Monitoring Emergency Power Supply Health and Performance to Ensure Peak Reliability

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Abstract

Emergency power supplies (EPS) are installed to provide power to critical loads either as a backup or an on-line supply. The reliability of the EPS is a key factor when selecting equipment. Once the supply is installed, routine maintenance and testing does not always ensure that the supply maintains its design reliability. Utility power supplies are becoming increasingly unreliable and interruptions from faults or deliberate load shedding is occurring more frequently. This paper will discuss how monitoring of emergency and Utility supplies can ensure the reliability of an EPS. Considerations in the design, selection and installation of monitoring systems will be presented as well as the methodologies used in the analysis of such data. Case study data from field measurement systems will be provided. Monitoring systems can assist engineers, consultants and facilities management personnel to maintain emergency supplies at peak reliability.

(Un)Reliable Power Supplies

It is estimated that power interruptions result in economic losses costing over an estimated $100 billion per year in the United States. There are many reasons for power interruptions. This includes equipment failure, natural disasters and deliberate actions by utilities. Many utilities that have previously provided uninterrupted power are now unable to provide for the full load of the power grid and now deliberately interrupt power to consumers during peak periods. This places an additional burden on the emergency and backup power systems.

Emergency Power Supply Considerations

Transfer Time

Emergency power systems provide backup power to critical loads when the main power system fails or is interrupted. The supply can be provided without any interruption, as in the case on an online UPS, or with some degree of interruption. In the latter case, the interruption can be as less than 1 cycle with a line interactive UPS, or up to a minute in the case of a standby generator. The choice of the backup power depends on the nature of the load. The more critical and sensitive the load is to interruption, the shorter the transfer time. The monitoring system must take into account if the EPS operates on-line or in standby.

Connection to the Utility

EPS's are normally connected in some way to the Utility supply. The Utility supply is either fed directly to the load with the EPS supply in parallel, or it feeds a secondary power source such as a battery in the case of an inverter or on-line UPS. EPS's also have to have sensing circuitry connected to the Utility supply to detect failures as well as chargers for batteries. The Utility supply is constantly stressing the connected components of the EPS. If any of these items fail, the emergency supply will also fail.

Reliability

The reliability of an EPS is a key design factor in a critical systems application. The equipment must be able to deliver the required performance when required to do. The factors that influence reliability are:

1. Design and Manufacture. It is essential to source equipment from reputable suppliers with a proven track record and customer references. There are numerous end-users who have purchased equipment that had technically sound specifications on paper but failed to meet these in service. Poorly designed or manufactured equipment will be a constant point of failure in the power system. Redundant systems can also be used to increase design reliability
2. Installation. Equipment needs to be installed correctly to meet its design specifications.
3. Maintenance. The EPS needs to be maintained to the manufacturer's recommendations to ensure ongoing reliable operation.
4. Environment. This includes the electrical connections to the equipment as well as other factors such as temperature, vibration, fuel quality etc. The environment is constantly changing and without monitoring these factors can be difficult to control, and may contribute to failure or malfunction of the EPS equipment.
5. Protection. Critical equipment may fail if subjected to power disturbances from adjacent equipment. The EPS may survive but the load equipment may fail.

The choice of monitoring system, as well as the method of monitoring is influenced by the above factors. Standby or off-line EPS systems have a problem in that in-service performance can usually only be determined when there is a Utility failure. At that stage it is too late to do anything about a malfunction. In the case of a standby or off-line system, the equipment must be placed in-service before the performance can be measured. This also presents a challenge that if the EPS equipment has failed or about to fail, putting it in service will precipitate the failure.

A potential solution is to the above is to periodically test the EPS equipment on non-critical loads and monitor its performance. This will require a bypass isolation circuit.

Equipment Immunity

Equipment in use today is increasingly susceptible to damage or will malfunction during periods of poor power-quality. The ability of the equipment to perform in the installed environment is an indicator of its immunity. The reliability of equipment depends on the susceptibility of the component that has the lowest immunity to power quality. Even if most of the equipment is capable of enduring severe power quality problems, one component with poor immunity can result in the entire machine being extremely unreliable. The following table illustrates how equipment immunity can be generally classified.

