VOLTAGE SAG MITIGATION PROPOSALS
FOR
MERBOK MDF LANKA PVT LTD

Master of Science Dissertation

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Abstract

Power Quality has been an important concept since the inception of power systems. With more and more sensitive equipment being used in the industries, the requirement of standards of power quality has been highlighted. Power quality related problems that result in loss of production in critical processes create a dilemma for both the serving utility and the customer. This research is based on giving proposals to solve a specific power quality problem involving voltage sags in one of the large scale customers of Ceylon Electricity Board i.e. Merbok MDF Lanka (Pvt) Ltd. The customer has installed considerable amount of sensitive equipment in his large scale manufacturing processes including PLC equipments, variable speed drives, etc. The customer has faced frequent power interruptions and subsequent production losses due to the said power quality problem.

Data was obtained from the customer prermses and from the Horana GSS. After analyzing the data it was revealed that most of the Voltage sags are due to fault conditions in the nearby distribution feeders. Voltage sags having 0.8 to 0.9 p.u. magnitude and 0.5 to 3s duration are the most common.

When giving a solution for the problem both system level improvements and device level mitigation solutions are proposed. In data analysis it is found that pattern of tripping is highly weather dependent. This is considered in system improvement proposals and regular way leave clearance of identified feeders is found to be executed. In addition to that installing auto reclosers at the Horana gantry is proposed in order to reduce the fault clearance time and to improve system reliability as it will directly reduce number of unnecessary tripping at the grid substation.

As a device level mitigation several options such as static transfer switch (STS), uninterruptible power supply (UPS), shunt connected voltage source converter (STATCOM), series connected voltage source converter (SVC) cum dynamic voltage restorer (DVR) are discussed. DVR is proposed as the best solution for this situation as it

can provide voltage support for individual loads. The power rating of the DVR and the capacity requirement of the energy source is calculated. It is expected that the outcome of the study would be much beneficial to the customer in solving the problem and it would be beneficial to other industrial consumers in solving similar problems. In addition to that, I expect it would be beneficial to Ceylon Electricity Board, i.e.my employer in managing Quality of Power.

DECLARATION

I do hereby declare that the work reported in this thesis was exclusively carried out by me under the supervision of Prof. Ranjit Perera, further no part of this thesis has been submitted previously or concurrently for the same or any other degree.

UOM Verified Signature

D.K.A.M. Dinamulla

Date: 30/01/2010

I endorse the declaration by the candidate.

Prof.Ranjit Perera UOM Verified Signature

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LIST OF ABBREVIATIONS

STS-Static Transfer Switch

UPS-Uninterruptible Power Supply

STATCOM- Shunt Connected Voltage Source Converter

SVC -Series Connected Voltage Source Converter

DVR -Dynamic voltage restorer

CEB-Ceylon Electricity Board

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Chapter 01

INTRODUCTION

1.1 Back ground

Power Quality is an aspect which has been with us since the inception of power systems. However growing concern to the issue has arisen with the introduction of power semiconductor switches to the industry where load equipment is less tolerant and sensitive to power quality variations. Voltage sags, Short interruptions, Harmonic disturbances and Voltage imbalances are the most prominent power quality problems in the industry.

Voltage sag has not been a new phenomenon but represents the majority of disturbances facing the industrial consumers. Since the manufacturing processes increasingly become more automated and integrated with modern sensitive devices, attention to power quality issues has become prominent. Even short time disturbances lasting for 100 ms may result in several hours of production loss and financial consequences of such interruption may be very high. The quality of power has become very important as it is having a direct economic impact on many industrial consumers [1]. This study is focused on voltage sags out of the said power quality problems.

Merbok MDF Lanka (Pvt) Ltd is one of the largest industrial electricity consumers having mega scale manufacturing facilities comprising modern equipment and located at Horana Export Processing Zone. Hereafter I refer Merbok MDF Lanka (Pvt) Ltd. as the customer. From several years, complaints are made repeatedly by the customer on frequent internal tripping due to voltage fluctuations in 33kV CEB system. The customer has claimed large number of hours of loss of production due to stopping of machines caused by unexpected power interruptions. In addition to the loss of production, he has faced expensive rework and higher overhead costs. According to the disturbance records at the customer premises, in some months tripping rate has been as high as one tripping per day. A Power Quality Monitor has been installed at his premises in order to get a solution for this problem.

The customer has expressed his view that his installation tripping occurrs due to the voltage fluctuations in the utility system (CEB). He has requested from CEB to give a solution to the problem. With the increasing importance of power quality, this is considered as an opportunity to discover a solution to a practical power quality problem through a proper way of studying the scenario.

1.2 Motivation

The outcome of this study will develop a methodology to reduce number of trippings at the customer premises and it will further assist in increasing the productivity of the customer premises.

The technical study will help as a guide line to solve problems in similar situations at the industry.

The concept of better power quality can be considered as one of the priorities of electricity utilities and to improve customer satisfaction. The reliability improvement will help industries and national economy to attract more investors.

1.3 Objective

The objectives of this study are to

- Identify the problem through date analysis
- Propose system level sag mitigation options and device level sag mitigation options to solve the problem.

1.4 The Scope of Work

The scope of work contains problem identification, analyzing the problem using practical data, drafting a methodology of solving the problem and conclusion.

The thesis has been organized in the consecutive chapters as described below.

- The Voltage sag Characteristics has been explained in Chapter 2.
- The Data Collection is explained at Chapter 3.
- Data Analysis is done in Chapter 4.
- The methodology of solving the problem is explained in Chapter 5.
- The results are discussed in Chapter 6.

Chapter 02

VOLTAGE SAG CHARACTERISTICS

2.1 Introduction

This chapter focuses on discussing the voltage sag characteristics, equipment behavior under voltage sag condition, propagation of voltage sag in the power system and the voltage sag detection techniques. Voltage Sags are said to be most severe as well as most common power quality disturbance faced by industrial consumers. Voltage sags can be caused by network faults, reclosure operations and by the start up of large loads such as induction motors. When the source of voltage sags is concerned it can be on the utility side or the internally within the customer premises. Voltage sags caused by the system faults are much severe compared to the voltage sags caused by the starting of motors [2].

2.2 Voltage Sag Magnitude and Phase Angle Jump

Voltage sags are characterized by reduction in voltage between 0.9 pu to 0.1 pu in rms voltage at the power frequency for duration from 0.5 cycles to 1 minute [1]. Therefore voltage sag wave form can be defined by it's depth and duration. However the voltage sag can be complicated due to the associated phase angle jump and voltage unbalance caused by asymmetrical faults. This voltage unbalance and the phase angle jump have a greater influence on tripping of sensitive equipment. Types of electronic equipment such as variable speed drive controls, motor starter contacters, programmable logic controllers, controller power supplies and control relays are sensitive to voltage sags. Loads such as thyristor based drives are sensitive to phase angle jump and it can lead to detection of wrong zero crossing and firing of thyristor may take in wrong time instances.

The duration of voltage sag depends on the fault clearing time of the protective devices. Generally a transmission system is equipped with fast acting circuit breakers resulting short duration voltage sags. But in a distribution system sags will last longer as fault clearing times are comparatively higher due to over current protection systems.

Propagation of voltage sags depend on the path and devices in the path. Voltage sag originated in transmission system propagates to a longer distance than that is originated in distribution system. Thus for a fault on a 220kV transmission line, Voltage sag may affect sensitive equipment up to several kilometers [2]. When the sag originates in a distribution system they propagate to a comparatively shorter distance.

2.3 Calculation of Voltage sag magnitude

The power system upstream to the point of common coupling (PCC) is modeled as a voltage source behind the source impedance Z_s. Z_s is normally calculated based on the fault level of the PCC. Since the short circuit current due to a fault is much higher than that of normal load current, the load current is normally neglected in calculating voltage sags. Voltage at point of common coupling (V_{PCC}) can be written as below [2];

Fig. 2.1 Voltage divider model to calculate voltage sag parameters

A voltage divider model is generally used to calculate parameters of a voltage sags in radial system as below.

$$\underline{V}pcc = \frac{Zf\underline{E}}{[Zf + Zs]} \quad (2.1)$$

$$\underline{V}sag = \frac{zl\underline{E}}{[Zs + zl]} \quad (2.2)$$

$$Phase\ Deviation = \tan^{-1}[xf/rf] - \tan^{-1}[(Xs + xf1)/(Rs + rf1] \quad (2.3)$$

PCC = Point of Common Coupling

$\underline{V}pcc$ = Voltage at PCC

$\underline{V}sag$ = Magnitude of remaining voltage at PCC

Zf = Impedance between PCC and fault location

Zs = Source Impedance

$\underline{E}$= Source Voltage

z = line impedance per unit length ; i.e. $rf + xf$ j

l = distance from point of Common Coupling

As the feeder impedance Zf depends on the distance to the location of fault from the PCC. It can be written in terms of the distance and line impedance per unit length.

2.4 Sag Variation

An example diagram showing variation of sag voltage magnitude (PU) with fault distance is shown below. This is a 33kV feeder at Horana area fed from Horana GSS and Line impedance is 0.431+0.375j per km.

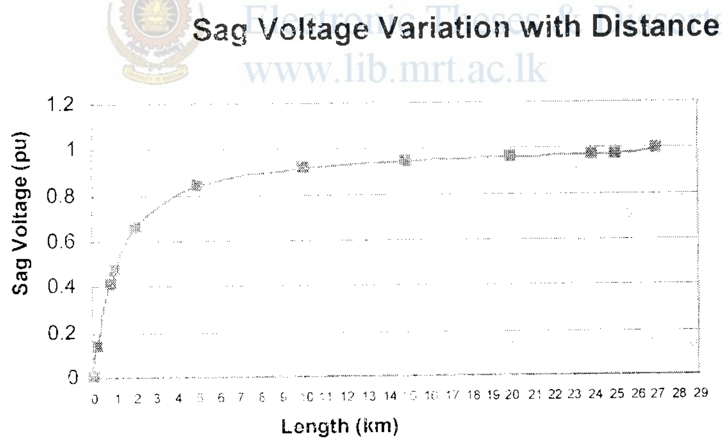


Fig.2.2 Sag voltage magnitude (PU) with fault distance

Sag Magnitude increases as the distance to the fault increases and Sag Magnitude increases as the fault level increases [2]. In a stronger system where Z_s is smaller a larger Vsag (means less voltage drop) results in. Phase angle jump associated with the voltage sag depends on the X/R ratio difference between the source and the feeder impedance. For a distribution system X/R ratio is less than the source X/R. Hence a negative phase angle jump is often accompanied with voltage sag due to a fault in distribution system.

In a meshed system like a transmission system different approach is needed as the system becomes complicated with the loop lines. Thevenin's superposition theorem and node impedance matrix principle can be used to calculate the voltage sag parameters in a meshed system [2].

2.5 Voltage sags due to switching of large loads to the system

Except for the power system faults, other source of voltage sag is due to the connection of large load like induction motors. Induction motors generally draw 5 to 6 times it's rated current at the start and this current gradually decreases with the motor reaching it's rated speed. The duration of the sag depends on the motor dynamics. The dynamics of the motor is decided by its parameters mainly on the inertia of the motor.

2.6 Voltage Sag Propagation in a Power Distribution System

A distribution system is normally radial other than exceptional places. The distribution system is connected to the transmission network through transformers, resulting a higher per unit impedance at the distribution network. Therefore the location of fault is very important and the consequence due to a fault can affect a large or relatively small number of customers depending on the location of the fault.

Due to the system interconnection the voltage sag may occur in one part of the power system which are several km away from the origin of the voltage sag. An example showing distance of sag propagation with the short circuit current of the system voltage level [2] is shown in Table 2.1.

Voltage level	Available short circuit current		
(kV)	10kA	25kA	50kA
230	250 km	100 km	50 km
100	110 km	45 km	22 km
50	50 km	20 km	11 km
33	36 km	15 km	7 km

Table 2.1 Example distance at which fault leads to a noticeable sag

An accepted demonstration of different types of voltage sags against duration is shown below [3].

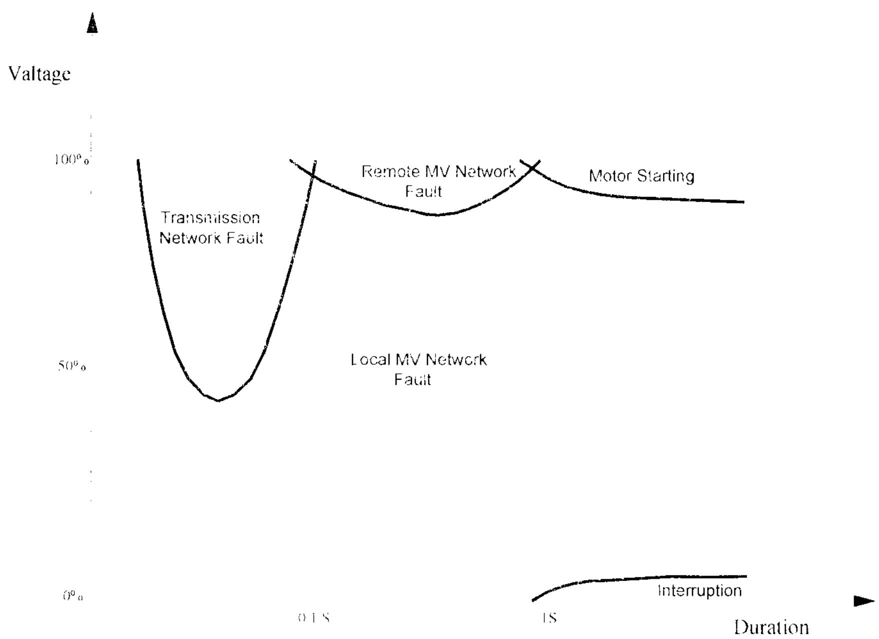
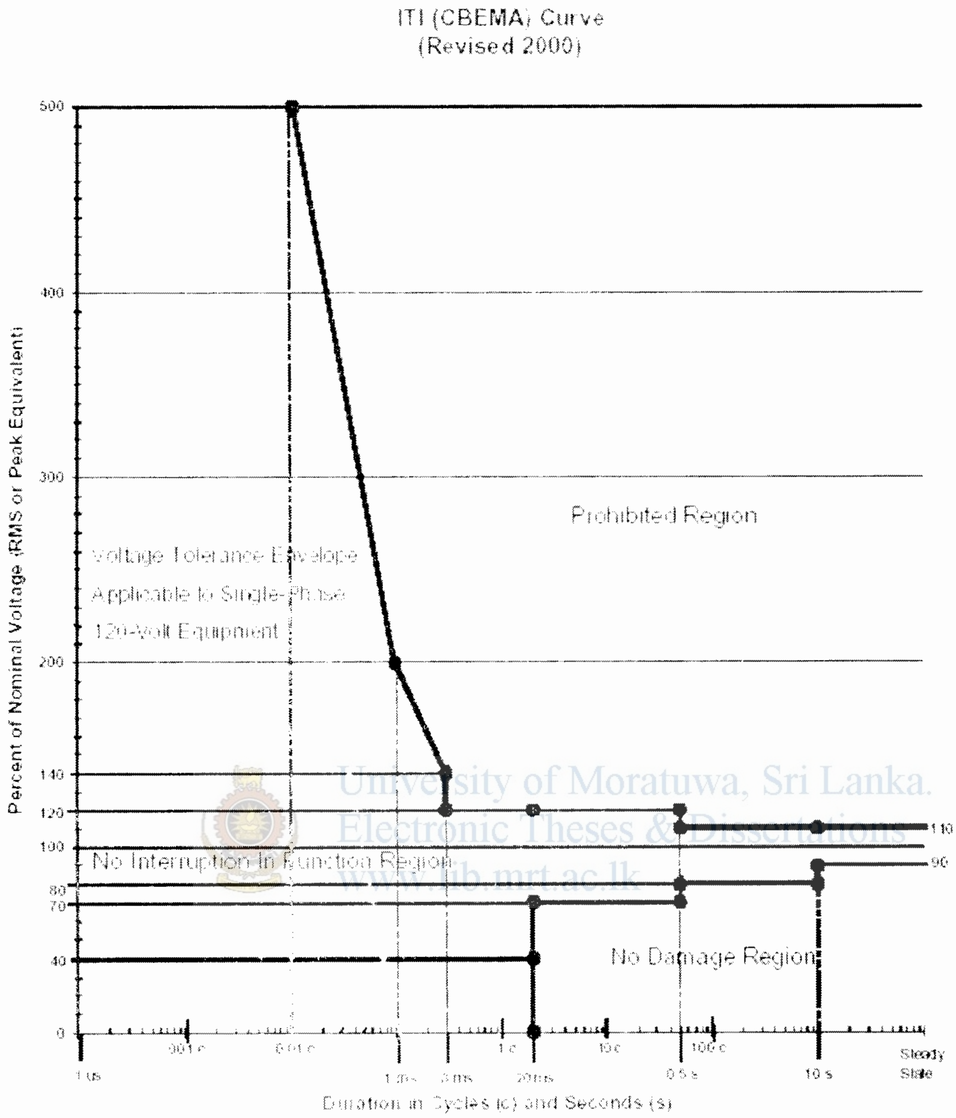


Fig.2.3 Causes of Sag origination

Computer and Business Equipment Manufacturers Association (CBEMA) has introduced CBEMA curve for computers and computer related equipments. The curve was originally developed to describe the tolerance of Main frame computers. While many modern computers have different tolerance different from this. the Curve has become a standard design target for sensitive equipment. The axes represent magnitude and duration of the event .The curve has since been modified and now known as the Information Technology Industry Council curve shown in Fig.2.4.



