated. Load growth can apply to distributed and/or spot loads [3].

2.3.2. Loop creation

In general, SynerGEE is oriented for use with radial distribution systems. However, it has a variety of features in place to handle looped situations, including transmission-style network analysis tools.

Preferences must be set up to allow loop creation. Otherwise, simulator will recognize looped situations and prevent you from creating them. Certain analysis types, such as contingency analysis and reliability analysis cannot operate on looped systems.

Chapter 03

Closed Loop Operation

3.1. Identical Transformers of Same Primary Substation

Transformers in the same primary substation can be operated in parallel to share the load on the MV voltage buses, if the following requirements are achieved

- Polarity and phase sequence must be the same.
- Transformers should be identical with similar turn ratios, percentage impedance and same kVA rating.
- Both transformers are fed with single feeder to ensure same high end voltage.
- Automatic Voltage Regulator (AVR) should have the capability to function as Master/Follower.
- Differential Protection is operated for transformers and busbars to ensure the isolation of the faulty parts from remaining system. If a fault occurs only the relevant area of protection marked in the Figure 3.1 will trip.

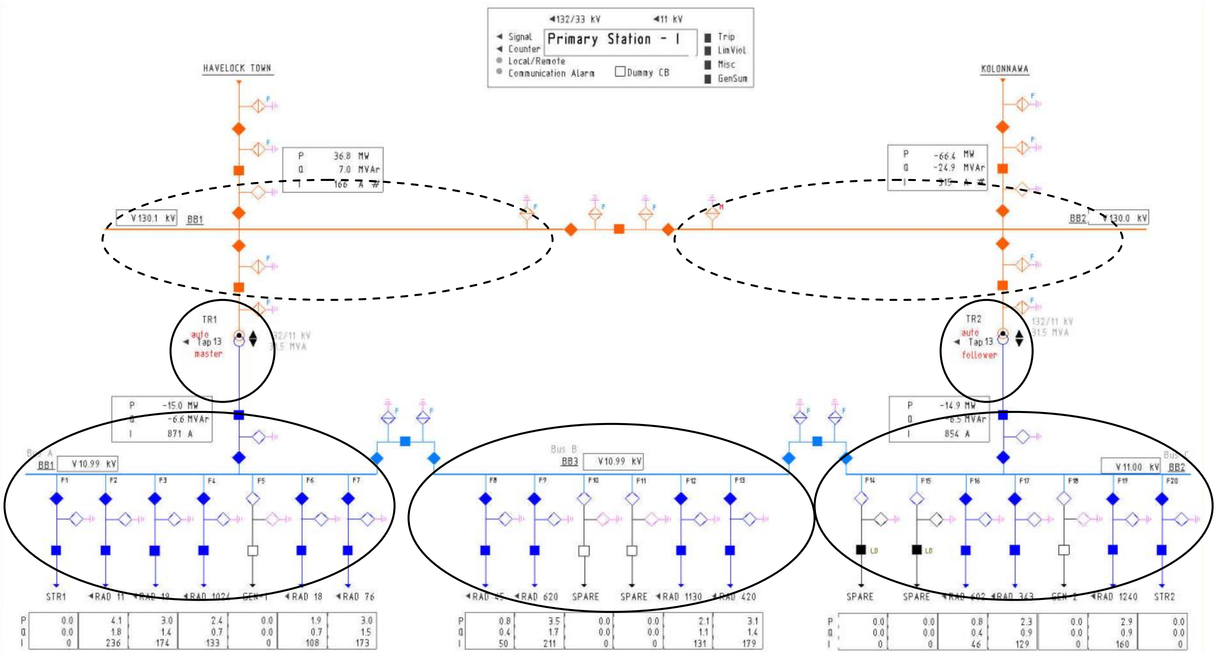


Figure 3.1:Parallel operation of PSS-I

Currently in Colombo City transformers in primaries A, B, C, D and I are operated parallel to cater the load requirement. Two identical transformers of Primaries E, F, G and H can also be operated in parallel. A third transformer was later installed and do not possess the Master/Follower configuration in tandem with the other two.

3.1.1. Equations for paralleling transformers

For a transformer to be parallel it must have same polarity, phase sequence and phase angle shift. Identical transformers should have equal turns ratio, percentage impedance, X/R ratio and kVA [12]

I_1 = load current from transformer 1

I_2 = load current from transformer 2

Z_1 = Percentage impedance of transformer 1

Z_2 = Percentage impedance of transformer 2

I_L = total load current

kVA_1 = kVA rating of transformer 1

kVA_2 = kVA rating of transformer 2

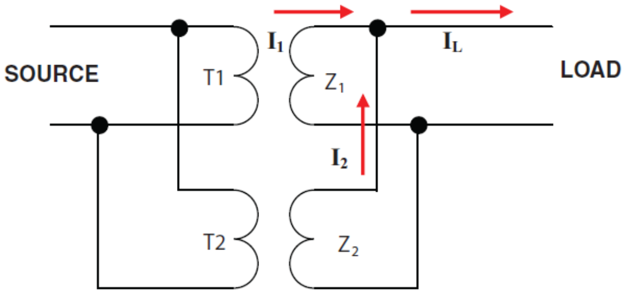


Figure 3.2:Typical single phase transformer[12]

Loading is shared based on the following equations. Therefore the load is shared equally between the two transformers[17].

$$kVA_1 = \frac{kVA_1/\%Z_1}{kVA_1/\%Z_1 + kVA_2/\%Z_2} \times kVA_L$$

$$kVA_2 = \frac{kVA_2/\%Z_2}{kVA_1/\%Z_1 + kVA_2/\%Z_2} \times kVA_L$$

3.1.2. Same polarity

Polarity of transformer means the instantaneous direction of induced emf in secondary. If the instantaneous directions of induced secondary emf in two transformers are opposite to each other when same input power is fed to both of the transformers, the transformers are said to be in opposite polarity.

The transformers should be properly connected with regard to their polarity. If they are connected with incorrect polarities then the two emfs, induced in the secondary windings which are in parallel, will produce a short circuit. Transformers operating in parallel should have the same polarity, otherwise huge circulating current flows through the secondary side of the transformers but no load will be fed from these transformers [17].

3.1.3. Same phase sequence

The phase sequence of line voltages of both the transformers must be identical for parallel operation of three-phase transformers. If the phase sequence is incorrect, pair of phases will get short-circuited for every cycle[17].

3.1.4. Same phase angle shift

The transformer windings can be connected in a variety of ways which produce different magnitudes and phase displacements of the secondary voltage. All the transformer connections can be classified into distinct vector groups.

- Group 1: Zero phase displacement (Yy0, Dd0, Dz0)
- Group 2:180° phase displacement (Yy6, Dd6, Dz6)
- Group 3: -30° phase displacement (Yd1, Dy1, Yz1)
- Group 4: +30° phase displacement (Yd11, Dy11, Yz11)

In order to have zero relative phase displacement of secondary side line voltages, the transformers belonging to the same group can be paralleled [17].

3.2. Radial & Ring Substations of Same Primary Substation

Generally large scale bulk suppliers are connected to the ring arrangement to provide higher reliability. If a radial cable tripped due to earth fault condition, it is to be isolated and the supply is to be restored through ring cables available for secondary feeding arrangements by closing the NOP. This will cause a temporary supply interruption for the consumer.

Ring feeding arrangement with NOP allows the protection coordination to operate under radial feeding principles with highest fault current and coordinating time interval at the feeding end.

Pilot wire differential unit protection schemes have traditionally been used in MV closed ring applications. They provide fast (<150 ms) fault clearance times by tripping both breakers at the end of each zone[2]. The differential principle is based on the comparison of the current magnitudes at each end of the zone. As the relays are distant apart, metallic pilot wires provide the necessary communication link between them. These have to be laid at the same time as the MV cable[2]. So the cost of installation is considerably high compared to directional protection.

Directional protection requires a voltage source as a reference which is normally available for incoming feeders or bussection of ring/radial substations. The principle of operation is based on the "comparison" of the fault current direction at each end of the protected feeder to establish if the fault is outside or inside the zone. The ring feeder circuit breakers are equipped with directional over current and earth fault relays capable of giving independent "start" and time delayed outputs for "forward" or "reverse" directions[2]. Minimum required number of directional relays is double the number of cables on the loop.

- Two parallel feeders to radial substation from Primary – four directional relays
- Two Substation loop – six directional relays
- Three Substation loop – eight directional relays
- Four Substation loop – ten directional relays

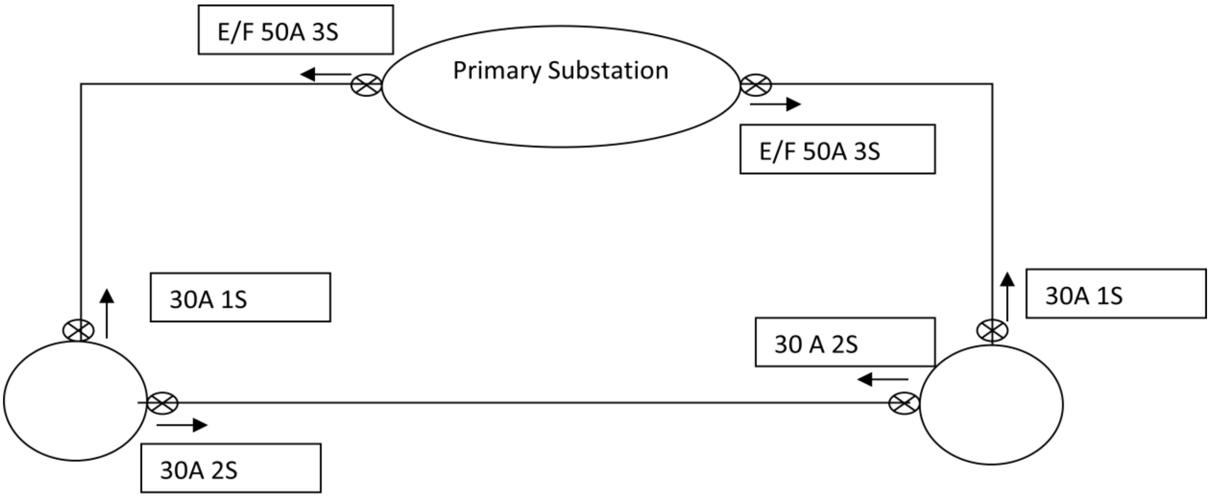


Figure 3.3: Two substations paralleled with directional relays

3.3. Satellite Substations of Same Primary Substation

The directional elements have IDMT characteristics to allow co-ordination with the MV/LV transformer protection. The RMUs in the protected zone would require directional fault passage indicators to facilitate the identification of the faulty section. Closed rings could be achieved by connecting two feeders from the same primary substation and installing three sectionalizing circuit breakers, effectively creating four unit protected zones[2]. Several RMUs can be included within the protected zone provided that discrimination can be achieved with the tee-off transformer protection[2].

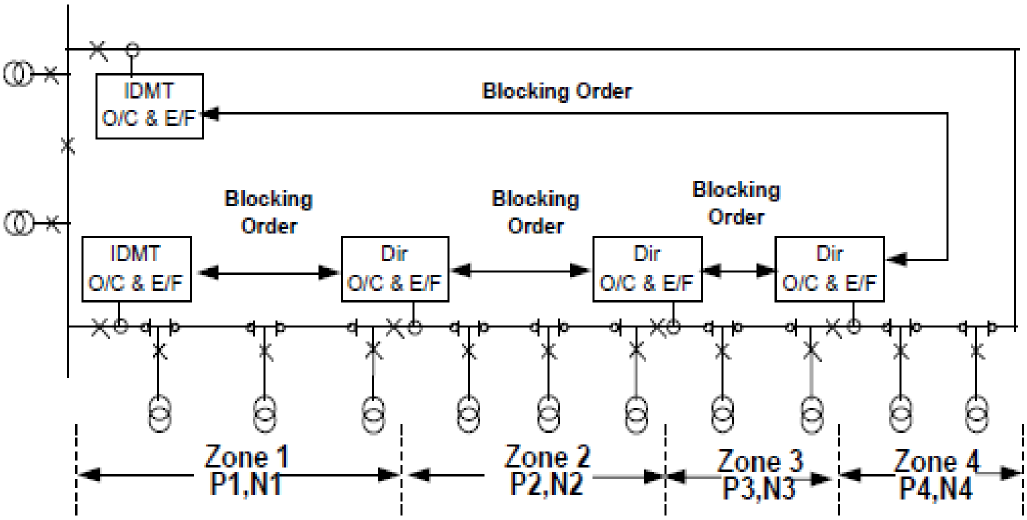


Figure 3.4: Closed ring with 3 sectionalizing points with directional logic sensitivity[2]

Relay based RMUs with directional IDMT protection with ability to send and receive blocking signal needed to be used as shown in the figure 3.3.The blocking signal is automatically removed 200ms after a trip to provide backup in case the downstream breaker fails to clear the fault. As the relays are a distance apart, a communication channel is required to send the blocking signal[2]. It is clearly noticeable that the cost associated with the above is unlikely to be feasible as it requires a number of changes to the existing system.

3.4. Non-identical Transformers of Same Primary Substations

Transformers are suitable for parallel operation when their turn ratios, percent impedances, and X/R ratios are the same. Connecting transformers when one or more of these parameters are different results in either circulating currents or unwanted current division. Both of these situations lower the efficiency and reduce the maximum amount of load the combined transformers can carry[12].

Typically, transformers should not be operated in parallel when:

- The division of load is such that, with the total load current equal to the combined kVA rating of the transformers, one of the transformers is overloaded.
- The no-load circulating currents in any transformer exceed 10% of the full load rating.

- The combination of the circulating currents and full load current exceed the full load rating of either transformer.

From the list above, the circulating currents represent the current flowing at no load in the high and low voltage windings, excluding exciting currents. Full load current is the current flowing in the transformer with a load connected absent of exciting and circulating currents[12].

Different types of transformer can be operated in parallel with continuous supervision for overloading and circulating current conditions by active and reactive power flow monitoring. Behavior for paralleling of transformer of different conditions is discussed.

3.4.1. Equal turn ratio, percentage impedance and unequal kVA

Sometimes two transformers with different kVAs and the same percent impedances are connected to one common bus. In this situation, the current division causes each transformer to carry its rated load. There will be no circulating currents because the voltages (turn ratios) are the same [17]. Even though there are different kVA ratings on transformers connected to one common load, that current division causes each transformer to only be loaded to its kVA rating[12]

3.4.2. Equal turn ratio, kVA and unequal percentage impedance

This is common when budget constraints limit the purchase of a new transformer with the same parameters. It is needed to understand that the current divides in inverse proportions to the impedances, and larger current flows through the smaller impedance. Thus, the lower percent impedance transformer can be overloaded when subjected to heavy loading while the higher percent impedance transformer will be lightly loaded.

3.4.3. Equal percentage impedance, kVA and unequal turn ratio

Small differences in voltage cause a large amount of current to circulate. Circulating currents do not flow on the line and they cannot be measured if monitoring equipment is upstream or downstream of the common connection points[17].

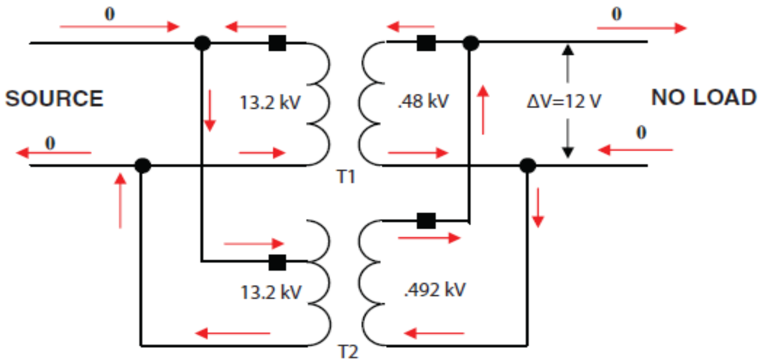


Figure 3.5: Single phase diagram with circulating currents for unequal turn ratio [12]

To calculate the circulating currents, the difference in ratios must be expressed in the percentage of the normal ratio. The circulating current is obtained by dividing this value by the sum of the impedances of the two transformers. This would be the total impedance through which the circulating current is flowing[12].

$$\%I_c = \frac{\%\Delta V \times 100}{\sqrt{(\%R' + k\%R'')^2 + (\%Z' + k\%Z'')^2}}$$

Where

$\%I_C$ = circulating current in the transformers in percentage of the rated current

%R’, %Z’, %R’’, %Z’’ are the percentage resistance and the reactance based on the X/R ratio on units kVA’ and kVA’’.

k = kVA’/kVA’’

ΔV = Different in voltage ratio expressed in percentage of normal [12]

It is clearly seen that circulating currents depend on the voltage difference created by the tap position. So it is of great importance that the tap positions were maintained same to achieve same voltages on secondary sides of the transformers or maintained to minimize the ΔV in the secondary sides of the transformers.

