TENAGA NASIONAL

Voltage Sag Solutions for Industrial Customers

5th edition

A Guidebook by Tenaga Nasional Berhad

The suggestions contained in this book are generic in nature. The reader must always consult the equipment manufacturer before applying any suggestions. TNB and the editorial members shall not be held responsible for any consequences arising from application of any suggestion contained herein.

Prepared and Edited by:

Author

Ir.Dr.Mohamed Fuad Faisal	Technical Specialist (Power Quality & EE) Asset Management Strategy & Design Standard, Distribution Network, Distribution Division TNB Sirim Tech Committee on Power Quality Sirim Tech Committee on Energy Efficiency Sirim Tech Committee on Power Systems Sirim Tech Committee on Electrical Installations & Wiring IEEE Power Energy Society IEC TC77/SC77A/WG2 (Voltage fluctuations etc.) IEC TC77/SC77A/WG8 (EMC Environment)

Editors

Wan Nazmy Wan Mahmood	Senior General Manager (Distribution Network) Distribution Division TNB
Rumaizi Abd Hamid	General Manager (Asset Management Strategy & Design Standard), Distribution Network Distribution Division TNB
Prof. Dr.Azah Mohamed	University Kebangsaan Malaysia (UKM)
Yap Kuan How	Senior Engineer (Power Quality & EE) Asset Management Strategy & Design Standard, Distribution Network, Distribution Division TNB

Foreword by President/CEO of TNB

First of all, congratulation to the Distribution Network, Distribution Division TNB, for taking the initiative to revise and continuously update the existing guidebook book on “Voltage Sag Solutions for Industrial Customers”.

The first edition of this guidebook was launched in 2007 with the objective to provide information to our customers on voltage sag mitigations. This guidebook has been updated due to introduction of new power quality regulation requirement, revised technical standards, and introduction of new technology for mitigating voltage sags.

The guidebook defines the most important concept of electromagnetic environment for the electrical power systems. Voltage sag is part of the electromagnetic environment for power systems.

Nowadays, in the modern industrial facility, many electrical and electronic devices have been incorporated with automated processes. No doubt that programmable logic controller (PLCs), adjustable-speed drives (ASDs), energy efficient motors, computer numerical control (CNC) machines, and other power electronic devices increase productivity, increase the quality of products, and decrease the cost to customers of those products. However, they also increase the equipment vulnerability to voltage sags. Due to this, the critical equipment experienced unexplained process interruptions and unplanned equipment shutdowns due to electromagnetic disturbances in particular due to voltage sags.

I believe this 5th edition power quality guidebook will provide more information on electromagnetic compatibility (EMC) and measures to achieve EMC with the electromagnetic environment. Both the IEC & IEEE standards clearly define the definition of EMC and the responsibilities to achieve EMC for both power utility and customers.

We at TNB are always willing to provide information and support our customers in their efforts to improve the electromagnetic compatibility (EMC) of their installations.

Dato’ Azman Mohd
President/CEO
Tenaga Nasional Berhad

Foreword by Chief Distribution Network Officer

Power Quality (PQ), which could be generally understood by many as the variations in the supply voltage, is indeed another critical dimension of service quality that TNB, customers and other industry stakeholders need to appreciate and contribute to manage under current and future business scenarios.

The most significant category of PQ disturbance from the perspective of both customers and power utility is the short duration voltage disturbances or more commonly known as voltage sags.

Voltage sags have been an intrinsic feature of public electricity supply since the earliest times. Yet in recent decades they have become an increasingly troublesome disturbance, giving rise to inconvenience and even considerable economic loss. The reason is that some modern electricity utilisation equipment, either in its own design or because of control features incorporated in it, has become more sensitive to voltage sags. There is therefore a need for an increased awareness of the phenomenon among the suppliers and users of electricity and the manufacturers of equipment.

This PQ guidebook is intended to provide useful illustrations to customers and utility engineers on many possible solutions towards ensuring adequate equipment immunity against voltage sags. Improving the immunity of highly sensitive equipment or controls will go a long way in ensuring EMC of customer’s equipment and processes to the power system electromagnetic environment. Such investments on mitigating solutions can indeed minimize costly equipment mal-operations and disruptions to manufacturing and business processes.

Datuk Ir. Baharin Din
Chief Distribution Network Officer
Tenaga Nasional Berhad

Chapters		Page Number
Chapter 1	**Introduction**	9-21
1.1	Power Quality Definitions	
1.2	Categories of Power Quality Disturbances	
1.3	Brief Descriptions of all Power Quality Disturbances	
1.4	Financial loss related to Power Quality Disturbances	
Chapter 2	**Steady State Supply Voltage Performance**	22-25
Chapter 3	**Understanding Electromagnetic Compatibility (EMC)**	26-40
3.1	Introduction	
3.2	Understanding Electromagnetic Disturbances	
3.3	Understanding Power Quality and EMC	
3.4	Common Power System Electromagnetic Phenomena	
3.5	Definition of compatibility levels in industrial plants	
3.6	Common Electromagnetic Environments	
3.6.1	Electromagnetic environment defined by EN 50160	
3.6.2	Electromagnetic environment defined by IEC 61000-2-4	
3.7	Electromagnetic environment classes	
3.8	Overcoming Electromagnetic Compatibility (EMC)	
Chapter 4	**Understanding Voltage Sags**	41-73
4.1	Definition of voltage sags	
4.1.1	Understanding the voltage sag information in TNB PQ SMS	
4.2	Difference between voltage sag and voltage dip	
4.3	Sources of voltage sags (dips)	
4.4	Classification of voltage sags	
4.5	Propagation of voltage sags.	
4.6	Impact of voltage sags to industrial equipment	
4.6.1	Impact of voltage sags to electronic equipment	
4.6.2	Sensitive equipment in industrial plants	
4.6.3	Impact of voltage sags to motors	
4.6.4	Impact of voltage sags to lighting systems	
4.7	Understanding level of equipment sensitivity to voltage sags	
4.7.1	Understanding control level sensitivity to voltage sag	
4.7.1.1	Understanding UnderVoltage Relay (UVR)	
4.7.1.2	Understanding contactors	
4.7.1.3	Understanding other sensitive electronic control system/equipment	
4.7.1.4	Equipment fails because an unbalance relay trip.	
4.7.1.5	A quick-acting relay shuts the system down	
4.7.1.6	A reset circuit may incorrectly trip at the end of the voltage sag.	
4.7.1.7	Understanding current transducer	

4.7.1.8 Understanding interlock sensitivity to voltage sags
4.8 Example of diagrams for control circuits for 3-phase equipment

Chapter 5 Monitoring Voltage Sags 74-88

5.1 Introduction
5.2 Power Quality Monitoring
5.2.1 Understanding True RMS meter
5.2.2 Description of PQ recording equipment
5.3 What to Monitor?
5.4 Locations to monitor Power Quality
5.5 Importance of having a good software to diagnose Power Quality
5.6 Examples on recorded waveforms for voltage sags

Chapter 6 Equipment Compatibility Requirement 89-97

6.1 Power quality design philosophy
6.2 Understanding equipment immunity requirement
6.3 Voltage sag immunity requirement
6.3.1 Available compatibility levels for voltage sags
6.3.2 Voltage tolerance curves
6.3.2.1 CBEMA standard
6.3.2.2 ITIC standard
6.3.2.3 SEMI F47 standard
6.3.2.4 IEC 61000-4-11 standard
6.3.2.5 IEC 61000-4-34 standard

Chapter 7 Characterizing Equipment Sensitivity 98-111

7.1 Introduction
7.2 Objective of equipment immunity testing
7.3 Analyzing machinery immunity and sensitivity to voltage sag
7.3.1 Simple method to verify the equipment sensitivity to voltage sags
7.3.2 Testing method to verify the equipment sensitivity to voltage sags
7.4 Evaluation of test results
7.5 Improving equipment immunity to voltage sag
7.6 Evaluating the Economics
7.7 Improving Equipment Ride-through Characteristics

Chapter 8 Solutions to Voltage Sags 112-133

8.1 Introduction
8.2 Equipment procurement specifications
8.3 Voltage sag solutions for existing industrial plant
8.3.1 Hardening requirement for control and logic circuits
8.3.1.1 SEMI F47 compliant power source

8.3.1.2 Change the trip setting of protection relay (UVR etc.)
8.3.1.3 Installing a coil hold-in device
8.3.1.4 Implement auto restart schemes
8.3.1.5 To maintain the DC link voltage for ASD.
8.3.1.6 Change the settings for unbalance relay
8.3.1.7 Employ a time delay settings for reverse power relay
8.3.1.8 Overall actions for hardening the control circuit & protection relays

8.4 Single phase power conditioners for voltage sag mitigation
8.4.1 Sizing procedure for single-phase power conditioners
8.4.1.1 Uninterruptible Power Supply (UPS)
8.4.1.2 Constant Voltage Transformer (CVT)
8.4.1.3 Dip Proofing Inverter
8.4.1.4 Voltage Dip Compensator (VDC)
8.4.1.5 Dynamic Compensator (Dynacom)
8.4.1.6 Dynamic Sag Corrector (DySC)

Chapter 9 Large Scale Solutions to Voltage Sags 134-148

9.1 Introduction
9.1.1 Sizing procedure for three phase power conditioners
9.2 Three Phase Uninterruptible Power Supplies (UPS)
9.3 Active Voltage Conditioner (AVC)
9.4 Datawave
9.5 Flywheel
9.6 Dynamic Voltage Restorer (DVR)
9.7 Three phase Dynamic Compensator (Dynacom)
9.8 Dynamic Sag Corrector (ProDysc)
9.9 Dynamic Sag Corrector (MegaDysc)
9.10 UPS-I, Industrial UPS
9.11 Medium Voltage UPS
9.12 PureWave® Outdoor UPS Systems
9.13 Sag Fighter

10.0 Summary of Guidebook 149

References 151

CHAPTER 1

OVERVIEW ON POWER QUALITY

1.0 INTRODUCTION

As factory automation continues to evolve with the movement of data centers from computer rooms to the factory floor, the importance of power quality (PQ) has escalated. The inclusion of more sensitive electronic equipment in industrial processes demands the delivery of clean and stable power. Even the smallest service or process interruption can have a devastating effect on the efficiency and productivity of a company. The most obvious signs of a PQ problem include flickering lights, damaged equipment or a complete loss of power. Shorter than expected life span of equipment or unexplained shutdowns can also be a result of PQ problems. In some cases, such problems are caused by improper wiring and grounding practices. PQ problems may also be caused by natural disruptions such as lightning strikes, operations of large nonlinear loads such as arc furnaces and large rotating motor loads. The types of PQ problems frequently experienced by customers are voltage sags and harmonics while the less frequent ones include transient, flicker and noise.

1.1 Power Quality Definitions

As any other product, electric power can also be characterized by the term quality. Customer generally grades the quality of the electrical power based on the effects of problems associated with the electric power supply. The more equipment outages, erratic behaviour or damage, the worse is the understanding on power quality (PQ).

The Institution of Electrical, Electronic Engineers (IEEE) defines PQ as “the concept of powering and grounding sensitive electronic equipment in a manner that is suitable to the operation of that equipment” [1]. Another definition of PQ is from IEC 61000-2-1. PQ is defined as conducted electromagnetic disturbances present in electrical supply network in the frequency range from 0 to 9 kHz, with an extension up to 148.5

kHz [2]. In power qualitu, the concept of Electromagnetic Compatibility (EMC) is important to ensure minimum equipment mal-operation due to electromagnetic environment. Electromagnetic Compatibility (EMC) is the ability of equipment or systems to function satisfactorily in their electromagnetic environment without introducing intolerable electromagnetic disturbances to anything in that environment.

While power quality is a convenient term for many, it is the quality of the voltage - rather than power or electric current - that is actually described by the term. Power is simply the flow of energy and the current demanded by a load is largely uncontrollable. The quality of electrical power may be described as a set of values of parameters, such as:-

- Continuity of service
- Variation in voltage magnitude
- Transient voltages and currents
- Harmonic content in the waveforms for AC power

It is often useful to think of power quality as a compatibility problem: is the equipment connected to the grid compatible with the events on the grid, and is the power delivered by the grid, including the events, compatible with the equipment that is connected? Compatibility problems always have at least two solutions: in this case, either clean up the power, or make the equipment tougher.

1.2 Categories of Power Quality Disturbances

Power quality or electromagnetic disturbance is defined as any electromagnetic phenomenon which, by being present in the electromagnetic environment can cause electrical equipment to depart from its intended performance. Electromagnetic phenomena are low-frequency conducted disturbances in the frequency range from 0 kHz to 9 kHz voltage deviations. An electromagnetic disturbance may be an electromagnetic noise, an unwanted signal or an immediate change in the propagation medium. Table 1.1

describes the IEEE categorization of electromagnetic disturbances used by the power quality community [3].

Table 1.1 Classifications of Power Quality Disturbances (IEEE Std.1159 2009)

Category of disturbance	Typical spectral content	Typical duration	Typical voltage magnitude in per unit (pu)
Impulsive transients			
Nanosecond	5 nsec rise	< 50 nsec	
Microsecond	1µsec rise	50 nsec – 1msec	
Millisecond	0.1 msec rise	> 1 msec	
Oscillatory transients			
Low frequency	< 5 kHz	0.3 – 50 msec	0 – 4pu
Medium frequency	5 – 500 kHz	20 µsec	0 – 4pu
High frequency	0.5 – 5 MHz	5 µsec	0 – 4pu
Short duration variations			
Instantaneous			
Interruption		0.5 – 30 cycles	< 0.1pu
Sag		0.5 – 30 cycles	0.1 – 0.9pu
Swell		0.5 – 30 cycles	1.1 – 1.8pu
Momentary			
Interruption		30 cycles – 3 sec	< 0.1pu
Sag		30 cycles – 3 sec	0.1 – 0.9pu
Swell		30 cycles – 3 sec	1.1 – 1.4pu
Temporary			
Interruption		3 sec – 1 min	< 0.1pu
Sag		3 sec – 1 min	0.1 – 0.9pu
Swell		3 sec – 1 min	1.1 – 1.2pu
Long duration variations			
		> 1 min	< 0.1pu
Interruption sustained		> 1 min	0.9 – 0.1pu
Undervoltage		> 1 min	>1.1pu
Overvoltage			

continue …

… continued

Voltage unbalance		Steady state	0.5 – 2 %
Waveform distortion			
DC offset		Steady state	0 – 0.1%
Harmonics	0 – 100th	Steady state	0 – 20 %
Inter-harmonics	harmonic	Steady state	0 – 2 %
Notching	0 – 6 kHz	Steady state	
Noise	Broadband	Steady state	0.1 %
Voltage fluctuation	< 25 Hz	Intermittent	0.1 – 7 %
Power frequency variation		< 10 sec	

1.3 Brief Descriptions of Common Power Quality Disturbances

Brief descriptions on the characteristics of the common power quality disturbances are presented as follows:-

i. A transient event is a short-lived burst of energy in a system caused by a sudden change of state. Transients are also known as surges or spikes are caused by lightning, appliances such as printers and copiers, as well as utility circuit breaker switching. Transients of sufficient energy can upset computers, corrupt data, or even cause damage to power supplies and components.

   Transients should be distinguished from surges. Surges are a special case of high-energy transient which result from lightning strikes. Voltage transients are lower energy events, typically caused by equipment switching.

   They are harmful in a number of ways :-

   a)They deteriorate solid state components. Sometimes a single high energy transient will puncture a solid state junction, sometimes repetitive low energy transients will accomplish the same thing. For example, transients which exceed the PIV (peak inverse voltage) rating of diodes are a common cause of diode failure.

   b) Their high-frequency component (fast rise times) cause them to be capacitively coupled into adjoining conductors. If those conductors are carrying digital logic, that logic will get trashed. Transients also couple across transformer windings unless special shielding is provided. Fortunately this same high frequency component causes transients to be relatively localized, since they are damped (attenuated) by the impedance of the conductors (inductive reactance increases with frequency).

Transients can be categorized by waveform. The first category is "impulsive" transients, commonly called "spikes," because a high-frequency spike protrudes from the waveform. The capacitor switching transient, on the other hand, is an "oscillatory" transient because a ringing waveform rides on and distorts the normal waveform. It is lower frequency, but higher energy.

Impulsive transients are sudden high peak events that raise the voltage and/or current levels in either a positive or a negative direction. These types of events can be categorized further by the speed at which they occur (fast, medium, and slow). Impulsive transients can be very fast events (5 nanoseconds [ns] rise time from steady state to the peak of the impulse) of short-term duration (less than 50 ns).

An oscillatory transient is a sudden change in the steady-state condition of a signal's voltage, current, or both, at both the positive and negative signal limits, oscillating at the natural system frequency. In simple terms, the transient causes the power signal to alternately swell and then shrink, very rapidly. Oscillatory transients usually decay to zero within a cycle (a decaying oscillation).

ii. Voltage step change: A single variation of the rms value or the peak value of the supply voltage (unspecified with respect to form and duration).

iii. Voltage sag is a brief drop in voltage and is caused by motor starting, heaters in printers and copiers cycling, as well as faults in the power system. Sags often cause lights to dim or flicker, computer equipment to lock up or lose memory etc.

iv. Voltage swell is a brief increase in the normal voltage level. Most swells are caused by stopping of a motor or single line to ground fault. Although not generally a problem, swells have been known to cause failure of marginal components in electronic equipment.

v. Harmonics are sinusoidal voltages or currents having frequencies that are whole multiples of the frequency at which the supply system is designed to operate (e.g. 50Hz or 60 Hz).

Harmonics are a regular distortion of the voltage waveform often caused by the power supplies of electronic equipment. Harmonics can cause overheating in transformers, building wiring, and motors.

vi. DC offset: Direct current (DC) can be induced into an AC distribution system, often due to failure of rectifiers within the many AC to DC conversion technologies that have proliferated modern equipment. DC can traverse the ac power system and add unwanted current to devices already operating at their rated level. Overheating and saturation of transformers can be the result of circulating DC currents. When a transformer saturates, it not only gets hot, but also is unable to deliver full power to the load, and the subsequent waveform distortion can create further instability in electronic load equipment.

vii. Noise is unwanted voltage or current superimposed on the power system voltage or current waveform. Noise can be generated by power electronic devices, control circuits, arc welders, switching power supplies, radio transmitters and so on. Poorly grounded sites make the system more susceptible to noise. Noise can cause technical equipment problems such as data errors, equipment malfunction, long-term component failure, hard disk failure, and distorted video displays.

    Noise due to radio frequency interference is electrical interference from equipment that radiates high frequency electrical energy such as TV/radio transmitters and cell phones. Interference can also be caused by arcing sources or switching power supplies such as those found in electronic ballasts and adjustable speed drives. This kind of noise often causes interference to control circuits.

viii. Power-line flicker is a visible change in brightness of a lamp due to rapid fluctuations in the voltage of the power supply. The source of this is the voltage drop generated over the source impedance of the grid by the changing load current of an equipment or facility. These fluctuations in time generate flicker. The effects can range from disturbance to epileptic attacks of photosensitive persons. Flicker may also affect sensitive electronic equipment such as television receivers or industrial processes relying on constant electrical power.

    Flicker may be produced, for example, if a steel mill uses large industrial electric motors or arc furnaces on a distribution network, or frequent starting of an electric motor, or if a rural residence has a large water pump starting regularly on a long feeder system.

ix. Voltage notching is described as a recurring power quality disturbance due to the normal operation of power electronic devices (i.e. rectifier), when current is commutated from one phase to another

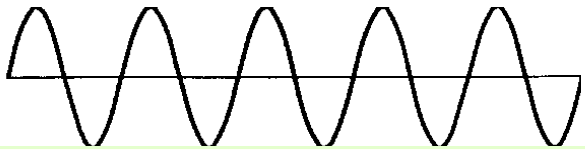
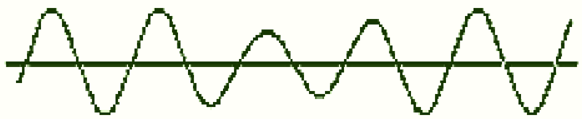
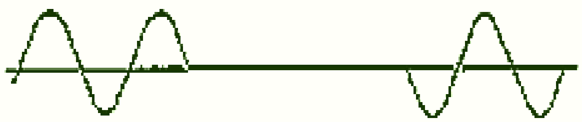
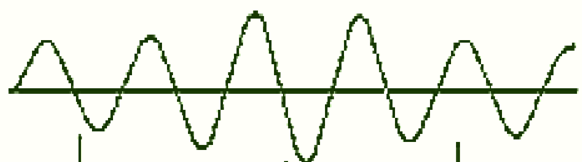
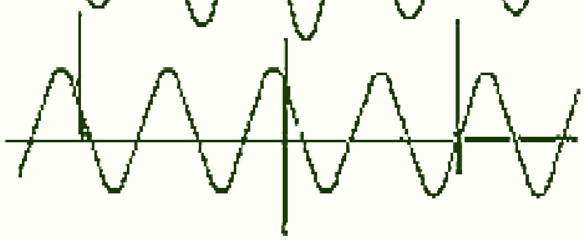
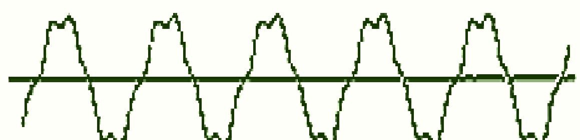
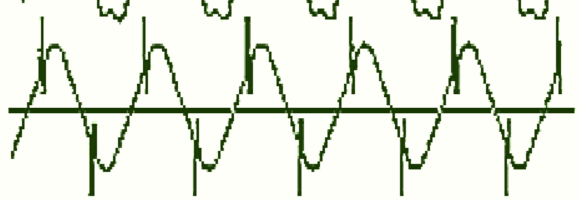
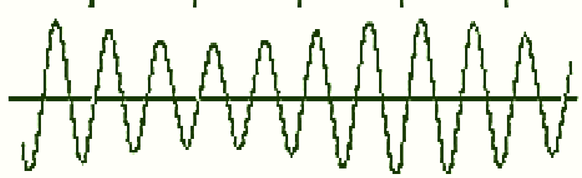
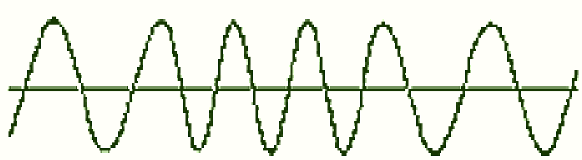
    Voltage notching is primarily caused by three-phase rectifiers or converters that generate continuous DC current. Voltage notches happen when the current commutates from one phase to another. Subsequently, a momentary short circuit between two phases will occur during this period.

    In addition, voltage notching characterizes an unusual case that falls between harmonics and transients. This is because notching takes place in steady-state, thus, it can be distinguished by the harmonic spectrum of the affected voltage. On the other hand, the components of the frequency related to voltage notching are somewhat high and may not be promptly categorized with a measurement device commonly employed for harmonic analysis.

x. Voltage unbalance occurs when the RMS line voltages on a poly-phase system are unequal. Voltages are seldom perfectly balanced between phases, but when this unbalance becomes excessive, it can create problems for poly-phase motors. Many of the newer induction motors are now more sensitive to unbalance than the older designs, and furthermore, adjustable speed drives can be even more vulnerable than standard motors.

Table 1.2 shows the common voltage waveforms for the respective PQ disturbances.

Table 1.2 Common power quality disturbance waveforms

Waveforms	Types of PQ disturbances
	Normal voltage waveform
	Voltage Dips / Sags
	Momentary Interruptions
	Voltage Swells
	Voltage Transients
	Harmonic Distortion
	Notches
	Voltage fluctuations
	Frequency Deviations

1.4 Financial loss related to Power Quality Disturbances

Power quality issues can cause business problems for industrial customers such as:-

- Lost productivity, idle people and equipment
- Equipment damage or failure
- Lost orders, good will, customers and profits
- Lost transactions and orders not being processed
- Revenue and accounting problems such as invoices not prepared, payments held up, and early payment discounts missed
- Customer and/or management dissatisfaction
- Overtime required to make up for lost work time

1.4.1 Financial loss related to Voltage Sag Disturbances

It is almost impossible to define a specific cost that can be related to some kind of standardized voltage sag, but there are some figures that can serve as guidelines to show the financial losses and the importance of voltage sag immunity. In the semiconductor industry, an interruption is very expensive. A manufacturer organisation, SEMI, has developed guidelines, test procedure and limits for voltage dip susceptibility for different types of equipment used in their factories [4]. SEMI also promotes minimum immunity requirement against voltage sags for essential semiconductor equipment.

There were few surveys conducted to document the monetary losses due to power quality in particular due to voltage sags. In November 2002, T. Andersson and D. Nilsson documented the sensitivity and cost of losses based on selected types on industries with regard to voltage sag [5]. An overview of different costs related to voltage sags in different industries is shown in Figure 1.1.

,

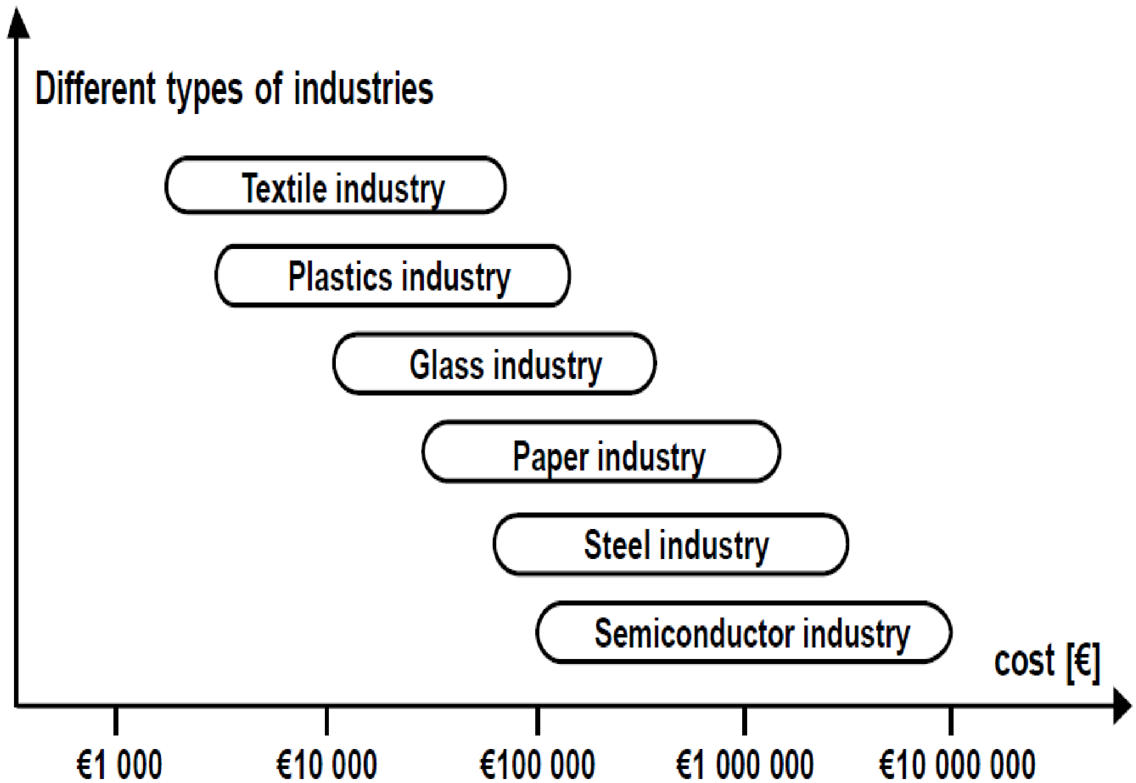


Figure 1.1 Estimated cost of losses due to voltage sags

Sensitivity of different industries to voltage sags expressed in estimated sags cost per industry. The highest position in this ranking is occupied by semiconductor industry which, experience the highest level of voltage sags cost compared to electricity bill or company turnover of any sector.

In another survey performed in 2003 by S. Quaia and F. Tosato [5], a survey on costs of voltage sags were documented for a range of industrial sectors. The results of the survey are shown in Table 1.3. The table presents the estimated voltage sag costs for a range of industrial sectors.

Table 1.3 Cost of voltage sags per type of industries

Industrial process	Voltage Sag Cost (% of total yearly power cost)		
	Category A	Category B	Category C
Semiconductor	0 to 2	2 to 10	5 to 6
Pharmaceutical	0 to 0.8	1 to 5	2 to 4
Chemical	0 to 1	1 to 3	2 to 4
Petrochemical	0 to 1	2 to 5	1.5 to 3.5
Manufacturing	0 to 0.2	0 to 1	0.8 to 1
Metallurgy	0 to 0.2	0 to 1.5	1 to 1.5
Food	0 to 0.5	0 to 1.5	0 to 2

Another documentation on voltage sags cost per event was prepared based on a study carried out in the University of Manchester former UMIST by J. V. Milanovic and N. Jenkins [5]. The results of the study was published in a paper titled “Power quality cost for manufacturing industries," presented on EdF workshop in Paris, 2003.

Table 1.4 Cost of voltage sags per type of industries

Industry	Duration	Cost/sag
UK steel work	30% for 3.5 cycles	£250k
US glass plant	Less than 1 second	$200k
US computer centre	2 second	$600k
US car plant	Annual exposure	$10M
South Africa	Annual exposure	$3B

The latest power quality survey was conducted by Leonardo Energy [5]. The main purpose of this project was to estimate the costs of wastage generated by inadequate power quality for those sectors within the EU-25 for which electrical power is critical. PQ costs reported in the categories of interruptions and voltage quality. All these cost were specified on an annual basis. The survey interviews and web based submission were conducted over a 2-year period in 8 European countries. In all, 62 complete and 6 partial (i.e. excluding detailed cases part) interviews were carried out. The results of the survey on reported number of PQ events in 12 months are shown in Table 1.5.

Table 1.5 Number of power quality events per industries

Type of industries	Number of events				Annual %
	Voltage sags	Short Interruption	Long interruptions	Surges & transients	Harmonics
Industry	15.7	6.9	2.2	13	9.0%
Services	7.7	5.4	2.1	6.7	7.5%
Average	13.2	6.4	2.2	11.3	8.5%

From the survey, the financial losses due to poor Power Quality amount to a total of €150 billion annually in the EU-25. The summary of this survey is as follows:-

- Voltage sags, short interruptions, surges and transients account for 80-90% of the €150bn financial costs/ wastage
- Equipment damage and operational waste (unrecoverable work in progress & Under performance) account for similar proportions of the totals identified
- For the most sensitive industrial sectors representing €3.63 trillion (or 20% of EU25 overall turnover) PQ costs amounts about 4% of their turnover.

The unit costs (per event) of PQ disturbances are:-

- The cost per voltage dip event is between 2,000 and 4,000€.
- Single short interruptions on average are 3.5 times more costly for industry and 9 times more costly for services.

- The average cost of long interruptions is 90,000€ and is more homogenous across the whole survey sample.
- Assessing the generic cost per event for surges and transients is more problematic because of the lack of other research into these PQ phenomena. For this Survey it spans between 120,000€ and 180,000€.

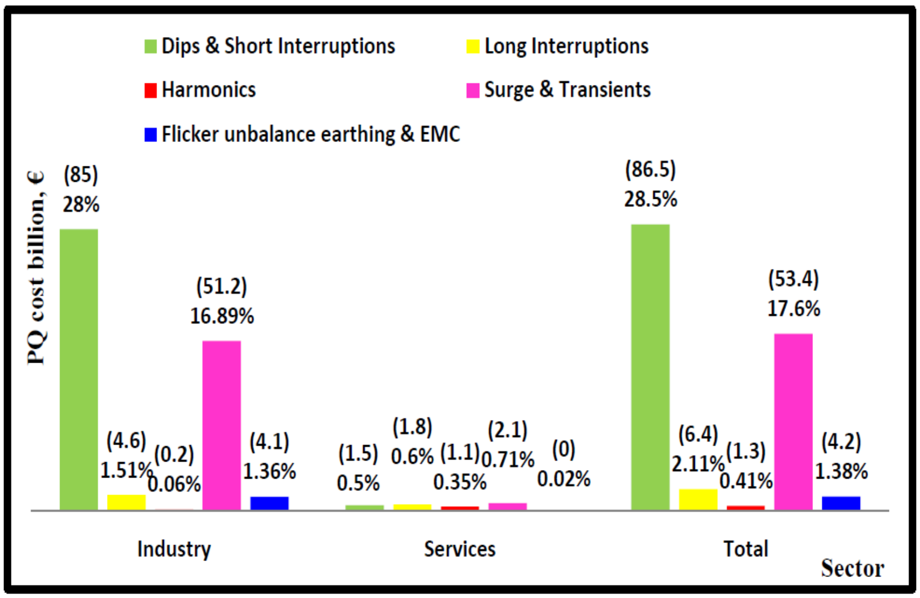


Figure 1.2 PQ cost to EU economy in LPQI surveyed sectors

On average the absolute share of impacts of the 6 categories of PQ disturbances taken from the total survey sample is as follows:-

- Voltage dips 23.6%
- Short interruptions 18.8%
- Long interruptions 12.5%
- Harmonics 5.4%
- Transients and surges 29%
- Other 10.7%

The summary of this study identifies that the industry wasted a huge amount of resource unnecessarily due to PQ disturbances.

CHAPTER 2

STEADY STATE SUPPLY VOLTAGE PERFORMANCE

Before more details are presented on the definition of electromagnetic disturbances, it is good that we first understand the definition of voltage regulation. The term "voltage regulation" is used to discuss long term variations in voltage. It does not include short term variations, which are generally called voltage sags, voltage swells and transients. The ability of equipment to handle steady state voltage variations varies from equipment to equipment. The steady state voltage variation limits for equipment is usually part of the equipment specifications. The Information Technology Industry Council (ITIC) specifies equipment withstand recommendations for IT equipment according to the ITI Curve (formerly the CBEMA curve). The 1996 ITI Curve specifies that equipment should be able to withstand voltage variations within +/- 10% of nominal voltage (variations that last longer than 10 seconds) [6].

In Malaysia, the voltage regulation requirements are defined in two categories: -

- Range A is for normal conditions and the required regulation is as follows:

  Table 2.1 Normal steady state voltage regulations

Nominal Voltage	**% Variation of nominal voltage**
400V and 230V	-6% and +10%
6.6kV, 11kV, 22kV, 33kV	± 5%
132kV and 275kV	± 5%

- Range B is for short durations or unusual conditions.

  Under contingency condition, when one or more circuit elements are on outage, the power frequency steady-state voltage at all points in the utility's distribution system including the points before the consumer metering must be planned to be maintained as follows:

Table 2.2 Steady state voltage regulation limits under contingency condition

Nominal Voltage	**% Variation of nominal voltage**
400V and 230V	±10%
6.6kV, 11kV, 22kV, 33kV	±10%
132kV and 275kV	±10%

2.1 Common misunderstanding on settings for UnderVoltage Relay (UVR)

Most customers and consultants are often confused between the definition of voltage regulation and voltage sags. Most consultants assumed the % ranges of the voltage regulations are also the maximum and minimum voltages that all equipment will be exposed to when connected to an electrical power system. The common mistake will be on the application and settings of the UnderVoltage Relay (UVR) to initiate the opening of circuit breaker (CB) and operation of standby generator during a power outage. During the occurrence of a voltage sag event, the CB will also operate and cause power interruption to the customers. In order for the UVR to operate properly, a time delay scheme must be part of the UVR.

Examples of relays with time delay schemes are shown in Figure 2.1. Details on the recommended settings (voltage magnitude and duration) for the UVR will be presented in Chapter 8 in this guidebook.

Figure 2.1 Example of relays for undervoltage and overltage with time delay

2.2 Method to regulate steady state voltages

The most common method to regulate voltages in the power system is done by a transformer tap changer. A tap changer is a device fitted to power transformers for regulation of the output voltage to required levels. This is normally achieved by changing the ratios of the transformers on the system by altering the number of turns in one winding of the appropriate transformer/s. Power utilities are under obligation to their customers to maintain the supply voltage between certain limits. Tap changers offer variable control to keep the supply voltage within these limits. Most power transformers today above 7.5 MVA incorporate on load tap changers as a means of voltage regulation

A power transformer

On load tap changer

Figure 2.2 A power transformer with on load tap changer

Figure 2.3 A distribution transformer with off load tap changer

CHAPTER 3

UNDERSTANDING ELECTROMAGNETIC COMPATIBILITY (EMC)

3.1 Introduction

Do you ever stop to wonder why you are asked to turn off mobile phones and electronic games in an aircraft or hospital, where there are a host of other electrical and electronic systems on which many people's lives may depend? Or is your favourite radio programme obliterated by interference? TV screen covered in 'haze' when someone /your wife uses a vacuum cleaner or cooking blender nearby? The vacuum cleaner and cooking blender cause ‘unwanted’ electromagnetic interference (EMI). And this problem is called electromagnetic compatibility (EMC) problem.

Vacuum cleaner

Cooking Blender

Figure 3.1 Common sources of electromagnetic interference (EMI) in household

In simple terms, EMC describes the ability of electronic equipment and electrical systems or components to work correctly when they are close together. In practice this means that the electromagnetic disturbances from each item of equipment must be limited and also that each item must have an adequate level of immunity to the disturbances in its environment. The aim of EMC is to ensure the reliability and safety of all types of systems wherever they are used and exposed to electromagnetic environments [7].