Published by:

Information Technology Industry Council (ITI)
1250 Eye Street NW Suite 200 Washington DC 20005
202-737-8888
http://www.itic.org

Fig.2.4. Information Technology Industry Council curve for computer equipments

The ITI (CBEMA) Curve describes an AC input voltage envelope which typically can be tolerated (no interruption in function) by most Information Technology Equipment (ITE). This curve is applicable to 120V equipment.

Low power as well as high power rated equipment are susceptible to voltage sags. The customer premises is having lot of Programmable Logic controllers (PLCs) and Variable speed drives where the effects of voltage sags on them are very significant. PLCs are based on power electronics control systems and sensitivity of this equipment to voltage sags varies greatly. Voltage tolerance range of various equipment presently in use are explained below [2],

Equipment	Voltage Tolerance		
	Upper range	Average range	Lower Range
PLC	20 ms,75%	260 ms, 60%	620 ms, 45%
PLC input card	20 ms, 80%	40 ms, 55%	40 ms , 30%
5 h.p. AC drive	30 ms, 80%	50 ms. 75%	80 ms, 60%
AC control relay	10 ms, 75%	20 ms, 65%	30 ms, 60%
Motor starter	20 ms, 60%	50 ms, 50%	80 ms, 40%
Personal computer	30 ms, 80%	50 ms, 60%	70 ms, 50%

Table 2.2 Voltage tolerance range of various equipment

2.7 Programmable Logic Controllers

PLCs are used to monitor industrial processes in such a way that they can monitor the status of the devices connected as input of certain processes such as relays, switches and sensors. They are based on power electronic control systems and have a computer memory. The software determines the status of the devices connected as outputs for instance, alarms, lights, fans, etc. The sensitivity of these equipment to voltage sags varies in a wide range (please see the table 2.2). However newer PLC controllers are found to be more sensitive to voltage sags.

2.8 Computer Power Supply

A typical computer power supply consists of two arm diode bridge rectifier, DC capacitor and DC-DC converter. The AC input power is rectified through the diode bridge and output voltage ripples are smoothened by DC capacitor. When the supply voltage drops due to voltage sag the diodes stop conducting. Energy is transferred from the stored energy of the DC capacitor. If the input DC voltage drops beyond a certain minimum value, the regulated DC voltage starts dropping resulting in an error in supply.

2.9 Adjustable Speed Drives

Adjustable Speed Drives are widely used in modern industrial processes. Power quality surveys have shown that ASD are more susceptible to power quality disturbances in the form of voltage sags.

2.9.1 Adjustable Speed AC drives

In a typical Adjustable Speed AC drive, the supply voltage is rectified through the diode bridge rectifier and the output voltage of the bridge is smoothened out by the DC –link capacitor. (The DC-link capacitor is selected to meet the maximum allowable DC-Link Voltage ripple). The AC motor is controlled by magnitude, frequency and phase adjustments of the voltage source inverter.

When the supply voltage experiences voltage sag the line to line supply voltage is less than the DC-link voltage. Under this condition the diodes don't conduct and there is no energy supplied to the DC-link, the DC-link voltage start to drop and the motor will loose it's control.

2.9.2 Adjustable Speed DC drives

Adjustable Speed DC drives are more vulnerable to voltage sags than Adjustable Speed AC drives as there is no DC link capacitor in the drive system. Any voltage change in the supply voltage immediately reflects to the DC link voltage of the motor. As the rectifier is thyristor-controlled type the motor controller performance not only depends on the voltage sag magnitude but also on the phase angle jump associated with the voltage sag. The phase angle jump may lead to detect wrong zero crossing and the controller will not perform as desired.

2.10 Voltage Sag Detection techniques

Due to harmful consequences of voltage sags customers as well as utilities have paid more attention to find a solution. Most of the solutions proposed are in the form of custom power devices. Under the normal operating conditions, voltage sag mitigation devices are by passed and it will be on line as soon as voltage sag is detected for performing its task. Detection of voltage sags plays an important role in proper operation of such mitigating devices.

Delay in sensing the supply results in increasing the time to bring mitigation devices in to operation. Basic requirement of such a detection method are speed accuracy and robust characteristics against noise.

Supply voltage parameters like magnitude and phase are necessary to implement control algorithms of some devices. Therefore selection of a detection technique plays a vital role in voltage sag mitigation. Popular Sag Detection Techniques commonly used are Discrete Fourier transforms (DFT), Kalman Filtering Techniques and DQ Transform method

2.11 Discrete Fourier Transform (DFT)

In Fourier series and in Fourier integral both the physically realizable time domain waveforms have been converted to frequency domain and vice versa. Past voltage data is stored in the memory and for every sample real and imaginary parts of the voltage is calculated. Then the rms voltage and phase shift of the supply voltage can be determined.

2.12 Kalman Filtering Technique

The Kalman filter is on line, recursive, optimal estimates suitable for a system described by state variables which are corrupted by noise. The Kalman filtering technique for power system application is gaining the acceptance due to its speed, accuracy and robustness.

2.13 D-Q Transform

In this method three phase voltage quantities are transformed in to synchronously rotating reference frame where one axis (d) is locked to the supply voltage phases. The supply voltage magnitude can be estimated using d.q component of vector.

Chapter 03

DATA COLLECTION

Problem identification has been done based on the practical data. Practical data has been categorized as Primary and Secondary data according to the importance. Thus in data analysis, calculations are directly done on Voltage measurements and break down records of the GSS that have been selected as primary data. Network Details and Equipment Data at customer premises which can be used as supportive information, have been selected as secondary data.

3.1 Primary Data Category 1: Measurement of voltage & current at the customer premises

In order to identify the problem voltage and current data has been obtained at customer premises

3.1.1 Method of obtaining primary data

A Power Quality Analyzer has been installed at the customer premises. It is fed from the 33kV utility supply through a potential transformer having a ratio of 33000/400 and a current transformer having a ratio of 200/5 at the customer premises.

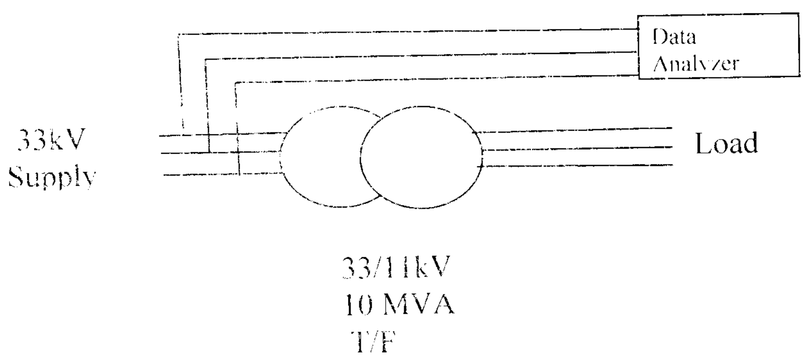


Fig.3.1 Measurements of voltage and current at the customer premises

3.1.2 Measurements

Measurements of voltage and current have been obtained from Power Quality Analyzer installed at the customer premises as mentioned above. Electricity waveforms have been monitored and stored by the equipment continuously. It has been noted that the form of disturbance the customer faced is the Voltage Sag problem.

Continuous analog voltage and current are recorded against the time as per the IEC 61000-4-30 [3]. IEC 61000-4-30 provides an international definition and measurement method for the most common characterization of voltage dips (i.e. in terms of magnitude and duration).

For the measurement of dips IEC 61000-4-30 states that the basic measurement of a voltage dip and swell shall be $U_{rms(1/2)}$ which is the value of the rms voltage measured over one cycle and refreshed each half cycle and dips that involve more than one phase should have been designated as a single event if they overlap in time. A form of the waveform obtained by the data analyzer are shown below,

Fig.3.2 Typical sag waveform obtained by the data analyzer (example 1)

Sag Voltage % = 93/110 = **84.55**

Voltage drop = 15.45

Duration = 2s

Sag Voltage = **27.9kV**

Voltage drop = 5.1 kV

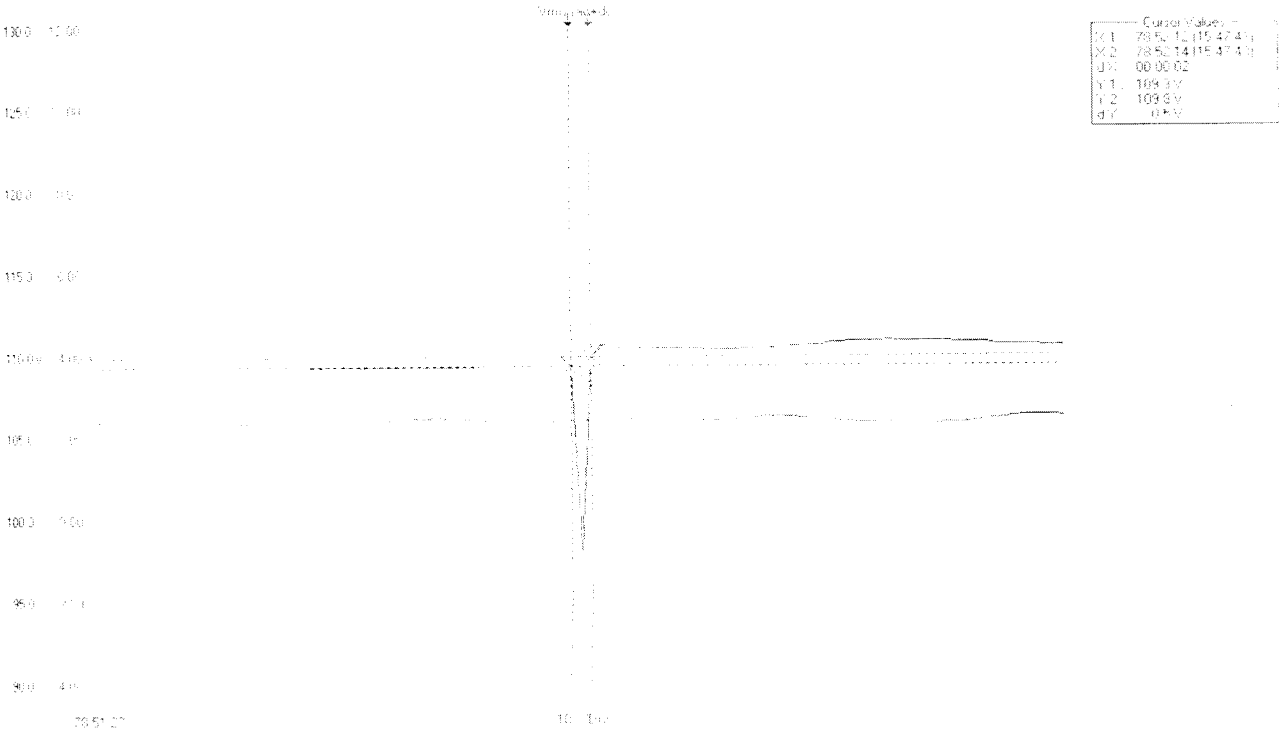


Fig.3.3 Typical sag waveform obtained by the data analyzer (example 2)

Sag Voltage % = 98 / 110 = **89.1**

Voltage drop = 10.9

Duration = 2s

Sag Voltage = **29.4 kV**

Voltage drop = 3.6 kV

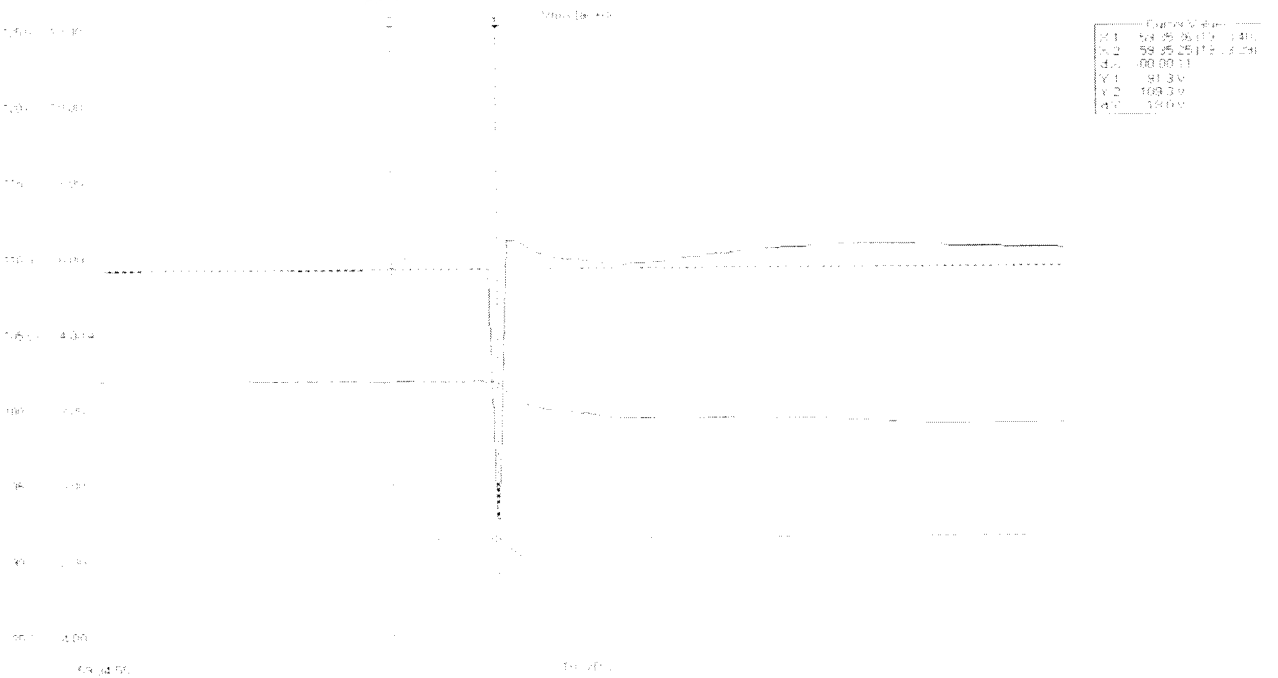


Fig.3.4 Typical sag waveform obtained by the data analyzer (example 3)

Sag Voltage % = 92 / 110 = **83.64**

Sag Voltage = **27.6 kV**

Voltage drop = 10.9

Duration = 2s

Voltage drop = 5.4 kV

3.2 Primary Data Category 2: *Break-down Records*

For the proper investigation of the problem following data has been obtained.