High immunity	Motors, transformers, incandescent lighting, heating loads, electromechanical relays
Moderate immunity	Electronic ballasts, solid-state relays, programmable logic controllers, variable speed drives
Low immunity	Signal, communication, and data processing equipment; electronic medical equipment

The immunity of equipment must be matched with the immunity provided by the EPS to ensure reliability. In addition there is interdependence between equipment connected to the same supply. This means that equipment that operates satisfactorily individually does not function correctly when connected together in an EPS. It is recommended that continuous monitoring of both the input to, and output from the EPS is continuously monitored to identify and correct problems that may occur.

Monitoring Systems

EPS equipment that is well designed, installed and maintained can still fail or become unreliable if the operational conditions or load circuits change from the equipment capacity. There are numerous case studies detailing problems experienced with EPS equipment when incorrect assumptions are made or when conditions in a plant change.

Monitoring systems are widely used to measure and report plant and equipment performance. A combination of proactive monitoring and maintenance will ensure both the EPS and load equipment operates at peak performance as operating and environmental conditions change. Often the monitoring will not directly reveal problems. Changes may be subtle and may be detected only by examining trends over a period of time.

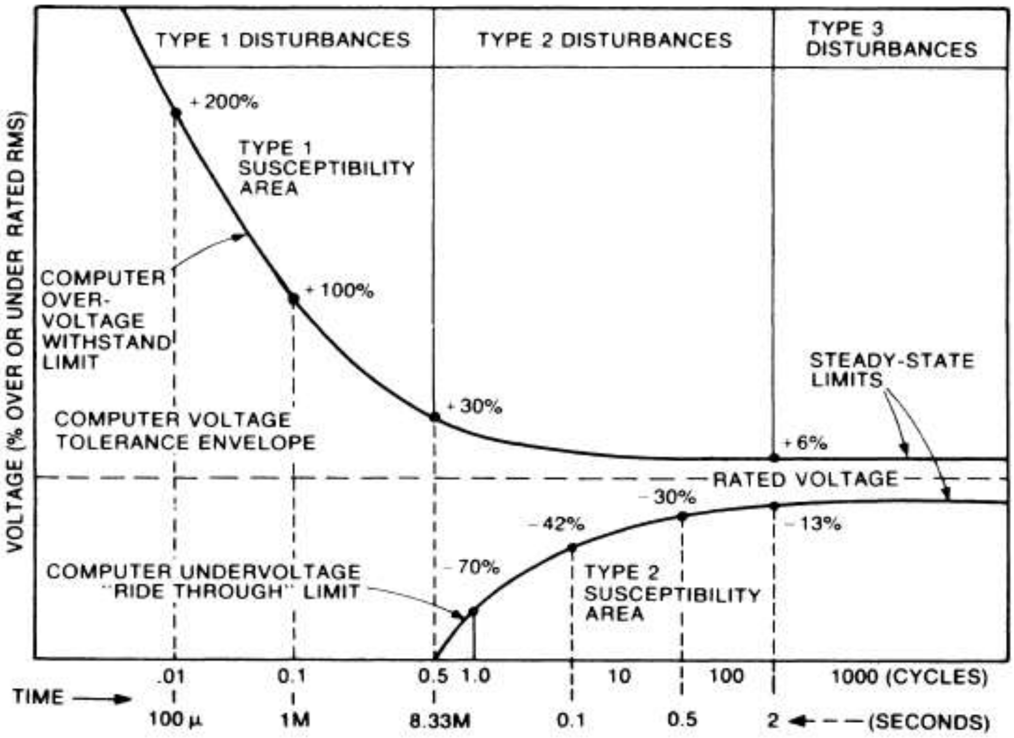
By monitoring both the input to the EPS and its output, the overall impact of any power quality disturbances can be assessed. Suggested monitoring parameters are listed below.