3.4.4. Different X/R ratio

A difference in the ratio of the reactance value to resistance value of the per unit impedance results in a different phase angle of the currents carried by the two paralleled transformers; one transformer will be working with a higher power factor and the other with a lower power factor than that of the combined output. Hence, the real power will not be proportionally shared by the transformers[17].

3.5. Transformers of Different Primary Substations

The standard procedure in CEB is a common earthing point for all the transformers of that primary substation. Paralleling of transformers in different primary substations creates multiple earthing points in the MV network. This could create unexpected current fluctuations for earth fault conditions. Therefore system behavior has to be analyzed for earth fault conditions under multiple earthing point networks before paralleling of transformers in different substations.

Chapter 4

Load Flow Analysis

4.1. Selection of PSSF

Hourly average CC demand for the month of December was taken from the Colombo City. Weekday load curve was calculated by averaging the values of weekdays from 3rd of December 2014 to 19th of December 2014. Weekend load curve was calculated by averaging 6th, 7th, 13th, 14th, 20th, and 21st of December 2014.

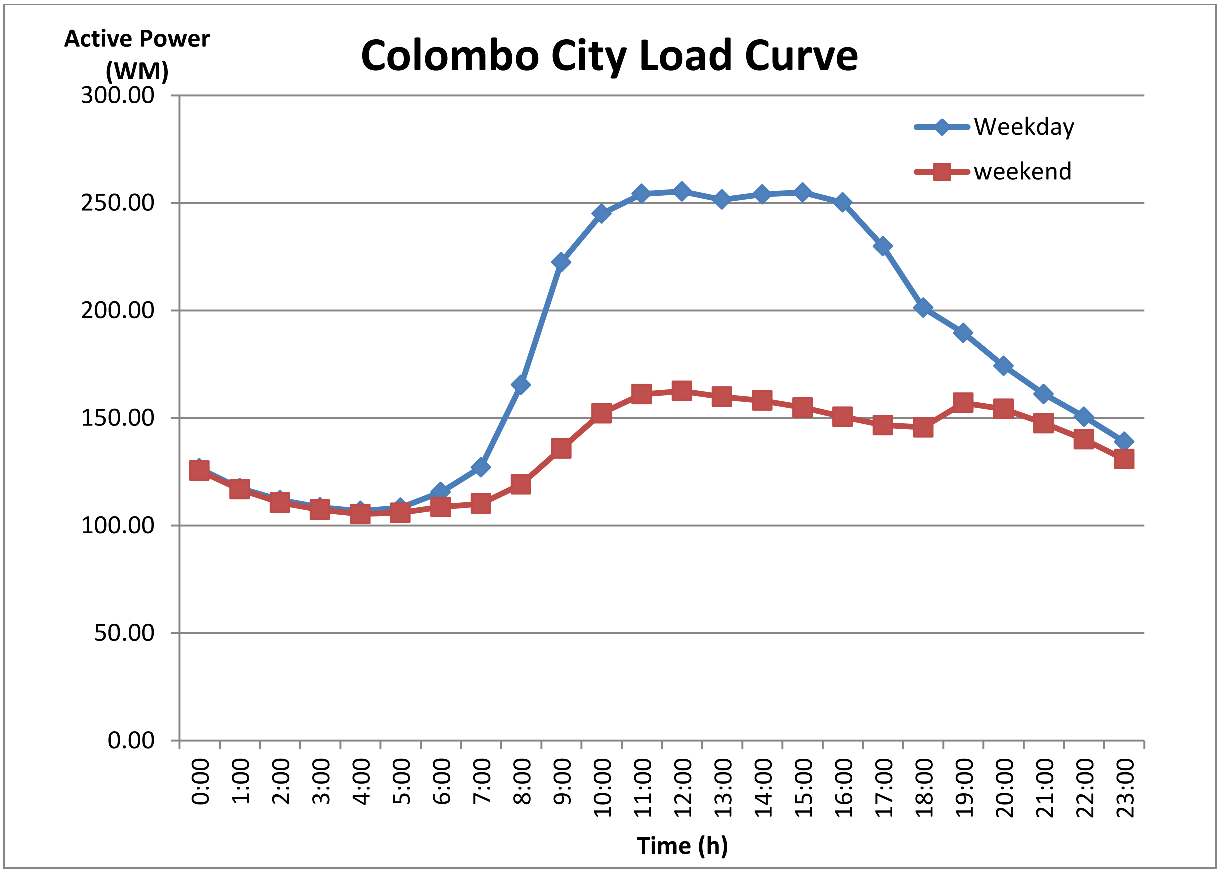


Figure 4.1: Colombo City load curve

Hourly average was calculated for the Primary Substation F demand. It was noticeable that the daily demand variation of the Colombo City is similar to the daily load variation of the primary substation F. For this study primary substation F was taken for analysis on behalf of Colombo City. Ratio of demand variation between Colombo City and PSSF for each hour for weekdays and weekends is shown in the table 4.1.

Time	Colombo City		PSS-F		ratio CC/PSS-F	
	Weekday	weekend	Weekday	Weekend	Weekday	Weekend
0:00	126.53	125.51	15.39	15.56	8.22	8.06
1:00	117.35	116.83	14.32	14.51	8.19	8.05
2:00	111.86	110.65	13.73	13.79	8.15	8.03
3:00	108.46	107.32	13.29	13.32	8.16	8.06
4:00	106.73	105.31	13.06	12.96	8.17	8.12
5:00	108.29	105.92	13.51	13.11	8.01	8.08
6:00	115.50	108.57	14.79	13.47	7.81	8.06
7:00	127.08	110.20	19.89	14.52	6.39	7.59
8:00	165.44	119.20	29.44	16.69	5.62	7.14
9:00	222.39	135.72	35.76	19.21	6.22	7.06
10:00	244.96	152.19	38.32	21.30	6.39	7.14
11:00	254.21	161.02	39.42	22.16	6.45	7.27
12:00	255.30	162.56	39.67	22.25	6.44	7.31
13:00	251.49	159.83	39.27	21.52	6.40	7.43
14:00	254.00	158.06	39.42	21.05	6.44	7.51
15:00	254.87	154.87	39.33	20.40	6.48	7.59
16:00	250.19	150.57	37.75	19.81	6.63	7.60
17:00	229.82	146.69	32.49	19.14	7.07	7.67
18:00	201.18	145.64	27.69	19.04	7.27	7.65
19:00	189.53	157.05	23.56	19.41	8.05	8.09
20:00	174.18	154.18	21.02	18.96	8.29	8.13
21:00	161.12	147.62	19.24	18.06	8.37	8.17
22:00	150.59	140.08	17.94	17.14	8.39	8.17
23:00	138.96	130.86	16.59	16.03	8.38	8.17

Table 4.1: Ratio and Load details of CC and PSSF

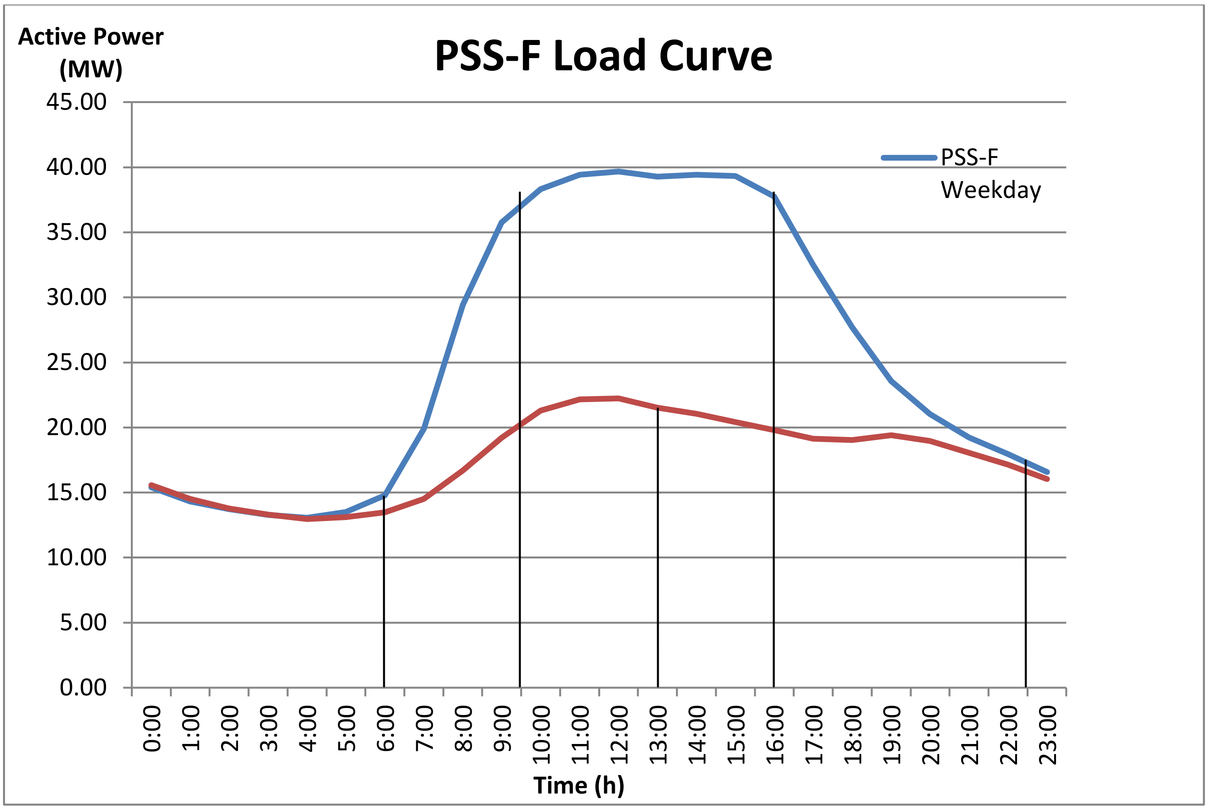


Figure 4.2: PSSF load curve with time zones

It is clearly noticeable from the Figure 4.2 that it consists of a longer high peak load on weekdays and shorter lower peak load on weekends. Both weekdays and weekends have a similar very low base demand.

Three different time zones were defined as peak load, off-peak load and base load for weekdays and weekends based on the demand variation as in the table 4.2. The average ratio of active power between Colombo City to PSSF and the average active power of PSSF for each time zone are also included in the table 4.2.

State		Time zone	Average ratio CC:PSS-F	PSSF Active power (MW)
Weekday	Peak load	10.00-16.30	6.46	39.73
	Off-peak load	16.30-23.00 & 06.30-10.00	6.93	25.23
	Base load	23.00-06.30	7.33	13.05
Weekend	Peak load	10.00-13.30	7.29	22.22
	Off-peak load	13.30-23.00 & 06.30-10.00	7.60	18.52
	Base load	23.00-06.30	7.76	13.05

Table 4.2: Time zones defined based on load variation

4.2. Steady State Analysis of PSSF

Using the load growth functionality in SynerGEE the growth factors were assigned to scale down the demand assigned to loads in SynerGEE to match with average demand for different time zones. Load flow analysis was carried out for radial and ring arrangements using SynerGEE 3.7for different time zones defined in the Table 4.2. Growth factor was changed to simulate the network for each demand in different time zones.

$$\text{GrowthFactor} = \frac{\text{Demand for the time zone}}{\text{Demand in SynerGEE for zero growth}}$$

Based on the simulated results active power loss reduction ($P_{L,Reduction}$), extra active power served to the loads (P_{Served}) and reactive power saved is calculated (Q_{Saved}).

Active power loss reduction is calculated as

$$P_{L,Reduction} = P_{L,radial} - P_{L,parallel}$$

Extra active power served to the load is calculated as

$$P_{Served} = (P_{D,parallel} - P_{L,parallel}) - (P_{D,radial} - P_{L,radial})$$

Reactive Power saved is calculated as

$$Q_{Saved} = Q_{D,radial} - Q_{D,parallel}$$

4.2.1. Weekday peak load analysis

Simulation was carried out after setting the growth factor to 0.82 for the demand of 39.73MW. Table 4.3 was constructed based on the feeder summary details for weekday peak loads.

Feeders	Load		Demand (kW)		Demand (kVar)		Current (A)		Loss (kW)	
	kW	kVar	Radial	Ring	Radial	Ring	Radial	Ring	Radial	Ring
PSSF to 0009	2473	1092	2478	2427	1047	1034	141	138	5	5
PSSF to 0116	1401	608	1402	1454	595	608	80	83	1	1
PSSF to 1428	2156	946	2161	2161	914	914	123	123	5	5
PSSF to 1494-I	2068	906	2070	2070	873	873	118	118	2	2
PSSF to 1494-II	2253	985	2255	2255	954	954	129	129	2	2
PSSF to 0176	1820	787	1821	1821	773	773	104	104	1	1
PSSF to 0252	0	0	0	0	-29	-29	2	2	0	0
PSSF to 0703-III	1050	476	1052	2223	442	831	60	125	2	3
PSSF to 0346	3474	1549	3487	2316	1469	1079	199	134	13	11
PSSF to 0986-I	1998	949	2006	1240	904	680	115	74	8	3
PSSF to 0351	991	429	991	1758	421	643	57	98	0	3
PSSF to 0405	1772	756	1772	1841	755	801	101	105	0	0
PSSF to 0043	910	405	911	842	384	337	52	48	0	0
PSSF to 0054	4551	2029	4589	4589	1930	1930	261	261	38	38
PSSF to 0624	2082	938	2101	2101	883	883	120	120	19	19
PSSF to 0703-I	896	385	896	1705	381	723	51	97	0	1
PSSF to 0703-II	2530	1080	2532	1723	1078	735	144	98	1	1
PSSF to 0008	2907	1371	2928	3462	1324	1495	169	198	21	22
PSSF to 0083	1927	846	1931	1397	816	645	110	81	4	2
PSSF to 0986-II	2334	1113	2345	2345	1055	1055	135	135	11	11
PSSF Total	**39592**	**17651**	**39727**	**39729**	**16967**	**16965**			**135**	**131**

Table 4.3: Weekday peak load analysis

For weakday peak load

$P_{L,Reduction}$ = 135 -131 = 4 kW

P_{Served} = (39729-131)-(39727-135) = 6kW

Q_{Saved} = (16967-16965) = 2kVar

4.2.2. Weekday off-peak load analysis

Simulation was carried out after setting the growth factor to 0.52 for the demand of 25.23MW. Table 4.4 was constructed based on the feeder summary details for weekday off-peak loads.

Feeders	Load		Demand (kW)		Demand (kVar)		Current (A)		Loss (kW)	
	kW	kVar	Radial	Ring	Radial	Ring	Radial	Ring	Radial	Ring
PSSF to 0009	1572	694	1574	1541	647	640	89	88	2	2
PSSF to 0116	890	386	890	923	372	379	51	52	0	0
PSSF to 1428	1370	601	1373	1373	568	568	78	78	2	2
PSSF to 1494-I	1314	576	1314	1315	541	542	75	75	1	1
PSSF to 1494-II	1431	626	1432	1432	594	593	81	81	1	1
PSSF to 0176	1156	500	1157	1157	485	485	66	66	1	1
PSSF to 0252	0	0	0	0	-29	-29	2	2	0	0
PSSF to 0703-III	667	302	668	1411	267	505	38	79	1	1
PSSF to 0346	2209	985	2214	1472	899	662	125	85	5	4
PSSF to 0986-I	1271	604	1274	788	554	419	73	47	3	1
PSSF to 0351	629	272	630	1116	264	398	36	62	0	1
PSSF to 0405	1125	480	1125	1169	478	505	64	67	0	0
PSSF to 0043	578	257	578	535	236	209	33	30	0	0
PSSF to 0054	2900	1293	2915	2915	1177	1177	165	165	15	15
PSSF to 0624	1326	598	1334	1334	536	536	75	75	8	8
PSSF to 0703-I	569	244	569	1083	241	458	32	62	0	0
PSSF to 0703-II	1607	686	1608	1094	683	466	92	62	1	0
PSSF to 0008	1851	873	1860	2199	820	926	107	125	8	9
PSSF to 0083	1225	538	1227	887	506	400	70	51	2	1
PSSF to 0986-II	1486	708	1490	1490	645	645	85	85	4	4
PSSF Total	**25178**	**11225**	**25232**	**25233**	**10485**	**10484**			**54**	**52**

Table 4.4: Weekday off-peak load analysis

For weakday off-peak load

$P_{L,Reduction}$ = 54 -52 = 2 kW

P_{Served} = (25233-52)-(25232-54) = 3kW

Q_{Saved} = (10485-10484) = 1kVar

4.2.3. Weekend peak load analysis

Simulation was carried out after setting the growth factor to 0.46 for the demand of 22.22MW. Table 4.5 was constructed based on the feeder summary details for weekend off-peak loads.