3.2.1. Break-down Records of the customer

In this study the break-down reports of the customer has been obtained for the period from January to December 2007. Break-down Records of the customer includes date, time Reason for failure, Restored Time, and Production down Time and Remarks. As an example a few break-down records obtained for the month of August are shown below.

Date	Time Failed	Reason	Restored Time	Down Time (min.)	Remarks
August 4 , 2007	2.54 PM	CEB Failure	3.40 PM	46	33kV VCB Tripped Under Voltage
August 5 , 2007	8.25 PM	CEB Failure	9.09 PM	48	33kV VCB Tripped Under Voltage
August 8, 2007	7.00 AM	CEB Failure	7.53 AM	53	33kV VCB Tripped Under Voltage

Table 3.1 A few break-down records obtained for the month of August

3.2.2. Break-down records at the GSS

Feeder tripping and relay start times have been obtained from Horana GSS relevant to the instances of tripping occurred at customer premises. These data has been used for analysis in the chapter 5. As an example some records obtained from GSS relevant to the instances of tripping occurred at the customer premises are listed in table 3.2.

Date	Time	Recorded details at the GSS	Comments
August 4 , 2007, 2.54 pm	CEB failure ,33kV Tripped UV	F2 , Earth Fault	Merbok is fed by F2 of Horana GSS ,this is an earth fault
August 5 , 2007, 8.25 pm	CEB failure ,33kV Tripped UV	F5 Tripped (Auto reclosed). Earth fault occurred at Ingiriya side.	Customer premise has tripped due to sag voltage wave originated due to tripping of feeder 05.
August 8 , 2007, 7.00 am	CEB failure ,33kV Tripped UV	F5 operated , Earth Fault , O/C	Customer premises has tripped due to sag voltage wave originated due to tripping of feeder 05

Table 3.2 A few break-down records obtained at the GSS

3.3 Secondary Data Category

3.3.1 Network Details

Network details of Horana 33kV system has been obtained and used in the investigation. These network details include 33kV feeder lengths, feeder routing, and location of protection and isolation equipment, etc. Network details available in the existing SynerGee database of WPSII are also used.

3.3.2 Equipment details of the customer

Equipment details of the customer have been obtained (See Annexure III) and Voltage sag has a greater effect on sensitive equipments.

Chapter 04

DATA ANALYSIS

4.1 Data Collection

As explained in chapter 2 break down data has been obtained at customer premises and at the GSS.

The sag voltage data obtained from the customer premises are classified and reported according to depth and duration (in accordance with the technical report IEC 61000-2-8). When classifying sag voltage data following important points are noted.

When there are several sag events in close succession, considering them as several sag events or one complex multiphase sag event has been done depending on the severity of the sag event (based on details of customer comments)[4]. When sags occur in quick succession, typically as a result of recloser operation, it is unlikely that these events to be recorded as individual sag events. The format is attached as Annexure II

4.2 Data Tabulation

Voltage sag data has been tabulated according to the sag voltage depth and duration. Summary of total collected data given below.

Voltage Depth	0.25 (s)-0.5 (s)	0.5 (s)-1 (s)	1 (s)-3 (s)	3 (s)-20 (s)	**Total**
80-90%	4	12	32	1	49
70-80%	_	24	11	_	35
60-70%	_	1	_	_	1
50-60%	_	_	_	_	_
Total	4	37	43	1	**85**

Table 4.1 Total events of Voltage sags from January to September

Total events located as Voltage sags = 85

Collected Voltage sag data for the months from January to September 2007 is given below,

Months	Voltage Depth (% of Nominal Voltage)	Voltage Duration			
		0.25 (s) - 0.5 (s)	0.5 (s) - 1 (s)	1 (s) - 3 (s)	3 (s) - 20 (s)
January	80 – 90 %	-	1	2	-
	70 – 80 %	-	2	1	-
	60 – 70 %	-	-	-	-
	50 – 60 %	-	-	-	-
February	80 – 90 %	-	1		-
	70 – 80 %	-	1		-
	60 – 70 %	-	-	-	-
	50 – 60 %	-	-	-	-
March	80 – 90 %	-	1	2	-
	70 – 80 %	-	1	1	-
	60 – 70 %	-	-	-	-
	50 – 60 %	-	-	-	-
April	80 – 90 %	-	1	4	-
	70 – 80 %	-	2	1	-
	60 – 70 %	-	-	-	-
	50 – 60 %	-	-	-	-
May	80 – 90 %	1	4	9	-
	70 – 80 %	-	5	3	-
	60 – 70 %	-	-	-	-
	50 – 60 %	-	-	-	-
June	80 – 90 %	1	2	6	1
	70 – 80 %	-	1	1	-
	60 – 70 %	-	-	-	-
	50 – 60 %	-	-	-	-
July	80 – 90 %	1	1	2	-
	70 – 80 %	-	5	2	-
	60 – 70 %	-	1	-	-
	50 – 60 %	-	-	-	-
August	80 – 90 %	-	-	2	-
	70 – 80 %	-	3	1	-
	60 – 70 %	-	-	-	-
	50 – 60 %	-	-	-	-
September	80 – 90 %	1	1	5	-
	70 – 80 %	-	4	1	-
	60 – 70 %	-	-	-	-
	50 – 60 %	-	-	-	-
	Total	04	37	43	01

Table 4.2 Voltage sag data from January to September

Considering above data, the voltage sags in the range of 80%-90% and having duration 1(s) - 3(s) are the most common. The voltage sags in the range of 70%-80% and having duration 0.5 (s) - 1(s) are the second most common. As per the voltage sag studies, the disturbances in the range of magnitude from 70%-90% for the duration from 0.1-1s normally occurs due to faults in the local distribution network and faults in the neighboring distribution network (Fig.2.3). In this practical situation sag durations are some what higher than the expected theoretical durations. Some sags in the range of 70%-80% has retained up to 3 seconds. This might have happened when sags occur in quick succession, typically as a result of recloser operation. When events have occurred less than a minute apart, only the event with the greatest voltage depth is recorded [5]. When observing the break down records at Horana GSS it is noted that occurrence of Voltage sags with longer duration has a relationship with auto reclosure operation. In Horana 33kV network the customer is fed from 33 kV Feeder number 2. Feeder number 3 and Feeder number 4 go to Horana gantry and having auto reclosing facility for some of the outgoing feeders at the gantry.

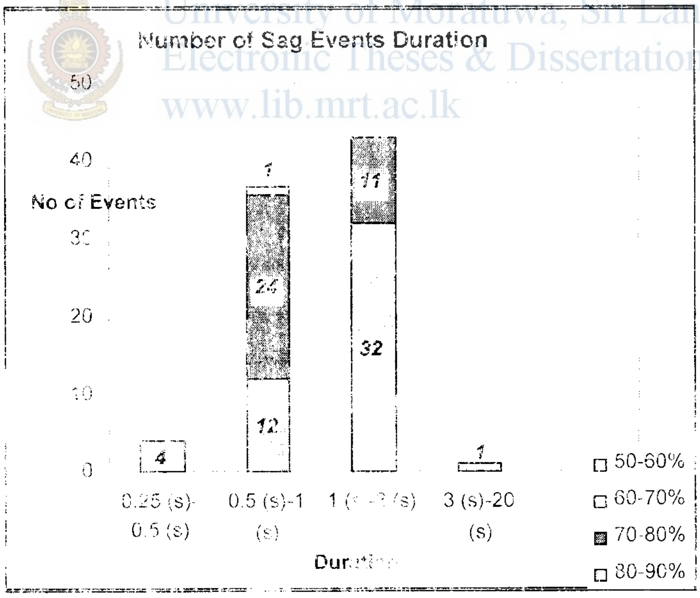


Fig: 4.1 Number of Sag events of difference duration

4.3 Voltage Sag magnitude calculation as per the network topology

4.3.1 Sag Voltage Variation for a three phase fault condition

Theoretical Values of sag voltages have been calculated for three phase fault condition at all 33kV feeders in Horana GSS. Secondly a zone of vulnerability has been identified.

Feeder 1 of Horana GSS –Feeder maximum length 1.6 km

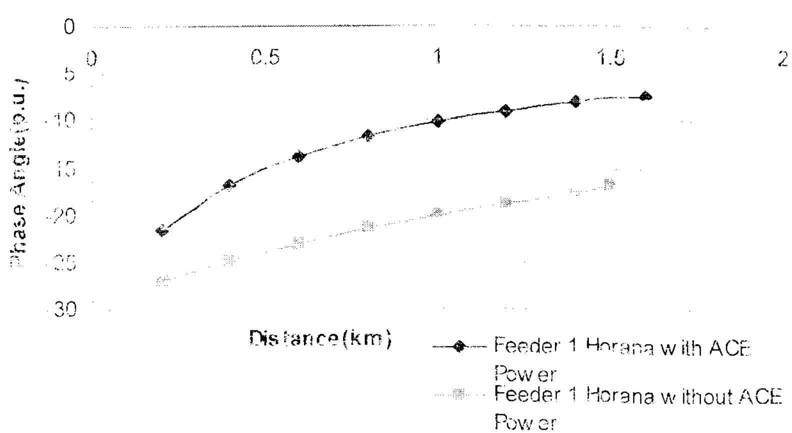


Fig: 4.2 Voltage Sag characteristic against line length

Length(km)	Vsag(P.U.)	angle
0.2	0.27977541	-21.5831
0.4	0.44255309	-16.9142
0.6	0.54707262	-13.8729
0.8	0.61928712	-11.7455
1	0.67196132	-10.1778
1.2	0.71199416	-8.97629
1.4	0.74340817	-8.02685
1.6	0.76869558	-7.25807

Table 4.3. Voltage Sag characteristic against line length with ACE Power plant connected

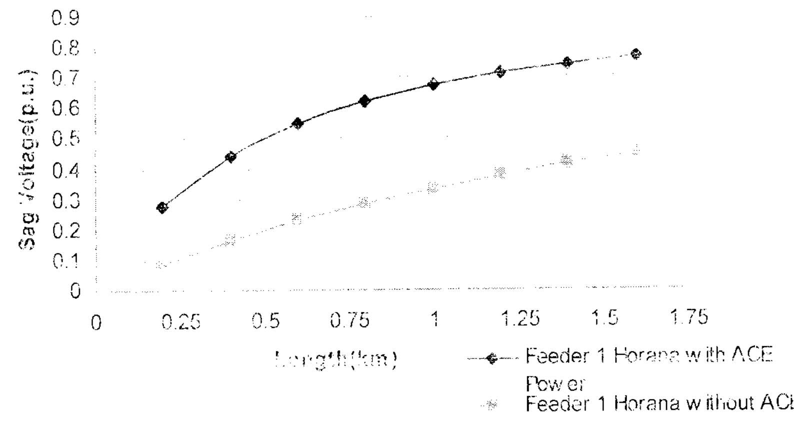


Fig: 4.3 Phase angle variation against line length

Length	Vsag(P.U.)	angle
0.2	0.08841732	-27.0072
0.4	0.16380689	-24.8756
0.6	0.22859667	-23.0388
0.8	0.28471134	-21.4425
1	0.3336753	-20.0445
1.2	0.37669988	-18.8115
1.4	0.414753	-17.7167

Table 4.4. Voltage Sag characteristic against length with ACE Power plant not connected

Feeder 2 of Horana GSS –Feeder maximum length 1.5 km

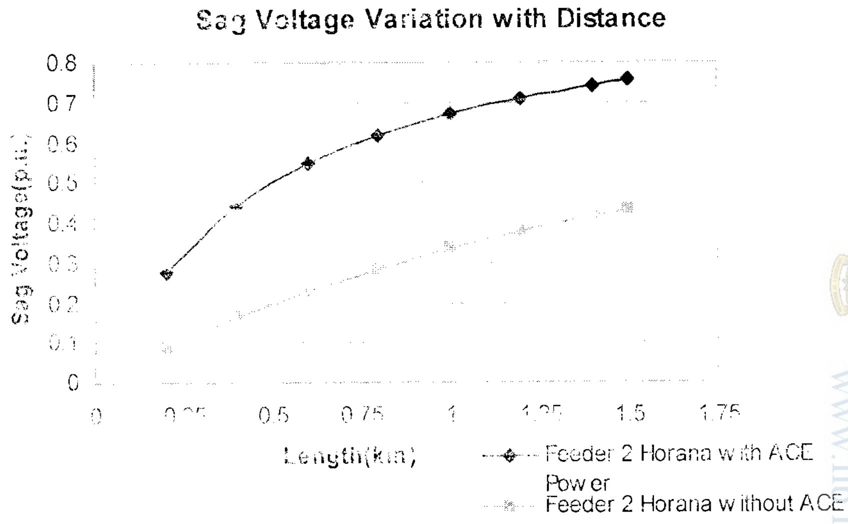


Fig: 4.4 Voltage Sag characteristic against line length

Length	Vsag(P.U.)	angle
0.2	0.27977541	-21.5831
0.4	0.44255309	-16.9142
0.6	0.54707262	-13.8729
0.8	0.61928712	-11.7455
1	0.67196132	-10.1778
1.2	0.71199416	-8.97629
1.4	0.74340817	-8.02685
1.5	0.75670102	-7.62324

Table 4.5 Voltage Sag characteristic against line length with ACE Power plant connected

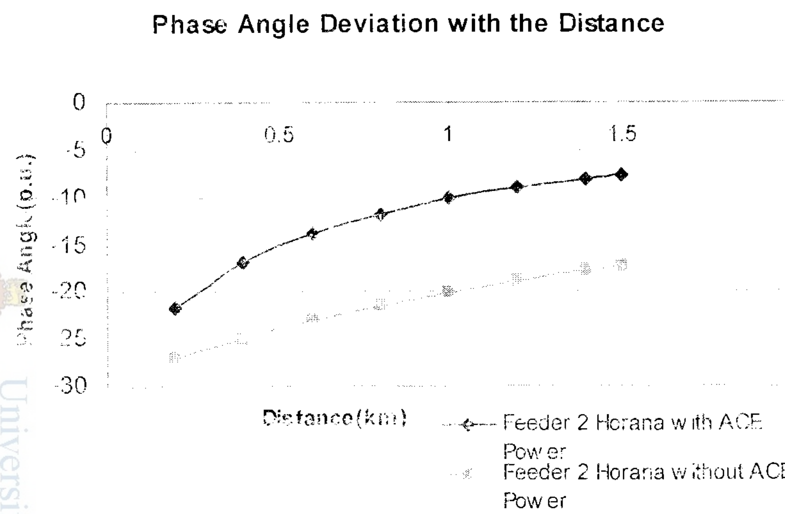


Fig: 4.5 Phase angle variation against line length

Length	Vsag(P.U.)	angle
0.2	0.08841732	-27.0072
0.4	0.16380689	-24.8756
0.6	0.22859667	-23.0388
0.8	0.28471134	-21.4425
1	0.3336753	-20.0445
1.2	0.37669988	-18.8115
1.4	0.414753	-17.7167
1.5	0.43216477	-17.2144

Table 4.6 Voltage Sag characteristic against length with ACE Power plant not connected

