

VOLTAGE DIP MANAGEMENT



Introduction

Why this guidebook?

This guidebook aims to provide customers the knowledge and management of voltage dips.

As most voltage dips are caused by electrical equipment failure from all stakeholders connected to the network, it can't be totally eliminated. As such, this guidebook covers the preventive measures taken by different stakeholders to minimise the occurrence and impact of voltage dips. It includes techniques for voltage dip monitoring, mitigating measures and case studies from past experiences.

With the principles, techniques and best practices outlined in this guidebook, we believe it will help Customers make informed decision in managing voltage dips depending on their risk appetite.

Collectively, let us work together to prevent voltage dips in the network.



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CHAPTER

01

What Is Voltage Dip
And Is It Avoidable?

1.1 What is Voltage Dip?

Voltage dip, as defined internationally [European Standard EN50160], refers to a sudden voltage reduction of more than 10% with duration between 10 milliseconds and 1 minute. [Fig 1]

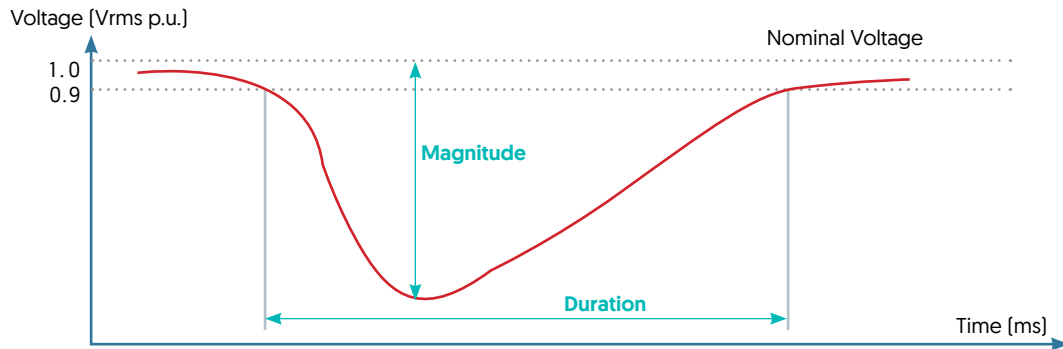


Fig. 1. Voltage Dip [RMS] Timeplot

1.2 Causes of Voltage Dips

Voltage dips are mainly caused by equipment failures at power grids, customer installations, power generation plants, or accidental damage to power cables. Voltage dips can also propagate from one part of the network to another part of the network and also across different utilities because they are interconnected.

1.3 Impact of Voltage Dips

Unlike power outages, voltage dips do not interrupt the electricity supply. Instead, they result in a temporary voltage reduction.

Voltage dips can have various impacts, ranging from momentary light dimming to lifts, escalators, and machines stopping, disrupting your operations.

1.4 Voltage Dips are unavoidable in the Network

Knowing the causes of voltage dips, it is understandable that voltage disturbances are a natural part of the network and is unavoidable.

Although it's not possible to completely eliminate voltage dips, everyone can certainly work together to minimise the occurrence and mitigate its impact.

Preventive Measures Against Voltage Dips

This chapter provides the overview of the preventive measures taken by various stakeholders – the electricity regulator [EMA – Energy Market Authority], the transmission licensee [SPPA – Singapore Power Assets] and the connected customers to minimise voltage dips occurrences.



2.1 Policies by EMA

EMA aims to ensure a reliable and secure energy supply, promoting effective competition in the energy market and developing a dynamic energy sector in Singapore. EMA takes various stringent measures such as enforcing policies for various stakeholders to comply and regulatory actions on the errant stakeholders [which will be covered in section 2.1.2] to minimise the occurrence of voltage dips in the network. It believes that the occurrence of the voltage dips can be minimised through proper maintenance of equipment.

Acknowledging that voltage dips is inevitable, EMA had also indicated in the Transmission Code that Customers whose operations cannot tolerate voltage fluctuations should install their own power quality devices, such as voltage stabiliser, uninterruptible power supply (UPS).

2.1.1 Policies for prevention of cable damages

Voltage dips may arise from damages to underground cable system due to earthworks. Hence, EMA has set out policies to manage and safeguard cables from damages¹.

The Electricity Act (Chapter 89A) requires that the earthwork contractors must obtain cable plans from transmission licensee (SPPA) and engage a Licensed Cable Detection Worker (LCDW) to ascertain the location of high voltage electricity cables in the work area before starting earthworks. The contractors shall submit the Notification for Commencement of Earthworks (NCE) to SPPA at least 7 calendar days before they commence earthworks in the vicinity of any high voltage electricity cables. Upon receiving such notification, SPPA will issue a Letter of Requirements (LRe) for earthworks. All contractors are required to comply with SPPA's LRe.

EMA and SPPA have implemented the Registered Earthworks Supervisor (RES) scheme to enhance prevention of cable damages. The RES scheme aims to ensure site supervisors are competent in cable damage prevention measures and adhere to them as required under SPPA's LRe. Only site supervisors who have passed the RES course, and are registered as a RES with SPPA, are allowed to supervise worksites in the vicinity of high voltage cables and medium/high pressure gas pipelines. Any non-compliance with SPPA's LRe would result in demerit points being given to the RES. The RES will have his registration pass suspended or revoked if his total number of demerit points exceeds a specified threshold.

EMA also encourages the contractors to refer to SS576:2019 [Code of Practice for Earthworks in the Vicinity of Electricity Cables] as a guide to best practices for earthworks near underground electricity cables to prevent cable damages. For cable damages due to negligence of a party, fines and penalties are imposed (maximum of S\$1 million and/or a jail term of up to 5 years under the Electricity Act).

Additionally, EMA has specific requirements for the transmission licensee and the connected customers on voltage dip prevention and the implementation details are provided in section 2.2 and section 2.3 respectively.

¹ https://www.ema.gov.sg/Earthworks_Contractors.aspx, Accessed on 06/06/2023

2.1.2 Regulatory actions on occurrence of voltage dips

EMA investigates each voltage dip incident and enforces regulatory actions against any stakeholders who fail to uphold the integrity of their high voltage equipment. According to Section 85(1)(a) of the Electricity Act [Chapter 89A], any person who removes, destroys or damages any electrical plant or electricity cable which is part of a transmission system that belongs to or under the management or control of an electricity licensee shall be guilty of an offence and shall be liable on conviction to a fine not exceeding S\$1 million or imprisonment for a term not exceeding 5 years or to both.

EMA establishes performance standards and impose financial penalties on SPPA where voltage dips results from equipment failure that could have been prevented. In the event of any shortcomings, EMA will take regulatory actions against SPPA and mandates the implementation of measures to prevent recurrence.

Furthermore, EMA possesses the authority to take regulatory measures against generating companies and connected customers if their equipment maintenance falls shorts, leading to adverse network effects. Regardless of whether a customer has maintained their high voltage electrical installation, a customer whose installation has caused three voltage dips within 24 months is required to engage an independent licensed electrical engineer to perform an audit and corrective actions.

The Licensed Electrical Engineers (LEE) with three high voltage installations causing voltage dips within a 24-months period are also accountable to appear before an Inquiry Committee of three Professional Engineers appointed by EMA. Failure to ensure proper maintenance of these electrical installations could lead to the suspension of the LEE's license.

2.2 Preventive Measures by SPPA

SPPA has devised strategies to meet the stringent regulatory requirements regarding power quality and reliability of the grid through condition monitoring and preventive maintenance of the switchgears, transformers, cables, and other electrical equipment. Over years, the focus of condition monitoring specifically partial discharge monitoring, has shifted from onsite to online monitoring, substantially averting failures and potential voltage dips.

To bolster the reliability of Singapore's electricity network, equipment renewal program is in-placed. Network segmentation has also mitigated the impact of network faults. For the protection of high voltage cables, certain extra high voltage cables [230kV and 400kV] are securely housed within dedicated cable tunnels. Construction sites are regularly patrolled to ensure adherence to earthwork procedures.

SPPA is also committed to knowledge-sharing through workshops, courses, and other educational programs aimed at enlightening customers and contractors on their responsibilities regarding power quality. The subsequent section elaborates on specific steps taken by SPPA to ensure power quality in Singapore.

2.2.1 Condition monitoring and preventive maintenance

Condition monitoring techniques such as partial discharge monitoring (PDM), ultrasonic scans and thermal infrared scans are performed on the network equipment. Online PDM is a permanent monitoring system offering continuous insulation condition status while electrical equipment is in operation, pre-emptively identifying potential defects before they fail.

Within Singapore's network, online PDM is primarily applicable to transmission equipment including high voltage gas insulated switchgears (400kV, 230kV, 66kV and selected 22kV), and gas insulated power transformers. A dedicated team at SPPA continually monitors and analyses data from the PDM system for anomalies.

Equipment not fitted with online PDM are periodically checked through onsite condition monitoring. Portable PD sets are used for PD scans at cable sealing ends of transformers, line reactors, and switchgears, and at all-accessible compartments in the switchgears.

Ultrasonic scans are performed on electrical equipment to detect any electrical discharges resulting from ionisation due to arcing or corona. The scanners can detect high frequency signals resulting from electrical discharges, the sound of which lies outside the normal human hearing range. Ultrasonic scans are used for power and distribution transformers, line reactors, medium and high voltage switchgears. Cable sealing ends of transformers and switchgears, main tanks of transformers, and all accessible compartments of the switchgears are examined using ultrasonic scanners. In addition to PD scans and ultrasonic scans, thermal infrared scans are also carried out periodically on the above-mentioned equipment to detect any potential hotspots.

Some other condition monitoring tests are the SF6 gas quality checks in gas insulated switchgears and dissolved gas analysis (DGA) of insulating oil in transformers. These tests ascertain the dielectric strength of the insulating material and potentially warn of any contamination.

SPPA's preventive maintenance program covers all network equipment under operation including the auxiliary systems (e.g., DC chargers, batteries, etc.) in the substations. The regular maintenance program generally involves examination, testing, servicing, replacement of parts, checks on operating mechanisms and contacts, oil change, etc., as applicable. OEM maintenance manual is adhered to in executing the maintenance activities.



Fig. 2 - Portable Partial Discharge Detection Devices

2.2.2 Renewal program for network equipment

The equipment renewal program for Singapore's electricity network prioritises replacements based on factors such as equipment performance, condition, age and substation criticality. Performance-based renewal ensures that the unreliable assets are timely replaced to prevent failures. Condition-based renewal makes sure that the assets with high potential of failure are replaced before they fail. Age-based renewal of assets ascertains that aging assets are retired from service before they enter the phase of high failure probabilities.

2.2.3 Splitting of the transmission network

Singapore's electricity transmission network is presently divided into four blocks – North-East, North-West, South-East and South-West, with the highest transmission voltage being 400kV. Division of the network in multiple blocks minimises the impacts of the voltage dips to a large extent. The voltage dip due to a fault at 66kV and below in one block hardly propagates to the other blocks. Moreover, a fault at 230kV in one block would result in much lesser voltage dip magnitudes in the other blocks. The transmission planning team in SPPA forecasts demand and generation determine the need for further splits or reconfiguration of the network.

2.2.4 Prevention of cable damage

To address concerns regarding voltage dips resulting from cable damage during excavation, SPPA conducts regular briefings for stakeholders such as contractors, developers, consultants, and excavation workers.



Fig. 3 - Cable detection Work and Cable Tunnels

Stringent procedures require contractors to engage licensed cable detection workers (LCDW) for site scanning and risk assessment before commencement of any excavation works. Trial holes are manually dug without any heavy machinery with reference to the cable plan drawing to confirm the presence of cables. SPPA ensures

that the appointed registered excavator operator (REO) and registered earthwork supervisor (RES) undergo mandatory training to ensure competency. Furthermore, SPPA representatives patrol the excavation area regularly, conduct spot checks, and pay special attention to the excavation works in the vicinity of the HV cables. In addition, some 230kV and 400kV cables are laid in cable tunnels under parts of Singapore to protect them from damage during earthworks.

2.2.5 Power Quality Monitoring for Voltage Disturbance Management

Whenever voltage disturbances occurred in the network, it is important that these disturbances are recorded for post fault analysis and effective network management. SPPA had setup a Power Quality Monitoring System to continuously monitor the Transmission and Distribution network's power quality performance.

2.3 Preventive Measures by Customers

Customers play a pivotal role too within the grid network and share responsibility for maintaining power quality. This section highlights the importance of customers taking proactive measures to minimise equipment failures and ensure seamless operation of their facilities.

2.3.1 Regular Equipment Maintenance

In accordance with the Electricity Act [Chap. 89A], customers are obligated to appoint a licensed electrical worker [LEW] of appropriate class to oversee electrical installations and conduct scheduled inspections of their electrical installations. Inspections occur at least once a year, with higher risk environments or premises undergoing more frequent checks. The appointed LEW assesses operating conditions, identify any wear and tear, and recommends suitable inspection frequencies, establish maintenance schedules, and additional measures based on their assessment.

2.3.2 Voltage Dip Management

Recognising that voltage dips are inherent and unavoidable, customers must proactively manage these occurrences.