EMC development is closely linked with that of the whole field of electrical and electronic engineering. The subject concerns all of us, not only those in industry who develop, test and manufacture equipment but also those more 'on the receiving end' who rely on, for example, the omnipresent electronic elements in heart pacemakers, ABS vehicle braking systems, laptop computers or air traffic control systems. It is therefore only natural that the EN, IEC, IEEE, SEMI etc with the global coverage of its standards and other technical publications, are deeply involved with EMC for many decades.

EMC is the branch of electrical sciences which study the unintentional generation, propagation and reception of electromagnetic energy with reference to the unwanted effects (electromagnetic interference, or EMI) that such energy may induce. EMC aims to ensure that equipment items or systems will not interfere with or prevent each other's correct operation through spurious emission and absorption of EMI. EMC is sometimes referred to as EMI Control, and in practice EMC and EMI are frequently referred to as a combined term "EMC/EMI" [7].

While electromagnetic interference (EMI) is a phenomenon - the radiation emitted or conducted and its effects - EMC is an equipment characteristic or property - to not behave unacceptably in the EMI environment. EMC ensures the correct operation, in the same electromagnetic (EM) environment, of different equipment items which use or respond to electromagnetic phenomena, and the avoidance of any interference effects. Another way of saying this is that EMC is the control of EMI so that unwanted effects are prevented.

An electromagnetic (EM) environment is created by the introduction of any electromagnetic phenomena/disturbance to a network/location that has electrical or electronic device in operation. Any electromagnetic phenomena/disturbance created by an appliance other that those intended for its practical use are regarded as electromagnetic interference (EMI). EMI spreads from one appliance to another via cables or as radiation. Phenomena such as stripes on a TV screen, the crackling of a radio or malfunctioning of a computer are often manifestations of interference caused by other electrical appliances.

The term EMI better reflects the fact that electrical and electronic systems may cause disturbances at any frequency between 0 Hz and the GHz (microwave) range. For the purposes of its EMC-related publications, IEC defines the EM environment as "the totality of EM phenomena existing at a given location."

EMC can be divided into a number of issues:

- EMI is the radiation emitted and its effects on the victim.
- Emission is the unwanted generation of electromagnetic energy by some emitter or source.
- Susceptibility or Immunity is the ability of the receptor or victim equipment to operate correctly in the presence of electromagnetic disturbances. Susceptibility and immunity are opposites - an equipment which has high susceptibility has low immunity, and vice versa.
- Coupling is the mechanisms by which EMI is able to travel from source to victim.

Besides understanding the phenomena in themselves, EMC also addresses the countermeasures, such as control regimes, design and measurement, which should be taken in order to prevent emissions from causing any adverse effect

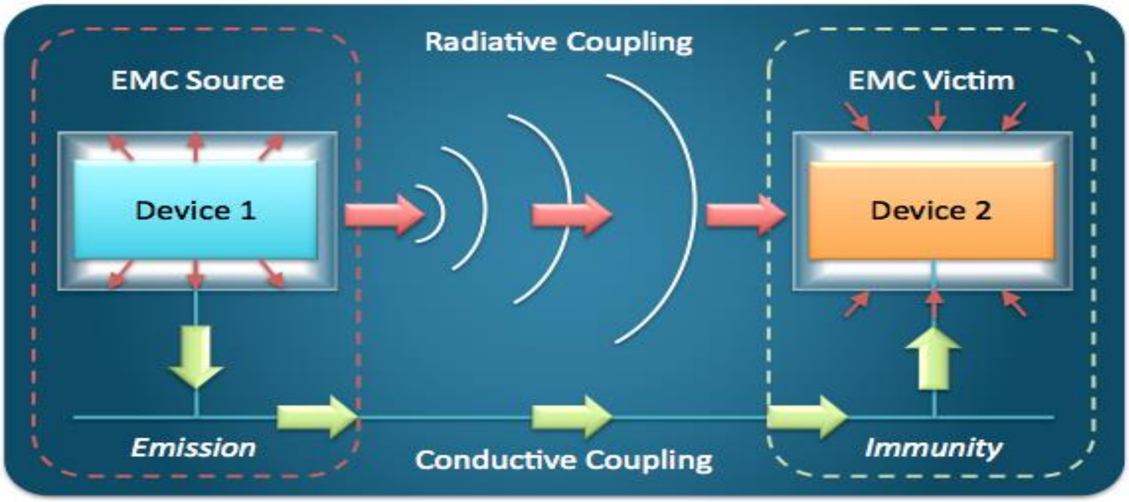


Figure 3.2 Concept of EMC (1)

Figure 3.3 Concept of EMC (2)

EMC is a characteristic of equipment or system that mutually with stand their respective electromagnetic emissions. EMC is a discipline aimed at achieving the 'peaceful' coexistence of equipment sensitive to electromagnetic disturbances (considered as the "victim") alongside equipment emitting such disturbances (considered as the "source").

This discipline investigates the unwanted interferences emitted (emissions), and unwanted susceptibility of equipment (immunity) against electromagnetic disturbances. The goal of EMC is to create a situation of functional and safe operation, in a common electromagnetic environment, of different equipment and the avoidance of any interference effects.

As well as safety, reliability and serviceability, electrical appliances must meet the further requirement of interference-free operation in the presence of other equipment in their intended operating environments. Interference-free operation of appliances intended for use in the same operating environment is guaranteed by electromagnetic compatibility (EMC). An electrical appliance must not generate unreasonable interference in its environment and must also tolerate reasonable levels of outside interference.

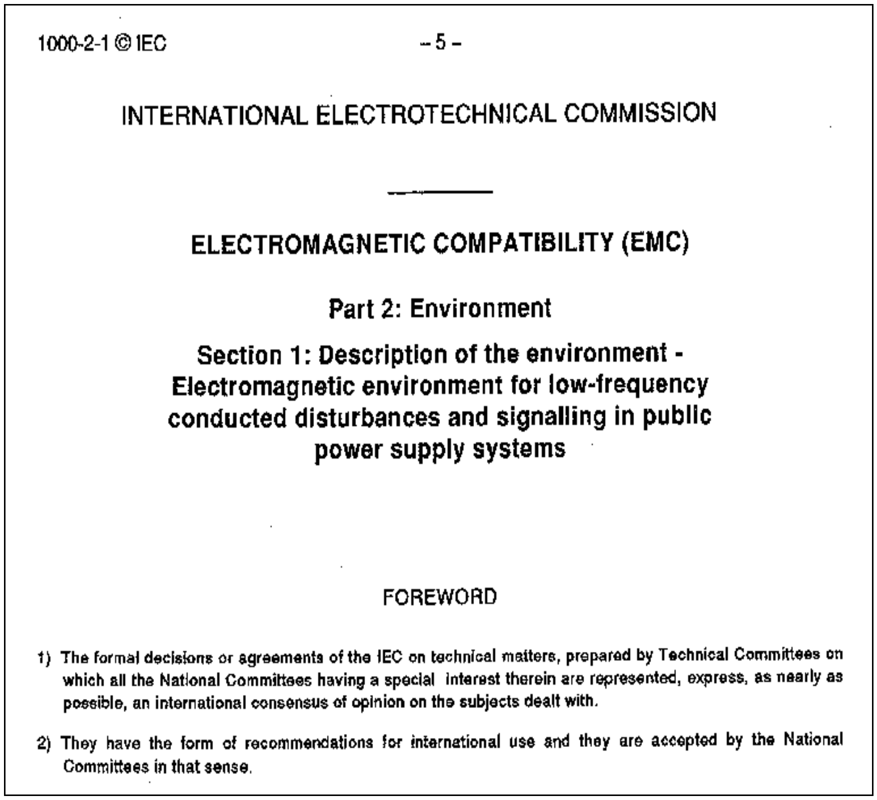
3.2 Understanding Electromagnetic Disturbances

Electromagnetic disturbance is an electromagnetic event, which may degrade the performance of a device, equipment or system, or adversely affect living or inert matter. An electromagnetic disturbance may be an electromagnetic noise, an unwanted signal or an immediate change in the propagation medium.

3.3 Understanding Power Quality and EMC

The IEC 61000 Electromagnetic Compatibility (EMC) standard is the counterpart of the IEEE power quality standards. It is important to note that IEC does not yet use the term power quality in any of its standard documents. Instead the IEC uses the term electromagnetic compatibility, which is not the same as PQ but there is a strong overlap between the two terms.

According to IEC 61000-2-1, PQ is defined as conducted electromagnetic disturbances present in electrical supply network in the frequency range from 0 to 9 kHz, with an extension up to 148.5 kHz. An electromagnetic disturbance is any electromagnetic phenomenon which, by being present in the electromagnetic environment that can cause electrical equipment to depart from its intended performance [2].


1000-2-1 © IEC – 5 –

INTERNATIONAL ELECTROTECHNICAL COMMISSION

ELECTROMAGNETIC COMPATIBILITY (EMC)

Part 2: Environment

Section 1: Description of the environment - Electromagnetic environment for low-frequency conducted disturbances and signalling in public power supply systems

FOREWORD

1) The formal decisions or agreements of the IEC on technical matters, prepared by Technical Committees on which all the National Committees having a special interest therein are represented, express, as nearly as possible, an international consensus of opinion on the subjects dealt with.

2) They have the form of recommendations for international use and they are accepted by the National Committees in that sense.

Figure 3.4 IEC 61000-2-1

Electromagnetic Compatibility (EMC) Standard consists of six parts, each consisting of several sections. Listed below are brief descriptions of IEC Standard sections that are related to power quality.

No	Description of IEC standard
1	IEC 61000-1-X: General
2	IEC 61000-2-X: Environment
3	IEC 61000-3-X: Limits
4	IEC 61000-4-X: Testing and Measurement Techniques
5	IEC 61000-5-X: Installation and Mitigation Guidelines
6	IEC 61000-6-X: Generic Standards

The issue of power quality is termed as an electromagnetic compatibility (EMC) problem between the electricity supply and the customers' equipment. Electromagnetic compatibility (EMC) itself is defined as: "the ability of an equipment or system to function satisfactorily in its electromagnetic (EM) environment (immunity) without introducing intolerable electromagnetic disturbances to anything in that environment (emission)".

The concept of electromagnetic compatibility (EMC) is important to ensure minimum equipment mal-operation due to its electromagnetic environment. Electromagnetic compatibility (EMC) is concerned with the possible degradation of the performance of electrical and electronic equipment due to the disturbances present in the electromagnetic environment in which the equipment operates. To ensure compatibility, there are two essential requirements:

- the emission of disturbances into the electromagnetic environment must be maintained below a level that would not cause an unacceptable degradation of the performance of equipment operating in that environment.

- all equipment operating in the electromagnetic environment must have sufficient immunity from all disturbances at the levels at which they exist in the environment.

Limits for emission and immunity cannot be set independently of each other. Clearly, the more effectively emissions are controlled, the less restrictive are the immunity demands that have to be placed on equipment. Similarly, if equipment is highly immune, there is less need for stringent limits on the emission of disturbances.

A range of technical standards/guidelines had been published to address the fundamental electromagnetic compatibility (EMC) issues governing the connection of sensitive equipment to a electrical power system. Standards documentation sets out guidelines for equipment connectivity and regulation of both conducted and radiated EMC emission and susceptibility. A sub-set of most EMC standards documentation governs the susceptibility of sensitive equipment to voltage sags and surges.

3.4 Common Power System Electromagnetic Phenomena

The IEEE 1159:2009 contains several additional terms related to the IEC terminology. The term voltage sag is used synonymously with the IEC term, voltage dip. The category of short duration variation is used to refer to the voltage dips and short interruptions as defined by the IEC standards [3].

The category of waveform distortion is used as a container category for the IEC harmonics, inter harmonics and dc in ac networks phenomena as well as an additional events from IEEE 519 called notching. Table 1.1 describes the IEEE categorization of electromagnetic phenomena used by the power quality community.

3.5 Definition of compatibility levels in industrial plants

A compatibility level is a specified electromagnetic disturbance level used as a reference level in a specified environment for coordination in the setting of emission and immunity limits. The compatibility levels are set down for the various disturbances on an individual basis only. However, the electromagnetic environment usually contains several disturbances simultaneously, and the performance of some equipment can be degraded by particular combinations of disturbances.

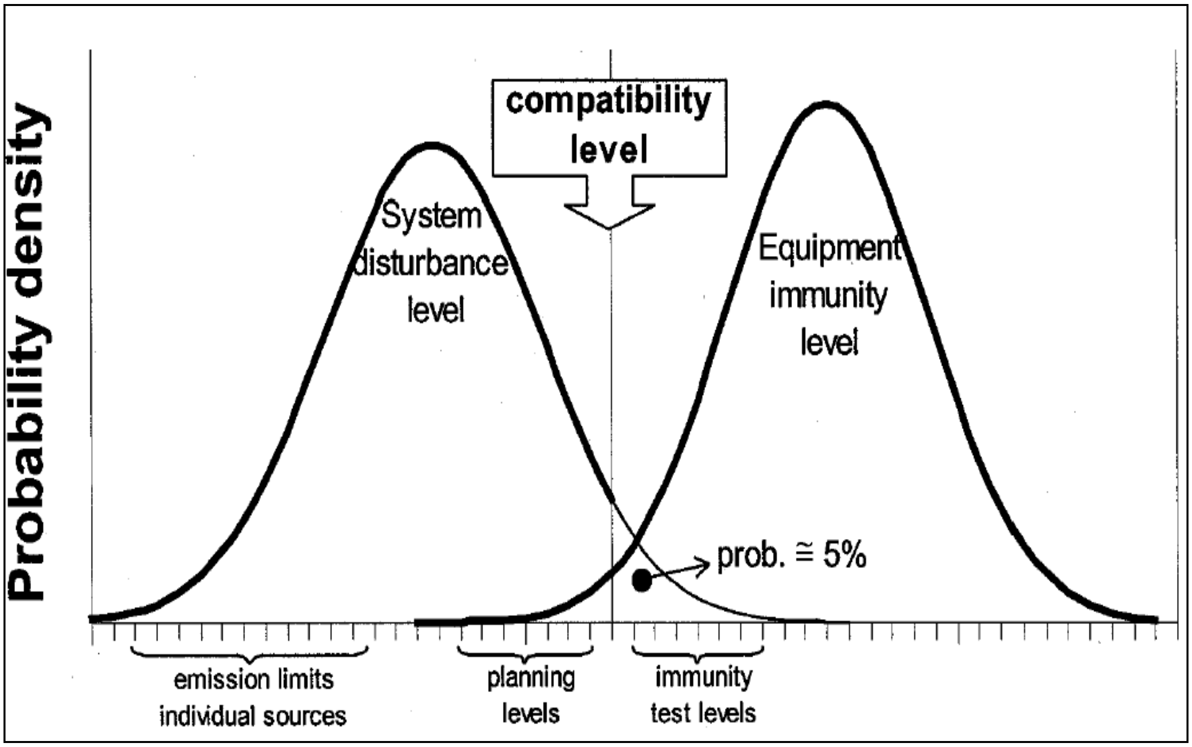


Figure 3.4 Definition of compatibility level

The goal of EMC is the correct operation of different equipment in the same electromagnetic environment, which involves electromagnetic phenomena in their operation. In order to achieve such objective, EMC pursues two different issues, namely emission and immunity compatibility levels. Emission issue is related to the reduction of unintentional generation of electromagnetic energy to avoid the propagation of such energy towards the external environment while immunity issue refers to the correct operation of electrical equipment in the presence of electromagnetic disturbances.

There are two aspects to EMC:-

- firstly, a piece of equipment should be able to operate normally in its environment
- secondly, it should not pollute the environment too much.

An agreement on immunity level is a matter of foremost concern between equipment manufacturers, utilities and customers. It is important that all sensitive equipment should be immune to its electromagnetic environment. A device connected to the electrical power system can be exposed to an electromagnetic environment not only due to the combined emission of all other devices connected to the system but also due to all kinds of events in the power system like switching actions, short circuit faults and lightning strikes. The immunity of a device should be assessed with reference to the compatibility level of the electromagnetic environment, for example, the frequency of voltage sags to be expected at a location concerned.

In-plant point of common coupling (IPCs) should be categorized according to their compatibility levels. To enable the selection of specific equipment or devices such as electronic machine, rotating machines, power-capacitor banks, filters etc. it may be necessary to obtain a specific description of the electromagnetic environment (voltage deviations) that may be present at the equipment terminals. Examples of common electromagnetic environment or voltage characteristics to be expected in public power systems are documented in BS EN 50160 (2000) and IEC 61000-2-4 (2006:13) as shown in Tables 3.1 and 3.2, respectively. The ranges of the acceptable limits are the numbers of electromagnetic disturbances in the electrical power systems to be experienced in 12 months.

3.6 Common Electromagnetic Environments

3.6.1 Electromagnetic environment defined by EN 50160 [8].

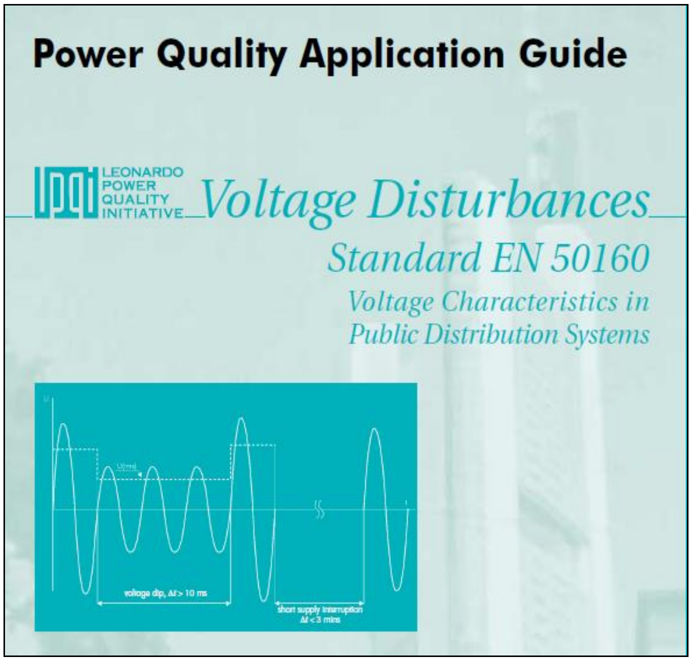
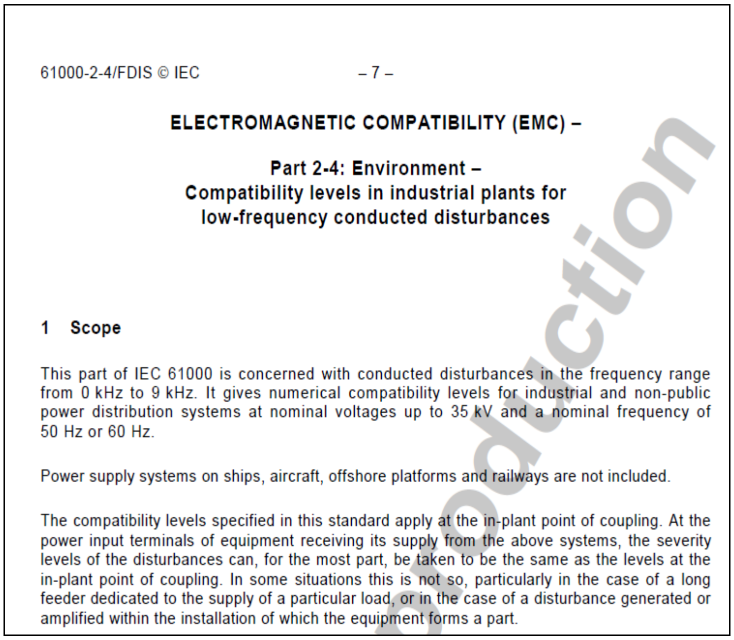


Figure 3.5 The EN 50160 standard

Table 3.1 EN 50160 2000: Voltage characteristics for public power systems

Supply voltage phenomenon	Acceptable limits	Measurement Interval
Grid frequency	49.5Hz to 50.5Hz 47Hz to 52Hz	10 s
Slow voltage changes	230Volt ± 10%	10 min
Voltage Sags or Dips (≤1min)	10 to 1000 times (under 85% of nominal)	10 ms
Short Interruptions (≤ 3min)	10 to 100 times per year (under 1% of nominal)	10 ms
Accidental, long interruptions (> 3min)	10 to 50 times per year (under 1% of nominal)	10 ms
Voltage unbalance	Mostly 2% but occasionally 3%	10 min
Harmonic Voltages	8% Total Harmonic Distortion	10 min

3.6.2 Electromagnetic environment defined by IEC 61000-2-4 [9].



61000-2-4/FDIS © IEC – 7 –

ELECTROMAGNETIC COMPATIBILITY (EMC) –

Part 2-4: Environment –
Compatibility levels in industrial plants for
low-frequency conducted disturbances

1 Scope

This part of IEC 61000 is concerned with conducted disturbances in the frequency range from 0 kHz to 9 kHz. It gives numerical compatibility levels for industrial and non-public power distribution systems at nominal voltages up to 35 kV and a nominal frequency of 50 Hz or 60 Hz.

Power supply systems on ships, aircraft, offshore platforms and railways are not included.

The compatibility levels specified in this standard apply at the in-plant point of coupling. At the power input terminals of equipment receiving its supply from the above systems, the severity levels of the disturbances can, for the most part, be taken to be the same as the levels at the in-plant point of coupling. In some situations this is not so, particularly in the case of a long feeder dedicated to the supply of a particular load, or in the case of a disturbance generated or amplified within the installation of which the equipment forms a part.

Figure 3.6 The IEC 61000-2-4 standard

Table 3.2 IEC 61000-2-4: Voltage characteristics for public power system

Supply Voltage Phenomenon	Acceptable limits	Measurement Interval
Grid frequency	49.5Hz to 50.5Hz	10 s
Slow voltage changes	230Volt ± 8%	10 min
Voltage Sags or Dips (≤1min)	100 times (Rural / Overhead system) 10-100 times (Urban/Underground system)	10 ms
Short Interruptions (≤ 3min)	10 to 100 times per year (under 1% of nominal)	10 ms
Transient over-voltages (line-to-ground)	Mostly < 6kV	N/A
Voltage unbalance	2%	10 min
Harmonic Voltages	8% Total Harmonic Distortion	10 min

3.7 Electromagnetic environment classes

The following classes of electromagnetic environment have been summarized from the IEC 61000-2-4 [9].

Class 1

This class applies to protected supplies and has compatibility levels lower than public network levels. It relates to the use of equipment very sensitive to disturbances in the power supply, for instance the instrumentation of technological laboratories, some automation and protection equipment, some computers, etc.

NOTE Class 1 environments normally contain equipment which requires protection by such apparatus as uninterruptible power supplies (UPS), filters, or surge suppressers.

Class 2

This class applies to points of common coupling (PCC's for consumer systems) and in-plant points of common coupling (IPC's) in the industrial environment in general. The compatibility levels in this class are identical to those of public networks; therefore components designed for application in public networks may be used in this class of industrial environment.

Class 3

This class applies only to IPC's in industrial environments. It has higher compatibility levels than those of class 2 for some disturbance phenomena. For instance, this class should be considered when any of the following conditions are met:-

– a major part of the load is fed through converters;
– welding machines are present;
– large motors are frequently started;
– voltage sensitive loads
– loads vary rapidly

NOTE 1: The supply to highly disturbing loads, such as arc-furnaces and large converters which are generally supplied from a segregated bus-bar, frequently has disturbance levels in excess of class 3 (harsh environment). In such special situations, the compatibility levels should be agreed upon.

NOTE 2: The class applicable for new plants and extensions of existing plants should relate to the type of equipment and process under consideration.

Class 4

This class applies to points of common coupling (PCC's for consumer systems) and in-plant points of common coupling (IPC's) ONLY for semiconductor industry. The compatibility levels in this class are identical to those of Semiconductor industrial standard SEMI F47-0706.; therefore components designed for application in semiconductor industry may be used in this class of industrial environment.

3.8 Overcoming Electromagnetic Compatibility (EMC) Issues

EMC is a characteristic of equipment or systems that mutually withstand their respective electromagnetic emissions. Equipment and systems are always subject to electromagnetic disturbances, and any electro-technical equipment is, itself, more or less an electromagnetic disturbance generator.

The standard approach to electromagnetic compatibility is to apply co-ordinated emission and immunity limits. The attempt is made, on the one hand, to prevent electromagnetic disturbance from being emitted at an excessive level and, on the other hand, to provide the equipment exposed to disturbance with an adequate level of immunity—a level that enables it to operate as intended.

For all electro-technical equipment, EMC must be considered right from the initial design phase and the various principles and rules carried on through to manufacture and installation. This means that all those involved, from the engineers and architects that design a building to the technicians that wire the electrical cabinets, including the specialists that design the various building networks and the crews that install them, must be concerned with EMC - a discipline aimed at achieving the "peaceful" coexistence of equipment sensitive to electromagnetic disturbances (which may therefore be considered as the "victim") alongside equipment emitting such disturbances (in other words, the "source" of the disturbances).

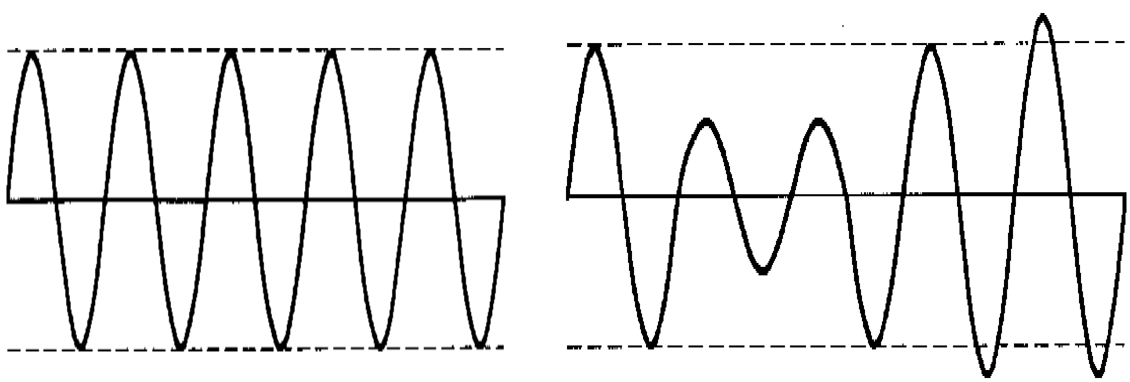
With regard to voltage sags that are moderate in depth and duration, some equipment can have certain level of inherent immunity, for example by virtue of its inertia or energy storage capacity. Alternatively, it may be possible to make design adjustments so that this property is provided. For most operations some form of sag mitigation equipment will be required at the load side and there is a wide range to choose from, depending on the type of load that is being supported. The cheapest solution is to specify equipment with the necessary resilience to voltage sags.

CHAPTER 4

UNDERSTANDING VOLTAGE SAGS

4.1 Definition of voltage sags

Voltage sags are one of the electromagnetic disturbances that exist in the electromagnetic environment that can affect sensitive & critical equipment. Voltage sag is a short-term reduction of rms voltage. It is specified in terms of duration and retained voltage, usually expressed as a percentage (%) of the nominal rms voltage remaining at the lowest point during the sag. Comparison between a normal voltage waveform and a voltage sag in shown in Figure 4.1. When a voltage sag occurs, the full required energy will not be delivered to the load and this can have serious consequences depending on the type of load exposed to the voltage sag.

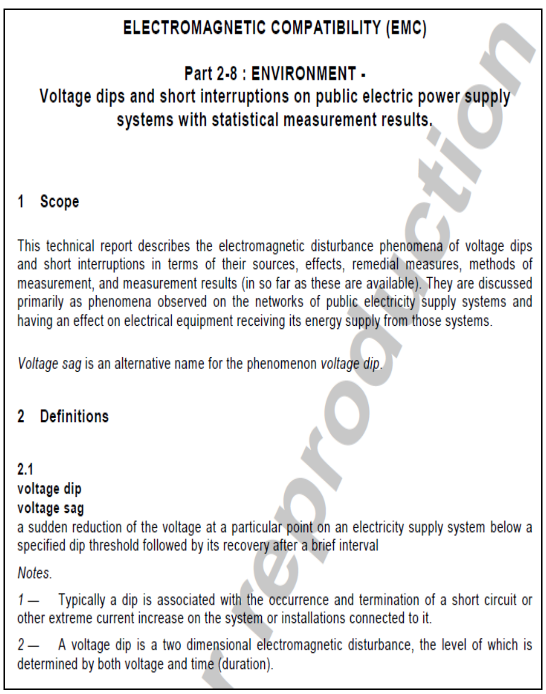


Normal waveform (sinewave) Sudden voltage change (Non Sinewave)

Figure 4.1 Normal waveform and power quality waveform (voltage sag)

Voltage sags are widely recognized as among the most common and important aspects of power quality problems affecting commercial and industrial customers - they are virtually unnoticeable by observing lighting blinks but many industrial processes would have shutdown. Possible effects of voltage sags would be system shutdown or reduce efficiency and life span of electrical equipment, specifically motors. Therefore, such disturbances are particularly problematic for industry where the malfunction of a device may result in huge financial losses

The IEC 61000-2-8 standard defines voltage dip (voltage sag) as a sudden reduction of the voltage at a particular point on an electricity supply system below a specified dip threshold voltage, followed by its recovery after a brief interval [10]. The common specified dip threshold voltage is 90 % of nominal voltage with values of the remaining voltage between 90 to 10% and duration between 10 ms (1/2 cycle) to 60 seconds. The IEEE 1159 standard also define voltage sag as a sudden reduction in voltage to a remaining value between 90% to 10 % of nominal voltage and duration of 10 ms (1/2 cycle) to 60 seconds [3]. Voltage sag (dip) durations are subdivided into three categories: instantaneous (½ cycle to 30 cycles), momentary (30 cycles to 3 seconds), and temporary (3 seconds to 1 minute). These durations are intended to correlate with typical protective device operation times as well as duration divisions recommended by international technical organizations. Figure 4.3 shows the summary of the IEEE categorization.



ELECTROMAGNETIC COMPATIBILITY (EMC)

Part 2-8 : ENVIRONMENT -
Voltage dips and short interruptions on public electric power supply systems with statistical measurement results.

1 Scope

This technical report describes the electromagnetic disturbance phenomena of voltage dips and short interruptions in terms of their sources, effects, remedial measures, methods of measurement, and measurement results (in so far as these are available). They are discussed primarily as phenomena observed on the networks of public electricity supply systems and having an effect on electrical equipment receiving its energy supply from those systems.

Voltage sag is an alternative name for the phenomenon *voltage dip*.

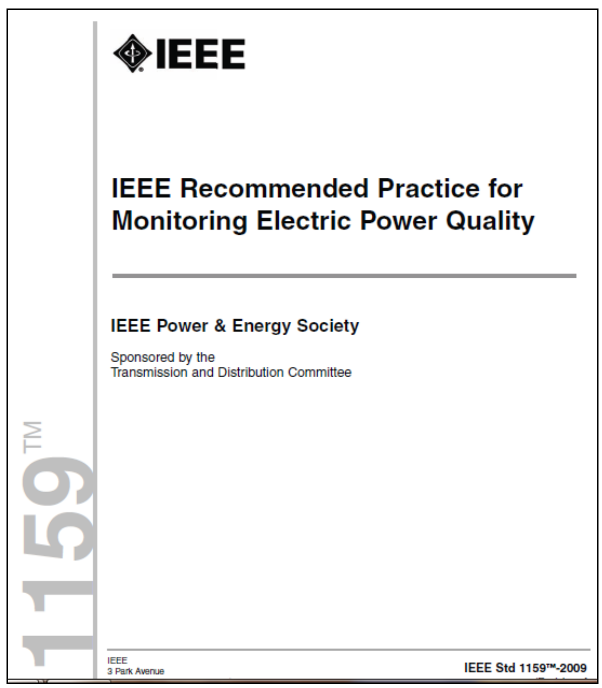
2 Definitions

2.1
voltage dip
voltage sag
a sudden reduction of the voltage at a particular point on an electricity supply system below a specified dip threshold followed by its recovery after a brief interval

Notes.

1 — Typically a dip is associated with the occurrence and termination of a short circuit or other extreme current increase on the system or installations connected to it.

2 — A voltage dip is a two dimensional electromagnetic disturbance, the level of which is determined by both voltage and time (duration).



IEC 61000-2-8 standard

IEEE 1159:2009 standard

Figure 4.2 Technical standards that define voltage sags (dips)

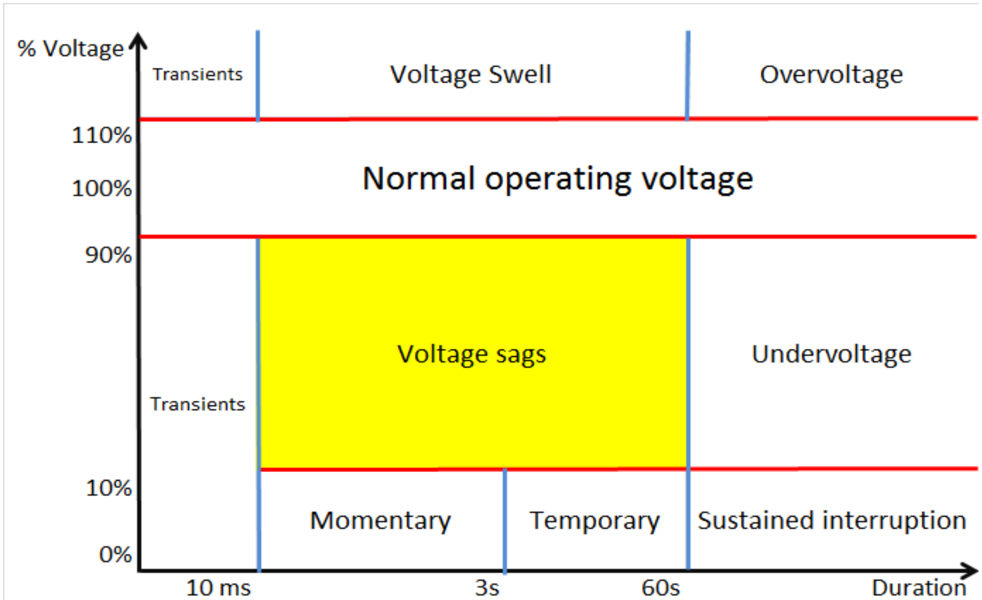
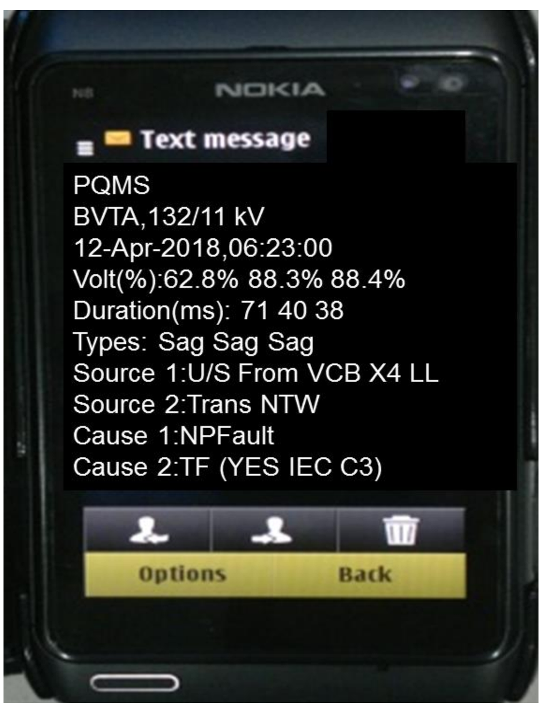


Figure 4.3 Definitions of voltage sags, swells & transients (IEEE 1159:2009)

4.1.1 Understanding the voltage sag information in TNB PQ SMS



Voltage sag (%):	62.8 %,	88.3%.	88.4 %
Duration (ms):	71	40	38
Types:	Sag	Sag	Sag

All the voltage sag values are less than 90 % from the nominal voltage (100%), and duration less than 60s.

Figure 4.4 Examples of SMS on voltage sags received from TNB.

Voltage sag (%):	88.5 %,	56.9%.	88.4 %
Duration (ms):	4	59	18
Types:	Sag	Sag	Sag

All the voltage sag values are less than 90 % from the nominal voltage (100%), and duration less than 60s.

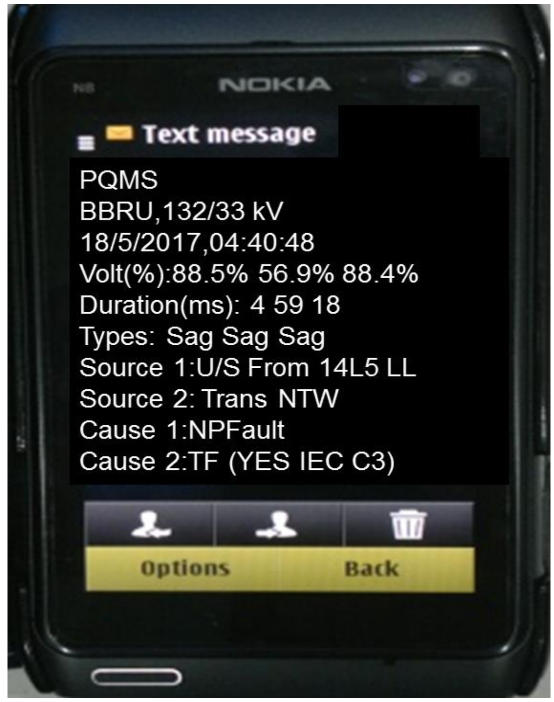


Figure 4.5 Examples of SMS on voltage sags received from TNB.