Feeder 3 of Horana GSS maximum length =25km

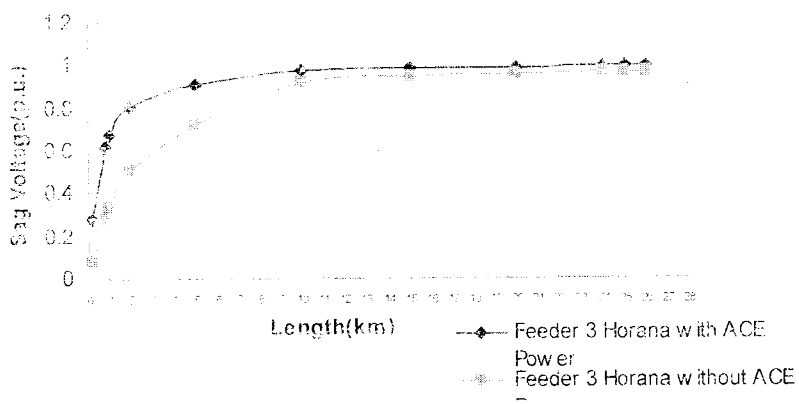


Fig: 4.6 Voltage Sag characteristic against line length

Length	Vsag(P.U.)	angle
0.2	0.08841732	-27.0072
0.8	0.28471134	-21.4425
1	0.3336753	-20.0445
2	0.50616355	-15.0681
5	0.7254293	-8.57097
10	0.9168618	-5.21258
15	0.94383554	-3.57467
20	0.95761567	-2.71941
24	0.96457484	-2.28239
25	0.96597203	-2.19422
26	0.96726329	-2.11261

Table 4.7 Voltage Sag characteristic against line length with ACE Power plant connected

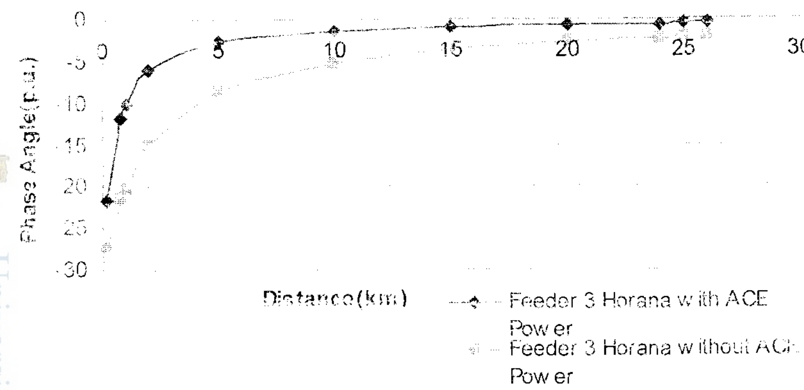


Fig: 4.7 Phase angle variation against line length

Length	Vsag(P.U.)	angle
0.2	0.27977541	-21.5831
0.8	0.61928712	-11.7455
1	0.67196132	-10.1778
2	0.80685473	-6.08987
5	0.91389237	-2.75498
10	0.97811545	-1.42175
15	0.98536993	-0.95481
20	0.9890127	-0.71874
24	0.99083786	-0.60005
25	0.99120319	-0.57626
26	0.9915405	-0.55429

Table 4.8 Voltage Sag characteristic against length with ACE Power plant not connected

Feeder 4 of Horana GSS maximum length =25km

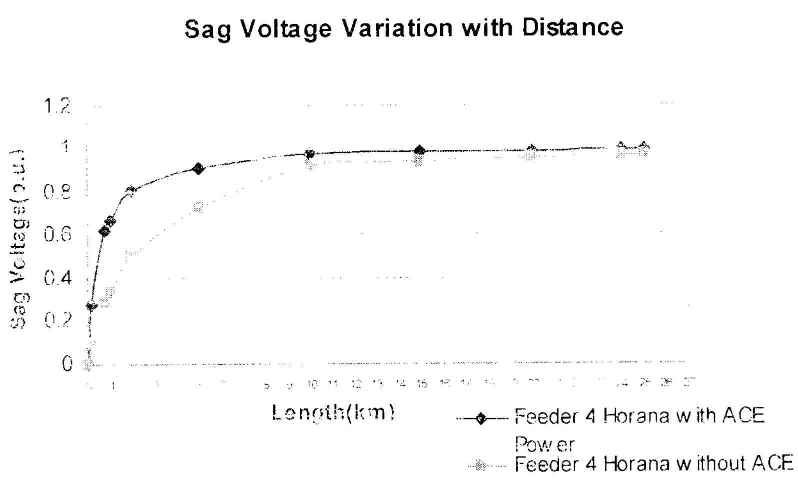


Fig: 4.8 Voltage Sag characteristic against line length

Length	Vsag(P.U.)	angle
0.2	0.27977541	-21.5831
0.8	0.61928712	-11.7455
1	0.67196132	-10.1778
2	0.80685473	-6.08987
5	0.91389237	-2.75498
10	0.97811545	-1.42175
15	0.98536993	-0.95481
20	0.9890127	-0.71874
24	0.99083786	-0.60005
25	0.99120319	-0.57626

Table 4.9 Voltage Sag characteristic against line length with ACE Power plant connected

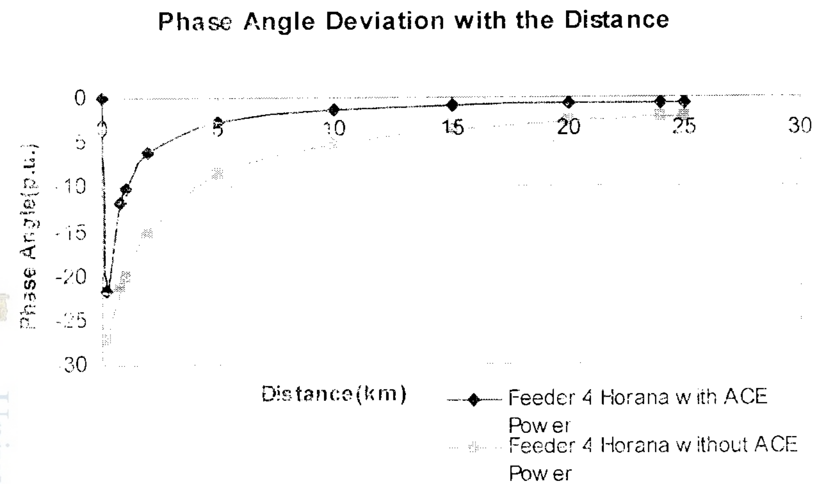


Fig: 4.9 Phase angle variation against line length

Length	Vsag(P.U.)	angle
0.2	0.08841732	-27.0072
0.8	0.28471134	-21.4425
1	0.3336753	-20.0445
2	0.50616355	-15.0681
5	0.7254293	-8.57097
10	0.9168618	-5.21258
15	0.94383554	-3.57467
20	0.95761567	-2.71941
24	0.96457484	-2.28239
25	0.96597203	-2.19422

Table 4.10 Voltage Sag characteristic against length with ACE Power plant not connected

Feeder 5 of Horana GSS –Feeder maximum length 27 km

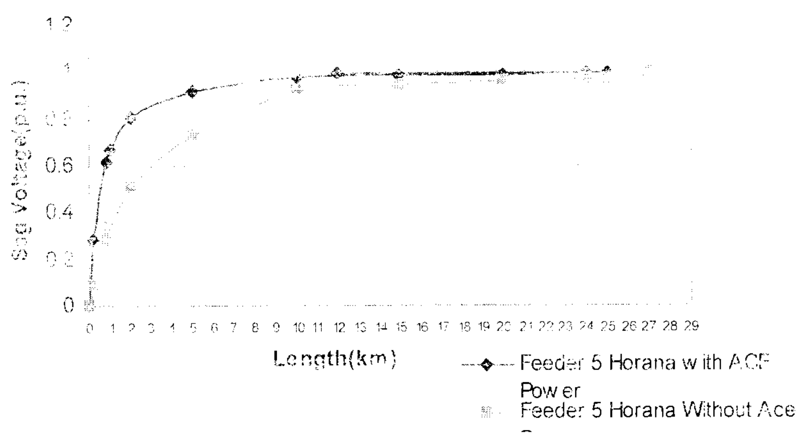


Fig: 4.10 Voltage Sag characteristic against line length

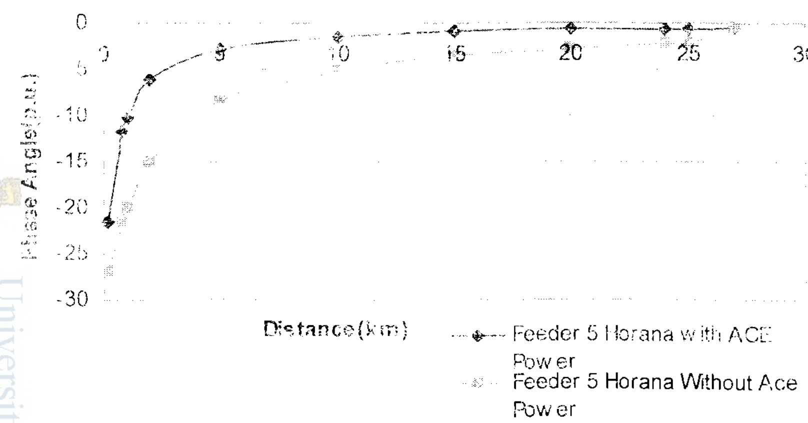


Fig: 4.11 Phase angle variation against line length

Length	Vsag(P.U.)	angle
0.2	0.27977541	-21.5831
0.8	0.61928712	-11.7455
1	0.67196132	-10.1778
2	0.80685473	-6.08987
5	0.91389237	-2.75498
10	0.97811545	-1.42175
15	0.98536993	-0.95481
20	0.9890127	-0.71874
24	0.99083786	-0.60005
25	0.99120319	-0.57626
27	0.9918529	-0.53392

Table 4.11 Voltage Sag characteristic against line length with ACE Power plant connected

Length	Vsag(P.U.)	angle
0.2	0.08841732	-27.0072
0.8	0.28471134	-21.4425
1	0.3336753	-20.0445
2	0.50616355	-15.0681
5	0.7254293	-8.57097
10	0.9168618	-5.21258
15	0.94383554	-3.57467
20	0.95761567	-2.71941
24	0.96457484	-2.28239
25	0.96597203	-2.19422
27	0.9918529	-0.53392

Table 4.12 Voltage Sag characteristic against length with ACE Power plant not connected

Feeder 8 of Horana GSS –Feeder maximum length 4 km

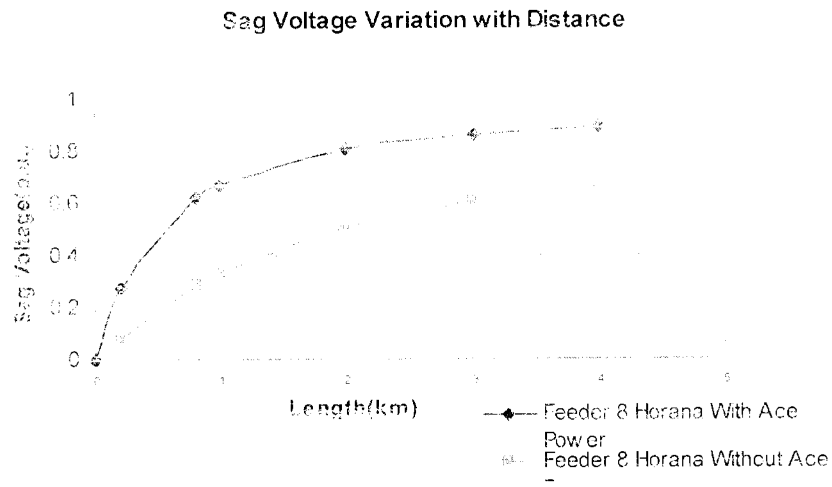


Fig: 4.12 Voltage Sag characteristic against line length

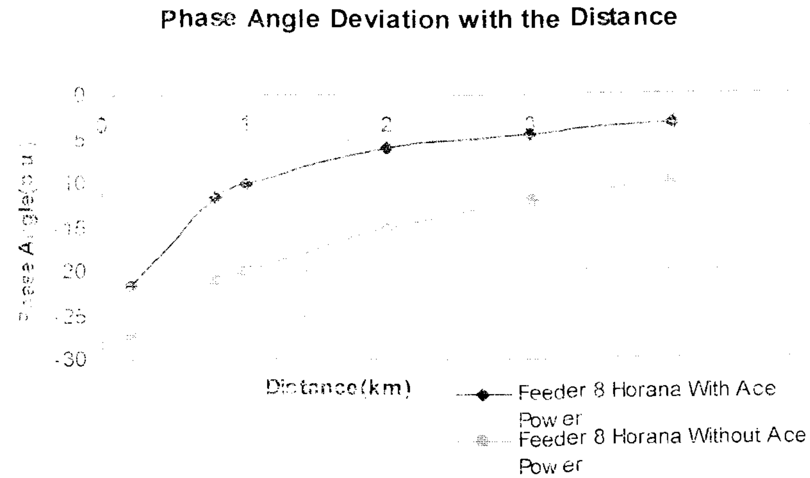


Fig: 4.13 Phase angle variation against line length

Length	Vsag(P.U.)	angle
0.2	0.27977541	-21.5831
0.8	0.61928712	-11.7455
1	0.67196132	-10.1778
2	0.80685473	-6.08987
3	0.86337354	-4.34028
4	0.89435111	-3.37073

Table 4.13 Voltage Sag characteristic against line length with ACE Power plant connected

Length	Vsag(P.U.)	angle
0.2	0.08841732	-27.0072
0.8	0.28471134	-21.4425
1	0.3336753	-20.0445
2	0.50616355	-15.0681
3	0.6092849	-12.0416
4	0.67733399	-10.0171

Table 4.14 Voltage Sag characteristic against length with ACE Power plant not connected

Voltage Sag characteristic against line length

When the above study is concerned it is clear that the magnitude of voltage sags will be severe with out the ACE power plant. In incidences when ACE power plant is not connected to the system and after the retirement of ACE power plant in 2013 the system may face voltage sags with higher magnitude.

