SOLUTIONS TO POWER QUALITY PROBLEMS AT KANDANA WATER SUPPLY SCHEME

A dissertation submitted to the
Department of Electrical Engineering, University of Moratuwa
in partial fulfilment of the requirements for the
Degree of Master of Science

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Abstract

Quality of the power supply becomes a key issue in plant automation. Especially, voltage sags appearing on the electricity supply cause voltage sensitive equipment to shut down and incur heavy financial losses to Industrial customers. -However, effects of voltage sags can be minimized or mitigated considerably if both utility and the plant are working with good cooperation. This thesis presents power quality issues and mitigating techniques of voltage sag problem at Kandana water treatment plant where sensitive equipment are used for different stage of water treatment and distribution process.

Kandana water treatment plant consists of five pumps having capacity of 500 kW and three pumps with 200 kW capacities. The pumps are controlled by several sensitive electronic devices which are vulnerable to voltage sags. By analyzing the past break down data at Horana Grid substation and plant disturbance recorded at treatment plant and measurement taken with a power quality analyzer it has been observed that the voltage sag appearing at the treatment plant are mainly caused by faults.

First, investigations were carried out to estimate the severity of voltage sag associated with different types of faults in the utility network and their impacts on the equipment installed in the water treatment plant. Then, the effects of voltage sags on the equipment vulnerable for water pumping and distribution process like large pumps with sensitive electronic controllers were investigated to find out a mitigating solution. Detail analysis with theoretical descriptions has been given to describe field observation.

In order to solve the power quality problem especially the voltage sag, several options system level and device level have been considered. It is noted most of the system level mitigating solutions have been implemented by the utility side. Then device level solutions have been introduced. In this sense, Dynamic Voltage Restorer

CDVR) was used to solve the voltage sag problem. Further, designing and controlling of the DVR have been with theoretical derivations and simulations results are given to justify the proposed solution. Remarkably good results have been gained by using this Dynamic Voltage Restorer.

Declaration

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

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

UOM Verified Signature

U.N.Attanayake.

Date 5|2|2010

We endorsed the declaration by the candidate.

Prof. H.Y.R.Perera. ***UOM Verified Signature***

Dr. H.M.Wijekoon

Content

Acknowledgements

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List of Figures

List of Tables

Abbreviations

PQ - Power Quality
CEB - Ceylon Electricity Board
DVR - Dynamic Voltage Restorer
GSS - Grid Substation
kV - Kilo Volts
MVA - Mega Volt Ampere
RMS - Root Mean Square
SLG - Single line to Ground
IGBT - Insulated gate bipolar transistor
VSC - Voltage Source Converter
UPS - Uninterruptable Power Supply
GMD - Geometrical Mean Diameter
GSS - Grid Substation

Chapter 1

Introduction

1.1 Background of the study

Dependency on a reliable and continuous electricity supply has been considered as a major factor in today's life due to increased living standards and thereby greater usage of electronic equipments in the industrial and commercial sectors, thus identification, quantification and resolving of power quality (PQ) problems is becoming a very important concern to customers as well as utilities. PQ problems such as sag, swell, harmonic distortion, unbalance transient and flicker can impact customer operations, causing malfunctions and cost on loss of production and down time.

Both electric utilities and end users of electric power are becoming increasingly concerned about the quality of electric power. The term power quality has become one of the most prolific buzzword in the power industry since late 1980s. It is an umbrella concept for a multitude of individual types of power system disturbances.

There are four major reasons for increasing power quality problems;

1. Newer-generation load equipment, with microprocessor-based controls and power electronic devices, is more sensitive to power quality variations than the equipment used in the past.

2. The increasing emphasis on overall power system efficiency has resulted in continued growth in the application of devices such as high-efficiency, adjustable speed motor drives and shunt capacitors for power factor correction to reduce losses. This is resulting in increasing harmonic levels on power systems and has many people concerned about the future impact on system capabilities.

3. End users have an increased awareness of power quality issues. Utility customers are becoming better informed about such issues as interruptions, sags, and switching transients and are challenging the utilities to improve the quality of power delivered.

4. Many things are now interconnected in a network. Integrated processes mean that the failure of any component has much more important consequences [1].

The figure 1.1 shows the power system interaction with customers. It is clear from this figure that initially the utility will provide pure sine wave supply to the customers and the customers inject non-linear current to the system. This results in distorting supply voltage to other customers. Thus the power quality becomes bi-directional phenomena.

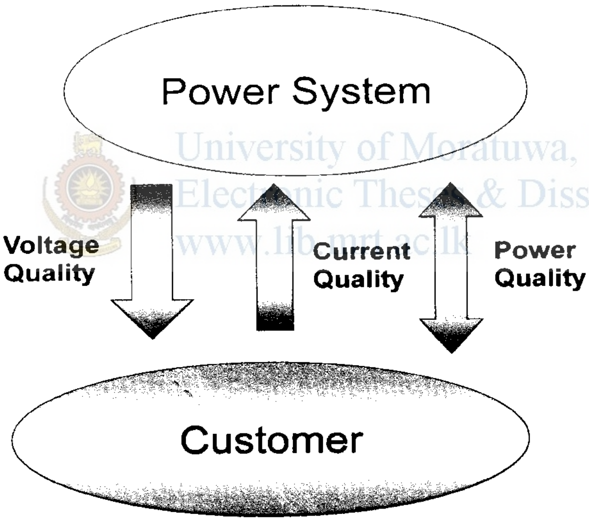

Fig. 1.1: Supply Voltage Quality and Customer Interaction

1.2 Power quality problems

Power quality problems can be categorized as

- Voltage Regulation /Unbalance
- Voltage Sags / Interruptions
- Flicker
- Transients
- Harmonic Distortion

Voltage sags are the most severe power quality disturbance faced by industrial consumers. Since the complexity of the electronic equipment used in the industrial plant increases, the equipment is becoming more sensitive to voltage sags [2]. Voltage sag is a momentary decrease in the rms voltage magnitude lasting for half a cycle to several seconds. Disruptive voltage sags are usually caused by fault condition on the utility transmission and distribution systems or within a customer's facility. Motors starting within the customer facilities can also result in voltage sag for neighborhood customers. The characteristics of these voltage sags are predictable and can be prevented.

This thesis discuss about the Power quality problem at Kandana water treatment plant where sensitive equipment are used for different stages of water treatment and distribution process. Further, the mitigation solutions in the form of custom power devices will be introduced. Finally, the economic analysis of the solution will be discussed.

1.3 Motivation

Frequent interruptions and long duration supply restorations are very common in the present supply system in Sri Lanka. Thus CEB has been paying attention to reduce number of interruptions and supply restoration duration thereby improving supply reliability of existing consumer supply. Hence a little or no attention has been paid on the power quality problems in the system, especially at sensitive loads like glass industry, cement industry, water supply schemes where precise microprocessor controllers are used for adjustable speed drive systems.

With the development of state of art technology, the uses of sensitive equipment in industrial processes are unavoidable since the development of industries directly affect to the economic and social development of the country as a whole. However, the quality of supply is not up to the level which is expected by the modern sensitive equipment.

Thus power quality improvement measures are becoming compulsory for the development of electricity sector in the country. However, a little or no data is available at present on the severity and extent of the problem, which considered as a major obstacle for the development of the sector.

Short-duration power disturbances, such as voltage sags, swells and short interruptions, are major concerns for industrial customers. Due to the wide usage of sensitive electronic equipment in process automation, even voltage sags last for only a few milliseconds may cause shut down of production process with considerable associated costs; these costs include production losses, equipment restarting at peak time, damaged or lower-quality product and reduced customer satisfaction [3].

In this context, a comprehensive study on a power quality problem in selected consumer location will be a good contribution in order to make avenues to the area of power quality research in the CEB network. Thus I as an engineer attached to Ceylon Electricity Board have been greatly motivated to study power quality problem in the Kandana Water Board Site where microprocessor based controllers which are sensitive to power quality problems are used in the water treatment process.

1.4 Objectives

- ☐ To investigate the power quality problem in Kandana Water Supply Scheme
- ☐ To propose a cost effective solution to mitigate identified power quality problems at kandana water supply Scheme
- ☐ To make avenues to the area of power quality research in the CEB network

1.5 Scope of the work

- Literature Survey
- Data Collection and System Identification
- Identification of voltage sag severity with the use of PQ Data Logger
- Designing of Series Compensating Device (DVR) to mitigate most common voltage sags.
- Mathematical Modeling and Simulation.
- Documentation

Chapter 2

Power Quality Measurements at the Site

2.1 Background

The Kandana water treatment plant is located in Horana area and is taking power from Horana 132 kV/33 kV Grid Substation. The installed capacity of Kandana water treatment plant is 4 MVA including phase II expansion. Presently, phase I has been completed and the operating capacity is 2.0 MVA. This treatment plant consists of five pumps having capacities of 500 kW and three Pumps having 200kW as major loads. In addition to above main pumps there are several small pumps which are needed in many different stage of the treatment plant. Motor controllers consist of sensitive electronic equipment which are vulnerable voltage variations.

A dedicated 33 kV overhead tower line (about 6km long) feeds power from the Horana Gantry to the Kandana Treatment Plant. The Horana Gantry has three outgoing feeders feeding Bulathsinghala, Natupana Area and Kandana Traetment Plant Horana Gantry is fed from the 132kV/33kV Grid substation using two 33 kV overhead lines. one feeder is an express line feeding directly Kandana/Bulathsinghala / Natupana Gantry, while other feeder is a distribution feeder.

During operation of the treatment plant there is frequent tripping due to voltage sags. After tripping of motors especially at peak time it is very difficult to restart the motors. It takes a long time due to high starting current of the motors with flywheels and the time taken to stabilize the chemical feeding and the settling.

When there is a fault in remote location in Bulathsinhala feeder of Horana grid substation, the 33 kV bus bar voltage drops well below the specified level until the fault is cleared by the feeder circuit breaker which is operated based on over current principle. The 33 kV bus voltage drop appear as a voltage sag to the Kandana Water Supply scheme and it leads to tripping of water pumps. Although a stand-by Generator is available, its operation is also not viable as the power is restored within a short time.

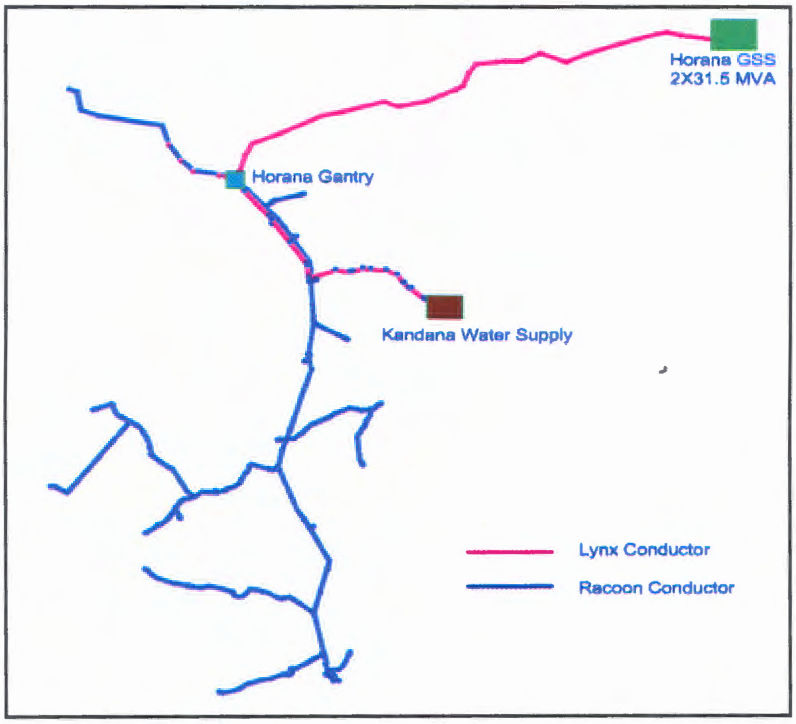

Fig. 2.1: Feeding arrangement to Kandana Water Project

2.2 Site measurements

In order to identify the problems in the electricity supply to particular site measurements which includes characteristics of the power supply should be obtained. In this case, an instrument called power quality data analyzer which gives different data sets like waveform distortion, voltage and current magnitude changes etc has been used.

There are several important reasons to monitor power quality. Type of power quality problem can be classified by monitoring the data. Effects on equipment and process operations can include maloperation, damage, process disruption, and other such anomalies. Such disruptions are costly since a profit-based operation is interrupted unexpectedly and must be restored to continue production. In addition, equipment damage and subsequent repair cost both money and time. Product damage can also result from electromagnetic phenomena requiring that the damaged product either be recycled or discarded, both of which are economic issues.

In addition to resolving equipment disruptions, a database of equipment tolerances and sensitivity can be developed from monitored data. Such a database can provide a basis for developing equipment compatibility specifications and guidelines for future equipment enhancements. In addition, a database of the causes for recorded disturbances can be used to make system improvements. Finally, equipment compatibility problems can create safety hazards resulting from equipment misoperation or failure.

Problems related to equipment misoperation can only be assessed if customer disturbance reports are kept. These logs describe the event inside the facility, the type of equipment that was affected, how it was affected, the weather conditions, and the losses incurred.
The recommended monitoring period is defined as a complete working cycle (power period). In all cases, the data obtained is a snap shot of the power quality profile [20]

2.3 Allocated Time slots for each site

The following is a summary of the installation of analyzer at each site

Site No.	Location	Time Interval
Hoarana GSS	Feeder 4	26.08.2009 - 20.09.2009
Kandana Plant	Incoming 33kV bus	20.09.2009 - 28.09.2009

Table 2.1: Time Table for installation of PQ Analyzer at sites

2.4 Data Logging

An important part of the research is the collection of measurement data for each site and all data have been collected via software named TOPAS which was distributed with the PQ analyzer.

Based on above process LEMQwave PQ Analyzer which belongs to Ceylon Electricity Board was installed at 33kV bus of Horana GSS monitoring feeder 4 as well as at the incoming of the Kandana water treatment plant. The figure 2.2 shown the events logged during the period given in section 2.3.

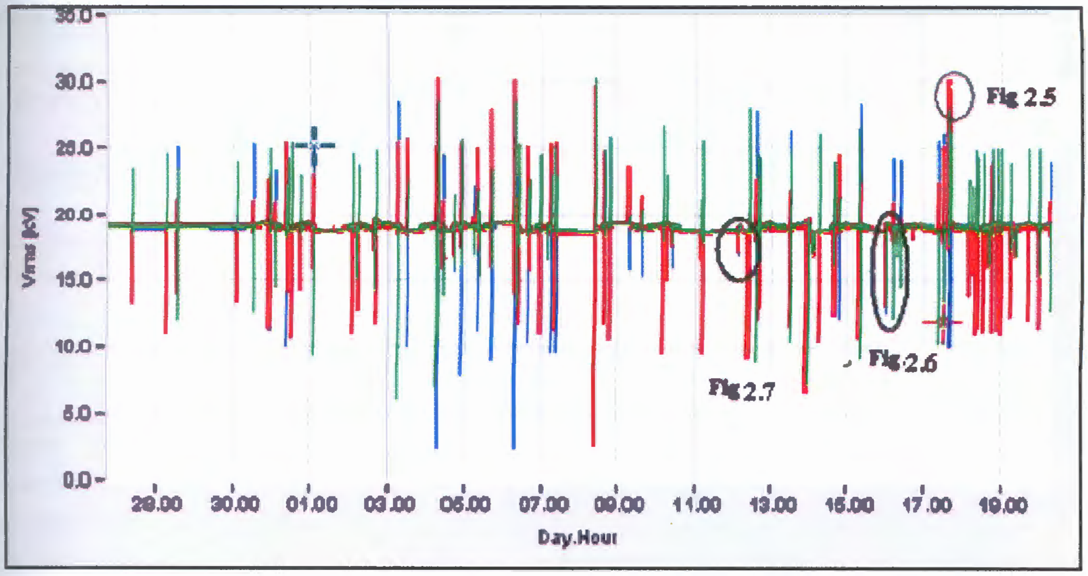

Fig. 2.2: Voltage Events at Horana GSS

2.5 33kV Bus Bar at Horana Grid Substation

Location: 33kV Bus Bar of Feeder 4

Analysis Time Period:

Start : 26.08.2009	18:30:00hrs
End : 20.09.2009	16:00:00hrs
Difference:	3W 3d 1h 20m 0s
Nominal Voltage:	33000.00Volts
Notations:	UL 12: Phase Voltage R-Y
	UL 23: Phase Voltage Y-B
	UL 31: Phase Voltage B-R

According to the time period mentioned above, required data have been collected using PQ analyzer. Table 2.2 shows the voltage events at Horana grid substation.

		UL12	**UL23**	**UL31**
Over Voltage > 36300	Quantity Max. Value Max. Duration	0 0 0.0000ns	0 0 0.0000ns	0 0 0.0000ns
Voltage Dips <29700	Quantity Max. Value / V_{rms} Max. Duration	55 8640.65 656.8406ms	38 11543.82 646.8744ms	42 12555.88 646.8744ms
Short Interruptions <1.00% Vn <3.00 Minutes	Quantity Max. Duration	0 0.0000ns	0 0.0000ns	0 0.0000ns
Long Interruptions <1.00% Vn > 3.00 Minutes	Quantity Max. Duration	0 0.0000ns	0 0.0000ns	0 0.0000ns

Table 2.2: Voltage events at Horana Grid Substation

2.6 33kV Incoming Bus at Kandana Treatment Plant

Location: 33kV Bus Bar of Kandana Treatment Plant

Analysis Time Period:

Start : 20.09.2009	19:30:00hrs
End : 28.09.2009	08:50:00hrs
Difference:	1W 0d 16h 50m 0s
Nominal Voltage:	33000.00Volts
Notations:	UL 12: Phase Voltage R-Y
	UL 23: Phase Voltage Y-B
	UL 31: Phase Voltage B-R

According to the time period mentioned above, required data have been collected using PQ analyzer. Table 2.3 shows the voltage events at Kandana water treatment plant.

		UL12	**UL23**	**UL31**
Over Voltage > 36300	Quantity Max. Value Max. Duration	0 0 0.0000ns	0 0 0.0000ns	0 0 0.0000ns
Voltage Dips <29700	Quantity Max. Value / V_{rms} Max. Duration	3 23842.90 338.9022ms	4 23916.59 368.7747ms	2 23631.29 348.8598ms
Short Interruptions <1.00% Vn <3.00 Minutes	Quantity Max. Duration	0 0.0000ns	0 0.0000ns	0 0.0000ns
Long Interruptions <1.00% Vn > 3.00 Minutes	Quantity Max. Duration	0 0.0000ns	0 0.0000ns	0 0.0000ns

Table 2.3: Voltage events at incoming bus at Kandana Treatment Plant

According to the measurement data at horana GSS, number of total voltage sags appeared at 33kV bus were 135. Furthermore, all the sags were appeared at the Kandana treatment plant only 62 no. of voltage sags caused to trip the treatment plant. Detail study shows that the severity of other voltages is outside the set limit at the Kandana treatment plant.

Figure 2.3 and 2.4 show the CBEMA curves at Horana GSS and Kandana treatment plant. Points below envelops were presumed to cause the load to drop out due to lack of energy. Those voltage sags were not tolerable. Points inside envelop were in acceptable level.