4.2 Difference between voltage sag and voltage dip

Voltage sags or dips which are the same thing are brief reductions in voltage, typically lasting from a cycle to a second or so, or tens of milliseconds to hundreds of milliseconds. The term voltage sag has been used in the power quality community for many years to describe a specific type of power quality disturbance - a short duration voltage decrease. The IEC definition for this phenomenon is voltage dip. The two terms are considered to be interchangeable. Generally, the term voltage sag is preferred in the United States of America (USA) and the term voltage dip is common in European countries.

Terminology used to describe the magnitude of voltage sag is often confusing. According to IEEE 1159-2009, the recommended usage is “a sag to 70%”, which means that the line voltage is reduced down to 70% of the normal value, not reduced by 70%. This preference is consistent with IEC practice, and with most disturbance analyzers that report remaining voltage. Just as an unspecified voltage designation is accepted to mean line-to-line potential, so an unspecified sag magnitude will refer to the remaining voltage. Where possible, the nominal or base voltage and the remaining voltage should be specified. A voltage dip of 70% will signify voltage reduced by 70% from the normal 100% voltage. The remaining voltage will be 30% or a sag to 30%. Figure 4.4 shows the difference between a normal voltage, voltage dip, voltage sag and voltage swell in simple graphic display.

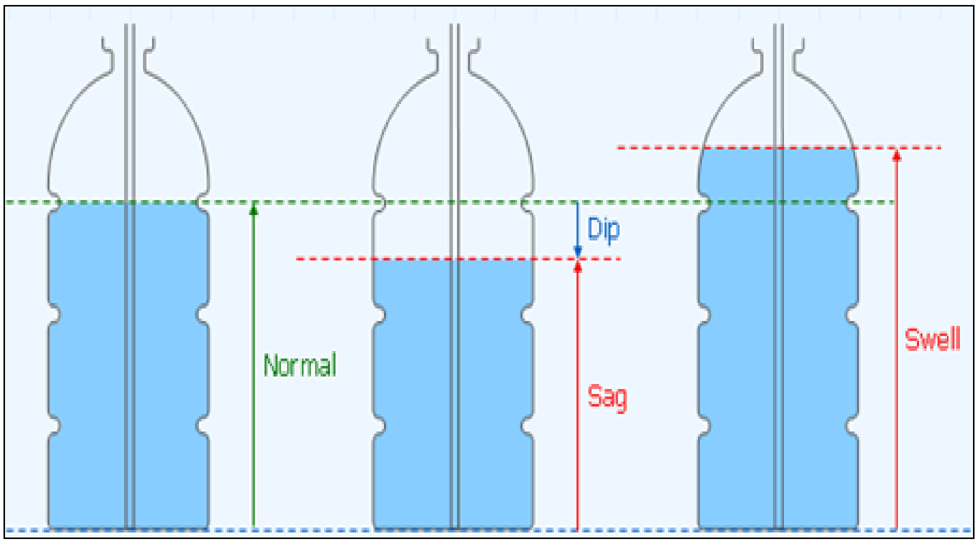


Figure 4.6 Graphic definitions of normal voltage, dip, sag and swell

4.3 Sources of voltage sags (dips)

Voltage sags are the most important power quality concerns for customers. Voltage sags are a reality in the electromagnetic environment. They can be expected at any place, at any time and at levels involving voltages down virtually to zero and durations up to and above one second. The frequency of their occurrence and the probability of their occurrence at any level are highly variable both from place to place and from one year to another.

Voltage sags have been an intrinsic feature of public electricity supply since the earliest times. Yet in recent decades they have become an increasingly troublesome disturbance, giving rise to inconvenience and even considerable economic loss. The reason is that some modern electricity utilisation equipment, either in its own design or because of control features incorporated in it, has become more sensitive to voltage sags.

Voltage sags are inevitable on the power system [11]. The most important of these variations occur during fault conditions on the power system. Since it is impossible to eliminate the occurrence of faults, there will always be voltage variations. This chapter will describe some of the concerns associated with short duration voltage sags. Voltage swells can also be associated with fault conditions but these short duration overvoltages are usually not severe and problems are uncommon.

The primary source of voltage sags observed on the public network is the electrical short circuit occurring at any point on the electricity supply system. The short circuit causes a very large increase in the fault current and this, in turn, gives rise to large voltage drops in the impedances of the supply system. Short circuit faults are an unavoidable occurrence on electricity systems. They have many causes, but basically they involve a breakdown in the dielectric between two structures which are intended to be insulated from each other and which normally are maintained at different potentials.
Example for a voltage sag due to a downstream fault current is shown in Figure 4.5

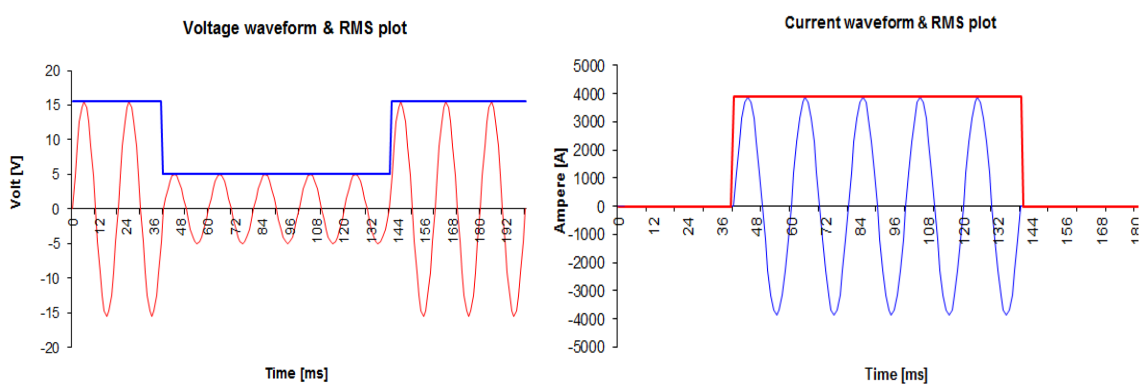


Figure 4.7 Downstream fault current causes voltage sag in the network

Many short circuits are also caused by overvoltages, which stress the insulation beyond its capacity. Atmospheric lightning is a notable cause of such overvoltages. Alternatively, the insulation can be weakened, damaged or bridged as a result of other weather effects, by the impact or contact of animals, vehicles, excavating equipment, etc., and as a result of deterioration with age.

At the point of the short circuit, the voltage effectively collapses near to zero. Simultaneously, at almost every other point on the system the voltage is reduced to the same or, more generally, a lesser extent. Supply systems are equipped with protective devices to disconnect the short circuit from the source of energy. As soon as that disconnection takes place, there is an immediate recovery of the voltage, approximately to its previous value, at every point except those disconnected. Some faults are self-clearing: the short circuit disappears and the voltage recovers before disconnection can take place.

The sudden reduction of voltage, followed by voltage recovery, as just described, is the phenomenon known as voltage sag. The switching of large loads, the starting of large motors and the fluctuations of great magnitude that are characteristic of some loads can all produce large changes in current similar in effect to a short circuit current. Although the effect is generally less severe at the point of occurrence, the resulting changes in voltage observed at certain locations can be indistinguishable from those arising from short circuits. In that case they also are categorised as voltage sags.

Examples of causes of voltage sags are shown in Figure 4.8 to Figure 4.16.

Conductor damaged due to a kite

Road work damaged underground cable

Figure 4.8 Examples of causes of voltage sags due to external events (1)

Forest/Bush fire

Crane encroachment

Figure 4.9 Examples of causes of voltage sags due to external events (2)

Crane encroachment

Metal thefts at transmission towers

Figure 4.10 Examples of causes of voltage sags due to external events (3)

Copper theft in distribution substation

Lightning

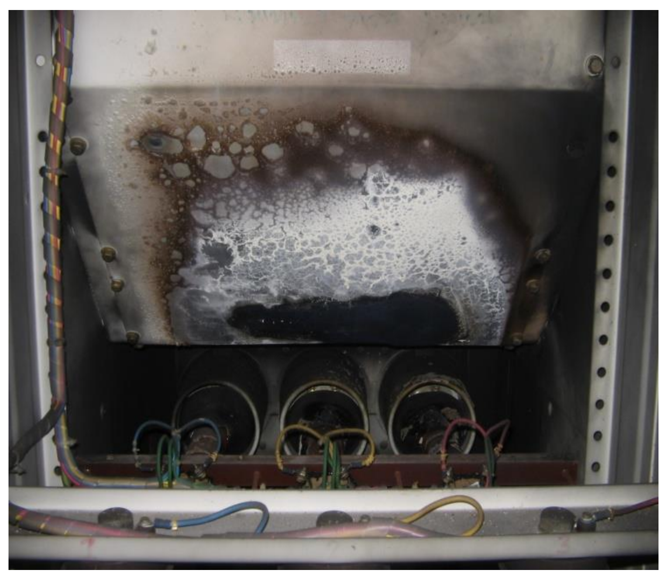
Figure 4.11 Examples of causes of voltage sags due to external disturbances (4)

Transformer short circuited

Cable fault at customer's installations

Figure 4.12 Causes of voltage sags due to equipment failure at customers' premises (1)

Flashover in switchgear



Flashover in switchgear

Figure 4.13 Causes of voltage sags due to equipment failure at customers' premises (2)

Flashover in switchgear

Flashover in switchgear

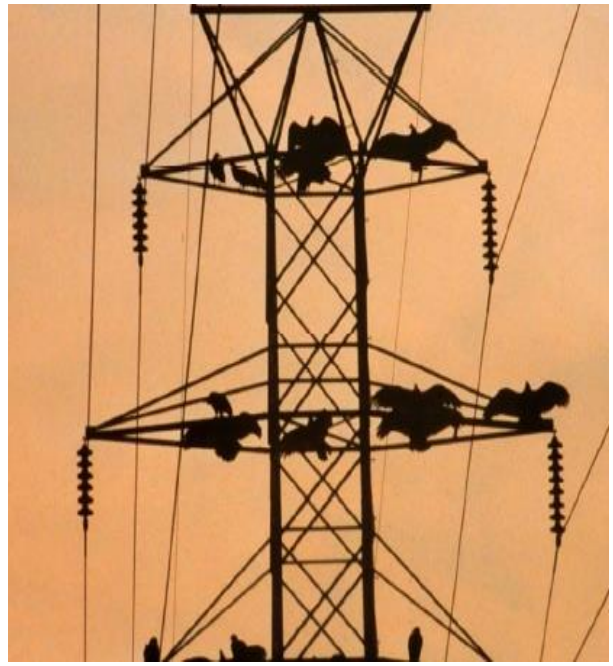
Figure 4.14 Causes of voltage sags due to equipment failure at customers' premises (3)

Birds on power lines

Monkeys on power lines

Figure 4.15 Causes of voltage sags due to animal encroachment (1)

Snake on transmission tower



Birds on power lines

Figure 4.16 Causes of voltage sags due to animal encroachment (2)

4.4 Classification of voltage sags

There are two common classification methods for voltage sags:

- Classification using a voltage sags magnitude and duration (ms)
- Professor Math Bollen’s classification .i.e. ABC classification. [12]

According to IEC-61000-4-30 [13], a voltage sag event is characterized by its magnitude, which is the lowest rms voltage during the event, and its duration, which is the time that the rms voltage stays below the threshold. Thus, the sag magnitude is the retained voltage during the voltage sag. The voltage sag duration depends on the fault clearing time. As the rms value of the voltage cannot change sharply, it is necessary to set a threshold, below which the duration starts to be measured. The voltage sag duration stops when the rms value is above the threshold again.

Voltage sag types are generally based on the individual voltages (both magnitude and angle) for each of the three phases during sags or dips [12]. Usually, three-phase voltage sags are categorized by either the ABC classification or the symmetrical components classification. However, voltage sag type according to the ABC classification is frequently used due to its simplicity as it is based on a simplified network model. Consequently, the classification is based on incomplete assumptions and cannot be used to obtain the characteristics of measured sags. The symmetrical component classification is more general and gives a direct link with measured voltages but is harder to understand and a translation to the ABC classification may be suitable for many applications. In addition, the ABC classification was developed to analyze the propagation of sag or dip from transmission to distribution levels, when a disturbance propagates through a transformer. Table 4.1 & Figure 4.17 give brief overviews of the different types of voltage sags, associated faults and waveforms.

Table 4.1 Different sag types and their associated faults

Type of voltage sag	Type of fault
Type A	Three-phase
Type B	Single-phase to ground
Type C	Phase to phase
Type D	Phase-to-phase fault (experienced by a delta connected load), single-phase to ground (zero sequence component removed)
Type E	Two-phase-to-phase fault (experienced by a Wye connected load)
Type F	Two-phase-to-phase fault (experienced by a delta connected load)
Type G	Two-phase to phase fault (experienced by a load connected via a non-grounded transformer removing the zero sequence component)

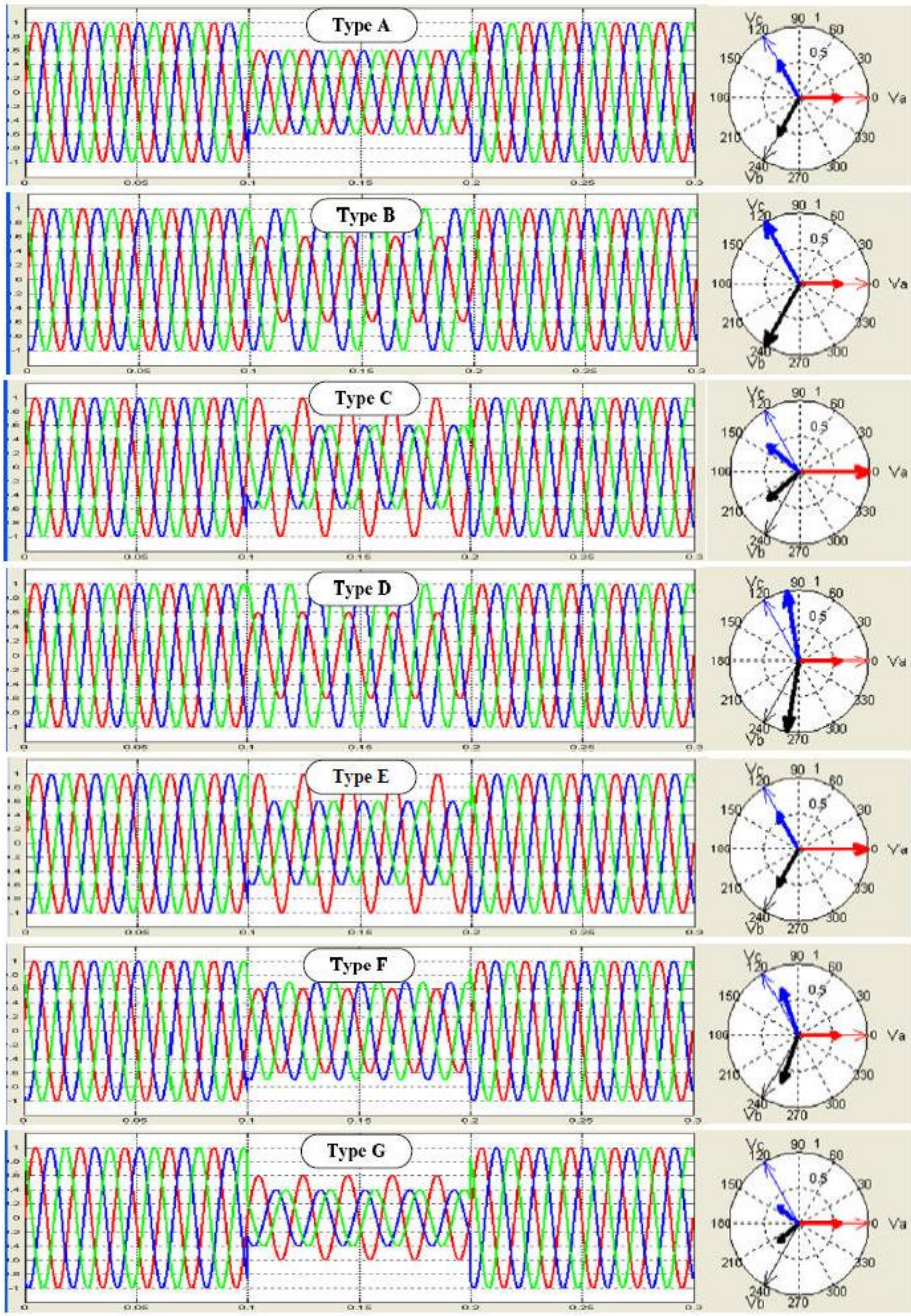


Figure 4.17 Voltage Sag Types - ABC Classification

Note: Before fault (single line) and during fault (solid line).

4.4.1 Factors that affect voltage sag type [14]

Specifically, at the equipment terminals, these factors affect the voltage sag type:

- Fault type

Voltage sags are primarily caused by system faults. Each fault type has a different effect to the voltages at the fault point, which subsequently defined the voltage sag types.

  - Single-Line-to-Ground Fault
  - Line-to-Line Fault
  - Double-Line-to-Ground Fault
  - Three Phase Fault

- Transformer Winding Connection

Transformer winding connections are classified into three types to explain the transfer of three-phase unbalanced voltage sags, as well as the change in voltage sag type, from one voltage level to another.

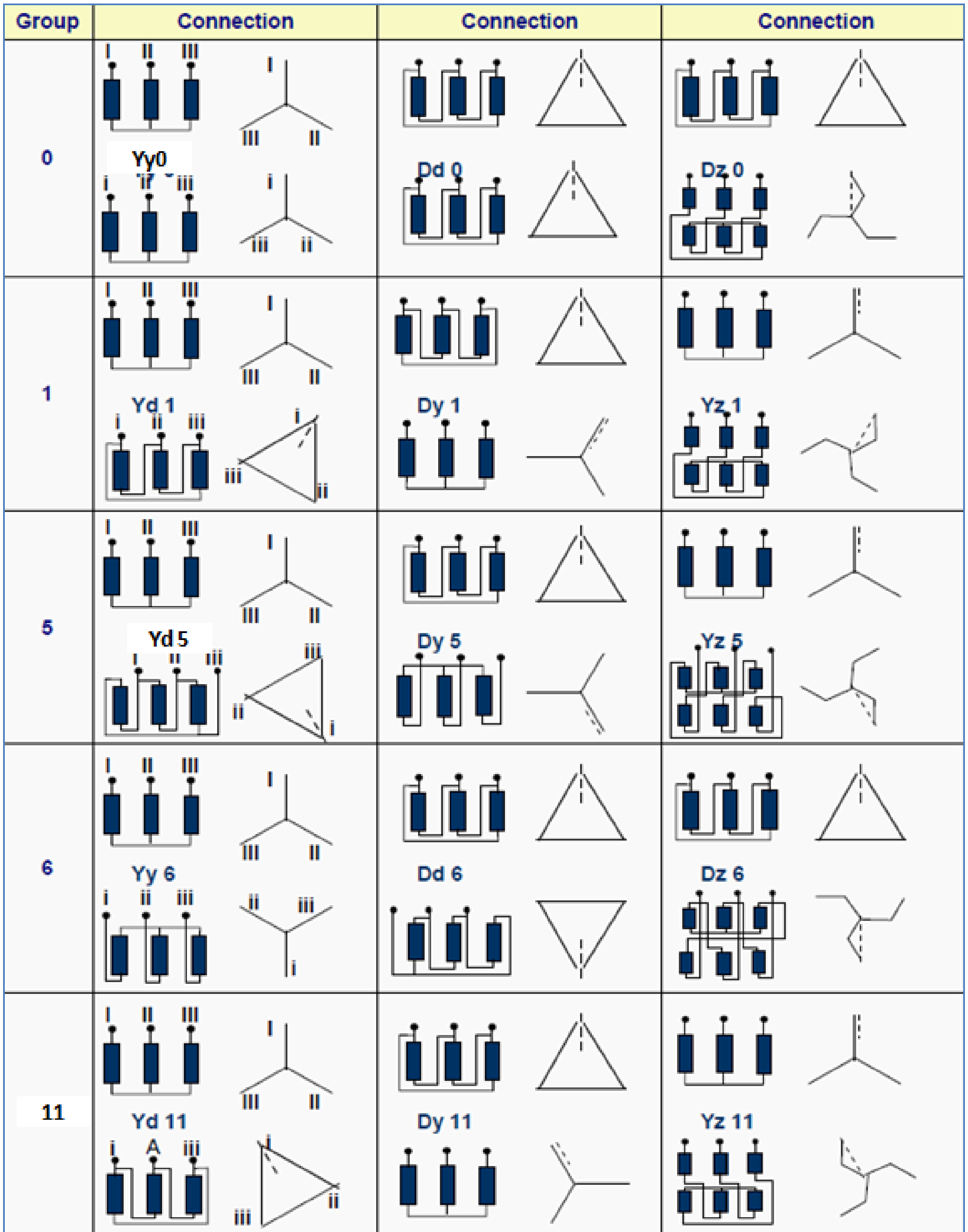
- Type 1 – Transformers that do not change anything to the voltages. The primary voltages (per unit) are equal to the secondary (per unit) voltages. The only transformer configuration that falls under this type is the WYE Grounded-wye grounded (YNyn).

- Type 2 – Transformers that remove the zero-sequence voltage. Basically, the secondary voltage (per unit) is equal to the primary voltage (per unit) minus the zero-sequence component. The DELTA-delta (Dd), DELTA-zigzag (Dz) and the WYE-wye (with both windings ungrounded or with only one star point grounded) belong to this type.

- Type 3 – Transformers that changes line and phase voltages. DELTA-wye (Dyn), WYE-delta (YNd) and the WYE-zigzag (YNz) fit under this type.

Details on transformers vector groups are shown in Table 4.2

Table 4.2 Common transformer connections and vector groups [15].



The table is formed based on IEC 60076 and the idea that the winding directions of the HV and LV windings are same

- Types of Load Connection
    - Wye-connected load
    - Delta-connected load

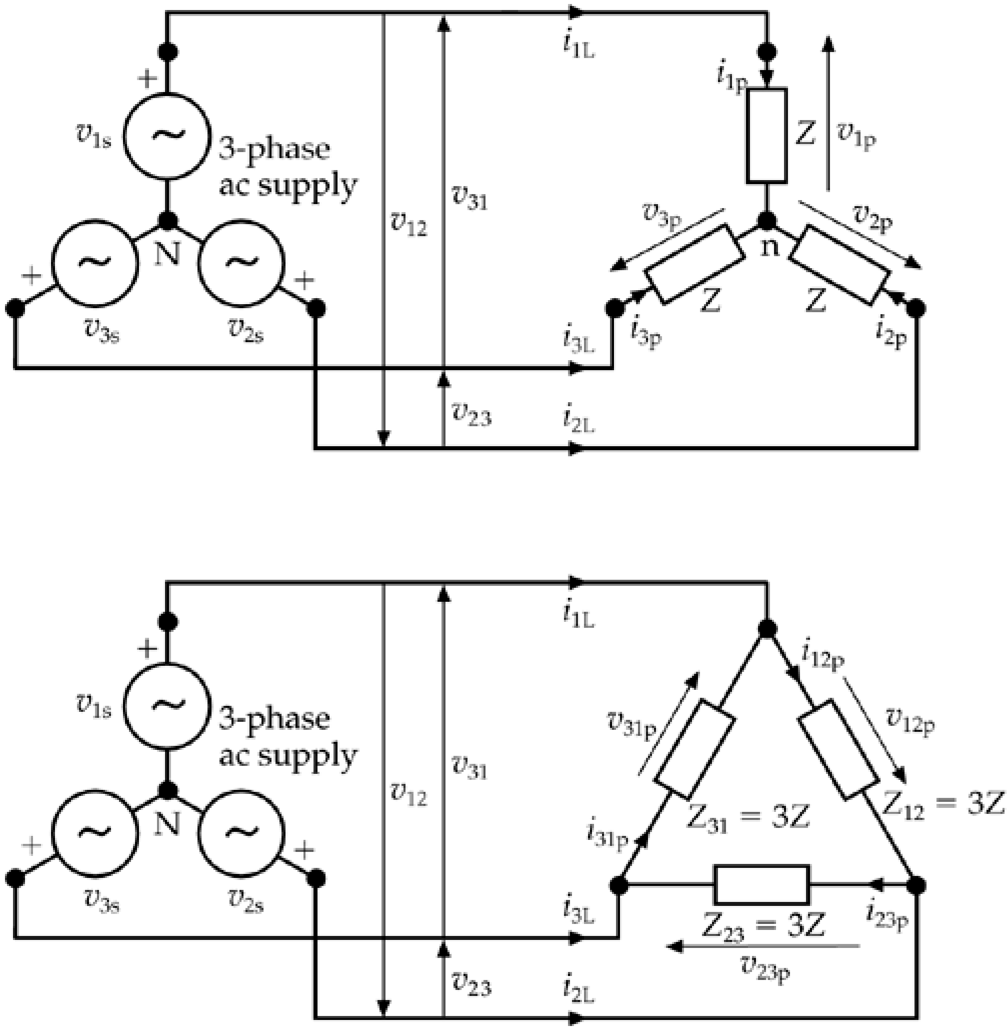


Figure 4.18 Star & Delta connections of three phase loads

4.5 Propagation of voltage sags.

The observed voltage sag magnitude arising from a particular causative event depends on whether the observation point and the event are on the same or different sides of a network or customer transformer. The phasing of the short circuit or other event, the phasing of the measurement system, and the connection methods of the primary and secondary transformer windings are all significant in this regard. For instance, considering the network or installations on either side of a step down transformer connected Dyn, a single line to ground fault can result, on the primary side, in a voltage dip of 0 V (residual voltage) on one phase, but, on the secondary side, a line to neutral voltage on two phases of 58% of the pre-existing voltage [10].

In practice, loads that are sensitive to voltage sags are often connected line-to-line in industrial installations. They would therefore be subjected to line-to-line voltage dips rather than line-to-neutral dips. This needs to be taken into account in considering whether measurements are conducted line-to-neutral, line to-line, or both.

Overall, the types of voltage sags and the transformation to lower voltage levels, for all seven types of three-phase unbalanced sags, are summarized in Tables 4.3 and 4.4.

Table 4.3 Transformation of voltage sag type to lower voltage level (after transformer)

Connection	Sag on primary side						
	Type A	Type B	Type C	Type D	Type E	Type F	Type G
Ynyn	A	B	C	D	E	F	G
Yy, Dd, Dz	A	D	C	D	G	F	G
Yd, Dy, Yz	A	C	D	C	F	G	F

Table 4.4 Transformation of voltage sag type to lower voltage level (Load connection)

Fault Type	Load Connection	
	Star	Delta
Three phase	A	A
Two phase to ground	E	F
Phase to phase	C	D
Single phase	B	C

4.6 Impact of voltage sags to industrial equipment

Today’s factory floors usually include a proliferation of sensitive electronics, such as programmable logic controllers (PLCs), variable-frequency drives (VFDs), and network communications devices, all of which have led to tremendous gains in productivity. Ironically, however, many of these same electronic devices also contribute to productivity losses because of their sensitivity to voltage sags, swells, and transients.

These electronic equipments, which are now so integral to industrial and commercial power systems, can fail or malfunction if subjected to a voltage, current, or frequency deviation. Before the era of solid-state electronics, power quality was not discussed because it had little or no effect on most loads connected to electrical distribution systems. When an induction motor suffered a voltage sag, it did not shut itself down but simply "spun out" fewer horsepower until the sag ended. The same was true for incandescent or fluorescent lighting systems in a facility-the lumen output just decreased temporarily.

The most common failure mechanism is lack of energy. This can manifest itself in something as simple as insufficient voltage to keep a critical relay or contactor energized or something as complex as an electronic sensor with a failing power supply giving an incorrect reading, which would cause essential equipment to react inappropriately.

But today, as sensitive equipment and processes become more complex and downtime costs increase, contractors and engineers have to specify and install specialized equipment to avoid undesirable situations. The ideal power-supply voltage for sensitive electronic equipment is an uninterrupted sinusoidal waveform of constant amplitude. Any event that compromises this condition is called a power quality disturbance. Power quality disturbances as brief as one-half cycle can affect the operation of sensitive electronic equipment.

4.6.1 Impact of voltage sags to electronic equipment

Electronic devices require a more controlled electrical environment than most other loads. This is especially true when it comes to the input voltage. If the voltage of the power supply varies beyond the specifications of the device, then problems can occur.

Recall that a voltage sag is not simply a change in the rms magnitude, but a change over a discrete period of time. This time interval is important in terms of determining acceptable voltage. The fundamental issue behind the symptoms related to voltage sags is how much energy is being transferred into the power supply. If inadequate energy is going into the power supply due to voltage sag, then the dc voltage applied to the integrated circuits drops. If this happens, the device will shut down, lock up, or garble data. If the device shuts down, it will usually restart as soon as enough energy gets back into the supply. On the other hand, if too much energy goes into the supply because of a voltage swell, it will probably cause damage. Blown power supplies are the most common result of large swells. Obviously, if the power supply fails then the whole device goes down.

Figure 4.19 Common electronic equipment in office

4.6.2 Sensitive equipment in industrial plants

Voltage sags and swells give severe impact to the industrial customer's equipment. Truly severe swells may stress components to the point of failure, but other than that there is seldom disruption or damage. Problems may arise as the system responds to the reaction of the load to the sag or swell. It is possible that if a sag or swell is extreme enough and lasts long enough, the resultant over current could trip breakers, blow fuses or damage the electronic components.

Sensitivity of adjustable speed drives (ASDs) to voltage sags is usually expressed as a voltage tolerance curve, in terms of only one pair of sag magnitude/duration values. These two values are denoted as the threshold values – if the voltage sag is longer than the specific duration threshold and deeper than the specific voltage magnitude threshold, the ASD will malfunction/trip. For ASDs, reported threshold values vary from 50-60% to 80-90% of rated voltage for magnitude and from 1/2 cycle (or even less) up to 5-6 cycles for the duration [16].

4.6.3 Impact of voltage sags to motors

Motors are extremely tolerant to voltage sags and voltage swells. Unless the rms magnitudes are either very low or very high, motors typically have little response to these voltage variations. Keep in mind that if the motors are controlled by electronic drive controllers, the discussion on electronic equipment applies. If the magnitudes are extreme, or if these disturbances occur frequently, then several symptoms may develop. First, extreme swells will electrically stress the windings on the stator. This leads to premature motor failure. Second, extreme sags may cause the motor to lose enough rotational inertia to affect its performance or task. Third and last, if sags happen frequently enough, the motor may draw high inrush currents often enough to trip a breaker.

4.6.4 Impact of voltage sags to lighting systems

Most lighting systems are tolerant of voltage sags and voltage swells. Incandescent systems will simply burn brighter or dimmer. Overall life expectancy may be affected, and the change in brightness may be annoying, but no other adverse reactions usually occur. This change in brightness is often called "flicker."

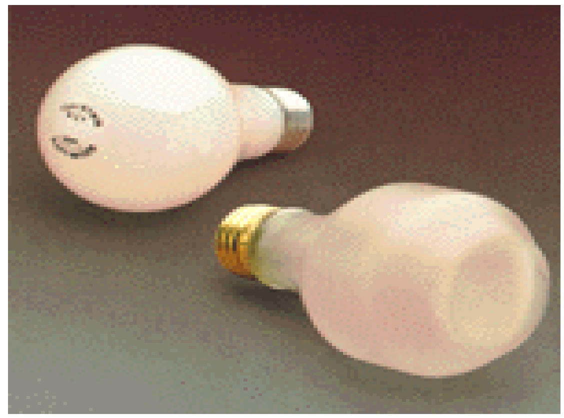


Figure 4.20 General lighting facilities

Fluorescent systems may not fare quite as well. Standard ballasts are typically more tolerant than electronic ballasts. In both cases there may be some flicker, but the real concerns are with restarts and reliability. If voltage sags are deep enough, then the ballast will no longer be able to provide the energy needed to generate the arc inside the fluorescent tube. This means a dark lamp. If swells are extreme, then the ballast is stressed, causing premature failure.

High intensity discharge, or HID lighting such as mercury vapor, metal halide, and high and low pressure sodium lights are also more sensitive to sags and swells. While their response is very similar to electronic fluorescent ballasts, the lamps themselves are typically more sensitive than the ballasts. A common problem is HID systems turning off during voltage sag. Sodium discharge lamps have a much higher striking voltage when hot than cold, so that a hot lamp may not restart after a dip. Unlike fluorescent systems that will quickly turn back on, the HID system must wait several minutes (10-15 minutes) before being restarted. This is not only annoying but can be dangerous.

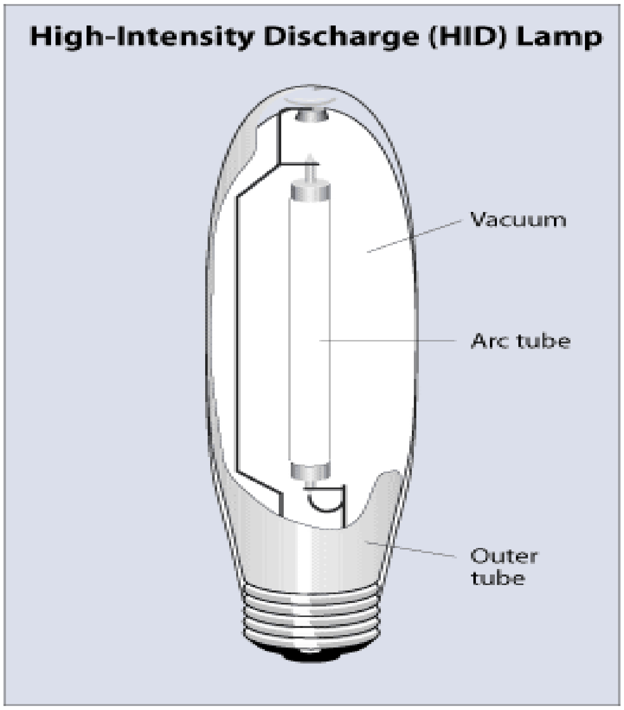


Figure 4.21 High intensity discharge lamps

4.7 Understanding Level of Equipment Sensitivity to Voltage Sags

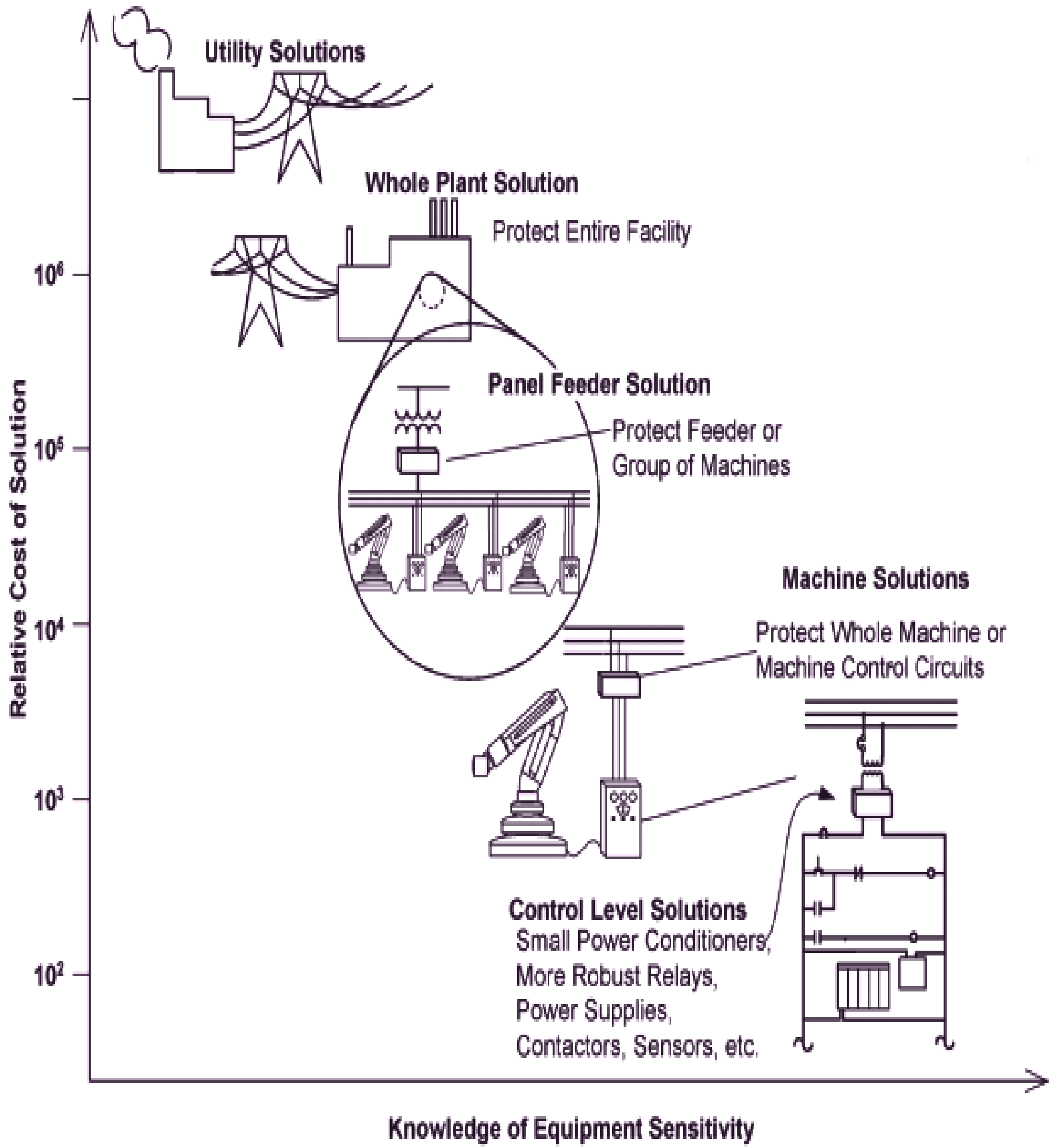


Figure 4.22 Levels of equipment sensitivity & cost of solutions [17]

Note: The diagram in Figure 4.22 is taken from training document from Electric Power Research Institute (EPRI) USA. The author of the document was Mr. Mark Stephens from EPRI. The link to access the document can be referred to reference [17].