A structured PDCA (Plan-Do-Check-Act) approach aids in systematic voltage dip management:

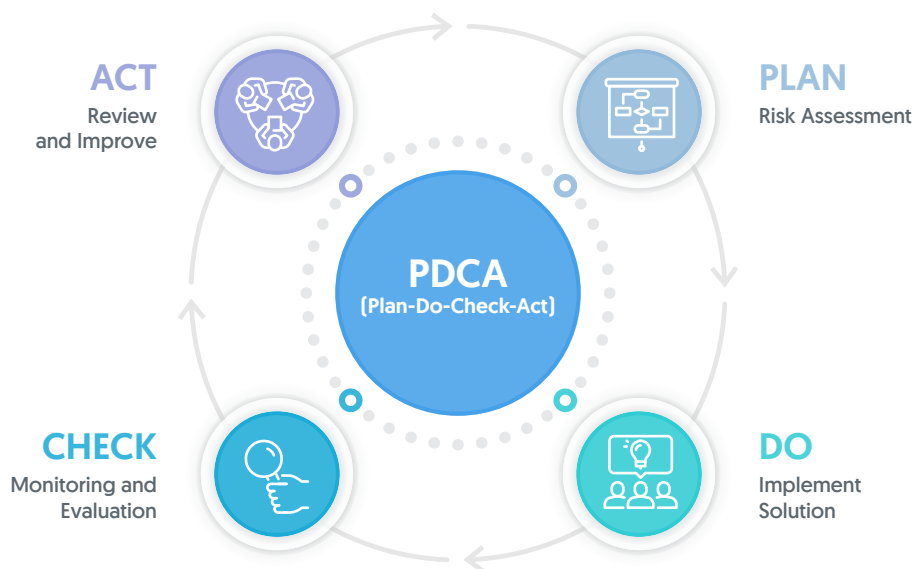
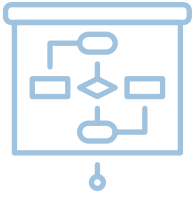


Fig 4 - Continuous improvement of Voltage Dip Management



Plan [Priority Setting and Risk Assessment]:

- Identify and prioritise critical processes and equipment that are most sensitive to voltage dips and have a significant impact on operations or safety.
- Perform a thorough risk assessment for these prioritised processes and equipment to understand potential vulnerabilities and the potential consequences of voltage dips.
- Define clear criteria for determining the urgency and severity of voltage dip mitigating efforts based on the outcome of the risk assessment.
- Establish a strategy for collaboration with relevant stakeholders, including licensed electrical workers (LEWs) and Original Equipment Manufacturers (OEMs), to gather expertise and insights to implement appropriate mitigating solutions.



Do [Implement Solutions for Voltage Dip Ride-Through]:

- Based on the prioritised list of critical processes and equipment, implement appropriate mitigating solutions [in Chapter 5] that enhance the ride-through capability during voltage dip events. These solutions may include Uninterruptible Power Supplies (UPS), Dynamic Rotary UPS (DRUPS), Voltage Dip Restorers, DC compensators, etc.
- Ensure that the chosen solutions are adequately sized and configured to match the specific requirements of each prioritised process or piece of equipment.
- Implement Business Continuity Management (BCM) and Recovery plans, including clear procedures for responding to voltage dip events and minimising downtime.
- Train relevant personnel to operate and respond swiftly to voltage dip situations, ensuring that they understand the recovery plans when operations are affected.



Check [Continuous Monitoring and Evaluation]:

- Continuously monitor the performance of the implemented mitigating solutions, and their effectiveness in providing voltage dip ride-through capability.
- Regularly review the recorded data on voltage dip events, analyzing the impact on critical processes and equipment that were prioritised in the planning phase.
- Compare the actual outcomes with the criteria established during the planning phase to determine if the implemented solutions are meeting the expected goals.
- Conduct periodic reviews with LEWs, OEMs, and internal stakeholders to gather feedback on the effectiveness of the solutions and identify any emerging issues or areas for improvement.



Act [Investigate, Review, and Improve]:

- Analyse the data collected during the Check phase to identify patterns, trends, or any incidents that indicate potential weaknesses or areas for enhancement.
- Investigate the root causes of any deviations from expected outcomes or incidents related to voltage dips.
- Based on the findings from the investigation, update and refine the risk assessment, priority-setting criteria, and mitigating strategies as needed.
- Implement any necessary changes or enhancements to the voltage dip management and recovery

By adopting this proactive approach, customers with voltage-sensitive equipment can significantly enhance their ability to withstand voltage dips, minimise disruptions, and maintain business continuity.



CHAPTER 03

Power Quality Monitoring

Different equipment exhibits varying tolerance levels and vulnerabilities to power quality. It malfunctions when power quality falls beyond their tolerances. Accurate data on power supply quality during such events is crucial for investigation. Consequently, it's imperative for companies with voltage-sensitive facilities to establish permanent power monitoring systems at strategic points to detect supply abnormalities.

3.1 Objectives of PQ Monitoring

The following objectives underpin the rationale for procuring and implementing a Power Quality Monitoring System:

1. Continuous Monitoring and Evaluation:

The need to continuously monitor and evaluate the supply system is driven towards identifying disturbances and variations in power quality that could potentially disrupt the seamless operation of the plant. By gathering data on these disturbance events, we not only enhance the resilience of existing equipment to withstand disruptions but also gain insights to fine-tune mitigating strategies and improve the ride-through capabilities.

2. Evaluation of Power Quality Characteristics:

The data garnered through monitoring serves as a means to assess the power quality attributes of the equipment situated within the facility. This encompasses vital considerations such as the interaction between harmonics generated by loads and power conditioning equipment. Additionally, the study of in-rush characteristics, exemplified by compressor motors and similar loads, comes into play due to their potential influence on the operation of backup generators. The evaluation extends to voltage transients linked to switching events within the facility or the equipment's response to voltage fluctuations originating either from the grid or internally. Over an extended period, the accumulation of monitoring data facilitates the early identification of supply quality issues, such as an undue escalation in harmonics levels, which could potentially impact other plant equipment if not addressed promptly.

3. Effective Energy Management:

Beyond power quality parameters, the data obtained also encompasses energy-related information. This information becomes instrumental in efficiently governing and managing energy consumption within the facility. This dual-purpose approach not only contributes to cost savings but also aligns with efforts to curtail carbon emissions.

For these purposes, a permanent Power Quality Monitoring System equipped with real-time online monitoring and reporting is essential. This system can process disturbances and steady-state power quality data, send alerts via SMS or email, and facilitate swift response when abnormalities occur.

3.2 PQ Monitor Fundamental

Within the vast market of power quality [PQ] monitors, both fixed and portable variants, the process of selecting a suitable monitor can be a daunting task, often entangled with challenges and confusion. In this section, we aim to explain the essential technical aspects to aid your selection process.



Fig 5. - PQ Monitor Samples

When selecting a PQ monitor, a pivotal criterion is the PQ measurement standards employed in calculating voltage disturbances and steady-state electrical parameters. PQ monitors adhering to internationally recognised standards, such as “IEC61000-4-30 on Testing and measurement techniques – Power quality measurement,” are strongly recommended. This standard is categorized into Class-A [with stringent requirements] and Class-S [for general PQ measurements with less stringent requirements]. Users should opt for the relevant Class that aligns with their PQ measurement objectives. In instances of voltage dip and swell disturbances, Class-A monitors adopt $U_{rms}[\frac{1}{2}]$, while Class-S monitors can use either $U_{rms}[\frac{1}{2}]$ or $U_{rms}[1]$. (Fig 6 illustrate $U_{rms}[1]$ and $U_{rms}[\frac{1}{2}]$ measurement method).

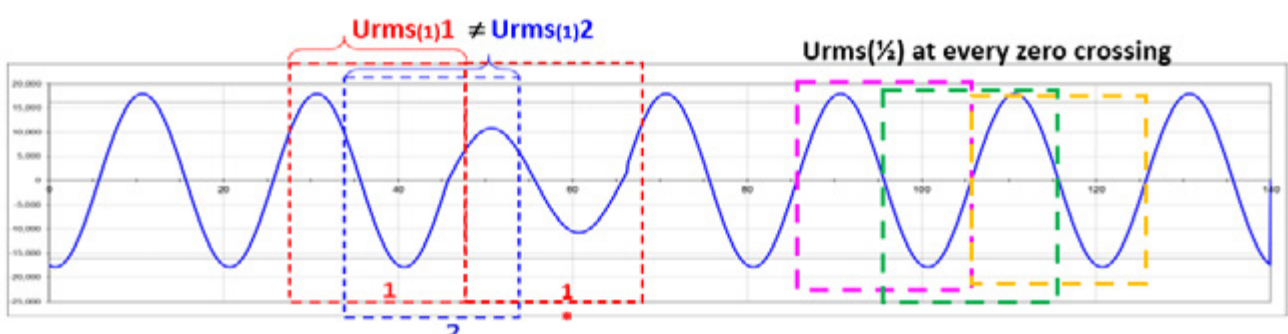


Fig 6 - $U_{rms}[1]$ and $U_{rms}[\frac{1}{2}]$ Calculation Methodology

A PQ monitor’s core function entails capturing voltage disturbances [Dip, Swell, and Transient] when they manifest, alongside continuous measurement of crucial steady-state parameters: voltage, current, frequency, harmonics [THD, orders, inter-harmonics], unbalance, flicker, power factor, energy, power, etc. The monitor also encompasses additional measurements [e.g., rapid voltage changes, superharmonics] that gain relevance in specific environments or conditions within the plant.

Given the nearly universal claim of compliance with IEC61000-4-30, distinguishing between PQ monitors can be challenging. To gauge superiority or suitability, it’s crucial to understand the calculation of “Mean” steady-

state parameter values as stipulated by the standard. However, the calculation methodology for Minimum and Maximum values remains unspecified, varying across monitor manufacturers. Thus, comprehending how these values [e.g., voltage, current, frequency] are calculated is essential for discerning their practical significance. **[Refer to Fig 7 for 24hrs Voltage RMS plot]**

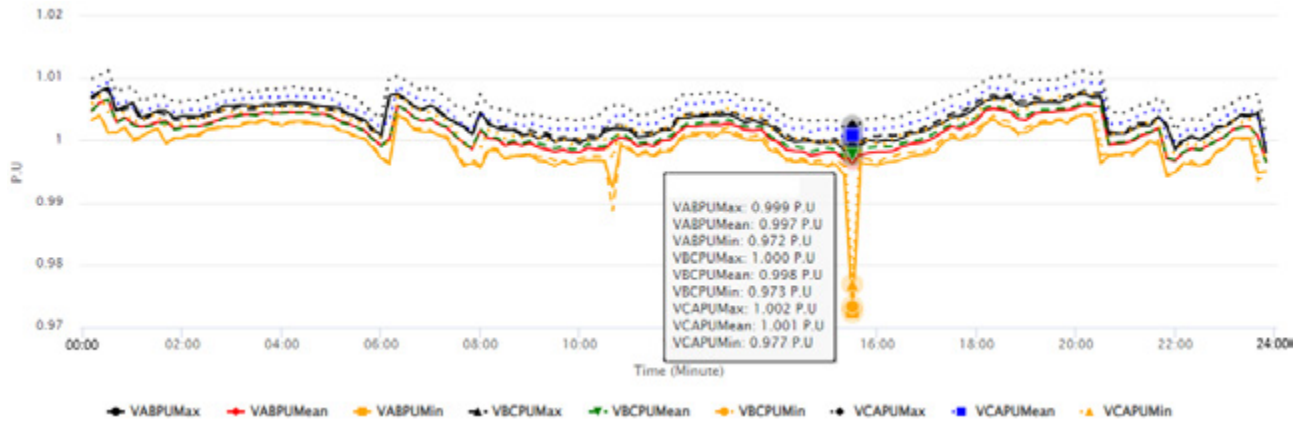


Fig 7 – 24Hrs Voltage RMS Plot [Min/Mean/Max]

In Fig 7 above, the 10-min Min and Max voltage was computed based on $Urms[\frac{1}{2}]$ [eg. voltage RMS is calculated per cycle at “every zero-crossing”) as defined in IEC61000-4-30. Based on this measurement method, this implied that the RMS voltage over the 10-min measurement interval as highlighted in the box do not exceed 1.002pu and below 0.972pu for the Max and Min value.

Another key aspect to take note during PQ monitor selection is the sampling rate. Some suppliers emphasise higher rates, like 512 samples/cycle compared to 128 samples/cycle counterparts. If both monitors complied to IEC61000-4-30 Class-A, then the voltage measurement accuracy is the same at 0.1% regardless of sampling rate. If the voltage in your operating environment is “relatively clean” and sinusoidal [Fig 8 bottom blue waveforms], there is no “significant” different when measuring at 128 or 256 samples/cycles. However, if the voltage is “noisy with many spikes” or “rapid fluctuation” in voltage waveform [Fig 8 top red waveforms], then the waveform captured will be different and steady-state measured values between the two sampling rates will likely be slightly more “significant”. Hence, it is important to establish the specification requirements needed for your operating environment.