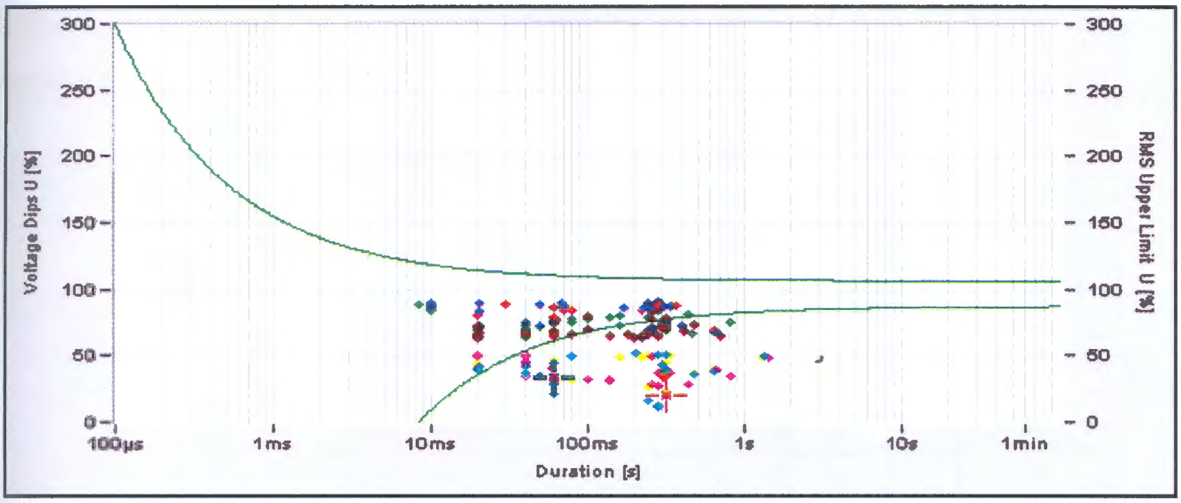

Fig. 2.3: Voltage Dips with CBEMA curve overlay for 33kV Bus Bar at Horana GSS

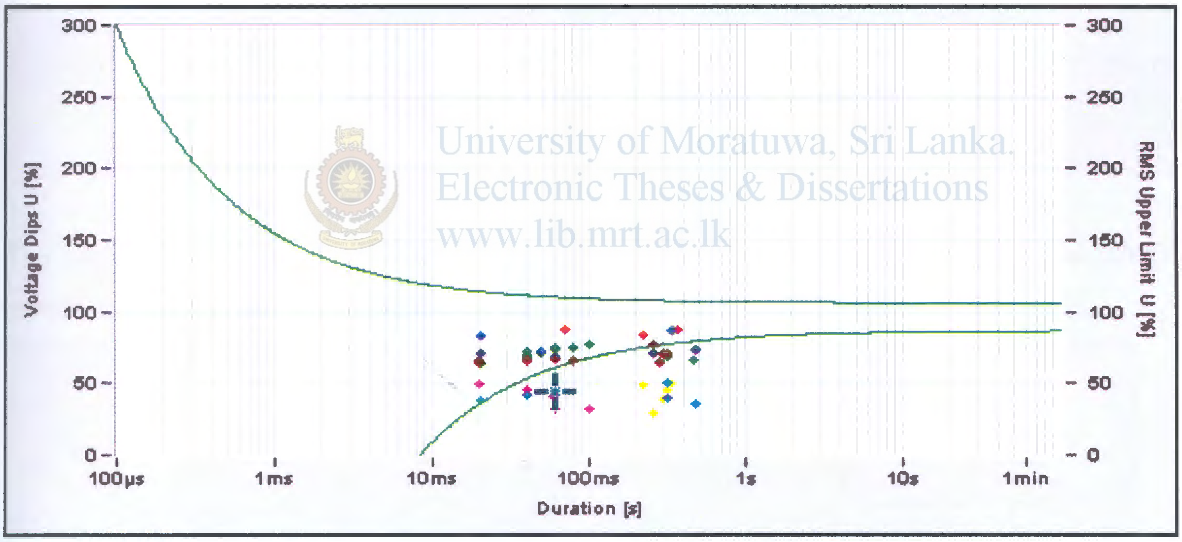

Fig. 2.4: Voltage Dips with CBEMA curve overlay for 33kV Bus Bar at Kandana Water treatment Plant

2.7 Analysis of Data

As per the standard, it is required to collect sag data for at least one year to get the actual assessment of voltage sag phenomena at the site. Definite measurement of the voltage sags for one year is not practically possible with this project. But with actual measurement and number of feeder tripping which are logged for last twelve months could be used to get fairly well approximated index about voltage sags for the site [21].

Period	No. of Trippings
October 2008	21
November 2008	20
December 2008	11
January 2009	13
February 2009	20
March 2009	30
April 2009	25
May 2009	33
June 2009	18
July 2009	28
August 2009	15
September 2009	11
October 2009	26
November 2009	36
Total	307

Table 2.4: No. of Tripping at Horana GSS

The captured RMS data shows that there were various shape of voltage sags at Horana GSS, certain common types are illustrated above in Figure 2.4, 2.5 and 2.6.

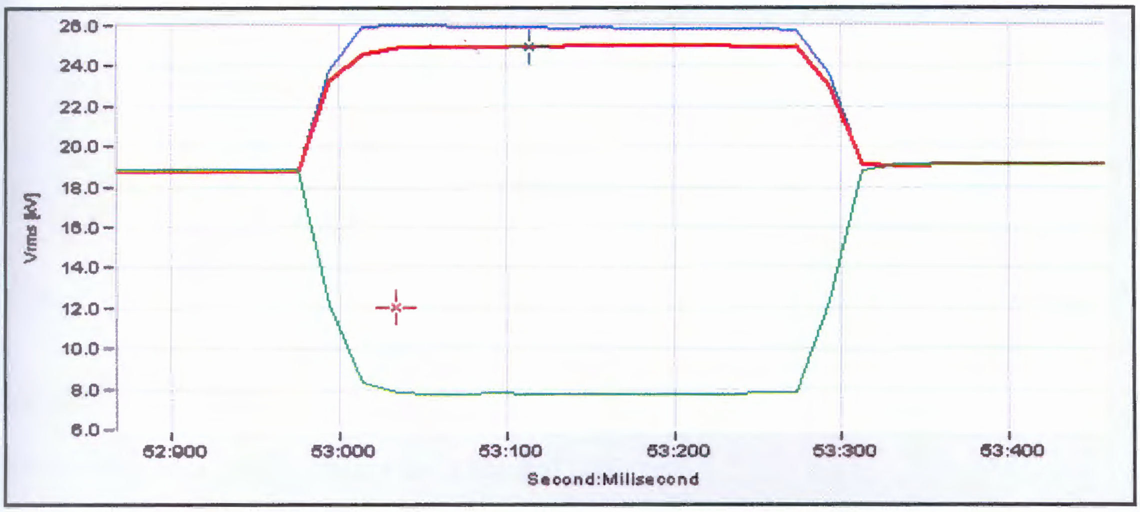

Fig. 2.5: Voltage Sag stamped on 17.09.2009, at 11:59:52:7999 due to single phase fault tripping of Feeder 4 - Horana GSS

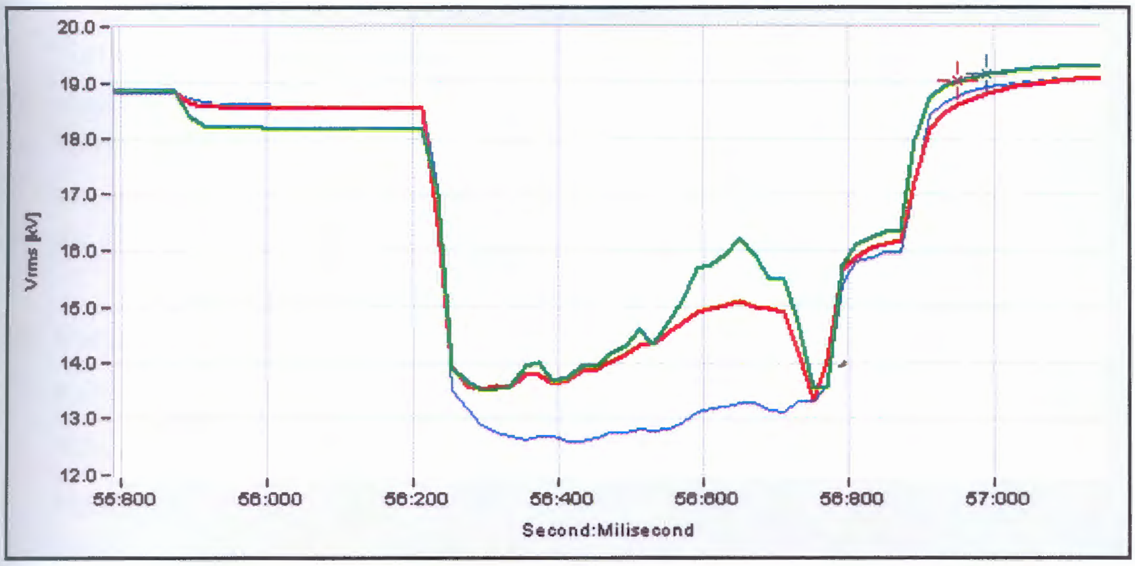

Fig. 2.6: Voltage Sag stamped on 16.09.2009, at 14:47:12:754 due to three phase fault tripping of Feeder 4 - Horana GSS

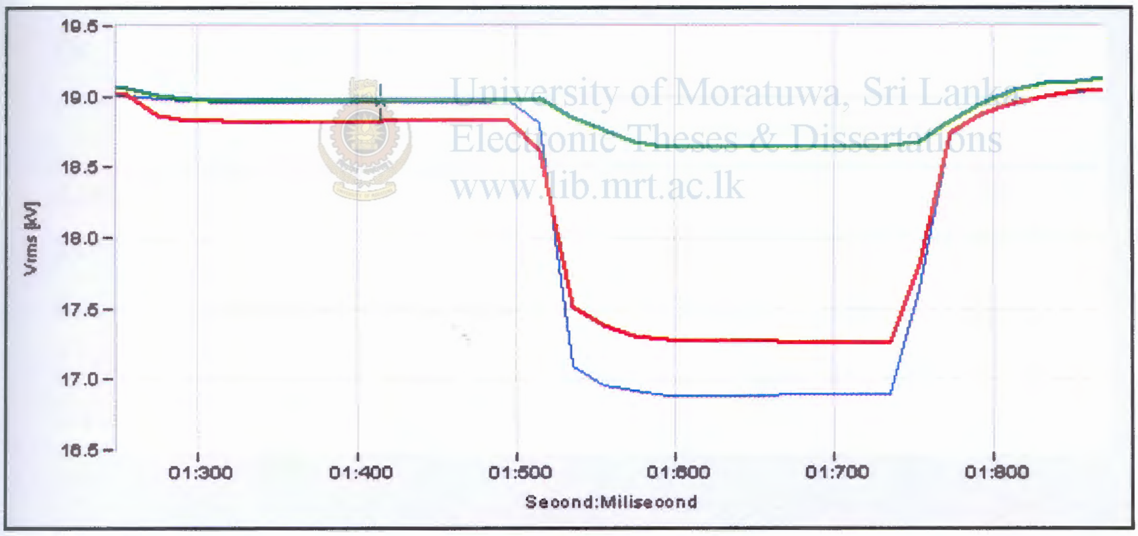

Fig. 2.7: Voltage Sag stamped on 12.09.2009, at 04:40:01:330 due to two phase fault tripping of Feeder 4 - Horana GSS

Using LEMQwave PQ Analyzer, logged all necessary power quality data.

Following power quality data were taken and analyzed.

- **Voltage Variation**

  95% of Tolerance range of the voltage variation V_{max} – 36300 V

  V_{min} - 29700 V

According to the results V_{max} – 33680 V

V_{min} - 32276 V

Therefore, all values of voltages are within the required tolerance range.

- **Harmonics**

  When considering the harmonic results of the data, a minimum of 95% of all values of the THD are within the tolerance range.

- **Voltage Unbalance**

  Required Voltage unbalance tolerance is 2%

  95% of value of voltage unbalances – 0.21%

  Maximum Value - 0.56%

  100% of all values are within the tolerance range

- **Long Term Flicker**

  Required tolerance is Plt < 1.00

  Plt The long-term flicker severity level as defined by IEC 61000-4-15, based on an observation period of 2 h[1].

According to the results

95 % of Value	**Max. Value**	**Appeared at**
0.9683	3.0472	13 / 9/ 2009 23:20
0.9608	4.5669	13 / 9/ 2009 23:20
0.8424	3.1302	2 / 9 / 2009 18:10

95% of values are within the tolerance range. Therefore flicker is not a dominant power quality problem in Horana GSS.

Considering the voltage sag data in table 2.2, the most dominant power quality problem is voltage sag. No other significant power quality problem appearing at the Kandana water treatment plant.

Chapter 3

Voltage Sags and their Impacts

3.1 Background

Sag is a voltage decrease in rms voltage between 0.1 and 0.9 pu at the power frequency for durations from 0.5 cycle to 1 min [1].

The power quality community has used the term sag for many years to describe a short-duration voltage decrease. Although the term has not been formally defined, it has been increasingly accepted and used by utilities, manufacturers, and end users. The IEC definition for this phenomenon is dip. The two terms are considered interchangeable, with sag being the preferred synonym in the U.S. power quality community.

Terminology used to describe the magnitude of voltage sag is often confusing. A "20 percent sag" can refer to a sag which results in a voltage of 0.8 or 0.2 pu. The preferred terminology would be one that leaves no doubt as to the resulting voltage level: "sag to 0.8 pu" or "a sag whose magnitude was 20 percent." When not specified otherwise, a 20 percent sag will be considered an event during which the rms voltage decreased by 20 percent to 0.8 pu. The nominal, or base, voltage level should also be specified.

Voltage sags are usually associated with system faults but can also be caused by energizing of heavy loads or starting of large motors. 80 percent sag exists for about 3 cycles until the substation breaker is able to interrupt the fault current. Typical fault clearing times range from 3 to 30 cycles, depending on the fault current magnitude and the type of over current protection [1]

Categories	Typical Spectral Context	Typical Duration	Typical Voltage Magnitude
1.0 Transients			
1.1 Impulsive			
1.1.1 Nanosecond	5 ns rise	< 50 ns	
1.1.2 Microsecond	1 μs rise	50 ns – 1 ms	
1.1.3 Millisecond	0.1 ms rise	> 1 ms	
1.2 Oscillatory			
1.2.1 Low Frequency	< 5 kHz	0.3 – 50 ms	0 – 4 pu
1.2.2 Medium Frequency	5 – 500 kHz	20 μs	0 - 8 pu
1.2.3 High Frequency	0.5 – 5 MHz	5 μs	0 – 4 pu
2.0 Short Duration Variations			
2.1 Instantaneous			
2.1.1 Interruption		0.5 – 30 cycles	< 0.1 pu
2.1.2 Sag		0.5 – 30 cycles	0.1 – 0.9 pu
2.1.3 Swell		0.5 – 30 cycles	1.1 – 1.8 pu
2.2 Momentary			
2.2.1 Interruption		30 cycles – 3 s	< 0.1 pu
2.2.2 Sag		30 cycles – 3 s	0.1 – 0.9 pu
2.2.3 Swell		30 cycles – 3 s	1.1 – 1.4 pu
2.3 Temporary			
2.3.1 Interruption		3 s – 1 min	< 0.1 pu
2.3.2 Sag		3 s – 1 min	0.1 – 0.9 pu
2.3.3 Swell		3 s – 1 min	1.1 – 1.2 pu
3.0 Long Duration Variations			
3.1 Interruption, sustained		> 1min	0.0 pu
3.2 Under voltage		> 1min	0.8 – 0.9 pu
3.3 Over voltage		> 1min	1.1 – 1.2 pu
4.0 Voltage Imbalance		Steady State	0.5 – 2%
5.0 Waveform Distortion			
5.1 DC Offset		Steady State	0 – 0.1%
5.2 Harmonics	0 – 100th H	Steady State	0 – 20%
5.3 Inter harmonics	0 – 6 kHz	Steady State	0 – 2%
5.4 Notching		Steady State	
5.5 Noise	Broad - Band	Steady State	0 – 1%
6.0 Voltage Fluctuations	< 25 Hz	Intermittent	0.1 – 7%
7.0 Power Frequency Variations		< 10 s	

Table 3.1: Categories and Typical characteristics of power system electromagnetic phenomena [1].

Figure 3.1 shows the 60% of voltage sag and figure 3.2 shows the 60% of rms voltage.

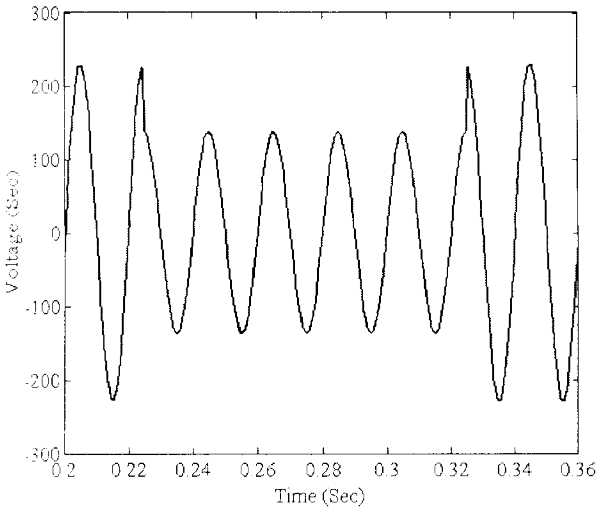

Fig. 3.1: Voltage Sag to 60%

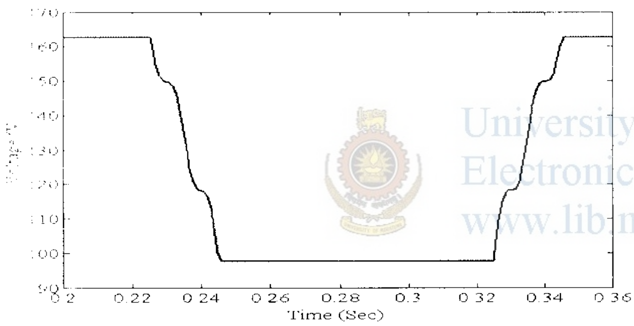

Fig. 3.2: Voltage Sag to 60% (RMS Value)

3.2 Voltage Sag Standards

There is a difference between the description of the voltage sag as given by the IEEE and IEC standards.

The IEC standard describes voltage sag as a sudden reduction of the voltage at a point in the electrical system, followed by a voltage recovery after a short period of time, from 0.5 cycles to a few seconds. The amplitude of voltage sag being the difference between the voltages during sag and the nominal voltage of the system, expressed as a percentage of nominal voltage.

The IEEE standard describes voltage sag as a decrease to between 0.1 to 0.9 pu in rms voltage (or current) at power frequency, for the duration of 0.5 cycle to 1 minute.

The voltage sag standards prescribed in table 3.2 have to be used with restrictions. There are no limit standards related to the voltage sag in the utility electrical systems, though the IEC standard 1000-2-2 title might lead one to think that it establishes the same. Orientation values applied to industrial and commercial systems are shown in the IEC Standard 1000-2-4, and most documents present criteria to voltage sag evaluation and reference limits for sensitive equipment.

3.2.1 The IEEE and IEC Voltage Sag Standards

Standard	Area of Applicability	Subject
IEEE p 1346	General Electrical System	Guide and methodology to Voltage Sag Evaluation
IEEE 493	Industrial & Commercial System	Criteria to Reliability Evaluation
IEEE 446	Industrial & Commercial System	Range of Sensibility Loads (CBEMA)
IEEE 1159	General Power System	Voltage Sag Definitions & Monitoring
IEEE 1100	General Power System	Voltage Sag Monitoring
IEEE 1250	Equipment	Guide to Electronic Equipment
IEC 1000-2-2	Utility Power System	-
IEC 1000-2-4	Industrial & Commercial Power System	Limits of Compatibility
IEC 1000-4-11	Equipment	Immunity Tests

Table 3.2: Voltage sag standards

IEEE (Institute of Electrical and Electronics Engineers) Standards

- IEEE 1159: Monitoring Electric Power Quality
- IEEE 1564: Voltage sag indices
- IEEE 1100: Power and grounding electronic equipment
- IEEE 1433: Power quality definitions
- IEEE 1453: Voltage Flicker
- IEEE 519: Harmonic control in electric power system
- IEEE 519A: Guide for applying harmonic limits on power system
- IEEE 446: Emergency and standby power

- IEEE 1409: Distribution Custom Power
- IEEE 1547: Distributed resources and electric power system Interconnections

IEC (International Electro technical Commission) Standards

- Part 1 IEC 6100-1: Fundamental principles and definitions
- Part 2 IEC 6100-2: Description and Classification of the Electro-Magnetic Environment and compatibility levels
- Part 3 IEC 6100-3: Emission and immunity limits
- Part 4 IEC 6100-4: Testing and Measurements Techniques
- Part 5 IEC 6100-5: Installation and mitigation guidelines.

3.2.2 Voltage Magnitude Events (IEEE Definitions)

IEEE definition can illustrate as follows.

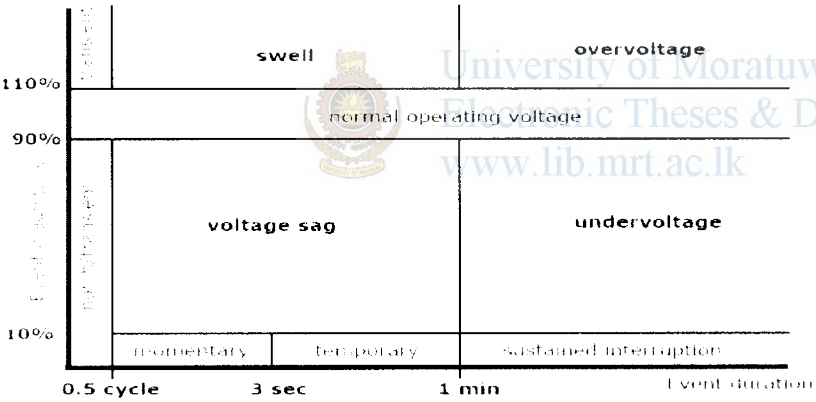

Fig. 3.3: Voltage Magnitude Events

3.3 Cause of voltage sags and their impacts

Voltage sags are usually associated with system faults but can also be caused by switching of heavy loads or starting of large motors. Voltage sags are also associated with a single line-to-ground (SLG) fault. Also, a fault on a parallel feeder circuit will result in a voltage drop at the substation bus that affects all of the other feeders until the fault is cleared. Typical fault clearing times range from 3 to 30 cycles, depending on the fault current magnitude and the type of over current detection and interruption.