4.7.1 Understanding control level sensitivity to voltage sag

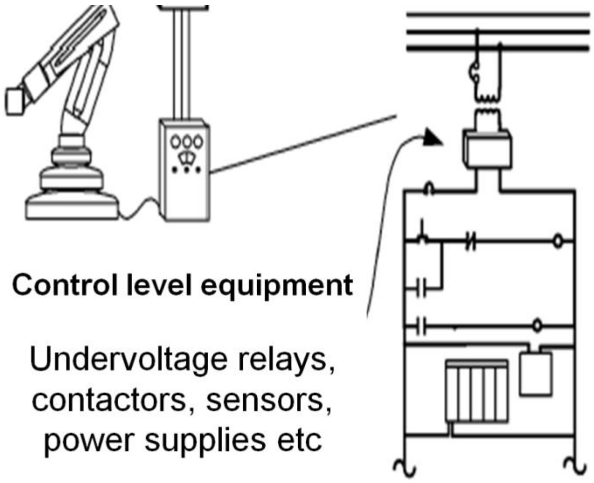


Figure 4.23 General control level equipment & solutions

As with all disturbance phenomena, the gravity of the effects of voltage sags and short interruptions depends not only on the direct effects on the equipment concerned, but also on how important and critical is the function carried out by that equipment. For example, modern manufacturing methods often involve complex continuous processes utilizing many devices acting together.

A failure or removal from service of any one device, in response to a voltage sag or short interruption can necessitate stopping the entire process, with the consequence of loss of product and damage or serious fouling of equipment. This can be one of the most serious and expensive consequences of voltage sags and short interruptions. Such consequential damage or loss, however, is a function of the design of the process and is an indirect or secondary effect of the voltage dip or short interruption.

Process machines comprised of common electrical components used in all types of processes. Since fundamental control components are used in every type of equipment, a basic understanding of their response to voltage sags can help designer build and service a more reliable machine. The basic control level equipment components normally used in industrial plants are:-

- Relays (Undervoltage, Overvoltage etc).
- AC contactors
- DC power supplies
- Controllers (Programmable logic control etc)
- Motor drives (AC, DC & Servo)
- Sensors
- Computers

EMC considerations are concerned with the direct effects on the performance of the actual appliances drawing an energy supply from the electricity network.

4.7.1.1 Understanding UnderVoltage Relay (UVR)

Figure 4.24 Example of relays for undervoltage and overvoltage with time delay

An option that is sometimes implemented in either the design or installation of the equipment is to incorporate a protective device for the purpose of interrupting the supply in the event of the voltage falling below a set threshold, thereby preventing damage or other unwanted effects in conditions of reduced voltage. This is a general function of an undervoltage relay schemes (UVR).

Such protection (UVR) can have the effect of converting voltage sag into a long interruption for the equipment concerned. The long interruption is not caused by the voltage sag, but is the intended result of a protective feature that is designed to respond in that way to reduced voltage. Careful system designers may include the UVR to monitors the ac power system for adequate voltage. But "adequate voltage" may not be well defined, or understood. For example, if the sensitive system is running at half load, it may be able to operate at only 70% ac voltage, even though it may be specified to operate with 90% - 110% ac voltage. When the voltage sags to 70%; the equipment can operate without a problem; but the under voltage monitor may decide to shut the system down.

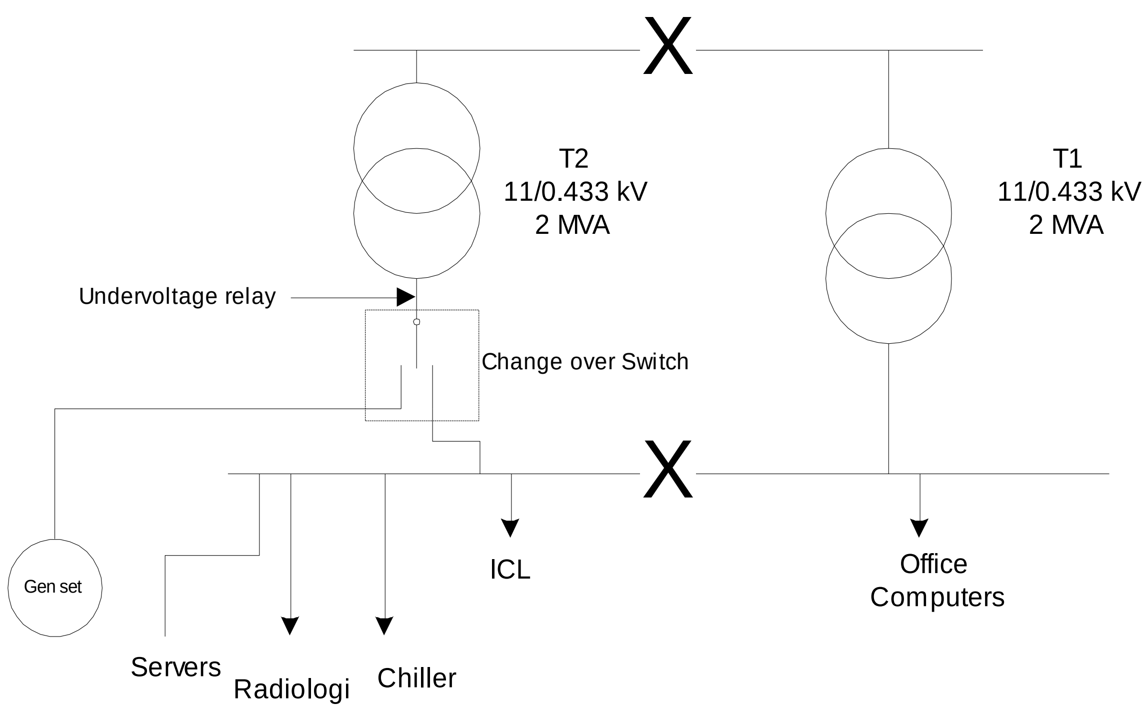


Figure 4.25 Common locations for under voltage relay (UVR)

4.7.1.2 Understanding contactors

A contactor is another name for an electrical relay. It is a device that allows a low current (normal) switch to turn on or off high current equipment such as heaters or air-conditioners that would be well beyond its capacity. Contactors are used extensively to control large loads in an industrial plant. Contactors typically have multiple contacts, and those contacts are usually (but not always) normally open, so that power to the load is shut off when the coil is de-energized. The most common industrial use for contactors is the control of electric motors.

Figures 4.26, 4.27 & 4.28 show a typical contactor application.

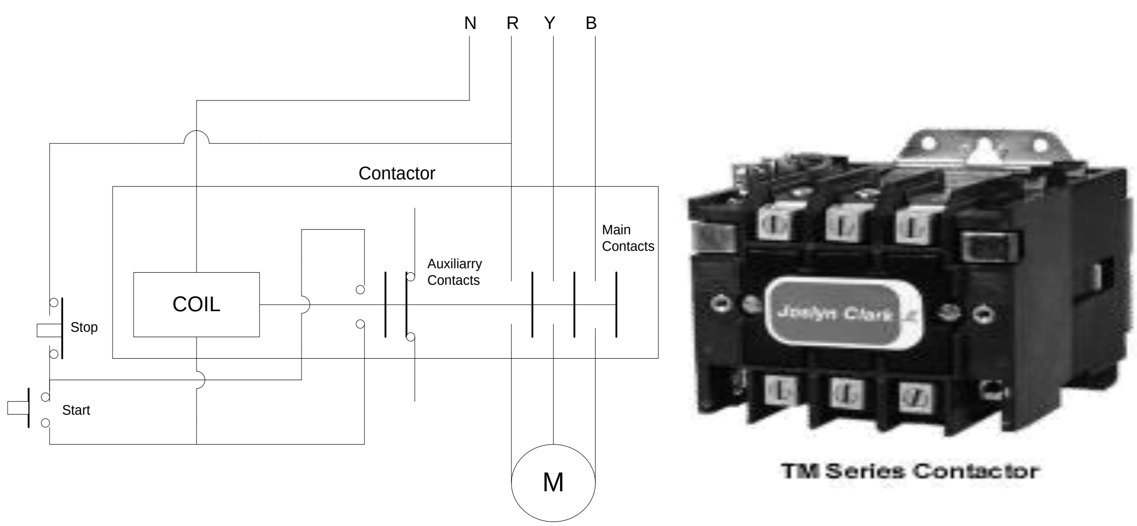


Figure 4.26 A common contactor

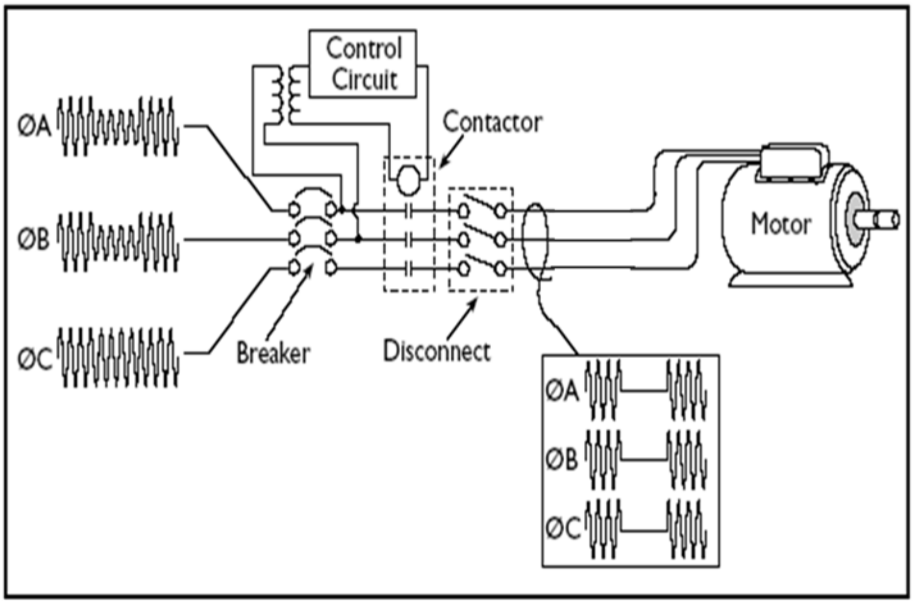


Figure 4.27 General circuit for control circuit & contactor (1)

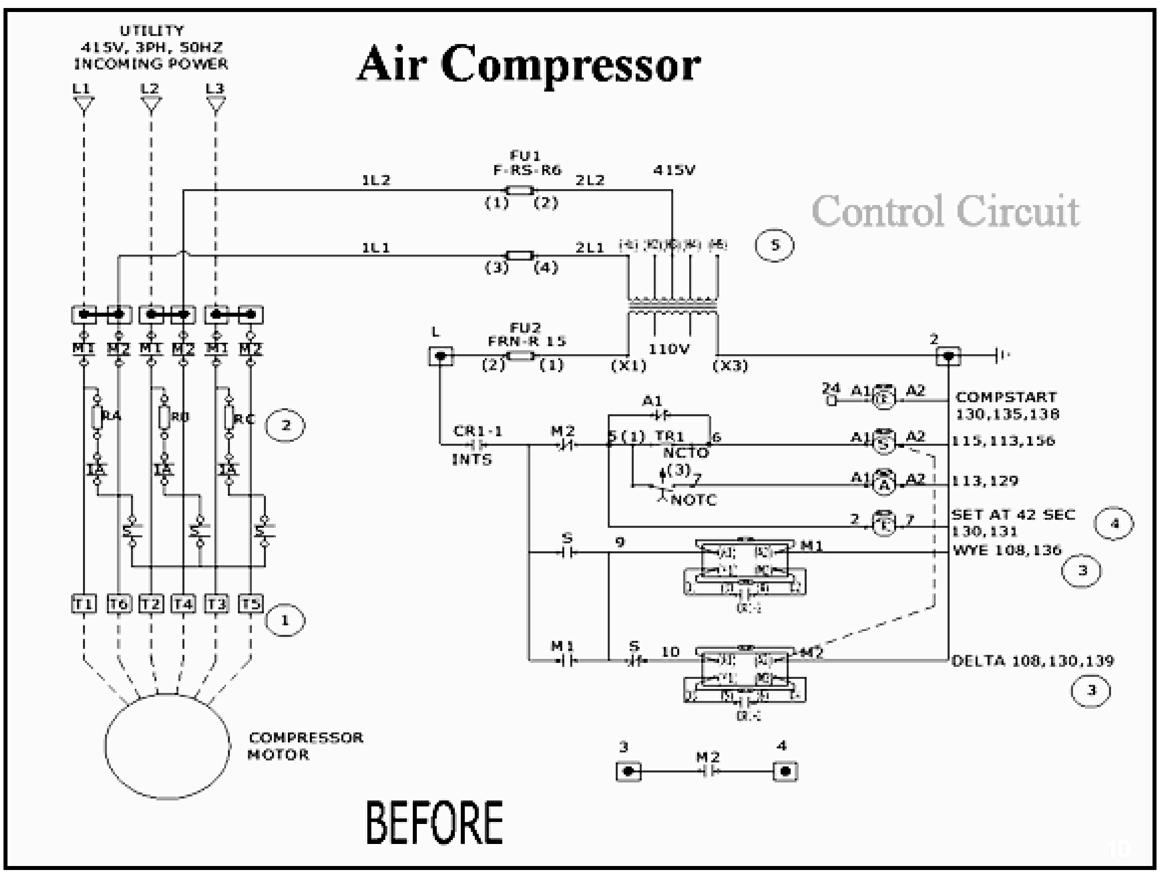


Figure 4.28 General circuit for control circuit & contactor (2)

4.7.1.3 Understanding other sensitive electronic control system/equipment

Electronic equipment, which is now so integral to industrial and commercial power systems, can fail or malfunction if subjected to a voltage, current, or frequency deviation. Electronic devices require a more controlled electrical environment than most other loads. This is especially true when it comes to the input voltage. If the voltage of the power supply varies beyond the specifications of the device, then problems can occur.

Recall that a voltage sag is not simply a change in the rms magnitude, but a change over a discrete period of time. This time interval is important in terms of determining acceptable voltage. The fundamental issue behind the symptoms related to voltage sags is how much energy is being transferred into the power supply. If inadequate energy is going into the power supply due to voltage sag, then the dc voltage applied to the integrated circuits drops.

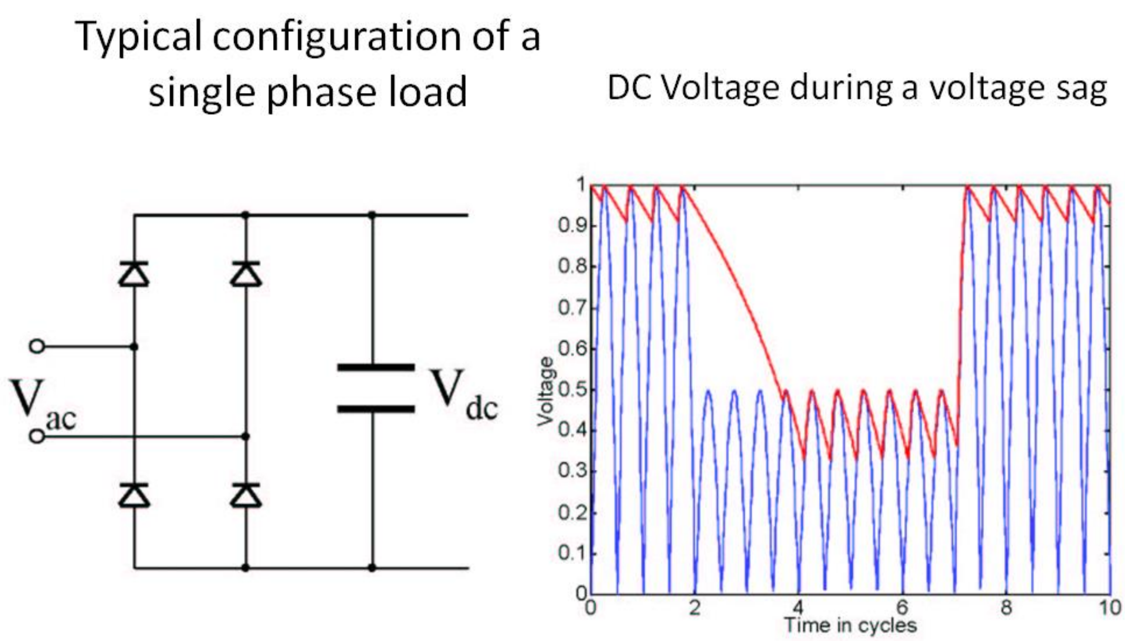


Figure 4.29 The resultant dc voltage during a voltage sag event

If this happens, the device will shut down, lock up, or garble data. If the device shuts down, it will usually restart as soon as enough energy gets back into the supply.

4.7.1.4 Equipment fails because an unbalance relay trip.

On three-phase systems, voltage sags are often asymmetrical (they affect one or two phases more than the remaining phases). Three-phase motors and transformers can be damaged by sustained voltage unbalance; it can cause the transformer or motor to overheat. So it makes sense to put in an unbalance relay, which is a device that shuts down the system if the voltage unbalance exceeds some threshold, typically a few percent. But a voltage sag that causes 20-50% unbalance for a second or two is never going to cause a motor or transformer to overheat. It just doesn't last long enough. Still, unbalance relays with inadequate delays can cause the sensitive system to shut down, even for a brief voltage sag event.

Figure 4.30 Example of unbalance relays

4.7.1.5 A quick-acting relay shuts the system down

The EMO (emergency off) circuit in an industrial load typically consists of a normally closed switch that can disconnect power to a latched relay coil. If the relay operates quickly enough, it may interpret a brief voltage sag as an operator hitting the EMO switch. The whole system will shut down unnecessarily.

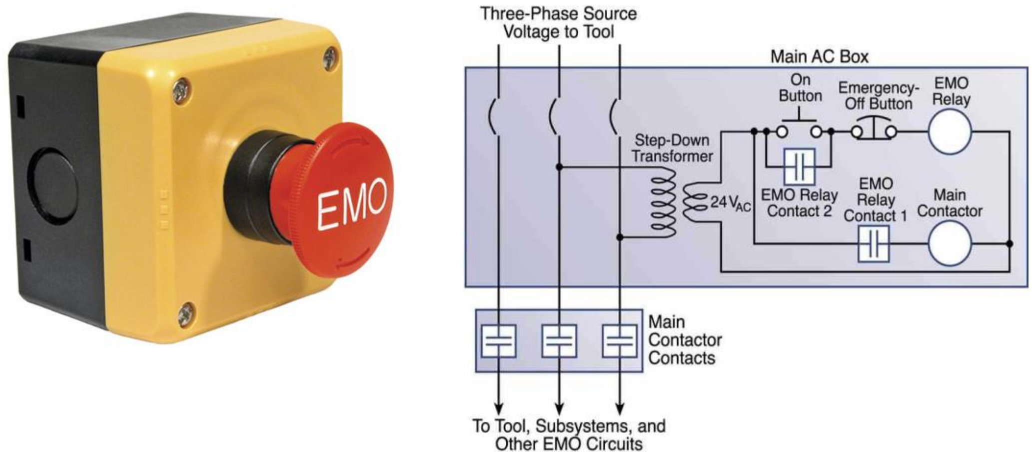


Figure 4.31 Example for EMO system

4.8 Example of diagrams for control circuits for 3-phase equipment

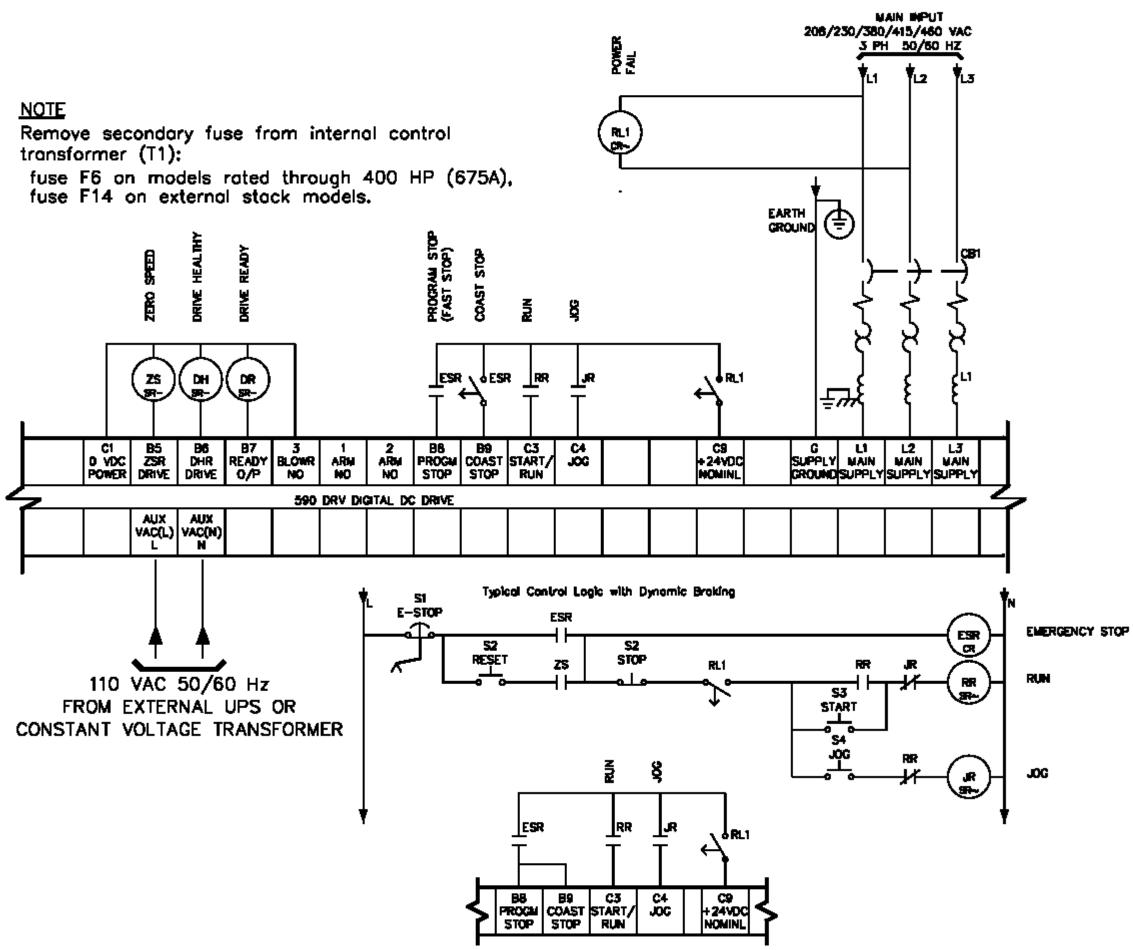
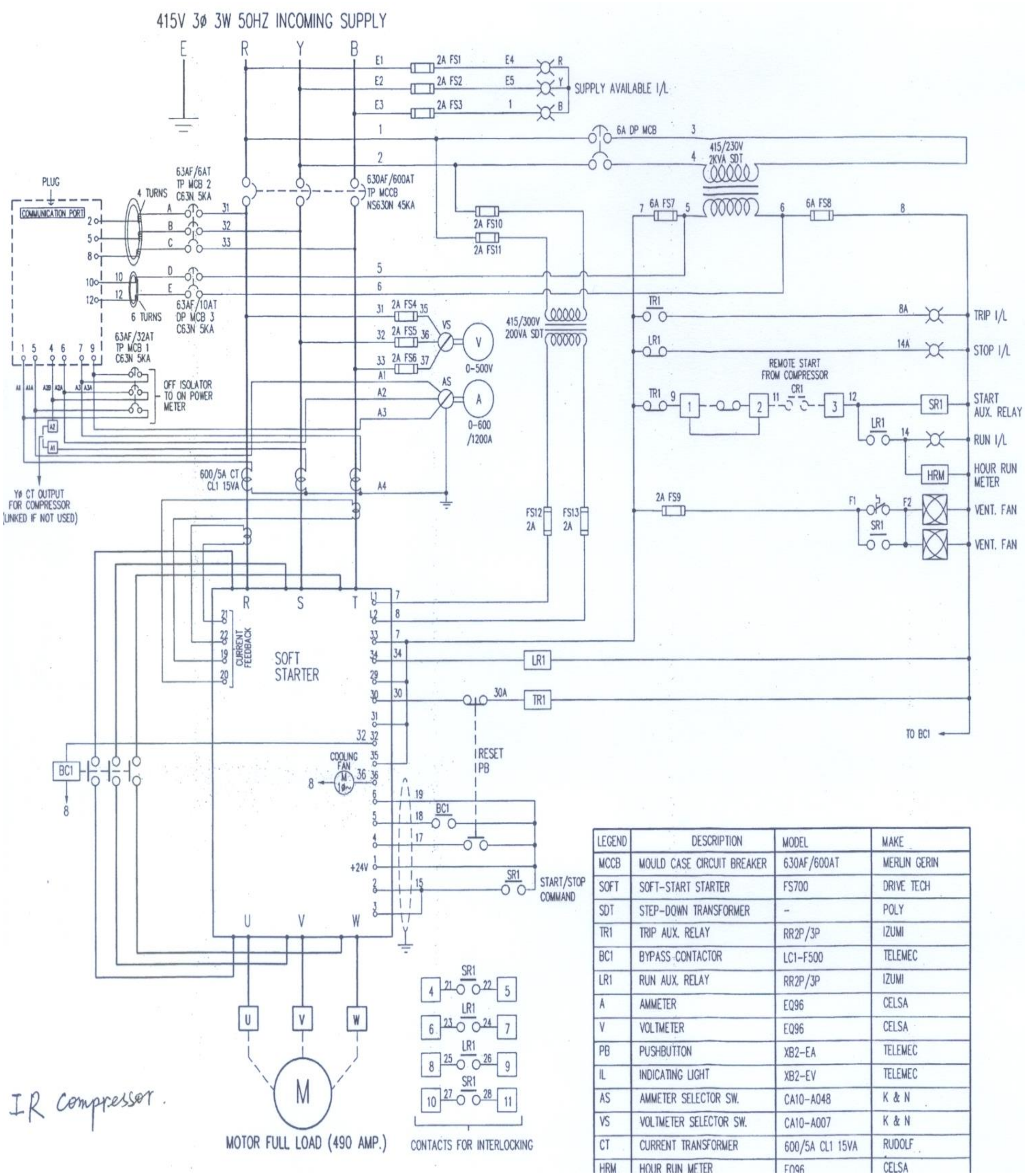


Figure 4.32 Control power to a 590 Drive for Power Loss Ride Through

Examples of typical diagrams for control circuits for compressor and chillers are shown in Figure 4.33 & 4.34.



LEGEND	DESCRIPTION	MODEL	MAKE
MCCB	MOULD CASE CIRCUIT BREAKER	630AF/600AT	MERLIN GERIN
SOFT	SOFT-START STARTER	FS700	DRIVE TECH
SDT	STEP-DOWN TRANSFORMER	-	POLY
TR1	TRIP AUX. RELAY	RR2P/3P	IZUMI
BC1	BYPASS CONTACTOR	LC1-F500	TELEMEC
LR1	RUN AUX. RELAY	RR2P/3P	IZUMI
A	AMMETER	EQ96	CELSA
V	VOLTMETER	EQ96	CELSA
PB	PUSHBUTTON	XB2-EA	TELEMEC
IL	INDICATING LIGHT	XB2-EV	TELEMEC
AS	AMMETER SELECTOR SW.	CA10-A048	K & N
VS	VOLTMETER SELECTOR SW.	CA10-A007	K & N
CT	CURRENT TRANSFORMER	600/5A CL1 15VA	RUDOLF
HRM	HOUR RUN METER	EQ96	CELSA

Figure 4.33 Diagrams for control circuits for compressor

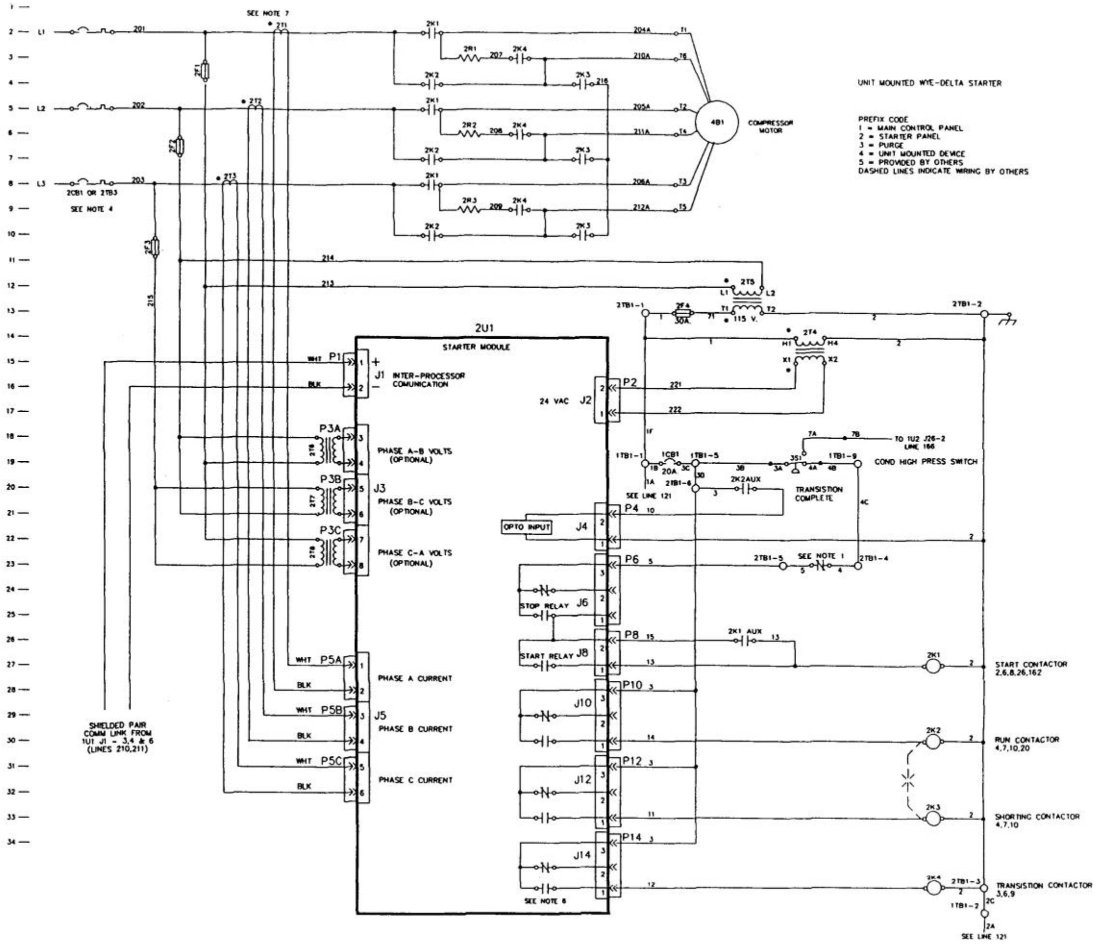


Figure 4.34 Diagrams for control circuits for chillers

CHAPTER 5

MONITORING VOLTAGE SAGS

5.1 INTRODUCTION

Electricity at the wall outlet is an electromagnetic phenomenon. Electrical power is provided as alternating current (ac), a silent, seemingly limitless source of energy that can be generated at power stations, boosted by transformers, and delivered over hundreds of miles to any location in the region. Seeing what this energy is doing in small slices of time can provide an understanding of how important simple, smooth ac power is to reliable operation of the sophisticated systems that we are dependent upon.

An oscilloscope allows one to see what this energy looks like. In a perfect world, commercial ac power appears as a smooth, symmetrical sine wave, varying at either 50 or 60 cycles every second (Hz) depending on which part of the world you're in. Figure 5.1 shows what an ac voltage sine wave would appear in an oscilloscope.

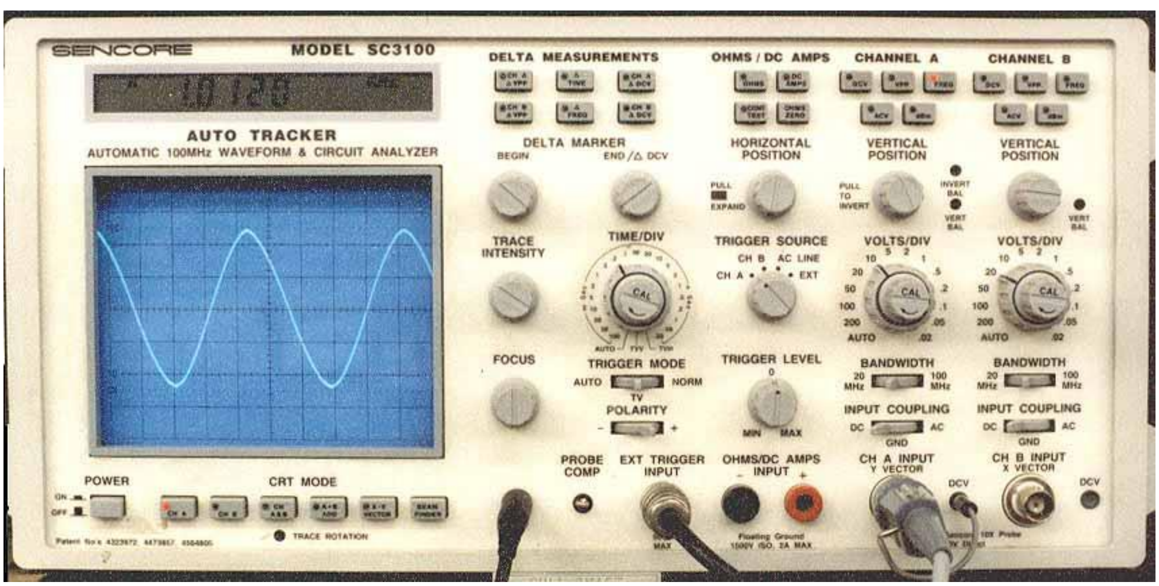


Figure 5.1 Oscilloscope: Image of an ac voltage sine wave

The sinusoidal wave shape shown above represents a voltage changing from a positive value to a negative value, 50 times per second. When this flowing wave shape changes size, shape, symmetry, frequency, or develops notches, impulses, ringing, or drops to zero (however briefly), there is a electrical power disturbance.

PQ or voltage incidents are often momentary occurring in a fraction of a cycle and are very hard to observe or diagnose without any proper tool. PQ disturbances can also be very high-speed events such as voltage impulses / transients, high frequency noise, wave shape faults, voltage swells and sags and total power loss. Each type of electrical equipment will be affected differently by these PQ issues. We can only verify the power PQ disturbances by installing a special type of high-speed recording equipment to monitor the electrical power.

Power quality (PQ) monitoring is a rewarding initiative for power utilities since it enables continuous monitoring of the power supply and early detection of electromagnetic disturbances. The PQ data will enable engineers to perform root cause analysis and take timely corrective actions to improve overall the power system reliability. PQ monitoring is also of interest to major energy consumers as they also want to avoid expensive equipment failures. Therefore, mutual interest of energy suppliers and energy consumers in PQ monitoring motivates the use of high performance PQ monitoring instruments.

Another important aspect in PQ monitoring is the collection of information regarding the performance of a power system in terms of voltage sag and interruption. Modern PQ monitoring systems now also provide the added benefit of simultaneously monitoring demand, energy and other parameters.

5.2 Power Quality Monitoring

As defined in Chapter 1, PQ disturbances can be classified as:-

- short duration disturbances (Sags, Swells & Transients)
- continuous & steady state disturbances (harmonics, notches, flickers, unbalance)

The short duration PQ disturbances are momentary occurring in a fraction of a cycle and are very hard to observe or diagnose without any proper tool. The continuous and steady state PQ disturbances are voltage waveforms that are not perfectly sinusoidal but continuous or in a steady state conditions. Examples of the steady state PQ disturbances are shown in figures 5.2 to 5.7.