Feeders	Load		Demand (kW)		Demand (kVar)		Current (A)		Loss (kW)	
	kW	kVar	Radial	Ring	Radial	Ring	Radial	Ring	Radial	Ring
PSSF to 0009	1385	612	1387	1359	564	559	79	77	2	2
PSSF to 0116	784	340	785	813	327	332	45	46	0	0
PSSF to 1428	1208	530	1209	1209	496	496	69	69	2	2
PSSF to 1494-I	1158	507	1158	1158	472	473	66	66	1	1
PSSF to 1494-II	1261	551	1262	1262	520	519	72	72	1	1
PSSF to 0176	1019	441	1019	1019	425	425	58	58	0	0
PSSF to 0252	0	0	0	0	-29	-29	2	2	0	0
PSSF to 0703-III	588	267	589	1243	231	437	33	69	1	1
PSSF to 0346	1947	868	1951	1297	782	576	110	74	4	3
PSSF to 0986-I	1121	532	1123	695	482	365	64	41	2	1
PSSF to 0351	555	240	555	984	232	348	32	55	0	1
PSSF to 0405	992	423	992	1030	421	444	57	59	0	0
PSSF to 0043	510	227	510	471	205	183	29	27	0	0
PSSF to 0054	2558	1140	2569	2569	1022	1022	145	145	12	12
PSSF to 0624	1169	527	1175	1175	465	465	66	66	6	6
PSSF to 0703-I	502	215	502	954	212	403	29	54	0	0
PSSF to 0703-II	1416	605	1417	964	601	410	81	55	0	0
PSSF to 0008	1632	770	1639	1938	716	809	94	110	6	7
PSSF to 0083	1080	474	1081	782	442	349	61	45	1	1
PSSF to 0986-II	1310	624	1313	1313	560	560	75	75	3	3
PSSF Total	**22194**	**9895**	**22236**	**22236**	**9146**	**9145**			**42**	**41**

Table 4.5: Weekend peak load analysis

For weekend peak load

$P_{L,Reduction}$ = 42-41 = 1 kW

P_{Served} = (22236-41)-(22236-42) = 1kW

Q_{Saved} = (10485-10484) = 1kVar

4.2.4. Weekend off-peak load

Simulation was carried out after setting the growth factor to 0.38 for the demand of 18.52MW. Table 4.6 was constructed based on the feeder summary details for weekend off-peak loads.

Feeders	Load		Demand (kW)		Demand (kVar)		Current (A)		Loss (kW)	
	kW	kVar	Radial	Ring	Radial	Ring	Radial	Ring	Radial	Ring
PSSF to 0009	1145	506	1146	1122	458	454	65	64	1	1
PSSF to 0116	648	281	648	671	267	271	37	38	0	0
PSSF to 1428	998	438	999	999	404	404	57	57	1	1
PSSF to 1494-I	956	419	957	957	384	385	54	54	0	0
PSSF to 1494-II	1042	455	1042	1042	424	423	59	59	0	0
PSSF to 0176	842	364	842	842	349	349	48	48	0	0
PSSF to 0252	0	0	0	0	-29	-29	2	2	0	0
PSSF to 0703-III	486	220	486	1027	185	350	27	57	0	1
PSSF to 0346	1609	718	1612	1072	630	464	91	61	3	2
PSSF to 0986-I	926	440	928	574	389	296	53	34	2	1
PSSF to 0351	458	198	458	812	190	283	26	45	0	1
PSSF to 0405	819	350	819	851	348	365	47	49	0	0
PSSF to 0043	421	187	421	389	166	149	24	22	0	0
PSSF to 0054	2115	943	2123	2123	821	821	119	119	8	8
PSSF to 0624	967	436	971	971	372	372	55	55	4	4
PSSF to 0703-I	414	178	414	788	174	332	24	45	0	0
PSSF to 0703-II	1170	500	1170	796	496	338	67	45	0	0
PSSF to 0008	1349	636	1354	1601	582	657	77	91	4	5
PSSF to 0083	892	392	893	646	359	284	51	37	1	0
PSSF to 0986-II	1083	516	1085	1085	451	451	62	62	2	2
PSSF Total	**18341**	**8177**	**18370**	**18370**	**7418**	**7418**			**28**	**28**

Table 4.6: Weekend off-peak load analysis

For weekend off-peak load

$P_{L,Reduction}$ = 28-28 = 0 kW

P_{Served} = (18370-28)-(18370-28) = 0kW

Q_{Saved} = (7418-7418) = 0kVar

4.2.5. Base load analysis

Simulation was carried out after setting the growth factor to 0.27 for the demand of 13.05MW. Table 4.7 was constructed based on the feeder summary details for weekend off-peak loads.

Feeders	Load		Demand (kW)		Demand (kVar)		Current (A)		Loss (kW)	
	kW	kVar	Radial	Ring	Radial	Ring	Radial	Ring	Radial	Ring
PSSF to 0009	814	359	814	798	311	310	46	45	1	1
PSSF to 0116	460	200	461	477	186	187	26	27	0	0
PSSF to 1428	709	311	710	710	277	277	40	40	1	1
PSSF to 1494-I	680	298	680	680	262	264	38	38	0	0
PSSF to 1494- II	740	324	741	741	292	290	42	42	0	0
PSSF to 0176	598	259	598	598	243	243	34	34	0	0
PSSF to 0252	0	0	0	0	-29	-29	2	2	0	0
PSSF to 0703-III	345	157	346	729	121	231	19	40	0	0
PSSF to 0346	1144	510	1145	762	422	311	64	43	1	1
PSSF to 0986-I	658	313	659	408	261	200	37	24	1	0
PSSF to 0351	326	141	326	577	132	193	18	32	0	0
PSSF to 0405	582	248	582	605	246	256	33	34	0	0
PSSF to 0043	299	133	299	277	112	102	17	15	0	0
PSSF to 0054	1505	671	1509	1509	546	546	84	84	4	4
PSSF to 0624	688	310	690	690	245	245	38	38	2	2
PSSF to 0703-I	294	126	294	560	123	235	17	32	0	0
PSSF to 0703-II	831	355	832	566	351	239	47	32	0	0
PSSF to 0008	960	452	962	1138	397	449	55	64	2	2
PSSF to 0083	634	278	635	459	245	194	36	26	0	0
PSSF to 0986-II	770	367	771	771	301	301	43	43	1	1
PSSF Total	**13039**	**5813**	**13053**	**13053**	**5044**	**5044**			**14**	**14**

Table 4.7: Base load analysis

For base load

$P_{L,Reduction}$ = 14-14 = 0 kW

P_{Served} = (13053-14)-(13053-14) = 0kW

Q_{Saved} = (5044-5044) = 0kVar

4.2.6. Observations

It was noticeable in ring operation that the current is shared through the parallel paths to reduce the losses in the system. This has improved the voltage profile which led to less reactive power usage in the network. Improvement in the voltage has resulted in feeding more active power to the loads. Observation of the analyzed data is summarized in the table 4.8.

State	Power loss reduction (kW)	Extra active power served (kW)	Reactive power saved (kVar)
Weekday Peak load	4	6	2
Weekday Off-peak load	2	3	1
Weekend peak load	1	1	1
Weekend Off-peak load	0	0	0
Base load	0	0	0

Table 4.8: Observations of feeder summary for radial & ring operation

Effect of paralleling is mostly noticeable for cases with high load condition where high current in the feeders causes higher losses and greater voltage reductions. So it is important to consider the loading requirement of the feeders before paralleling as lower loaded feeders are unlikely to give desirable outcomes.

It was noticeable in the data that some feeders (PSSF-0043/PSSF-0405 & PSSF- 0083/PSSF-008) have shared the load in a manner that the feeder with the higher load has increased its load. Current in parallel path is shared based on the impedance of the paths to provide the highest voltage at the paralleling end. So it is important to notice that paralleling of feeders does not always reduce the load in parallel paths with higher load. Parallel operation of PSSF-0043 and PSSF-0405 is used to elaborate the above.

Cable	Impedance (Ω)	Current (A)	Voltage drop (V)	Active power flow (kW)	Reactive Power flow (kVar)
PSSF-0405	0.0107	101	2.750	1772	756
0405-0748	0.1862	0	0	0	0
PSSF-0043	0.0400	52	4.583	910	384
0043-0748	0.1574	7	0.917	61	112

Table 4.9: Voltage drop and Power flow in radial operation for PSSF-0043/PSSF

Cable	Impedance (Ω)	Current (A)	Voltage drop (V)	Active power flow (kW)	Reactive Power flow (kVar)
PSSF-0405	0.0107	105	2.75	1841	803
0405-0748	0.1862	4	0	69	54
PSSF-0043	0.04	48	3.67	842	337
0043-0748	0.1574	3	-0.92	-8	65

Table 4.10: Voltage drop and Power flow in ring operation for PSSF-0043/PSSF

PSSF-0043 cable has higher impedance than the PSSF-0405 cable. Even though higher current is flowing through the cable PSSF-0405 the voltage drop across the cable is lower than that of PSSF-0043 cable. Therefore more power is fed to the load by PSSF-0405 cable to improve the voltage.

Load	Voltage drop	
	Radial	Ring
0405	2.750	2.75
0043	4.583	3.67
0748	5.500	2.75

Table 4.11: Load end voltage drop for radial and ring operation

This condition of increased current flow from the feeder with higher load will not trigger over current as feeders are designed with excessive capacity to bear the adjacent feeders in case of cable faults.

4.3. Reliability Improvement

SynerGEE 3.7 does not have the capability to access the reliability for the closed loop operation [3]. Reliability improvement was calculated based on the number of consumers unaffected by the failure of radial or ring cable due to closed loop operation of the PSSF network.

Failure rate for a ring or radial cable was calculated using the failures occurred in the last year.

$$Failure\ rate\ of\ ring\ or\ radial\ cable\ per\ km$$
$$= \frac{Number\ of\ failures\ in\ ring\ or\ radial\ cables\ in\ CC\ for\ year\ 2014\ (45)}{Total\ length\ of\ ring\ or\ radial\ cables\ in\ CC(235.572km)}$$

Total length of radial and ring cable in Colombo City is 235.572km. 45 ring or radial cable failures were reported for the year 2014[15]. Failure rate of ring or radial cable is 0.1910244 per km.

$$Failure\ rate\ of\ the\ cable$$
$$= cable\ length\ \times Failure\ rate\ of\ ring\ or\ radial\ cable\ per\ km$$

Number of consumers interrupted was calculated based on the number of transformers and bulk suppliers connected to the relevant feeders of PSSF network. Number of consumers connected to a transformer is assumed to be 112[16], which is the value used in CC reliability report.

Cable name	Number affected		
	transformer	Bulk customer	Total consumer
PSSF-0116		2	2
PSSF-0009	22	0	2464
PSSF-0176	1	1	113
PSSF-0008	18		2016
PSSF-0083	2	2	226
0083-0412	2		224
PSSF-1494-1		1	1
PSSF-1494-2		1	1
PSSF-0624	1		112
PSSF-0043	2	1	225
0043-0748	2		224
PSSF-0405	1	2	114
PSSF-0346	9	2	1010
PSSF-703-3			1
PSSF-703-1		1	1
PSSF-703-2		1	1
PSSF-1428	4	2	450
PSSF-0054	30		3360
PSSF-0986-2	1	1	113
0075-986-2	1		112
PSSF-0351		2	2
PSSF-0986-1		1	1
PSSF	96	20	10773

Table 4.12: Affected number of customers due to cable fault

$$\begin{aligned}&The\ number\ of\ avoidable\ consumer\ interruptions\ per\ year\\&\qquad = failure\ rate\ of\ the\ cable\ \times number\ of\ customers\ affected\end{aligned}$$

$$\begin{aligned}&The\ avoidable\ consumer\ minutes\ interrupted\ per\ year\\&\qquad = failure\ rate\ of\ the\ cable\ \times number\ of\ customers\ affected \times time\end{aligned}$$

Time required for the switching of automated feeders after isolating a faulty cable is assumed as three minutes and time required for the operations crew to attend a failure of a non-automated substation is assumed as 60 minutes.

Cable name	Cable length (m)	Failure rate	Time (min)	Number of interrutions per year			Number of minutes interrupted per year		
				Service connection	Important Customer	Total customers	Service connection	Important customer	Total customers
PSSF-0116	192	0.0367	3	-	0.07	0.07	-	0.22	0.22
PSSF-0009	328	0.0627	3	154.38	-	154.38	463.15	-	463.15
PSSF-0176	366								
PSSF-0008	220	0.0420	3	84.72	-	84.72	254.17	-	254.17
PSSF-0083	785	0.1500	60	33.59	0.30	33.89	2,015.38	17.99	2,033.38
0083-0412	572	0.1093	3	24.48	-	24.48	73.43	-	73.43
PSSF-1494-1	1430	0.2732	60	-	0.27	0.27	-	16.39	16.39
PSSF-1494-2	1430	0.2732	60	-	0.27	0.27	-	16.39	16.39
PSSF-0624	495	0.0946							
PSSF-0043	303	0.0579	3	12.97	0.06	13.02	38.90	0.17	39.07
0043-0748	618	0.1181	60	26.44	-	26.44	1,586.63	-	1,586.63
PSSF-0405	70	0.0134	3	1.50	0.03	1.52	4.49	0.08	4.57
PSSF-0346	320	0.0611	3	61.62	0.12	61.74	184.85	0.37	185.22
PSSF-703-3	172	0.0329	3	-	-	0.03	-	-	0.10
PSSF-703-1	185	0.0353	3	-	0.04	0.04	-	0.11	0.11
PSSF-703-2	172	0.0329	3	-	0.03	0.03	-	0.10	0.10
PSSF-1428	442	0.0844							
PSSF-0054	1198	0.2288							
PSSF-0986-2	1692	0.3232							
0075-986-2	1309	0.2501							
PSSF-0351	300	0.0573	3	-	0.11	0.11	-	0.34	0.34
PSSF-0986-1	1691	0.3230	3	-	0.32	0.32	-	0.97	0.97
PSSF				399.70	1.63	401.36	4,621.01	53.13	4,674.24

Table 4.13: Avoided customer interruptions

Improvement of SAIFI and SAIDI is calculated by the following equations.

$$Reliability\ improvement\ (SAIFI) = \frac{Number\ of\ avoidable\ consumer\ interruptions}{Total\ number\ of\ consumers\ in\ PSSF}$$

$$Reliability\ improvement\ (SAIDI) = \frac{Avoidable\ interrupted\ consumer\ minutes}{Total\ number\ of\ consumers\ in\ PSSF}$$

Reliability improvement	service connections	important customer	Total customers
SAIFI (per year)	0.0372	0.0816	0.0373
SAIDI (minutes per year)	0.4298	2.6566	0.4339

Table 4.14: Reliability improvement

Table 4.11 indicates that the reliability improvement for the important customers is higher than the overall reliability improvement. This is due to the fact that most of the important customers are in the ring network operated under closed loop condition.

4.4. Voltage Improvement

Voltages are analyzed in SynerGEE with 120V as the base voltage. The effects of the paralleling are at highest for the high load conditions. So the voltage was analyzed only for the weekday peak load of 39.73MW.

Paralleling of the feeders has improved the lower voltage of the two voltages at the paralleling point and slightly decreases the higher voltage.

Parallel Feeder	Actual Minimum Voltage		Voltage status	Percentage improvement
	Ring	Radial		
PSSF-0009/PSSF-0116	10966	10966	No change	0.000
PSSF-0405/PSSF-0043	10995	10995	Slight improvement	0.008
PSSF-0346/PSSF-0703-3	10910	10907	Slight improvement	0.034
PSSF-0703-II/PSSF-0703-I	10995	10994	Slight improvement	0.017
PSSF-0083/PSSF-0008	10954	10956	Slight reduction	-0.017
PSSF-0351/PSSF-0986-I	10967	10951	Slight improvement	0.151
PSSF-1494-I/PSSF-1494-II	10987	10987	No change	0.000

Table 4.15: Voltage analysis

Paralleling of the feeders has improved the lower voltage of the two voltages at the paralleling point and slightly decreases the higher voltage while slightly increasing the lower voltage at paralleling point. As seen in the table 4.12 one end feeder voltage has reduced. This feeder has a higher voltage at paralleling point than the other, so in paralleling the voltage has slightly decreased while increasing the other feeder’s voltage. This feeder has a long satellite which results in giving a lower voltage at the far end.

4.5. Energy Saving in Colombo City

Energy is saved due to the reduction of losses in the distribution network and extra income is received due to the extra energy served to the end users.