Voltage sags can also be caused by large load changes or motor starting. An induction motor will draw six to ten times its full load current during starting. This lagging current causes a voltage drop across the impedance of the system. If the current magnitude is large relative to the system available fault current, the resulting voltage sag can be significant [14].

Some types of faults on the power system cause voltage sags. These faults are typically caused by the following.

- Lightning Strikes
- Tree or Animal contact.

When sag occurs, equipment connected to the power system can misoperate or even fail. When this equipment fails, it can affect the safety and the production of facility related equipment.[15] The ever increasing penetration of automation in industrial end-use dramatically increases production processes susceptibility to voltage sag problems. The proliferation of voltage sensitive equipment has made industrial processes more vulnerable to supply voltage deviations. Such voltage deviations, commonly in the form of voltage sags, can cause severe process disruptions and result in substantial production loss [13].

A momentary interruption of power during a critical stage can be disastrous, collapsing and contaminating the critical environment surrounding the product, resulting in material losses in the tens of thousands of dollars and requiring another several thousand dollars in recovery time and effort. Recovery times of 1-3h were required for voltage sag of less than 300 ms.

Short-duration power disturbances, such as voltage sags, swells and short interruptions, are major concerns for industrial customers. Due to the wide usage of sensitive electronic equipment in process automation, even voltage sags which last for only few tenths of a second may cause production stops with considerable associated costs; these costs include production losses, equipment restarting, damaged or lower-quality product and reduced customer satisfaction.[15] Following graph illustrates that different type of faults causes different voltage sags.

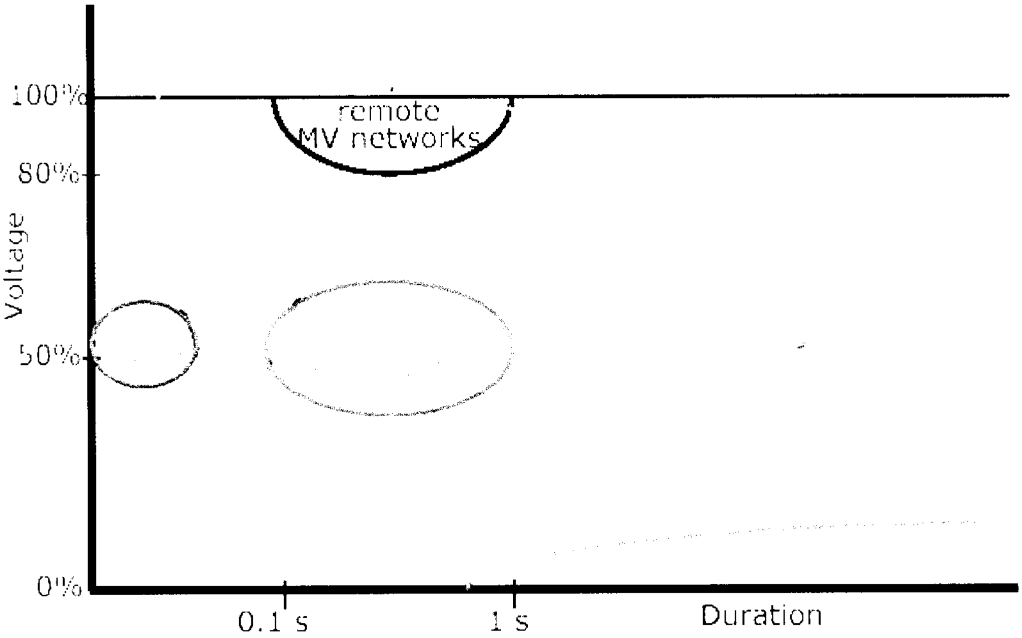

Fig. 3.4: Different types of faults

3.4 Voltage Sag Propagation

Propagation of voltage sags depend on the path and the devices in that path. Voltage sag propagates from one voltage level to another through a transformer. Thus winding arrangement of the transformer plays an important role in propagating voltage sag. Voltage sag originated in transmission system propagates to longer distance than that is originated in Dist. system. Thus for a fault on a 220 kV transmission line, voltage sag may affect sensitive equipment up to several kilometers.

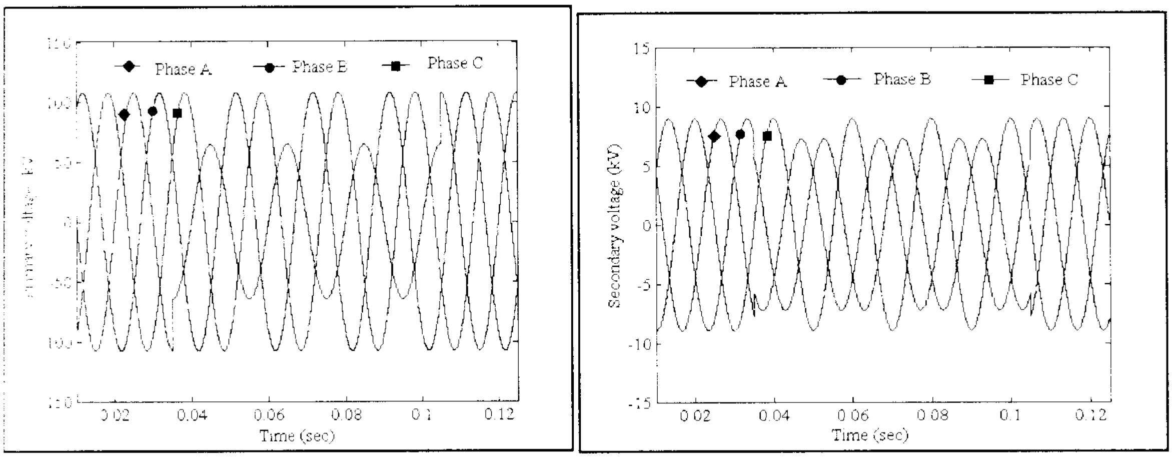

Fig. 3.5: Primary voltage (Y/Δ)

Fig. 3.6: Secondary voltage (Y/Δ)

3.5 Voltage sag calculation

3.5.1 Balance voltage Sag

Balanced voltage sags mainly originate from three phase faults. The sustained voltages sensed at the source side are balanced but the post-fault voltages are likely to be not in phase with their pre-fault quantities [15].

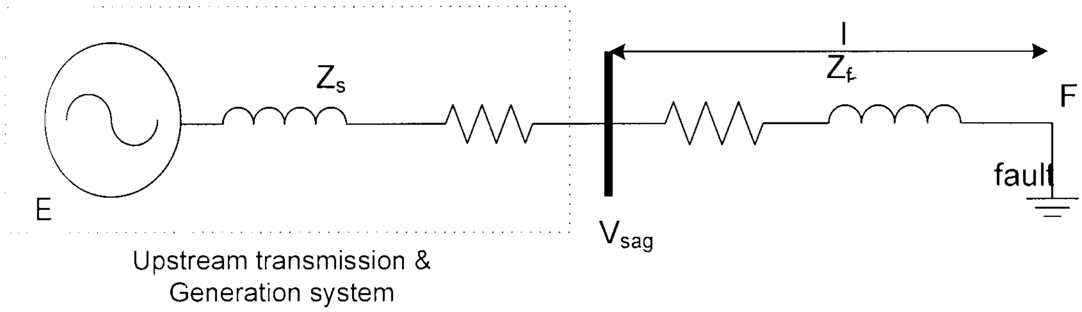

Fig. 3.7: Voltage divider model to analyze balance voltage sags

We can write a expression for voltage sag, using figure 3.7

$$V_{sag} = \frac{E*Z_f}{Z_s + Z_f} \tag{3.01}$$

$$V_{sag} = \frac{E*zl}{Z_s + zl} \tag{3.02}$$

Where $Z_f = z*l$

Phase Angle θ can be written as follows.

$$\theta = \operatorname{Tan}^{-1}\left[\frac{x_f}{r_f}\right] - \operatorname{Tan}^{-1}\left[\frac{x_f + x_s}{r_f + r_s}\right] \tag{3.03}$$

Where Z_S is calculated based on the fault level at the 33 kV bus.

Where z - Impedance of the conductor, Ω/km

l - Length of the transmission line, km

I_f - Fault current

3.5.2 Unbalance Voltage sag

Unbalanced voltage sags are caused by either single phase to ground fault or two phase faults or the combinations of these faults. Voltage characteristics during typical fault conditions are analyzed. It is assumed that the positive and negative phase sequence source impedance is equal.

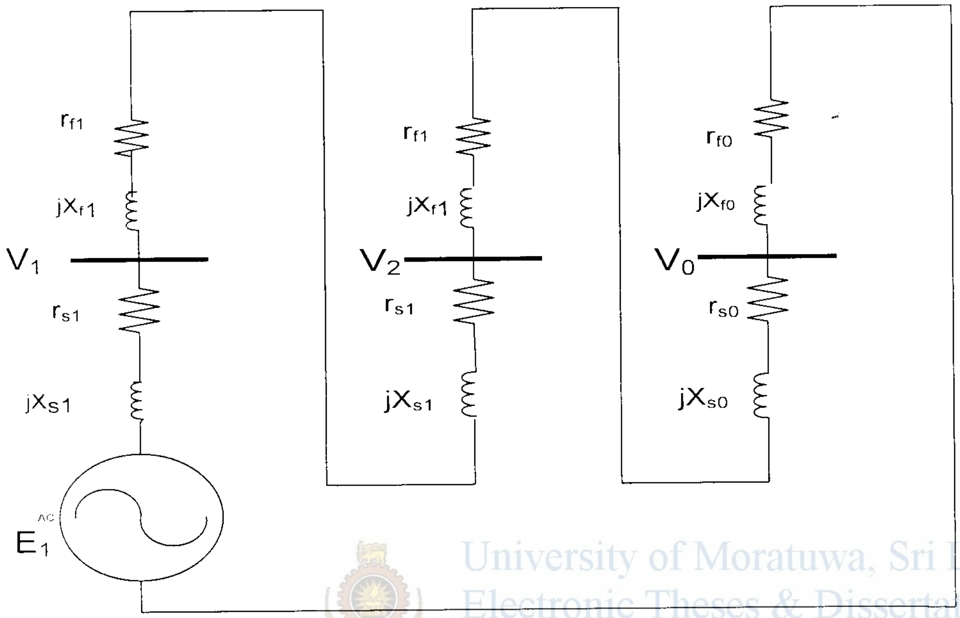

Fig. 3.8: Voltage divider model to analyze unbalance voltage sags

Taking Positive, Negative and Zero sequence voltages for the above circuit,

$$V_1 = E_1 - [(r_{s1} + r_{f1}) + j(x_{s1} + x_{f1})]I_1 \qquad (3.05)$$

$$V_2 = -[(r_{s2} + r_{f2}) + j(x_{s2} + x_{f2})]I_1 \qquad (3.06)$$

$$V_0 = -[(r_{s0} + r_{f0}) + j(x_{s0} + x_{f0})]I_0 \qquad (3.07)$$

$$I_1 = \frac{E_1}{[(r_{s1} + r_{s2} + r_{s0} + r_{f1} + r_{f2} + r_{f0}) + j(x_{s1} + x_{s2} + x_{s0} + x_{f1} + x_{f2} + x_{f0})]}$$

But. $I_1 = I_2 = I_0$

Calculating positive sequence voltage sag V_{pcc1}

$$V_{pcc1} = V_1 + I_1(r_{f1} + jx_{f1})$$

$$V_{pcc1} = E_1 - I_1(r_{s1} + r_{f1})$$

Calculating Negative sequence voltage sag V_{pcc2}

$$V_{pcc2} = V_2 + I_1(r_{f2} + jx_{f2})$$

$$V_{pcc2} = -I_1(r_{s2} + jx_{s2})$$

Calculating zero sequence voltage sag V_{pcc0}

$$V_{pcc0} = -I_0(r_{s0} + jx_{s0})$$

Total Voltage Sag V_{sag}

$$V_{sag} = V_{pcc1} + V_{pcc2} + V_{pcc0} \tag{3.08}$$

$$V_{sag} = \frac{E_1[(2r_{f1} + r_{f0}) + j(2x_{f1} + x_{fo})}{[(2r_{s1} + 2r_{f1} + r_{s0} + r_{f0}) + j(2x_{s1} + 2x_{f1} + x_{s0} + x_{f0})}$$

$$V_{sag} = \frac{E_1[2Z_{f1} + Z_{f0}]}{[2Z_{s1} + 2Z_{f1} + Z_{s0} + Z_{f0}]} \tag{3.09}$$

3.5.3 Calculation of Source Impedance

Fault current of the 33kV Bus at Horana GSS is 9.2 kA [27].

Source Impedance $Z_S = \left[\frac{33/\sqrt{3}}{9.2}\right]$

$$\mathbf{Z_S = 2.07093\ \Omega}$$

For Positive Sequence

Resistance $R = 0.358\ \Omega/\text{km}$

Reactance $X = 2.04\ \Omega/\text{km}$

For Zero Sequence

Resistance $R_0 = R + 3\mu_0\pi f/4\ \Omega/\text{km}$

Reactance

$$X_0 = \mu_0 f\left[\left(3\ln\left\{\frac{\delta}{\sqrt[3]{r(GMD)^2}}\right\}\right)+\frac{1}{4}\right] \qquad (3.10)$$

Where $\delta = \dfrac{1.85}{\sqrt{\mu_0\omega/\rho}}$

$\delta = 0.0278\ \text{mm}^2/\text{m}$

Then

$R_0 = 1.075\ \Omega/\text{km}$

$X_0 = 6.12\ \Omega/\text{km}$

3.6 SynerGEE Software

SynerGEE® Electric is a software package developed by Advantica Stoner designed for simulation, analysis, and planning of 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 based on an object-oriented design consisting of highly detailed models for power system devices such as lines, transformer banks, regulator banks, switched capacitors, active generators, and others.

The models for these devices are built to reflect the actual construction of real power system equipment. Likewise, the usability and capability of SynerGEE demonstrate the level of commitment involved in producing quality analysis software.

Using SynerGEE software, load flow simulation was done for horana GSS. By creating the faults at different locations of the network and taking the voltages at different location using Synergy software. the voltages were compared with those under normal conditions. Then following results were obtained.

Distance From GSS / km	3 Phase Fault / A	Line to Ground Fault / A	%Volt Drop @ 3 Phase Fault	%Volt Drop @ Line to Ground Fault
1	7770	4486	82.6	27.1
2	6436	3683	65.7	22.1
3	5445	3114	54.0	18.6
4	4738	2716	46.0	16.1
5	4181	2404	40.0	14.2
6	3725	2150	35.2	12.6
7	3365	1948	31.4	11.4
8	2972	1755	27.9	10.3
9	2571	1576	22.0	9.0
10	2197	1399	17.8	7.8
11	2158	1346	18.0	7.6
12	2029	1264	16.9	7.1
13	1911	1189	15.9	6.7
14	1639	1075	12.7	5.9
15	1714	1065	14.3	6.0

Table 3.3: Results from SynerGEE software

Distance from GSS / km	% of Volt Drop without fault	% of Volt Drop with fault
1	0.1	82.6
2	0.3	65.7
3	0.5	54.0
4	0.7	46.0
5	0.9	40.0
6	1.1	35.2
7	1.3	31.4
8	1.5	27.9
9	1.8	22.0
10	2.0	17.8
11	2.1	18.0
12	2.2	16.9
13	2.2	15.9
14	2.3	12.7
15	2.4	14.3

Table 3.4: Voltage comparison using SynerGEE software

3.7 Evaluation of Voltage Sag

The utilities play a key role in the quality of supply, though it is also affected by other factors such as the user's operating conditions, the apparatus, the customer's industrial plants and the limits set by the Standard Authorities.

Utilities must have the PQ evaluation and management process. The main role is represented by the monitoring activity, which consists in the collection of data taken from the network and from the users. Then utilities can evaluate their quality of supply such as voltage sags with use of collected data [17].

3.7.1 Effect of Conductor type on voltage sag

The voltage sag for difference conductors and difference fault levels has been studied. As an example for higher fault levels gives low voltage sags. Figure 3.9 and 3.10 shows the graphs of voltage sag Vs Distance for Lynx and Racoon conductors for different fault levels. Figure 3.11 and 3.12 shows the graphs of phase angle jump Vs distance for Lynx and Racoon conductors in different fault levels.