4.3.2 Sag Voltage Variation for a Single line to ground fault condition

Single line to ground fault condition has been more common than three phase symmetrical fault condition in the selected area. Theoretical Values of sag voltages have been calculated for single line to ground fault condition at all 33kV feeders in Horana GSS. Secondly a zone of vulnerability has been identified

Feeder 1 of Horana GSS –Feeder maximum length 1.6 km

Length	Vsag (P.U.)
0.2	0.289747
0.4	0.485719
0.6	0.618264
0.8	0.708742
1	0.771991
1.2	0.817413
1.4	0.850891
1.6	0.876158

Table 4.15 Voltage Sag Characteristic against line length with ACE Power plant connected

Length	Vsag (P.U.)
0.2	0.100659
0.4	0.199534
0.6	0.296819
0.8	0.386667
1	0.466454
1.2	0.535653
1.4	0.594872
1.6	0.645219

Table 4.16 Voltage Sag Characteristic against line length with ACE Power plant not connected

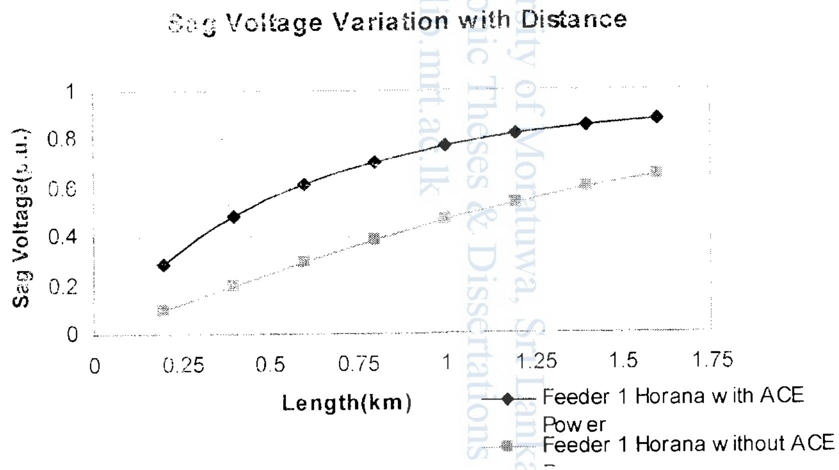


Fig: 4.14 Voltage Sag Characteristics against line length

Feeder 2 of Horana GSS –Feeder maximum length 1.5 km

Length	Vsag (P.U.)
0.2	0.289747
0.4	0.485719
0.6	0.618264
0.8	0.708742
1	0.771991
1.2	0.817413
1.4	0.850891
1.5	0.864376

Table 4.17 Voltage Sag Characteristic against line length with ACE Power plant connected

Length	Vsag (P.U.)
0.2	0.100659
0.4	0.199534
0.6	0.296819
0.8	0.386667
1	0.466454
1.2	0.535653
1.4	0.594872
1.5	0.621078

Table 4.18 Voltage Sag Characteristic against line length with ACE Power plant not connected

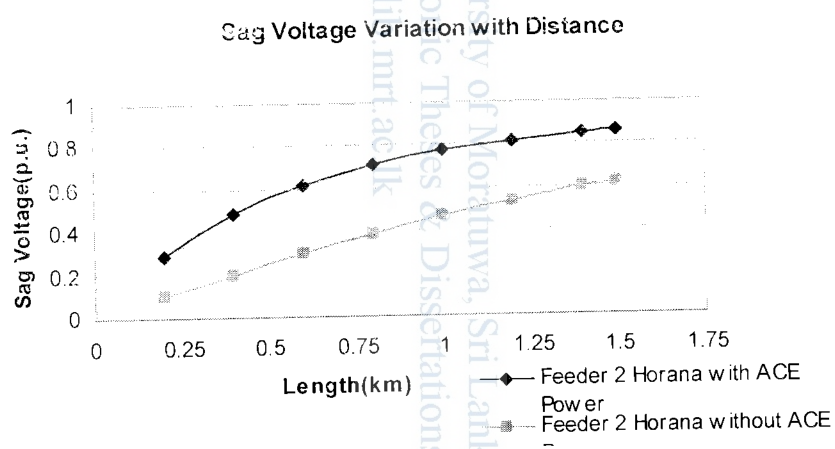


Fig: 4.15 Voltage Sag Characteristics against line length

Feeder 3 of Horana GSS maximum length =25km

Length	Vsag (P.U.)
0.2	0.289747
0.8	0.708742
1	0.771991
2	0.910932
5	0.980969
10	0.995273
15	0.997801
20	0.998734
24	0.999111
25	0.999178
26	0.999239

Table 4.19 Voltage Sag Characteristic against line length with ACE Power plant not connected

length	Vsag (P.U.)
0.2	0.100659
0.8	0.386667
1	0.466454
2	0.72419.
5	0.929594
10	0.981786
15	0.991465
20	0.995073
24	0.996535
25	0.996798
26	0.997033

Table 4.20 Voltage Sag Characteristic against line length with ACE Power plant connected

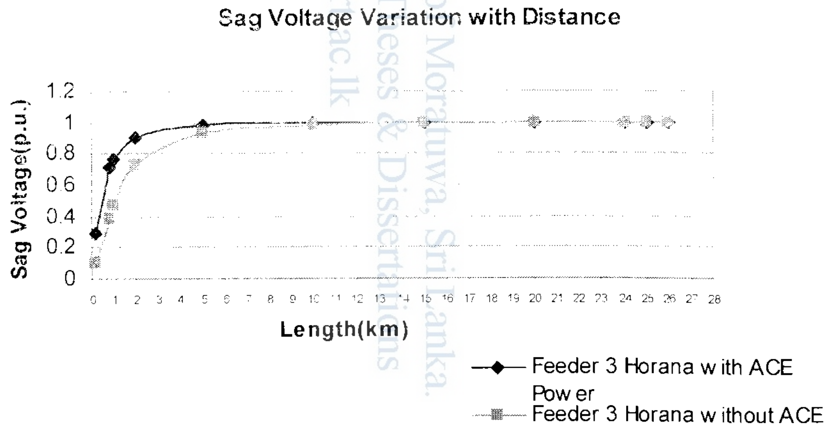


Fig: 4.16 Voltage Sag Characteristics against line length

Feeder 4 of Horana GSS maximum length =25km

Length	Vsag (P.U.)
0.2	0.289747
1	0.771991
2	0.910932
5	0.980969
10	0.995273
15	0.997801
20	0.998734
24	0.999111
25	0.999178

Table 4.21 Voltage Sag Characteristic against line length with ACE Power plant connected

Length	Vsag (P.U.)
0.2	0.100659
0.8	0.386667
1	0.466454
2	0.72419
5	0.929594
10	0.981786
15	0.991465
20	0.995073
24	0.996535
25	0.996798

Table 4.22 Voltage Sag Characteristic against line length with ACE Power plant not connected

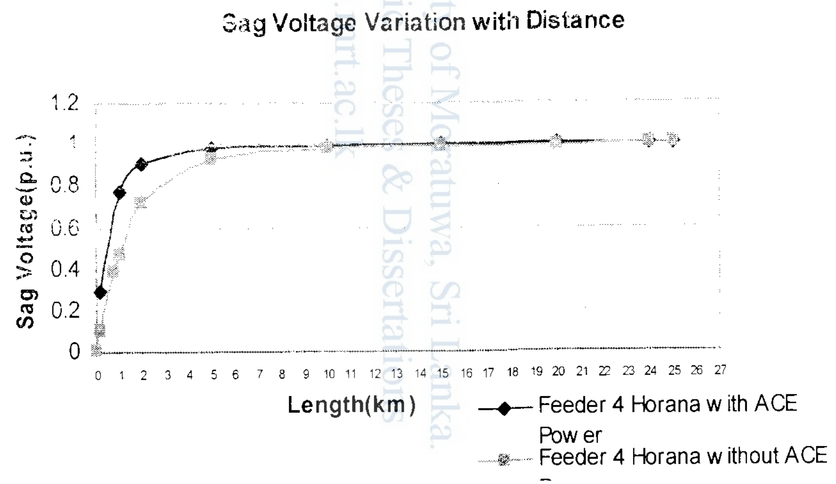


Fig: 4.17 Voltage Sag Characteristics against line length

Feeder 5 of Horana GSS –Feeder maximum length 27 km

Length	Vsag (P.U.)
0.2	0.289747
0.8	0.708742
1	0.771991
2	0.910932
5	0.980969
10	0.994955
15	0.997801
20	0.998734
24	0.999111
25	0.999178
27	0.999293

Table 4.23 Voltage Sag Characteristic against line length with ACE Power plant connected

Length	Vsag (P.U.)
0.2	0.100659
0.8	0.386667
1	0.466454
2	0.72419
5	0.929594
10	0.98058
15	0.991465
20	0.995073
24	0.996535
25	0.996798
27	0.997243

Table 4.24 Voltage Sag Characteristic against line length with ACE Power plant not connected

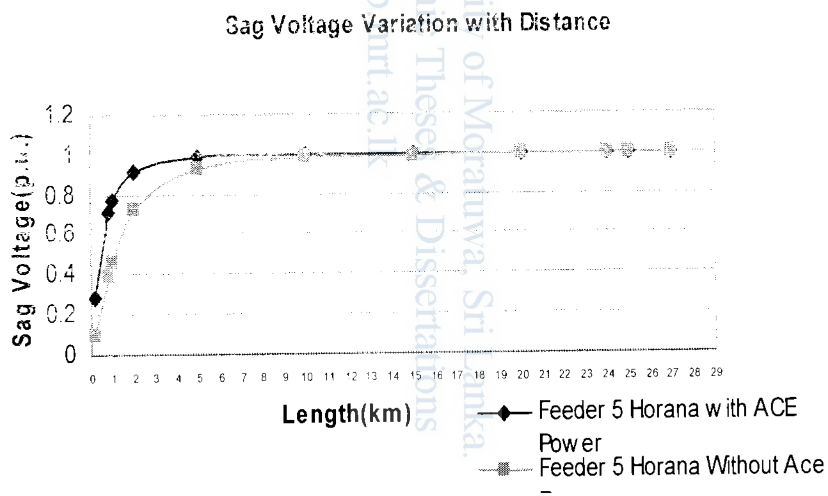


Fig: 4.18 Voltage Sag Characteristics against line length

Feeder 8 of Horana GSS –Feeder maximum length 4 km

Length km	Vsag (P.U.)
0.2	0.289747
1	0.771991
2	0.910932
3	0.953563
4	0.971678

Table 4.25 Voltage Sag Characteristic against line length with ACE Power plant connected

Length km	Vsag (P.U.)
0.2	0.100659
1	0.466454
2	0.72419
3	0.840367
4	0.897858

Table 4.26 Voltage Sag Characteristic against line length with ACE Power plant not connected

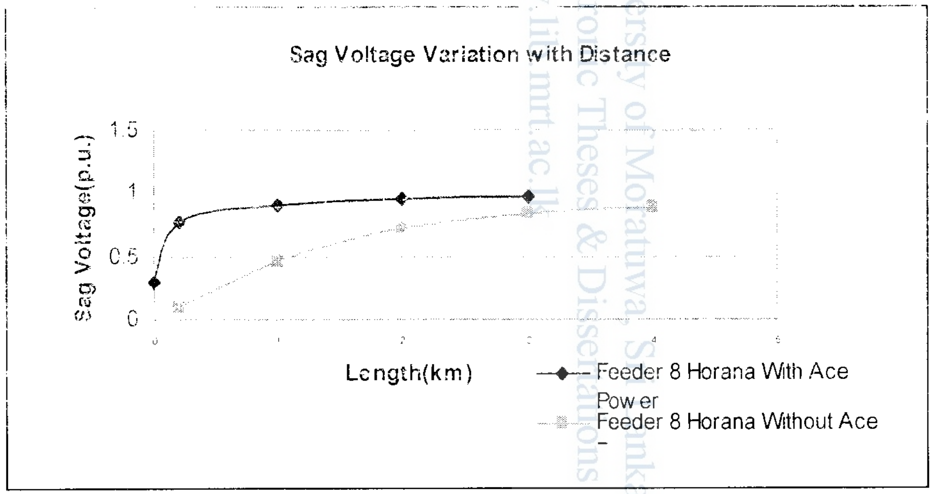


Fig: 4.19 Voltage Sag Characteristic against line length with ACE Power plant not connected

4.4 A Data Analysis

To understand the nature of voltage dips following analysis have been done using the different methods available for power quality analysis.

4.4.1 Voltage Magnitude –Duration Charts

According to the research done in the field of power quality voltage dips have been categorized according to the source, duration and voltage drop [7]. The reason of different voltage dips in the axes of duration and magnitude can be depicted as below. Different zones have been identified as A, B, C, D and E.

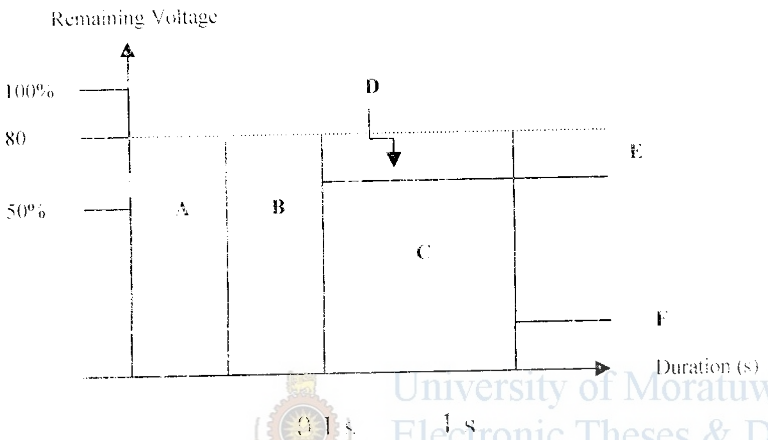


Fig: 4.20 Voltage Magnitude –Duration chart for voltage dips

A = Fuses Blown
B = Transmission System Faults
C = Faults in Local distribution network
D = Faults in other distribution network
E = Motors and transformers faults
F = Interruptions

The sag Voltage data obtained in this study can be depicted in the as below.

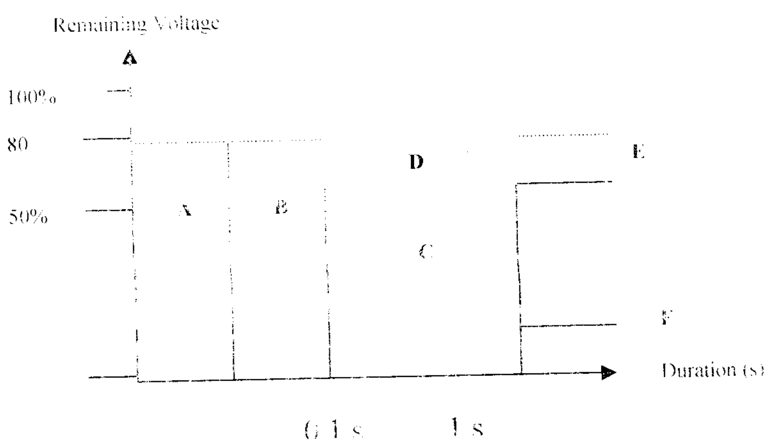


Fig: 4.21 Voltage Magnitude –Duration chart for voltage dips in this study

This leads to the confirmation that the voltage sags originate from the faults in the local distribution network and from the faults in neighboring distribution network.

4.4.2 Calculation of Voltage Dip Indices

Voltage sag data analysis by to counting of events is done in this section.

4.4.2.1 Counting according to ESKOM table [8]

ESKOM is a South African utility and ESKOM table gives a type of sag characterization of a site as a measure of all the sags recorded over an agreed period (usually a year). They define rectangular regions in the duration/magnitude plane and give the number of sag incidents falling in to each region.

The voltage sags are grouped according to the following characteristics.

Class Y: 80 %-90% magnitude, 20ms-3s duration

Class X: 40 %-80% magnitude, 20ms-150ms duration

Class S: 40 %-80% magnitude, 150ms-600ms duration

Class T: 0 %-40% magnitude, 20ms-600ms duration

Class Z: 0 %-80% magnitude, 600ms-3s duration

A graphical representation of this is in Fig.2.2.