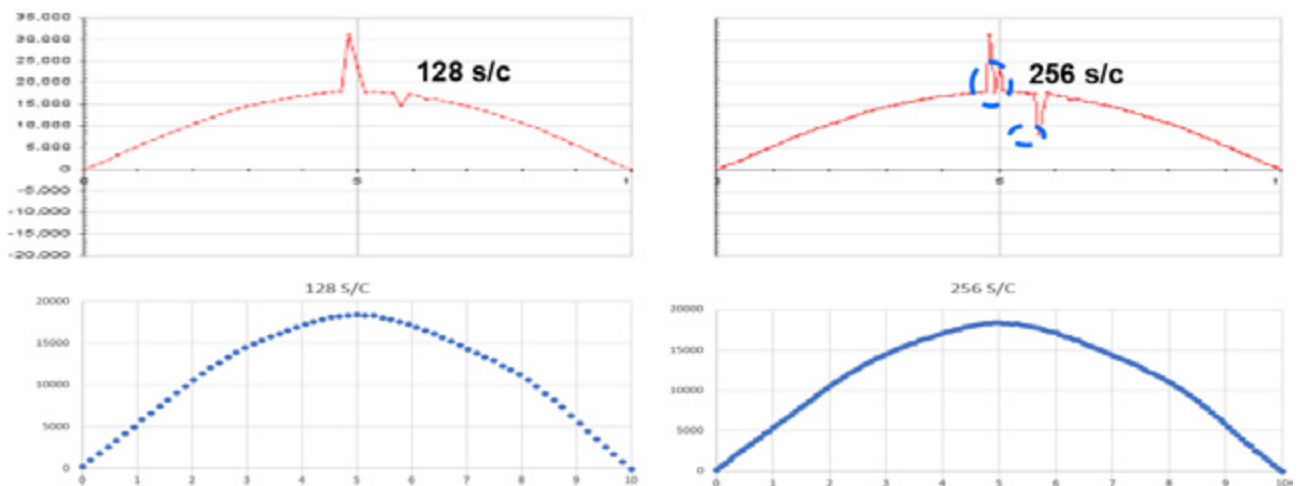


Fig 8 – 128 and 256 samples/cycle waveforms

Another frequent question on PQ monitor's specification is how much memory/storage size is required. For permanent PQ monitors connected to servers for regular data downloads, a storage size accommodating about one month of trending and disturbance data suffices. However, for a portable PQ monitor that is placed on-site for investigation without communication link to server, it requires a much larger storage size especially when numerous disturbances are anticipated. Hence, it's prudent to consult vendors regarding memory storage needs for specific data intervals such as for a 1-week trending data at fixed time interval setting of e.g., 10mins, and waveform captures, e.g., 15 cycles (300ms) and 50 cycles (1-second) including both 3-phase voltage and current. When we know how much trending and disturbance data storage size are, then we can calculate the minimum memory storage size is needed example for 1-month of trending data and a minimum numbers of disturbance waveforms [e.g. 20 disturbance waveforms].

Permanent PQ monitoring systems are essential for any voltage-sensitive facilities, enabling proactive identification and resolution of conditions that could jeopardise operations. The selection of monitoring locations depends on the facility design, critical loads, power conditioning equipment and the specific objectives of the monitoring. Minimally, PQ monitoring should be installed at the power supply intake from network and outputs of power conditioning equipment. For sites with redundant or backup supplies, monitoring each feed is advisable. More extensive monitoring could be carried out to include critical loads, such as clean room air-conditioning, critical tools, and communications equipment. For less critical points, Class-S monitors can be installed to optimise PQ measurement coverage.

In medium to extra high voltage power system, there are only 3 phases and "NO" neutral conductor. The voltage transformers (VTs) used for metering are generally phase-phase or phase-neutral/earth type [Fig 9]. When connecting PQ monitor voltage input configuration to Phase-neutral VTs, the choice lies between Star [phase-neutral] or Delta [phase-phase] voltage input setting. The Star configuration highlights the "faulted" phase/phases in captured disturbance waveforms and is useful for fault investigation. Since medium/high voltage customers are connected to SPPA via 3-conductor cables, voltage dip magnitudes shared by SPPA based on phase-phase are more applicable as experienced by customer's LV equipment due to "delta-star" transformation to low voltage.

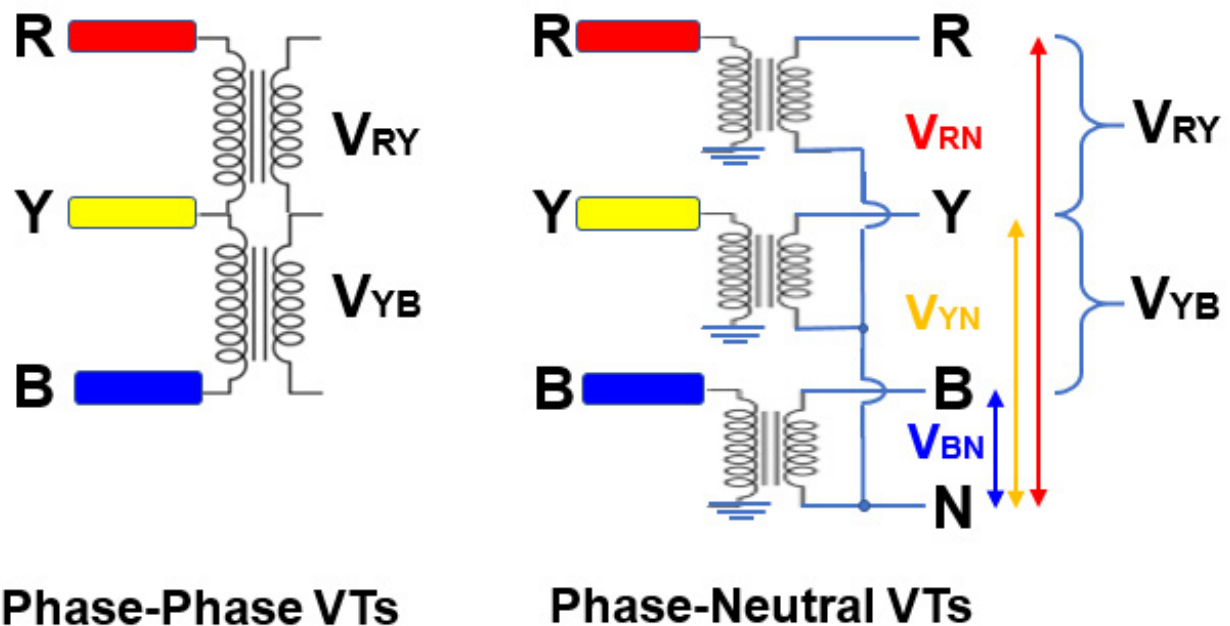


Fig 9 – Type of Voltage Transformers Connection

It is important that the PQ Monitor software offered is user-friendly. It should facilitate navigation and allow user customisation and configuration of measurements based on site conditions. Features like zoom functions [preferably with x and y axis independently], panning, measurements between markers, exporting screen captures and exporting data to text files are useful to enhance viewing, analysis and reporting capabilities. Beyond collecting PQ data, the PQ software is an important tool for data viewing and analysis. Hence, the software flexibility and capability also need to be considered when evaluating the PQMS system.

3.3 Other PQ monitor features

While most PQ monitors available in the market proficiently capture voltage and current based on voltage threshold configurations, situations necessitating the investigation of transformer or motor in-rush or starting current episodes warrant a different approach. Here, the utilisation of current threshold settings for waveform recording becomes essential to ensure the consistent capture of in-rush current waveforms when the need arises.

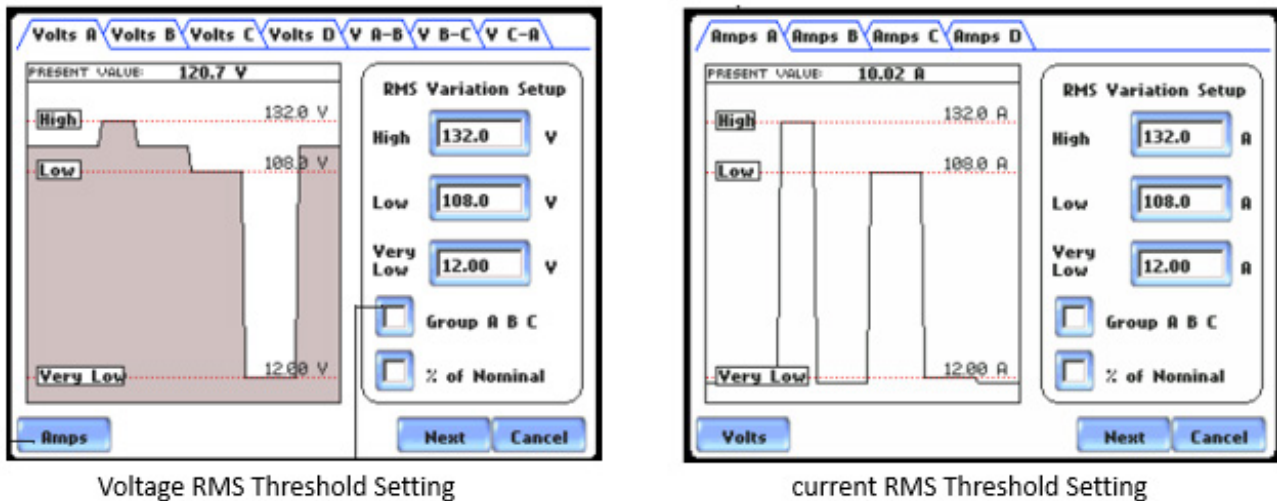


Fig 10 – Voltage and Current RMS Threshold Setting

Another useful feature is “High-Speed” [HS] transient module to capture “high” frequency transient waveform [especially in low voltage [LV] network investigation]. It’s worth noting that some monitors excel in High-Speed “detection” yet lack the ability to capture and record the waveform for subsequent analysis. There are many different HS transient modules available in the market, boasting sampling rates spanning from a few hundred Kilohertz [KHz] to tens of Megahertz [MHz], with the majority falling within the 1MHz and below range.

In Fig 11 below, the transient waveform frequency is about 600KHz as captured at 5MHz sampling rate. It's important to recognize that employing a 1MHz HS module yields a fundamentally “different” captured waveform due to the incredibly short 1 μ s sampling interval, despite the actual duration of the one-cycle transient waveform being 1.8 μ s. However, this HS feature generally has limited application when monitoring the secondary side voltage of a medium or high voltage transformer (VT) due to VT's frequency response characteristic.

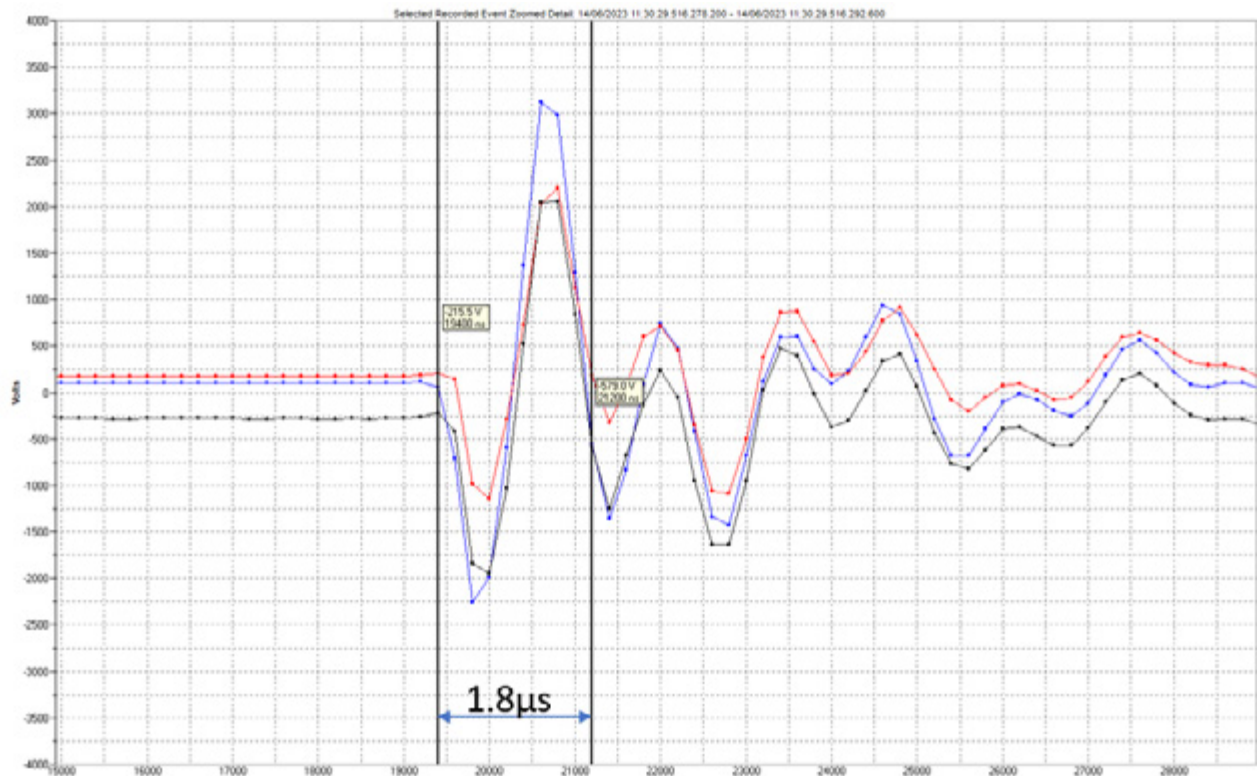


Fig 11 – High-Speed Transient Voltage Waveform @5MHz

3.4 Other benefits of PQ monitoring

After a PQ monitor recorded a voltage dip disturbance, one of the most common and often asked question pertains to determining the fault's point of origin – whether it stemmed from upstream or downstream of the monitoring location. If the recorded current reading reflects a “significant” increase in magnitude, it is implied that the fault originated downstream of the measurement point. Conversely, the absence of a significant increase in current magnitude during the fault implied that the disturbance originated from upstream of the measurement point. [Refer to Fig 9 below for illustration].