Time Zone	Extra Active Power served (kW)	Active Power saved (kW)	time (h)	PSS-F energy saving per day (kWh)	Ratio CC:PSS-F	energy per day (kWh)	days	Extra energy per year for CC (MWh)
weekday peak demand	6	4	6.5	65	6.46	420.02	240	100.804
weekday off-peak demand	3	2	10	50	6.93	346.56	240	83.174
base demand	0	0	7.5	0	7.33	0.00	240	0.000
weekend peak demand	1	1	3.5	7	7.29	51.00	125	6.375
weekend off-peak demand	0	0	13	0	7.60	0	125	0
base demand	0	0	7.5	0	7.76	0	125	0
Total								190.353

Table 4.16: Energy saving in Colombo City

Assumption was made that the unit cost of the energy to be Rs.12. The number of working days is taken as 20 per month and the remainders were considered to be as weekends. So the total income due to energy saved and extra energy served is 2.284 million rupees.

4.6. Cost Analysis

Total earning due to the closed loop operation of the PSSF is concluded in the Table 4.14.

Time Zone	Active Power served (kW)	Active Power saved (kW)	time (h)	PSS-F energy per day (kWh)	days	Energy per year (MWh)	Income generated and saved (Rs)
weekday peak demand	6	4	6.5	65	240	15.6	187,200
weekday off-peak demand	3	2	10	50	240	12	140,000
base demand	0	0	7.5	0	240	0	0
weekend peak demand	1	1	3.5	7	125	0.875	10,500
weekend off-peak demand	0	0	13	0	125	0	0
base demand	0	0	7.5	0	125	0	0
Total							341,700

Table 4.17: Yearly earnings due to parallel operation in PSSF

Additional improvement required for the closed loop operation of PSSF network is shown in Table 4.15.

Parallel Feeder	Number of directional relay	Number of voltage transformers
PSSF-0009/PSSF-0116	6	2 (available)
PSSF-0405/PSSF-0043	8	3(available)
PSSF-0346/PSSF-0703-3	6	2(available)
PSSF-0703-II/PSSF-0703-I	4	1(available)
PSSF-0083/PSSF-0008	8	3(available)
PSSF-0351/PSSF-0986-I	6	2(available)
PSSF-1494-I/PSSF-1494-II	4	1(available)

Table 4.18: Improvement requirement

The following cost was based on the general quoted prices of the suppliers of MV switch gear. Cost of a MV panel with non-directional O/C and E/F protection is around US$ 11,000.00 and the cost of a MV panel with directional O/C and E/F protection is around USS 11,345.00 for a single panel purchase. So the incremental cost for using directional O/C and E/F relays is around US$345.00. The selling price of US$ is taken from the Central bank exchange rate as 135 rupees per 1 US$.

The simple payback period is

345*135*42/341,700 =5.75 years

So the simple payback period is roughly six years.

4.7. Barriers for Closed Loop Operation

4.7.1. Feeder failures in multiple locations

The existing CC distribution network is not designed to operate in closed loop arrangement. In the existing network, lowest protection setting is set at the furthest end of the cable and the protection setting increases towards the feeding end of the network.

Protection relays of two ends of the cables in closed loop must be replaced with directional relays. Voltage transformer is required in the panel substation for feeding a voltage reference to the directional relay.

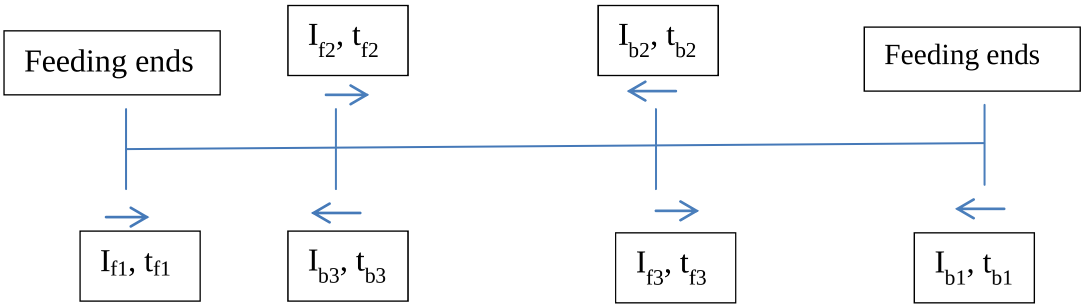


Figure 4.3: Protection coordination for closed loop ring network

$I_{f1}, t_{f1} > I_{f2}, t_{f2} > I_{f3}, t_{f3}$

$I_{b1}, t_{b1} > I_{b2}, t_{b2} > I_{b3}, t_{b3}$

Protection has to be coordinated as indicated in the chapter 5 to avoid nuisance tripping of the network.

4.7.2. Reactive power flow in primary substation

Closed loop operation of cables from different transformers can produce circulation currents in the closed loop network. For a no load condition the circulating current can be calculated by dividing the voltage difference of the secondary side by the total impedance of the current path.

$$I_c = \frac{V_{tr1} - V_{tr2}}{(Z_{tr1} + Z_{tr2} + Z_l)}$$

I_c = circulating current

V_{tr1} = Secondary voltage of the transformer 1

V_{tr2} = Secondary voltage of the transformer 2

Z_{tr1} = Secondary side Impedance of the transformer 1

Z_{tr2} = Secondary side impedance of the transformer 2

Z_l= Total impedances of the cables

Most of the primaries have identical transformers which can be operated in parallel mode with master-follower configuration. The identical transformers fed from same HT bus needs to maintain their tap position equal in return keeping the MV busbar voltage the same. This will avoid circulating currents that create the reactive power flow in the system. Master follower functionality is implemented to ensure that the transformers tap positions are kept the same.

Different types of transformers with the same phase angle and phase rotation can be parallel under supervision as indicated in chapter 2.4. The reactive power flow between transformers has to be continuously monitored and minimized. The tap positions of the transformers must be maintained to minimize the voltage difference between the two MV busbars. Closed loop operation of different types of transformers are not recommended as small changes in voltages may create high circulation currents in the closed loop which could create nuisance over current tripping.

4.7.3. Complexity in operation and maintenance

Supervisory control system is already installed in Colombo City which eases the controlling and monitoring of the network. It provides the limit violation function for current flow of the cables ensuring that overloading shall not occur.

Permit to work is issued after isolation of the cable and panel for the maintenance crew to carry out the maintenance. So the both live side of the network is isolated and grounded, so does not possess any danger to the maintenance crew.

All operations are monitored and controlled by single operation engineer through SCADA system, who makes the required field decisions which ensures a safer operational environment as the decision regarding the MV network are made at a single point.

4.7.4. Extensive loading to one feeder due to failure of other

Due to the failure of one feeder of the closed loop network the other may try to overload due to the resultant loads. This may cause the remaining feeder to be tripped by over current protection.

But network is operated with excess capacity under radial operation to ensure that in case of a failure of one feeder the supply is switched through the other feeders without creating a continuous outage in the system. So the feeders have the capability to cater the resultant load.

$$I_{f1}, I_{f2} \geq \sum_{L=1}^{n} I_L$$

I_{f1}, I_{f2} = Maximum current of feeder 1 and feeder 2 of the closed loop

I_L = Current of the loads in the closed loop network

4.7.5. Variation of zero current position on the closed loop

When a closed loop system is connected with multiple distributed loads, variation of the loads fluctuate the zero current position of the distribution network.

For two feeders feeding the same substation has only single spot load, no zero current fluctuation will occur.

For two substations in closed loop function as two spot loads and the variation of these loads within the following constrains creates a zero current fluctuation in cable between substations.

$$S_{12} \geq \left|\left(S_{p1} + S_{s1}\right) - \left(S_{p2} + S_{s2}\right)\right| \geq 0$$

S_{l2}= Apparent power usage of the cable between substation 1 and substation 2

S_{p1}= Apparent power usage of the cable between primary and substation 1

S_{p2}= Apparent power usage of the cable between primary and substation 2

S_{s1}= Apparent power usage of the loads in substation (radial) 1

S_{s2}= Apparent power usage of the loads in substation (radial) 2

For all other instances zero current position will be at one of the substations.

For three substations in closed loop function as three spot loads and the variation of these loads within creates a zero current fluctuation in cables between substations under following conditions.

$$S_{13} \geq \left|\left(S_{p1} + S_{s1}\right) - \left(S_{23} + S_{s2} + S_{p2} + S_{s3}\right)\right| \geq 0$$

$$S_{23} \geq \left|\left(S_{p1} + S_{s1} + S_{13} + S_{s3}\right) - \left(S_{p2} + S_{s2}\right)\right| \geq 0$$

S_{l3} = Apparent power usage of the cable between substation 1 and substation 3

S_{23} = Apparent power usage of the cable between substation 2 and substation 3

S_{p1} = Apparent power usage of the cable between primary and substation 1

S_{p2} = Apparent power usage of the cable between primary and substation 2

S_{s1}= Apparent power usage of the loads in substation (radial) 1

S_{s2}= Apparent power usage of the loads in substation (radial) 2

S_{s3} = Apparent power usage of the loads in substation (ring) 3

The power loss in the cable is far less in comparison with the loads fed at the substations. So the zero current fluctuation occurs very rarely only in case of above mentioned conditions.

Chapter 05

Protection Coordination

5.1. Non-directional relays

Non directional relays with IDMT over current, definite time over current, IDMT earth fault and definite time earth fault are used to differentiate between the protection zones in NOP ring network. Following time settings are used to create the IDMT protection tripping hierarchy in the network in CC network.

Transformer feeders	– 1000 ms
Primary Bus section	– 850 ms
Primary feeders	– 700 ms
Radial bus section	– 600 ms
Radial feeders	– 500 ms
Ring bus section	– 400ms
Ring feeder	– 300 ms
Satellite feeders	– 100 ms
Bulk consumer	– 100 ms

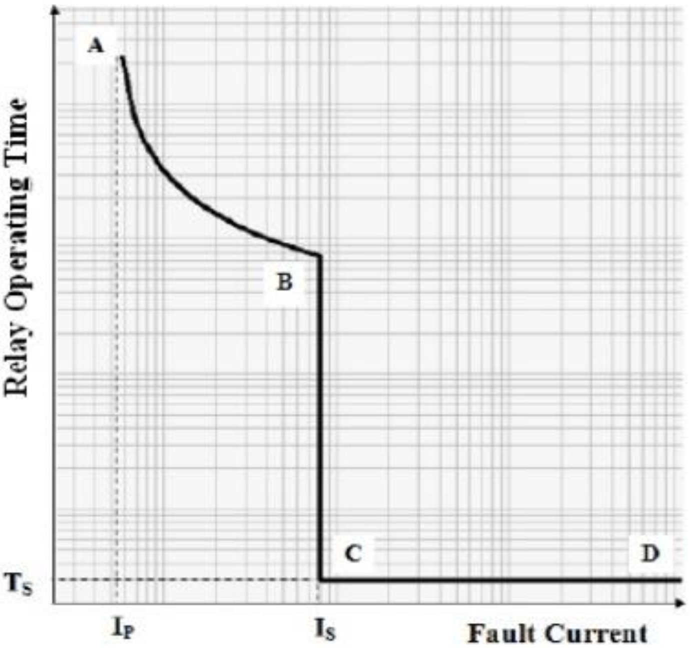


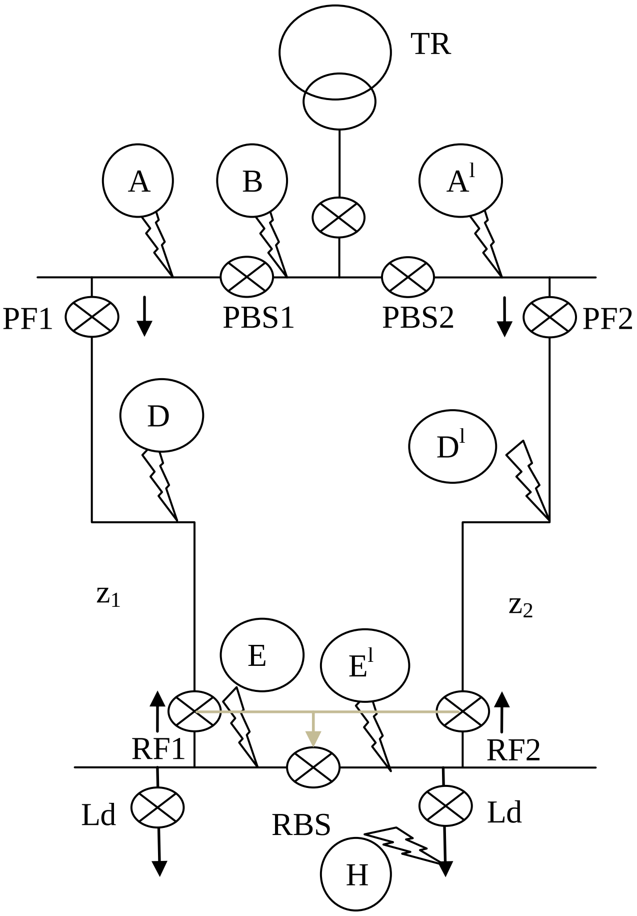
Figure 5.1: Protection relay characteristic

The fault currents are calculated for the radial and closed loop operation based on the fault level at primary substation, cable impedances and current protection setting used in CC distribution network. Maximum current of the feeder or maximum demand current of the consumer is set as the relay pick up setting. Based on the calculated fault levels and Maximum current of the feeder value for Plug Setting Multiplier (PSM) is set in the relay. Based on the time setting Time Setting Multiplier (TSM) is set up in the relays. These settings provide the IDMT protection for the feeder and eighty percent of fault current is set as the definite time tripping value.

5.2. Closed Loop Operation of Two Feeders in Radial Substation

5.2.1. Ring protection analysis

Feeding arrangement is set up to maximize the bus sections to consider the case with highest complexity.



FL = fault level for O/C (15.2kA) & E/F (1.6kA)
SI = source impedance
P = primary substation
R = radial/ring substation
F = feeder
BS= bus section
Ld = load
z = impedance of the cable
V = medium voltage level (11000V)
Ld = consumer load feeder
Z = impedance
I_{FL} = fault current
CB= circuit breaker

Figure 5.2: Two parallel feeder operation

System in the figure 5.2 was analyzed for failures in different location

Location A, B and A^l: Bus bar protection is available for primary substations. So CBs of the relevant bus will trip.

Location D: Fault current flowing through the primary feeder 1 side will trigger the relays at PF1 and PBS1. PF1 relay having the lower fault current setting and time setting, so it will trip.

Fault current flowing through the primary feeder 2 will trigger the relays at RF1, RBS, PF2 and PBS2. RF1 relay has the lowest fault current and time setting, so it will trip.

Location E: Fault current flowing through the primary feeder 1 side will trigger the relays at PF1 and PBS1. PF1 relay has the lower fault current setting and time setting, so it will trip.

Fault current flowing through the primary feeder 2 will trigger the relays at RBS, PF2 and PBS2. RBS has the lowest fault current and time setting, so it will trip.

Fault level calculations for the closed loop operation of two feeders in radial substation

PTRCB;	$Z = SI$	$TS = 1000ms$	$I_{FL} = V/Z$
PBSCB1;	$Z = SI$	$TS = 850ms$	$I_{FL} = V/Z$
PBSCB2;	$Z = SI$	$TS = 850ms$	$I_{FL} = V/Z$
PF1CB;	$Z = SI+z_1//z_2$	$TS = 700ms$	$I_{FL,IDMT} = V/Z*z_2/(z_1+z_2)$
	$Z = SI+z_1)$	$TS = 0ms$	$I_{FL,DT} = V/Z$
PF2CB;	$Z=SI+z_1//z_2$	$TS = 700ms$	$I_{FL,IDMT} = V/Z *z_1/(z_1+z_2)$
	$Z = (SI + z_2)$	$TS = 0ms$	$I_{FL,DT} = V/Z$
RBSB;		$TS = 600ms$	I_{FL}= lowest (PF1CB$I_{FL,IDMT}$, PF2CB$I_{FL,IDMT}$)
		$TS = 0ms$	I_{FL}= lowest (PF1CB$I_{FL,DT}$, PF2CB$I_{FL,DT}$)
RF1CB;	$Z=SI+z_1//z_2$	$TS = 100ms$	$I_{FL,IDMT} = V/Z*z_1/(z_1+z_2)/2$
	$Z=SI+z_1+z_2$	$TS = 0ms$	$I_{FL,DT} = V/Z$
RF2CB;	$Z=SI+z_1//z_2$	$TS = 100ms$	$I_{FL,IDMT} = V/Z*z_2/(z_1+z_2)/2$
	$Z=SI+z_1+z_2$	$TS = 0ms$	$I_{FL,DT} = V/Z$
LdCB;		$TS = 100ms$	I_{FL}= 2*lowest (PF1CB$I_{FL,IDMT}$, PF2CB$I_{FL,IDMT}$)

5.2.2. Protection coordination for radial operation

Table 5.1 specify the protection setting included for the substation 981, where two feeders are feeding the loads in either side of the NO bussection.