3.7.2 Voltage Sag Vs Distance

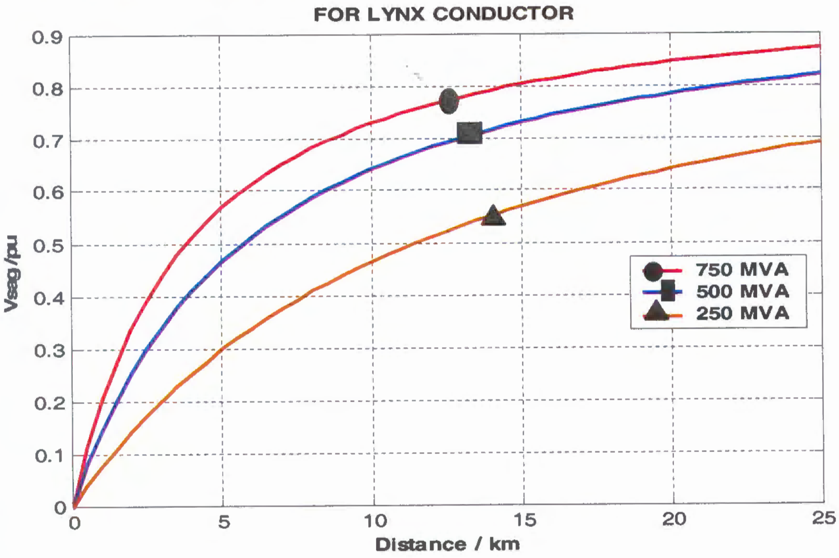

Fig. 3.9: Voltage Sag versus distance from GSS for Lynx Conductor

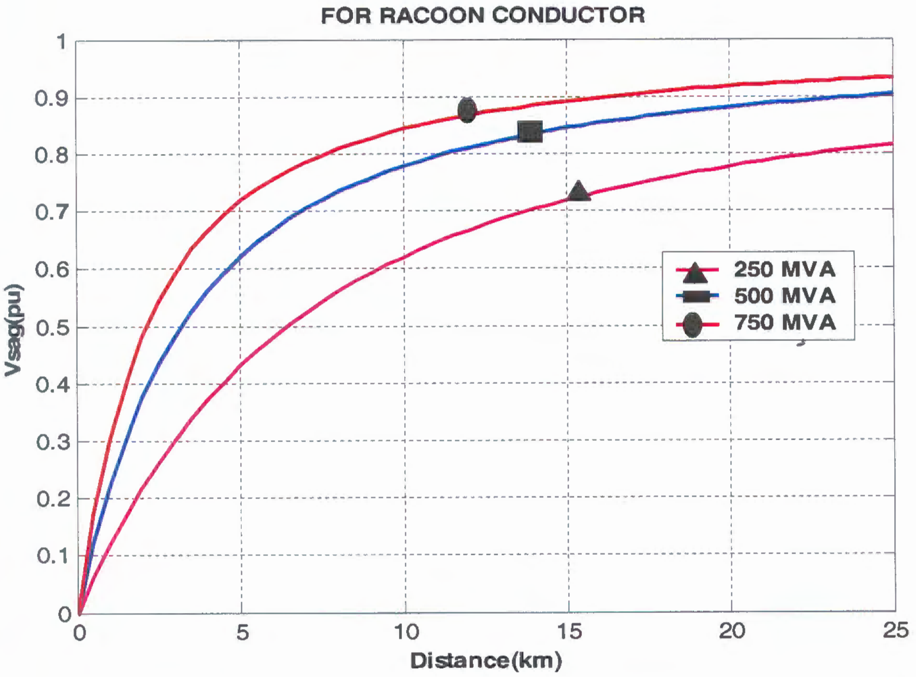

Fig. 3.10: Voltage Sag versus distance from GSS for Racoon Conductor

3.7.3 Phase Angle jump Vs Distance

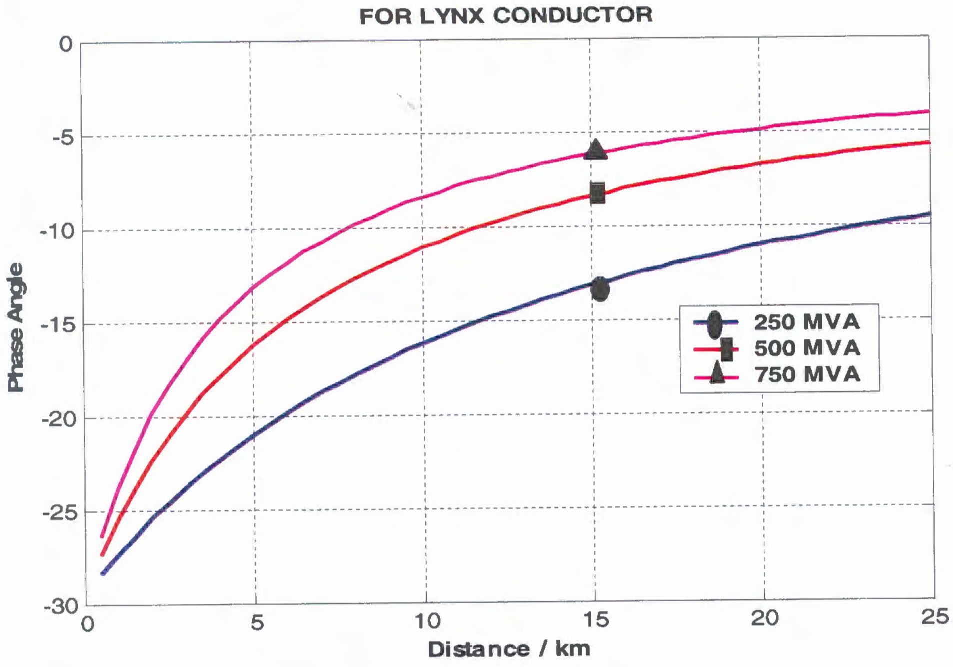

Fig. 3.11: Phase Angle jump versus distance from GSS for Lynx Conductor

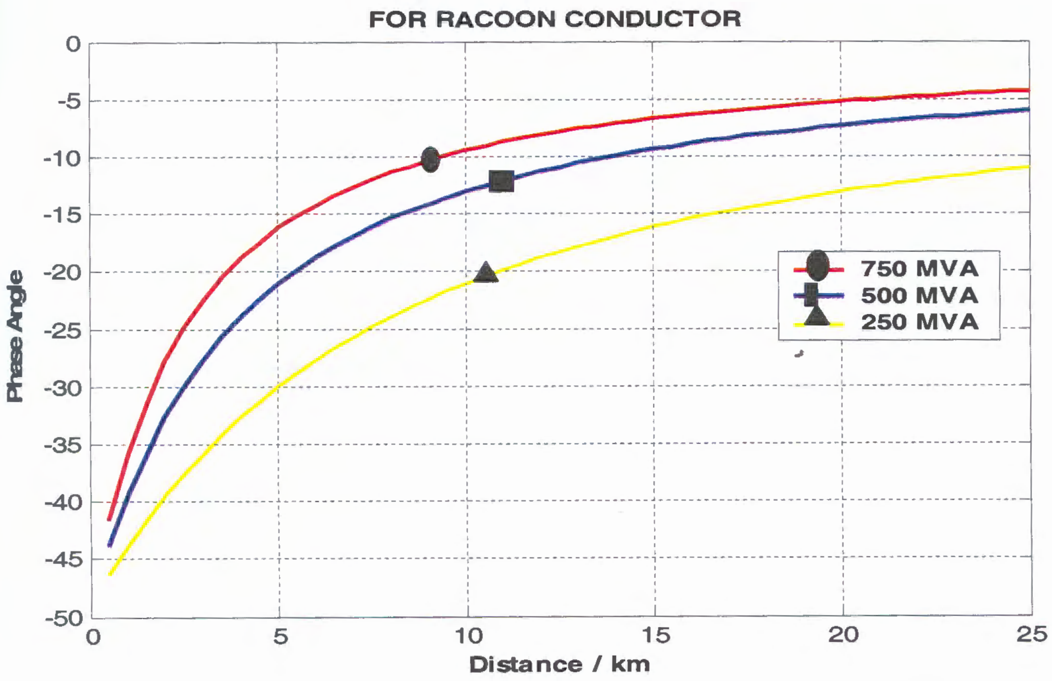

Fig. 3.12: Phase Angle jump versus distance from GSS for Racoon Conductor

3.7.4 Effect of onsite Generators

4 × 5MVA, oil fired generators are connected to 33 kV bus of Horana GSS.

Let us see the effect of these generators on voltage sag severity

Each generator has a reactance of 17.2% based on 5MVA, the rating of the generators [27].

Fault Level with Ace power $I_f = 9.2kA$

Fault Level without Ace power $I_f = 7.7kA$

Distance / km	Voltage Sag with Acepower / pu	Voltage Sag without Acepower / pu
0	0.00	0.00
5	0.48	0.44
10	0.65	0.62
15	0.75	0.71
20	0.80	0.77
25	0.84	0.80

Table 3.5: Data about on site generator (Acepower)

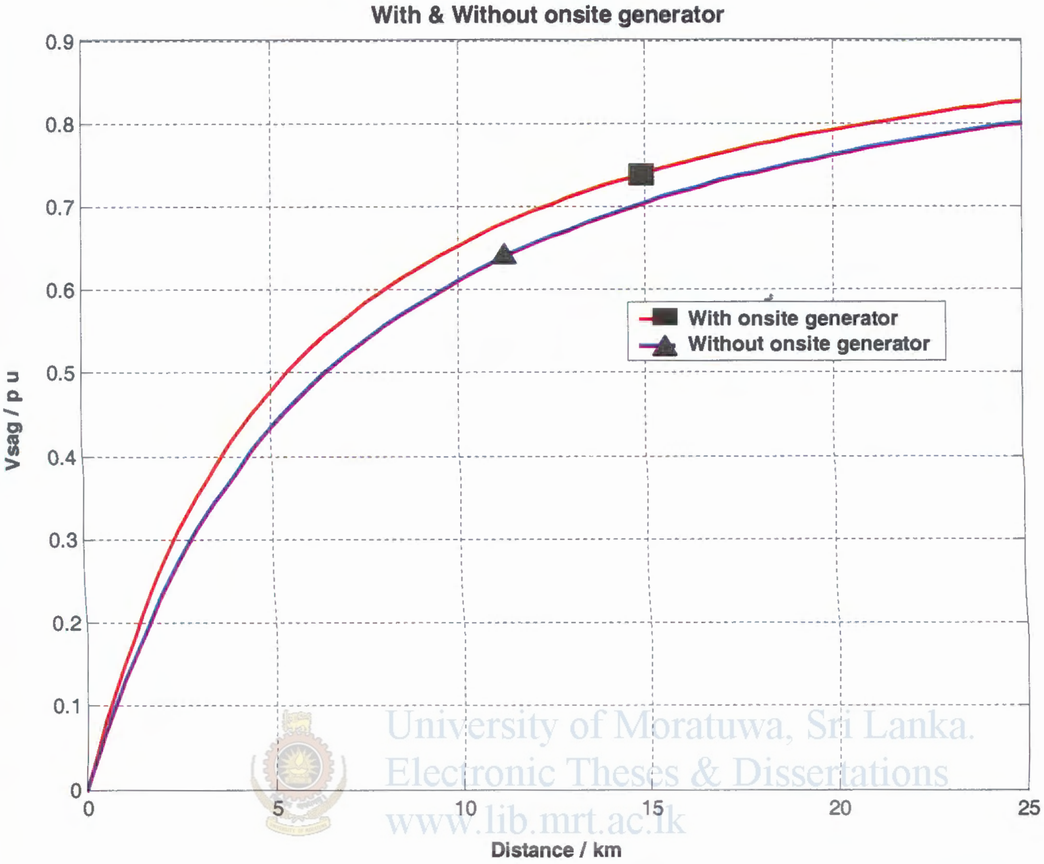

Fig. 3.13: Voltage Sag versus distance for the effect of onsite generators

3.8 Area of Vulnerability

The concept of an area of vulnerability has been developed to help evaluate the likelihood of sensitive equipment being subjected to voltage lower than its minimum voltage sag ride-through capability. The latter term is defined as the minimum voltage magnitude a piece of equipment can withstand or tolerate without misoperation or failure. This is also known as the equipment voltage sag immunity or susceptibility limit. An area of vulnerability is determined by the total circuit length of exposure to balance or unbalance faults that can cause voltage magnitudes at an end-user facility to drop below the equipment minimum voltage sag ride-through capability. The loads will be subject to faults on both the transmission system and the distribution system. The actual number of voltage sags that a facility can expect is determined by combining the area of vulnerability with the expected fault performance for this portion of the power system. The expected fault performance is usually determined from historical data [1].

Using SynerGEE, voltage drops of horana area were discussed in Section 3.6. Then the area of vulnerability was developed for balanced and unbalanced faults as shown in figure 3.14 and 3.15.

3.8.1 Area of Vulnerability for 3ph Balance Faults

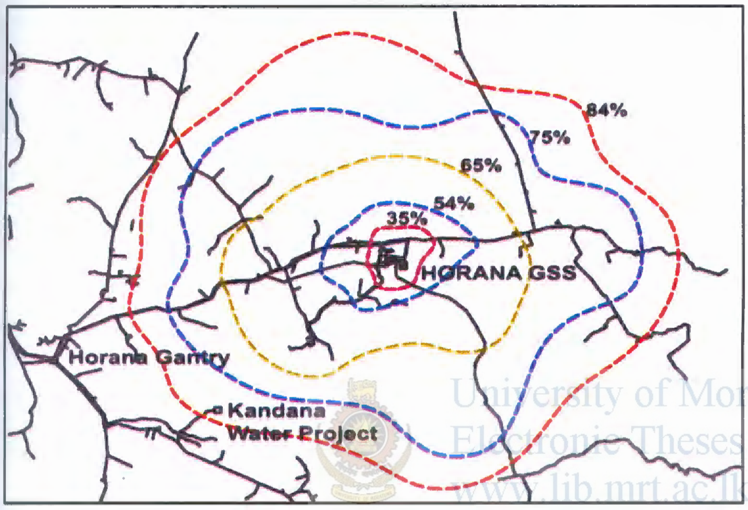

Fig. 3.14: Area of vulnerability for 3ph balanced faults

3.8.2 Area of Vulnerability for Unbalance faults

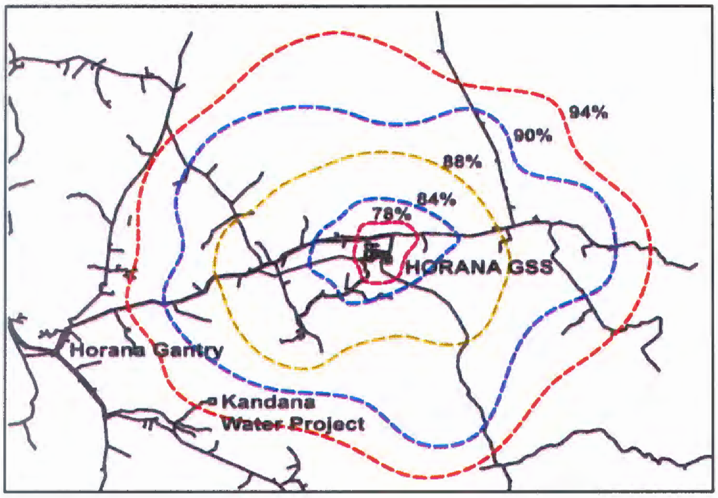

Fig. 3.15: Area of vulnerability for unbalanced faults [SLG]

Considering the area of vulnerability, when 3ph. fault occurs between 8km and 10km from Horana GSS, The 33kV bus voltage drops by 25% - 16%. After simulating the model of Horana

MV network following results were obtained

- Line distance from Horana GSS to Horana Gantry = 16.8 km
- Feeder Length from Horana Gantry to Kandana = 4.062km
- Voltage at Kandana is = 32.27 kV
- Percentage Voltage Drop without fault at Kandana is 2.2%

Considering both fault and the normal voltage drop, motors at kandana treatment plant cannot operate until the fault is cleared.

One of the most severe power quality disturbance faced by industry customers is voltage sag. Most of the modern industrial loads are sensitive to these voltage sags and can degrade their performances. Even power supply has been designed for maximum reliability, such disturbances cannot be eliminated. Therefore additional measures have to be taken to protect sensitive load from such bus voltage sags. The equipment tripping has to be understood first in devising voltage sag mitigation method. Device level solution has become more economically and technically feasible for voltage sag mitigation. In the device level approach, the ideal solution is to solve this problem at equipment level.

Chapter 4

Design of a Mitigation Device

4.1 Voltage Sag Mitigation Techniques

To understand the different ways of mitigating voltage sags, various factors contributing to the problem have to be understood. The cause of most voltage sags is a short-circuit fault occurring either within the industrial facility under consideration or on the utility system. The starting of large motors also results in voltage sags, but these are not usually very severe. The short-circuit fault causes the voltage to drop to almost zero at the fault position. This zero voltage turns them into an event of a certain magnitude and duration at the interface between the power system and the equipment. A typical voltage sag waveform is shown as follows.

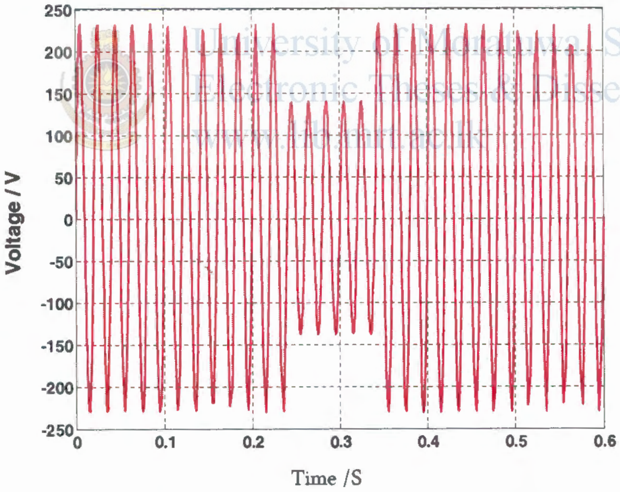

Fig 4.1: Typical waveform of voltage sag caused by remote fault clearing

The magnitude of the voltage sag is mainly determined by the impedance between the faulted bus and the load and by the method of connection of the transformer windings. The voltage sag lasts until the fault is cleared by a protective device, therefore the duration of the sag is determined by the fault-clearing time of the protection system adopted. Moreover, if automatic Recloser is used by the utility, the voltage sag condition can occur repeatedly in the case of a permanent fault. Finally, depending on its magnitude and duration, the sag can cause an equipment trip, thus becoming a power quality problem [15].

Based on the mechanism leading to a voltage sag three different "locations", for the mitigation of voltage sags can be distinguished: on the power system side or "upstream of the meter", on the equipment, "downstream of the meter", or, finally, at the system-equipment interface, "at the meter".

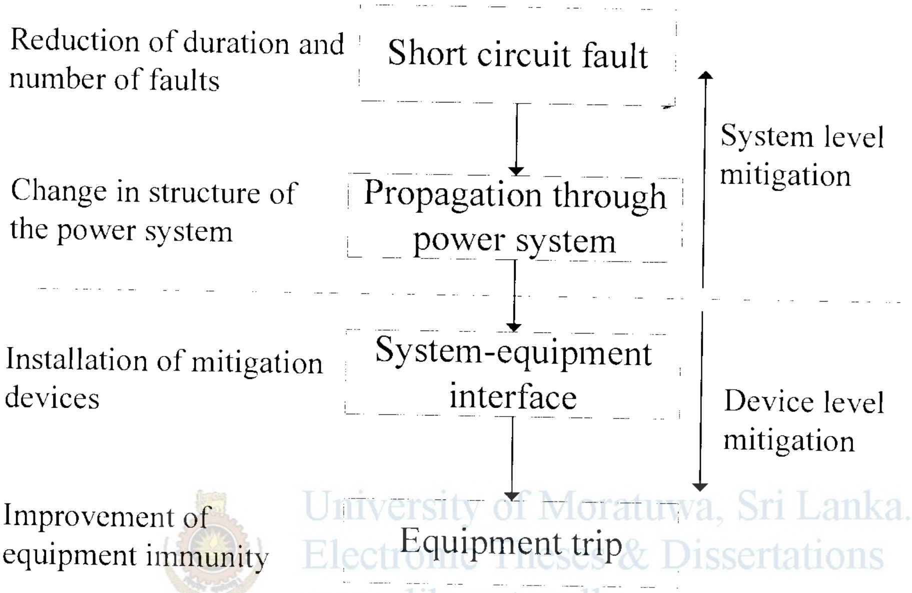

Fig.4.2: Different types of voltage sag mitigation [15]

4.1.1 Reduction of duration and number of faults

Limiting the number of faults is an effective way to reduce not only the number of voltage sags, but also the frequencies of short and long interruptions.

Fault prevention actions may include tree trimming policies of the institution, the addition of lightning arresters, insulator washing and the addition of animal guards. Insulation on transmission systems cannot withstand the most severe lightning strokes, but lines which are often subject to lightning-induced faults should be carefully investigated for improvement of the insulation level. Faults due to lightning can be reduced by lowering the ground resistance at the foot of the tower for overhead static wires. Other measures include the use of recently introduced special wires, which are covered by a thin layer of insulation material, or the installation of additional shielding wires, placed in such a way that they are more likely to be hit by a lightning stroke than the phase conductors.

4.1.2 Reducing the fault clearing time

Reducing the fault-clearing time leads to less severe voltage sags; this method affects not the number of events, but their duration. Present utility equipment for clearing faults on distribution circuits has been shown to be generally incompatible with customer equipment. Therefore utilities could consider the opportunity to install current-limiting fuses or modern static circuit breakers, which are able to clear the fault well within a half cycle at the power frequency, thus ensuring that no voltage sag can last longer [15].

4.1.3 Changes in the Power System

For distribution systems a simple, radial structure is usually preferred, particularly because it enables the use of a simple and cheap system of over current protection. The performance of radially-operated systems can be improved by reducing the number of feeders originating from the same bus, thus limiting the number of faults leading to voltage sag for equipment fed from that bus. A common practice is to supply the sensitive load through a dedicated feeder. Where it is not possible, a certain improvement can be achieved by installing current-limiting reactors or fuses in all the other feeders originating from the same bus as the sensitive load. This increases the "electrical distance" between the fault and the common bus, thus decreasing the depth of the sag for the sensitive load [15].

4.1.4 Increasing Immunity

Case studies and power quality surveys show that sensitive equipment include both low-power electronics (computers, process-control devices, consumer-electronics) and high power electronics (for ac and dc drives) . It has been reported that an installation using only electromechanical control could be tolerated sag down to 60% voltage without problems, while a completely automated factory could be disrupted by sag to 85%.

Improvement of equipment voltage tolerance thresholds appears as the most effective solution against voltage sags in the long term. This is especially true for short-duration and shallow sags which can hardly be mitigated by means of the utility-side solutions described above. Unfortunately, customers can only require a specific voltage tolerance level for very large industrial equipment, and these are usually tailored for specific applications. In most cases, the customer has no direct contact with the manufacturer and can in no way intervene to modify equipment sensitivity to voltage disturbances [15].

4.1.5 Mitigation Device

Customer solutions usually involve power conditioning for sensitive loads. Different devices are currently available for the mitigation of power quality problems. Correct understanding of their features, as well as that of load requirements, is needed for their proper application. To provide voltage sag ride-through capability, the different solutions available always include some kind of energy storage. As shown in figure 4.3 mitigation devices have been connected at the sensitive load.

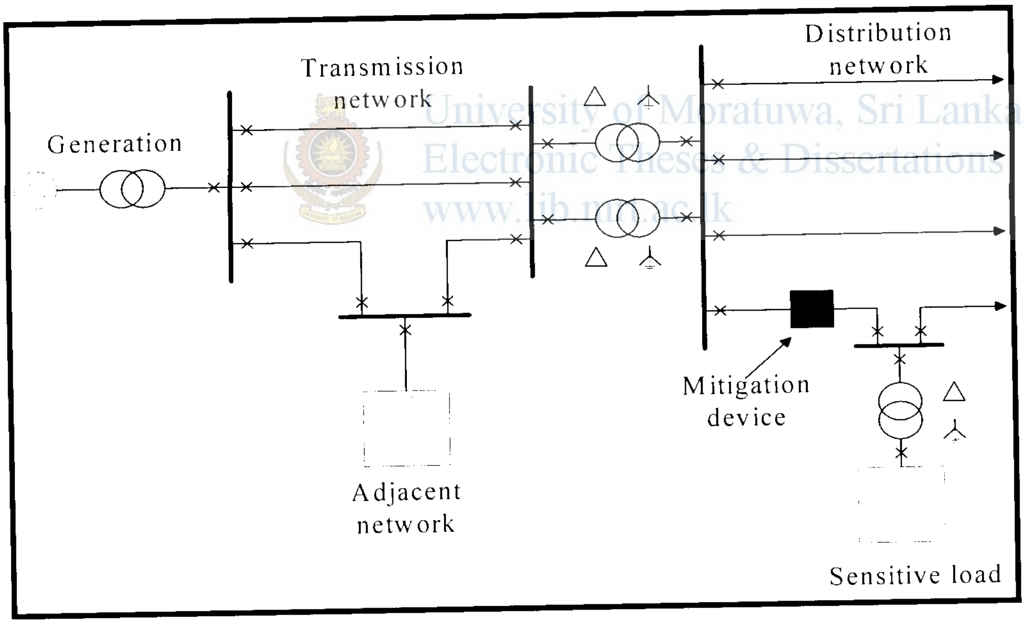

Fig.4.3: Typical arrangement of power system with mitigation device

4.2 Background of Technical Feasibility

Motor-generator sets store energy in a flywheel. They consist of a motor supplied by the plant power system, a synchronous generator supplying the load and a flywheel, all connected to a common axis. The rotational energy stored in the flywheel can be used to perform steady-state voltage regulation and to support voltage during disturbances. This system has high efficiency, low initial costs and enables long duration ride through (several seconds) but can only be used in industrial environments, due to its size, noise and maintenance requirements.