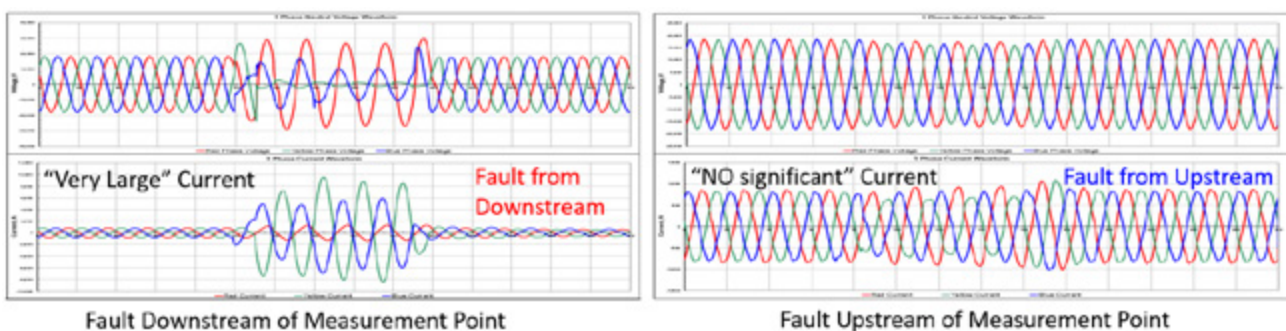


Fig 12 – Determine direction of fault based on current waveform



CHAPTER

04

Voltage Dip Mitigating Techniques

This chapter provides the overview of the various voltage dip mitigating options and techniques that can be implemented at different level depending on customers risk appetite to minimise the impact of voltage dips. It is paramount to understand that when implementing any voltage dip mitigating solution, the solution can only protect against disturbances originated upstream, but it cannot mitigate against downstream disturbances.

4.1 Voltage Dip Mitigating Options depending on Risk Appetite

While voltage dip is unavoidable, its adverse effects can be mitigated through the deployment of solutions designed to counteract voltage dips. In this way, even if the supply voltage momentarily plummets, continuity of voltage supply to equipment or processes remains unscathed.

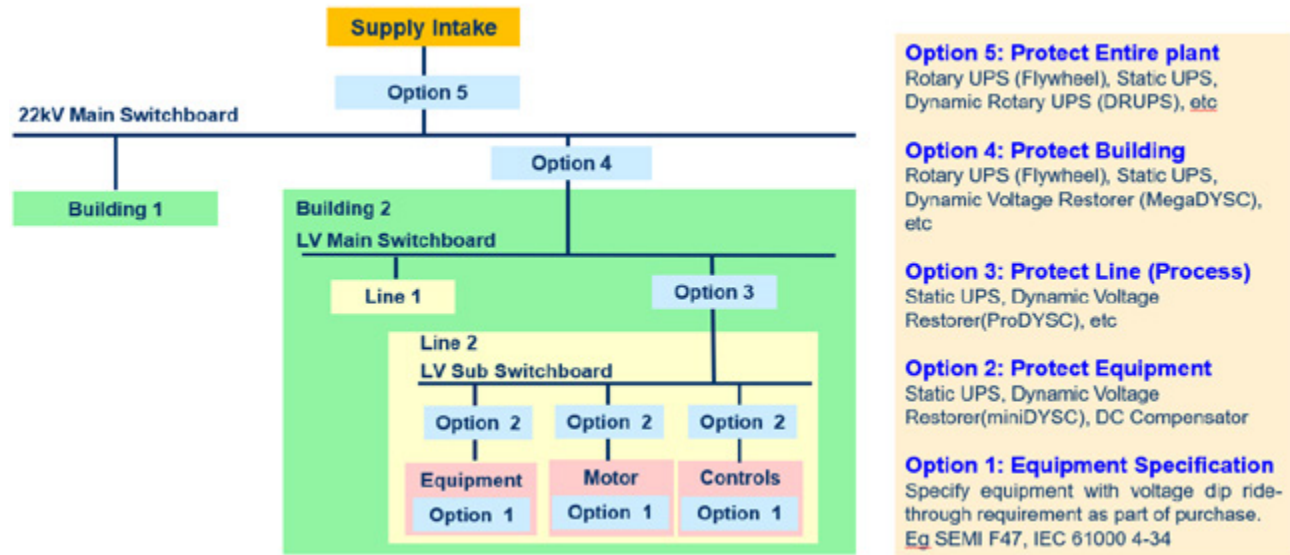


Fig 13: Voltage Dip Mitigating Solutions at various Options level

In the following sections [4.2 to 4.6], a more in-depth explanation will be provided on the type of voltage dip mitigating solutions at various options level. These solutions are tailored in accordance to the voltage sensitivity of the equipment and its criticality of operations. Furthermore, the level of mitigating solution pursued acts as a direct indicator of the identification of pivotal buildings, assembly lines, or equipment warranting voltage dip mitigating interventions.

4.2 Option 1: Protection through Equipment Specification

At Option 1 level, the focus shifts to the identification of voltage-sensitive equipment. During the procurement phase, voltage dip mitigating solutions are integrated into equipment specifications. Customers can specify upfront that the ride-through performance requirement to be compliant with reference to an industry standard, guidelines [e.g. SEMI F47, ITIC, IEC61000-4-34] or tailored to their specific requirements (eg. Samsung Power Vaccine).

The important point here is that the required equipment immunity to power quality variations should be specified upfront and addressed at an early stage. Determining the requisite equipment immunity involves leveraging historical voltage dip records as shown in Fig 14. By understanding the various ride-through performance standards and checking against the past voltage dips statistics, it will help make an informed decision on which standard to specify to the OEM for those voltage sensitive equipment.

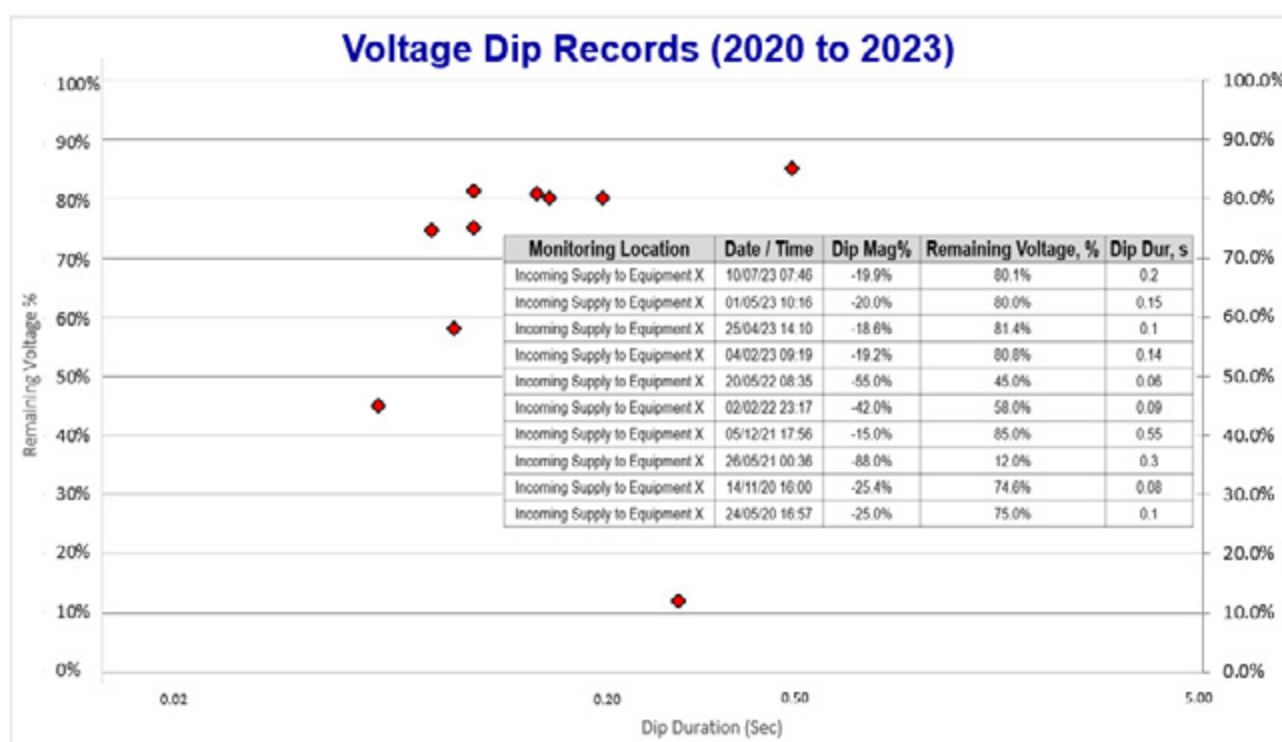


Fig 14: Voltage Dip Records from 2020 to 2023

Voltage dip ride-through performance charts are used to show the capability of electrical equipment to withstand voltage dips. Different standards and specifications define the criteria for voltage dip ride-through performance. We delve into each of the specified standards and guidelines, exploring their respective voltage dip ride-through performance charts.

4.2.1 SEMI-F47

SEMI is a global industry association that develops standards for the semiconductor manufacturing industry. Established in 1999, the SEMI F47 standard specifies the requirements for voltage dip immunity for semiconductor manufacturing equipment, with subsequent revisions, including the latest in 2004. The standard delineates permissible voltage dip depth and duration, ensuring equipment sustains uninterrupted operation. Due to its cost-effectiveness, this standard has since been widely adopted for non-semiconductor industry as well.

In the Fig 15, the red line represents the SEMI 47's voltage dip ride-through performance line, and the green highlighted zone shows the protection zone, indicating the acceptable operating region where the equipment can continue to function without disruptions during voltage dips. Based on the past voltage dips records, it was observed that there were 2 voltage dip incidents [highlighted in yellow], which are below the SEMI F47 ride-through curve. It's worth noting that compliance with the SEMI F47 requirement does not ride through all voltage dips.

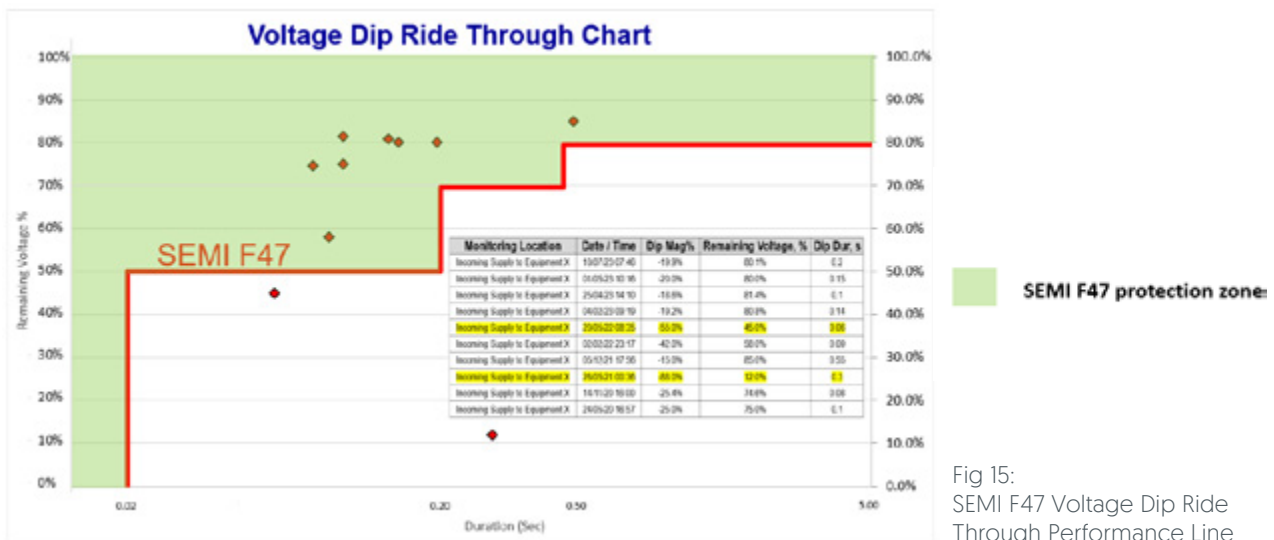


Fig 15:
SEMI F47 Voltage Dip Ride Through Performance Line

4.2.2 ITIC [CBEMA]

Originating in the 1970s, the Computer Business Equipment Manufacturers Association [CBEMA] developed the CBEMA curve as a guideline for the power supply design. The main application was to describe the tolerance of mainframe computer business equipment to the magnitude and duration of voltage variations on the power systems. As the computer equipment start to evolve over the years, the Information Technology Industry Council [ITIC] was formed in 1994 to derive a curve as shown in Fig 16, accounting for the performance of single-phase, 120 V, 60 Hz computers and related technology peripherals.

The latest revised ITIC curve was in 2000 and it now applies broadly to general power quality evaluation and various loads and devices containing solid-state components.