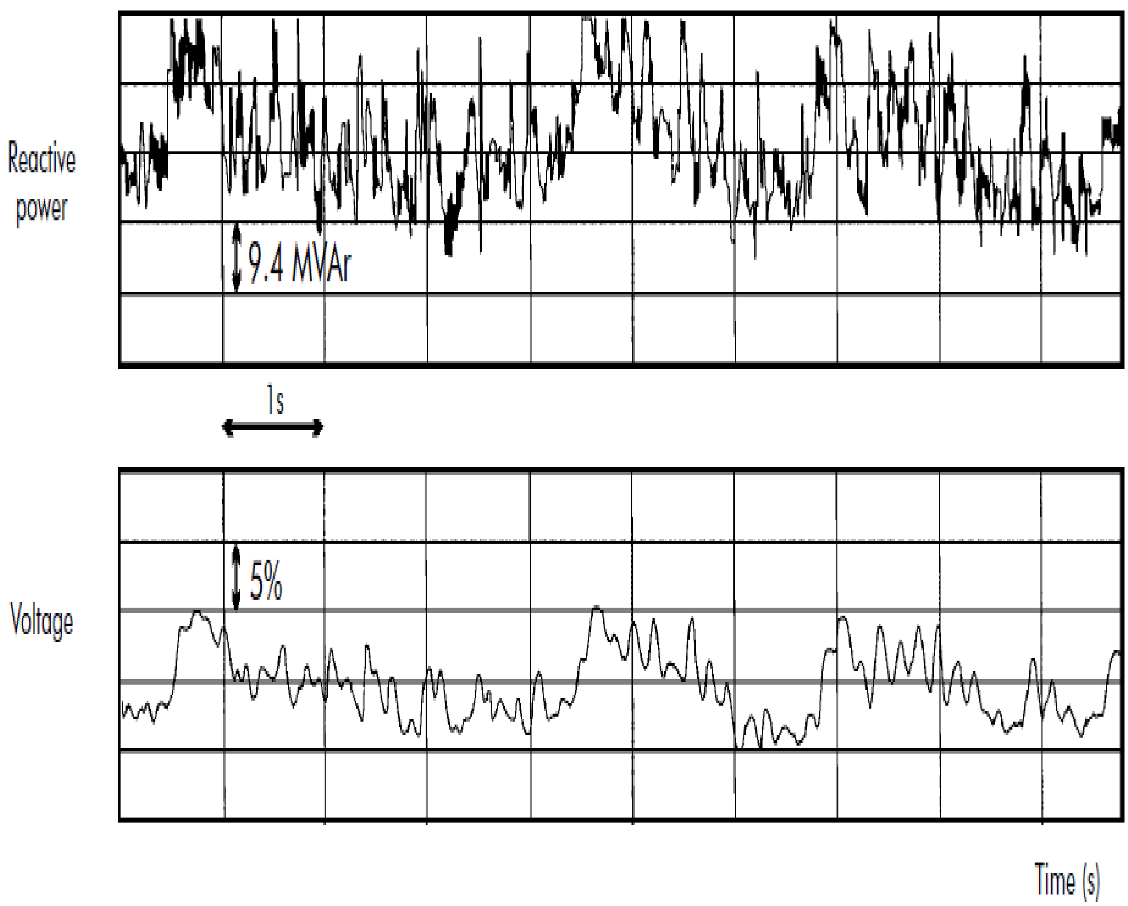


Figure 5.2 Changes in the reactive power and the resulting voltage fluctuations at the point of connection of an arc furnace

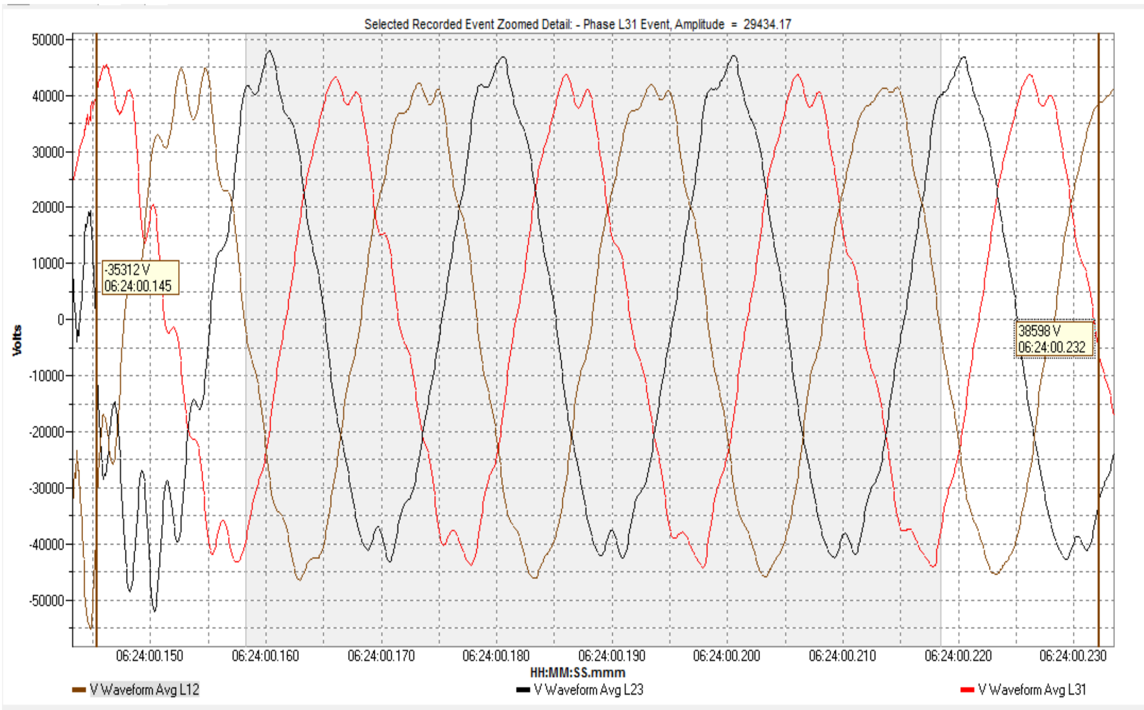


Figure 5.3 Harmonics waveforms recorded in a steel mill

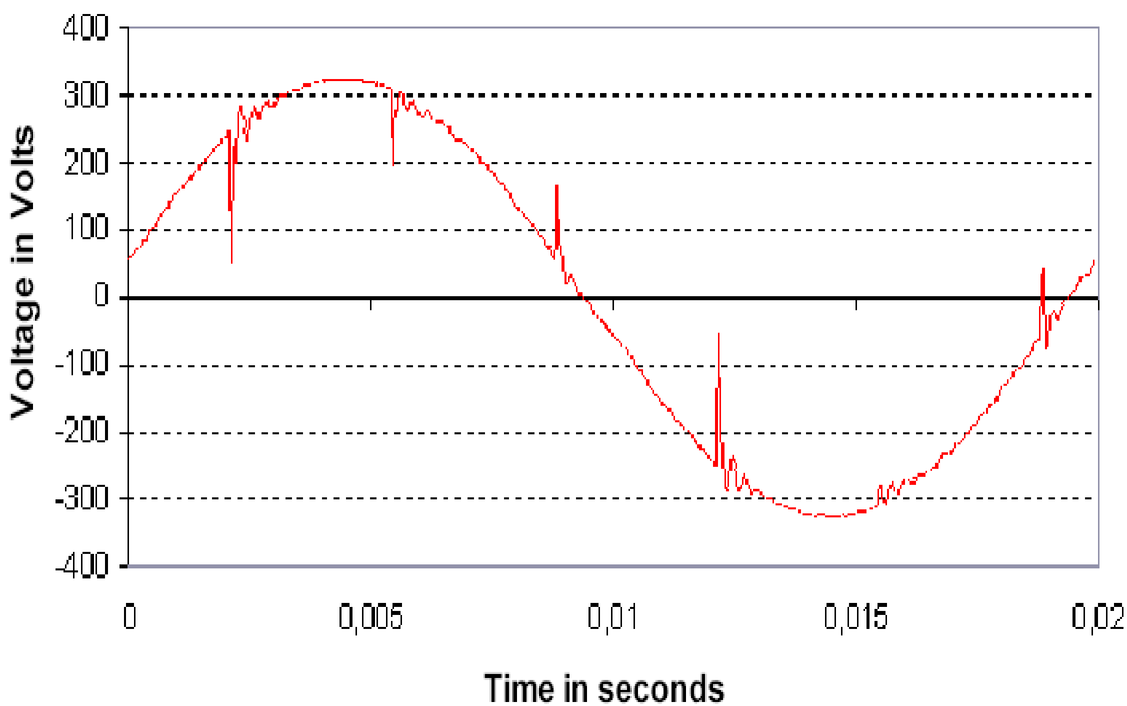


Figure 5.4 Notches voltage waveform

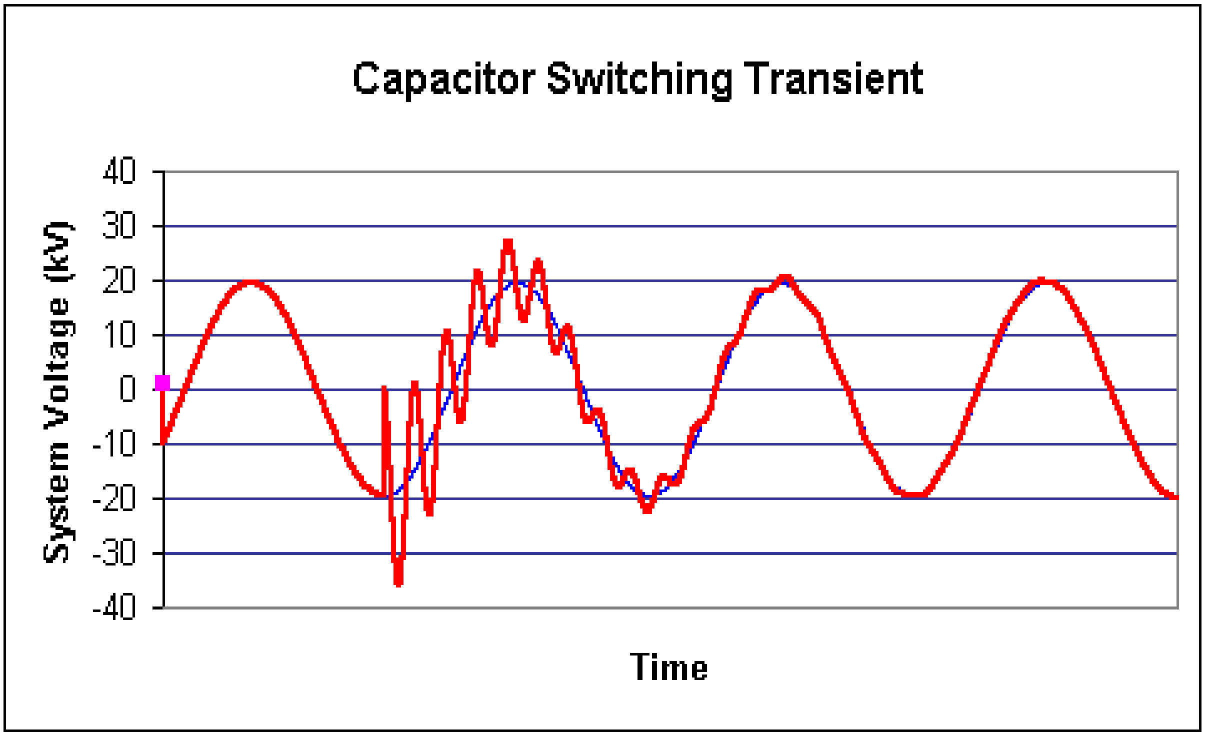


Figure 5.5 Oscillatory Transient due to capacitor switching

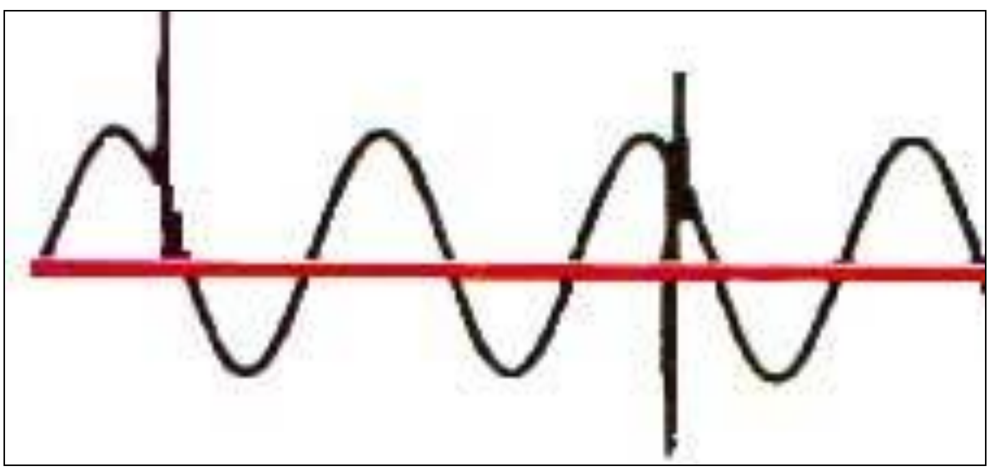


Figure 5.6 Waveform due to Impulsive Transient

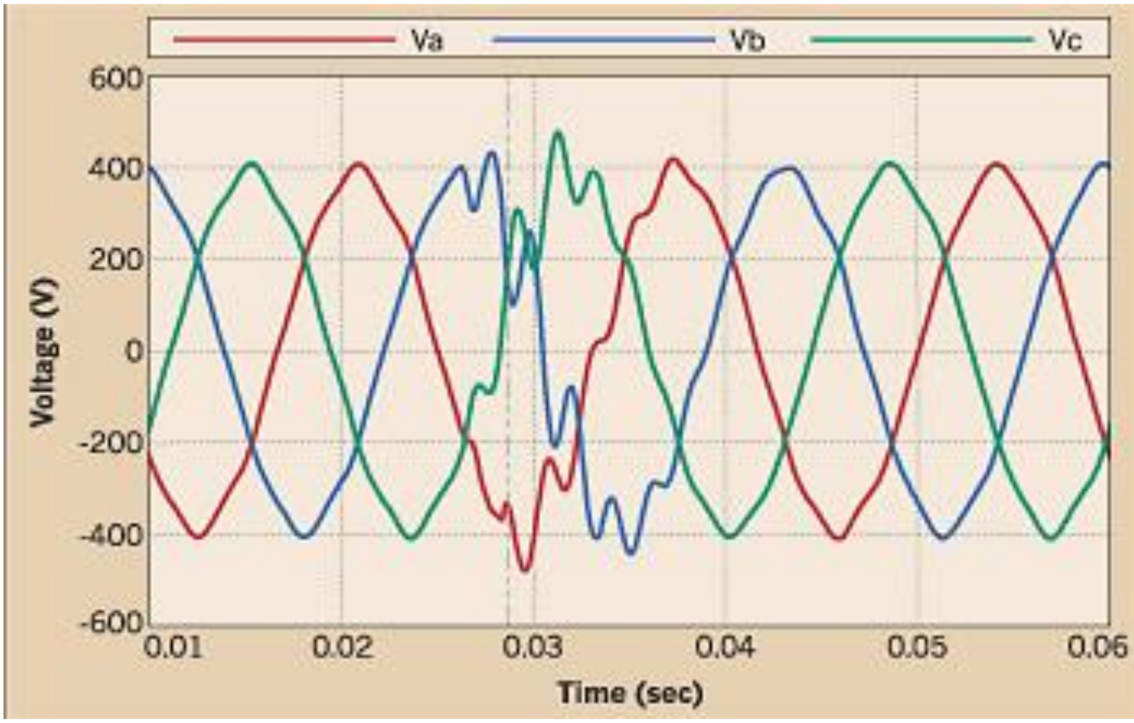


Figure 5.7 Multiple PQ disturbances (Oscillatory Transient & Harmonics)

The PQ monitoring devices must able to record both the continuous & steady state PQ disturbances. These PQ monitors must perform both as a highly accurate digital meter for measuring and logging electrical quantities, such as current, voltage, power factor, and energy, and as a monitor for watching for voltage transients and other power quality events, alarming on occurrence, and capturing waveforms and other useful data.

Although PQ monitors have been able to detect and record steady-state PQ disturbances for some time, the ability to capture sub-cycle transients today requires much more sophistication when it comes to a piece of monitoring equipment. Only recently has the technology become available to design compact, affordable PQ monitors that perform high-speed transient detection without compromising accuracy, metering performance, data logging, or other functions.

To ensure correct recording of PQ disturbances, the PQ device must have the following features:-

- **Fast sample rate.** The required sample rate depends on the frequency of the transients. Since most low-and medium-frequency oscillatory transients occur in the kilohertz frequency range, circuit monitors that sample voltage input channels at 128, 256 or 512 samples-per-cycle can occasionally detect and capture oscillatory transients. On the other hand, impulsive transients are often shorter in duration and require much higher sample rates.

  A monitoring device that samples data at the rate of 512 samples-per-cycle can sample data only once per 32.5 µsec. This is adequate for general disturbance monitoring and some oscillatory transients, but it's far too slow to characterize a 1.2×50-µsec impulsive transient. PQ monitors with the fastest transient detection capabilities sample voltage data at 5 MHz per voltage channel or 83,333 samples-per-cycle, which is fast enough to detect even very short impulsive transients.

- **Ample onboard memory.** The PQ monitor should be able to store multiple, high-resolution captured waveforms and the associated rms data while still performing data logging functions, such as load profiling and energy usage, for standard monitoring purposes. It also should store transient waveform data in nonvolatile memory to prevent data loss if the circuit monitor should lose control power.

- **Sag/swell alarms.** The PQ monitor should support high-speed alarms with a detection rate of less than half a cycle for capturing sag/swell disturbances. It's also useful when this alarm operates output relays. Alarms should trigger a waveform capture up to 60 cycles in duration; record the event in the circuit monitor's onboard event log, including a date/time stamp and the rms magnitude of the most extreme value of the sag or swell; and force the circuit monitor to log other pertinent data in its onboard memory.

Currently, there are two types of PQ monitoring devices. A handheld PQ meter can only record steady state power system parameters and PQ disturbances in particular harmonics. A full PQ monitor or PQ recorders can record the power system parameters and both the short duration voltage disturbances and steady state PQ disturbances.

5.2.1 Understanding True RMS meter

A RMS multimeter

True RMS voltage/current meter

Figure 5.2 RMS & True RMS clamp meters

A RMS clamp meter and a common RMS multimeter only record steady state fundamental (50 Hz) data. The ‘Root Mean Square’ magnitude of an alternating current is the value of equivalent direct current that would produce the same amount of heat in a fixed resistive load. For a perfect sinewave, the RMS value is 0.707 times the peak value (or the peak value is √2, or 1.414, times the RMS value). This is the approach taken in all analogue meters and in all older and most current, digital multimeters. This technique is described as ‘mean reading, RMS calibrated’ measurement. However, the RMS technique only works for pure voltage waveform and will give an inaccurate value for non sinusoidal voltage waveforms.

To overcome this inaccuracy, a True RMS meter is required. A true RMS meter works by taking the square of the instantaneous value of the input current, averaging over time and then displaying the square root of this average. Perfectly implemented, this is absolutely accurate whatever the waveform. There are two limiting factors to be taken into account to the implement the True RMS measurement:- frequency response and crest factor. True RMS measurement will give a higher ampere reading as compared to that of a normal RMS meter.

True RMS measurement is essential in any installation where there is a significant number of non-linear loads (ASD, Computers, electronic ballasts, compact fluorescent lamps, etc.). A normal RMS meters will give an under measurement of up to 40 % which can result in cables and circuit breakers being under rated with the risk of failure and nuisance tripping.

5.2.2 Description of PQ recording equipment

We can only verify the existence of PQ disturbances by installing a special type of high-speed recording equipment (PQ recorder) to monitor the electrical power. This type of test equipment will provide information used in evaluating if the electrical power is of sufficient quality to reliably operate the equipment.

The process is similar to a doctor using a heart monitor to record the electrical signals for your heart. Monitoring will provide us with valuable data, however the data needs to be interpreted and applied to the type of equipment being powered. The use of a PQ recorder is also ‘similar’ to the use of a stethoscope to hear irregular heart beat.

A medical device that is also used for recording heart rate is the ECG. ECG (Electrocardiography) is used to measure the rate and regularity of heartbeats, as well as the size and position of the chambers, the presence of any damage to the heart, and the effects of drugs or devices used to regulate the heart, such as a pacemaker.

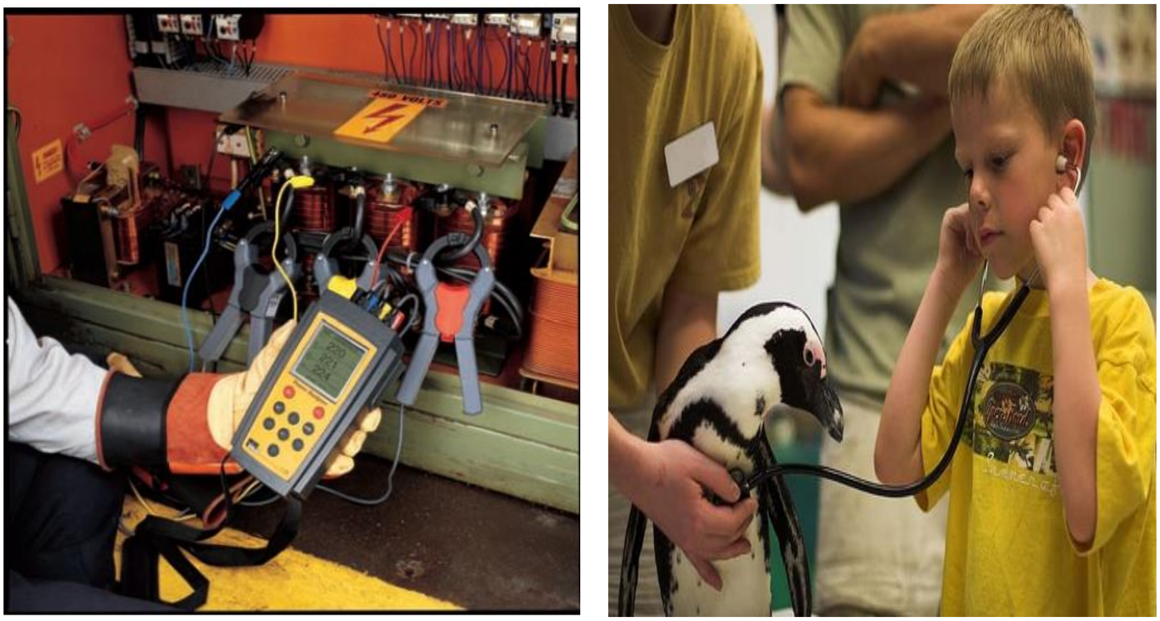
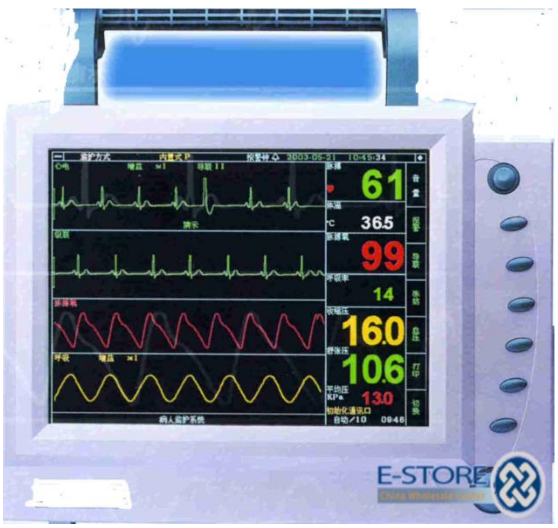


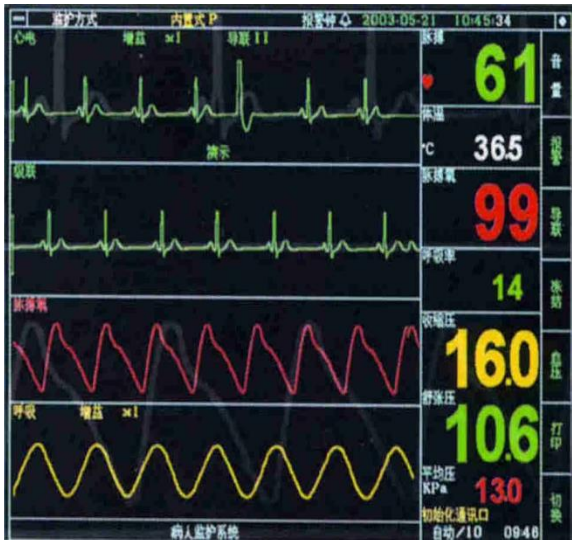
Figure 5.3 Comparison : Equipment to evaluate power quality and heart beat



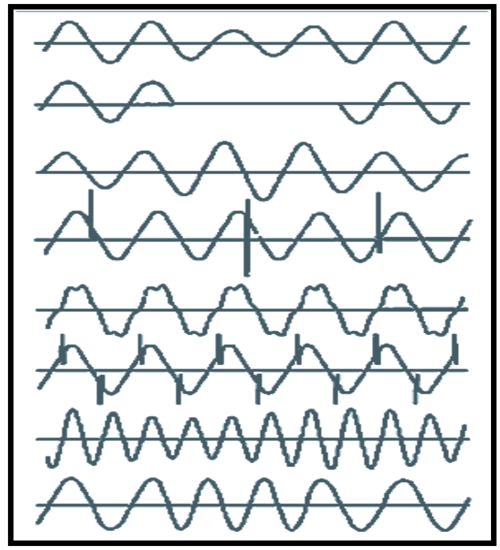
Equipment to record heart beat

Equipment to record power quality

Figure 5.4 Comparison : Equipment to monitor heart beat and power quality (1)



Waveforms recorded by a
heart monitoring recorder



Waveforms recorded by a
power quality recorder

Figure 5.5 Comparison : Equipment to monitor heart beat and power quality (2)

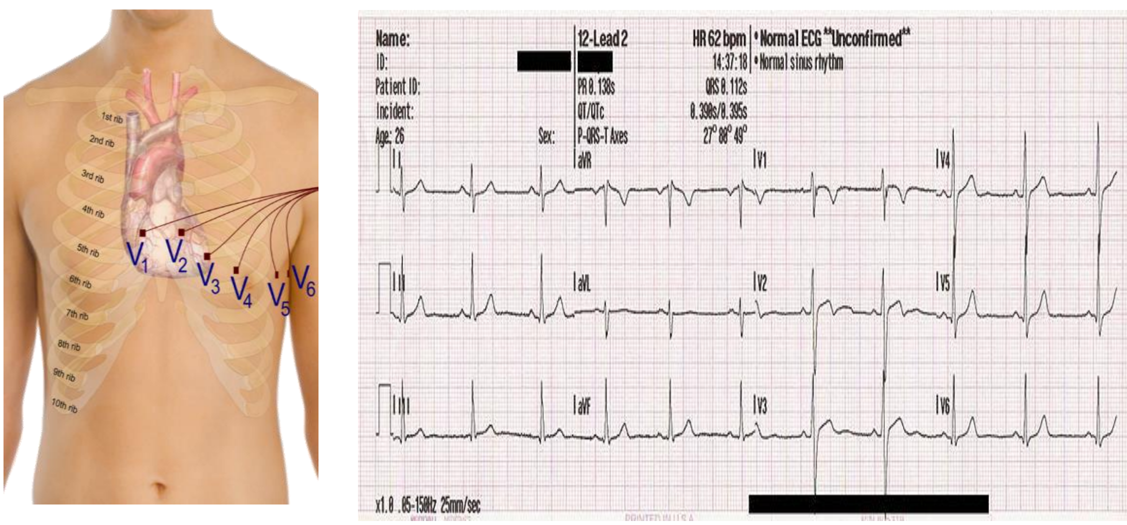


Figure 5.6 Example on ECG monitoring and test results

ECG will provide us with valuable health data, however the recorded data needs to be interpreted or diagnosed by a medical specialist. The graph in Figure 5.6 shows the results of a stress test and can only be diagnosed by a the medical specialist.

Likewise, PQ monitoring will provide us with valuable electrical data on the performance of the power systems. A power quality monitoring will provide more data than a ECG monitoring. The occurrence of a PQ events normally involves a drastic change in voltage (a period of time <10 ms) that may disrupt the operation of equipment in factories.

PQ recorder brand B

PQ recorder brand C

Figure 5.7 Examples of PQ recorders

5.3 What to Monitor?

PQ monitoring at critical facilities must be done very details. The systems should characterize steady state events (voltage regulation, unbalance, harmonics, flickers,) as well as disturbances (transients, voltage sags, voltage swells, interruptions, outages). PQ events should be characterized with complete voltage and current waveform information for evaluating interaction issues and the response of equipment that may be sensitive to microsecond variations in the voltage.

5.4 Locations to monitor Power Quality

The selection of monitoring locations will depend on the facility design, critical loads, power conditioning equipment, and the specific objectives of the monitoring. As a minimum, the monitoring should include the utility supply locations, outputs of power conditioning equipment, and the backup generators. If there are redundant or backup supplies, each feed should be monitored. More extensive monitoring would include critical air conditioning loads and possible individual loads within the facility (communications equipment, individual load buses). Monitoring within the facility can help characterize load interaction issues.

PQ monitoring should be an integral part of the design for high reliability facilities. The monitoring will characterize the performance of the supply system and the performance of any power conditioning equipment at the facility, including possible interaction issues with facility loads. Advanced data analysis functions and alarming are making these systems even more valuable and convenient access to the information via a web browser eliminates any need for training or software maintenance.

The recommended locations to perform PQ monitoring are shown in Figure 5.8.

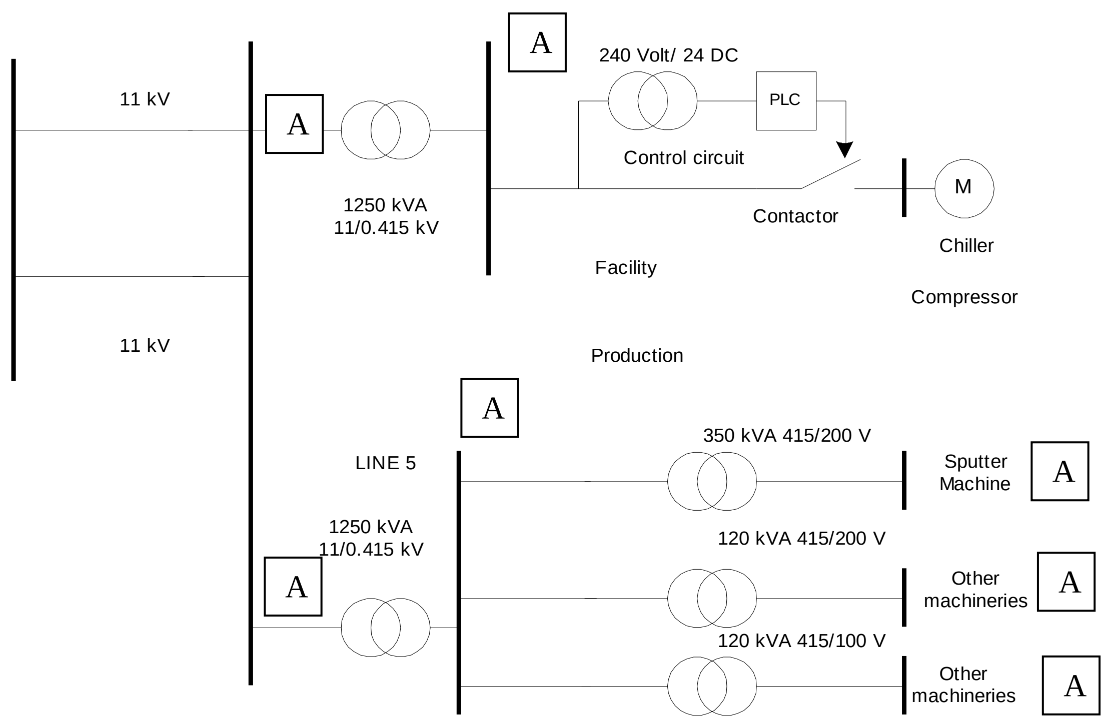


Figure 5.8 Locations to monitor power quality indicated by A

5.5 Importance of having a good software to diagnose Power Quality

PQ recorder converts electrical current and voltage readings to graphic representations called waveform signatures. All types of PQ disturbances such as voltage sag, transient overvoltage and interruption can be identified by specific waveform signatures. It is desirable to have a system that can automatically detect and classify all PQ disturbances especially if the database is large. The data capturing is based on triggering levels applied at the PQ recorder.

All types of voltage disturbances such as voltage sags, transient overvoltages, interruptions, etc. can be identified by a specific signature/waveform. These signatures/waveforms can help to solve PQ disturbance problems experienced by customers. However, the amount of data recorded by the PQ recorder is vast and to a layman the data provides little information related to the PQ disturbances. To analyze manually all the PQ disturbances is a nontrivial task mainly due to the huge volume of disturbance records. Therefore it is important to have a good software or technique that can assist in the analysis of all the recorded PQ disturbances. The software should be user friendly as to show displays for all the PQ disturbances in graphic and tabular data.

A good software must be a requirement for the PQ recorder, it's necessary to annunciate alarms, view captured waveforms, store waveforms and related data to a disk, and so on. Other useful features include the ability to view harmonic spectral plots and rms plots, zoom on and overlay waveforms, and export waveforms in a standard file format like excel, PQDIF etc.

Example of a typical software for power quality is shown in Figure 5.9.

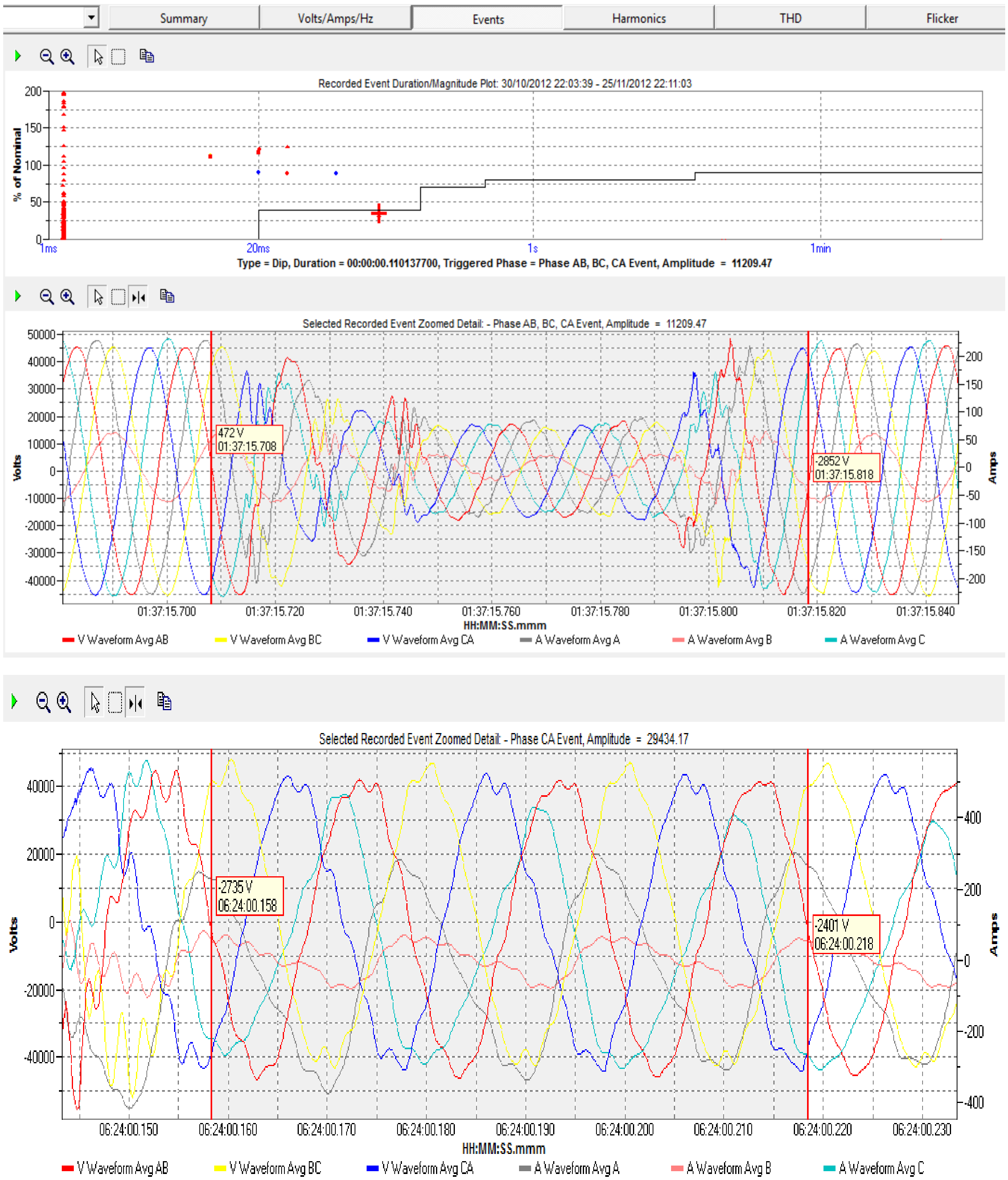


Figure 5.9 Example of a PQ analysis software

A good PQ software will enable one to diagnose the PQ waveforms and assist in the preparation of a simple technical report.