Voltage

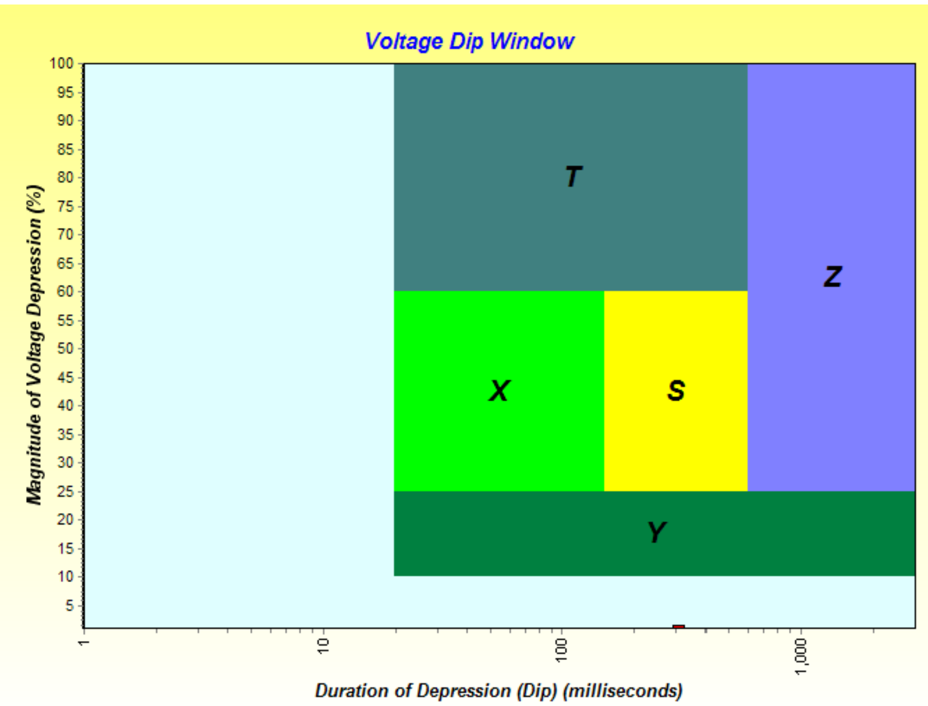
Voltage is a fundamental characteristic of an AC power system. In a study conducted by the Naval Facilities Engineering Command, three distinct categories of recurring disturbances on Utility power systems were identified. These are shown in the following table.

Parameter	**Type 1**	**Type 2**	**Type 3**
Definition	Transient and oscillatory overvoltage	Momentary undervoltage or overvoltage	Power outage
Causes	Lightning, power network switching, operation of other loads	Power system faults, large load changes, Utility company equipment malfunctions	Power system faults, unacceptable load changes, Utility equipment malfunctions
Threshold[1]	200-400% of rated rms voltage or higher (peak instantaneous above or below rated rms)	Below 80–85% and above 110% of rated rms voltage	Below 80–85% of rated rms voltage
Duration	Transients 0.5–200 µs wide and oscillatory up to 16.7 ms at frequencies of 200 Hz to 5 kHz and higher	From 4–6 cycles, depending on the type of power system distribution equipment	From 2–60 s if correction is automatic; from15 min to 4 hr if manual
[1]: The approximate limits beyond which the disturbance is considered to be harmful to the load equipment			

This study also found that more than 50% of data processing equipment failures occurred during bad weather accompanied by lightning and Utility power failures. This led to the well known Computer Business Equipment Manufacturers Association (CBEMA) curve which was developed during the 1970's utilizing historical data from mainframe computer operations. This curve is shown below indicates the range of acceptable power supply voltages for computer equipment. The horizontal axis shows the duration of the sag or swell, and the vertical axis shows the percent change in line voltage.



There have been a number of revisions to this curve for various industries and types of equipment. They all provide guidelines to the voltage tolerance limits within which equipment should function satisfactorily. Similar data in South Africa (NRS048-2:1996) is presented in the form of a two-dimensional plot of dip depth and duration as shown below.



The various disturbance classes are based on the following observations:

- A vertical line at 20ms. Blocks off phenomena below 1 cycle as such events are not generated on interconnected power systems and do not affect customer's plant.

- A horizontal line at 20% marks the onset of problems with large variable speed drives.
- Motor control contactors drop out in the range 20% -60% at durations of 20ms to 150ms
- At durations exceeding 200ms substantive loss of motive power can be a problem.