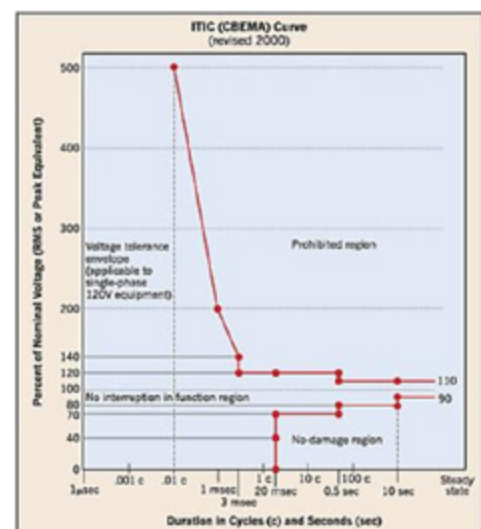


Figure 16: ITIC [CBEMA] Curve

>> CHAPTER 4: VOLTAGE DIP MITIGATING TECHNIQUES

In particular to voltage dips events, the lower ITIC curve up to the “No-damage region” serve as a reference for specifying the ride-through requirement of the voltage sensitive equipment as shown in Figure 17. “No-damage region” specify conditions where voltage dip might occur but shouldn't result in equipment damage. Based on the past voltage dips records, it was observed that there were 3 voltage dip incidents [highlighted in yellow] below the ITIC ride through curve. This underscores that even adherence to ITIC ride-through requirements does not ride through all voltage dips.

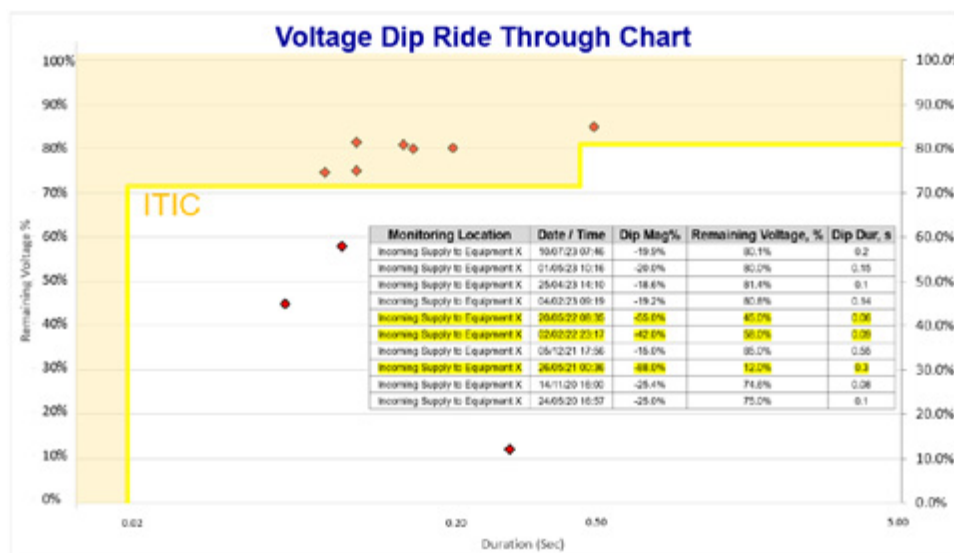


Figure 17:
ITIC Voltage Dip Ride
Through Performance Line

4.2.3 IEC 61000 4-34

IEC 61000-4-34, a component of the International Electrotechnical Commission [IEC] 61000 series, serves as a comprehensive framework for electromagnetic compatibility [EMC] testing and standards. The most recent iteration, published in 2009, focuses on evaluating the immunity of electrical and electronic equipment when subjected to voltage dips, short interruptions, and voltage variations.

For voltage dips events, IEC 61000-4-34 prescribed recommended test levels as illustrated in Fig 18 for the equipment in different electromagnetic environment classes, which is specified in IEC61000 2-4 [Annex B]. It shows the voltage dip % magnitude and duration in cycles applied to the equipment to assess its immunity to such events to verify its compliance to the IEC 61000-4-34.

Classes ^a	Test level and durations for voltage dips (r_c) (50 Hz/60 Hz)				
Class 1	Case-by-case according to the equipment requirements				
Class 2	0 % during ½ cycle	0 % during 1 cycle	70 % during 25/30 ^c cycles		
Class 3	0 % during ½ cycle	0 % during 1 cycle	40 % during 10/12 ^c cycles	70 % during 25/30 ^c cycles	80 % during 250/300 ^c cycles
Class X ^b	X	X	X	X	X

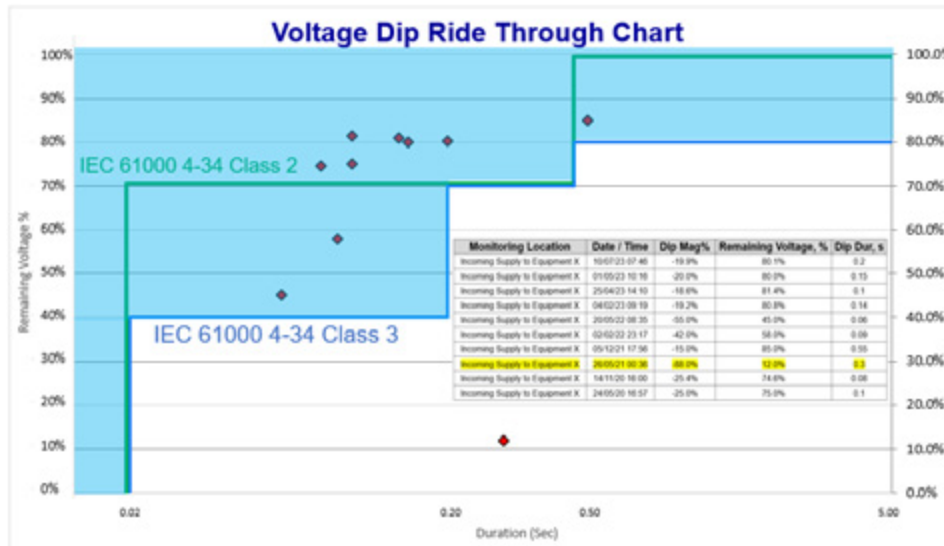
^a Classes as per IEC 61000-2-4; see Annex B.

^b To be defined by product committee. For equipment connected directly or indirectly to public network, the levels must not be less severe than class 2.

^c "25/30 cycles" means "25 cycles for 50 Hz test" and "30 cycles for 60 Hz test", "10/12 cycles" means "10 cycles for 50 Hz test" and "12 cycles for 60 Hz test" and "250/300 cycles" means "250 cycles for 50 Hz test" and "300 cycles for 60 Hz test".

Fig 18: Preferred test level and durations for voltage dips

Fig 19 shows the performance ride-through lines for the IEC 61000-4-34 Class 2 and Class 3. The protection zone, denoted in blue, corresponds to the IEC 61000-4-34 Class 3 standard. Notably, despite compliance with IEC 61000-4-32 Class 3 requirements, analysis of past voltage dip instances reveals an occurrence [highlighted in yellow] that remains below the stipulated standard. Thus, it is apparent that even adherence to IEC 61000-4-34 Class 3 specifications does not ride through all voltage dips.



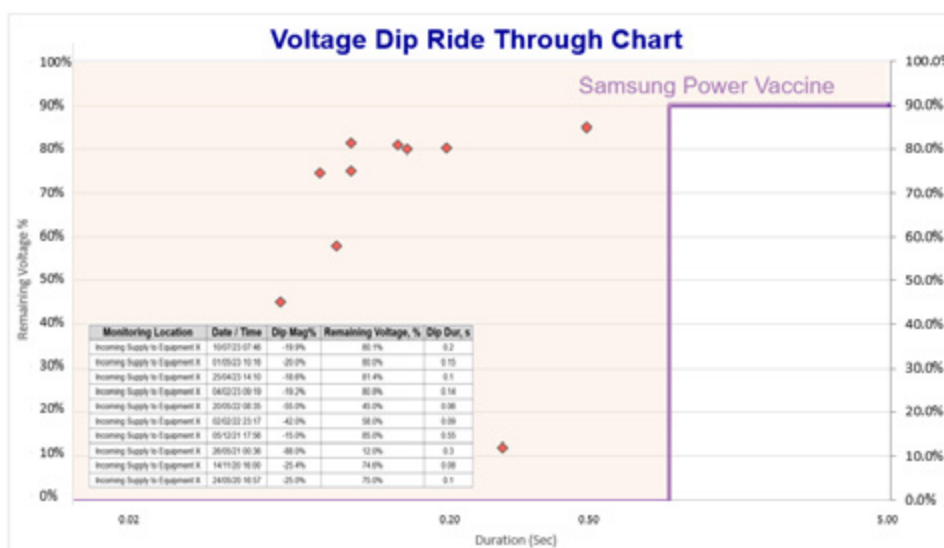
IEC 61000 4 34 Class 3 protection zone

Figure 19: IEC 61000-4-34 Voltage Ride Through Performance Line

4.2.4 Samsung Power Vaccine

The concept of “Power Vaccine” immunity levels was innovated by Samsung Semiconductor. Hence, the name “Samsung Power Vaccine”. Equipment adhering to the Samsung Power Vaccine specifications must be able to sustain uninterrupted operation, even when subjected to a 100% voltage dip magnitude up to 1 second. It’s important to note that its stringent requirement as compared to the other voltage dip ride-through performance standards, might potentially necessitate higher implementation costs due to the need for more energy storage to withstand the deeper voltage dips and endured over longer periods.

Fig 20 shows the performance ride through line for the Samsung Power Vaccine. The protection zone, highlighted in orange, pertains to equipment aligning with the Samsung Power Vaccine. Based on the past voltage dips records, it is evident that if equipment conforms to the Samsung Power Vaccine requirements, its operation will not be affected at all.



Samsun Power Vaccine protection zone

Fig 20: Samsung Power Vaccine Voltage Ride Through Performance Line

Overall, when adopting Option 1 which involves specifying the voltage dip ride-through performance for the voltage sensitive equipment, implemented during the procurement phase can be a seamless and cost-effective approach, as customers do not need to install external voltage dip devices. Understanding the various voltage dip ride performance requirement and analysing past voltage dip statistics will help to make better informed decision on which standard or guideline to follow. However, for existing equipment that were not originally mandated to adhere to any voltage dip ride-through performance standards, there are external voltage dip mitigating solutions available in the market to fortify equipment resilience and bring them in line with these requirements, as elaborated in subsequent sections. Where customer's risk appetite is not able to tolerate any voltage dips, which are beyond any option 1 voltage dip ride-through protection zone, option 2 or above mitigating solutions will be required.

4.3 Option 2: Protection at Equipment level

For Option 2, the mitigating solution is implemented at the incoming supply to the identified voltage sensitive equipment. Seeking advice from voltage dip mitigation providers is advisable to achieve the optimal solution for the voltage sensitive equipment. This category of voltage dip mitigating solutions includes static Uninterruptible Power Supplies [UPS], voltage dip restorers [eg. MiniDYSC] or DC Compensators.

In various motor soft-starter applications, the Variable Speed Drive [VSD] is a prevalent choice due to its ability to effectively regulate the speed and torque of an electric motor by adjusting the frequency and voltage supply. However, it has been noted that in the event of a voltage dip, the VSD can become vulnerable points systems like chiller operations if they are not adequately protected or hardened against voltage dips.

An example of a voltage dip mitigating device that is suitable to harden such equipment is the DC Compensator, which is installed at the DC link of the VSD. A DC Compensator grounded in power electronics-based functions to counterbalance the power loss due to voltage dip by compensating for voltage drops in the VSD's DC link. The key components of a DC compensator are a charger, an energy storage (typically a capacitor bank) and the ride-through voltage regulator.

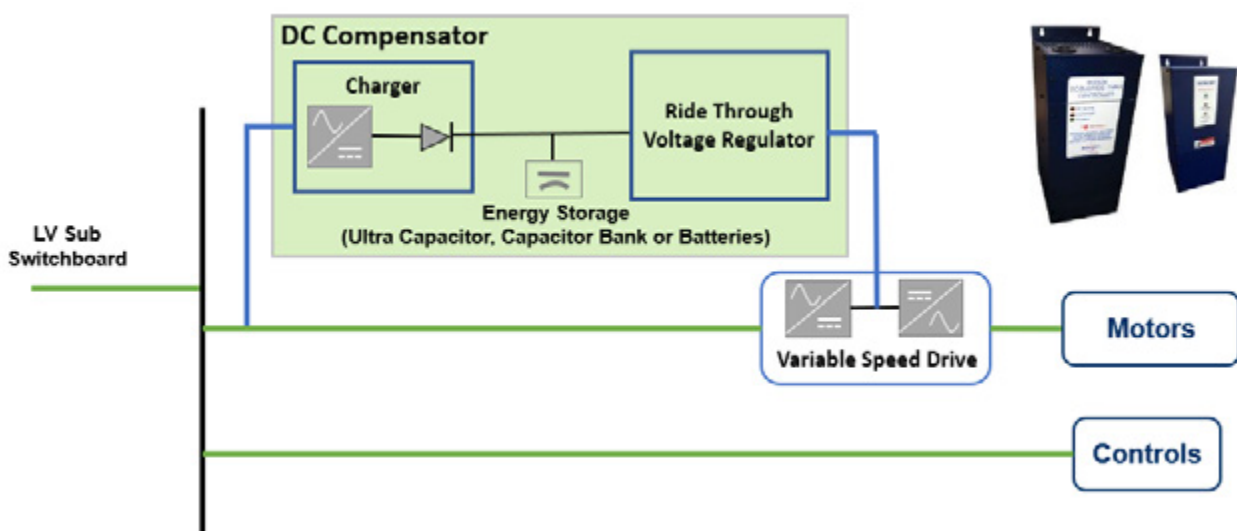


Fig 21: Example of Option 2 voltage dip mitigating solution: DC Compensator

During normal operation where the voltage supply to the VSD remains stable, the charger of the DC compensator continuously monitors the incoming AC voltage, ensuring it remains within acceptable thresholds and sustaining the capacitor bank's charge.