Electronic tap changers can be mounted on a dedicated transformer for the sensitive load, in order to change it's turns ratio according to changes in the input voltage. They can be connected in series on the distribution feeder and placed between the supply and the load. Part of the secondary winding supplying the load is divided into a number of sections, which are connected or disconnected by fast static switches, thus allowing regulation of the secondary voltage in steps. This should allow the output voltage to be brought back to a level above 90% of nominal value, even for severe voltage sags. Thyristor-based switches which can only be turned on once per cycle are used, therefore the compensation is accomplished with a time delay of at least one half cycle.

A UPS (Uninterruptible Power Supply) consists of a diode rectifier followed by an inverter. The energy storage is usually a battery block connected to the dc link. Low cost, simple operation and control have made the UPS the standard solution for low-power equipment like computers. For higher-power loads the costs associated with losses due to the two additional conversions and the maintenance of the batteries become too high and this solution no longer appears to be economically feasible.

A series voltage controller consists of a voltage-source converter connected in series with the distribution feeder by means of an injection transformer. It can inject voltages of controllable amplitude, phase angle and frequency into the distribution feeder, thus restoring the voltage to critical loads during sags. The reactive power exchanged between the series controller and the distribution system is internally generated by the controller, while the real power exchanged at its ac terminals must be provided at the dc terminal by an energy storage system.

The inverter is usually based on IGBTs characterized by high switching frequencies: therefore, with proper control, it is possible to perform perfect voltage compensation in less than half a cycle.

This solution, although still costly (but the prices are likely to decrease rapidly in the near future), is very attractive for large industrial customers (a few MVA) which have very high power quality demands. It allows for the protection of the entire plant from voltage sags (usually down to 50% magnitude and a few hundred milliseconds' duration) through the installation of only one device.

The shunt-connected voltage controller is a voltage source converter that is shunt connected to the distribution feeder circuit via a tie reactance. It can exchange both real and reactive power with the distribution system by varying the amplitude and phase angle of the voltage source with respect to the line terminal voltage. The result is controlled current flow through the tie reactance between the device and the distribution line, which enables a certain voltage support capability. The contribution of the shunt controller to the bus voltage is equal to the injected current times the impedance seen by the device. This is the source impedance in parallel with the load impedance. This impedance becomes very small for faults at the same voltage level, close to load. The device will then draw a very large reactive current without providing any noticeable change in voltage. For these reasons, a shunt controller is normally used not for mitigating voltage sags.

If the Power Quality problems are related to short interruptions and/or voltage sags, some devices mainly based on power electronic components, and so called "custom power technology" can be adopted by the distribution company. With reference to a Dynamic Voltage Restorer (DVR) for MV distribution feeders, with the compensation degree of 90% of the nominal voltage, the economical actual net value is estimated to be 900,000USD.

The ratio between the cost of the compensating device and the advantages due to its installation, that in this case is equal to 1/2, can also become in the future 1/3 with the expected increase of sensitive loads [17].

4.3 Dynamic Voltage Restorer (DVR)

Dynamic Voltage Restorer is a very important tool to improve the power quality of the electrical distribution lines. The main function of a DVR is the protection of sensitive loads from voltage sags coming from the network. A DVR is basically a controlled voltage source that is connected in series with the network. It injects a voltage on the system in order to compensate any disturbance affecting the load voltage. The main element of the device is the energy storage system, the voltage source converter, the LC filter and the coupling transformer [18].

4.4 Principles of the DVR operation

The DVR is connected in series with power distribution line as shown in figure 4.4. The DVR is able to control the voltage across a sensitive load by injecting an appropriate voltage phasor through an injection transformer. As a result, any voltage disturbance appears in up-stream can be compensated through the DVR and the disturbance is unseen to the load.

The in-phase boosting technique where the correction voltage is in-phase with the supply voltage has been used widely for correcting voltage disturbances. Under in-phase boosting, the DVR required to inject a certain amount of active power during the period of compensation. Therefore, the stored energy becomes the limiting factor in the disturbance compensation process especially sags which lasts longer.

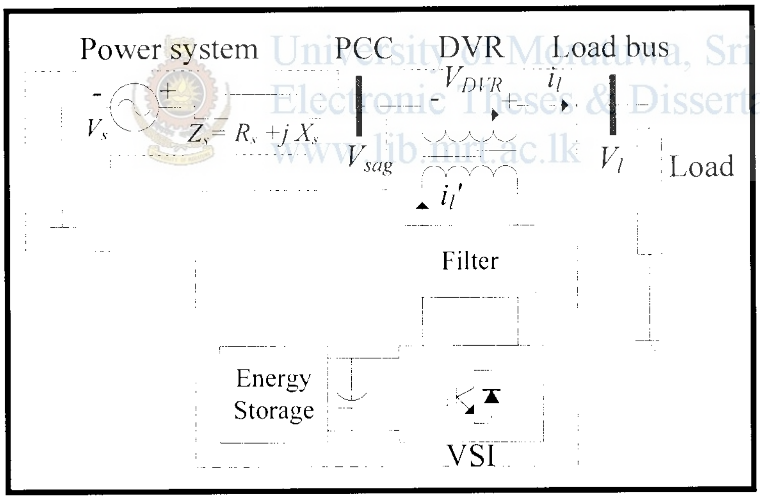

Fig.4.4: Typical schematic diagram of a power system compensated by the DVR

There are three types of voltage injection mode applicable to the DVR. They are in phase injection, pre-sag restoration and minimum energy voltage injection mode. Figure 4.5 depicts these three injection modes.

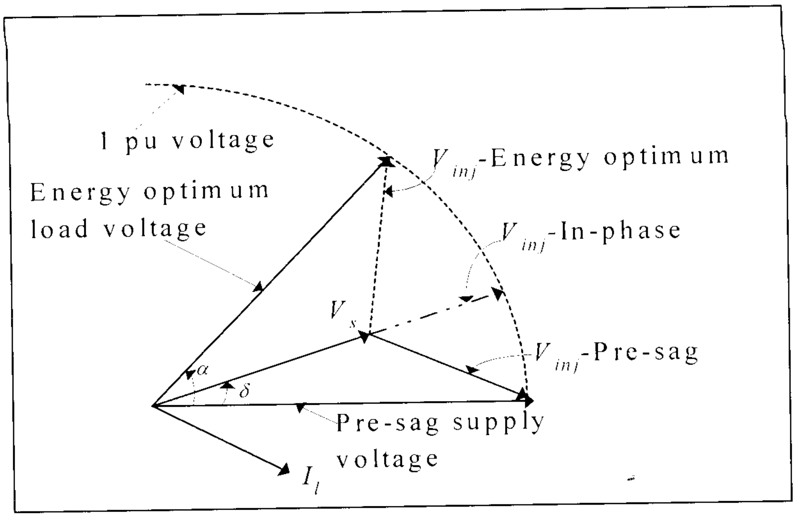

Fig.4.5: Phasor Diagram of Power distribution system during sag

In Fig. 4.4, the DVR controls the voltage across the sensitive load by injecting an appropriate voltage phasor (V_{DVR}) through the series-connected injection transformer. If an up-stream voltage disturbance can be compensated effectively, then the impact of the disturbance on the load is minimized. In most sag correction techniques, the DVR is required to inject active power into the distribution line during the period of compensation.

The DVR is a nonlinear device due to the presence of power semiconductor switches in the inverter bridge. However, with the application of state-space averaging technique it is possible to express the DVR behavior in differential equation form. The dynamic characteristic of the DVR is very much determined by the filter and the connected load. While the filter (which usually takes the form of a simple LC section) is easy to model as it is well-defined, this is not so for the connected load as it can vary from a linear time-invariant to a nonlinear time-varying type. In view of this complexity, a linear constant impedance load is assumed here and the purpose is to design the controller such that the DVR can exercise robust control in the face of the load model uncertainty. Such load representation is deemed reasonable as the sag disturbance is usually of relatively short duration. If the load contains a significant amount of rotating machinery, the electromechanical dynamics of the load would have insufficient time to manifest themselves as to significantly impact on the external system.

Fig. 4.6 shows that the load voltage is regulated by the DVR through the injection voltage V_{dvr} .

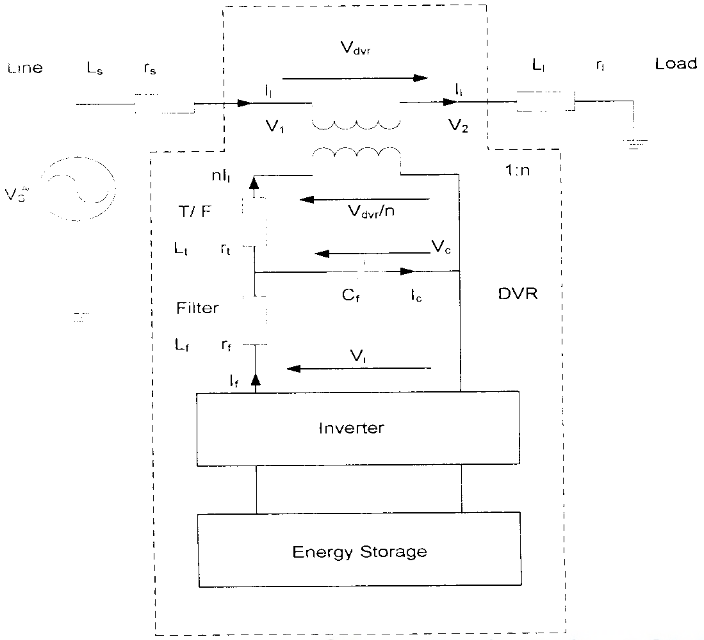

Fig.4.6: DVR connected power system

Assume that the load has an inductance L_l and resistance r_l and the DVR harmonic filter has an inductance of L_f, a resistance of r_f and a capacitance of C_f. The DVR injection transformer has a combined winding resistance of r_t , leakage inductance of L_t and turns ratio of 1 : n. The following state–space equations can be obtained [13]:

$$V_i = V_c + I_f r_f + L_f \frac{dI_f}{dt} \qquad (4.1)$$

$$I_f = I_c + nI_t \qquad (4.2)$$

$$I_c = C_f \frac{dV_c}{dt} \qquad (4.3)$$

$$V_{dvr} = n\left(V_c - n\left(r_t I_t + L_t \frac{dI_l}{dt}\right)\right) \qquad (4.4)$$

$$V_2 = V_1 + V_{dvr} \qquad (4.5)$$

Equations (4.1)–(4.5) form the basis of the DVR model which will be used for the controller design [13].

4.5 DVR Controller Design

With the rapid advances in microelectronics, real-time digital control of custom power devices using cost-effective digital- signal-processor (DSP) based hardware system has become feasible. The DSP hardware architecture enables most of its instructions to be executed in a single instruction cycle and complex control algorithms to be processed at a faster rate compared to single-chip microprocessors. In the light of this development, it is proposed herewith that a multi-loop control structure for the DVR be considered whereby the resulting load voltage is regulated to track a sinusoidal reference [13].

The design of such control scheme is necessary as it will be shown in figure 4.7 that the consequence of using the DVR open-loop control can result in poor system damping following voltage sag. In the new control scheme, the filter capacitor current and load voltage are sensed as feedback variables and the control algorithm evaluates the necessary switching pulse widths for the dc–ac inverter in every sampling interval. The comparison between the response characteristics resulting from the two schemes will enable one to observe the superiority of the proposed scheme over the open-loop control method [13].

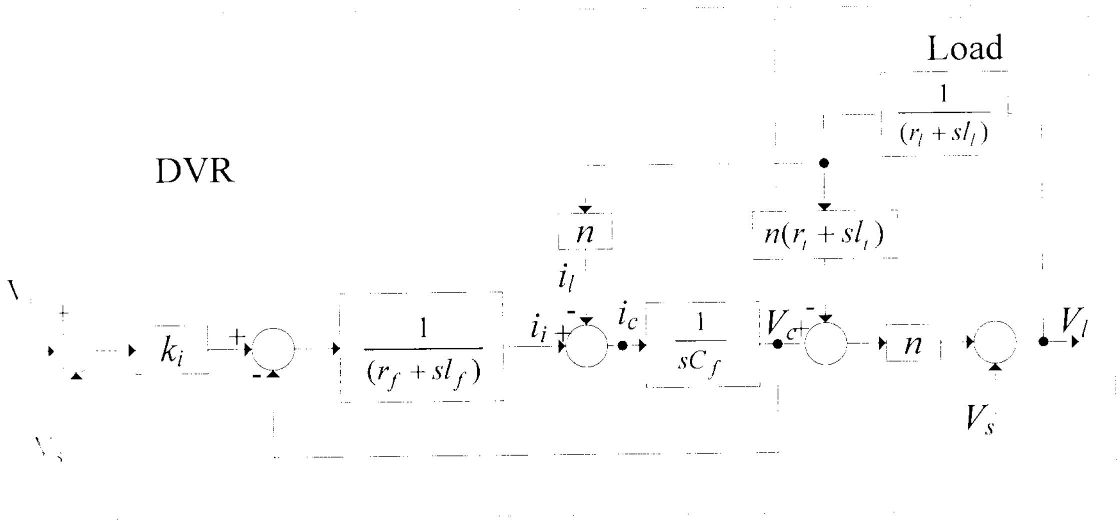

Fig.4.7: Block diagram representation of DVR system with open – loop controller

It is now clear that the open-loop control technique in the DVR system needs to be improved on. With regard to the tracking of the reference voltage, one can adopt the classical approach whereby the reference and the actual load voltages are compared and the error is fed back to the inverter PWM pulse generator.

However, as demonstrated in, the frequency response of the open-loop transfer function of this system has inadequate phase and gain margins. It means that this outer feedback loop of the load voltage acting alone may not be sufficient.

One possibility to improve the stability margins is to include inner feedback loop(s). Current mode control techniques are usually applied to power electronic circuits wherein an inner current loop is employed within the outer voltage loop in the closed loop regulation of power converters. Notice that from eqn. (4.3), the rate of change of the DVR output voltage is proportional to the current of the filter capacitor. If this current can be regulated appropriately, the load voltage can also be controlled in the event of load changes. This control feature, together with the outer voltage feedback loop described earlier, can be readily incorporated into the DVR control scheme. This is shown in Fig.4.8 where it is shown that the DVR load-side voltage is compared with its reference value and the error is multiplied with the voltage error feedback gain k_v and fed to the second stage as a reference for the capacitor current. This virtual capacitor current reference is compared with the actual capacitor current and the error is multiplied with the current error gain k_c to form the inner feedback loop. The resulting quantity of this loop is subsequently fed to the PWM generator of the inverter. As the inherent delay in the feedback control system can result in excessive overshoot or undershoot in the injected voltage following a sudden change in V_1, a feed forward control signal has also been added to the inverter input voltage signal in order to provide instantaneous response to the change in V_1.

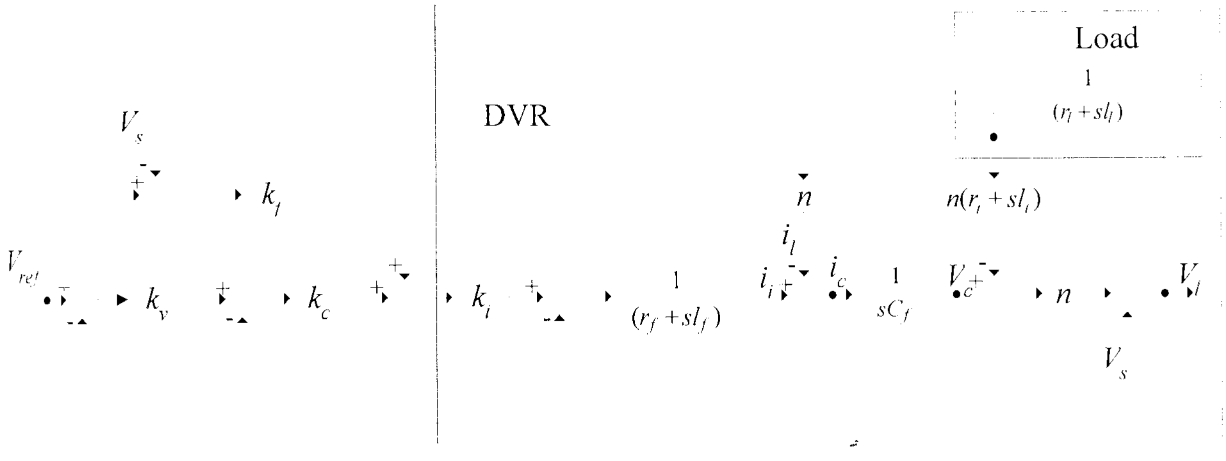

Fig.4.8: Block diagram representation of DVR system with multi – loop feedback controller

4.6 Design of DVR for Kandana Water Treatment Plant

As discussed in chapter 3, the most frequent and average magnitude of the voltage sag at Kandana water treatment plant is 40%. It may specify that the DVR be able to restore a 40% three phase voltage sag in the incoming feeder supplying a 4 MVA load during a fault lasting 300 ms.

In order to fulfill device specifications, the following design considerations that influence the rating and performance of the DVR must be accounted for:

- Protected load MVA and power factor
- Magnitude of three phase voltage sags to be compensated and fault duration.
- Permissible voltage drop across DVR under steady state conditions.
- Short circuit impedance of the booster, network side and load side transformers.
- Winding connections of network and load side transformers.
- Three phase fault level at incoming bus.

The required energy during sags has to be supplied by an energy source. In most cases storage capacitors resulting in a drop in DC link voltage. The necessary amount of energy that must be delivered by the energy source depends on the first two considerations mentioned above.

The nominal DC link voltage is chosen for full utilization of the blocking capabilities of the IGBTs. This in turn has an influence on the selection of winding ratio of the booster transformer to enable the VSC to compensate for voltage sags at the minimum DC link voltage.
Under normal conditions the short circuit impedance of the booster transformer determines the voltage drop across the DVR. This impedance must be low and has an impact on the fault current through the VSC on secondary side caused by short-circuit at load side. The impedance of the booster transformer was affected by filter design.

Harmonics produced by the operation of the VSC must be reduced to an acceptable limit with negligible impact on the load and utility supply. A sophisticated modulation scheme is used to effectively attenuate low order harmonics whilst a small filter on the primary side of the booster transformer filters out residual high order harmonics.

Statistical data on voltage sags such as average number of three phase sags per year, sag duration, size of sag and cost of lost production have also to be considered in order to design an economical DVR [6].

4.6.1 Design Issues

The correct sizing of the passive elements of the component-minimized structures presented plays an important role in the correct operation of the compensator during disturbances.

➢ Rating of Inverter

In this study historical data are used to calculate the average depth of the voltage sag. The average depth of the sag is 40%. IGBT Current is equal to load current. Voltage level of the system is 33kV. Inverter switches are designed to suit flow load current.

➢ Selection of Injection Transformer

The detection and evaluation of voltage sag is necessary when mitigating a sag. Obviously, the classical RMS calculation can be used to evaluate the magnitude and duration of the sag according to its definition. The "Missing voltage Technique" was proposed and the missing voltage is defined as the difference between the desired instantaneous voltage and the actual instantaneous value. The voltage sag can be perfectly corrected when a series compensation device injects the missing voltage. In reality, a series device is designed to provide a certain percent voltage injection, the characteristics of the sag is very important in sizing the device [26]. To inject the missing voltage, the isolation transformer is design to have the turns ratio of 1:1

Voltage Rating of the Transformer – 33kV

Load - 4MVA

Load Current is equal to Transformer load current

At the starting of the DVR there will be a high inrush current which may drive the injection transformer to its saturation region. To avoid that, the flux handling capability of the isolation transformer should be able to handle the double of the rated flux.

LC Filter

The main objective of the LC filter is to remove high frequency components from the output voltage of the inverter. However, an evaluation of the filter immunity against load current harmonics should be included, since the load currents can distort the output voltage of the filter. The increase of the immunity is achieved with the utilization of a higher filter capacitance. It should be noted that, the higher the capacitance of the filter, the higher the reactive current necessary to establish the output voltage, which increases the required power rating of the inverter switches [23]. In this design of LC filter the THD is less than 2% and switching frequency is taken as 5kHz considering the technical literatures.

Energy Storage DC Capacitor

The capacitor is charged from source during the normal conditions, and it supplies the active power to load during the fault condition. The critical issue in the design of the capacitor is the amplitude and duration time of the fault. So if we know those parameters, the capacitance can be calculated from the view point of input / output energy [24].