From the above it is recommended that monitoring of the voltage into and out of the EPS is required. EPS's comprise a number of sensitive components that are connected to the Utility supply. These circuit elements are most vulnerable to failure as they are subjected to high energy surges from lightning and other sources. Voltage also directly effects equipment rating. Over-voltages result in overheating and premature aging of the insulation. This results in increased maintenance and a reduction in the equipment life. Under-voltages can cause equipment to switch off. Induction motors may stall if the supply voltage is reduced. A lower line voltage reduces motor starting current and torque. A motor may fail to start if the line voltage is too low.

Current

Load current is usually proportional to supply voltage. During transient conditions, the measurement of current can provide important information regarding the source of a disturbance. A change in voltage that precedes a change in current is usually a disturbance on the utility side. However if the current changes before the voltage, the disturbance is from a change in load. The EPS supply and load current will also provide information on line and load regulation. Changes of load to the EPS with time can be identified, and overload conditions can be rectified before this results in a failure.

Unbalance or Sequence Components

This is not relevant in a single phase EPS, but must be carefully monitored in a 3 phase system. An unbalance of more than a few percent can cause overheating and equipment failure. Unbalance in an EPS will cause

- Negative sequence torque in motors resulting in lower efficiencies, additional maintenance and failure of couplings and gearboxes
- Additional heating effects from circulating currents leading to premature aging of insulation and reduced service life
- Stalling of motors and loss of cooling when a phase is lost
- Reversal of direction if the phase sequence is changed, leading to equipment malfunction.

Unbalance can be a result of equipment malfunction as well as incorrect connection of single phase loads to the output of a three phase UPS.

Harmonics

EPS systems are often designed to suppress line transients and harmonic disturbances. These distortions in voltage and current wave shapes can upset end-use equipment and cause other problems. If an uninterruptible power supply (UPS) detects excessive supply voltage distortion, it may switch to its battery supply. When the batteries run out, the critical load may drop out. Harmonics result in:

- Heating Effects
- Resonance
- Unexpected currents in the neutral (vector additions)
- Vibration
- Electromagnetic Interference
- De-rating of equipment

Harmonics can be generated by loads on the output of an EPS as well as be present on the supply input.

Power Factor

Poor power factor decreases efficiency and increases both the voltage drop and percentage losses in an EPS. The addition of reactance into a power circuit increases the current for same power and results in decreased capacity. In some utilities an additional billing charge is levied for power factor or maximum demand.

Frequency

The Utility frequency is carefully controlled, often to within 0.1 Hz of the nominal. Equipment tolerance to frequency varies. Most switch mode power supplies have a wide tolerance (48Hz to 60Hz). Rotating machinery is however usually highly susceptible to frequency changes. This can be a serious issue with standby generators that do not have automatic speed control.

EPS Parameters

There are a number of additional parameters that can be recorded that are specific to the type of EPS. These include battery voltage, battery cell condition and charge status

EPS Monitoring Equipment

The measurement of the above electrical parameters on the Utility supply to the EPS and its output to the load can be provided by modern high speed computer based recorders. Monitoring equipment can be installed in the EPS facilities room or distribution panel. A typical system is shown below.

The monitoring system should have the following features:

- Measure and record voltage disturbances with sub-cycle resolution
- Measure and record steady-state power parameters such as phase voltage and current, harmonics, unbalance, frequency, power and power factor
- Measure and record EPS specific parameters such as battery voltage, cell condition and charger status
- Save recorded data in history files and transmit these to a central database
- Provide data analysis facilities

The monitoring equipment must be able to give the user a comprehensive and detailed record of the power quality of the utility supply into the EPS, as well as the power quality from the EPS to the critical load. In this way it is possible to assess the threat to critical equipment from the power system.

Storage of the data from the monitoring system into a central database allows easy analysis and comparison of historical data. Identification of trends in the data can be used to avert potential problems.

Data analysis

Once the measurements have been taken, the data must be analysed to determine if there is a problem and then what can be done about it. The measurements are usually divided into two categories – events and trends.