Arrangement	Relay Feeder	Over current Protection			Earth fault protection			Time Setting (mS)
		Max current (A)	IDMT Fault current (A)	DT Fault current (A)	Max. current (A)	IDMT Fault current (A)	DT Fault current (A)	
Radial feeding 1	PSSF-TR1	1500	15200	15200	300	1600	1600	1000
	PSSF-BS1	1000	15200	15200	100	1600	1600	850
	PSSF-R986	400	11490	11490	60	1550	1550	700
	0986-PSSF	400	11490	11490	60	1550	1550	500
	0986-Ld1	367	11490	11490	30	1550	1550	100
Open bus	0986-BS	300	11490	11490	60	1550	1550	600
Radial feeding 2	PSSF-TR1	1500	15200	15200	300	1600	1600	1000
	PSSF-BS2	2000	15200	15200	100	1600	1600	850
	PSSF-R986	400	11490	11490	60	1550	1550	700
	0986-PSSF	400	11490	11490	60	1550	1550	500
	0986-Ld2	367	11490	11490	30	1550	1550	100

Table 5.1: Protection setting for radial operation of feeders in substation 981

5.2.3. Protection coordination for ring operation

Arrangement	Relay		Over current Protection			Earth fault protection			Time Setting (ms)
	Feeder	Direction	Max. Current (A)	IDMT fault current (A)	DT fault current (A)	Max. Current (A)	IDMT Fault current (A)	DT Fault current (A)	
Incoming Feeder	PSSF-TR1	N/A	1500	15200	15200	300	1600	1600	1000
Closed Loop	PSSF-BS2	N/A	1000	15200	15200	100	1600	1600	850
	PSSF-R986	Forward	400	6583	11490	60	787.4	1550	700
	0986-PSSF	Backward	200	3289	9236	30	398.4	1502	100
	0986-BS	N/A	300	11490	11490	50	1550	1550	400
	0986-PSSF	Forward	200	3291	9236	30	393.7	1502	100
	PSSF-R986	Backward	400	6579	11490	60	786.9	1550	700
	PSSF-BS1	N/A	2000	15200	15200	100	1600	1600	850
Outgoing Feeders	0986-Ld1	N/A	367	13158	13158	30	1574	1574	100
	0986-Ld2	N/A	367	13158	13158	30	1574	1574	100

Table 5.2: Protection setting for closed loop operation of feeders in substation 981

5.2.4. Simulation of load flow

Substation with two feeders operating in closed loop arrangement is modeled in Matlab Simulink for analysis of the current flow under breaker operation. Cable data and the load data are inserted to match with the feeder details in R986.

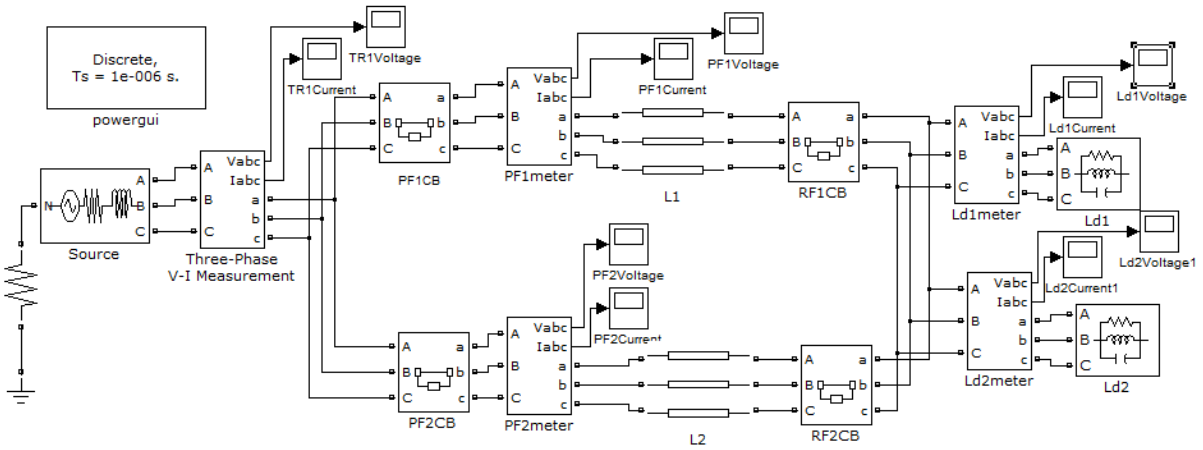


Figure 5.3: Matlab model

RF1CB is opened at 0.2s and the PF1CB is opened at 0.4s to simulate the change in the network for isolation of Feeder 1 and the current variation is monitored

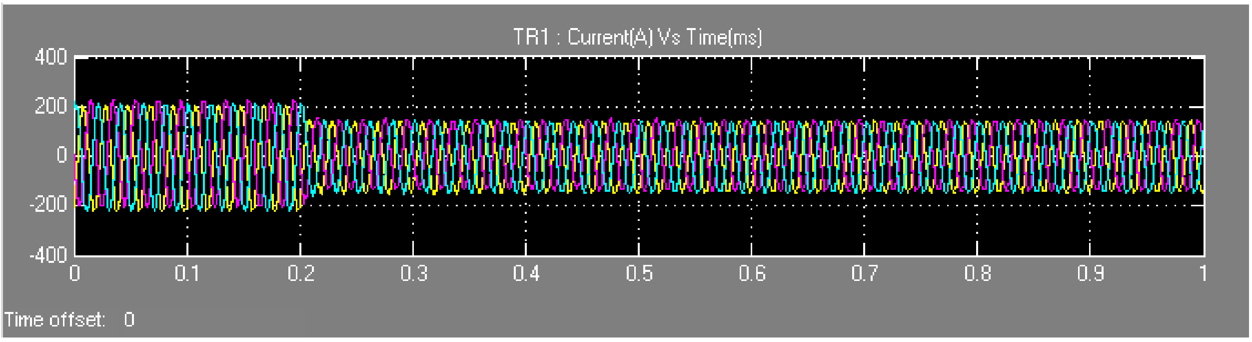


Figure 5.4: Current variation at supply end for feeder 1 isolation

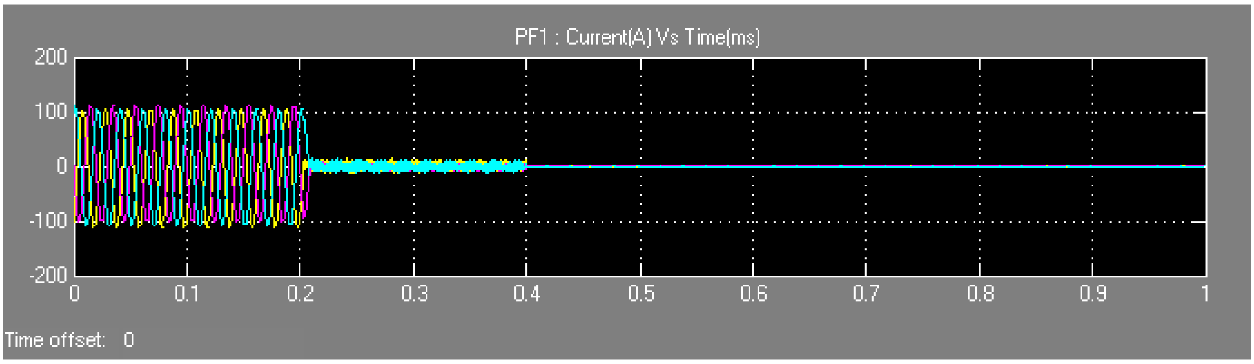


Figure 5.5: Current variation of the feeder 1 for feeder 1 isolation

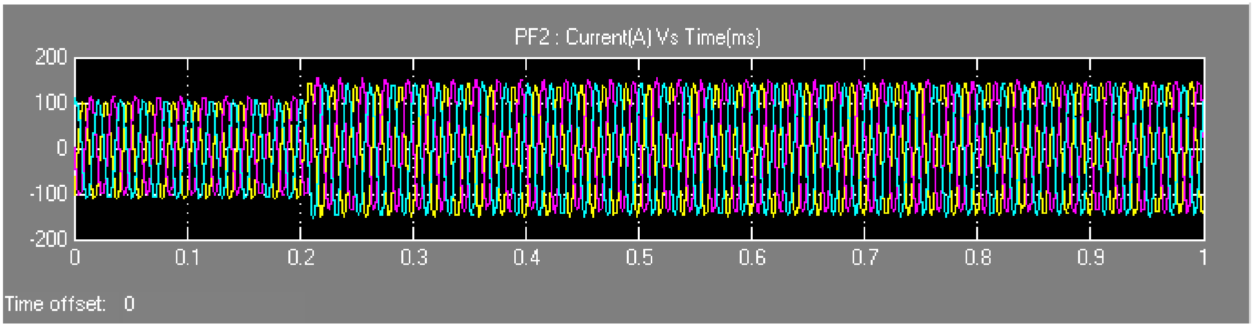


Figure 5.6: Current variation of the feeder 2 for feeder 1 isolation

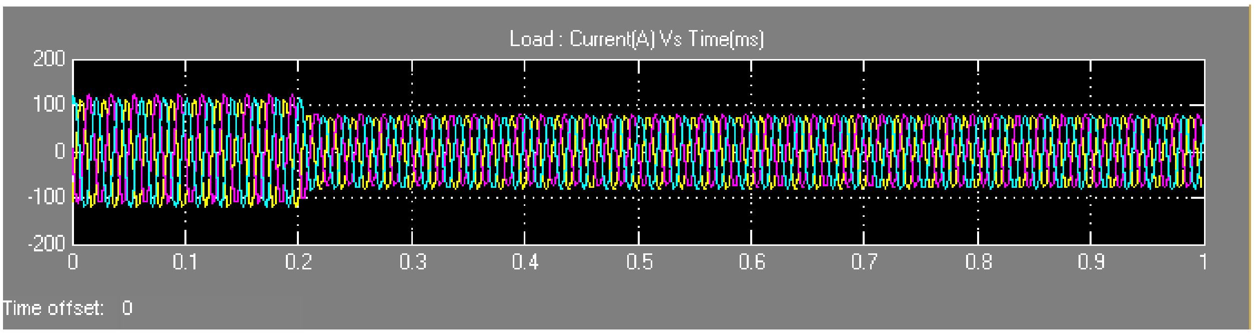


Figure 5.7: Current variation at load end for feeder 1 isolation

It is clearly noticeable from the figure 5.4 that the current at the supply end is higher when operated in parallel. This is due to the reduced resistance in the parallel path. This allows more power to be fed to the load as seen in figure 5.7. Upon the opening of RF1CB total load is transferred to PF1 feeder.

Ld1 is disconnected at 0.3s and reconnected at 0.6s to simulate the changes n network with load variations.

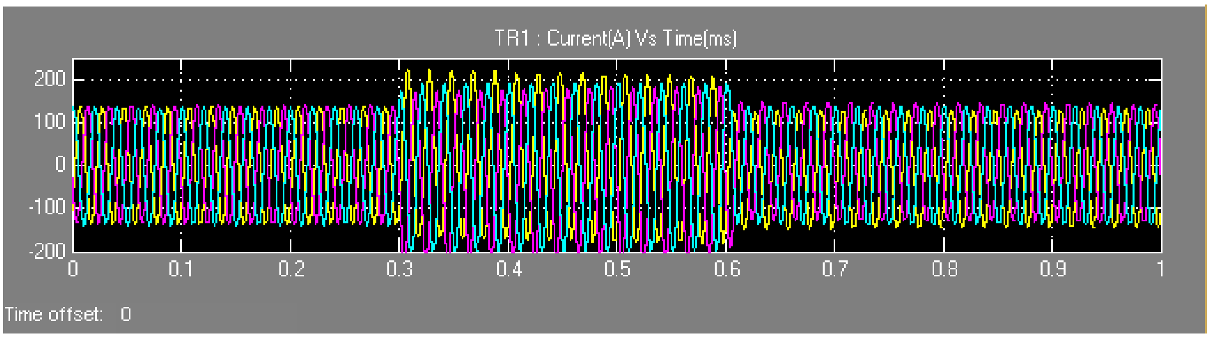


Figure 5.8: Current variation at supply end for load changes

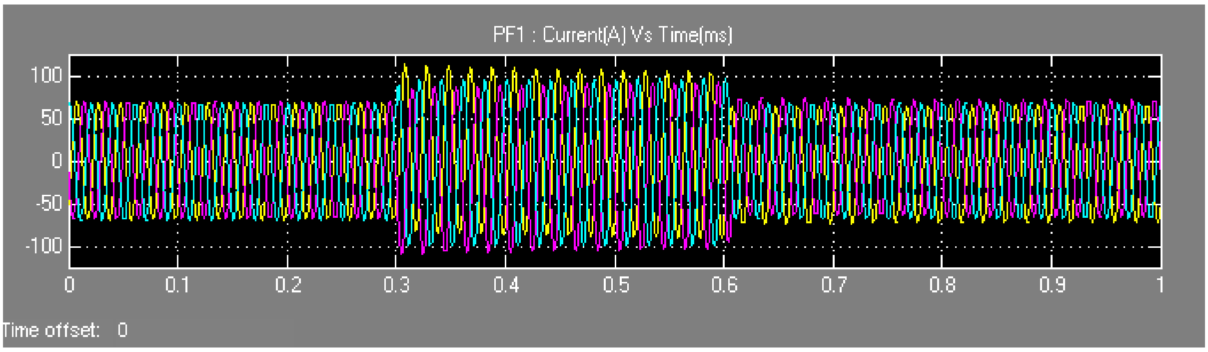


Figure 5.9: Current variation of feeder 1 for load changes

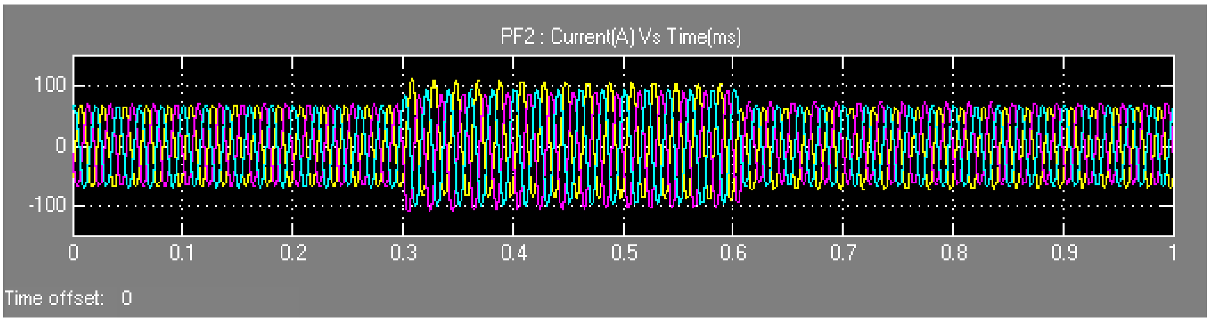


Figure 5.10: Current variation of feeder 2 for load changes

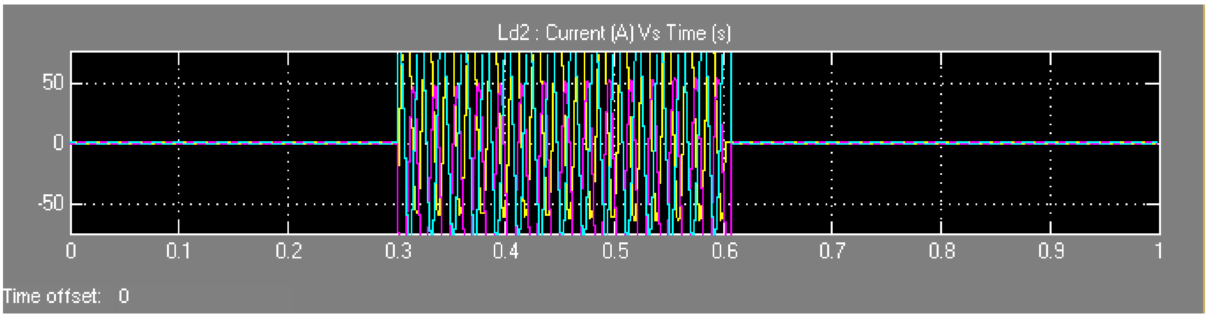


Figure 5.11: Current changes at load Ld1 for load changes

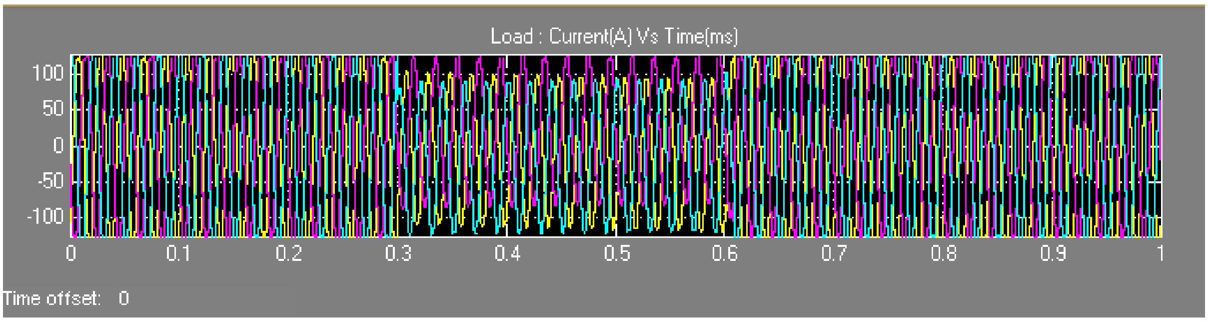


Figure 5.12: Current changes at load Ld2 for load changes

Increased load due to closing of Ld1 circuit breaker has been shared between the two parallel feeders.