For convenience, we will assume that:

1. No loss in the switching elements and output filter.
2. No loss in the transformer

DVR was designed to compensate pre-sag voltage. The load voltage is compensated by the method of pre-sag voltage.

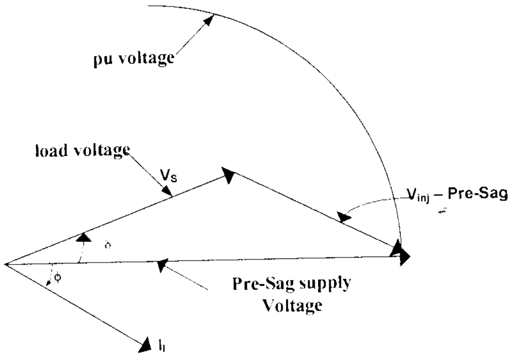

Fig.4.9: Pre-sag voltage compensation

For pre-sag compensation

$$P_{DVR} = P_{load} - P_{supply} \tag{4.6}$$

Equation (4.6) can be written as

$$P_{DVR} = P_{load} - \sum_{j=1}^{3} V_J I_l \cos(\emptyset + \delta_j) \tag{4.7}$$

$$I_l = \frac{4 \times 10^3}{\sqrt{3} \times 33} = 69.98 \approx 70A$$

Where V_J - Sag Voltage

I_l – Load Voltage

ϕ - Phase Angle

δ - Angle between sag voltage and load voltage

Then

$$P_{DVR} = P_{load} - 3V_S I_l \cos(\emptyset + \delta) \tag{4.8}$$

Kandana Treatment plant has 0.85 power factor lagging voltage and assumed δ=10°. Voltage sag is 40% and average duration is 300ms.

Substituting values to Eqn. (4.8)

Then

$P_{DVR} = 4 \text{ x } 10^3 \text{x} 0.85 - 3V_S I_1 \cos(\emptyset + \delta)$

$P_{supply} = 3 \times \frac{33}{\sqrt{3}} \times 0.6 \times \cos(31.8 + 10) \times 70 \times 10^{-3}\ MW$

$P_{supply} = 1789.6\ kW$

$P_{DVR} = 3400 - 1789.6$

$\mathbf{P_{DVR} = 1610.4\ kW}$

Let consider energy of DVR is E_{DVR}

Then

$E_{DVR} = P_{DVR} \times T_{sag}$ (4.9)

Where

T_{sag} – Duration of Sag

$E_{DVR} = 1610.4 \times 0.3$

$\mathbf{E_{DVR} = 483kJ}$

But

$E_{DVR} = \frac{1}{2} C(V_{Max}^2 - V_{Min}^2)$ (4.10)

Let us take

$V_{Min} = 0.8V_{DC}$

$V_{DC} = 40 \text{ kV}$

$E_{DVR} = \frac{1}{2} \times C \times (1^2 - 0.8^2) \times (40 \times 10^3)^2$

$483 = \frac{1}{2} \times C \times 0.36 \times 40^2$

Then,

$C = \mathbf{1.67\ mF}$

Required Capacitor for energy storage is 1.67 mF.

Chapter 5

Modeling and Simulation

5.1 Modeling of Dynamic Voltage Regulator (DVR)

This chapter discusses the computer modeling of a Dynamic Voltage Regulator in MATLAB / SIMULINK environment. The name MATLAB stands for MATrix LABoratory and is a software package with high performance numerical computation and visualization. It provides an interactive environment with lots of built – in functions for technical computation, graphics and animation. Simulink is a software package cooperated in MATLAB for modeling, simulating and analyzing dynamic systems. It supports linear and non-linear systems modeled in continuous time, sampled time or a hybrid of the two.

In this thesis Dynamic Voltage Restorer is selected for the modeling. Figure 5.1 gives the DVR with closed loop model for compensating available voltage sag at kandana water treatment plant. The complete model is developed in number of steps, which corresponds to the development of main components of the DVR and the connected power system. DVR has been modeled with control types such as open loop and closed loop. Figure 5.2 shows the DVR model with open loop.

5.1.1 Model of Control Block

Control block is a major part of the DVR model. Closed loop control block consists of three voltage gain blocks per phase having $k_v = 1.2$, $k_c = 50$ and $k_{na} = 1/V_{rms}$. But open loop control block has only one voltage gain block per phase. Discrete PWM generator blocks are included in both controllers. They consist of three arm bridges with six pulses. Carrier frequency selected for the model is 5 kHz and sample time of both controllers is 1×10^{-6} s. Figure 5.3 and 5.4 show closed loop control block and open loop control block respectively.

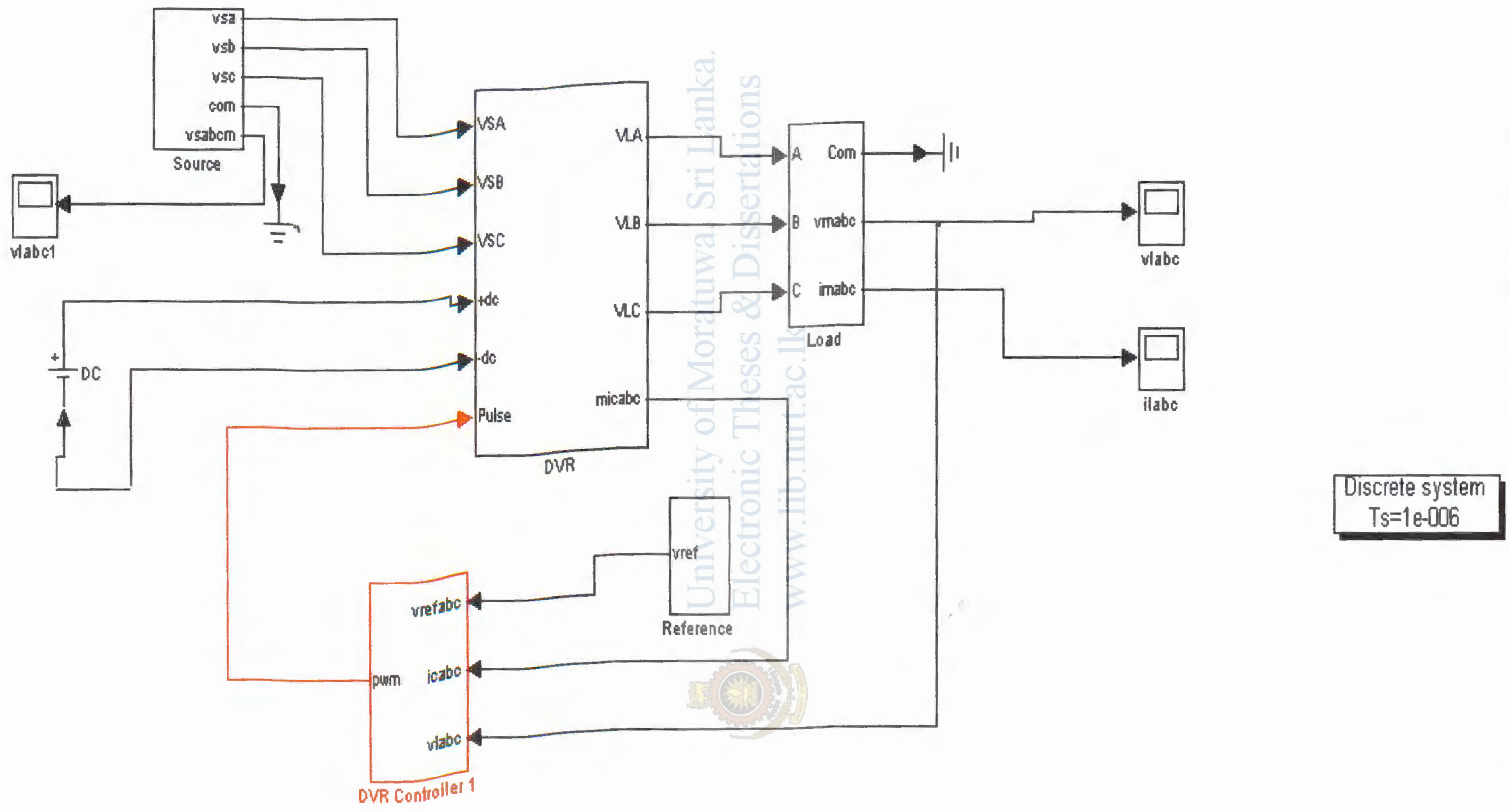

Fig 5.1: Model of the Dynamic Voltage Restorer with closed loop controller

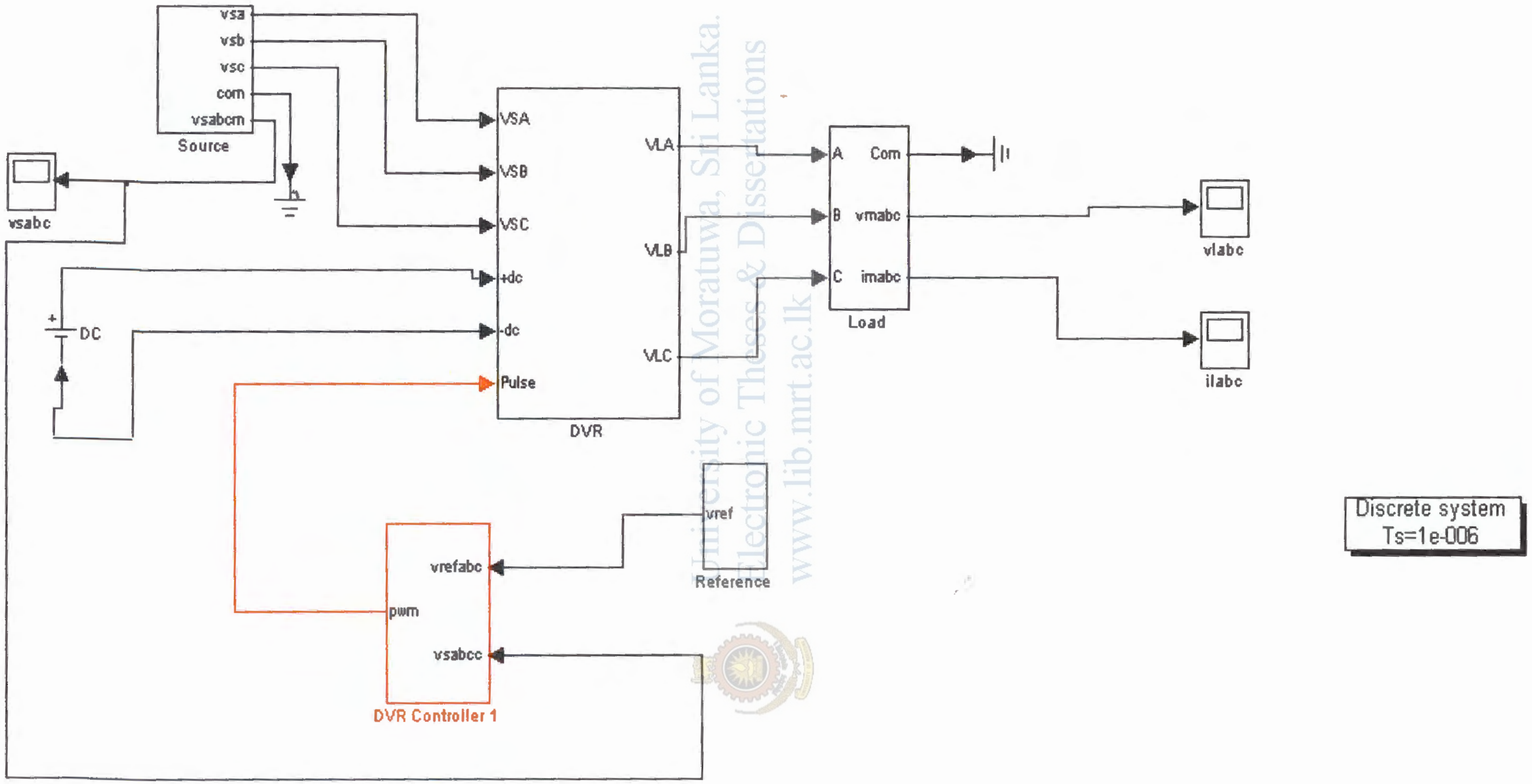

Fig 5.2: Model of Dynamic Voltage Restorer with open loop controller

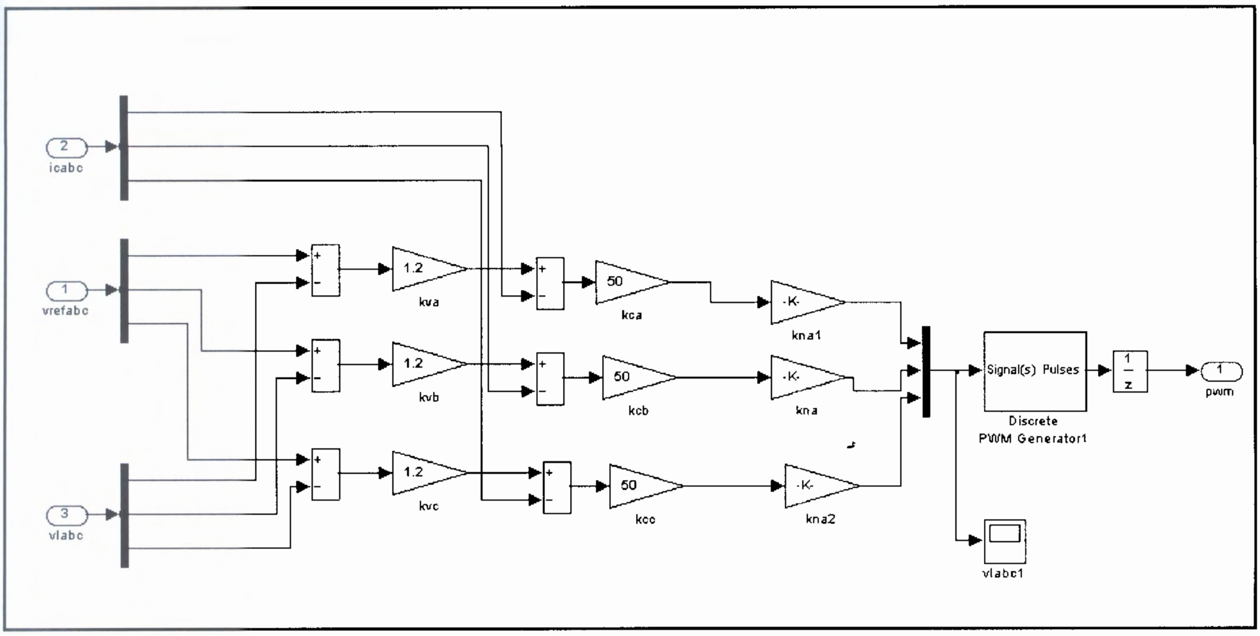

Fig.5.3: Simulink Block for closed loop controller

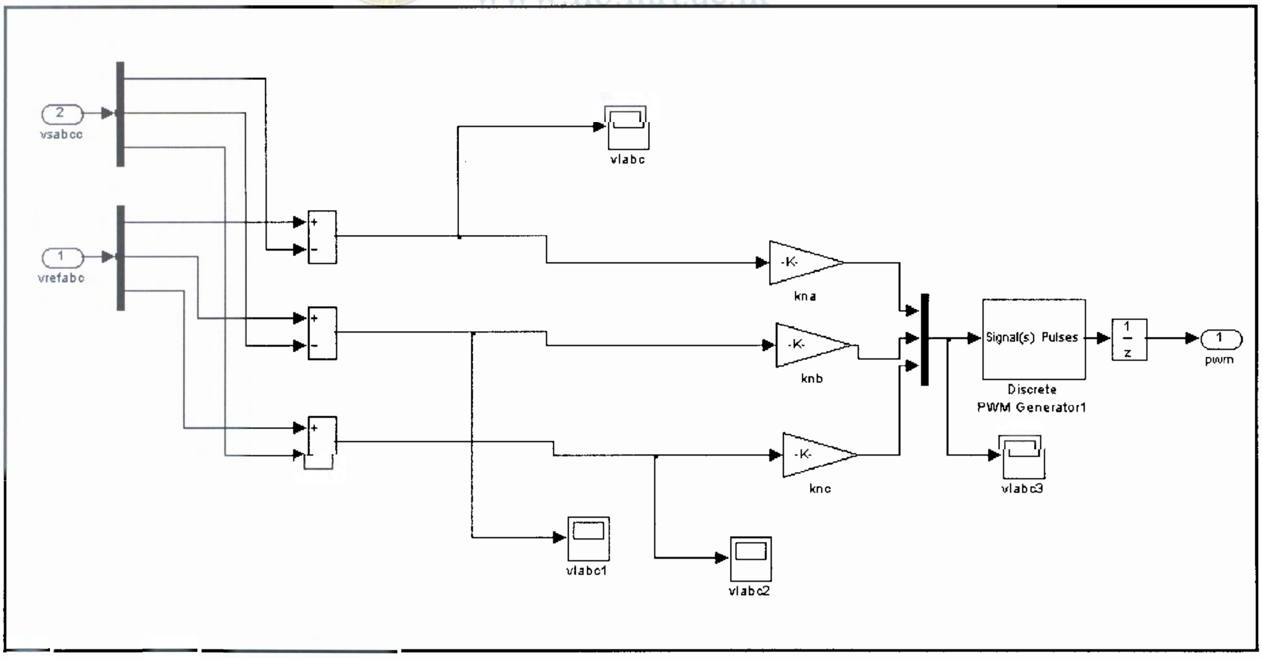

Fig.5.4: Simulink Block for open loop controller

5.1.2 Model of injection Transformer

This block has three two winding transformer having power of 4 kVA. These three transformers fed from LC filter. Output of the transformers is connected to the load. Figure 5.5 shows the Component of the transformers

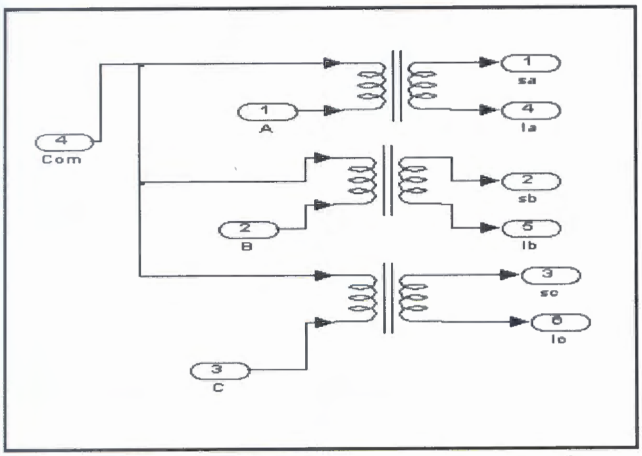

Fig.5.5: Simulink Block for Injection Transformer

5.1.3 Model of Inverter

Inverter block is taking DC voltage from DC source which having 40,000 V. The block parameters were selected to derive three arm IGBT bridge. The IGBT bridge output is connected to RL smoothing circuit. Figure 5.6 shows the model of the inverter.

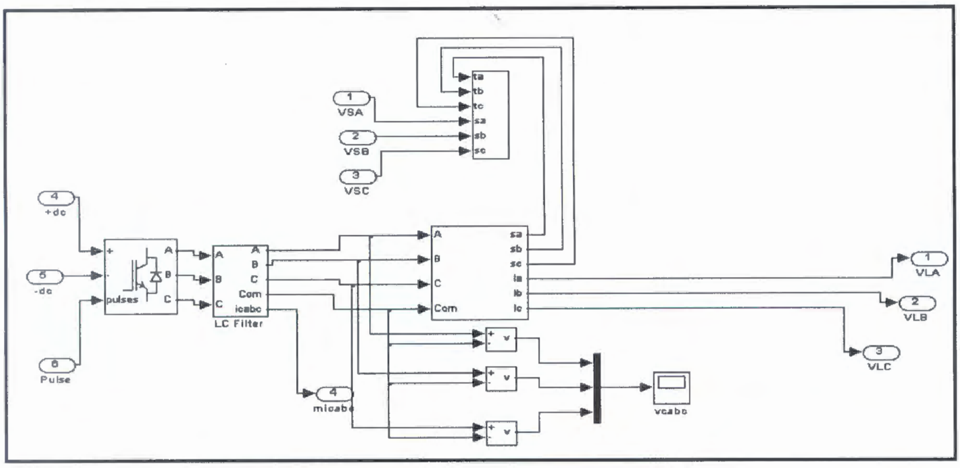

Fig.5.6: Simulink Block for Inverter

5.2 Simulation and Results

A detailed simulation of the DVR control system, using MATLAB/SIMULINK program were carried out in order to verify the effectiveness of the proposed control technique. In the simulation, the inverter has been realistically modeled to represent the switching nature of the process. The parameters for the DVR simulation are obtained using the configuration as shown in Fig. 5.7 and assuming a 33 kV distribution system delivering a load of 4 MVA. The filter inductor and capacitor values have been determined for this particular application on the assumption that switching harmonics above 5 kHz are attenuated by at least 40 dB. The parameters of the DVR system are as follows.