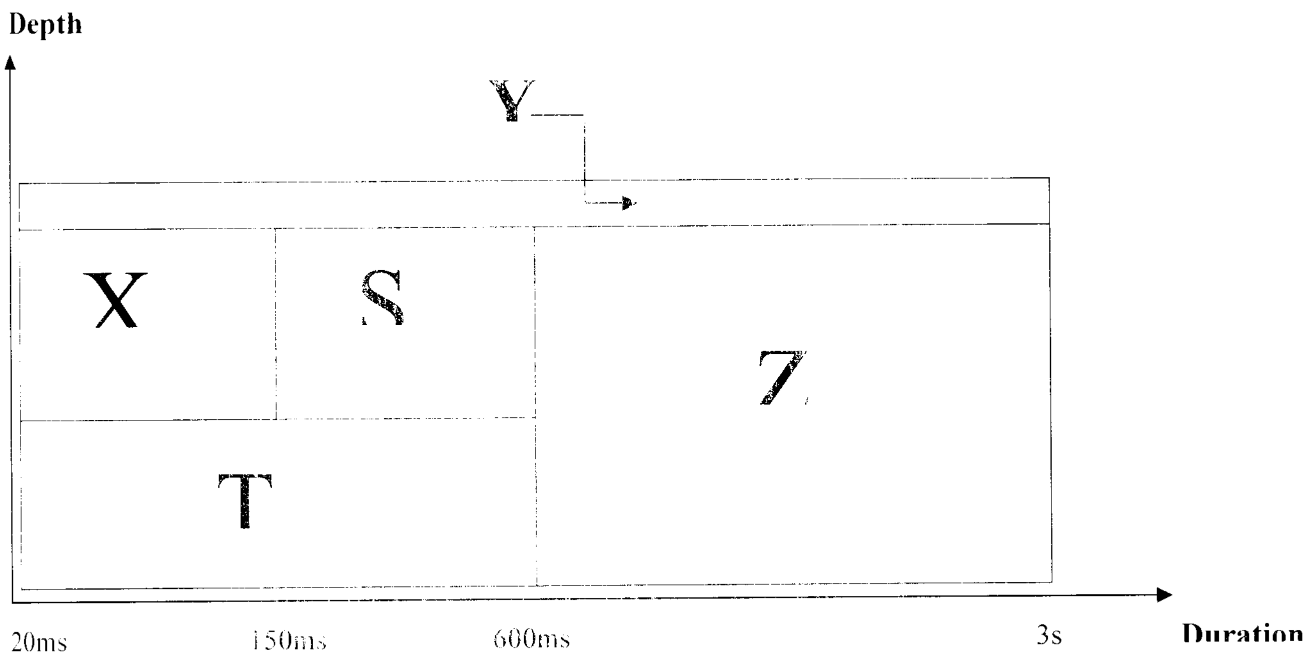


Fig: 4.22 Eskom table

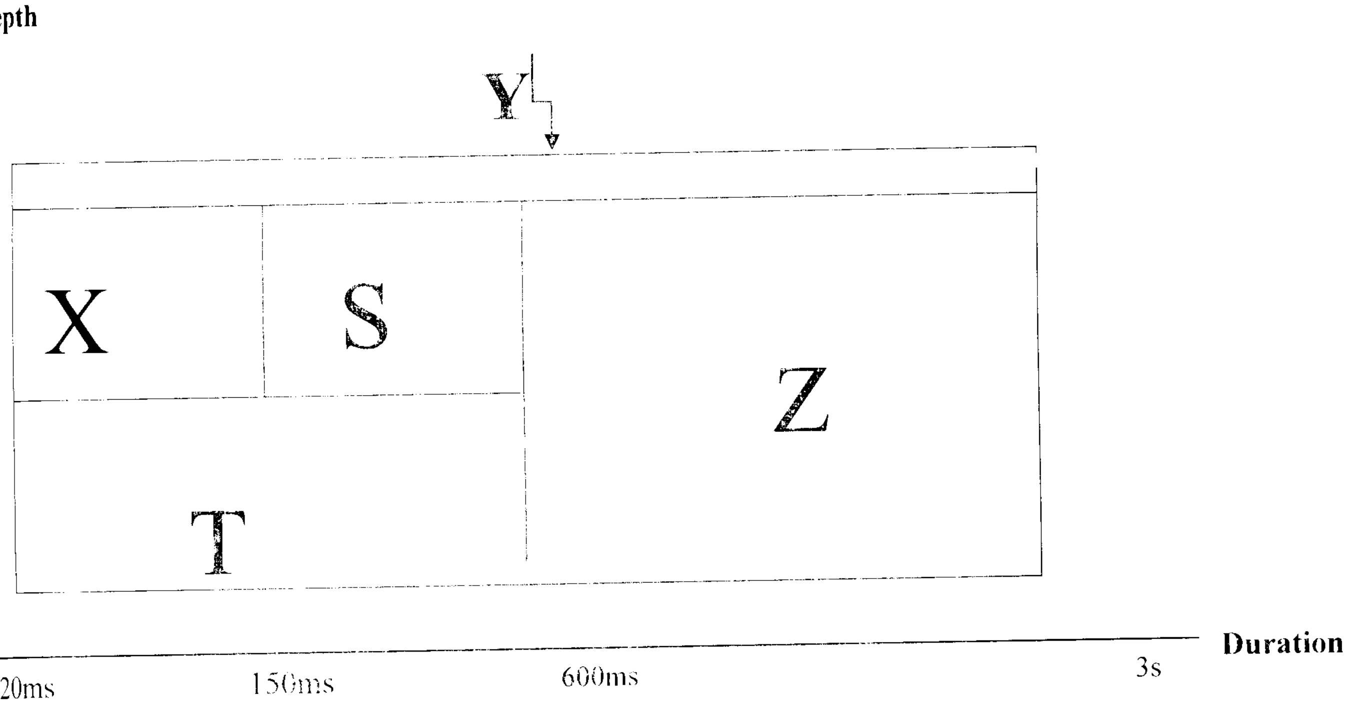


Fig: 4.23 Eskom table for voltage dips in this study

Practical values of Voltage sag data are indicated in the second ESKOM table. As per the diagram most of the disturbances are in the class of S, Z and Y.

4.4.2.2 Counting according to EPRI – Electrotek [9]

When analyzing sag voltage data according to EPRI power quality survey the magnitude duration plane is divided into five magnitudes and three duration ranges.

RMS variation frequency for voltage thresholds X; RFx with X = 90%, 80%, 70%, 50%, 10%: the number of events per year with magnitude below X, and duration between 0.5 cycles and 60 s.

Instantaneous RMS variation frequency for voltage thresholds X; IRFx with X = 90%, 80%, 70%, 50%: the number of events per year with magnitude below X, and duration between 0.5 cycles and 0.5 s

Momentary RMS variation frequency for voltage thresholds X; MRFx with X = 90%, 80%, 70%, 50%: the number of events per year with magnitude below X, and duration between 0.5 cycles and 3 s

Momentary RMS variation frequency for voltage thresholds 10%; MRF10: the number of events per year with magnitude below X, and duration between 0.5 cycles and 3 s

Temporary RMS variation Frequency for voltage threshold X: TRFx, with X=90%, 80%, 70%, 50%, 10% : the number of events per year with magnitude below 10%, and duration between 0.5 cycle and 3 sec.

The duration ranges are based on the definition of instantaneous, momentary and temporary, as given in IEEE Std.1159-1995.

Range	0.5cycle-60 s	0.5cycle-0.5 s	0.5s - 3s	3s - 60s
<90%	RF_{90}	IRF_{90}	MRF_{90}	TRF_{90}
<80%	RF_{80}	IRF_{80}	MRF_{80}	TRF_{80}
<70%	RF_{70}	IRF_{70}	MRF_{70}	TRF_{70}
<50%	RF_{50}	IRF_{50}	MRF_{50}	TRF_{50}
<10%	RF_{10}	MRF_{10}		TRF_{10}

Table 4.27 RMS voltage variation frequencies

In this practical situation most of the voltage sags lie in the range of 0.25 seconds to 5 seconds and a few of the voltage sags go to the range of 0.25 (s) to 0.5 (s) and 3 (s)-20 (s). Hence the above indices can be calculated for the events at the customer's site as follows,

Range	0.5cycle-60 s	0.5cycle-0.5 s	0.5s - 3s	3s - 60s
<90%	$RF_{90} = 113$	$IRF_{90} = 5$	$MRF_{90=107}$	$TRF_{90} = 1$
<80%	$RF_{80} = 48$	$IRF_{80=0}$	$MRF_{80} = 48$	$TRF_{80=0}$
<70%	$RF_{70} = 3$	$IRF_{70=0}$	$MRF_{70=3}$	$TRF_{70=0}$
<50%	$RF_{50} = 0$	$IRF_{50=0}$	$MRF_{50=0}$	$TRF_{50=0}$
<10%	$RF_{10} = 0$	$MRF_{10=0}$		$TRF_{10=0}$

Table 4.28 RMS voltage variation frequencies for this study

4.5 Discussion

As per the above data analysis, it gives evidence that most of the voltage sags that affect the customer have been originated due to voltage sags originated in the near by distribution network. To get this point further confirmed, customer break down data has been analyzed against grid substation tripping and relay pick up data. The analyzed data in August and September months have been included as Annexue IV.

When this data is analyzed, it is noted that the circuit breaker at the customer trips for the voltage sag waveforms originated due to the switching and tripping of nearby 33kV feeders other than the Feeder 2 which feeds the customer. Most of the trippings have been occurred due to occurrence of faults at feeder 5. In some cases faults and tripping at customer premises have been recorded due to a relay pick up at 33kV side due to a fault at 132kV side (transmission side fault). The information of feeder 5 has been obtained and it is noted that this feeder is routed through areas with vegetation.

When listing the tripping data obtained from the customer the number of monthly trippings are tabled below.

Month	No of trippings	Voltage Sag data As per table 4.2	No of trippings in Feeder 5
January	7	6	2
February	3	2	-
March	6	5	2
April	9	8	3
May	25	22	7
June	14	12	4
July	13	12	1
August	7	6	2
September	14	12	3
Total	98	85	**24**

Table 4.29 number of trippings Versus Month

From the above data it is noted that 87% of trippings at the customer premises are due to voltage sags initiated in the CEB electricity network.

Further, it is noted that the pattern of tripping is weather dependent. In the months of February and August a very few trippings were recorded.

As per the recommendations of the study way leave clearance of Feeder 5 has been done in mid October and some improvements of the system has been observed.

4.5.1 Comments based on the data analysis,

1. **87%** of trippings at the customer premises are due to voltage sags initiated in the CEB electricity network. The balance 13% should be due to internal, external causes other than the said cause.

2. As the pattern of tripping is weather dependent some improvements in the situation would be possible by system improvements by way of way leave clearance and alternative switching arrangements.

3 .The possibilities of minimizing the tripping by improving the fault clearance times of the system, which means system improvements and through device improvements will have be to be discussed .

4. If ACE power plant is not connected to the system, voltage sags will be severe during a fault condition.

Chapter 05

VOLTAGE DIP MITIGATION PROPOSALS

When finding a solution to voltage dip problem, it is necessary to understand even though the power system has been designed for maximum reliability, such disturbances cannot be completely eliminated since the power system by which these loads are fed is subjected to atmospheric influences as well as unpredictable equipment failure. Therefore additional measures have to be taken to protect the sensitive loads which are susceptible to voltage sags. The mechanism of equipment tripping has to be understood first in devising voltage sag mitigation method.

Based on the mechanism leading to equipment trip different locations for mitigation of voltage sags can be distinguished as shown below [2].

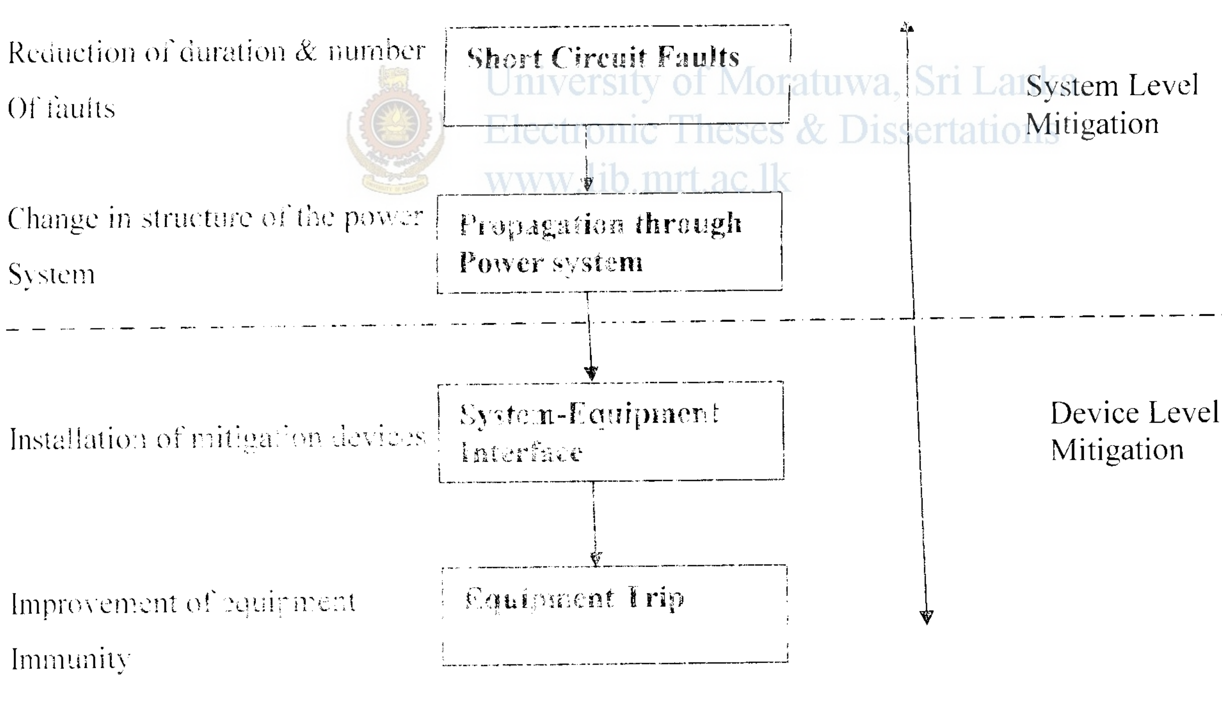


Fig: 5.1 Voltage Sag Mitigation

The solutions to the voltage sag problem are discussed at two levels.

5.1 System Level Mitigation

Based on the data analysis following observations have been made on the 33kV system of Horana.

- It has been noted that the customer has experienced Voltage sags due to the trippings of nearby feeders. These are mainly Feeder No.5 (F5) and Feeder No.3 (F3) and Feeder No.4 (F4) also to a considerable amount.
- The pattern of tripping is weather dependent as it has been observed that only a small number of trippings occurred during the months of February and August.
- As per the site surveys and information obtained from relevant officials (Area Engineer Horana . Planning Engineer WPS II) the 33kV distribution Feeder No.5(F5) which runs to a distance of 20km closer to Rathnapura is having a lot of way leave problem

As a proposal for sag mitigation and minimization of faults as a result of this study following proposals are forwarded.

5.1.1 Way leave clearance of Feeder 5 – Actually this proposal has come to a partial implementation and to some distance way leave clearance has been done and a system improvement has been observed. The duration of voltage sag depends on the fault clearing time of the protective device in the particular location. Hence reducing the fault clearing time leads to less severe voltage sags.

As per the data analysis the customer trippings were experienced for the trippings of nearby feeders. Feeder No. 3(F3) and Feeder No.4 (F4). F3 feeds Horana new gantry and F4 feeds Horana Old gantry. After a site inspection it is noted that some of the Auto reclosures in the two gantries are not functioning and in some out going feeders auto reclosures are not installed. The out going feeder connecting to Bulathsinhala side is routed through lot of vegetation and experiences lot of trippings. As the auto reclosure of that side is not functioning, fault clearance times are too high.

Hence as a result of the study as a system improvement it is proposed to install an autoreclosure at out going feeders to Bulathsinhala area. In addition to that a new feeder is proposed from Horana to Meegahakiula. Work on this job has been already completed.

After the construction is completed the feeding arrangement can be rearranged such that part of 33kV feeder 5 load is diverted to this new feeder. After this a reduction of voltage sags can be expected.

If auto reclosures are installed in all out going feeders of the gantry and if the 33kV feeders are sectionalized by installing suitable isolating mechanism fault clearance times and system reliability can be improved. However, it is not proposed to include additional switches and auto reclosures to all out going feeders in the gantry in the system as a method of reducing fault clearing time at this step as it may not be economically viable, since reduction of number of faults and fault duration in a time graded over current protective scheme requires replacement of all the over current relays in the graded scheme by expensive circuit breakers which will incurr large amount of cost that may not be economical.

As a sag mitigation method, a power system with sensitive loads can be protected by a sag mitigation device which is connected either to the distribution feeder or just before the sensitive load. When this is concerned, the first option is not economical for the specific case in this study, as only a few customers with sensitive loads are connected to 33kV Feeder No.2 (F2)

5.2 Device Level Mitigation

Some of the custom power devices proposed for voltage sag mitigation are listed below,

- Static transfer switch (STS)
- Uninterruptible power supply (UPS)
- Shunt connected voltage source converter (STATCOM)
- Series connected voltage source converter (SVC)

5.2.1 Static transfer switch (STS)

The static transfer switch is an electrical device that allows an instantaneous transfer of power sources to the load. The load can be transferred to an alternative source by means of a static transfer switch within ¼ to ½ cycles when there is a supply voltage disturbance in the primary source. This superior switching time means that if one power source fails, STS automatically switches to the back up power source so quickly that the load may not feel that the transfer is initiated. STS monitor two power sources and automatically shift to the higher quality source upon sensing failure or degradation of either source.