In the event a voltage dip occurs in the AC supply, the ride-through voltage regulator of the DC compensator promptly detects the voltage drop and triggers the discharge process of the capacitor bank. Depending on the extent of the voltage drop, the capacitor bank rapidly releases its stored energy through power electronic switches, converting it into DC voltage. This DC voltage harnessed to offset the voltage drop in the VSD's DC link. This compensation mechanism effectively maintains a relatively stable voltage in the VSD's DC link during the voltage dip. As a result, the VSD is empowered to deliver an uninterrupted supply of adequate voltage or frequency to the connected motor, enabling seamless motor operation at the desired speed without being impacted by the voltage dip.

The DC compensator offers varied energy storage options such as ultracapacitors, capacitor banks and batteries. Under the ultracapacitor option, in scenarios where voltage dip leaves 40% remaining voltage (a 60% dip), the compensator can restore the voltage back to nominal levels for up to 2 seconds. In instances of 0% remaining voltage (100% dip), it can compensate for the voltage drop for up to 0.5 seconds. For comprehensive protection against complete outage and prolonged voltage dips (up to 1 minute), battery-based energy storage becomes the preferred choice as it can compensate up to 15 minutes full outage. However, this option will be the most costly and additional space is required to store the batteries.

Overall, a DC compensator with ultracapacitor emerges as a cost-effective solution in maintaining stable voltage levels in variable speed drives during voltage dips. This contributes to the reliability and performance of the connected motors and its associated systems. Notably, its smaller footprint, relative to Dynamic Sag Corrector (DYSC), due to the absence of DC to AC converter and ease of installation, marks an advantage. Its parallel installation to the VSD facilitates implantation without disrupting ongoing operations and its ultracapacitor system is sufficient to compensate for the full voltage loss for up to 0.5 seconds during severe voltage dip incidents.

4.4 Option 3: Protection at Process/Line level

Option 3 entails the implementation of the mitigating solution at the process or line supply level, typically at the LV sub-switchboard. This approach targets the critical process or line of the manufacturing operation, as well as the points where voltage-sensitive equipment are connected. This category of voltage dip mitigating solutions includes static Uninterruptible Power Supplies (UPS) or voltage dip restorer [e.g., ProDYSC].

An example of a voltage dip mitigating device for deployment at the LV sub-distribution panel is the Dynamic Sag Corrector (DYSC). The DYSC is a power electronics-based device, generally leverages the unaffected healthy phase of the voltage during voltage dips, or alternatively employs an extended energy storage system, often capacitors for longer interruption, to compensate for the power loss to the loads during the voltage dip incidents. The key components of a DYSC include the controller, static switch, power electronics converter and the option for an extended energy storage system.

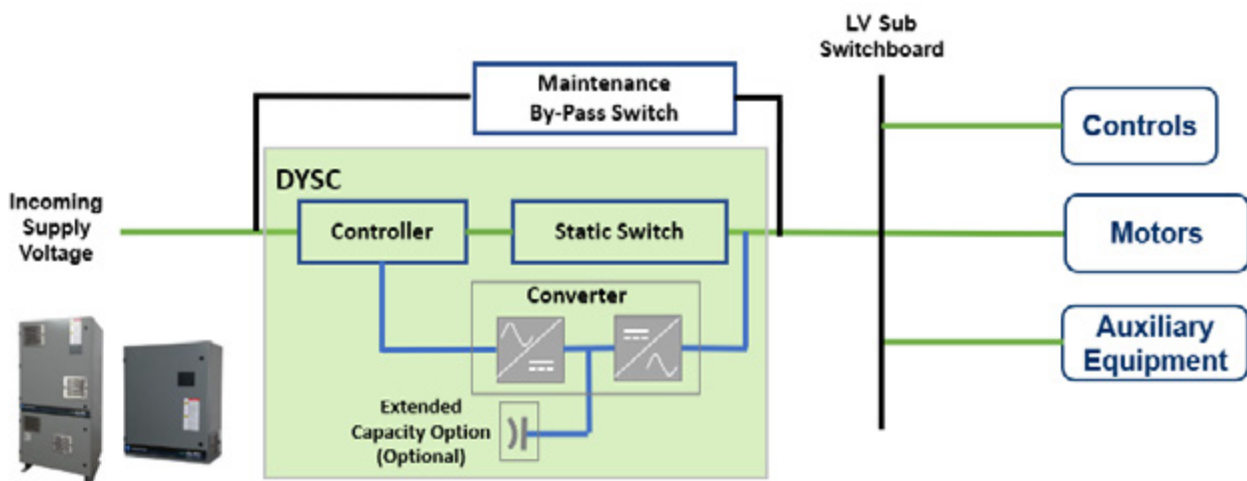


Figure 22: Example of Option 3 voltage dip mitigating solution: DYSC

During stable voltage supply, the DYSC continuously monitors the voltage waveform at its input through the voltage sensor in the controller. When the input voltage is within the acceptable range, the DYSC operates through the static switch mode, allowing voltage to pass through without compensation.

When the DYSC detects a voltage dip below a predetermined threshold, the voltage sensor control circuit initiates corrective action. The power electronics converter, which consists of thyristors or IGBTs, will switch into position and starts injecting electrical energy from unaffected voltage phase or from the extended energy storage system (if present). This energy is then supplied to the loads. The controller ensures precise timing and synchronization of voltage correction with the voltage dip, thus minimising the impact on connected equipment. Once the voltage dip event has passed, and input voltage returns to the acceptable range, the DYSC reverts to the static switch mode, allowing unimpeded power flow.

The DYSC offers both standard and extended capacity option. Under the standard option, it can compensate for voltage drops from 87% to 50% remaining voltage, restoring voltage to nominal levels up to 5 seconds during voltage dip incidents. For instances of 0% remaining voltage (a 100% dip), compensation can extend up to 50ms for standard capacity and 200ms for the extended capacity option.

It is important to note that even with the extended energy storage, there is a limit to the duration of dip it can compensate. Hence if it is deemed necessary to protect against severe and long voltage dip duration [>50% dip and > 200ms dip duration], static UPS may be the suitable option.

Overall, the DYSC proves to be a valuable asset in modern power distribution systems, offering dynamic and swift responses to voltage dips. This ensures the seamless operation of sensitive equipment and preventing potential damage or disruptions caused by these temporary voltage drops. Key advantages include its compact footprint and independence from battery-based energy storage to compensate for power loss during voltage dip occurrences. Depending on the load capacity requirements, MegaDYSC rating can be rated up to 1.6MVA [3Phase, 400V], ProDYSC up to 140kW [3Phase, 400V] and MiniDYSC up to 12KW [Single phase, 240V]. By selecting the appropriate DYSC rating, it can also serve as a voltage dip mitigation solution for LV main switchboards [Option 4] or even down to equipment-level applications [Option 2]

4.5 Option 4: Protection at Building level

For option 4, the solution can only protect against disturbances originated upstream of the building premises. It cannot mitigate against downstream disturbances within the building premises.

Option 4 involves implementing the mitigating solution at the building level, typically at the LV main switchboard. This strategy targets critical operations within the entire plants or the points where voltage-sensitive equipment is connected. Voltage dip mitigating solutions at this level include static Uninterruptible Power Supplies UPS, rotary UPS (flywheel) or Dynamic Voltage Restorer (MegaDYSC).

An example of a voltage dip mitigating device that can be installed at the LV main distribution panel is the Static UPS. It uses batteries as an energy storage to provide backup power to electrical equipment during power outages or grid network fluctuations. Key components of a static UPS include batteries, an inverter, and UPS, consisting of the rectifier, charging, and monitoring system.

The UPS continuously monitors incoming power supply from the grid network for any voltage or frequency irregularities. When the grid network delivers stable power within the acceptable voltage and frequency ranges, the UPS permits power to flow directly through to the connected equipment without intervention.

Upon detecting a dip or interruption in the grid power supply, such as a voltage drop or an outage, the UPS immediately activates its internal battery system, which remains charged and prepared to provide backup power when needed. The UPS seamlessly switches the power source from the grid to the battery-powered inverter, typically within milliseconds, to

avoid any interruption to the connected equipment. The UPS supplies power to the connected equipment from its battery system, compensating for the power dip or outage in the grid network. The backup power enables equipment to continue operating without disruption, safeguarding against data loss, equipment damage, or downtime.

Once the grid power stabilizes or returns, the UPS detects the improvement and seamlessly switches the power source back to the grid supply, once again to avoid any interruption. While operating on the grid power, the UPS simultaneously recharges its internal batteries to ensure that the batteries are ready for the next power dip or outage.

Overall, a static UPS acts as a buffer between the grid power supply and the connected equipment, providing continuous and reliable power during power dips or outages. When sized appropriately, it ensures the smooth operation of critical equipment and protects against any voltage disturbance including interruptions. When coupled with a step-up transformer and appropriately sized for sensitive loads, it can also be used as a voltage dip mitigation at the MV main switchboard [option 5 level].

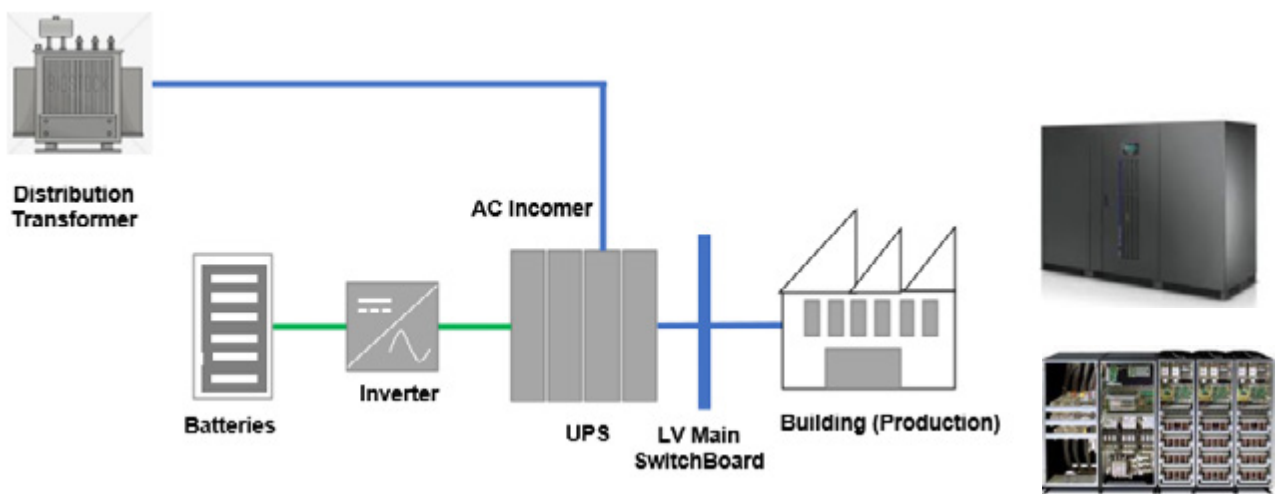


Fig 23 - Example of Option 4 voltage dip mitigation solution: Static UPS with battery

4.5 Option 5: Protection at Plant level

Similarly for option 5, the solution can only protect against disturbances originated upstream of the plant network. It cannot mitigate against downstream disturbances within the plant network.

In Option 5, the voltage dip mitigating solution is implemented at the high voltage (HV) supply intake level to the entire plant as shown in Fig 24. This approach typically overprotects the plant, protecting both sensitive and non-sensitive loads. HV devices can be expensive due to the high component cost of HV equipment such as the HV switchgear and transformers. Another consideration would be the footprint requirement of these devices, which can be substantial. Nevertheless, this solution offers a one-off connection. Importantly, the solution protects against voltage dips originating from the supply network but not from those occurring within the plant network. Such voltage dip mitigating solutions include Rotary [Flywheel] UPS, Static [Battery] UPS or Dynamic Rotary [Flywheel with diesel engine] UPS.

An example of voltage dip mitigating solution installed at the HV [e.g. 22kV] main switchboard is the Rotary Uninterruptible Power Supply [UPS]. This system combines mechanical and electrical components to provide continuous and reliable power to critical loads when a voltage dip occurs. The key component of a rotary UPS is a high-speed flywheel, which acts as an energy storage device. The flywheel is connected to an electric motor/generator set, commonly known as a motor-generator [MG] set.

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During normal operation when the utility voltage supply is stable, the motor-generator set operates as a motor. It draws electrical energy from the grid and converts it into mechanical energy to spin the flywheel at high speeds. As the flywheel rotates, it stores kinetic energy.

In the event of a voltage dip from the grid, the flywheel takes over as the primary source of energy. It releases the stored kinetic energy which is converted back into electrical energy by the motor-generator set, now operating as a generator. As the flywheel slows down, it releases the stored energy, allowing the generator to produce electricity. This energy conversion process is rapid, typically within a few milliseconds, allowing the critical load to receive continuous power without interruption. The rotational energy of the flywheel bridges the gap between the loss of utility power and the startup and stabilisation time of an alternative power source, such as a diesel generator. The rotary UPS system also incorporates power electronics, such as inverters and rectifiers, to regulate the voltage, frequency, and waveform of the electrical output, ensuring compatibility with the critical load's requirements.

Overall, a rotary UPS provides reliable power backup by utilising kinetic energy stored in a high-speed flywheel, enabling it to compensate for power loss or voltage fluctuations from the grid network.