CHAPTER 6

EQUIPMENT COMPATIBILITY REQUIREMENT

6.1 POWER QUALITY DESIGN PHILOSOPHY

More recently, engineers around the world have realized that voltage sag is really a compatibility problem with at least two classes of solutions: You can improve the power or you can make the equipment tougher. The latter approach is called "voltage sag immunity," and has gained importance around the world.

The effect of a voltage sag and short duration interruption on the user's equipment must be considered, with particular regard to the depth-duration characteristics that are critical, and the user must take due account of the possible consequences of any deterioration of performance or lapse in operation of that equipment. In the light of these consequences, the installation should from the very first stage of planning, be designed to minimize disturbance and loss arising from voltage sags, with due regard given to the economic considerations that apply.

Satisfactory operation of the distribution system and customers' equipment is only obtained when electromagnetic compatibility (EMC) exists between them. The normal approach to electromagnetic compatibility is to observe coordinated limits for both emission and immunity for the disturbance events involved.

6.2 Understanding equipment immunity requirement

There are two aspects to EMC: (1) a piece of equipment should be able to operate normally in its environment and (2) it should not pollute the environment too much. An agreement on immunity is a matter of foremost concern between equipment manufacturers, utilities and customers.

A device connected to the power system is exposed to an electromagnetic environment not only due to the combined emission of all other devices connected to the system but also due to all kinds of events in the power system (like switching actions, short circuit faults and lightning strokes). The immunity of the device should be assessed with reference to this electromagnetic environment.

For some locations and in some countries it may be possible for the electricity utilities to provide basic information on the level of the electromagnetic environment, for example the frequency of voltage sags to be expected at the location concerned, subject to the uncertainties that are unavoidable.

6.3 Voltage sag Immunity requirement

Immunity standards define the minimum level of electromagnetic disturbances that a piece of equipment shall be able to withstand. Before being able to determine the immunity of a device, a performance criterion must be defined.

6.3.1 Available compatibility levels for voltage sags

Compatibility levels are reference values used for the coordination of emission and immunity of equipment making up a network in order to ensure electromagnetic compatibility throughout the whole system. A range of standards had been published to address the fundamental electromagnetic compatibility (EMC) issues governing the connection of sensitive equipment to a power system. Standards documentation sets out guidelines for equipment connectivity and regulation of both conducted and radiated EMC emission and susceptibility. A sub-set of most EMC standards documentation governs the susceptibility of sensitive equipment to voltage sags and surges.

There are three main primary voltage sag immunity standards: IEC 61000-4-11, IEC 61000-4-34, and SEMI F47. There are others in use—such as IEEE 1100, CBEMA, ITIC, Samsung Power Vaccine, international standards, and MIL-STD—but the first three seem to have the widest acceptance in the marketplace. (IEC is the International Electrotechnical Commission, SEMI is the Semiconductor Equipment and Materials Institute, CBEMA is the Computer Business Equipment Manufacturers Association, ITIC is the Information Technology Institute Council, and MIL-STD is the U.S. Defense Department's specification.)

IEC 61000-4-11 and IEC 61000-4-34 are a closely related set of standards that cover voltage sag immunity. IEC 61000-4-11 Ed. 2 covers equipment rated at 16 amps per phase or less while IEC 61000-4-34 Ed. 1 covers equipment rated at more than 16 amps per phase. The latter was written after IEC 61000-4-11, so it seems to be more comprehensive.

SEMI F47 is the voltage sag immunity standard used in the semiconductor manufacturing industry, where a single voltage sag can result in the multi-million-dollar loss of product if a facility is not properly protected. The semiconductor industry has developed specifications for its manufacturing equipment and for components and subsystems in that equipment. Enforcement is entirely customer-driven in this industry, as semiconductor manufacturers understand the economic consequences of sag-induced failures and generally refuse to purchase new equipment that fails the SEMI F47 immunity requirement. SEMI F47 is currently going through its five-year revision and update cycle.

All three standards specify voltage sags with certain depths and durations for the equipment under test (EUT). For example, a specification may state 70 percent of nominal for 500 milliseconds. The percentage is the amount of voltage remaining, not the amount that is missing. Each standard specifies pass-fail criteria for EUT when a voltage sag is applied; the IEC standards have a range of pass-fail criteria, but the SEMI F47 standard is more explicit.

Details of the standards are presented in the next subchapters.

6.3.2 Voltage tolerance curves

6.3.2.1 CBEMA standard [18]

The CBEMA (Computer and Business Equipment Manufacturers' Association) power quality graph plots the depth of voltage sags on the vertical axis against the duration of voltage sags on the horizontal axis. See Figure 6.1.

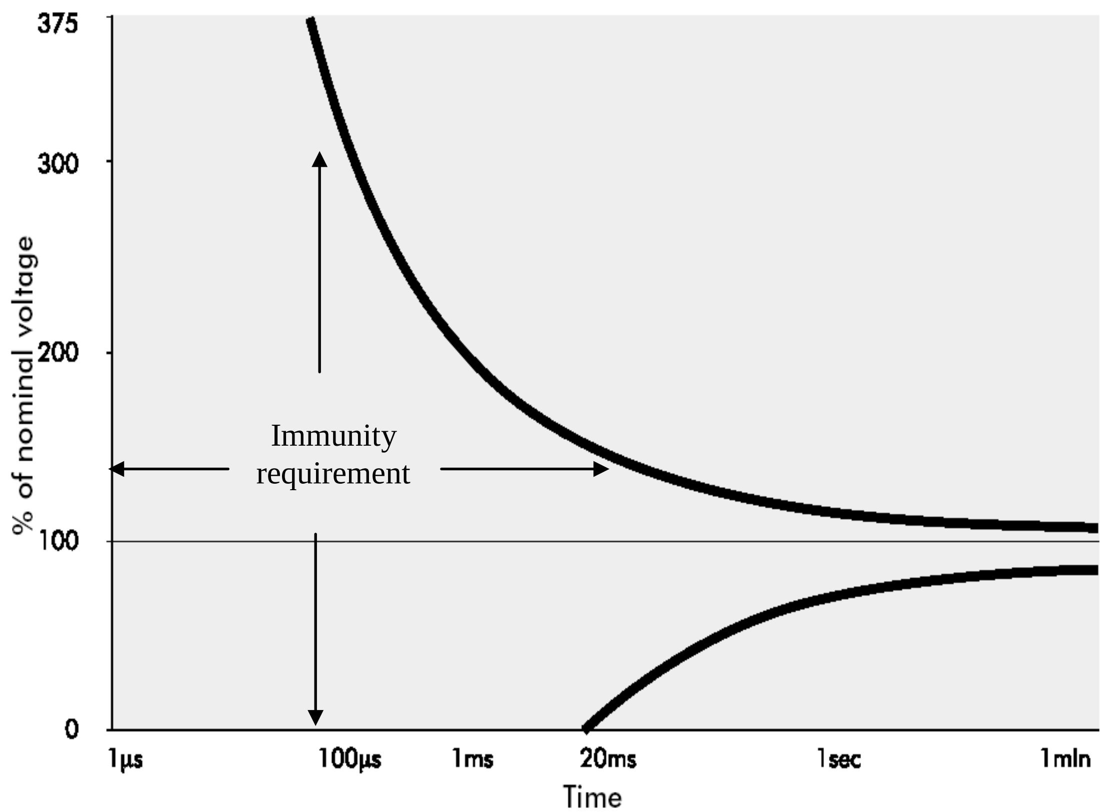


Figure 6.1 CBEMA curve

The line on the graph shows the sag immunity suggested by CBEMA. The area inside the graph is the recommended voltage immunity for computers and other business equipment.

6.3.2.2 ITIC standard [19]

ITIC Curve is a modified version of the CBEMA power acceptability curve, but the concept remains the same. It was developed by a working group of the CBEMA, which later changed its name to the Information Technology Industry Council (ITI). The intent was to derive a curve that can better reflect the performance of typical single-phase, 120 V, 60 Hz computers and their peripherals, and other information technology items like fax machines, copiers and point-of-sales terminals.

The ITIC curve has been applied to general power quality evaluation, even though it was primarily developed for 120 V computer equipment just like the CBEMA curve.

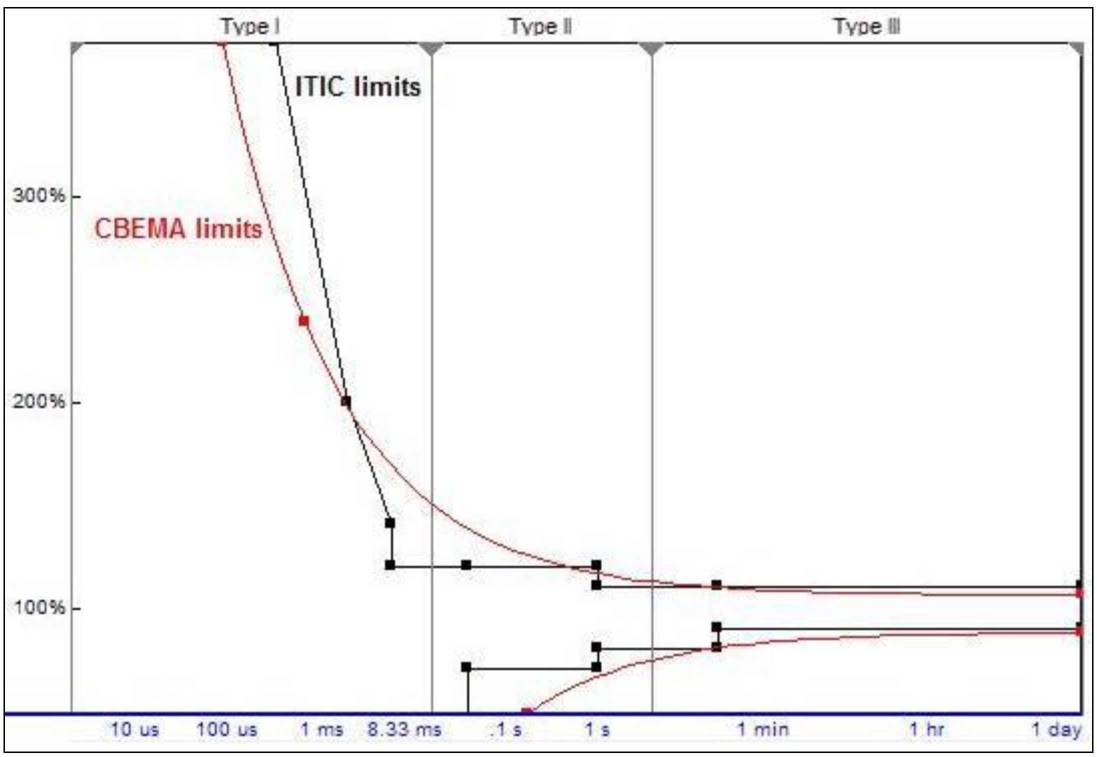


Figure 6.2 ITIC & CBEMA curve

6.3.2.3 SEMI F47 standard [20]

A notable addition to the industrial and IT process power quality standards has been the recent specification SEMI F47-0706. The requirements of the SEMI specification were developed to satisfy the needs of the semiconductor industry. This specification sets minimum voltage sag immunity requirements for equipment used in the semiconductor industry. Immunity is specified in terms of voltage sag depth (in percent of nominal voltage remaining during the sag) and voltage sag duration (in cycles or seconds). This specification also sets procurement requirement, test methods, pass/fail criteria, and test report requirements.

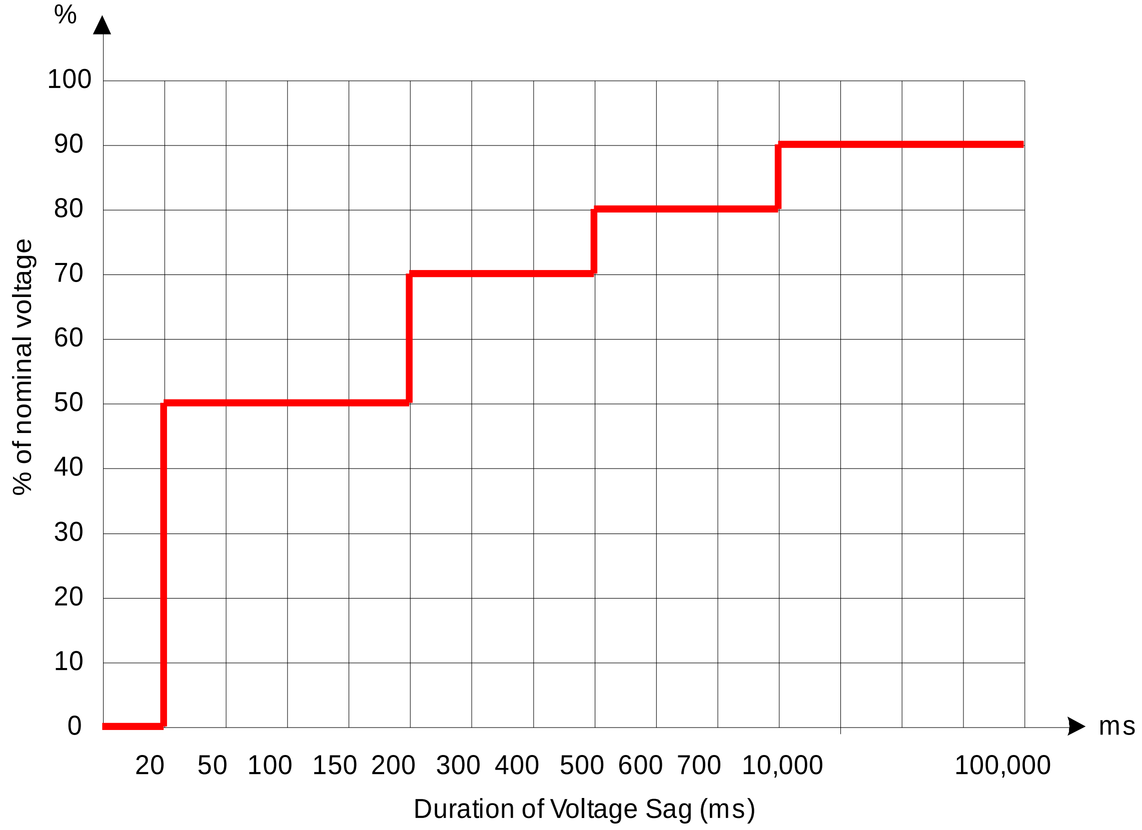


Figure 6.3 SEMI F47-0706 curve

Thus, the requirements developed in the SEMI specification are better suited to the semiconductor industry. The SEMI (curve) staircase is specified for voltage dips with a duration 0.05s – 1s. An arguable advantage of the SEMI curve as a benchmark for site performance profiling and CBEMA equipment testing and approval is the stringent requirement on equipment to continue to function down to 50% retained voltage for dips of duration 0.05 – 200 ms. Although specified for semiconductor equipment, the tighter limits imposed by the SEMI curve, (if applied as a benchmark for compliance) present the electricity supply industry (ESI) and IT industrial process and manufacturing industries with a more robust basis for ride-through declaration. While delivering greater constraints at all levels in the supply chain, compliance with a more rigid benchmark breeds a higher level of confidence in equipment operability.

6.3.2.4 IEC 61000-4-11 – Testing and measurement techniques – Voltage dips, short interruptions and voltage variations immunity tests for equipment with input current less than 16 A per phase [21]

The IEC 61000-4-11 standard defines the immunity test methods, minimum immunity requirement and range of preferred test levels for electrical and electronic equipment connected to low-voltage power supply networks for voltage sags (Graph A), short interruptions (Graph B), and voltage variations. The test levels for voltage dips are shown in Table 6.1.

Table 6.1 – Preferred test level and durations for voltage dips

Classes	Test level and durations for voltage dips (t_s) (50 Hz/60 Hz)				
Class 1	Case-by-case according to the equipment requirements This class applies to protected supplies and has compatibility levels lower than public network levels. It relates to the use of equipment very sensitive to voltage disturbances in the power supply, for instance the instrumentation of technological laboratories, some automation and protection equipment, some computers, etc. NOTE Class 1 environments normally contain equipment which requires protection by such apparatus as uninterruptible power supplies (UPS), filters, or surge suppressers.				
Class 2	0% during ½ cycle	0% during 1 cycle	70% during 25/30 cycles		
Class 3	0% during ½ cycle	0% during 1 cycle	40% during 10/12 cycles	70% during 25/30 cycles	80% during 250/300 cycles
Class X[b]	X	X	X	X	X

a. Classes as per 61000-2-4

b. For equipment connected directly or indirectly to public network, the levels must not be less severe than class 3.

c. Class X[b] is a new voltage tolerance test to be developed in the future.

d. "25/30 cycles" means "25 cycles for 50 Hz test" and "30 cycles for 60 Hz test".

The IEC 61000-4-11 covers equipment installed in residential areas as well as industrial machinery, specifically for voltage sags and short interruptions for equipment connected to either 50 Hz or 60 Hz a.c networks, including 1-phase and 3-phase mains.

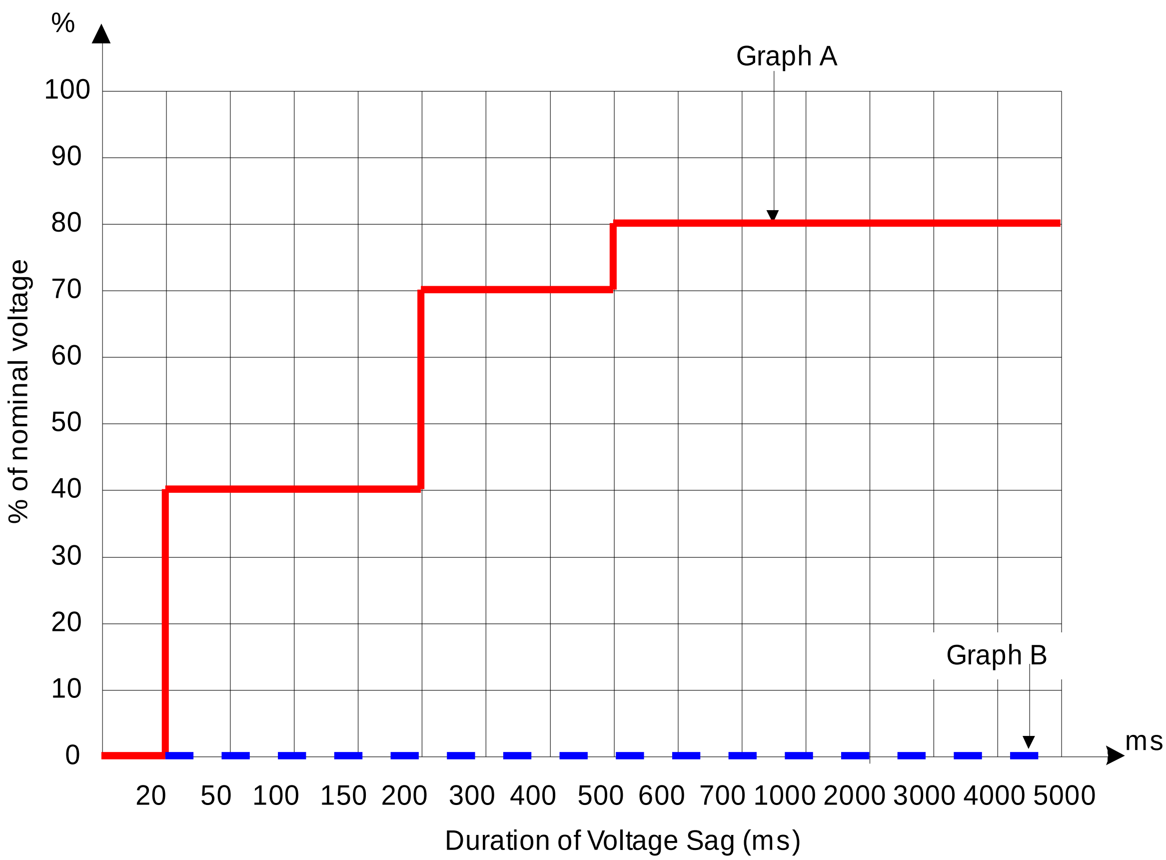


Figure 6.4 IEC 61000-4-11 (Class 3) curve

Graph A is the test level for voltage sag. Graph B is the test level for short interruption.

6.3.2.5 IEC 61000-4-34 – Testing and measurement techniques – Voltage dips, short interruptions and voltage variations immunity tests for equipment with input current more than 16 A per phase [22]

The IEC 61000-4-34 standard is similar to the IEC 61000-4-11 standard. The main difference is that it only applies to electrical and electronic equipment having a rated input current exceeding 16 A per phase.

It also covers equipment installed in residential areas as well as industrial machinery, specifically for voltage dips and short interruptions for equipment connected to either 50 Hz or 60 Hz a.c. networks, including 1-phase and 3-phase mains.

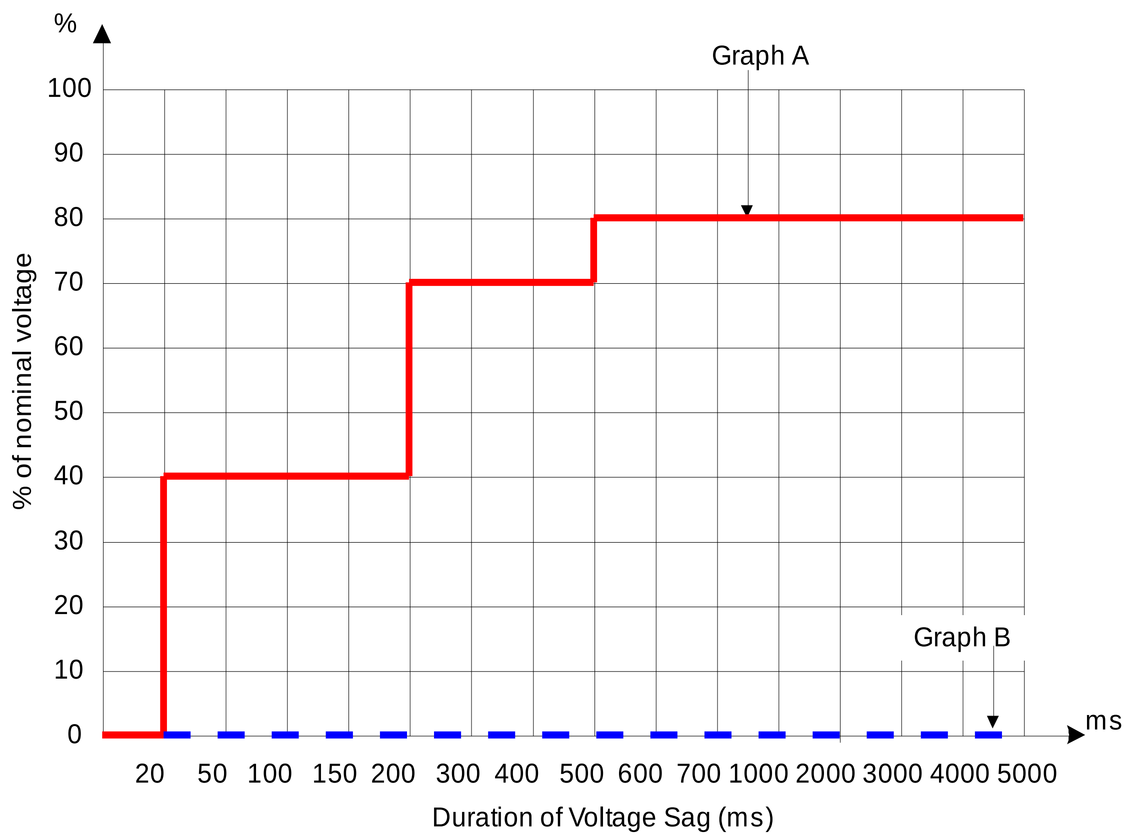


Figure 6.5 IEC 61000-4-34 (Class 3) curve

Graph A is the test level for voltage sag. Graph B is the test level for short interruption.

CHAPTER 7

CHARACTERIZING EQUIPMENT SENSITIVITY

7.1 INTRODUCTION

Voltage sags at equipment terminals are influenced by the transformer connections between the fault location on the supply system and the equipment connection point. The transformer connections will influence both the magnitude and the phase relationship of the voltage sag experienced by the equipment.

These phenomena are random in nature and can be minimally characterized for the purpose of laboratory simulation in terms of the deviation from the rated voltage, and duration. Consequently, different types of tests are developed to simulate the effects of abrupt voltage change.

7.2 Objective of equipment immunity testing

The objective of this section is to define the test method used to characterize the susceptibility of automated processes and automated test equipment to voltage sags. In this section, the scope covers: -

a. Characterizing the susceptibility of equipment to voltage sags by showing voltage sag duration and magnitude performance data for the equipment.

b. Qualifying equipment to meet voltage sag ride-through specifications by comparing the equipment voltage sag ride-through performance to industry/technical standards.

Sensitive machinery will be experiencing mal-operation every time a voltage sag event occurs. This is due to the incapability of the equipment to ride through the voltage sag event or in other words the immunity of the equipment is very low.

The typical equipment sensitivity to voltage sag is shown in Table 7.1.

Table 7.1 Typical equipment sensitivity

Type of Equipment	Remaining voltage (%)	Duration (ms)
Motor starter	50	40
Variable speed motor with electronics	85	10
PLC I/O Device	50-90	8-20
Frequency inverter	82	1.5
Variable Speed Drive rectifier	50-80	2-3
Process controller	70	< 8
Computerized numerical controlled lathe	70	< 8
Direct Current drive controller	88	< 8
Personal Computer	50-70	60-160
Contactors	50-60	20-30
Electromagnetic disconnecting switch	50	10
Electromagnetic relays	50-60	15-40
Medical equipment	60	130
Servo drives	80	50
Laser marker	90	100

Figure 7.1

Programmable Logic Control (PLC**)**

Alternating current (ac) drive

Direct current (dc) drive

Servo Drive

Frequency Inverter

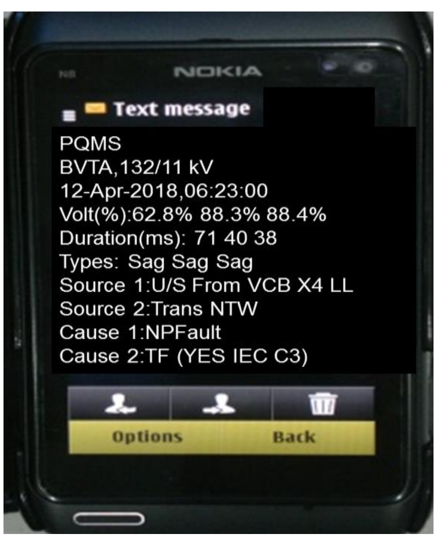
Figure 7.2 Examples of sensitive equipment in industrial plants

7.3 Analyzing machinery immunity and sensitivity to voltage sag

7.3.1 Simple method to verify the equipment sensitivity to voltage sags

The first step towards a cost-effective solution is to understand the sensitivity of the electronic equipment to momentary interruptions and voltage sags. Customers can find this information by consulting the equipment manufacturer's specifications and testing data. Another simple method to verify the equipment sensitivity is to use the existing data for voltage sag recorded via existing power quality recorder installed nearest to the plant and equipment. Most power utilities install online power quality monitoring system (PQMS) at their substation to monitor power quality.

After the occurrence of a voltage sag event, TNB will share the data on voltage sag received via short message system (SMS) with the affected prime customers. These data are obtained from online PQMS which is located at the nearest substation to the customers. The voltage sag data are recorded at the medium voltage level at the substation at 11, 22 or 33 kV. As explained in sub chapter 4.5 (propagation of voltage sags**)**, the types of voltage sag will undergone transformation once it travels from the power system to the step down transformer, to the lower voltage levels and to the customer's loads.



SMS A

SMS B

Figure 7.3 Examples of SMS on voltage sags received from TNB.

Examples of the SMS shared with customers are shown in Figure 7.3. The voltage sags were recorded at the 11 kV (SMS A) and 33 kV (SMS B) voltage levels. Referring to tables 4.3 & 4.4, the customers can estimate the type of the voltage sag experience at their critical equipment.

From Table 4.3 Transformation of voltage sag type to lower voltage level (after Tx)

Connection	Sag on primary side						
	Type A	**Type B**	**Type C**	**Type D**	**Type E**	**Type F**	**Type G**
YNyn	A	B	C	D	E	F	G
Yy, Dd, Dz	A	D	C	D	G	F	G
Yd, Dy, Yz	A	C	D	C	F	G	F

From Table 4.4 Transformation of voltage sag type to lower voltage level (Load side)

Fault Type	Load Connection	
	Star	**Delta**
Three phase	A	A
Two phase to ground	E	F
Phase to phase	C	D
Single phase	B	C

Below are the steps to follows:

Part 1 Verification of voltage sag event

1.1 Verify the symptoms of voltage sags i.e. light blinks and critical equipment trips.

1.2. Verify which relay, control systems and equipment were affected by the voltage sags.

1.3. Verify the available power quality data (if available) from power quality recorder in the plant,

1.4. Please confirm the source of the voltage sag event either from outside the plant or due to internal equipment fault.

1.5. Verify with TNB via special WhatsApp group or contact directly to the TNB engineers

If data are available, TNB will share the SMS on voltage sag (Figure 7.3)

If the cause of the voltage sag was due to an event that originated from outside the plant, please do the following:-

1.6 Record the date and time of the voltage sag disturbance

1.7 If the system fault has been isolated, immediately commence the process to restart the affected production.

1.8 Request an official report from TNB.

If the cause of the voltage sag **was not confirmed** due to an event that originated outside the plant, please do the following:-

1.9 Record the date and time of the voltage sag disturbance

2.0 Please confirm with the nearby customers on any possible equipment flashover.

2.1 If the source of the event was not confirmed due to external causes, please perform an internal investigation to verify possible internal equipment failure.

Part 2 Identification of weak links and immunity level

From the information obtained from 1.1 to 2.1, please summarize all the affected control circuit and equipment together with the available power quality data,

If the data are sufficient, the sensitivity of the control circuit and critical equipment can be estimated from the available power quality data. Examples of equipment sensitivity are shown in Table 7.2.

Table 7.2 Typical equipment sensitivity based on voltage sag data

Equipment affected by voltage sags	Minimum values of voltage sag	
	Voltage (%)	Duration (ms)
PLC	90	50
VSD	85	80
Contactors	60	80
Relays	80	50

Based on the information in Table 7.2, next, refer to subchapter 7.5 for procedure to harden the sensitive process & selection of power conditions to protect the sensitive equipment against voltage sag.

7.3.2 Testing method to verify the equipment sensitivity to voltage sags

Another way to identify the sensitivity of equipment to voltage sags is by using a measuring device called a voltage sag generator, which can generate controlled voltage sags and records the responses of the equipment. In the market today, there are a few types of programmable sag generators available. Examples are the programmable ac source [23], the industrial power corruptor (IPC) [24], Voltage Dip & Swell Simulator VDS 2002, Voltage DIP Simulator VDS-220B & Voltage dip, interrupt and variation simulator PFS2216.

Figure 7.4 Programmable AC source

Figure 7.5 Industrial Power Corruptor (IPC)

Figure 7.6 Voltage Dip & Swell Simulator VDS 2002

Figure 7.7 Voltage dip, interrupt and variation simulator PFS2216**.**

Figure 7.8 Voltage Dip Simulator VDS-220B

Figure 7.9 Voltage Dip & Swell Simulator VDS 2002,

The standards that describe procedures on how to obtain voltage tolerance for equipment are IEC 61000-4-11, IEC 61000-4-34 and SEMI F42. The preferred test levels for voltage sag immunity are shown in Table 7.2 [21 & 22].

Table 7.2 Preferred test level and durations for voltage sags at 50 Hz

Classes	Test level and durations for voltage dips				
Class 1	Case by case according to the equipment requirement				
Class 2	0% during ½ cycle	0% during 1 cycle	70% during 25 cycle		
Class 3	0% during ½ cycle	0% during 1 cycle	40% during 10 cycle	70 % during 25 cycle	80 % during 250 cycle
Class X^b	X	X	X	X	X

***Note**: The types of classes are defined in MS IEC 61000-2-4*
X^b – To be defined by product committee
Sensitive equipment in industrial plants must be tested at minimum Class 3.

7.3.1 Test instrumentation for voltage sag generator

The following features are common to the generator for voltage sags, short interruptions and voltage variations.

Table 7.3 Characteristics and performance of the sag generator [23]

Output voltage at no load	As required in Table 7.2. ±5% of residual voltage values
Voltage at the output of generator during equipment test	As required in Table 7.2, ± 10% of residual voltage value, measured as r.m.s. value refreshed each ½ cycle per IEC 61000-4-30
Output current capability	Less than 16 A r.m.s (MS IEC 61000-4-11) or more than 16 A r.m.s (IEC 61000-4-34) per phase at rated voltage.
Voltage rise (and fall) time t_r (and t_f), during abrupt change, generator loaded with resistive load	Between 1 µs and 5 µs
Phase angle at which the voltage dip begins and ends	0° to 360° with a maximum resolution of 5°
Phase relationship of voltage dips and interruptions with the power frequency	Less than ± 10 °
Zero crossing control of the generators	± 10°

The test setup should consist of the following equipment as shown in Figure 7.10.

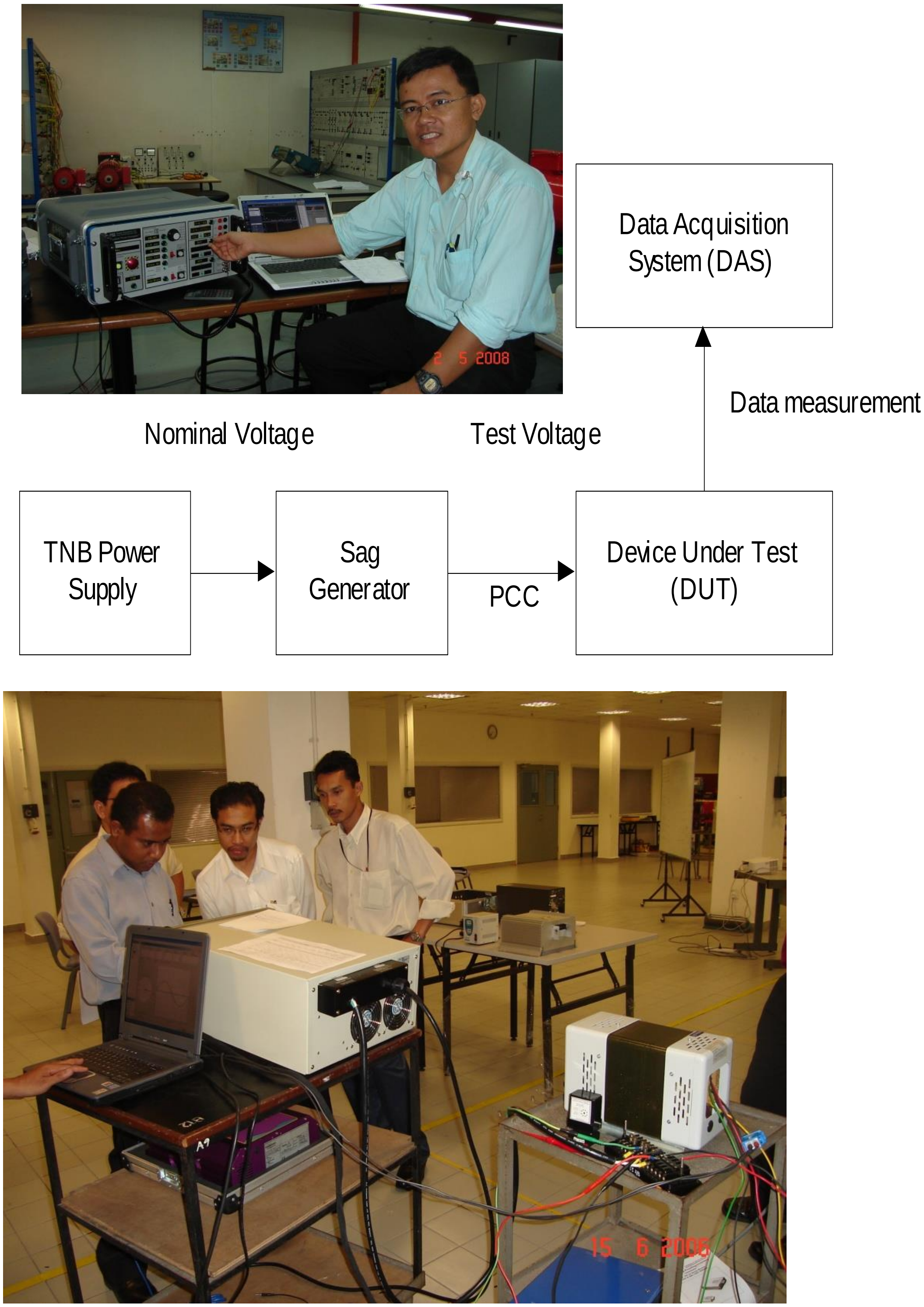


Figure 7.10 Voltage tolerance testings using IPC & Chroma equipment

7.4 Evaluation of test results for voltage sag testing

The test results shall be classified in terms of the loss of function or degradation of performance of the equipment under test, relative to a performance level defined by its manufacturer or the requestor of the test, or agreed between the manufacturer and the purchaser of the product.