Supply Voltage : 33kV
Series transformer turns ratio : 1:1
DC link Voltage : 40kV
Filter Capacitance : 100μF
Filter Inductance : 5mH

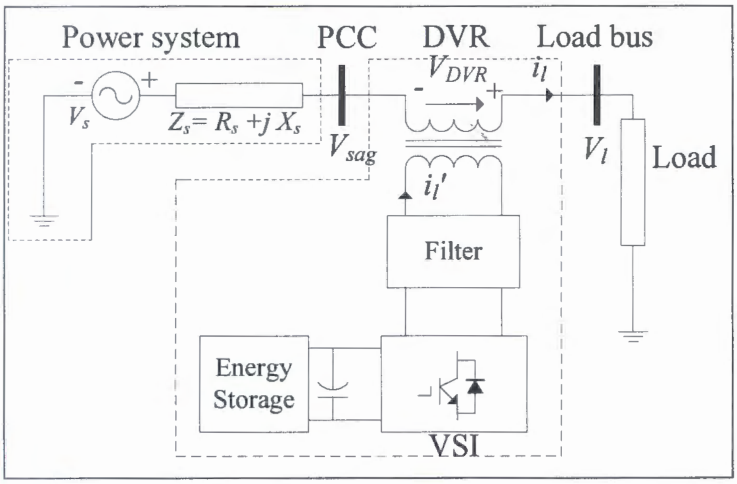

Fig.5.7: Schematic Diagram of DVR

Power source supplies the R-L load through a bank of series injection transformers. The injection transformer primary windings are connected to the PWM voltage source inverter via the LC low pass filter. The voltage source inverter consists of six IGBT switches with anti-paralleled diodes connected across each switch. The dc-link of the inverter is fed by a separate power supply. The sampling frequency of the control system is set at 5 kHz. The parameters of the proposed controller are $k_v = 1.2$ and $k_c=50$.

5.2.1 DVR with Open-Loop Control System

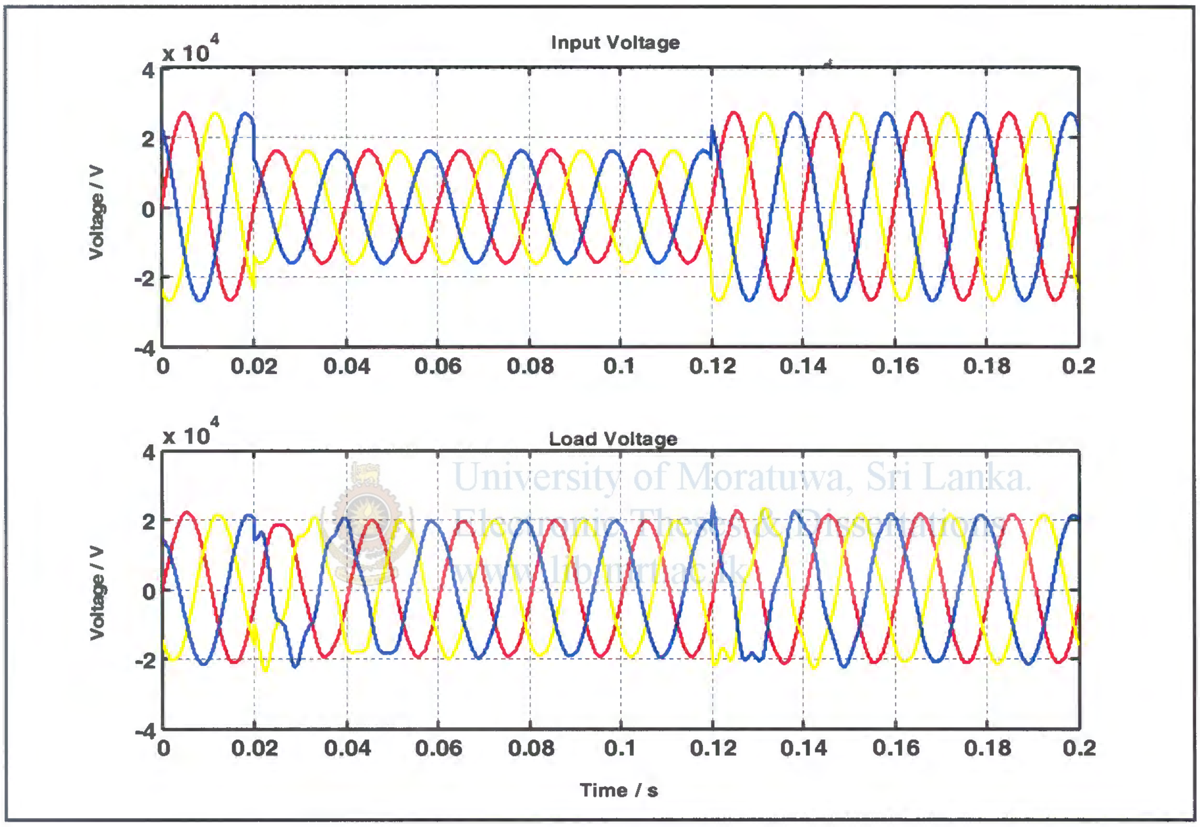

Fig. 5.8: Supply Voltage with 40% Voltage sag and Compensated load voltage (open loop)

Consider an occurrence of three phases, 40% voltage sag started at .02sec which lasts for 10 cycles as shown in figure 5.8. The compensated load voltage is also shown in bottom figure of figure 5.8. The waveforms are obtained from simulations carried out with a detailed model of the dynamic voltage restorer including the pulse width modulation process. According to the simulation results shown in figure 5.8 it can be seen that there is a voltage spike at the end of the sag owing to sudden recovery of the sag. These sharp spikes due to open loop control of the model of DVR. Also open loop control depicts.

- Guaranteed stability
- Poor dynamic performances
- Inadequate stability margin
- No sufficient damping to control large overshoot.
- Poor damping results in sustained oscillations in compensated voltage.

5.2.2 DVR with Close -Loop Control System

According to the simulation results shown in figure 5.9, sharp spikes are not available in load voltage wave forms at the end of the voltage sag. DVR with closed loop control has been used. These simulations have been carried out for voltage sags up to 90% and an excellent DVR output behavior with a balanced and nominal amplitude sinusoidal waveform has been accomplished.

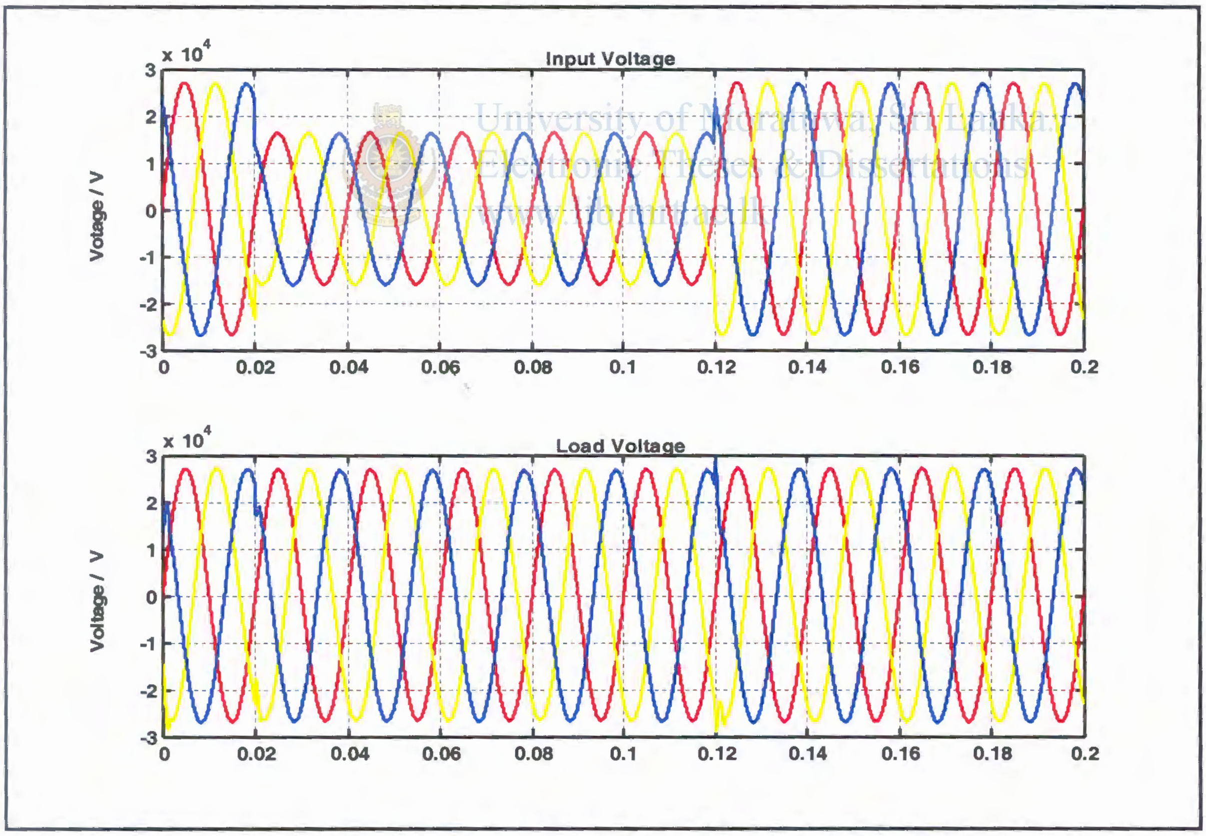

Fig. 5.9: Supply Voltage with 40% Voltage sag and Compensated load voltage (closed loop)

Figure 5.10 shows the compensated voltage from DVR controller. During sag controller generate the voltage in order to compensate the voltage sag.

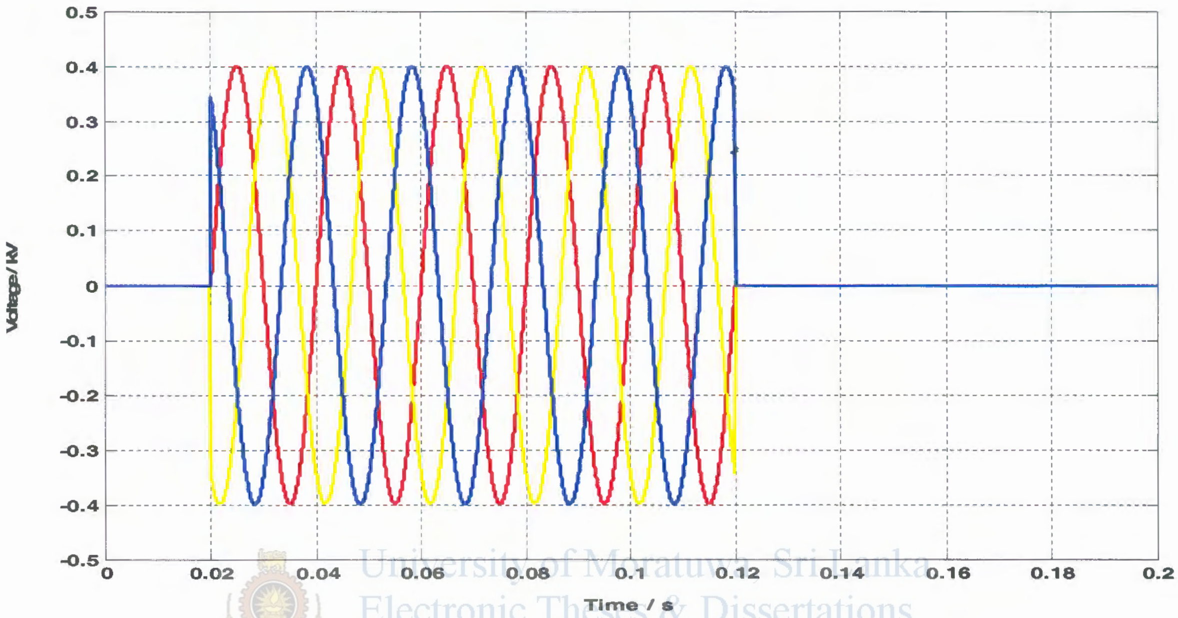

Fig. 5.10: Compensation voltage

Chapter 6

Conclusion Recommendations and Future work

6.1 Conclusion

This thesis discussed about the Power quality problems at Kandana water treatment plant where sensitive equipment are used for different stages of water treatment and distribution process. For this study a PQ analyzer was used at Horana Grid Substation and as well as the incoming bus of the kandana treatment plant. After analyzing the logged data, it was revealed that the dominant power quality problem faced is the voltage sag.

Solution to voltage sag problem can be made at two levels. System level solution also can be made at locations such as at fault location and power system level. Thus the solutions are in the form of reducing number of faults and durations. Prevention action may include maintenance policy, adding lighting arrestors to feeders, washing insulators. Also faults due to lightning can be reduced lowering tower foot grounding resistance, adding another shielding wire. The duration of the voltage sag can be reduced replacing existing protective devices with fast acting devices. However, the above feasible solutions are already done and some are not economically feasible as the power systems have been operating for 10 to 20 years or even more. Thus device level solution has become more economically and technically feasible for voltage sag mitigation.

Out of the following custom power devices, DVR is recommended to mitigate the voltage sag problem at Kandana Water Treatment Plant.

- Static Transfer Switch (STS)
- Uninterruptible power supply (UPS)
- Shunt connected voltage source converter (STATCOM).
- Series connected voltage source converter (DVR).
- Unified power quality controller (UPQC).

It is understood that the voltage sags are most dominant factor as far as industries using sensitive control systems are concerned. It is also recommended that voltage sags are to be continuously monitored for the period of one year. This requirement is hard to be achieved by using a portable PQ analyzing unit. To implement any PQ improving program, exact cause for PQ violation has to be found.

Sensitive loads can be mainly categorized as magnitude sensitive, phase sensitive and both magnitude and phase sensitive to the supply voltage. It can be seen that the magnitude and phase sensitive load can be corrected using proposed DVR control method which has good economical advantage. Furthermore, the rating of the DVR could be reduced, If only the critical load is considered. This will reduce the cost of the DVR.

The proposed closed loop controller has increased the quality of load voltage by continuously maintaining the voltage within allowable limits in the face of supply disturbances. Such behavior is utmost important as the DVR is supposed to safe guard highly priced industrial processes. To implement the DVR need a big land area. Kandana area has lots of bare lands. Therefore proposed DVR can be implemented near the treatment plant.

6.2 Future Work

Voltage sag survey duration at Kandana treatment plant is not sufficient study in detail. In future, proposed to study the seasonal variations of atmospheric condition with the sag conditions. The survey period must be sufficiently long. It is accepted that a minimum period for acceptable result is one year.

Design of DVR should be implemented and have to be checked whether it operates efficiently and effectively. Designed DVR control parameters are not real time parameters. Therefore, before implementation should be built a prototype. Real time adjustment must be done and implement the hardware system. Gains have to be fine tuned before implementation. It is proposed that the design parameters should be reviewed in order to overcome the voltage sag problem at Kandana Treatment Plant.

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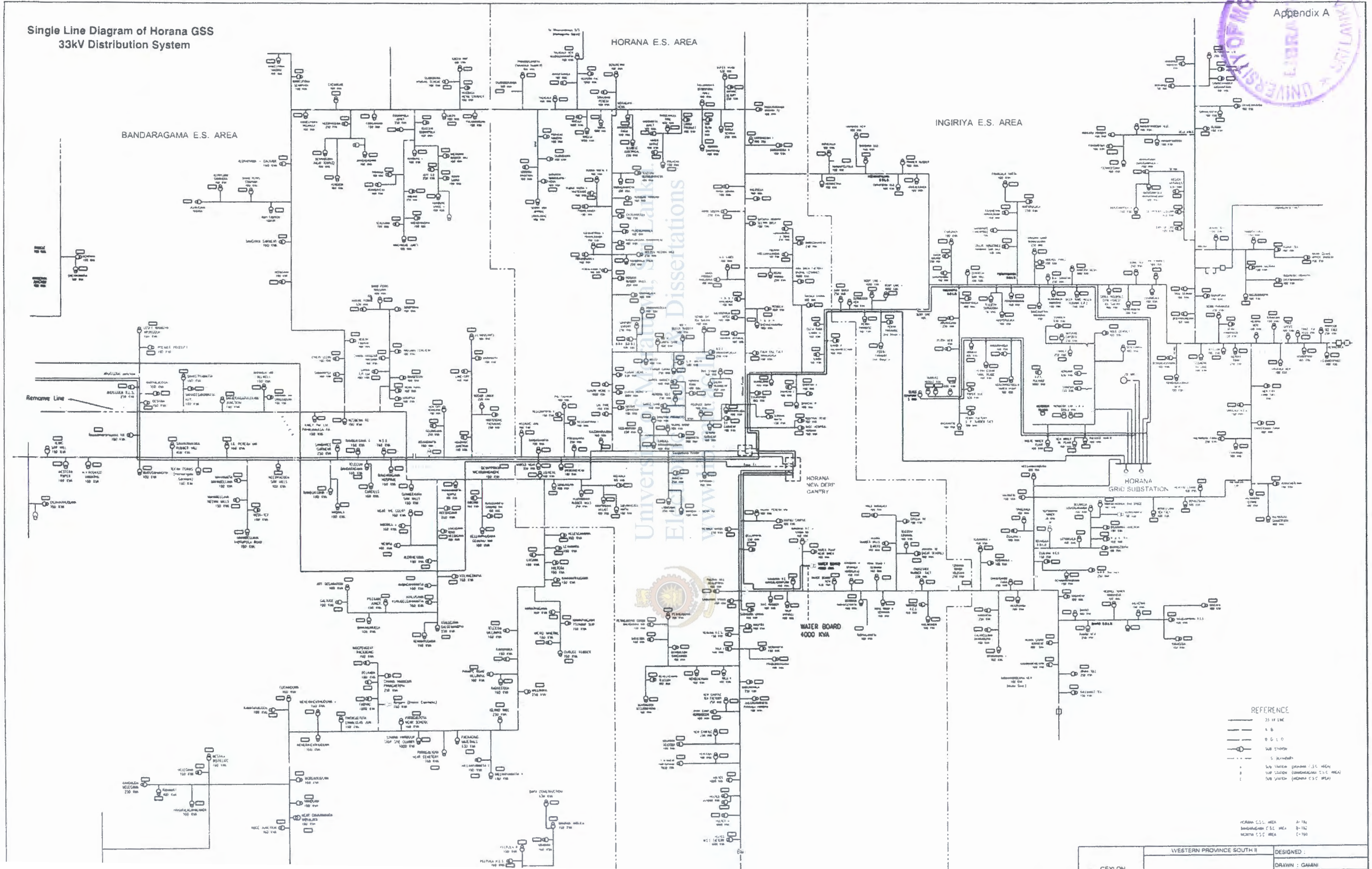
Appendices