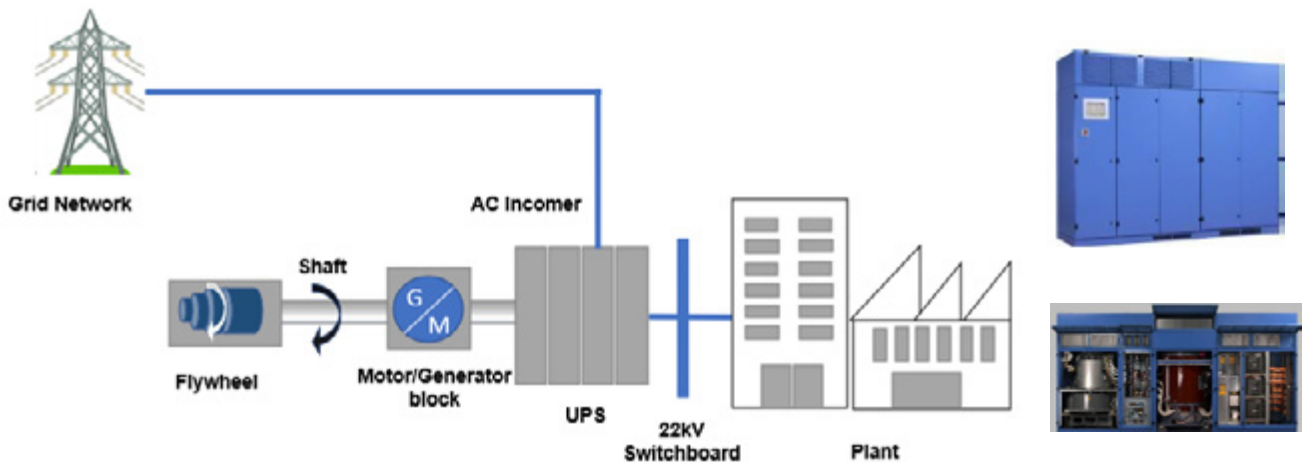


Fig 24: Example of Option 5 voltage dip mitigating solution: Rotary UPS [RUPS] with Flywheel

CHAPTER

05

Voltage Dip Case Studies



Case Study 1: Chillers

In this case study, we examine the impact of voltage dips on chiller operations.

Chillers are one of the most common equipment used in all industries from commercial buildings to manufacturing plants. The chiller system consists of compressor, condenser and cooler with motors that are controlled by voltage-sensitive variable speed drives. It plays a crucial role in various industries, providing chilled air and water for critical processes. Any interruption in chiller operation due to voltage dips can disrupt plant operations, leading to the loss of process cooling water. In high-tech industries like semiconductors and data centers, uninterrupted chiller operation is vital. In data center operations, chiller stoppage can result in a rapid rise in temperature within server racks, eventually causing server shutdowns and related issues.

The customer faced an issue where their chiller tripped and stopped during a voltage dip incident. Investigation revealed that the failure might have been caused by relay dropouts in the control circuit of the chiller system during voltage dip. Relays were commonly used for the starters of the condenser pump motors. Additionally, it was noted that the control board in the microcomputer also had an auxiliary relay, which potentially be a weak point when the voltage dip occurred.

The customer requested SPPA to conduct voltage dip tests on their chiller's control circuit together, including the microprocessor in the circuit. It was discovered that the relay contacts operated when voltage dipped by about 30%, leading to the motor's tripping. After identifying the chiller's control circuit's vulnerability to voltage dip, the customer decided to install a voltage dip mitigating device for the control circuit to evaluate its effectiveness. Subsequent voltage dip tests were conducted at various dip magnitudes and durations, demonstrating that the installed dip mitigating device effectively protected the control circuit from tripping. It successfully rode through dip tests according to SEMI F47 which met customer's requirement. [Note: Implementation of SEMI F47 guidelines does not assure full immunity against all disturbances. For more stringent dip ride through requirements, customer may consider higher guideline like Samsung Power Vaccine or customized guidelines.].

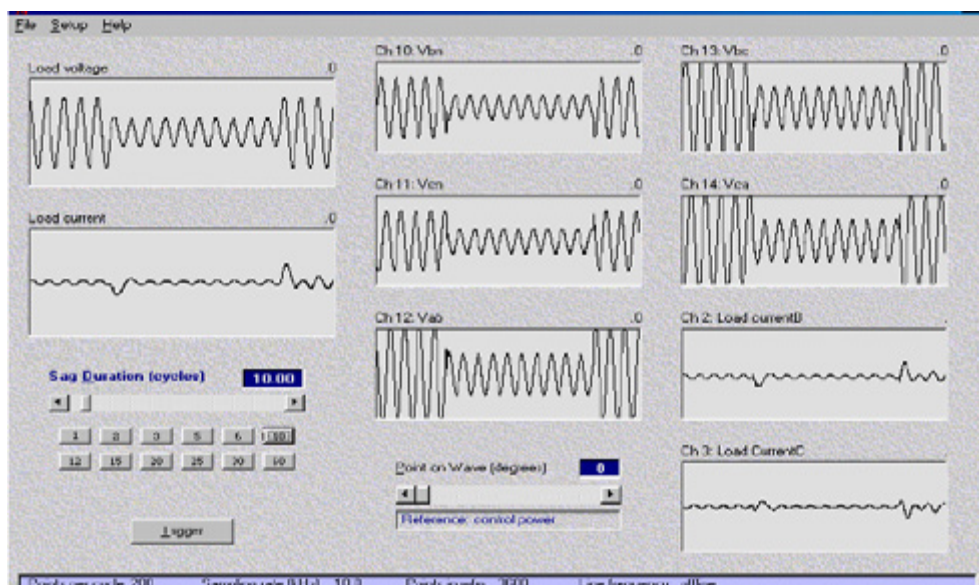


Fig 25 – Voltage Dip Testing – Supply/Load Voltage and Current Waveforms

Case Study 2: Exhaust Air Fans

Exhaust air fans (EAF) are commonly used in many high-tech manufacturing plants, particularly in controlled indoor environments or clean rooms. These fans must operate continuously to maintain the controlled environment within the clean room. Typically, these fans are usually driven by Variable Speed Drives (VSDs) to provide optimal airflow, soft starting and precise speed control.

A customer noticed that the air pressure monitored by the EAF's sensor fell below specified levels during voltage dip incidents. According to the operation requirements, the air pressure within the EAF should not drop to zero because doing so would compromise air quality in the controlled clean room environment, necessitating the disposal of affected products.

During voltage dip incidents, the VSD would “trip” and cause the exhaust air fan to slow down and stop. Subsequently, the exhaust air-pressure sensor would trigger an alarm after detecting zero pressure. Although the VSD was configured to restart automatically after the fan had stopped, this still resulted in the problematic zero air pressure situation, leading to products scrapping. Voltage dip tests were conducted jointly with the customer to explore mitigating solution for the VSD to prevent this zero air pressure scenario.

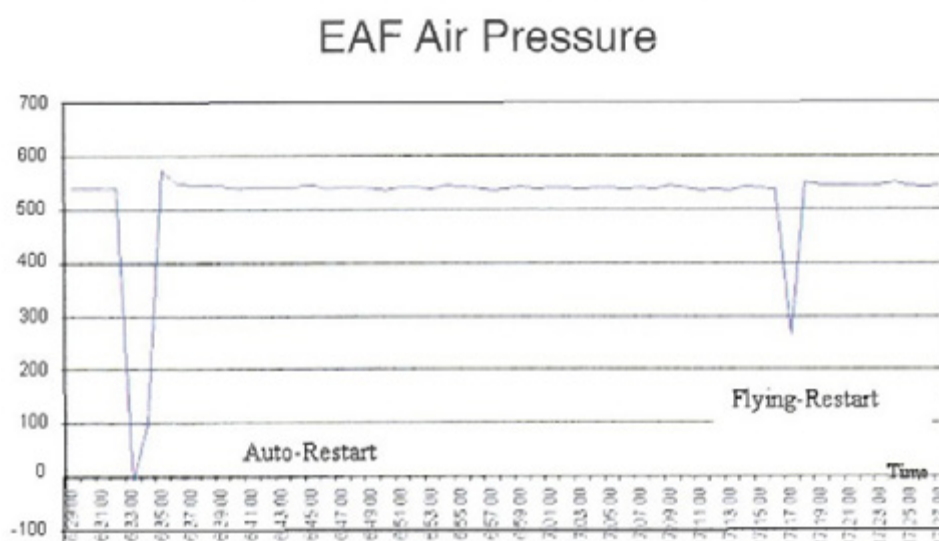


Fig 26 – Air Pressure of Exhaust Air Fan

During voltage dips tests, the EAF air pressure was monitored using the plant's Facility Management Control System. When the VSD was set to auto-restart, it was observed that the monitored air pressure dropped to zero. The customer consulted the VSD supplier, who suggested changing the VSD setting from auto-restart to a “flying” restart. With this adjustment, the VSD would rapidly increase the fan's speed to normal before it came to a complete stop during the voltage dip. During subsequent voltage dip test with the VSD set to “flying” restart, the air pressure sensor recorded pressure drops, but the pressure did not drop to zero and production is not affected. Since the VSD had this “flying” restart built-in, the customer decided to enable this function as a mitigating measure against voltage dip incidents. The customer was highly satisfied with this dip mitigating solution as it incurred minimum costs and effectively prevented production losses.

Case Study 3: Flywheel UPS

Many customers use flywheel Uninterruptible Power Supply (UPS) to protect their voltage sensitive equipment from voltage dip disturbances that could disrupt plant operations. However, in one case, a customer faced an unexpected issue where the entire plant's supply was disrupted when all their flywheel UPS units were activated, despite no observable voltage drip disturbances during this activation. Intriguingly, there was a minor voltage drop of about 3% during this incident.

This incident puzzled us as we were aware that the customer's plant is equipped with multiple voltage dip mitigating devices that have successfully handled more severe drops, some as low as 7-8%. During investigation with the customer, it was revealed that the flywheel UPS units were activated due to frequency threshold violation. These frequency thresholds were set at $\pm 1\%$ [49.50hz and 50.5hz] by their OEM during commissioning of the UPS units.

The customer explained that all the flywheel UPS were intermittently cutting in and out over a short duration, and when their stored energy was depleted, the plant was left without power because the flywheel UPS units had earlier disconnected the grid's incoming circuits when they were activated. Although the voltage fluctuation was relatively small, the system frequency had indeed dropped below 49.50hz and the disturbance originated from a power generation plant. Upon further discussion, it became clear that the customer's equipment was not sensitive to frequency fluctuations. Consequently, the customer was advised to either "disable the frequency threshold setting (if possible) or "de-sensitise" it by adjusting it to a higher, less restrictive value. This change would prevent the flywheel UPS units from activating unnecessarily due to minor frequency variations and avoid disruptions caused by frequency threshold violations.

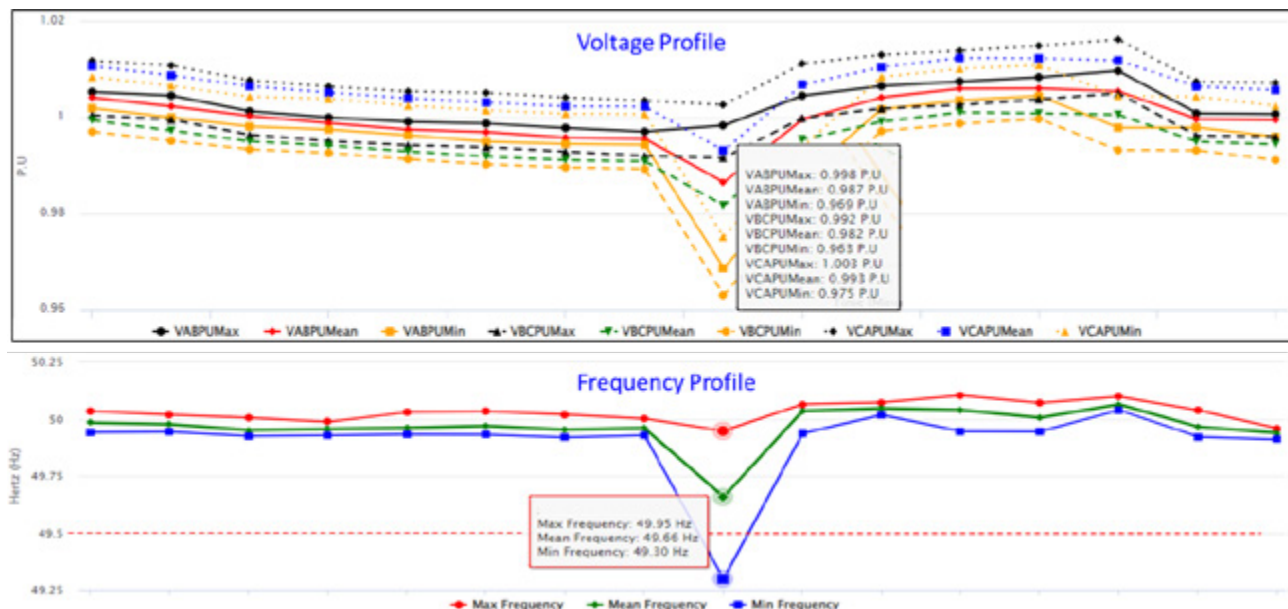


Fig 27 – Voltage RMS and Frequency Plot

Case Study 4: Under/Over Voltage Relay

In this case, a customer reported a significant disturbance in half of their plant due to a voltage dip event, which coincided with a single-phase cable fault occurring on the same distribution network to which the customer was connected. The customer shared that their equipment recorded a “very high” voltage swell and a “severe” voltage dip during this incident.