The recommended classification is as follows:-

a) normal performance within limits specified by the manufacturer, requestor or purchaser;
b) temporary loss of function or degradation of performance which ceases after the disturbance ceases, and from which the equipment under test recovers its normal performance, without operator intervention;
c) temporary loss of function or degradation of performance, the correction of which requires operator intervention;
d) loss of function or degradation of performance, which is not recoverable, owing to damage to hardware or software, or loss of data.

The manufacturer's specification may define the effects on the DUT, which may be considered insignificant, and therefore acceptable. This classification may be used as a guide in formulating performance criteria, product and product-family standards, or as a framework for the agreement on performance criteria between the manufacturer and the purchaser, for example in instances where no suitable generic, product or product-family standard exists.

7.5 Improving equipment immunity to voltage sag

After the voltage sensitivity of the equipment is known, analysis can be done to identify measures to improve its immunity to voltage sag. With regard to voltage sags that are moderate in depth and duration, some equipment can have a certain level of inherent immunity, for example by virtue of its inertia or energy storage capacity. Alternatively, it may be possible to make design adjustments or use of additional support equipment i.e. power conditioner, so that this internal property is manifest.

Based on the information obtained from both methods (simple method and test method), please refer to chapters 8 & 9 for common hardening process & selection of power conditioners to protect the sensitive equipment against voltage sag.

However, for short interruptions, immunity is not, in its strict sense, a feasible concept. The essential character of the event is that it involves the complete cessation or severe diminution of the energy supply for a brief interval. No electrical device can continue to operate as intended in the absence of its energy supply. Therefore, such immunity as can be provided from these disturbances tends to be extrinsic - it is a matter of either providing for:

- fast restoration of energy from an alternative source or,
- arranging for the equipment and its associated process to adapt in an intended manner to the brief interruption or diminution of power.

7.6 Evaluating the Economics [25]

Deciding on the best alternative for improving voltage sag ride-through performance at a customer's facility is a problem that comes down to simple economics. We need to understand the sensitivity of the equipment and how much it costs every time the equipment is affected.

Then we need information from the electric utility that estimates how many voltage sags to expect on your system per year. With this information in hand we can then determine the costs associated with voltage sags. The optimum solution will minimize the combined costs of the ride-through solution and the resulting losses from the events not solved by the specific solution — the cost of the solution plus the cost of the disturbances.

The solution costs are lower as we focus on the particular equipment and controls that are sensitive. However, this approach may have additional costs associated with characterizing the sensitivity of the process components and installation. Efforts to understand the sensitivity of all parts of your process are usually very worthwhile in coming up with the best solution.

7.7 Improving Equipment Ride-through Characteristics

Ultimately, better equipment design is the best long-term solution for voltage sag problems. If manufacturers offered options for improved ride-through, it might be more economical to purchase these options than to install external devices for protection.

CHAPTER 8

SOLUTIONS TO VOLTAGE SAGS

8.1 INTRODUCTION

In the blink of an eye, a voltage sag event can bring production and facility systems in a company to a halt. To the human eye, voltage sags can cause the lights to dim. To automation equipment, sags can mean shutdown of equipment, loss of data and unexplained resets. Over time, voltage sags can stress components, resulting in premature wear and failure.

For processes that rely on high speed, any interruption can lead to significant production shortages. For processes that take hours to create one part, or a single batch of parts, process interruptions have a significant impact on company profits. Shutdowns result in scrapped work, production shortages, reduced service levels to customers and less income for the company.

Many manufacturing and process industries need to focus on ensuring full protection against voltage sag to maintain maximum competitiveness, productivity and quality. The Semiconductor Equipment and Materials Institute have gone so far as to establish a minimum standard with regard to sag immunity performance for semiconductor tools and equipment. SEMI F47 introduced a well thought out voltage-to-time curve that most equipment will be exposed to during normal operation. In addition, a specific method of test and reporting had been developed.

.

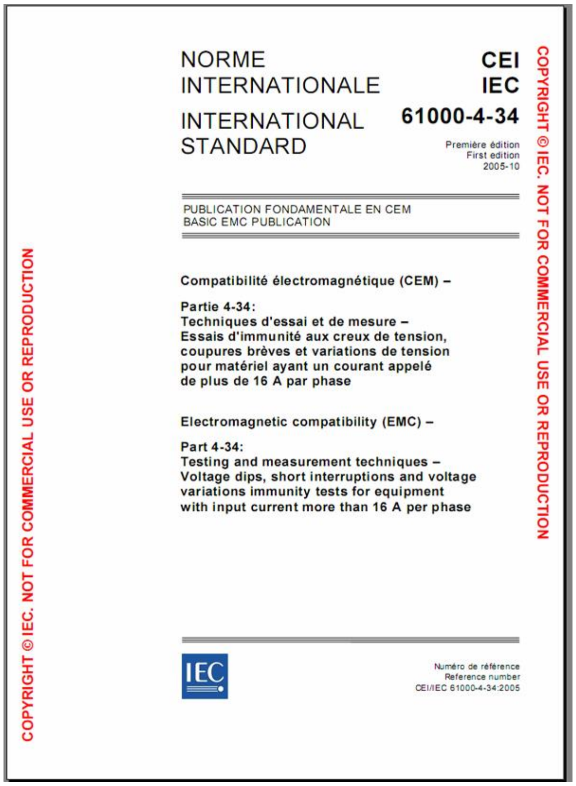
The IEC 61000-4-11 and IEC 61000-4-34 also promotes minimum voltage sag immunity requirement. These standards also specify the requirement for the sag generator and testing methodology.

Fortunately, there are ways to prevent voltage sags from disrupting factory's operations. As with most system enhancements, the costs of the solutions must be evaluated against the monetary losses associated with the disturbance. This section will identify the most common solutions and where best to apply them.

8.2 Equipment procurement specifications

Generally, the least expensive approach is to purchase control and other electronic equipment designed with the minimum immunity requirement mentioned in the previous page. Improvement of equipment immunity is probably the most effective solution against equipment trips due to voltage sags.

The best way to ensure that a machine meets the above requirements for voltage sag ride through is to include the requirement in the purchase contract terms and to demand proof of compliance. The requirement from IEC 61000-4-34 or SEMI F47 must be part of the equipment specifications. IEC 61000-3-4 specify more stringent requirement based on its 4 classes of voltage immunity requirement. It is advisable for very critical equipment to adopt IEC 61000-4-34 Class 1 immunity requirement.



NORME INTERNATIONALE
INTERNATIONAL STANDARD
CEI IEC 61000-4-34
Première édition
First edition
2005-10

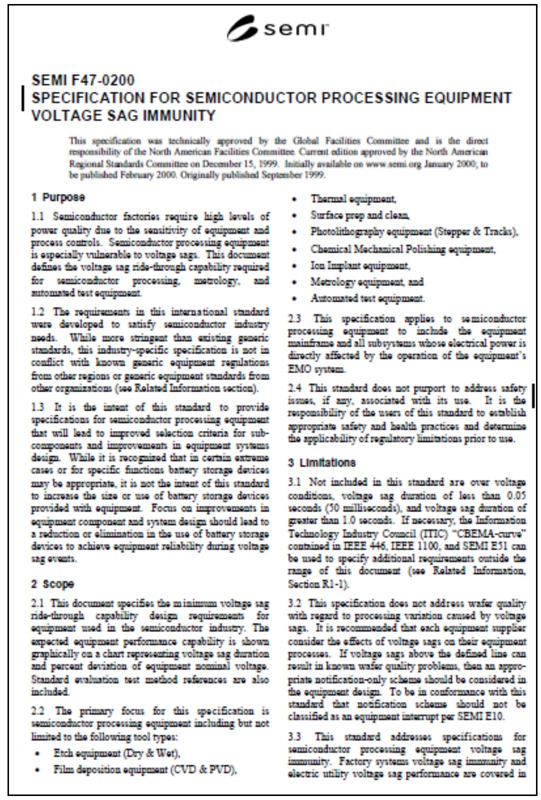
PUBLICATION FONDAMENTALE EN CEM
BASIC EMC PUBLICATION

Compatibilité électromagnétique (CEM) –
Partie 4-34:
Techniques d'essai et de mesure –
Essais d'immunité aux creux de tension, coupures brèves et variations de tension pour matériel ayant un courant appelé de plus de 16 A par phase

Electromagnetic compatibility (EMC) –
Part 4-34:
Testing and measurement techniques –
Voltage dips, short interruptions and voltage variations immunity tests for equipment with input current more than 16 A per phase

Numéro de référence
Reference number
CEI/IEC 61000-4-34:2005

IEC 61000-4-34



SEMI F47-0200
SPECIFICATION FOR SEMICONDUCTOR PROCESSING EQUIPMENT VOLTAGE SAG IMMUNITY

This specification was technically approved by the Global Facilities Committee and is the direct responsibility of the North American Facilities Committee. Current edition approved by the North American Regional Standards Committee on December 15, 1999. Initially available on www.semi.org January 2000, to be published February 2000. Originally published September 1999.

1 Purpose

1.1 Semiconductor factories require high levels of power quality due to the sensitivity of equipment and process controls. Semiconductor processing equipment is especially vulnerable to voltage sags. This document defines the voltage sag ride-through capability required for semiconductor processing, metrology, and automated test equipment.

1.2 The requirements in this international standard were developed to satisfy semiconductor industry needs. While more stringent than existing generic standards, this industry-specific specification is not in conflict with known generic equipment regulations from other regions or generic equipment standards from other organizations (see Related Information section).

1.3 It is the intent of this standard to provide specifications for semiconductor processing equipment that will lead to improved selection criteria for sub-components and improvements in equipment systems design. While it is recognized that in certain extreme cases or for specific functions battery storage devices may be appropriate, it is not the intent of this standard to increase the size or use of battery storage devices provided with equipment. Focus on improvements in equipment component and system design should lead to a reduction or elimination in the use of battery storage devices to achieve equipment reliability during voltage sag events.

2 Scope

2.1 This document specifies the minimum voltage sag ride-through capability design requirements for equipment used in the semiconductor industry. The expected equipment performance capability is shown graphically on a chart representing voltage sag duration and percent deviation of equipment nominal voltage. Standard evaluation test method references are also included.

2.2 The primary focus for this specification is semiconductor processing equipment including but not limited to the following tool types:

- Etch equipment (Dry & Wet),
- Film deposition equipment (CVD & PVD),
- Thermal equipment,
- Surface prep and clean,
- Photolithography equipment (Stepper & Tracks),
- Chemical Mechanical Polishing equipment,
- Ion Implant equipment,
- Metrology equipment, and
- Automated test equipment.

2.3 This specification applies to semiconductor processing equipment to include the equipment mainframe and all subsystems whose electrical power is directly affected by the operation of the equipment's EMO system.

2.4 This standard does not purport to address safety issues, if any, associated with its use. It is the responsibility of the users of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.

3 Limitations

3.1 Not included in this standard are over voltage conditions, voltage sag duration of less than 0.05 seconds (50 milliseconds), and voltage sag duration of greater than 1.0 seconds. If necessary, the Information Technology Industry Council (ITIC) "CBEMA-curve" contained in IEEE 446, IEEE 1100, and SEMI E51 can be used to specify additional requirements outside the range of this document (see Related Information, Section R1-1).

3.2 This specification does not address wafer quality with regard to processing variation caused by voltage sags. It is recommended that each equipment supplier consider the effects of voltage sags on their equipment processes. If voltage sags above the defined line can result in known wafer quality problems, then an appropriate notification-only scheme should be considered in the equipment design. To be in conformance with this standard that notification scheme should not be classified as an equipment interrupt per SEMI E10.

3.3 This standard addresses specifications for semiconductor processing equipment voltage sag immunity. Factory systems voltage sag immunity and electric utility voltage sag performance are covered in

SEMI F47

Figure 8.1 Voltage sag requirement for new equipment specification

Therefore, the best solution is to ensure new equipment has a built in immunity against voltage sags by ensuring the immunity specifications are part of the procurement procedure. Equipment manufacturers should design equipment with ride through capability for voltage sags.

8.3 Voltage sag solutions for existing industrial plant

The first step towards improving the immunity of any industrial plant is to identify which process in the plant is sensitive to voltage sags. Secondly, one must understand the product manufacturing process and the operation of the equipment related to the process. Next, identify which components are critical to the related machine operation and would be adversely affected by voltage sag. Most motors, lighting and indicators can tolerate short-duration sag with negligible detriment to production.

Normally, the most critical and normally sag-sensitive component is normally the ac-dc power supply used to power all dc control and programmable logic circuits. A majority of power supply modules currently available on the market average 10 to 20 ms of hold-up time at full load. These devices will not meet the sag immunity performance needed to work during common sag events without special considerations taken by the system designer.

The immediate action plan that one can consider is to protect or harden the control and logic circuits from voltage sags. There are a few methods available to protect these circuitries. By implementing these methods, the control circuitries will be protected against voltage sags but not the primary equipment they are controlling.

For chillers, compressors or other motor loads, by protecting their control circuitries only, the motors will be experiencing a slight reduction in speed during a voltage sag event. The plant engineer must understand the impact of the motors slowing down. The production process in the plant must not be affected by the reduction of the motor speed. The other thing to consider is the impact of the voltage sags to the primary equipment, for example motors, etc. The protected control circuitry will ensure the primary equipment is still connected and exposed to the short duration voltage sags. Will there be any side effect on the motor etc?

Therefore, to ensure a successful voltage sag solution for existing industrial plants, a detailed discussion must be done with the plant engineer and equipment supplier before implementing the voltage sag immunity solutions.

8.3.1 Hardening requirement for control and logic circuits

One simple option is to use a universal input power supply (85-264 Volt) and power from the higher line voltage (208/240 Volt). This, of course, only meets the needed level of performance when powered from the higher line voltage.

8.3.1.1 SEMI F47 compliant power source

Another simple method is to use a SEMI F47 compliance power supply to power the control circuit.

Figure 8.2 Example of a SEMI F47 compliance power supply

8.3.1.2 Change the trip setting of protection relay (UVR etc.)

Another inexpensive and simple solution is to adjust the trip thresholds of sensitive equipment. If a relay is frequently tripping during a voltage sag, try to change its settings i.e. either the voltage threshold or the trip delay. However, this measure can be done only if the original trip settings were set too conservative, so it is important to understand what they were designed to protect.

If an unbalance relay, an under voltage relay, or an internal reset or protection circuit is inadvertently tripping during a voltage sag, first try to change its settings. Consider changing the voltage threshold, and consider changing the trip delay, either or both to slow it down. Sometimes this can be as simple as twisting a knob; sometimes it may take a component change or firmware adjustment.

It is important to note that this simple solution can be implemented if the trip settings were set too conservatively to begin with; trips are useful and important, so we do not want to eliminate them completely. The recommended settings for an UnderVoltage relay (UVR) is 70% with a time delay of 2-3 second. Always refer to the equipment manufacturer before changing the relay settings.

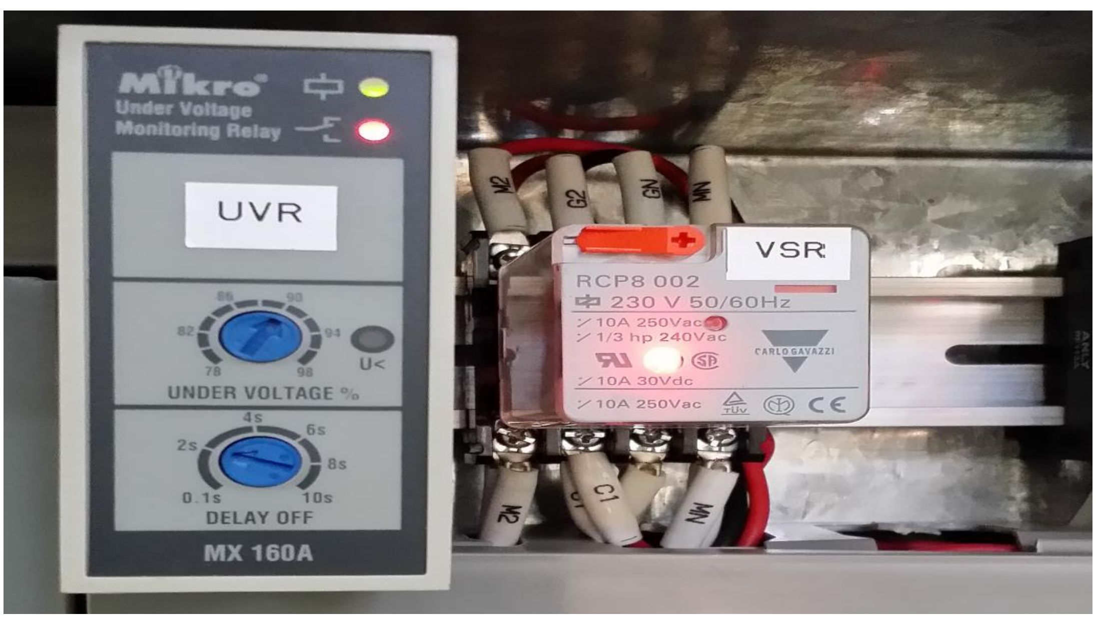


Figure 8.3 Changing the voltage threshold and time delay

8.3.1.3 Installing a coil hold-in device [26].

Another option is to install a coil hold-in device. These devices are designed to mitigate the effects of voltage sags on individual relays and contactors. Coil hold-in devices are installed between the relay or contactor coil connection terminals and the incoming alternating current (ac) control line. They allow a relay or contactor to remain engaged until the voltage drops to about 25 % of nominal, significantly improving its voltage sag tolerance without interfering with emergency shutoff functions. The best application for this type of device is to support relays and contactors in an emergency off (EMO) circuit, master control relay, or motor control circuit.

Figure 8.4 A coil hold-in device

During a voltage sag, this device maintains a current flow through the coil that is sufficient to hold in the contacts closed. The circuit is designed to provide current to hold in the coil for sags down to 15-25% voltage. It is not designed to hold in the coil for cases where the voltage goes below 15%. This allows “emergency stop” circuits to act correctly and will prevent any problems with out-of-phase conditions following an interruption.

8.3.1.4 Implement auto restart schemes

Reprogramming the response of an Adjustable Speed Drive (ASD) response to a voltage sag may be an option if the process requirements allow deviations in the speed and torque of the motor. If the application does not require an operator to restart the process, the ASD may be able to be reprogrammed to provide a non-synchronous time-delay restart. Once the motor coasts down to zero speed, this feature will restart the motor after a user-defined time delay.

Figure 8.5 Adjustable Speed Drive (ASD)

Another programming option is to reduce the dc bus under voltage trip point. Some processes require precise speed and torque regulation. Because the torque and speed vary when the dc bus reaches the under voltage trip point, some drive manufacturers offer software revisions for existing drive applications that allow users of ac drives to lower the dc bus under voltage trip point. By lowering the trip point, drives and processes can ride through longer and deeper voltage sags without interrupting production.

Often, the software revisions are not part of the standard drive control software and must be requested from the manufacturer. The drawback to this approach is that rectifiers and fuses may be damaged due to high inrush current and over current conditions. The current increases as the dc bus under voltage trip point decreases. These conditions should be considered when lowering the under voltage trip point.

8.3.1.5 To maintain the DC link voltage for ASD.

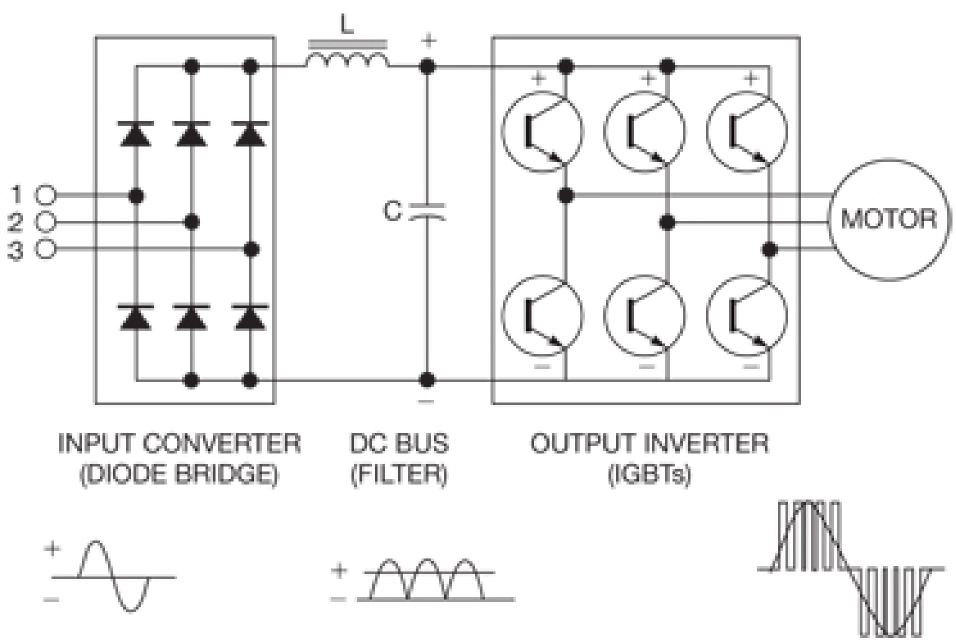


Figure 8.6 Single line diagram for a typical Adjustable Speed Drive (ASD)

Note: IGBT- An insulated-gate bipolar transistor (**IGBT**) is a three-terminal power semiconductor device primarily used as an electronic switch which, as it was developed, came to combine high efficiency and fast switching.

There are different ways to improve ride-through for ASD. In the literature mainly three ideas for voltage sag ride-through are mentioned. The first two are aimed at maintaining the DC-link voltage.

The ideas for voltage sag ride through are as follows:

• Keep up the DC-link voltage electronically.

This can be made by making the energy storage larger, i.e., a larger DC-link capacitor or relying on batteries (so-called uninterruptible power supplies, UPS).

These solutions tend to become bulky and expensive if the voltage should remain at the nominal level for longer periods.

Another solution is to use an active rectifier or a chopper

• Keep up the DC-link voltage with load inertia,

If the plant is equipped with large rotating masses (e.g., paper mills) these energy storages can be used as generators to keep up the DC-link voltage during the sag.

This works even for a sag of longer duration. It is also a good solution to a controlled shutdown (at an interruption), as the DC-link voltage can be held at the highest possible level for the time it takes to make this shutdown.

A requirement is that the process uses several motor drives that are fed by a common DC link. If the process does not have a large rotating mass, there is the possibility to use an extra flywheel. (The drawback is that the system becomes slower due to the extra inertia.)

• Let the DC-link voltage vary and control the drive properly.

Naturally, the above two solutions are costly. If we can accept that the DC-link voltage varies (and instead use better control), a less expensive solution is obtained.

8.3.1.6 Change the settings for unbalance relay

On three-phase systems, voltage sags are often asymmetrical (they affect one or two phases more than the remaining phases). Three-phase motors and transformers can be damaged by sustained voltage unbalance; it can cause the transformer or motor to overheat. So it makes sense to put in an unbalance relay, which is a device that shuts down the system if the voltage unbalance exceeds some threshold, typically a few percent.

To minimize the impact of voltage sag, it is recommended to set the unbalance relay at 20-50% unbalance with a delay time of 2 seconds.

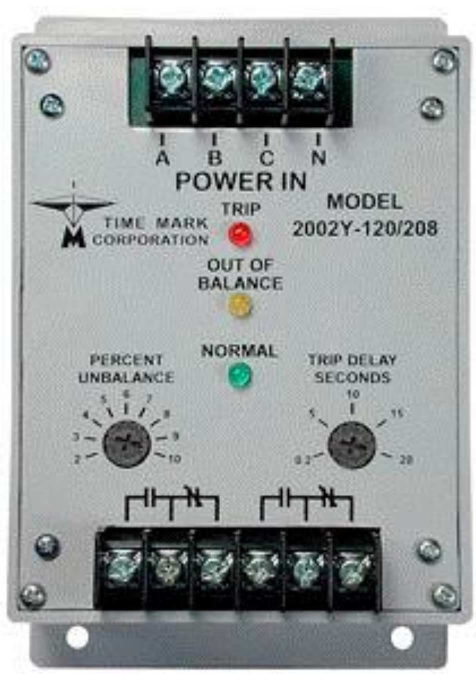


Figure 8.7 Unbalance relay

.

8.3.1.7 Employ a time delay settings for reverse power relay

Figure 8.8 Reverse power relay

The reverse power relay is a directional protective relay that prevents power from flowing in the reverse direction. The relay is used in installations where a generator runs in parallel with the utility or another generator so as to prevent power from the bus bar or another generator from flowing back to the active generator when its output fails.

The relay monitors the power from the generator and in case the generator output falls below a preset value, it quickly disconnects the generator coil to avoid power from flowing into the stator coil. The generator output can also fail due to problems with the prime mover, – turbine or engine that drives the generator, issues with speed controller, or different frequencies during synchronization. When the prime mover fails, the generator stops producing power and may instead start drawing power from the other parallel sources and start motoring. The reverse power relay senses any reverse direction of power flow and disconnects the generator to avoid any possible damage.

Overall advantages of reverse power relay are:-

- Prevents power from flowing in the reverse direction and damaging the generator stator
- Prevents damage to the prime mover
- Prevents fire or explosions that may be caused by unburned fuel in the generator

During the occurrence of voltage sag in the utility power system, a reverse power flow condition may happen due to sudden difference in voltages between the utility system and the generator. The reverse power relay senses any reverse direction of power flow and disconnects the main circuit breaker to avoid any incident the generator feeding into the system faults. To minimize the tripping of the main circuit breaker due to reverse power flow, it is recommended to activate the time delay to 3 second.

8.3.1.8 Overall actions for hardening the control circuit & protection relays

Tip No	Descriptions
1	Use a universal & compliance power supply (85-264 Volt)
2	Use DC supply (if applicable)
3	Wire load devices in a phase-to-phase configuration
4	Identify & improve sensitive ice cube relays
5	Do not use phase monitoring relays or under voltage relays (UVR) in the interlock circuit, VCB etc.
6	Install auto restart schemes (if applicable)
7	Employ Time Delay tripping for Motors, Contactors, UVR etc (Voltage 70%, t= 3 seconds)
8	To study on maintaining DC link voltage for VFD, ASD etc.
9	Employ delay tripping for unbalance relay (20-50 %, t = 2 second)
10	Employ delay tripping for reverse power relay (t = 3 second)

8.4 Single phase power conditioners for voltage sag mitigation

Another method employed to protect against short-term power sags is to use power-conditioning devices to regulate and ensure sufficient power to the control devices or single phase equipment during voltage sag event. The alternative to adding these mitigating devices to the production equipment is to purchase and develop equipment designed to tolerate sags. This proactive approach takes more planning, but results in lower overall system costs. To ride through a voltage sag event, the load will need some kind of system that can react within about ½ cycle and provide near-normal power for a few seconds until the voltage is fully restored. This requires either a source of stored energy at the site or an alternate source of energy. These devices must either be capable of being switched very quickly or be always on-line.

To achieve this condition, one needs to install some form of a power-conditioning device. These solutions increase in cost with the size and scope of the equipment or circuits being protected. The locations to install the power conditioner will also determine the coverage areas of protection against voltage sags.

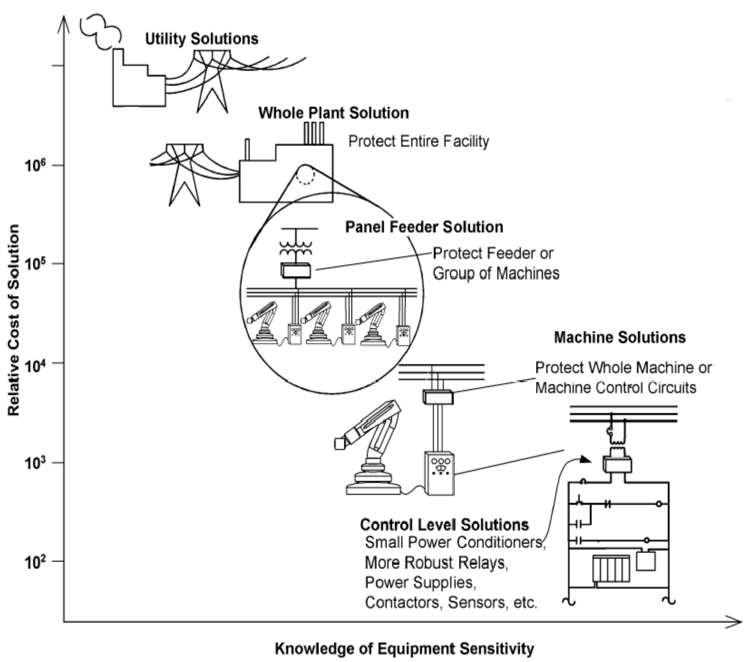


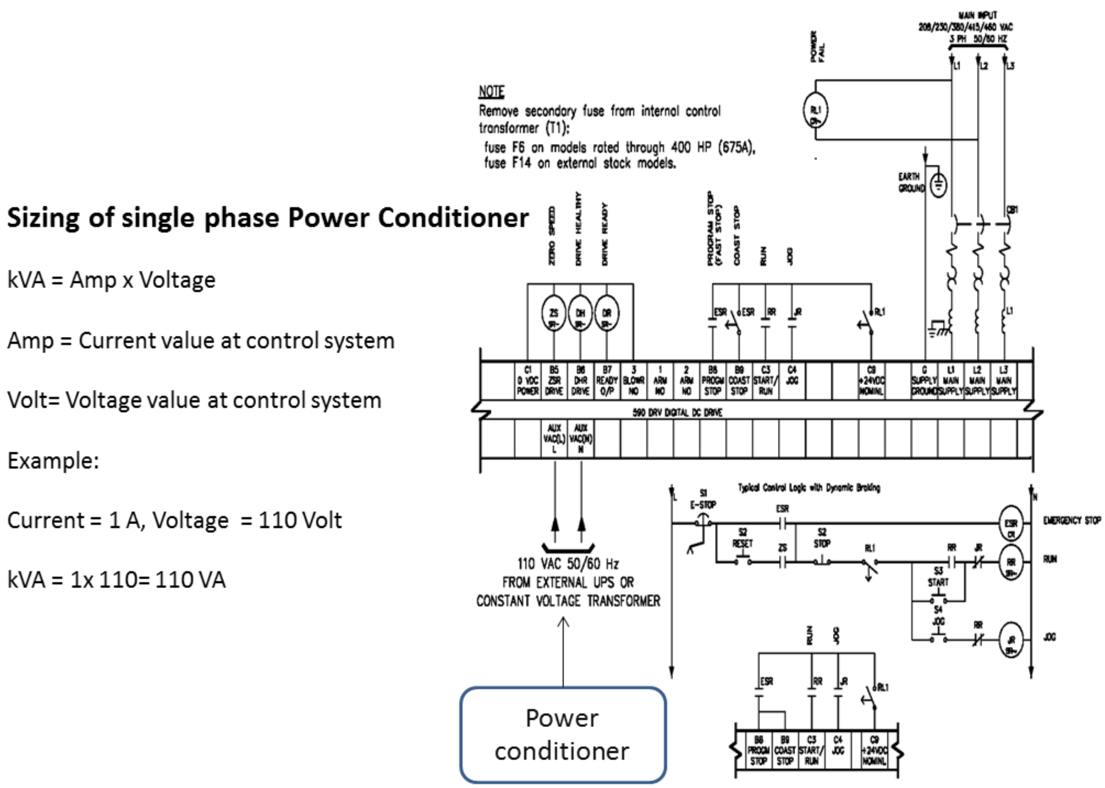
Figure 8.9 Level of equipment sensitivity and cost of solutions

8.4.1 Sizing procedure for single-phase power conditioners

The power conditioners must be installed at the control system or at the control transformer for the control system. Please refer to **subchapter 4.8** for sample diagrams for control circuits. To ensure correct sizing of the power conditioner, please take the current & voltage values at the control transformer using a current clamp meter and voltage indicator. Select the next highest rating (kVA) for the power conditioner.

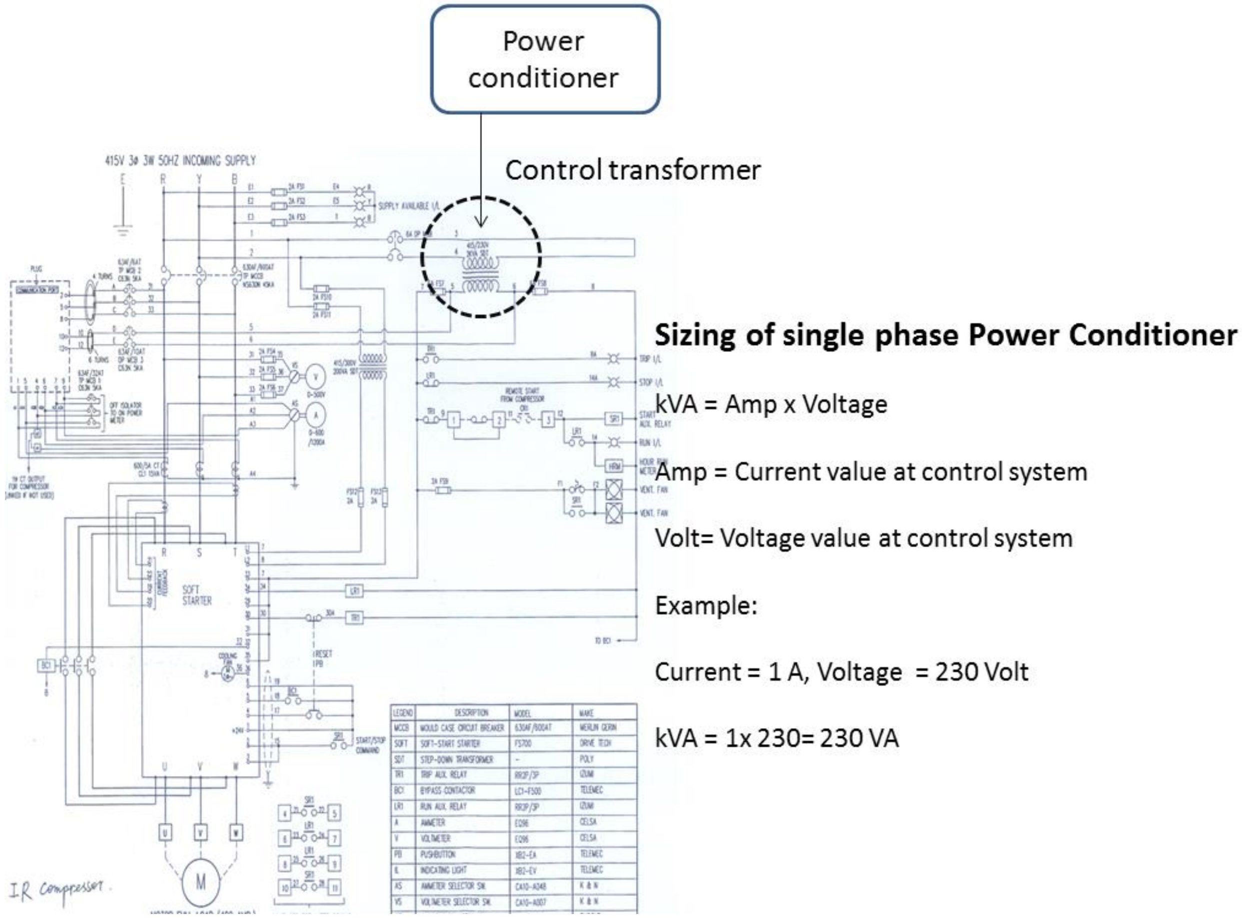
Examples of the sizing of the power conditioners are shown in figures 8.10 & 8.11.

Once the size of the power conditioner is known, please choose the best power conditioner to protect the control circuit from voltage sags. Please refer to IEC standards in subchapters 6.3.2.4 & 6.3.2.5, to determine the immunity class requirement (C1, C2 or C3).



Note. Please ensure there is no undervoltage relay (UVR) at the control circuit.

Figure 8.10 Example on sizing of single phase power conditioner 110 Volt



Note. Please ensure there is no undervoltage relay (UVR) at the control circuit.

Figure 8.11 Example on sizing of single phase power conditioner 230 Volt

8.4.1.1 Uninterruptible Power Supply (UPS)

Installing an uninterruptible power supply (UPS), on a computer, programmable logic control (PLC) or controls to switch to battery during a voltage sag or an interruption will minimize process interruption. The down side to this approach is the battery. As an example, lead acid batteries have the following disadvantages: a) generates hydrogen gas, must be ventilated, b) battery lead is a hazardous waste, and c) battery life is limited and decreases rapidly when cycled often.

An advantage is that the UPS will ride through not only sags, but also momentary and extended interruptions up to the limit of the battery capacity, maybe 5 to 10 minutes.