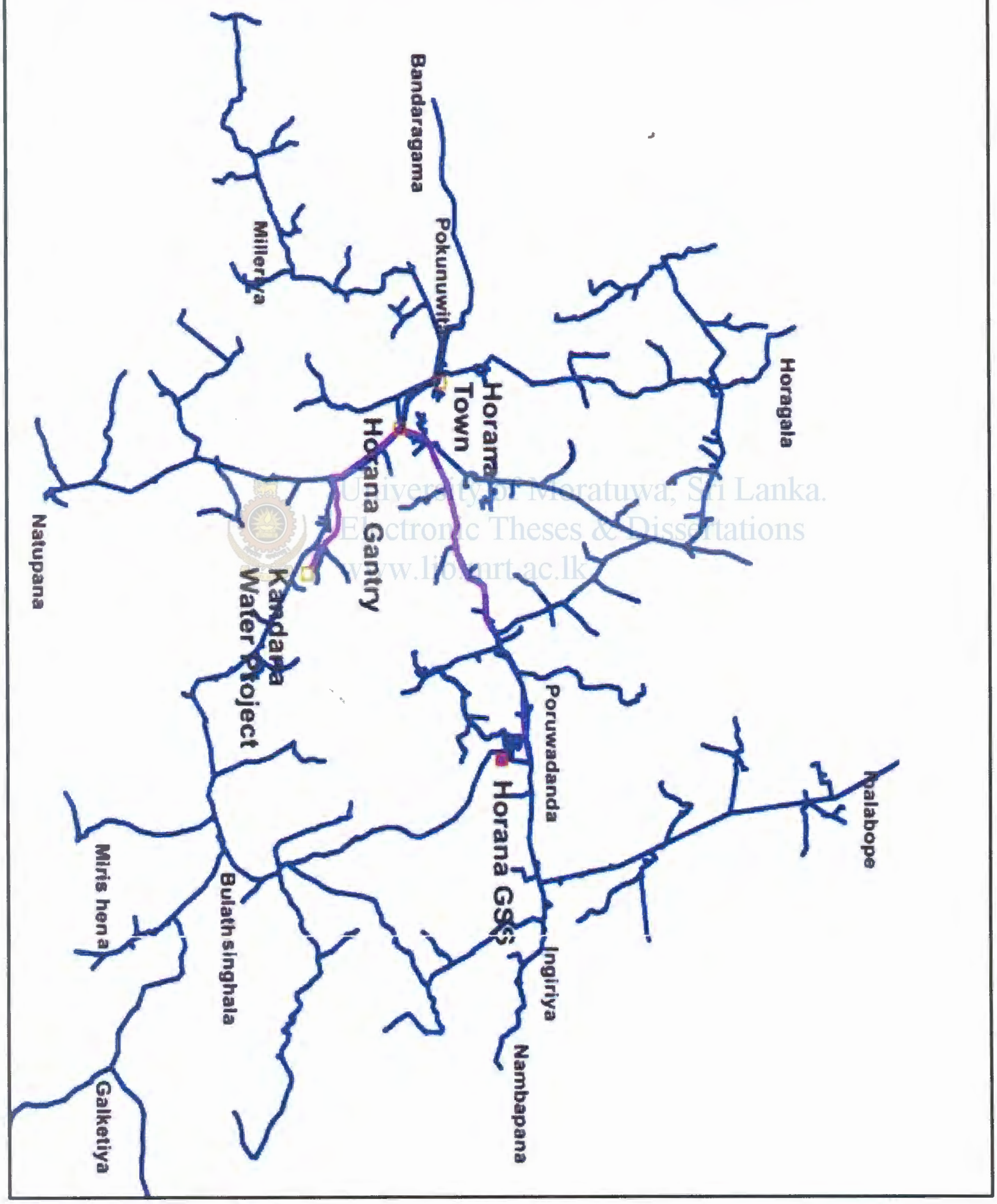
Appendix A

Single Line Diagram of Horana GSS
33kV Distribution System



Appendix B

Distribution Network Of Horana Grid Substation



Appendix C

List of Pumps at Kandana Water Treatment Plant

Facility/Equipment	Specification	Power (kW)	Total No. of Motors	Remarks
01.Intake Facility				
Coarse Screen (L)	Bar Screen 3.0mW x 0.5mH x 50mm	-	2	
Coarse Screen (H)	Bar Screen 3.0mW x 3.9mH x 25mm	-	2	
Screening Hoist	Electrically Operated 1.0 Ton	0.95	2	
Inflow Gate	Hand operated Sluice 1.5mW x 1.5mH x	-	2	
Fine Screen	Motorized Net Screen 3.0mW x 6.0mH x 15mm	4	2	
Fine Screen Hoist	**Electrically Operated 2.0 Ton**	**1.9**	**1**	**New**
Screening Trough	U-Shaped Trough 0.4mw x 10.3mL	-	1	
Screen Wash Pump	Hrizontal Centrifugal 1.0m3/min x 62m	5.5	2	
Wash Water Valve with actuator	Electrically Operated Dn80		2	
Outflow Gate	Hand operated Sluice 1.5mW x 1.5mH x	-	2	
Suction Valve	DN 600 Manually operated Sluice valve,PN 16	-	3	
Raw Water Pump	**Vartical Centrifugal 730L/s x 19m**	**200**	**3**	**With Flywheel (35kgm2,WR2)**
Check Valve	**DN 600Swing check,PN 16**	-	**3**	**St.2valve with counter weight**
Discharge Valve	Motorized Butterfly Dia.600mm	0.4	3	

Sump Drainage Pump	Submersible 0.24m3/min x 15m	2.4	2	Stg.1:2.4k W
Overhead Crane (1)	Manually operated 5.0ton	-	1	
Overhead Crane (2)	Manually operated 5.0ton	-	1	
RWP Hoist	Electrically Operated 5.0 Ton with Geard Trolley	**3.0**	**1**	**New**
Air inlet fan	Multiblade Fan 40m3/min x 30mmAq	0.95	1	
Air inlet fan	Wall Mounted Fan 75m3/min x 30mmAq	0.3	3	
Exhaust Fan	Wall Mounted Fan 90m3/min x 5mmAq	0.5	0	
Intake shudge disturbing pipe isolating vaive	DN 75 Manually operated Sluice valve,PN 10		2	New
Intake Channel Strring Pump	Centrifugal Pump 14.5L/s x 30m	7.5	1	New
Sump Well Drainage Pump	Portable Type submersible pump,0.3m³/min x 15m	2.2	1	New with 30m - Hose
02. Distribution Chamber				
Distribution Gate	Hand operated Sluice Dia.500mm, L=5.15m	-	6	
Alum Tank	Rectangular 0.6mW x 1.8mL x 0.6mH	-	1	
Alum Distribution chamber Valve	Hand operated Ball type valve SS,DN 32	-	6	
Lime Mixing Tank	Cylindrical 1.5m3	-	1	
Lime Mixer	Vertical	0.75	1	
Lime Feed Pump	Progressive Cavity Pump 0.78m3/min x 5m	1.5	2	
Drain Gate	Hand operated Sluice W300mm x H300mm	-	1	

03. Flocculation / Sedimentation Basin				
Sludge Collector	Chain Scraper 10mW x 47.6mL x 4mD	0.37	6	Non-metaric
De-sludge Valve.1	Electrically operted, Eccentric DN150	0.08	24	
De-sludge Valve.2	Manually operated gate valve,DN150	-	24	
Roof mountal Ventilation Fan	Ventilation tower and rain bood;Axial Flow Fan 2770m^3/hr.at static head 8.2mm Aq 1400	0.3	2	
De-sludge Valve.3	Manually operated gate valve,DN250	-	4	
Sump Drainage Pump	Submersible 0.24m3/min x 15m	2.4	4	Stg.1:2.4k W
Check Valve on sump drainage pumps	Check valve,DN50	-	4	
Discharge Valve on sump drainage Pumps	Manually operated gate valve,DN50	-	4	
Intermediate Chlorine Disch.Valve	Manually operated gate valve & 40 PVC	-	2	PVC
Sampling Pump	Self-priming Centrifugal 0.06m^3/min x 12m	0.4	2	
04.Filters				
Inflow Gate	Motorized Sluice 0.5mW x 0.5mH x L=1.79m	0.75	4	
Inflow Valve	Motorized Butterfly Dia.600mm	0.4	4	Tyupe change
Backwash Drainage Gate	Motorized Sluice 0.6mW x 0.6mH x L=1.79m	0.75	4	
Backwash Drainage Valve	Motorized Butterfly Dia.700mm	0.75	4	Tyupe change
Stop log	Manual,on channel W1000	-	8	
Effluent Valve	Motorized Butterfly Dia.400mm	0.2	8	
Backwash Valve	Motorized Butterfly Dia.500mm	0.37	8	

Air Scour Valve	Motorized Butterfly Dia.400mm	0.75	8	
Drain Valve	Manual Gate with Headstock Dia.150mm	-	8	
Stop log	Manual,on channel W2000,W2710	-	3	
Backwash Pump	Horizontal Centrifugal 9.8m³/min x 8m	22	3	
Backwash Line Valve	Manually operated Butterfly valve,DN500	-	2	
Air Blower	Roots Blower 39Nm3/min x 3500mmAq	33	3	
Sump Drainage Pump	Submersible 0.24m3/min x 15m	2.4	2	
Check Valve	Check valve,DN50	-	2	
Discharge Valve	Manually Operated DN50	-	0	
Lime Mixing Tank	Cylindrical 1.5m3 (Dia.1.2m x 1.6mH)	-	1	Relocate to New PLR
Lime Mixer	Vertical (Dia.1.2m x 1.6mH)	0.75	1	Relocate to New PLR
Lime Feed Pump	Pregressing Cavity Pump 0.78m3/min x 5m	1.5	2	Relocate to New PLR
Lime Satulation Tank Mixer	Vertical,Imp.Dia.700mm,with Draft Tube	1.5	1	New,Tank Dia.8.0m
Drain Valve	Electrically Operated Eccentric,DN100	0.2	1	New
Satulation Tank Water Pump	Self-priming Centrifugal 1.7m³/min x 10m	5.5	2	New
Check valve	Swing check valve,DN150	-	2	New
Discharge Valve	Manual operated gate valve DN150	-	2	New
Sampling Pump	Self-priming Centrifugal 0.06m³/min x 12m	0.125	2	
Air Blower Swing check valve,DN250			3	
Air Blower Butterfly valve,DN250			3	
Back wash Pump Gate Valve DN300			3	
Back wash Pump Butterfly Valve DN300			3	

Satulation Tank Water Flow meter	Float Type Flow Meter DN100	0	1	Local Indication without signal New
Isolation Valve	Manually operated Butterfly valve,DN150	0	2	New
Isolation Valve	Manual operated gate valve DN100	0	1	New
05.Clear Water Reservoir and High Lift Pump Station				
High Lift Pump	**Horizontal Centrifugal 348L/s. x 85.0m**	**500**	**5**	**Remove Flywheel St.1:500kW**
DN1000 Manually Operated	Butterfly Valve 1000dia		6	On Duty
DN500 Manually Operated	Butterfly Valve 500dia		5	(on duty,2St.by) Pipe Gallery
Check valve	DN 400 Swing Check Valve, PN 16	-	5	St.2 valve with counter weight
Discharge Valve	Motorized Butterfly Dia.400mm x Lh=2.02m	0.09	5	
Sump Drainage Pump	Submersible 0.1m3/min x 12m	2.5	2	
Plant Water Supply Pump	Horizontal Centrifugal 1.0m3/min x 35m	9.3	3	
Chlorination Booster Pump	Horizontal Centrifugal 0.4m3/min x 52m	7.5	3	
Overhead Crane	Manual Operated 5.0 Ton	-	1	
Air inlet fan	Multibrade Fan 400m3/min x 5mmAq	5.5	2	
Exhaust Fan	Wall Mounted Fan 100m3/min x 5mmAq	0.06	8	
HLP Hoist	Electrically Operated 5.0 Ton with Geard Trolley	3	1	New
Surge Vessel	Hydropnewmatic surge Vessel, Approx.22m3	-	4	New Reference
Air Compressor	Pressure Swith Type 700L.min, 10kg/cm2	5.5	2	New Reference
Isolation Valve	Butterfly Valve Dia.500,PN16	-	1	New
Isolation Valve	Gate Valve Dia.250,PN16	-	1	New
Check Valve	Swing Check Valve Dia.500,PN16	-	1	New

06. Chemical Building

Alum Mixer	Vertical (2.2m x 2.8m x 3.5mH)	4.4	4	Stage 1,4.4 kw
Alum Pump	Ceramic Gear Pump 0.2 L/s x 14m	3	2	
Alum Dust Collector	Filter Type Approx.9.0m2, Filtreration Air 10m3/min	1.5	4	New Stainless steel /No
Portable Belt Conceyor	Portable Belt Conveyer W350	1	1	
Isolation Valve	DN 50 Brass Ball Cock Hand Operated	-	4	
Isolation Valve	Hand Operated Valve, Dn 50 stainless steel Ball	-	4	
Isolation Valve	Hand Operated Valve Dn 50 stainless Steel Ball	-	4	
Isolation Valve	Hand Operated DN 63, Stainless Steel (2 1/2")		2	
Isolation Valve	Hand Operated DN 50, Stainless Steel (2")		2	
Isolation Valve	Hand Operated DN 37, Stainless Steel(1 1/2")		2	
Isolation Valve	Hand Operated DN 50, Stainless Steel (2")		3	
Check Valve	PVC63		1	

07. Lime Dosing System

Lime Mixer	Vertical (2.2m x 2.8m x 3.5mH)	4.4	4	Stage 1,4.4 kw
Lime Pump	Rubber Lined Centrifugal 2.3L/s x 13m	2.2	3	
Lime Dust Collector	Filter Type Approx.9.0m2, Filtreration Air 10m3/min	1.5	4	New Mild Steel
Exhaust Fan	10m3/min x 50mmAq	0.75	1	
Chemical Crane	Motorized with Trolley 2.0 Ton	0.95	1	
Sump Drainage Pump	Stainless Steel Submersible 0.24m3/min x 15m	2.4	2	Stage 1,2,4kw
Isolation Valve	Gate Valve, DN 50 Bronze	-	4	

Isolation Valve	Hand Operated Valve, DN 50 Stainles Steel Ball	-	4	
Isolation Valve	Hand Operated Valve, DN 50 Stainles steel Ball	-	4	
Isolation Valve			2	
Isolation Valve			3	
Isolation Valve			3	
Isolation Valve			3	
Isolation Valve			2	
Isolation Valve			6	
08. Chlorination System				
Chlorine Containaer	Steel Container 1.0t Cylinder	-	16	
Weighing Scale	Load Cell 4.0 Ton	-	2	
Chlorinator -Pre	Auto Vacuum Type 20kg/hr	0.025	3	Floor mounted
Chlorinator-Post	Auto Vacuum Type 20kg/hr	0.025	3	Floor Mounted
Injector -Pre	Injector	-	2	
Injector - Post	Injector	-	2	
Chlorine crane	Motorized with Trolley 2.0 Ton	4.25	1	
Exhaust Fan	Wall Mounted Fan 80m3/min x 5mmAq	0.4	4	
Isolation Valve	Gate Valve, 40mm dia PVC (1 1/4")	-	8	
Strainer	Strainer, 40mm dia PVC (1 1/4)")	-	4	
09.Backwash Recovery Facility				
Recycle Inlet Gate	Manual Sluice W800 x H800	-	2	
Backwash Recovery Pump	Submersible Slurry 1.8m3/min x 17m	13.5	2	
Isolation Valve	Manually Operated Butterfly DN 150	-	2	
Check Valve	DN 150 Swing check Type	-	2	

10. Sludge Lagoon				
Sludge Lagoon Inlet Gate	Manual Sluice Dia 250	-	4	
Stop log	650 x 200 Aluminium		16	
11. Electrical Substation (Electrical Works Generator Facility)				
Generator	1500 KVA Continental Operted	1250	2	
Fuel Transfer Pumps	Geav Pumps		2	
Day Tank	3500L		2	
Intake Sourd Alternator			2	
Discharge Sound Alternator			2	
12. High Level Reservoir				
Isolation Valve	Hand Operated Butterfly With Headstock Dia 500mm	-	2	
Outlet Valve	Motorited Butterfly	0.75	2	
	Manual Butterfly		4	
Drain Valve	Manual Butterfly		4	

Appendix D

SynerGEE Fault Report for Feeder 4 of HORANA GSS

- Sections
- Protective Devices

Section Fault Summary for HORANA F4

Section	Flt	Phase	Dist	Phs	Cuml. Impedance				Nominal	Symmetrical Amps				
Id	Loc	Conductor	kM	Cfg	R1	X1	R0	X0	kV	Min G	Max G	L-L	L-L-G	3 Ph
Feeder HORANA-F4				ABCN	0.358	2.040	1.075	6.120	33.0	2909	5519	7966	8207	9199
Section_275129111	Section_275129111	33KV LYNX SC H	0.2	ABCN	0.385	2.087	1.124	6.361	33.0	2871	5340	7773	8002	8976
Section_1567577117	Section_275209020	33KV LYNX SC H	1.0	ABCN	0.530	2.344	1.392	7.664	33.0	2673	4539	6865	7046	7927
Section_1567584221	Section_275209020	33KV LYNX SC H	2.3	ABCN	0.769	2.767	1.832	9.807	33.0	2388	3639	5746	5880	6635
Section_275209020	Section_275209020	33KV LYNX SC H	4.3	ABCN	1.115	3.378	2.469	12.911	33.0	2053	2827	4638	4735	5355
Section_18022876	Section_18022876	33KV LYNX SC H	4.7	ABCN	1.195	3.519	2.616	13.626	33.0	1987	2688	4439	4530	5126
Section_1567590027	02-1320513	33KV LYNX SC H	5.3	ABCN	1.301	3.708	2.812	14.582	33.0	1905	2523	4199	4283	4848
Section_1567592831	02-1320513	33KV LYNX SC H	7.8	ABCN	1.736	4.476	3.612	18.480	33.0	1623	2017	3437	3501	3968
Section_1567595735	02-1320513	33KV LYNX SC H	8.7	ABCN	1.903	4.772	3.921	19.981	33.0	1534	1873	3212	3270	3708
Section_1567613839	02-1320513	33KV LYNX SC H	10.9	ABCN	2.295	5.465	4.642	23.495	33.0	1358	1604	2784	2833	3215
Section_1567621543	02-1320513	33KV LYNX SC H	12.0	ABCN	2.486	5.803	4.994	25.210	33.0	1285	1499	2614	2659	3018
Section_1567624547	02-1320513	33KV LYNX SC H	14.4	ABCN	2.907	6.548	5.770	28.991	33.0	1148	1309	2303	2342	2659
02-1320513/1	02-1320513	33KV LYNX SC H	14.6	ABCN	2.938	6.603	5.828	29.270	33.0	1139	1297	2283	2321	2636
01-BB-018	01-BB-018	33KV LYNX SC H	14.6	ABCN	2.945	6.614	5.839	29.327	33.0	1137	1295	2279	2317	2632
01-BB-17	01-BB-17	33KV LYNX SC H	14.6	ABCN	2.945	6.615	5.840	29.332	33.0	1137	1295	2279	2317	2631
01-1241420	01-1241420	33KV BUS	14.6	ABCN	2.945	6.615	5.840	29.332	33.0	1137	1295	2279	2317	2631
02-1213518	02-1213518	33KV BUS	14.6	ABCN	2.945	6.615	5.840	29.332	33.0	1137	1295	2279	2317	2631
02-197953347	02-197953347	33KV LYNX SC H	14.8	ABCN	2.973	6.664	5.891	29.577	33.0	1129	1284	2261	2299	2611
02-1320513/18198060	02-1320513/1819	33KV LYNX SC H	14.9	ABCN	2.991	6.695	5.924	29.738	33.0	1124	1278	2250	2288	2598

	8060													
Section_18180530	Section_18180530	33KV LYNX SC H	18.1	ABCN	3.566	7.713	6.984	34.902	33.0	983	1093	1942	1973	2242
01-BB-19/6	01-BB-19/6	33KV BUS	14.6	ABCN	2.945	6.615	5.840	29.332	33.0	1137	1295	2279	2317	2631
01-1241455	01-1241455	33KV BUS	14.6	ABCN	2.945	6.615	5.840	29.332	33.0	1137	1295	2279	2317	2631
01-1229270	01-1229270	33KV LYNX SC H	14.6	ABCN	2.946	6.617	5.842	29.342	33.0	1137	1294	2278	2316	2630
01-1241254	01-1241254	33KV BUS	14.6	ABCN	2.946	6.617	5.842	29.343	33.0	1137	1294	2278	2316	2630
01-1241255	01-1241255	33KV BUS	14.6	ABCN	2.946	6.617	5.842	29.343	33.0	1137	1294	2278	2316	2630
01-1241257	01-1241257	33KV BUS	14.6	ABCN	2.946	6.617	5.842	29.343	33.0	1137	1294	2278	2316	2630
01-1241256	01-1241256	33KV BUS	14.6	ABCN	2.946	6.617	5.842	29.343	33.0	1137	1294	2278	2316	2630
01-1241260	01-1241260	33KV BUS	14.6	ABCN	2.946	6.617	5.842	29.343	33.0	1137	1294	2278	2316	2630
01-1241452	01-1241452	33KV BUS	14.6	ABCN	2.945	6.615	5.840	29.332	33.0	1137	1295	2279	2317	2631
01-1241453	01-1241453	33KV BUS	14.6	ABCN	2.945	6.615	5.840	29.332	33.0	1137	1295	2279	2317	2631
01-1241452/1	01-1241452/1	33KV BUS	14.6	ABCN	2.945	6.615	5.840	29.332	33.0	1137	1295	2279	2317	2631
Section	**Flt**	**Phase**	**Dist**	**Phs**	**Cuml. Impedance**				**Nominal**	**Symmetrical Amps**				
Id	**Loc**	**Conductor**	**kM**	**Cfg**	**R1**	**X1**	**R0**	**X0**	**kV**	**Min G**	**Max G**	**L-L**	**L-L-G**	**3 Ph**
01-BB-19/4	01-BB-19/4	33KV BUS	14.6	ABCN	2.945	6.615	5.840	29.332	33.0	1137	1295	2279	2317	2631
01-1241446	01-1241446	33KV BUS	14.6	ABCN	2.945	6.615	5.840	29.332	33.0	1137	1295	2279	2317	2631
02-18199593	01-1241446	33KV BUS	14.6	ABCN	2.945	6.615	5.840	29.332	33.0	1137	1295	2279	2317	2631
01-1241447	01-1241447	33KV BUS	14.6	ABCN	2.945	6.615	5.840	29.332	33.0	1137	1295	2279	2317	2631
01-1228966	01-1228966	33KV RACOON SC T	15.4	ABCN	3.267	6.933	6.332	30.453	33.0	1092	1239	2153	2190	2486
Section_1278497	01-1228966	33KV RACOON SC T	15.7	ABCN	3.399	7.064	6.534	30.914	33.0	1074	1217	2105	2142	2430
01-1228987	01-1228987	33KV RACOON SC T	16.1	ABCN	3.565	7.228	6.788	31.494	33.0	1053	1190	2047	2083	2364