5.2.5. Simulation of cable fault

Three phase fault at the end of PF1 is simulated after 0.1s and the status changes are set in circuit breaker to simulate the protection tripping.

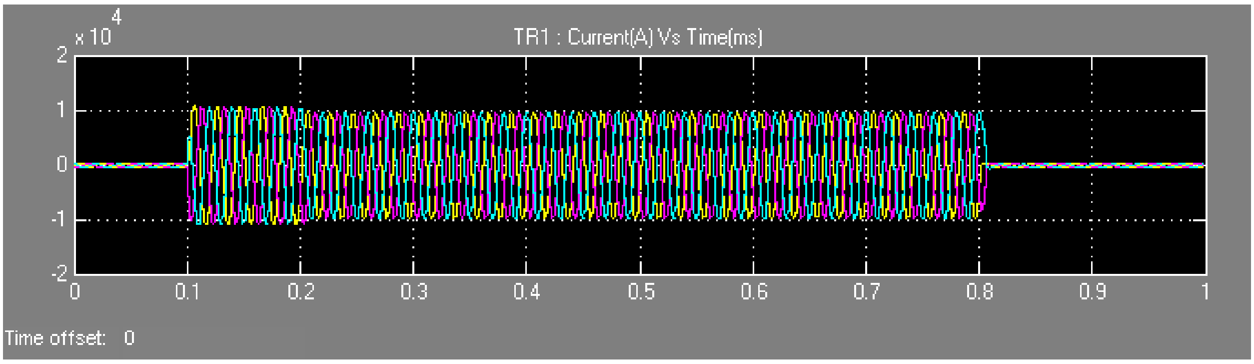


Figure 5.13: Current variation at supply end for cable fault at substation end

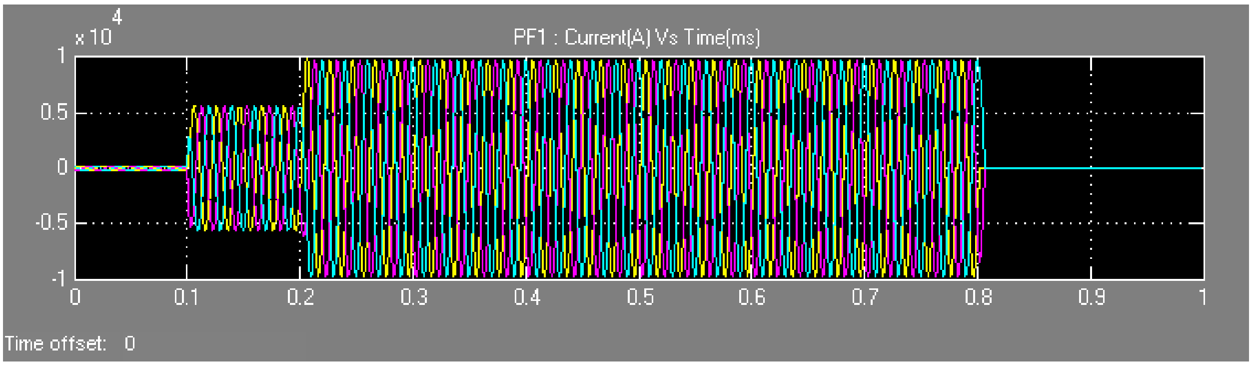


Figure 5.14: Current variation at PF1 for cable fault at substation end

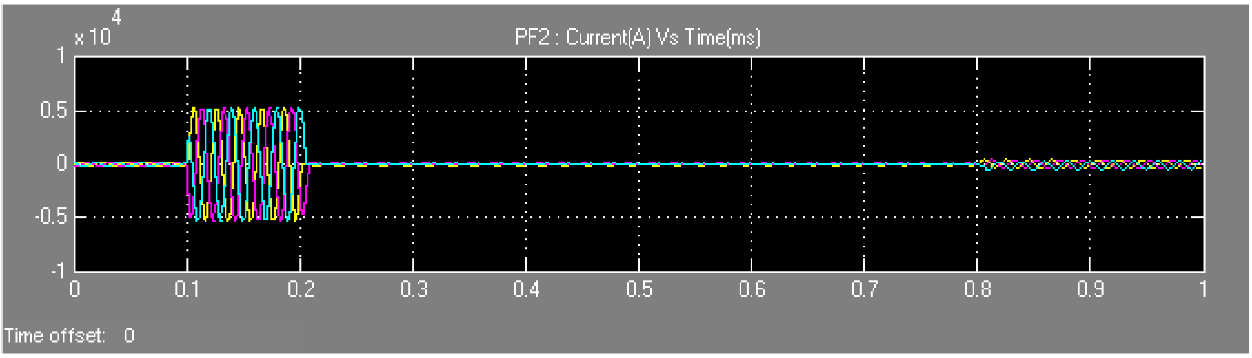


Figure 5.15: Current variation at PF2 for cable fault at substation end

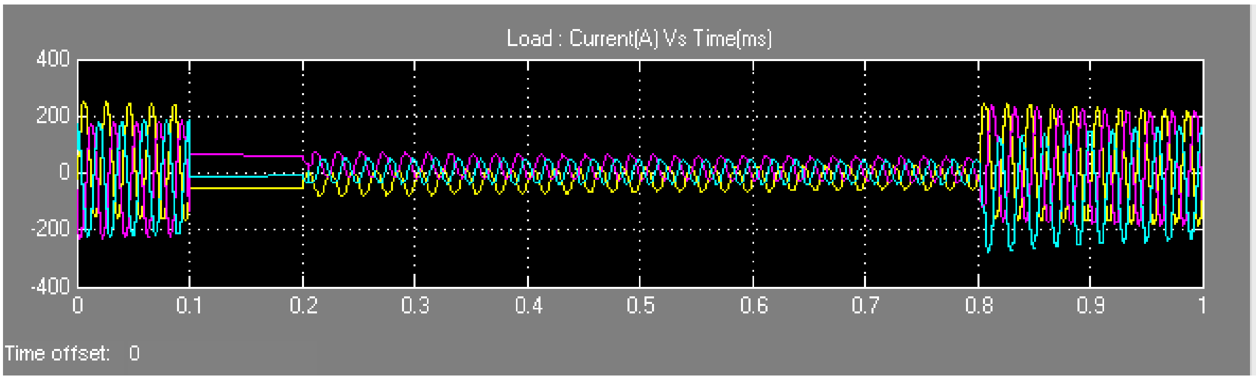


Figure 5.161: Current variation at load for cable fault at substation end

Load is fed by both PF1 and PF2 under closed loop operation. When the cable fails, the fault current is shared between the two feeders as seen in figure 5.9 and figure 5.10. The fault current is shared near equally as the cable length and type is similar. Fault current simulated is close to the calculated protection setting and will trip the PF2CB around 0.1ms. Then the fault current in the PF2 increases which will trip within the 0.7s. So the fault is completely isolated within 800ms.

The fault is greatly felt from 0.1s to 0.2s where the load is close to the fault due to the closed loop arrangement. But with the opening of the RF1CB network take the shape of a radial feeding arrangement. Beyond 0.2s fault is felt as if there is a fault in another radial feeder.

After clearing of the fault at 0.8s the load current normalizes. It is also seen from the figure 5.8 that the fault current is greater when system is in closed loop arrangement.

Three phase fault at the end of Ld1 (load side) is simulated after 0.2s and the status changes are set in circuit breaker at 0.3s to simulate the protection tripping.

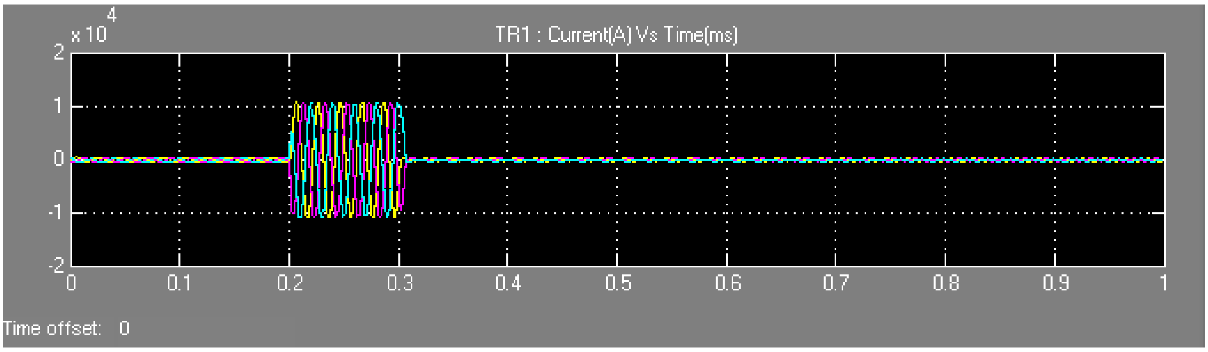


Figure 5.17: Current variation at supply end for cable fault at load side

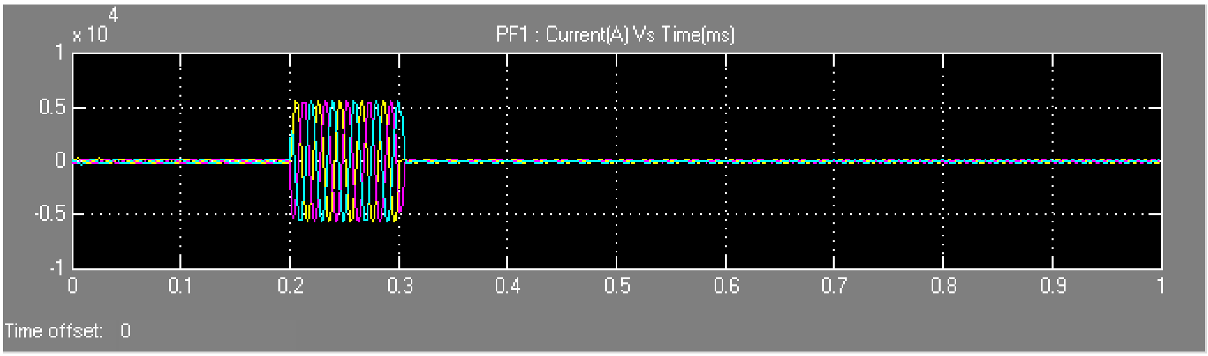


Figure 5.18: Current variation on feeder 1 for cable fault at load side

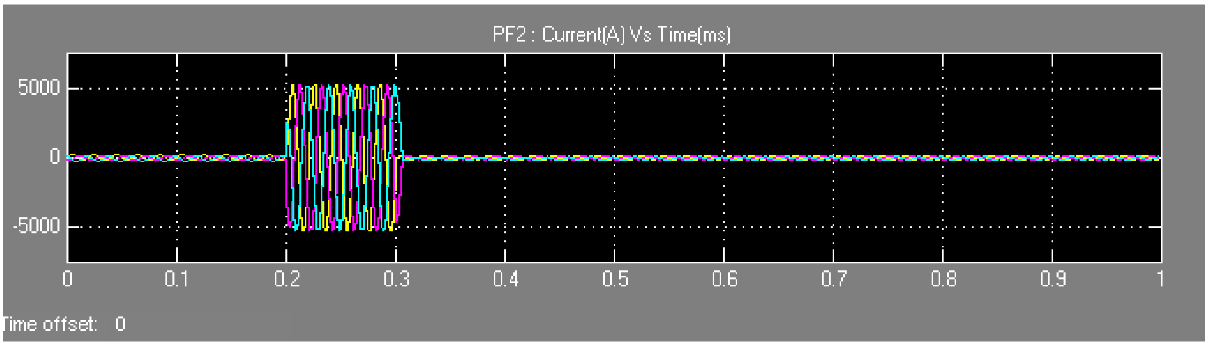


Figure 5.19: Current variation on feeder 2 for cable fault at load side

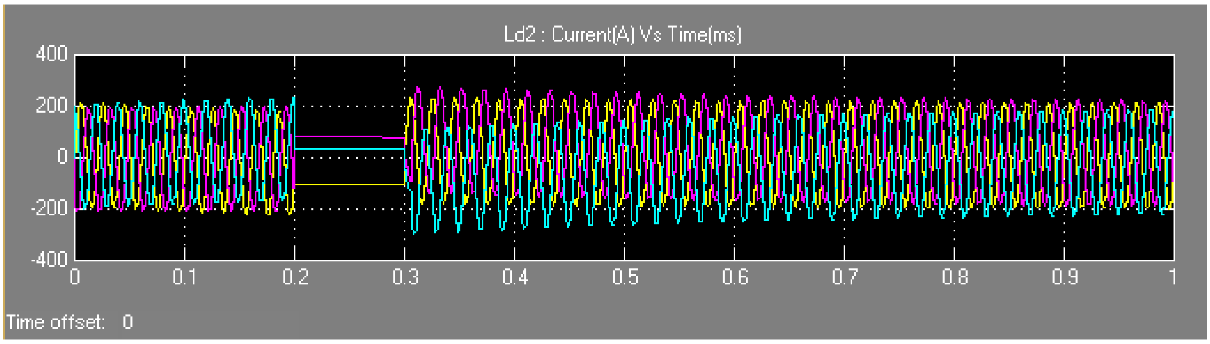


Figure 5.20: Current variation on Ld1 for cable fault at load (Ld2) side

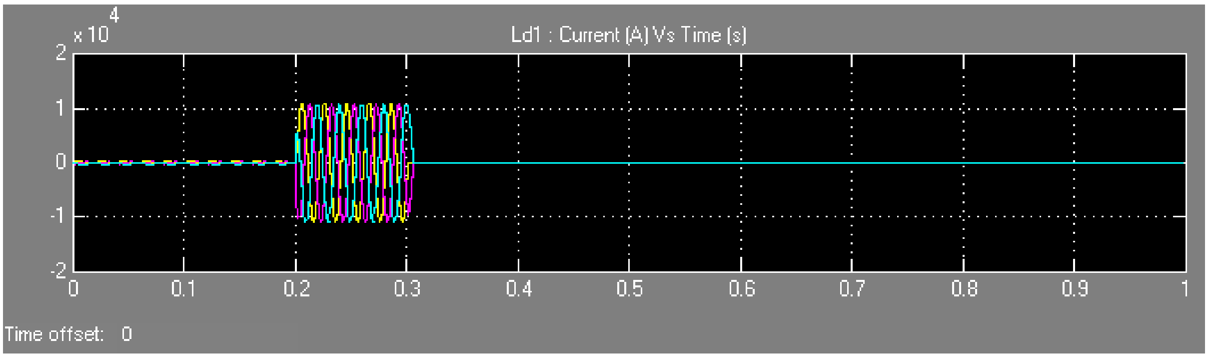


Figure 5.21: Current variation on Ld2 for cable fault at load (Ld2) side

The total impedance for the fault current is source impedance plus the parallel impedance of the two feeders. Therefore The fault current is higher than in radial feeding arrangement as the fault current is flowing through the both feeders in parallel.

It is noted that the fault current through the load is greater than the fault currents through the feeders this allows easy protection coordination between the relays at feeder ends and the relays at load ends.

Three phase fault at the feeder end is simulated after 0.2s and the status changes are set in PF1CB at 0.25s to simulate the instantaneous tripping and RF1CB at 0.35s to simulate the protection tripping.