The root of the issue lay in the customer’s electrical setup, specifically the presence of Neutral-Resistor-Ground (NGR) connection installed at the transformer star point. In the event of a single-phase fault, such as the cable fault mentioned, fault current flows through the NGR, causing the two healthy phases voltages to “swell” at the neutral-star point. However, this process doesn’t lead to significant fluctuations in line voltages, with variations typically remaining below 10%. [Fig 28 for phase and line voltage disturbance waveform].

The problem arose from the under/over voltage relay, which had activated during the event, resulting in an outage for half of the plant. The suspicion was that the customer’s voltage relay setting was based on phase voltage, as the recorded voltage disturbance magnitude closely matched the phase voltage values captured by SPPA. This misalignment occurred because the customer’s distribution transformers are “Delta-Star” configuration, where the LV supply did not experience voltage “swell/dip” for this single-phase fault, as the transformer primary voltages are Line-Line.

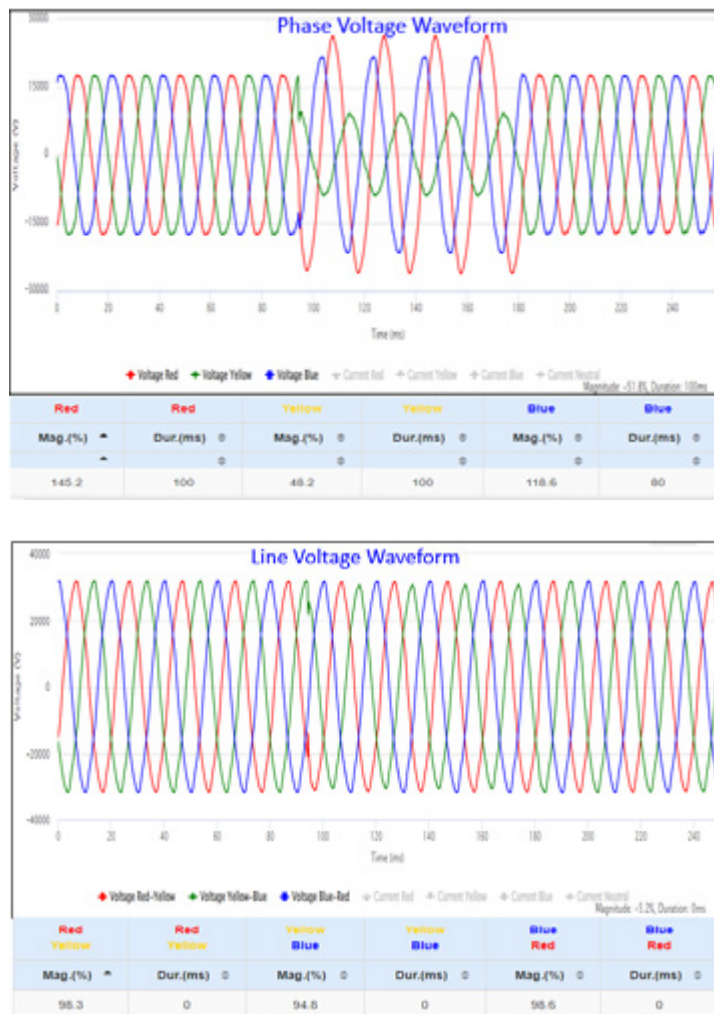


Fig 28 – Phase and Line Voltage Waveform of A Single-phase Fault

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To address this issue, the customer was advised to consult with their electrical plant designer to determine the correct relay settings. Additionally, it was recommended that for over/under voltage relay protection schemes at customer's installation, the relays should be placed as close to the equipment or processes they are intended to protect. This would minimise unnecessary disruptions to other equipment. If the relays needed to be installed at the incoming feeders or main incoming switchboard, the relay's magnitude and duration settings should be configured based on "back-up" value, considering more serious dip magnitudes and longer durations. This adjustment would ensure that downstream protection relays had sufficient time to operate in the event of a disturbance.

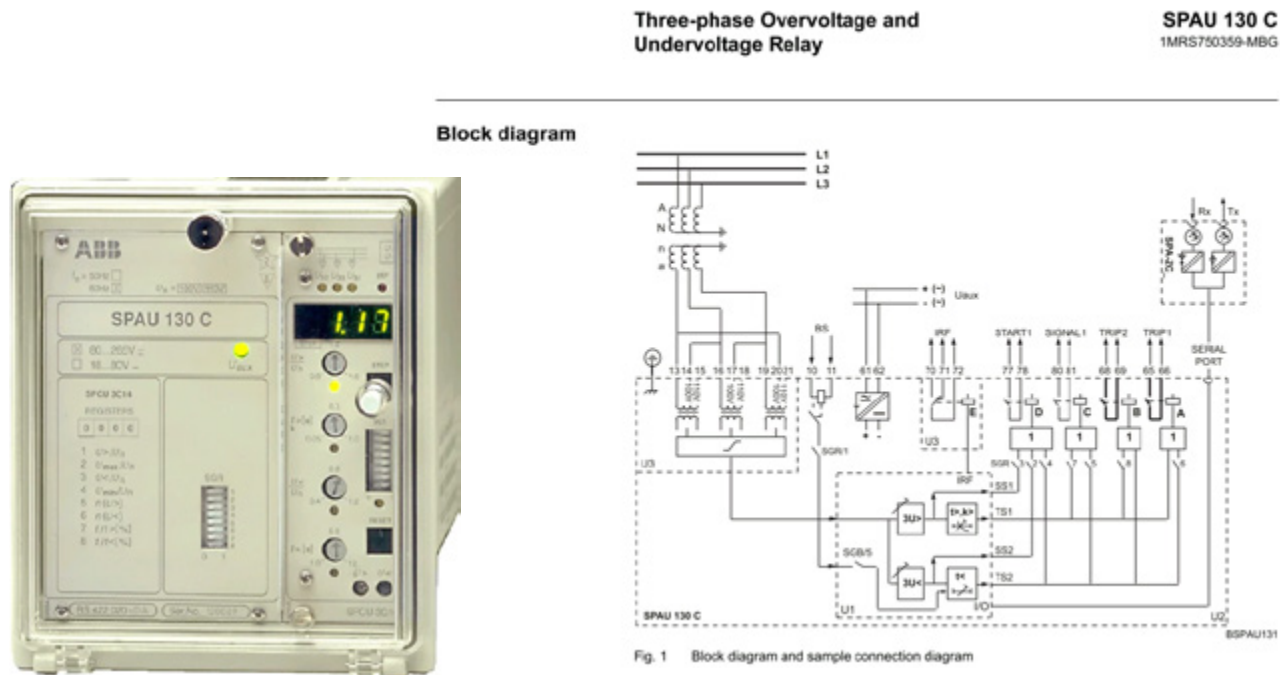


Fig 29 – Example of a ABB Over/Under Voltage Relay Photo and Connection Diagram

Case Study 5: Other observations and suggestions

a) Intelligent Drive Restart Planning in Plants Enable “Auto-Restart” and “Flying-Restart” of Multiple Drives in a Plant

Customer considering implementing “auto” or “flying” restart for their drives in their plant should be aware of the potential issues that can arise. For example, enabling all their drives to “flying” restart simultaneously after a voltage dip incident might result in a collective in-rush current surge that can overload the upstream breaker at the sub or main distribution switchboard and cause it to trip. Once the “in-rush” characteristic is understood, a strategic plan can be developed to configure the drives to “flying” restart, “auto” restart and manual restart setting. For those drives that are configured to “auto” restart, it is crucial to implement a “delayed staggering” timing approach. This means that some drives will restart immediately after the incident, while others restart at a short delay, such as 5 minutes, and still others after a longer delay, like 10 minutes. This staggered approach helps prevent over-current conditions and breaker tripping.

b) Replace faulty protection device with the correct type and characteristics

A customer reported an issue with one of the escalators stopping during a voltage dip incident, while the others remained unaffected. Investigation revealed that the escalator’s Miniature Circuit Breaker (MCB) has tripped due to overcurrent. Further investigation reviewed that although the MCB rating was the same as those used in other escalators, the MCB that tripped was the “incorrect” type, labelled as “Type-B”. In contrast, the MCBs in the other escalators were “Type-C”.

Type-B MCBs are designed to trip at fault currents of 3-5 times rated current (I_n), while Type-C MCBs are designed to trip at 5-10 times rated current (I_n). It was discovered that the maintenance crew had previously replaced the MCB with the “incorrect” Type-B when it failed. This case highlights the importance of training and reminding maintenance staff to use the correct type of characteristics of protection devices when replacements are necessary. Using the wrong type of protection device can lead to unexpected interruptions in the equipment operation during voltage disturbances.

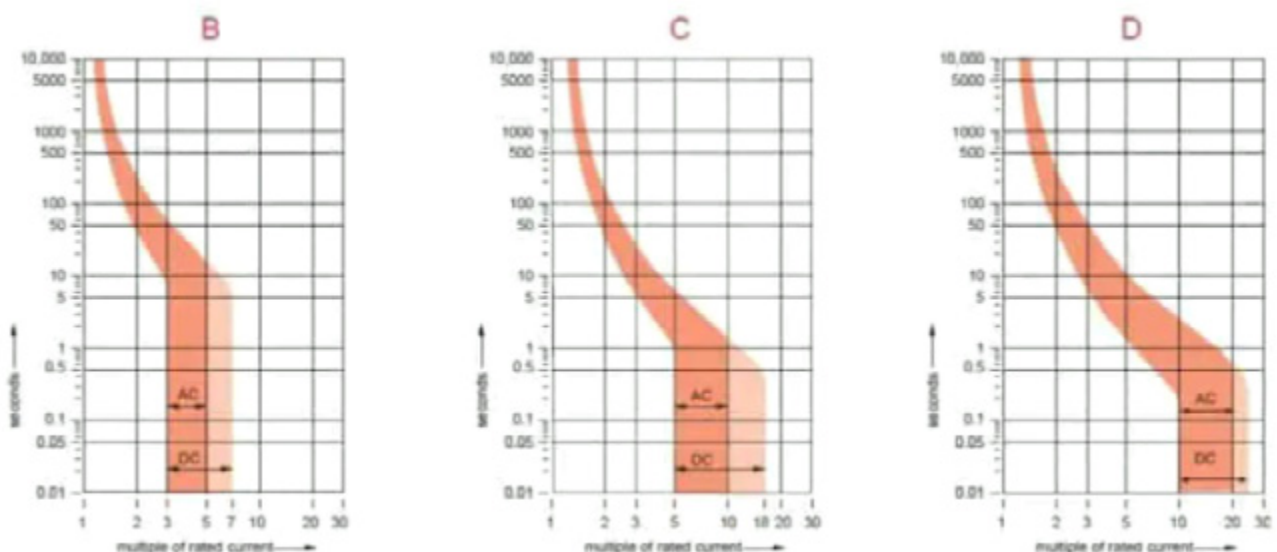


Fig 30 – Typical MCB Type Current/Tripping Time Characteristic

>> APPENDIX A: WHERE TO GET MORE INFORMATION

This section provides links to additional information on power quality concerns and solutions. Good resources include standards organisations, power quality monitoring equipment and manufacturers of voltage dip mitigating equipment.

This is not meant to be a comprehensive list.

ORGANISATIONS

Organization	Website
EMA	https://ema.gov.sg
IEEE	https://www.ieee.org
IET	https://www.theiet.org
IEC	https://iec.ch
CIGRE	https://cigre.org
Cired	https://cired.net/
SEMI	https://semi.org
ITI	https://itic.org

PQ MONITORING EQUIPMENT MANUFACTURERS

Company	Website
A.Eberle	https://a-eberle.de/en
Dranetz	https://dranetz.com
Elspec	https://elspec-ltd.com
Fluke	https://fluke.com
Hioki	https://hioki.com
Powerside	https://powerside.com
Qualitrol	https://qualitrolcorp.com
Satec	https://satec-global.com
Schneider Electric	https://schneider-electric.com
SEL	https://selinc.com
Siemens	https://siemens.com
Unipower	https://unipower.se

VOLTAGE DIP MITIGATING EQUIPMENT MANUFACTURERS

Company	Website	Voltage Restorer	Static Var Compensator	UPS	
				Rotary	Static
ABB	https://abb.com	✓	✓		✓
Active Power	https://www.activepower.com			✓	
Allen Bradley [by Rockwell Automation]	https://ab.rockwellautomation.com	✓			✓
American Superconductor	https://amsc.com	✓			
Ametek Solid State Controls	https://solidstatecontrolsinc.com				✓
APC [by Schneider Electric]	https://apc.com				✓
Bonitron	https://bonitron.com	✓			✓
Controlled Power	https://controlledpwr.com				✓
Emerson Industrial Automation	https://emersonindustrial.com				✓
Hitzinger	http://www.hitzinger.at/			✓	
Piller Power Systems	https://www.piller.com			✓	✓
Precise Power Corporation	http://www.written-pole.com			✓	
PowerSmiths	https://powersmiths.com				✓
Schneider Electric	https://schneider-electric.com	✓			✓
Toshiba International Corporation	https://www.toshiba.com/tic				✓
Tripplite	https://tripplite.com	✓			✓