The static transfer switch consists of two thyristor blocks where one unit comprises two anti parallel thyristors. Each thyristor block contains three thyristor modules corresponding to the three phases of the system.

It is important to note that if this equipment is used for voltage sag mitigation alternative sources are required, therefore the total system will be more costly.

5.2.2 Uninterruptible power supply (UPS)

Uninterruptible power supplies (UPS) are used to protect sensitive loads such as computers, communication equipment and industry control process when the supply voltage experiences voltage disturbances. The UPS system mainly consists of diode bridge rectifier, voltage source inverter and energy storage usually a battery block connected to the DC-link. Under the normal operating condition power taken from the supply mains is rectified and fed to the DC-link.

UPS of higher rating are expensive and bulky compared with sag mitigation such as STATCOM and SVC. The disadvantage of this method is having a shorter battery life and high cost of high power UPS's.

5.2.3 Shunt Connected Voltage Source Converter (STATCOM)

STATCOM is essentially a voltage Source Converter and used for reactive power compensation. When it is used at a distribution power system it is connected shunt to a particular bus in the power system via a coupling transformer to maintain the bus voltage at a desired level by absorbing or injecting reactive power. A STATCOM basically comprises of Voltage Source Inverter, Coupling Transformer, Connection filter and small DC-Energy Storage device in the form of a capacitor.

The STATCOM with energy storage can be used for mitigating voltage sags in the power system. To compensate deep voltage sags the STATCOM requires injecting large current to the system. Thus a large size of energy storage sometimes even greater than the load real power rating is required to mitigate sags with phase angle jumps.

STATCOM is more suitable for solving voltage sag problems encountered by group of consumers connected to a common feeder other than a sag problem of an individual customer as it is shuntly connected to the feeder.

5.2.4 Series Connected Voltage Source Converter (SVC)

The major difference of this from STATCOM is, the latter is connected in series with the distribution feeder or sensitive load through an injection transformer. The term Dynamic Voltage Restorer (DVR) is synonymously used with series connected VSC in literature. As in the figure 5.2. DVR consists of voltage source inverter, modulating unit, series injection transformer, output LC filter, energy storage and control unit.

Voltage source inverter is the vital component of DVR. It consists of semiconductor devices such as Integrated Bipolar Transistors (IGBT), Insulated Gate commutated thyristors (IGCT) and Metal Oxide Semiconductor Field Effect Transistors (MOSFET) as switching devices. Semiconductor switches are selected based on their performance related to switching frequency, the conducting and switching losses and desired voltage and current ratings. In most of the modulation unit of the DVR, pulse width modulation technique is widely used.

The DVR is connected to the distribution feeder through three single phase transformers.

The real and reactive power supplied by the DVR depends on the type of the voltage sag and it's duration, the protected load and the direction and magnitude of the injected voltage. The required reactive power can be generated internally; however the active power has to be supplied externally. DVR injects voltage which is controllable both in magnitude and in phase series with the up coming supply voltage. DVR is the best solution for the problem discussed in this study as it can provide voltage support for individual loads.

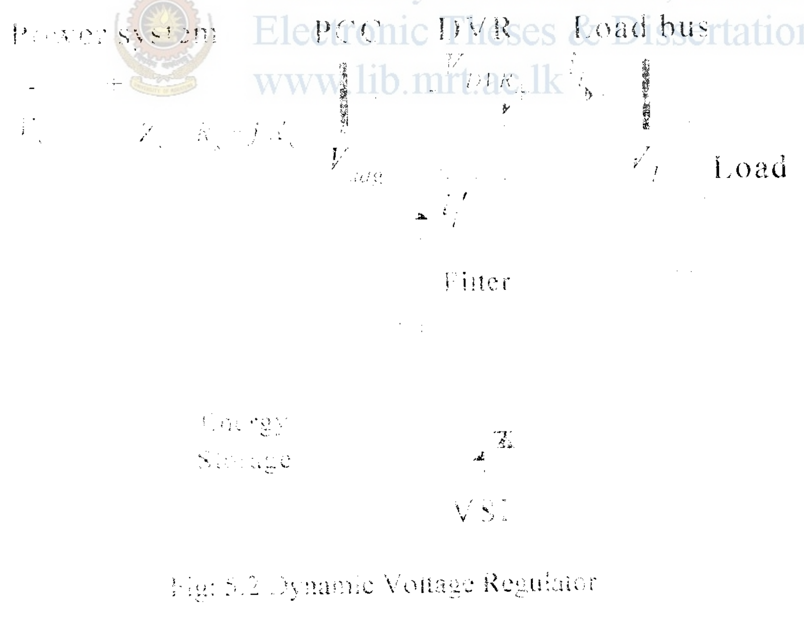


Fig: 5.2 Dynamic Voltage Regulator

The operating principle of the conventional DVR shown in Fig. 5.2 is based on injecting AC voltages through three single-phase injection transformers in series with the incoming three-phase supply voltage. The purpose of such voltage injection is to improve voltage quality by adjustment in voltage magnitude, wave-shape and phase shift. The voltage sag compensation involves injection of real and reactive power to the distribution system and this determines the capacity of the energy storage device required in the restoration scheme.

5.2.5 Voltage source inverter and modulating unit

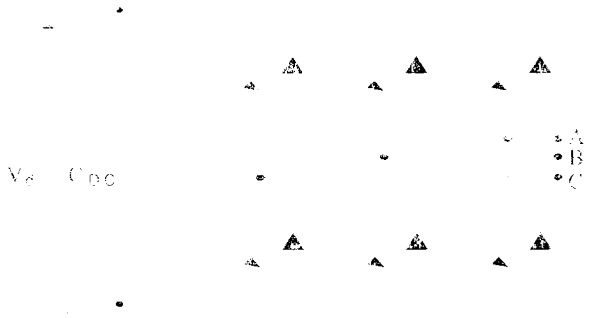


Fig: 5.3 Voltage Source Inverter

The voltage source inverter (VSI) is the most important component of the DVR which produces the required voltage to be injected in series with the incoming supply voltage.

The DC – supply to the inverter is most of the time either battery or capacitor bank. Each leg contains two semiconductor switches and each switch has an anti parallel diode connected to it. Semiconductor devices like Integrated Bipolar Transistors (IGBT), Insulated Gate Commutated Thyristors (IGCT) and Metal Oxide Semiconductor Field Effect Transistors (MOSFET) can be used as switching devices. Selection of semiconductor switches is based on three factors such as the required dynamic performances related to switching frequency, the conducting and switching losses and desired voltage and current ratings. The dynamic performance is the most important factor, as the DVR has to be on line without a significant delay. Thus semiconductor devices are selected after satisfactory choice of appropriate switching frequency and lower switching and conductor losses depending on the required power rating of the DVR.

The output of the voltage in each phase depends on the state of the switch and the DC-link voltage.

Pulse width modulation (PWM) technique [2] is widely used in most of the DVR application due to the flexibility of controlling ratio between fundamental frequency component of output voltage and DC – link voltage, fast response for load and source

changes, elimination of low order harmonics which result in reduction of output filter rating and simplicity of implementation. One of such disadvantages of the scheme is under utilization of DC-link voltage which results in reduction of maximum output voltage and higher switching losses.

5.2.6 Series injection transformer

The conventional DVR is connected to the utility distribution feeder through three single phase transformers. The selection of a suitable transformer for voltage sag mitigation depends on MVA rating of the sensitive load, maximum allowable voltage drop across the transformer, characteristics of the voltage sags to be compensated, harmonic filter system in DVR, energy storage size and the control algorithm used [5] The advantages of using the series transformer are (possibility of coupling with higher voltages) resulting in reducing the voltage rating of the semiconductor devices, providing a galvanic isolation between supply side and the DVR side and help in filtering of harmonic in the injected voltage by its leakage inductance.

The disadvantages of including a series injection transformer are transformer costliness and saturation. In order to avoid the transformer saturation and guarantee the DVR performances under all conditions the injection transformer must be sized to handle at least twice the normal steady state flux requirement at maximum rms injection voltage [5]. The method is based on the form factor which limits the initial flux of the transformer.

5.2.7 Output LC filter

The primary objective of the output filter connected to the DVR is to attenuate high frequency switching ripples in the inverter output voltage. The use of output filter helps to reduce the dv/dt stress on the injecting transformer winding, which in turn increases the lifetime of the transformer. Design of output filter for DVR application has unique features like compensation capability of the DVR. It is highlighted that the inclusion of output filter will increase the rating of the DVR inverter.

The output filter can be placed either on inverter side or on the line-side (supply side). However the filter at the inverter side is preferred.

The advantages of the inverter side filter are given below.

- Filter installed in the low voltage side and it will reduce the voltage rating of the filter capacitor.
- It is closer to the harmonic source and the filter performances are better.
- Higher order harmonic currents are not penetrated to the injection transformer.

This will reduce the losses due to eddy currents introduced by the high frequency component of the injected voltage.

• dv/dt rating stress on the transformer is reduced.

5.2.8 Control unit of the DVR

The function of the control unit is to derive the necessary control signal in order to generate the PWM gating pulse for the DVR inverter. The basic requirement of the DVR controller is to obtain an AC waveform with low total harmonic distortion, good dynamic performance and adequate stability margin.

5.2.9 Energy storage in the DVR

The DVR functions by injecting three single-phase AC voltages in series with three-phase incoming network voltage during voltage sags, compensating for the difference between faulty and nominal voltages. The required reactive power can be internally generated while the real power should be supplied by external energy storage. The supply of real power is met by means of an energy storage facility connected to the DC-link. Large capacitors are used as the energy storage in most of the commercially available DVRs. Other available energy storage devices are battery bank, super capacitors, superconducting magnetic energy storage (SMES), flywheels and fuel cells.

DC Capacitors

Capacitor banks made up of individual capacitors connected to form a number of separate units are most feasible solutions to provide energy storage requirement of the DVR since they have a fast discharging response and do not consist of moving parts. When the energy is delivered to the loads during the compensation process the DC-link voltage decreases. Once the DC-link voltage drops below a certain value the inverter cannot inject required voltage to compensate the voltage sag. Hence the energy that can be extracted from the DC-link capacitors can be expressed as below.

$$C_{DC} = \frac{2T_{sag}(P_{in} + P_{loss})}{(V^2_{DCmax} - V^2_{DCmin})}$$

Where C_{DC} is the DC – link capacitance, T_{sag} is the sag voltage, V_{DCmax} and V_{DCmin} are maximum allowable DC-link voltage and minimum allowable DC-link voltage respectively.

It is clear that larger capacitors are required to mitigate deep sags with long duration. This increases the cost of the DVR and the space requirement for installing the DVR.

Battery energy storage, super capacitors and flywheel energy storage are also used.

5.3 Voltage rating of the DVR

One of the main facters affecting the DVR capability to restore the load voltage to the desired reference is the voltage rating of the DVR inverter. The maximum voltage that can be injected will be decided by the voltage rating of the DVR. This in turn determines the range of the voltage sags which the DVR can mitigate effectively.

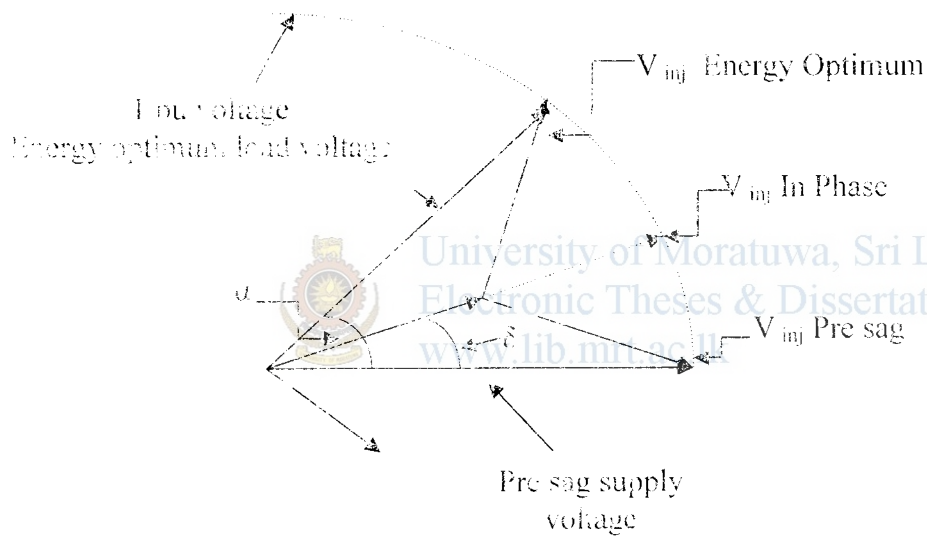


Fig: 5.4 Phasor diagram representation of different voltage injection methods

There are three methods of voltage injection used in voltage compensation. In pre-sag voltage compensation, the load voltage is compensated to the pre-sag supply voltage. Though this method gives undisturbed load voltage, it requires sizable energy storage. On the other hand the load voltage is always in phase with the supply voltage in the in-phase injection mode. This results in a minimum injected voltage, as there is no phase difference between the supply and injected voltages. However, this compensation introduces a phase angle jump δ to the load. In the energy optimum injection method, the load voltage is advanced by a certain angle α to minimize the energy requirement from the DVR. This method needs a larger injection voltage than that required in the in-phase boosting method.

The active power provided by the DVR and the size of the capacitor for the said active power requirement is calculated based on the pre-sag voltage injection mode.

5.3.1 Calculation of the Capacity of the proposed DVR

As per the above study for this specific problem since voltage support for individual load is required, a DVR is the most suitable solution. The active power requirement of the DVR can be calculated as given below [2]. The load voltage can be written as the summation of the supply side voltage and the voltage injected by the DVR as in (5.1)

$$\underline{V}_{load} = \underline{V}_{sag} + j\,\underline{V}_{dvr} \qquad (5.1)$$

The Voltage at the supply side (at PCC) is characterized through a magnitude V and phase angle jump δ and the load current is taken as 1 pu with a lagging power factor as given in (5.2) and (5.3) respectively.

$$\underline{V}_{sag} = \underline{V}_{cos(\delta)} + j\,\underline{V}_{sin(\delta)} \qquad (5.2)$$

$$\underline{I}_1 = cos(\emptyset) - j sin(\emptyset) \qquad (5.3)$$

Thus the complex power injected by the DVR can be expressed as in (5.4) with $\underline{\mathbf{V}}_{load} = 1$pu

$$\underline{S}_{dvr} = \underline{V}_{dvr}\underline{I}_1 = (1 - V_{cos(\delta)} - j\,\underline{V}_{sin(\delta)})(cos(\emptyset) + jsin(\emptyset)) \qquad (5.4)$$

The real power injected by the controller is then given by (5.5)

$$P_{DVR} = \left[1 - \frac{V cos(\emptyset + \delta)}{Cos(\emptyset)}\right] P_{Load} \qquad (5.5)$$

Where P_{Load} is the load real power in pu

For a distribution system phase angle jump δ is always negative.

As per analysis in chapter three, in this particular case phase angle jump is between 0-30 degrees. The customer is supplied with a 10 MVA supply. The power factor at the customer premises is taken as 0.83.

Cos(ϕ) = 0.88

P_{Load} = 10* 0.88 = 8.8 MW,

ϕ = 0.[illegible]

According to the sag voltage data in table 4.2.1. sag voltages are available in the range of 0.5 pu to 1 pu. Therefore the real power injection of DVR can be graphically shown as below.