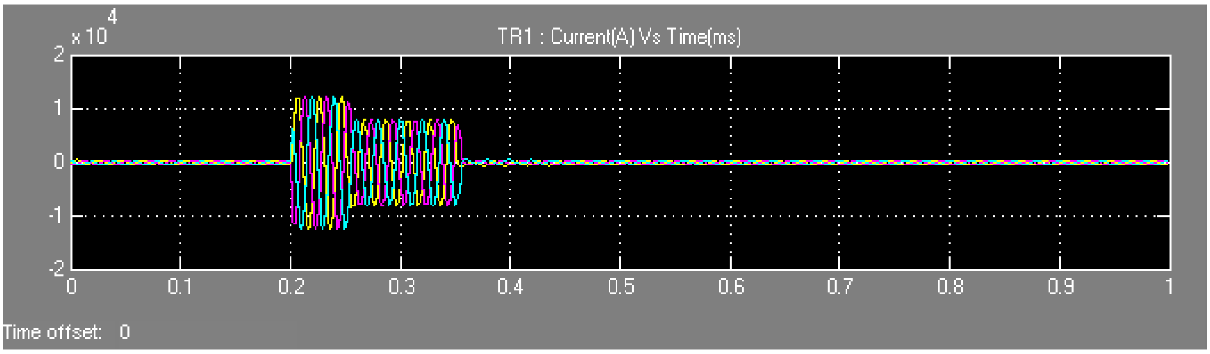


Figure 5.22: Current variation on supply end for cable fault at primary side

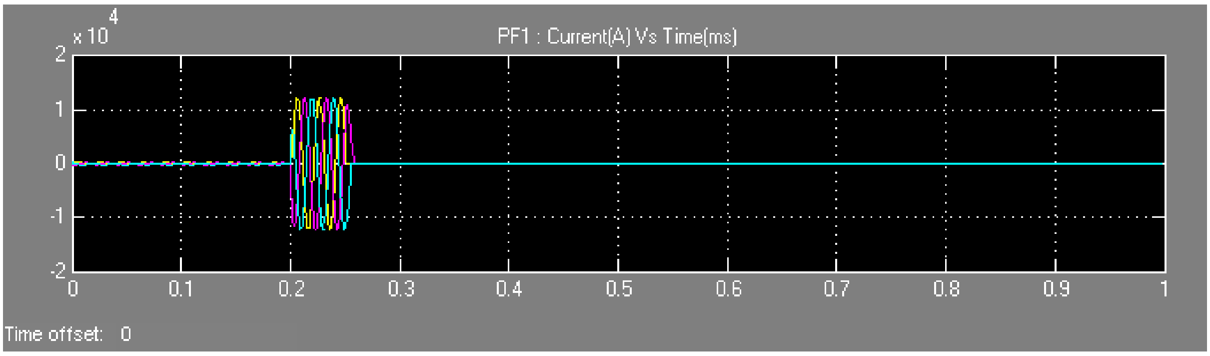


Figure 5.23: Current variation on feeder 1 for cable fault at primary end

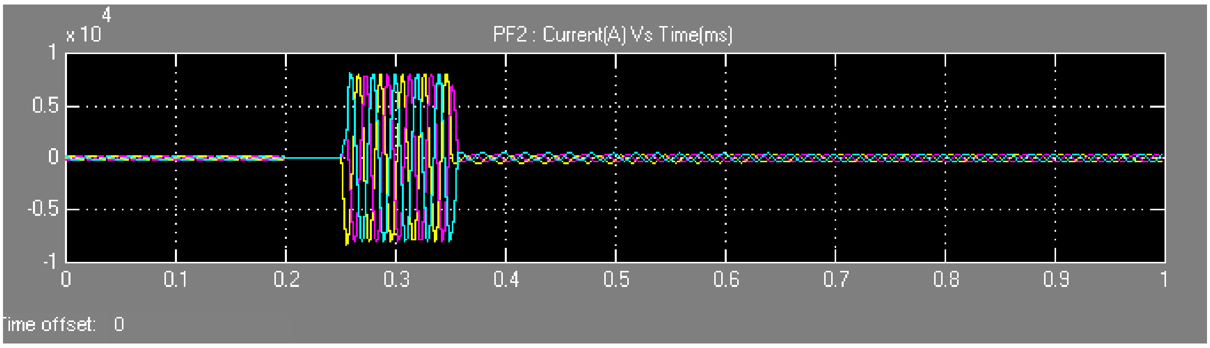


Figure 5.24: Current variation on feeder 2 for cable fault at primary side

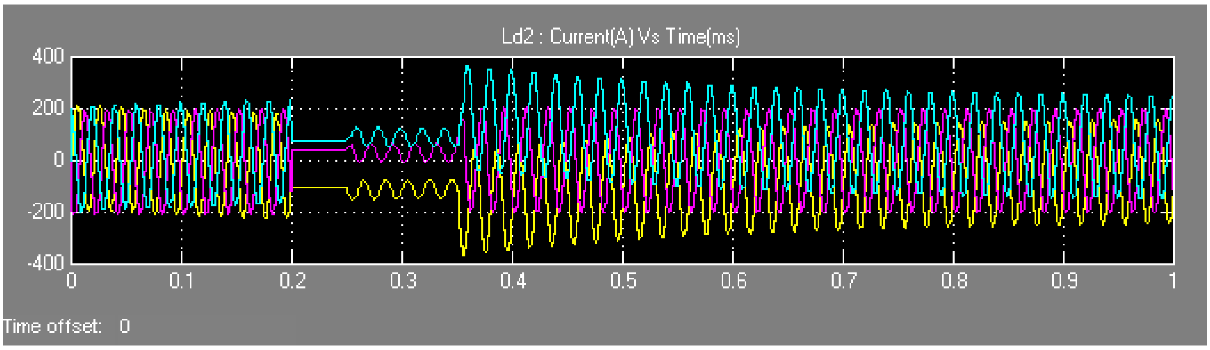


Figure 5.25: Current variation at load side for a cable fault at primary side

When the fault has occurred at the primary side cable end, feeder 1 only has impedance of the PF1CB which is nearly zero compared to the impedance for the fault current through feeder 2. Therefore current will not flow through the feeder 2 and the total fault current flows through the PF1CB nearly matching the fault level of the 11kV primary busbar. PF1CB trips on instantaneous over current. Then the fault current will flow through feeder 2. RF1CB trips thereafter.

Therefore in any case faulty cable is isolated from the distribution network.

5.3. Closed Loop Operation of Two Substation

5.3.1. Ring protection analysis

Highest complexity occurs for closed loop two radial substations when they are operated in across a bus section. So the analysis was carried out for the above state.

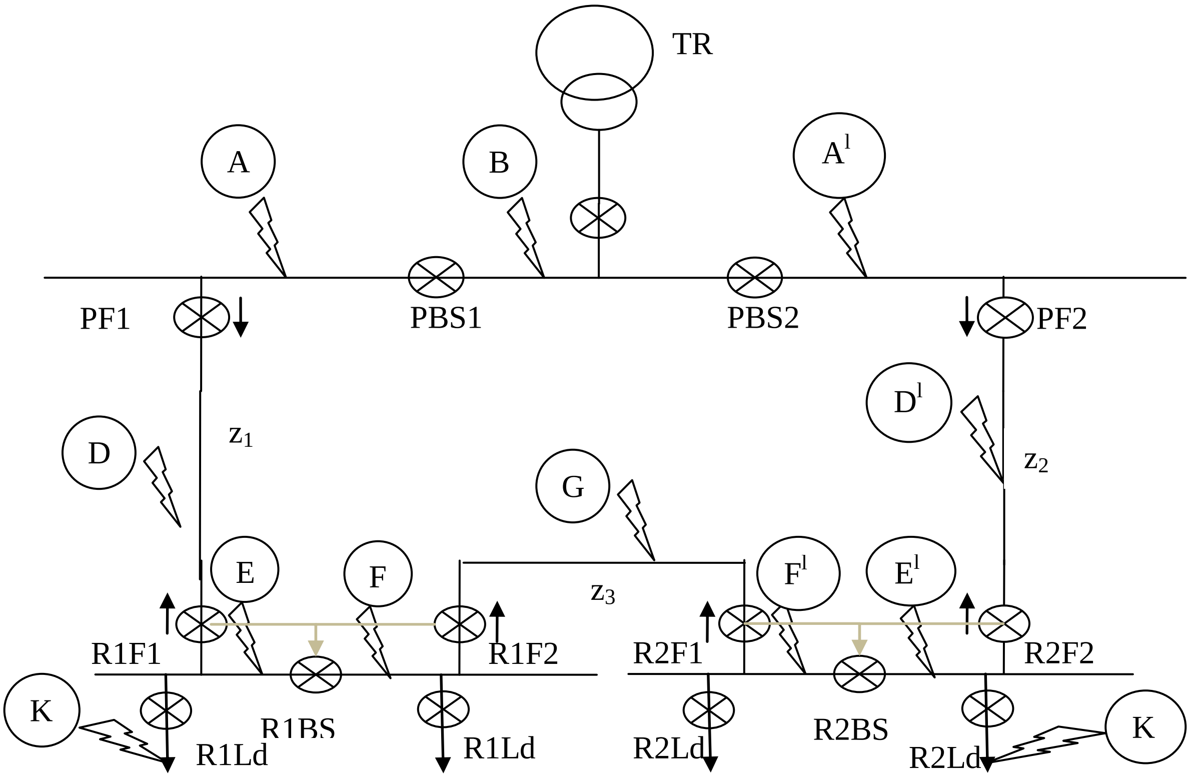


Figure 5.26: Closed loop operation of two radial substations

System in the figure 5.2 is analyzed for failures in different locations

Location A, B and A^l: Bus bar protection is available for primary substations. So CBs of the relevant busbar trip.

Location D: Fault current flowing through the primary feeder 1 side triggers the relays at PF1 and PBS1. PF1 relay having the lower fault current setting and time setting trips.

Fault current flowing through the primary feeder 2 will trigger the relays at R1F1, R1BS, R2F1, R2BS, PF2 and PBS2. R1F1 relay has the lowest fault current and time setting trips.

Location E: Fault current flowing through the primary feeder 1 side triggers the relays at PF1 and PBS1. PF1 relay has the lower fault current setting and time setting trips.

Fault current flowing through the primary feeder 2 triggers the relays at R1BS, R2F1, R2BS, PF2 and PBS2. R1BS relay has the lowest fault current and time setting trips.

Location F: Fault current flowing through the primary feeder 1 side triggers the relays at R1BS, PF1 and PBS1. R1BS relay has the lowest fault current setting and time setting trips.

Fault current flowing through the primary feeder 2 triggers the relays at R2F1, R2BS, PF2 and PBS2. R2F1 relay sends a blocking signal to R2BS relay so R2BSCB does not trip. R2F1 relay has the next lowest fault current and time setting trips.

Location G: Fault current flowing through the primary feeder 1 side triggers the relays at R1F2, R1BS, PF1 and PBS1. R1F2 relay sends a blocking signal to R1BS relay so R1BSCB does not trip. R1F2 relay has the next lowest fault current setting and time setting trips.

Fault current flowing through the primary feeder 2 triggers the relays at R2F1, R2BS, PF2 and PBS2. R2F1 relay sends a blocking signal to R2BS relay so R1BSCB does not trip. R1F2 relay has the next lowest fault current setting and time setting trips.

Fault level calculations for the closed loop operation of two radial substations

PTRCB; $Z=SI$ TS = 1000ms $I_{FL} = V/Z$

PBSCB1; $Z=SI$ TS = 850ms $I_{FL} = V/Z$

PBSCB2; $Z=SI$ TS = 850ms $I_{FL} = V/Z$

PF1CB; $Z=SI+z_1//(z_2+z_3)$ TS = 700ms $I_{FL,IDMT}= V/Z *(z_2+z_3)/(z_1+z_2+z_3)$

$Z=SI + z_1$ TS = 0ms $I_{FL,DT}= V/Z$

PF2CB; $Z=SI+z_2//(z_1+z_3)$ TS = 700ms $I_{FL,IDMT}= V/Z*(z_1+z_3)/(z_1+z_2+z_3)$

$Z=SI+z_2$ TS = 0ms $I_{FL,DT} = V/Z$

R1F1CB; $Z=SI+z_1//(z_2+z_3)$ TS = 100ms $I_{FL,IDMT}= V/Z*z_1/(z_1+z_2+z_3)/2$

$Z=SI+z_1+z_2+z_3$ TS = 0ms $I_{FL,DT}= V/Z$

R2F2CB; $Z=SI+z_2//(z_1+z_3)$ TS = 500ms $I_{FL,IDMT}= V/Z*z_2/(z_1+z_2+z_3)/2$

$Z=SI+z_1+z_2+z_3$ TS = 0ms $I_{FL,DT}= V/Z$

R1F2CB;$Z_1=SI+z_2//(z_1+z_3)$ $Z_2=SI+z_1//(z_2+z_3)$

TS = 500ms $I_{FL, IDMT}$ = lowest $[V/Z_1*z_2/(z_1+z_2+z_3),V/Z_2*(z_2+z_3)/(z_1+z_2+z_3)]$

$Z=SI+z_1+z_3$ TS = 0ms $I_{FL,DT}= V/Z$

R2F1CB;$Z_1=SI+z_1//(z_2+z_3)$ $Z_2=SI+z_2//(z_1+z_3)$

TS = 500ms I_{FL} = lowest $[V/Z_1*z_1/(z_1+z_2+z_3),V/Z_2*(z_1+z_3)/(z_1+z_2+z_3)]$

$Z=SI+z_2+z_3$ TS = 0ms $I_{FL,DT}=V/Z$

R1BSCB; TS = 400ms $I_{FL, IDMT}$= lowest (PF1CB$I_{FL,IDMT}$, R2F1CB$I_{FL,IDMT}$)

TS = 0ms $I_{FL,DT}$=lowest (PF1CB$I_{FL,DT}$, R2F1CB$I_{FL,DT}$)

R2BSCB; TS = 400ms $I_{FL, IDMT}$=lowest (PF2CB$I_{FL,IDMT}$, R1F2CB$I_{FL,IDMT}$)

TS = 0ms $I_{FL,DT}$= lowest (PF2CB$I_{FL,DT}$, R1F2CB$I_{FL,DT}$)

R1LdCB; TS = 100ms I_{FL}= 2*lowest (PF1CB$I_{FL,IDMT}$, R2F1CB$I_{FL,IDMT}$)

R2LdCB; TS = 100ms I_{FL}=2*lowest (PF2CB$I_{FL,IDMT}$, R1F2CB$I_{FL,IDMT}$)

5.3.2. Protection coordination for radial operation

Table 5.3 specify the protection setting included for the substation 9 and 116, where two radial substation are feeding the loads with a NO cable between them.

Arrangement	Relay	Over current protection			Earth fault protection			Time setting (ms)
		Max. current (A)	Fault current (A)	Instantaneous (A)	Max. current (A)	Fault current (A)	Instantaneous (A)	
Radial Feeding	PSSF-TR3	2000	15200	15200	100	1600.00	1600.00	1000
	PSSF-BS1	1000	15200	15200	50	1600.00	1600.00	850
	PSSF-R9	600	14161	14161	60	1589.96	1589.96	700
	0009-PSSF	400	14161	14161	60	1589.96	1589.96	500
	0009-F4	26.2	14161	14161	10	1589.96	1589.96	100
cable with NO end	0009-R116	225	12545	12545	40	1567.28	1567.28	300
	0116-R9	240	12310	12310	40	1563.56	1563.56	300
Radial Feeding	PSSF-TR3	2000	15200	15200	100	1600.00	1600.00	1000
	PSSF-R116	400	13859	13859	60	1586.07	1586.07	700
	0116-PSSF	400	13859	13859	60	1586.07	1586.07	500
	0116-F6	131.2	13859	13859	30	1586.07	1586.07	100

Table 5.3: Protection setting for radial operation of substations 116 & 9

5.3.3. Protection coordination for ring operation

Protection settings were modified for existing field arrangement to be operated in closed loop condition.