Note: Please verify the output voltage from the UPS is always +/-5 % from the nominal voltage when exposed to voltage sag or momentary interruptions.

Figure 8.12 A Single Phase Uninterruptible Power Supply (UPS)

8.4.1.2 Constant Voltage Transformer (CVT)

Most voltage-sag solutions can be handled by ferroresonant transformers. These power conditioners are also known as constant-voltage transformers (CVTs). CVTs are ideally suited for constant, low-power loads. Unlike conventional transformers, the CVT allows the core to become saturated with magnetic flux, which maintains a relatively constant output voltage during input voltage variations such as under voltages, over voltages, and harmonic distortion.

Installing a ferroresonant (constant voltage transformer-CVT) transformer on a computer, programmable logic control (PLC) or controls will provide sag ride through capability. They also provide filtering of transients. CVT will not ride through a momentary or sustained interruption. They have no moving parts, no battery and are very reliable. Another consideration when sizing a CVT is the load characteristic. A CVT must be sized for the maximum load.

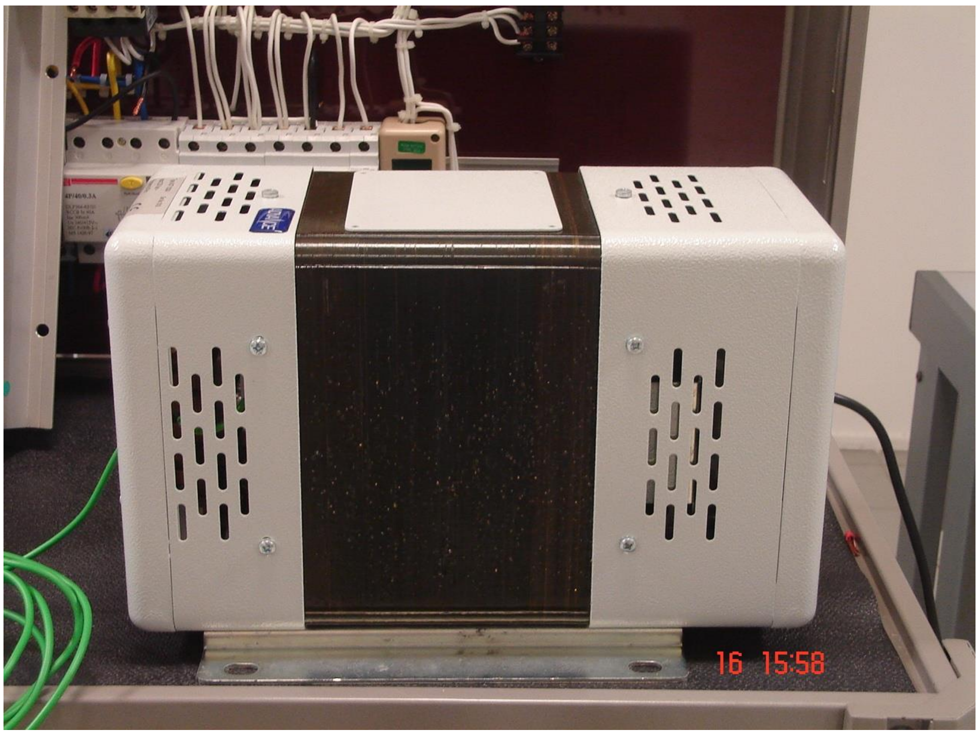


Figure 8.13 Constant Voltage Transformer

When the transformer is overloaded, the voltage will decrease and collapse to zero at approximately 150% of loading. Therefore, if the load profile includes an inrush current or a starting motor, the transformer must be sized for this transient load, not the steady-state load. CVTs provide voltage sag ride-through of 25 % for 1 second and also filter spikes, but they are not able to protect against interruptions, either momentary or sustained. CVTs are often used for relatively constant, low-power loads, and have the advantage of lower operating and maintenance costs than UPSs, because CVTs do not require batteries.

8.4.1.3 Dip Proofing Inverter [27]

For an individual computer, process control circuits or a group of machines, another simple solution is to install a Dip Proofing Inverter (DPI), which can ride through a voltage sag event down to 0 % of nominal voltage for up to 3.1 seconds.

Figure 8.14 Dip Proofing Inverter (DPI)

8.4.1.4 Voltage Dip Compensator (VDC) [28]

A Voltage Dip Compensator (VDC), which can ride through a voltage sag down to 37 % of nominal voltage for up to 3.1 seconds can also be used to protect single phase equipment and control circuits.

Figure 8.15 Voltage Dip Compensator (VDC)

8.4.1.5 Dynamic Compensator (Dynacom)[29]

DynaCom is a low voltage dynamic voltage compensator designed to mitigate voltage sags by injecting a compensating voltage directly into the power supply. Under normal system operating conditions, Dynacom allows system voltage to pass through with high efficiency. In the event of a voltage sag, Dynacom produces a compensating voltage of an appropriate magnitude and duration to “fill in” the sag, thus reproducing the original voltage waveform. The direct injection technique used in Dynacom provides accurate and efficient voltage compensation. The Dynacom can correct input voltage to as low as 40 % of nominal voltage for up to 1 second.

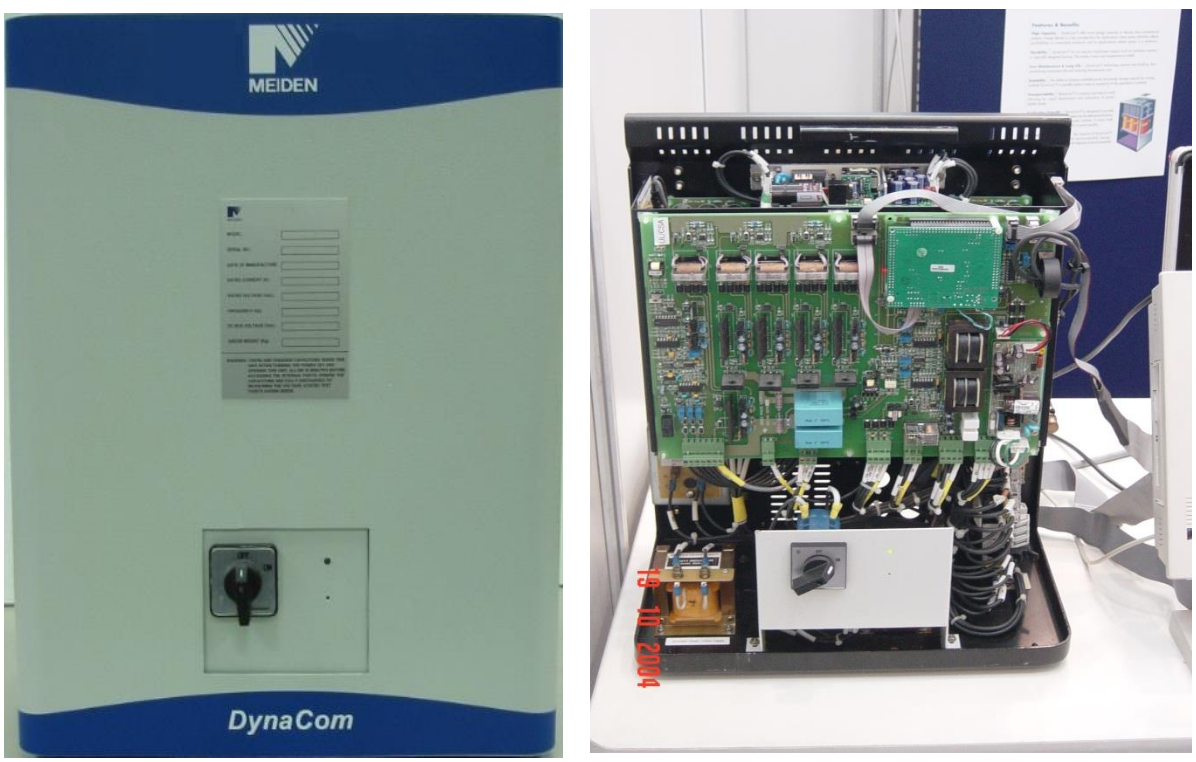


Figure 8.16 Dynamic Compensator (Dynacom)

8.4.1.6 Dynamic Sag Corrector (DySC) [30]

The DySC (pronounced 'disk'), rated at 250VA to over 3,000 kVA specifically protects sensitive equipment and manufacturing processes from deep voltage sags and momentary interruptions, the most common power quality events. The DySC can correct input voltage to as low as 0 % of nominal voltage for 50 ms and 50 % voltage for 2 seconds.

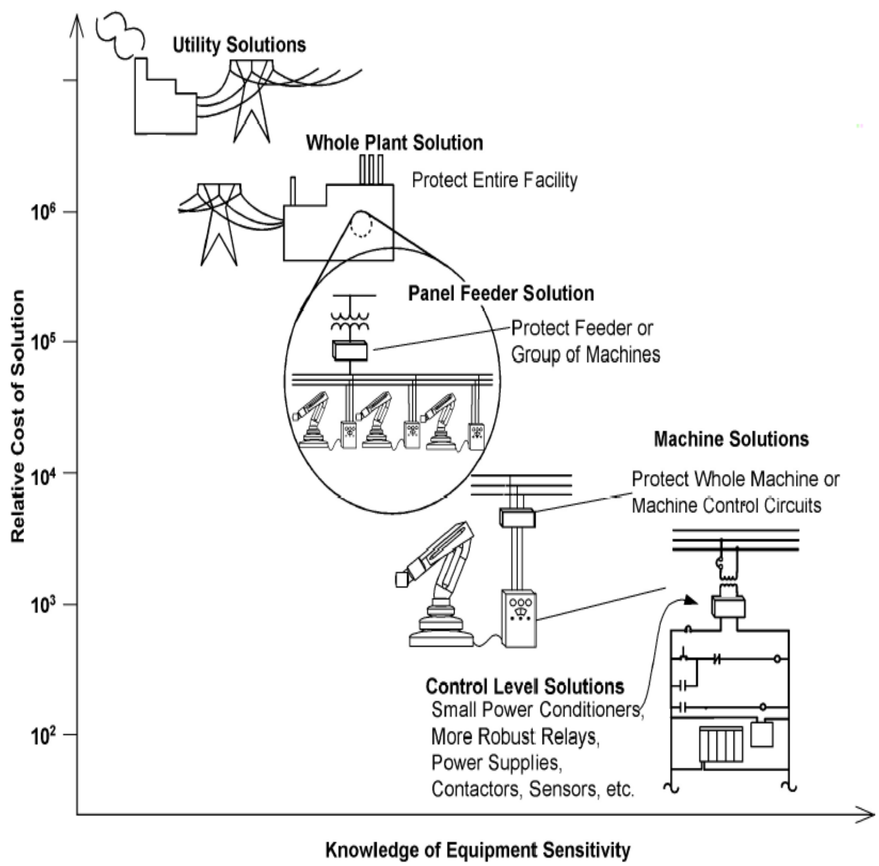
Figure 8.17 Mini DySc

CHAPTER 9

LARGE SCALE SOLUTIONS TO VOLTAGE SAGS

9.1 INTRODUCTION

In Chapter 8 of this guidebook, solutions related to the control level solutions were discussed. The solutions range from hardening processes (changing of UVR setting etc.) and installation of single phase power conditioner. In this chapter, another level of solutions to voltage sags, which are more comprehensive, are the panel feeder and whole plant solutions. These solutions increase in cost with the size and scope of the equipment or circuits being protected.



From Figure 8.9 Level of equipment sensitivity and cost of solutions

To achieve the large scale solutions for voltage sag requires the use of three-phase power conditioners.

9.1.1 Sizing procedure for three phase power conditioners

The power conditioners must be installed at the panel feeder and whole plant solutions.

To size the power conditioner, please take the current & voltage values at the Main Switch Board or Circuit Breaker. Examples of the sizing of the power conditioners are shown in Figure 9.1. Select the next highest rating (kVA) for the power conditioner and please consider any potential current inrush in sizing the power conditioner when starting the equipment.

Once the size of the power conditioner is known, please choose the best three phase power conditioner to protect the panel feeder and whole plant solutions from voltage sags. Please refer to IEC standards requirement in **subchapters 6.3.2.4 & 6.3.2.5.**

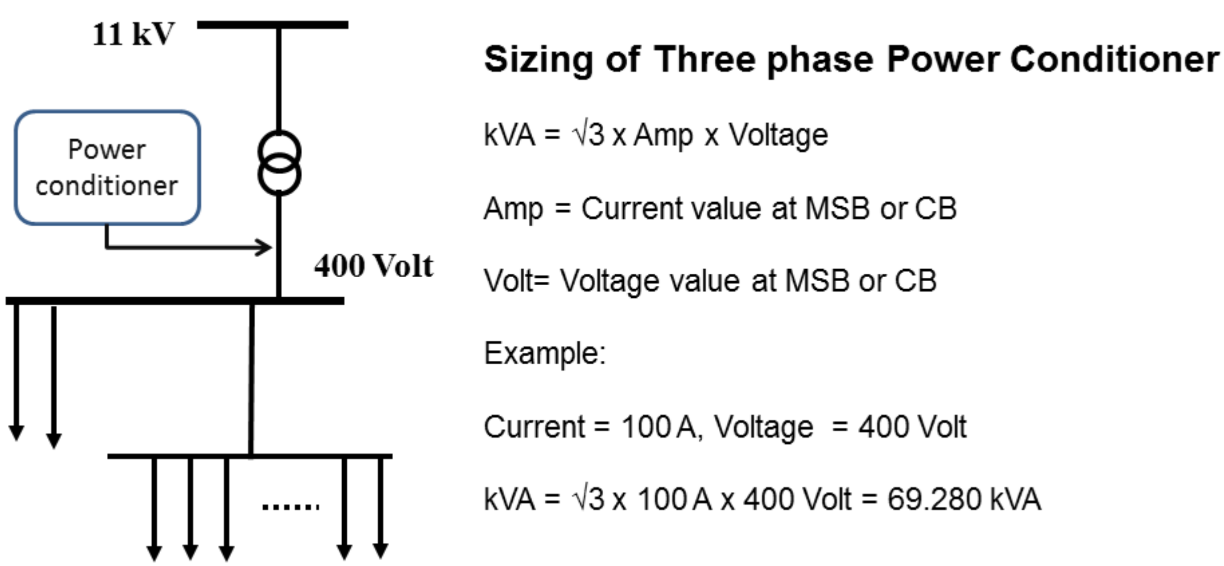


Figure 9.1 Example on sizing of three phase power conditioner

Descriptions of a few three-phase power conditioners available in the market are described in this chapter.

9.2 Three Phase Uninterruptible Power Supplies (UPS)

An uninterruptible power supply (UPS) is a device that allows a computer or electrical device to keep running for at least a short time when the primary power source is lost. A UPS contains a battery that "kicks in" when the device senses a loss of power from the primary source. A UPS will provide full power backup based on the limit of the battery capacity, maybe 5 to 10 minutes. The size of the UPS ranges from 10kVA to Megawatt Systems.

A UPS also provides protection from voltage sags and power surges. The down side to this approach is only the battery systems.

Figure 9.2 Three Phase Uninterruptible Power Supplies (UPS)

9.3 Active Voltage Conditioner (AVC) [31]

9.3.1 PCS100 AV-40

The PCS100 Active Voltage Conditioner (AVC) or Omniverter is an inverter-based system that protects sensitive industrial and commercial loads from voltage disturbances. The PCS100 AVC-40 provides fast, accurate voltage sag correction, continuous voltage regulation and load voltage compensation. It has been optimally designed to provide the required equipment immunity from the level of voltage sags expected on the AC supply network.

Table 9.1 Technical specifications for PCS100 AVC-40

Details	40 % AVC
Protection for 3 phase sags	60 % remaining voltage to 100 %. 50 % remaining voltage to 90 %
Protection for 1 phase sag	Single-phase sags down to 40 % remaining voltage
Nominal ratings range	40 % correction 150 to 3600 kVA @ 480 V 150 to 3600 kVA @ 400 V 150 to 1800 kVA @ 220 V

Figure 9.3 PCS100 AVC-40 & PCS100 AVC-20 Active Voltage Conditioners

9.3.2 PCS100 AVC-20

The PCS100 AVC-20 is a power protection system designed for use by industrial and large commercial operations in environments where an unstable network or utility voltage affects productivity. The PCS100 AVC-20 ensures a continual, regulated supply of utility voltage where electric infrastructure is stressed, unstable or unreliable.

Table 9.2 Technical specifications for PCS100 AVC-20

Details	20 % AVC
Full correction to 100%	Yes
Continuous Regulation	+/-20% to +/-1% +/-30% to +/-10%
Nominal ratings range	250 to 3300 kVA @ 380, 400, 415V

Active Voltage Conditioner

Omniverter is in the background

Figure 9.4 Active Voltage Conditioner & Omniverter installed in other countries

9.4 Datawave [32]

The Datawave is a Magnetic Synthesizer that generates a stable output waveform to distribute to the sensitive electronic equipment. The self-contained system can be used to condition utility power, distribute it to sensitive electronics, and monitor power parameters. Systems are available with outputs ranging from 15 to 200 kVA.

This system makes available total power conditioning under the worst power conditions – maintaining consistent output quality even during - 40% under voltages and +40% over voltages for 1 second. This equipment enables power conditioning, monitoring and flexible output distribution from a single factory tested unit. It also enables handling of non-linear loads and high neutral current without over sizing.

The general specifications are:

Voltage Regulation: For input voltages of ± 40%, output voltage is within +5% for any load condition up to full load. Single Phase Protection: For loss of one input phase, output voltages remain within 6% and –4% up to 60% load.

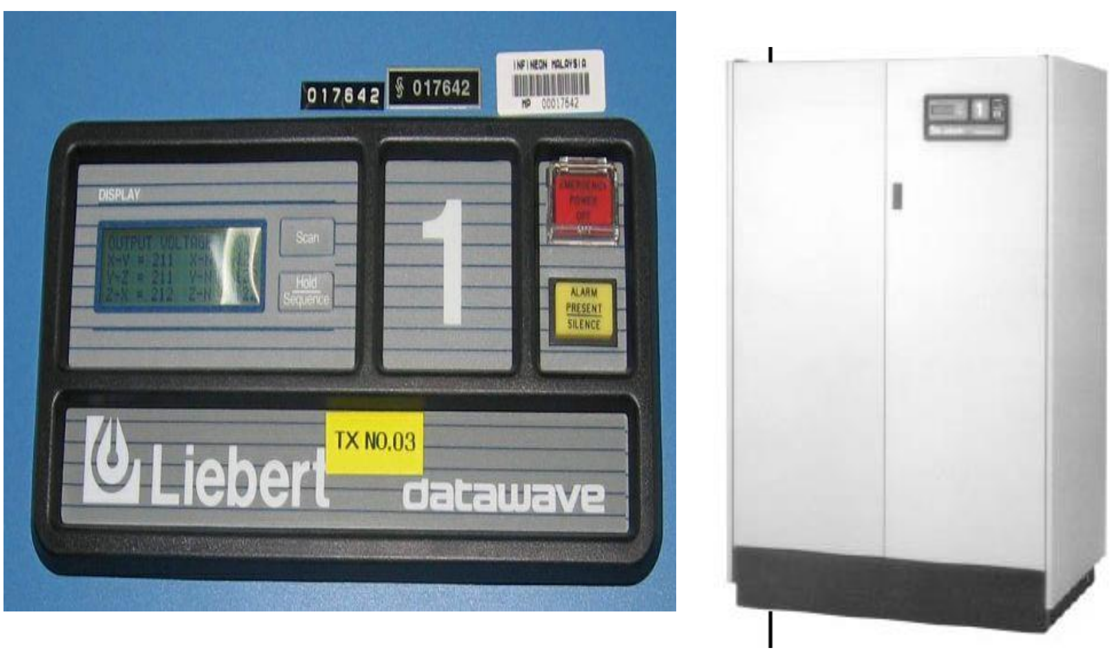


Figure 9.5 Datawave Magnetic Synthesizer

9.5 Flywheel

A flywheel is a simple form of mechanical (kinetic) energy storage. Energy is stored by causing a disk or rotor to spin on its axis. The stored energy is proportional to the mass of the flywheel and the square of its rotational speed. Advances in power electronics, magnetic bearings, and flywheel materials coupled with innovative integration of components have resulted in direct current (dc) flywheel.

A flywheel together with a motor-generator (M/G) set can immunize critical processes against all voltage sags. When a voltage sag occurs, the motor- generator set feeds the load, the energy being supplied by slowing down the flywheel. Different connection topologies of the flywheel to the M/G set exist of which Figure 10.3 shows the main components of a connection using power electronics.

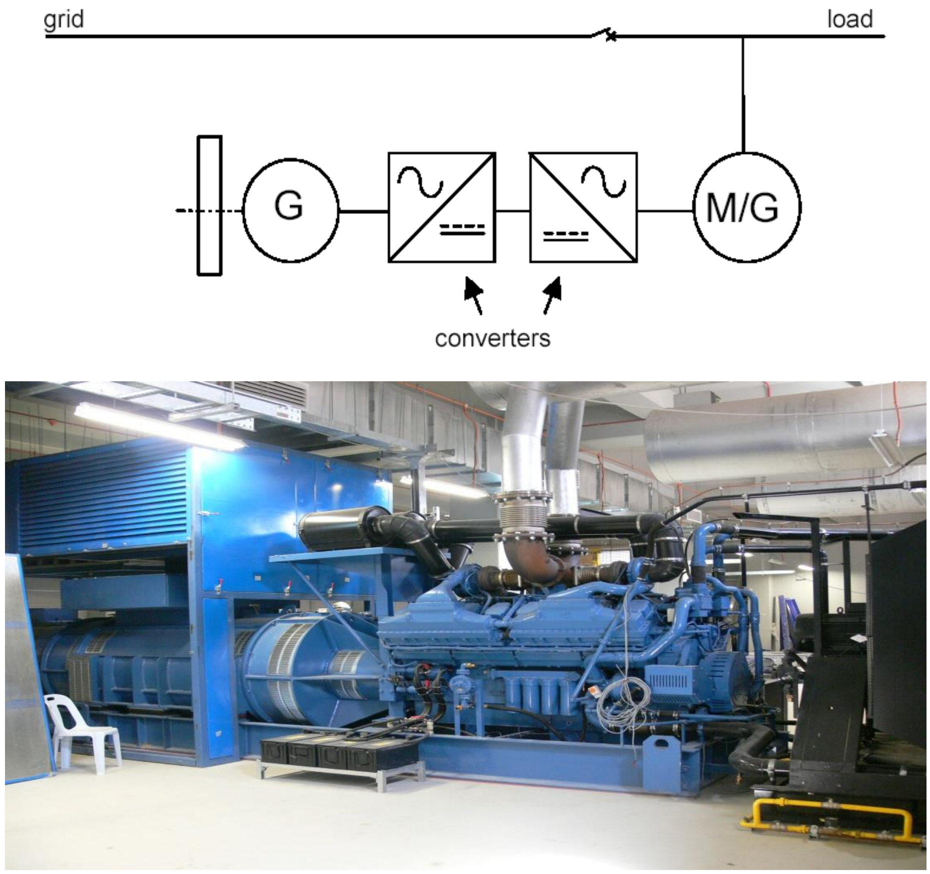


Figure 9.6 Flywheel

9.6 Dynamic Voltage Restorer (DVR) [33]

The DVR is designed for series connection in a medium voltage distribution line. It maintains the voltage applied to the load during sags and swells by injecting a voltage of compensating amplitude and phase angle into the line.

The DVR is a means to satisfy the stringent power quality demands of industrial and commercial customers. It also provides a means for energy users to isolate themselves from voltage sags, swells, and unexpected load changes originating from the transmission or distribution system.

The general specifications for the DVR are as follows:

Phase	Three Phase
Voltages	4.6 – 34.5 kV
Power	2-30 MVA
Ride Through Capability	50% for single phase fault for 1 second
	50% for three phase fault for 333 ms

Figure 9.7 Dynamic Voltage Restorer

9.7 Three-phase Dynamic Compensator (Dynacom)

Under normal system operating conditions, DynaCom allows system voltage to pass through with high efficiency. In the event of a voltage sag, DynaCom produces a compensating voltage of an appropriate magnitude and duration to “fill in” the sag, thus reproducing the original voltage waveform. The direct injection technique used in DynaCom provides accurate and efficient voltage compensation.

The specifications for the Dynacom are as follows:

Phase	Three Phase
Voltages	208-690 volts
Power	342 - 987 kVA
Ride Through Capability	40% for 1 second
	0% for 60 ms

Figure 9.8 Three phase Dynacom

9.8 Dynamic Sag Corrector (ProDysc)[30]

The second version of the Dynamic Sag Corrector is called the ProDysc. The first version is called the MiniDySc as mentioned in Chapter 8.

The ProDysc is suitable to protect the entire equipment or the panel feeders depending on the loading capacity of the feeder.

The specifications for the ProDysc are as follows:

Phase	Three Phase
Voltages	208-480 volts
Power	10-1640 kVA
Ride Through Capability	0% for 50 ms
	50% for 2 second

Figure 9.9 ProDysc

9.9 Dynamic Sag Corrector (MegaDysc) [30]

The third version of the Dynamic Sag Corrector is called the MegaDysc. The MegaDysc is suitable to protect whole panel feeders (process level) depending on the loading capacity of the feeder. The specifications for the MegaDysc are as follows:

General Specifications

Phase	Three Phase
Voltages	480 volts
Currents	400-2400 A
Power	333 kVA- 2 MVA

Figure 9.10 1 MVA MegaDySc

9.10 UPS-I, Industrial UPS [34]

The PCS100 UPS-I is an industrially rated UPS designed specifically for the challenging motor, AC drives, and other industrial loads. The PCS100 UPS-I is the ideal solution where very deep sags or short term power outages occur. The PCS100 UPS-I uses energy storage, coupled through an inverter to allow the downstream load to ride through very deep sags and short term outages. The PCS100 UPS-I is an industrial, single conversion UPS.

Table 9.3 Technical specifications for PCS100 UPS-I

Details	PCS100 UPS-I
Batteries	30 Seconds autonomy
Ultracapacitors	2 seconds autonomy
Nominal ratings range	150 to 3000 kVA @ 480 V 50/60 Hz 150 to 3000 kVA @ 400 V 50 Hz 150 to 1500 kVA @ 220 V 50/60 Hz

Figure 9.11 PCS100 UPS-I, Industrial UPS

9.11 Medium Voltage UPS

The PCS100 MV UPS is an industrially rated UPS suitable for datacenters, motors, AC drives and other loads found in typical industrial plants. The PCS100 MV UPS uses energy storage coupled through an inverter, to allow the downstream load to ride through very deep sags and short-term outages. The MV UPS is an industrial, single conversion UPS.

Table 9.4 Technical specifications for PCS100 MV UPS

Details	PCS100 MV UPS
Batteries	15 minutes autonomy
Ultracapacitors	2 seconds autonomy
Nominal ratings range	2000, 4000, 6000kVA @6.6kV
Nominal ratings range	2250kVA to 11,250kVA @11kV and 22kV

Figure 9.12 PCS100 MV UPS

9.12 PureWave® Outdoor UPS Systems [35]

The PureWave UPS System protects power-sensitive equipment from the detrimental effects of PQ disturbances such as voltage sags, surges, transients, momentary disruptions, and complete outages. This solution supports the entire load with clean power for up to 60 seconds, eliminating 99% of all power quality problems. It supports reduced loads for up to 180 seconds. A high-efficiency static switch provides immediate 2 to 4 millisecond response. An extended run-time version is called the PureWave® UPS-XT. This product provides battery run-times in excess of 1 minute to 15 minutes. The PureWave UPS System can be seamlessly coordinated with a backup generator set. Ride-through time can be tailored to permit start-up, then "soft" load transfer to the backup generator, for 100% protection through extended outages. No costly utility paralleling switchgear is needed. And the backup generator can be sized up to 35% smaller than with conventional UPS systems.

Product ranges:-

- Low-voltage models. Available in capacities from 313 kVA up to 2500 kVA for 208- to 600-volt applications.
- Medium-voltage models. Available in capacities from 2.5 MVA to 20 MVA for 5- to 33-kV applications.

Figure 9.13 PureWave® Outdoor UPS Systems

9.13 Sag Fighter

The Sag Fighter provides solid, affordable protection for sensitive equipment from deep voltage sags (dips) without batteries or energy storage. Available in sizes from small three phase applications up to complete facility protection, the Sag Fighter is compatible will all load types and power factors. The Sag Fighter works simply by using additional current to create a properly shaped injection voltage to replace those portions of the voltage waveform that is missing during a sag event. The unit monitor the incoming waveform for any deviation from normal and reacts to correct a sag when the voltage starts failing below 90% of nominal voltage. Table 10.2 shows the sag correction/operation characteristics.

Table 9.5 Sag correction/operation for Sag Fighter

Sag Correction	1 or 2 phase sags to 30% remaining voltage (-70% sag) corrected to 95% of nominal voltage
	3 phase sags to 60% remaining voltage (-40% sag) corrected to 95% of nominal voltage
Response Time	Full sag correction within 2 ms regardless of load or load power factor
Correction Duration	Sags corrected for a minimum of 100 seconds regardless of load or power factor

Figure 9.14 Sag Fighter

CHAPTER 10

SUMMARY OF GUIDEBOOK

According to IEC 61000-2-8 [10], voltage sags have been an intrinsic feature of public electricity supply since the earliest times. Yet in recent decades they have become an increasingly troublesome disturbance, giving rise to inconvenience and even considerable economic loss. The reason is that some modern electricity utilisation equipment, either in its own design or because of control features incorporated in it, has become more sensitive to voltage sags. There is therefore a need for an increased awareness of the phenomenon among the suppliers, customers of electricity and the manufacturers of equipment using electricity.

This awareness must encompass all the conclusions already mentioned in this guidebook, including the voltage and duration values observed, the frequency with which voltage sag can occur and the variability of that frequency, with the uncertainty that arises there from. The effect of a voltage sag on the customer's equipment must be considered, with particular regard to the depth-duration characteristics that are critical, and the customer must take due account of the possible consequences of any deterioration of performance or lapse in operation of that equipment. In the light of those consequences, the installation should, from the very first stage of planning, be designed to minimise disturbance and loss arising from voltage sags, having regard to the economic considerations that apply.

The normal approach to manage electromagnetic compatibility (EMC) is to observe co-ordinated limits for both emission and immunity for the disturbance phenomenon involved. The special constraints that apply to voltage sags and short interruptions with regard to that approach have already been described—the limitation of emissions is virtually impracticable, while intrinsic immunity can be obtained with proper design requirement based on technical standard.

The customer, in consultation with all the parties, can then make a balanced assessment of the possible effects of the expected sags and make economically viable decisions regarding any mitigating action that can be taken, using methods of which examples have been given in this guidebook or related technical standards/guidelines. The summary of the mitigation actions explained in this guidebook is shown in Figure 10.1 & Table 10.1.

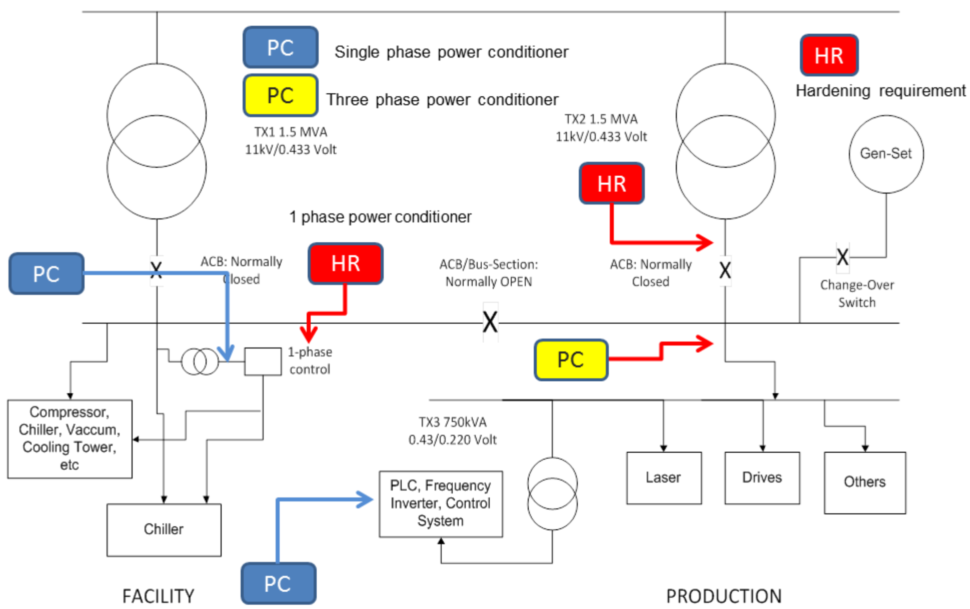


Figure 10.1 Location to implement mitigation action to improve the immunity of the critical process and equipment against voltage sags.

Table 10.1 Summary of action plans to improve equipment sensitivity

Mnemonic	Description	Details
HR	Hardening requirement	Use a universal & compliance power supply (85-264 Volt) Use DC supply (if applicable) Wire load devices in a phase-to-phase configuration Identify & improve sensitive ice cube relays Install auto restart schemes (if applicable) Maintain DC link voltage for VFD, ASD etc. Compliance power supply Undervoltage relay (70 %, t=3 s) Unbalance relay (20-50%, t=2 s) Reverse power relay (t= 3s)
PC	Power Conditioner	Single phase power conditioners Three phase power conditioners

References

[1] IEEE Std.1100-1999, IEEE Recommended Practice for Powering and Grounding

[2] IEC Std. 61000-2-1, Electromagnetic compatibility (EMC) - Part 2: Environment: Description of the environment - Electromagnetic environment for low-frequency conducted disturbances and signaling in public power supply systems.

[3] IEEE 1159, IEEE Recommended Practice for Monitoring Electric Power Quality, 2009

[4] SEMI F47-0706 - Specification for Semiconductor Processing equipment Voltage Sag Immunity

[5] http://www.leonardo-energy.org/sites/leonardo-energy/files/root/pdf/2007/PQAADA_2007_Presentation%20Roman%20Targosz.pdf

[6] http://www.powerqualityworld.com/2011/04/itic-power-acceptability-curve.html

[7] Cahier technique no. 149. EMC: electromagnetic compatibility by Jacques DELABALLE, 2001

[8] http://www.copperinfo.co.uk/power-quality/downloads/pqug/542-standard-en-50160-voltage-characteristics-in.pdf

[9] IEC 61000-2-4: Compatibility levels in industrial plants for low frequency conducted disturbances.

[10] IEC 61000-2-8: Guide on voltage dips and short interruptions on Public Electric Power Supply system

[11] http://www.electrotek.com/voltsag.htm

[12] Understanding Power Quality Problems (Voltage Sag and interruption), Math Bollen, IEEE Press, 2000

[13] IEC 61000-4-30: Power Quality Monitoring Standard

[14] http://www.powerqualityworld.com/2011/04/voltage-sag-types-abc-classification.html

[15] http://electrical-engineering-portal.com/transformer-routine-test-measurement-voltage-ratio-phase-displacement

[16] http://f47testing.epri.com/voltage_dip_immunity.html

[17] https://jointventure.org/images/stories/pdf/7_epri.multi-level.approaches.for.mitigating.power.quality.issues.d1.pdf

[18] http://www.powerqualityworld.com/2011/04/cbema-curve-power-quality-standard.html

[19] http://www.powerqualityworld.com/2011/04/itic-power-acceptability-curve.html

[20] http://f47testing.epri.com/f47abstract.html

[21] IEC 61000-4-11 Testing and measurement techniques –voltage dips, short interruption and voltage variation immunity tests for equipment less than 16 A per phase

[22] IEC 61000-4-34 Testing and measurement techniques –voltage dips, short interruption and voltage variation immunity tests for equipment more than 16 A per phase

[23] Chroma: www.chromausa.com

[24] Power Standards Lab USA: www.powerstandards.com

[25] http://ecmweb.com/archive/dealing-voltage-sags-your-facility

[26] http://www.pqsi.com/

[27] Dip Proofing inverter (DPI): www.dipproof.com

[28] Voltage Dip Compensator (VD.C): www.dipproof.com

[29] Dynamic Compensator (Dynacom): www.meidensg.com.sg

[30] Dynamic Sag Corrector (DySC): www.softswitching.com

[31] Active Voltage Conditioner (AVC): www.abb.com/product/seitp322/e039976253ee76f8c12576f600410658.aspx

[32] Datawave: www.liebert.com

[33] PureWave DVR: www.sandc.com/edocs_pdfs/EDOC_030092.pdf

[34] UPS-I, Industrial UPS, www.abb.com/product/seitp322/2747fc63c7439d8dc12576f6004073ea.aspx

[35] PureWave® Outdoor UPS Systems, www.sandc.com/products/power-quality/purewave-ups.asp

Contact Us

Tenaga Nasional Berhad (TNB) is committed to maintaining and delivering a reliable supply of electricity. We are always pleased to provide further information on power quality or EMC to customers.

If you have any enquiry on power reliability, power quality, EMC or energy related matters, please contact the nearest TNB office near you.

www.tnb.com.my

Asset Management Standard & Design Standard
Distribution Network Division TNB