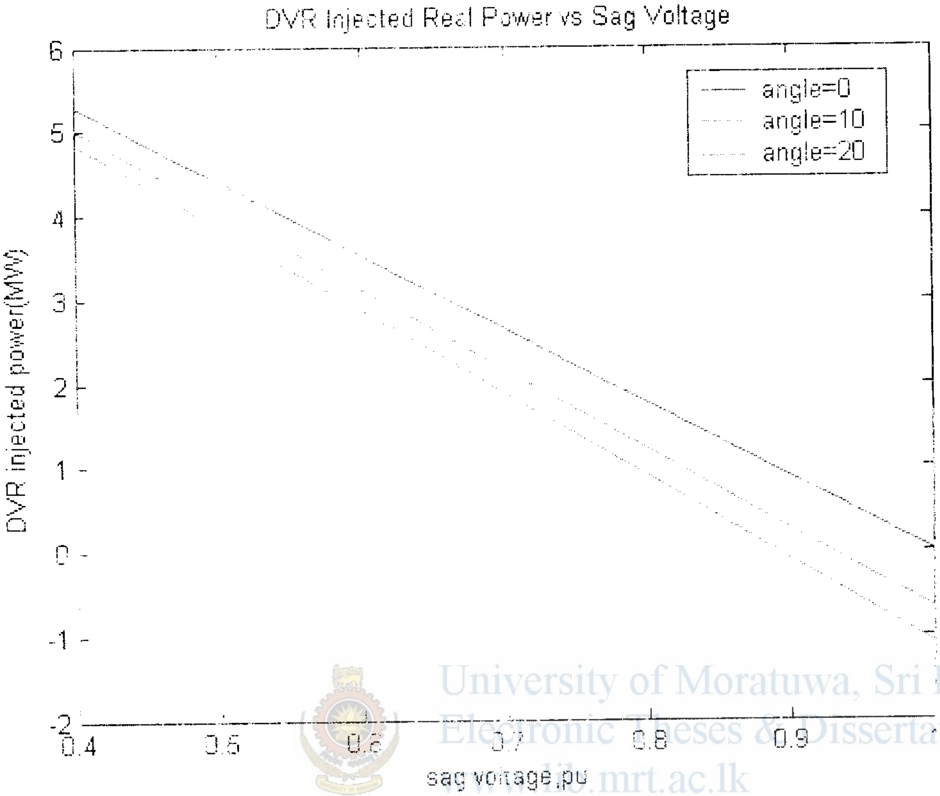


Fig: 5.5 Sag Voltage Vs DVR injected Real Power

As per the sag voltage data analysis in table 4.2.1. the magnitude of the most frequent Voltage sag range for the customer is 0.8 pu to 0.9 pu. Therefore Dynamic Voltage Restorer for the system is designed to cater for the range of voltage sags with magnitude 0.8 pu and more

Substituting values in (5.5).

$$P_{DVR} = \left[1 - \frac{V\cos(\emptyset+\delta)}{\cos(\emptyset)}\right] P_{Load} \qquad (5.5)$$

P_{DVR} = [1-(0.8*0.88) / 0.88] (10*0.88) = 1.76 MW

Therefore the required capacity of the Dynamic Voltage Regulator is **1.76MW**.

5.3.2 Energy Storage in the DVR

In a DVR required reactive power can be internally generated, however the real power have to be supplied through an external energy source. Since Capacitor banks made up of individual capacitors have a fast discharging response not having moving parts they are more preferable solution to provide energy storage.

The factors affecting the energy storage requirements are the depth of the Voltage sag, sag duration, phase angle jump, load power factor, voltage injection mode and the maximum allowable range of change of DC link Voltage. Therefore it is clear that the compensation capability of a particular DVR depends on the maximum amount of real power that can be transferred to the load during the restoration process [2]. The size of the energy storage capacitor in a conventional DVR can be expressed as.

$$C_{DC} = \frac{2T_{sag}(P_{inj} + P_{loss})}{(V^2 DCmax - V^2 DCmin)} \qquad (5.6)$$

In this equation, P_{inj} denotes the injected active power of the series device. T_{sag} : voltage sag duration, C_{DC}: DC – link capacitance, V_{DCmax} : maximum allowable DC – link voltage, V_{DCmin} : Minimum allowable DC- link voltage, P_{loss} : active power loss in the series device.

The variation of capacitor size with voltage sag magnitude for different sag durations are shown in Fig.5.5. In this situation active power loss in the series device is considered negligible and minimum allowable DC- link voltage is considered as half of the maximum allowable DC- link voltage.

It is clear that the size of the capacitor is mainly governed by the depth of the sag and the voltage sag duration. If the correct size of the capacitor is not used with the DVR, it cannot effectively mitigate the voltage sag. However increase of the capacitor size leads to increase of the total cost of the DVR, as the energy storage is a substantial portion of the overall cost of the DVR.

As the energy storage becomes the main limiting factor specially for mitigating voltage sags with long duration.

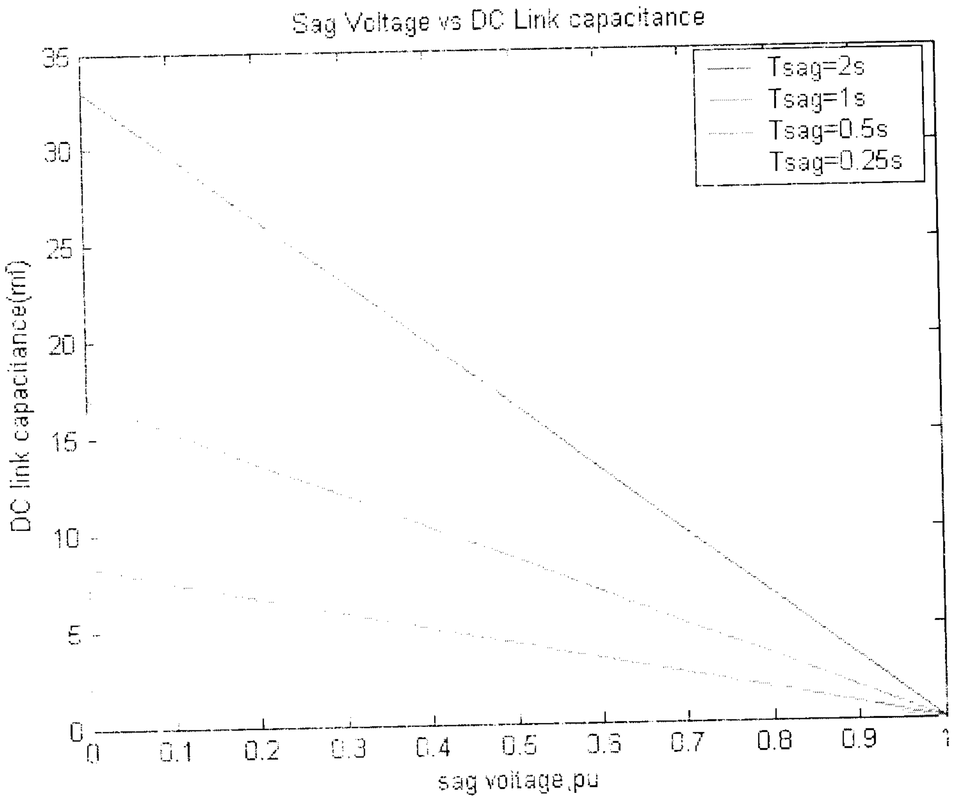


Fig: 5.6 Sag Voltage Vs DC link capacitance

As explained above it is difficult to obtain a DVR to compensate all the voltage sags experienced by the customer. However if a DVR is designed to mitigate voltage sags with magnitude 0.8 pu and more and duration less than 2s around 56% of the voltage sags can be eliminated.

The Capacitor requirement to mitigate voltage sags with magnitude 0.8 pu and more and duration less than 2s can be obtained by substituting in equation 5.6

$$C_{DC} = \frac{2T_{sag}(P_{inj} + P_{loss})}{(V^2DCmax - V^2DCmin)}$$

Tsag = 2s; Pinj = 1.76MW; Ploss = 0; VDCmax = 33kV;

VDCmin = 0.5(VDCmax)

$$C_{DC} = (2(2)(1.76 + 0) * 10 - 6)/((332 - 0.25332))$$

C_{DC} = **8.62 mF**

Based on the above calculations, we can propose a satisfactory solution for the problem we have studied through a Dynamic Voltage Regulator with an injected power rating 1.76MW together with a capacitor size 8.62 mF.

Chapter 06

CONCLUSION

The study shows that the practical failure data obtained are highly weather dependent and a reduction of Voltage sag problem faced by the customer can be achieved through System improvements. Therefore, following System Level Mitigation Solutions are proposed

- Regular Way leave clearance of Feeder 05 of Horana GSS (See 5.1.1)

- Installing an autoreclosure at out going feeder to Bulathsinhala area in the Horana new gantry (See 5.1.1)

System level mitigation solutions require higher level of capital investment and giving a complete solution needs system improvement in many network sections. Therefore here a complete solution to Voltage sag problem at system level is not proposed. Possibility of giving a solution through device level mitigation is discussed and the following solution is proposed.

- Installing Dynamic Voltage Regulator of capacity having 1.76MW and with a capacitor size 8.62 mF at the incoming 33kV CEB supply at the customer premises. (See 5.3.1)

References:

[1] Roger C. Dugan , Mark F. McGranghan , H.Wayne Beaty , " Electrical Power Systems Quality", vol.01 , McGraw-Hill Professional Engineering,1986

[2] H.M.Wijekoon, " Voltage Restoration Systems", PhD Thesis, Nanyang Technological University, Singapore ,2004

[3] IEC 61000-4-30,Power Quality Measurement Standard,2003

[4] " Power Quality- Technical Note No.4 "Power Quality Centre, United States , CRC Press LLC,United States, 2006

[5] "Overview of Voltage sag mitigation technique"Ambra Sanino-Department of Electrical Engineering, University of Palermo, Italy, pp 1-14,2000

[6] " Technical Notes of Power Quality" ,Travelodge- Industrial Power Quality Centre , , 2004

[7] "Voltage Sag Measurement and Characterization" Power Quality centre, Integral Energy, , 2002

[8] Dan Sabin (DS) ,"Voltage Sag Indices – Math Bollen(MB) with contributions" , McGraw-Hill Professional Engineering ,2002

[9] D.Mahinda Vilathgamuwa, H.M.Wijekoon, S.S.Choi,"A novel dynamic series compensator with closed-loop voltage and current mode control for voltage sag mitigation," International Journal of Electronics ISSN 0020, 2003.

Voltage Depth	0.25 (s)-0.5 (s)	0.5 (s)-1 (s)	1 (s)-3 (s)	3 (s)-20 (s)
80-90%				
70-80%				
60-70%				
50-60%				
Total				

Equipment Details of the customer

No	Drive Type	Drive Capacities	No, of Drives
	D/C Drive's		
1	ABB-DCS500-B	216kW	3
2	RELIANCE FlexPak 3000	75kW	1
3	RELIANCE FlexPak 3000	45kW	3
4	RELIANCE MaxPak 111	45kW	3
5	RELIANCE MaxPak 111	11kW	5
6	LENZE	216kW	1
	A/C Drive's		
7	ABB-ACS401	11kW	1
8	ABB-ACS401	7.5kW	1
9	ABB ACS550	30kW	1
10	ABB ACS401	4kW	4
11	ABB-ACS550	4kW	1
12	ABB-ACS800	200kW	1
13	ABB-ACS550	132kW	1
14	ABB-ACS550	22kW	1
15	ABB-ACS550	11kW	2
16	ABB-ACS800	11kW	1
17	ABB-ACS550	7.5kW	4
18	ALLEN-BRADLEY 1336 Plus 11	260kW	1
19	ALLEN-BRADLY 1336 Plus 11	22kW	1
20	ALLEN-BRADLY 1336 Pose 11	7.5kW	6
21	ALLEN BRADLEY 1336 Impact Force Technology	55kW	2
22	ALLEN-BRADLEY Power Flex 700	90kW	1
23	ALLEN BRADLEY 1336 Impact Force Technology	4kW	10
24	SIEMENSE Micro Master 440	160kW	1
25	SIEMENSE Micro Master 430	22kW	1
26	SIEMENSE Micro Master 440	.37kW	1
27	SIEMENSE Micro Master 430	.37kW	2
28	TELEMECANIQUE Atv 71	132kW	1
29	TELEMECANIQUE Atv 71	55kW	1
30	TELEMECANIQUE Atv 58	18.5kW	1
31	TELEMECANIQUE Atv 58	7.5kW	7
32	TELEMECANIQUE Atv 58	4kW	1
33	TELEMECANIQUE Atv 31	7.5kW	1
34	TELEMECANIQUE Atv 31	4kW	1
35	TELEMECANIQUE Atv 28	4kW	2
36	RELIANCE ELECTRIC GV 3000S/E AC DRIVE	60kW	1
37	RELIANCE GV 3000SE	45kW	2
38	RELIANCE GV 3000SE	15kW	3

39	RELIANCE GV 3000SE	11kW	
40	RELIANCE GV 3000SE	7.5kW	5
41	RELIANCE ELECTRIC GV 3000S/E AC DRIVE	5.5kW	2
42	RELIANCE ELECTRIC GV 3000S/E AC DRIVE	4kW	6
43	RELIANCE ELECTRIC GV 3000S/E AC DRIVE	2.2kW	3
44	KEB Combivert	4kW	3
45	BAUMULLER NURNBERG	15Kw	5
46	BAUMULLER NURNBERG	37Kw	8
47	RELIANCE ELECTRIC MaxPak 111 VCI Drive	45kW	1
48	HR 2000 Servo Control AC Drive	4kW	2
49	AMK AMKASYN KU10 Servo Controller	7.5kW	1
50	RELIANCE ELECTRIC GP 2000 AC DRIVE	7.5kW	6
	SOFT STARTERS		
51	Telemecanique Altivar 46	250kW	2
52	SIEMENCE SIKOSTART 3RW34	185kW	3

Analyzed data in August & September months,

Date & Time	Customer's reasons & Remarks	Observations at the GSS	Comments
August 4 , 2007, 2.54 pm	CEB failure ,33kV Tripped UV	F2 , Earth Fault	Merbok is fed by F2 of Horana GSS ,this is an Earth fault
August 5 , 2007, 8.25 pm	CEB failure ,33kV Tripped UV	F5 Tripped (Auto reclosed). Earth fault occurred at Ingiriya side.	Customer premises might have tripped due to sag voltage wave originated due to tripping of feeder 05.
August 8 , 2007, 7.00 am	CEB failure ,33kV Tripped UV	F5 operated , Earth Fault , O/C	Customer premises might have tripped due to sag voltage wave originated due to tripping of feeder 05
August 18 , 2007, 8.55 am	CEB failure ,33kV Tripped UV	132kV side protection operated	Voltage sag has been originated due to 132kV breaker operation
August 24 , 2007, 3.41am	33kV VCB Tripped over current	Common inverter alarm	-
September 1, 2007, 5.22 am	CEB failure ,33kV Tripped UV	F2 , Earth Fault	Merbok is fed by F2 of Horana GSS ,this is an obvious fault
September 2, 2007,	CEB failure ,33kV Tripped Over current	F5 bus bar tripped OC/EF	Customer premises have been tripped due to a voltage sag originated from F5 tripping
September 7,	Voltage Fluctuation	F4 fault trip	Customer premises have

2007,			been tripped due to a voltage sag originated from F4 tripping
September 12, 2007,	CEB failure ,33kV Tripped Over current	F5 bus bar tripped OC/EF	Customer premises have been tripped due to a voltage sag originated from F1 tripping
September 13, 2007, 4.35 pm	CEB failure ,33kV Tripped Over current	F3 over current tripping	Customer premises have been tripped due to a voltage sag originated from F3 tripping
September 14, 2007, 4.40 pm	CEB failure ,33kV Tripped Over current	132kV relays have been operated & restored	
September 14, 2007, 6.25 pm		F4 tripped & current restored	