Arrangement	Relay	Direction	Over current protection			Earth fault protection			Time setting (ms)
			Max. current (A)	IDMT fault current (A)	DT fault current (A)	Max. current (A)	IDTM fault current (A)	DT fault current (A)	
incoming	PSSF-TR3	N/A	2000	15200	15200	100	1600.0	1600.0	1000
Closed loop	PSSF-BS1	N/A	1000	15200	15200	70	1600.0	1600.0	850
	PSSF-R9	Forward	600	11420	14161	60	1252.6	1589.9	700
	0009-PSSF	Backward	400	3095	11740	60	339.4	1553.9	100
	0009-R116	Forward	225	2128	12545	40	235.6	1567.2	500
	0116-R9	Backward	240	1547	12310	40	169.7	1563.5	500
	0116-PSSF	Forward	400	4256	11737	60	471.3	1553.9	100
	PSSF-R116	Backward	400	10101	13859	60	1118.8	1586.0	700
Outgoing feeders	0009-F4	N/A	26.2	6190	6190	10	1592.0	1592.0	100
	0116-F6	N/A	131.2	8512	8512	30	1590.1	1590.1	100

Table 5.4: Protection setting for closed loop operation of substations 116 & 9

5.4. Closed Loop Operation of Three Substation

5.4.1. Ring protection analysis

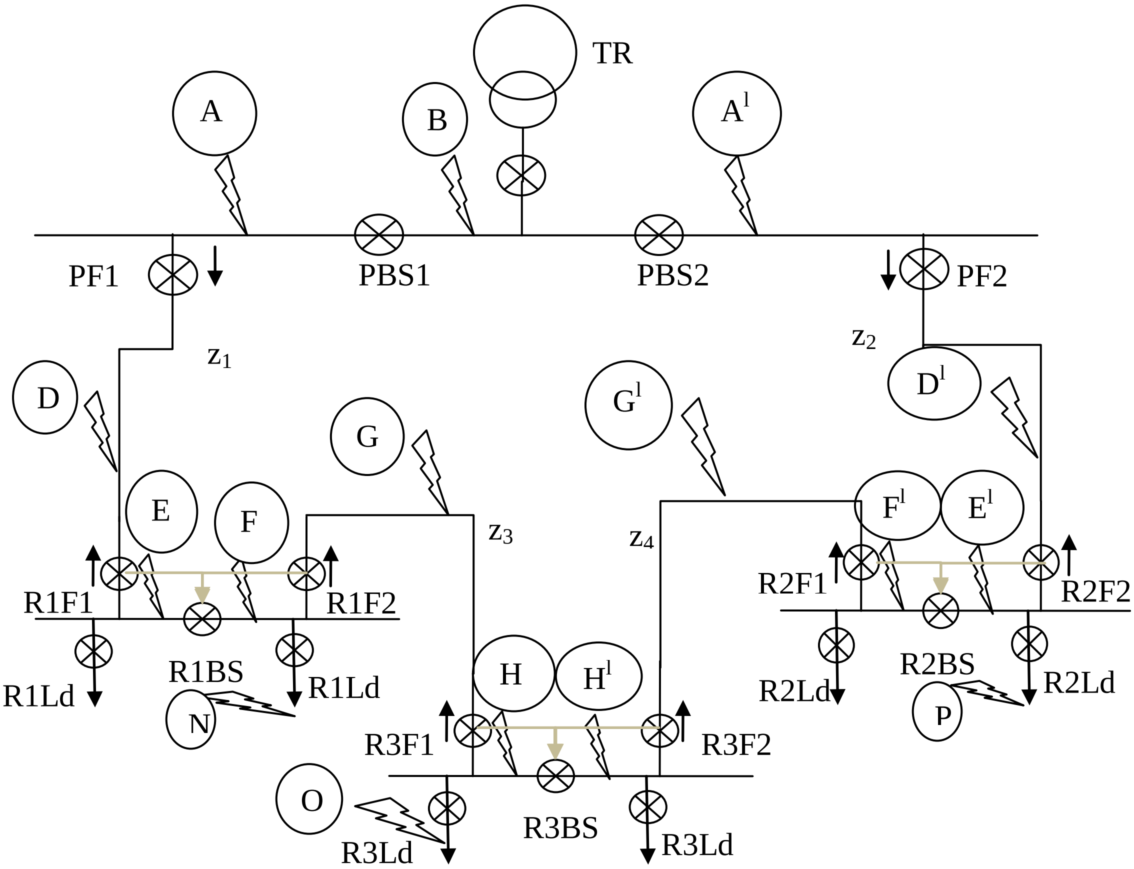


Figure 5.27: Closed loop operation of three substations

System in the figure 5.3 is analyzed for failures in different location

Location A,B and A^l: Busbar protection is available in most of primary substations. So all connected CBs for that busbar trips.

Location D: Fault current flowing through the primary feeder 1 side triggers the relays at PF1 and PBS1.PF1 relay having the lower fault current setting and time setting trips.

Fault current flowing through the primary feeder 2 triggers the relays at R1F1, R1BS, R3F1, R3BS, R2F1, R2BS, PF2 andPBS2. R1F1 relay has the lowest fault current and time setting trips.

Location E: Fault current flowing through the primary feeder 1 side triggers the relays at PF1 and PBS1. PF1 relay has the lower fault current setting and time setting trips.

Fault current flowing through the primary feeder 2 triggers the relays at R1BS, R3F1, R3BS, R2F1, R2BS, PF2 and PBS2. R1BS relay has the lowest fault current and time setting trips.

Location F: Fault current flowing through the primary feeder 1 side triggers the relays at R1BS, PF1 and PBS1. R1BS relay has the lowest fault current setting and time setting trips.

Fault current flowing through the primary feeder 2 triggers the relays at R3F1, R3BS, R2F1, R2BS, PF2 and PBS2. R3F1 relay has the lowest fault current and time setting trips.

Location G: Fault current flowing through the primary feeder 1 side triggers the relays at R1F2, R1BS, PF1 and PBS1. R1F2 relay sends a blocking signal to R1BS relay so R1BSCB does not trip. R1F2 relay has the next lowest fault current setting and time setting trips.

Fault current flowing through the primary feeder 2 triggers the relays at R3F1, R3BS, R2F1, R2BS, PF2 and PBS2. R3F1 relay has the lowest fault current and time setting trips.

Location H: Fault current flowing through the primary feeder 1 side triggers the relays at R1F2, R1BS, PF1 and PBS1. R1F2 relay sends a blocking signal to R1BS relay so R1BSCB does not trip. R1F2 relay has the next lowest fault current setting and time setting trips.

Fault current flowing through the primary feeder 2 triggers the relays at R3BS, R2F1, R2BS, PF2 and PBS2. R3BS relay has the lowest fault current and time setting trips.

Fault level calculations for the closed loop operation of three substations

PTRCB; $Z=SI$ TS = 1000ms $I_{FL} = V/Z$

PBSCB1; $Z=SI$ TS = 850ms $I_{FL} = V/Z$

PBSCB2; $Z=SI$ TS = 850ms $I_{FL} = V/Z$

PF1CB; $Z= SI+z_1//(z_2+z_3+z_4)$ TS =700ms $I_{FL,IDMT}= V/Z*(z_2+z_3+z_4)/(z_1+z_2+z_3+z_4)$

$Z= SI+z_1$ TS = 700ms $I_{FL,DT} = V/Z$

PF2CB; $Z=SI+z_2//(z_1+z_3+z_4)$ TS = 700ms $I_{FL,IDMT} = V/Z*(z_1+z_3+z_4)/(z_1+z_2+z_3+z_4)$

$Z=SI+z_2$ TS = 700ms $I_{FL,DT} = V/Z$

R1F1CB; $Z=SI+z_1//(z_2+z_3+z_4)$ TS = 100ms $I_{FL,IDMT} = V/Z*z_1/(z_1+z_2+z_3+z_4)/2$

$Z=SI+z_1+z_2+z_3+z_4$ TS = 0ms $I_{FL,DT}=V/Z$

R2F2CB; $Z=SI+z_2//(z_1+z_3+z_4)$ TS = 100ms $I_{FL,IDMT} = V/Z*z_2/(z_1+z_2+z_3+z_4)/2$

$Z= SI+z_1+z_2+z_3+z_4$ TS = 0ms $I_{FL,DT}=V/Z$

R1F2CB; $Z_1=SI+(z_1+z_3)//(z_2+z_4)$ $Z_2=SI+z_1//(z_2+z_3+z_4)$

TS = 500ms $I_{FL,IDMT}= \text{lowest}[V/Z_1*(z_2+z_4)/(z_1+z_2+z_3+z_4),V/Z_2*(z_2+z_3+z_4)/(z_1+z_2+z_3+z_4)]$

$Z = SI+z_1+z_3$ TS = 0ms $I_{FL,DT} = V/Z$

R2F1CB; $Z_1=SI+ (z_2+z_4)//(z_1+z_3)\}$ $Z_2=\{SI + z_2//(z_1+z_3+z_4)\}$

TS = 500ms $I_{FL,IDMT} =\text{lowest}[V/Z_1*(z_1+z_3)/(z_1+z_2+z_3+z_4),V/Z_2*(z_1+z_3+z_4)/(z_1+z_2+z_3+z_4)]$

$Z= SI+z_2+z_3$ TS = 0ms $I_{FL,DT} = V/Z$

R3F1CB; $Z_1=SI+ (z_1+z_3)//(z_2+z_4)\}\{SI + z_1//(z_2+z_3+z_4)\}$

TS = 300ms $I_{FL,IDMT} = \text{lowest}[V/Z_1*(z_1+z_3)/(z_1+z_2+z_3+z_4),V/Z_2*z_1/(z_1+z_2+z_3+z_4)]$

$Z = SI+z_2+z_3+z_4$ TS = 0ms $I_{FL,DT} = V/Z$

R3F2CB; $Z_1=SI+(z_2+z_4)//(z_1+z_3)$ $Z_2=SI+z_2//(z_1+z_3+z_4)\}$

TS = 300ms $I_{FL,IDMT} = \text{lowest}[V/Z_1*(z_2+z_4)/(z_1+z_2+z_3+z_4), V/Z_2*z_2/(z_1+z_2+z_3+z_4)]$

$Z_{DT} = SI+z_1+z_3+z_4$ TS = 0ms $I_{FL,DT} = V/Z$

R1BS; TS = 200ms $I_{FL,IDMT}$= lowest(PF1CBI$_{FL,IDMT}$,R3F1CBI$_{FL,IDMT}$)

TS =0ms $I_{FL,DT}$= lowest (PF1CBI$_{FL,DT}$,R3F1CBI$_{FL,DT}$)

R2BS; TS = 200ms $I_{FL,IDMT}$= lowest(PF2CBI$_{FL,IDMT}$,R3F2CBI$_{FL,IDMT}$)

TS = 0ms $I_{FL,DT}$= lowest (PF2CBI$_{FL,DT}$,R3F2CBI$_{FL,DT}$)

R3BS; TS = 400ms $I_{FL,IDMT}$= lowest(R1F2CBI$_{FL,IDMT}$,R2F2CBI$_{FL,IDMT}$)

TS=0ms $I_{FL,DT}$= lowest (R1F2CBI$_{FL,DT}$, R2F1CBI$_{FL,DT}$)

R1LdCB; TS = 100ms I_{FL}= 2*lowest(PF1CBI$_{FL,IDMT}$,R3F1CBI$_{FL,IDMT}$)

R2LdCB; TS = 100ms I_{FL}= 2*lowest(PF2CBI$_{FL,IDMT}$,R3F2CBI$_{FL,IDMT}$)

R3LdCB; TS = 100ms I_{FL}= 2*lowest(R1F2CBI$_{FL,IDMT}$,R2F2CBI$_{FL,IDMT}$)

5.4.2. Protection coordination for radial operation

Arrangement	Relay Feeder	Over current protection			Earth fault protection			Time Setting (ms)
		Max. Current (A)	IDMT fault current (A)	DT fault current (A)	Max. Current (A)	IDMT fault current (A)	DT fault current (A)	
Radial feeding for sub 43 and 748	PSSF-TR2	2000	15200	15200	100	1600	1600	1000
	PSSF-R43	400	14222	14222	60	1590	1591	700
	0043-PSSF	400	14222	14222	50	1590	1591	500
	0043-748	240	8909	8909	30	1491	1491	300
	0043-BS	400	14222	14222	40	1590	1591	400
	0043-Ld	83	14222	14222	10	1590	1591	100
	0748-R43	240	8909	8909	20	1491	1491	300
	748-Ld	33	8909	8909	10	1491	1491	100
Cable with NO end	0748-R405	240	7742	7742	20	1454	1454	300
	0405-R748	240	11824	11824	20	1555	1555	300
Radial feeding for sub 405	PSSF-TR2	2000	15200	15200	100	1600	1600	1000
	PSSF-R405	350	14783	14783	60	1597	1597	700
	0405-PSSF	350	14783	14783	50	1597	1597	500
	0405-Ld	79	14783	14783	10	1597	1597	100

Table 5.5: Protection setting for radial operation of substations 43,748 & 405

5.4.3. Protection coordination for ring operation

Arrangement	Relay		Over current protection			Earth fault protection			Time Setting (ms)
	Feeder	Direction	Max. Current (A)	IDMT fault current (A)	DT fault current (A)	Max. Current (A)	IDMT fault current (A)	DT fault current (A)	
Incoming	PSSF-TR2	N/A	2000	15200	15200	100	1600	1600	1000
Closed loop	PSSF-R43	Forward	400	13295	14222	60	1481	1590	700
	0043-PSSF	Backward	400	495	7632	50	55	1452	100
	0043-R748	Forward	240	3637	8909	30	451	1491	500
	0748-R43	Backward	240	991	7905	20	110	1460	300
	0748-R405	Forward	240	420	7742	20	45	1454	300
	0405-R748	Backward	240	8994	11824	20	1116	1555	500
	0405-BS	N/A	350	420	7632	40	45	1452	400
	0405-PSSF	Forward	350	210	7632	50	23	1452	100
	PSSF-R405	Backward	350	14373	14783	60	1552	1597	700
Outgoing feeders	0043-Ld	N/A	82.7	1982	1982	10	221	2920	100
	0748-Ld	N/A	33.1	840	840	10	91	2905	100
	0405-Ld	N/A	78.7	840	840	10	91	2905	100

Table 5.6: Protection setting for closed loop operation of substations 43,748 & 405

It is clearly notable that Fault current calculated for the IDMT protection has a very lower value which is nearly the maximum current of the feeders. So the protection coordination is not viable in this case.

The impedance for the fault current within the loop network will depend upon the addition of source impedance and the parallel impedance of the two paths in the loop network. And the fault currents in each path of the loop network are inversely proportional to impedances of the paths. So if one path has very high impedance the fault current in that path will be very low. This has been the reason for the very low IDMT protection settings for some feeders, when operated in parallel. This is verified through the cable impedances data in the table 5.7

Cable	Impedance (Ohms)
PSSF-R43	0.050
0043-748	0.461
0748-R405	0.186
PSSF-R405	0.020

Table 5.7: Cable impedances [18]

There is high impedance cable between R43-R748 in comparison to cables between PSSF-R43 & PSSF-R405.This has resulted in the lower fault currents in parallel operation through some paths. Substations that have high impedance cable between substations are not recommended for closed loop operation as they are unable to have better protection coordination.

Increasing the number of substations in the closed loop network could also create a similar result for parallel operation as the overall cable impedance between the radial substations increases. Time coordination used in the current distribution system is fully utilized for closed loop operation of three substations. So increasing the number of substations in closed loop will require having smaller time intervals for tripping hierarchy. So it is recommended to keep the number of substations in the closed loop to three numbers.

If a fault was to occur at the cable end of the panel at the primary substation while in closed loop operation, there will be very low impedance for the fault current flowing through the circuit breaker, where as the other path contains the total resistance of the cables in the closed loop. Total fault current will pass through the PF1/PF2 circuit breaker which is the lowest impedance path. The relay at the R1F1/R2F2 end will not trigger until the tripping has occurred in the primary side which has a time setting of 700ms. So instantaneous tripping is essential at primary level to clear the fault quickly from primary side in such conditions. Thus the fault clearing is faster.

The lowest current flowing through the R1F1/R2F2 for worst case scenario is zero, in which case the fault has occurred at the PF1CB/PF2CB. The fault occurring at the R1F1CD/R1F1CB will have a similar effect as a fault in the R1BS/R2BS. So the IDMT setting is set as half the BS setting to achieve better coordination and faster tripping times.

Chapter 6

Conclusions

Closed loop operation of the ring and radial substation in the primary substation F will improve the reliability indices SAIFI by 0.0373 and SAIDI by 0.4339 in primary substation F. The current in the closed loop feeders are shared to minimize the line losses in the parallel paths. This will improve the voltage of the feeders. This results in more active power and reactive power being fed to the consumer.

Existing panel substation in Colombo City provides a low cost transformation towards closed loop operation by replacing the existing relays with directional relays. Relay protection setting has to be coordinated to avoid nuisance tripping in closed loop arrangement.

Effectiveness of the closed loop operation increases at higher loads when the line losses and voltage drops are at the highest. Loading has to be considered in looking into viability of closed loop operation.

High impedance cable between the substations creates difficulties to achieve better protection coordination. Increasing the number of substations in the closed loop creates a similar effect because longer cable length increases the impedances between substations in the ring.

5.5. Future Work

Data on different types of transformers in Colombo City primary substations are collected and the possibility of parallel operation with controlled loading and voltage regulation is analyzed and simulated. Table is implemented showing the capability of parallel operation of different transformers in primaries and explaining the nature of load sharing and minimum circulating currents for the parallel operation of primary transformers in Colombo City. Network is analyzed for earth fault conditions with multiple earthing points for parallel operation of transformers in different primaries.

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