Trends are long-term changes in EPS system parameters. Measurements are typically taken on a cycle by cycle basis and then averaged over a period of typically 10 minutes to arrive at a single value. These values are then taken to establish the baseline and deviations of various parameters. The following parameters are usually measured as trends.

- Voltage regulation
- Unbalance
- Harmonics
- Flicker
- Power factor
- Load current
- Maximum demand

There are many short term events that take place. These are typically shorter than 3 seconds in duration. The measurement is made by capturing waveforms and then extracting the necessary parameters. The following parameters are measured as events.

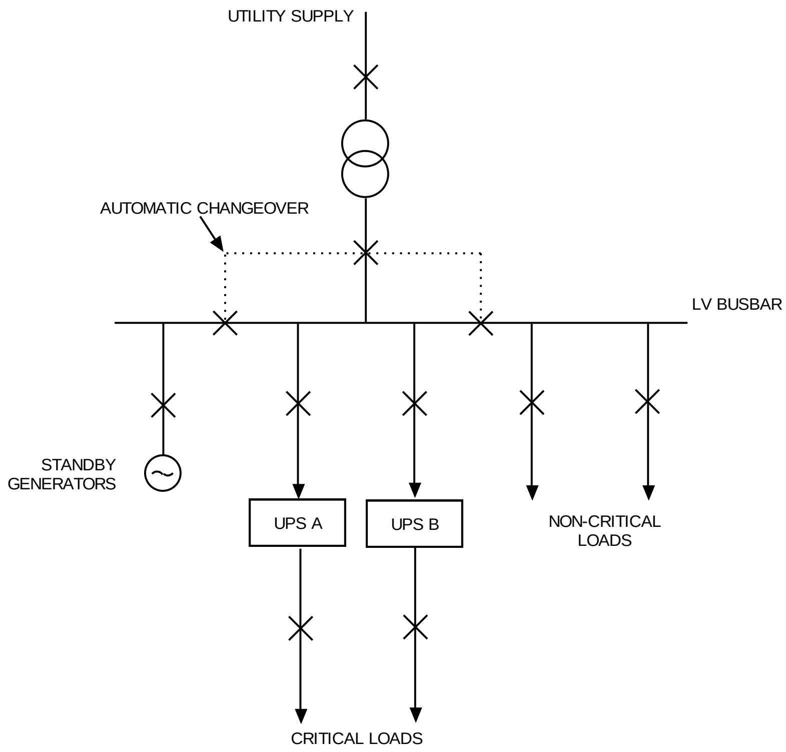
- Voltage dips
- Voltage swells
- Voltage transients

The data can be compared with well established industry norms to determine if there is a problem. If there is no absolute standard, data will be analysed according to a baseline and trends. As discussed previously, each industry has acceptable limits for power system parameters (e.g. ITIC). For example the following table provides recommendations for data processing equipment.

Environmental Attribute	Typical Environment	Acceptable Limits for DP Systems	
		Normal	Critical
Line frequency	± 0.1 to ± 3%	± 1%	± 0.3%
Rate of frequency change	0.5 to 20 Hz/s	1.5 Hz/s	0.3 Hz/s
Over- and under-voltage	± 5% to +6, –13.3%	+ 5% to –10%	± 3%
Phase imbalance	2 to 10%	5% max	3% max
Tolerance to low power factor	0.85 to 0.6 lagging	0.8 lagging	less than 0.6 lagging, or 0.9 leading
Tolerance to high steady state peak current	1.3 to 1.6 peak, rms	1.0 to 2.5 peak, rms	Greater than 2.5 peak, rms
Harmonic voltages	0 to 20% total rms	10 to 20% total, 5 to 10% largest	5% max total, 3% largest
Voltage deviation from sine wave	5 to 50%	5 to 10%	3 to 5%
Voltage modulation	Negligible to 10%	3% max	1% max
Surge/sag conditions	+10%, –15%	+20%, –30%	+5%, –5%
Transient impulses	2 to 3 times nominal peak value (0 to 130% Vs)	Varies; 1.0 to 1.5 kV typical	Varies; 200 to 500 V typical
RFI/EMI normal and common modes	10 V up to 20 kHz, less at high freq.	Varies widely, 3 V is typical	Varies widely, 0.3 V typical
Ground currents	0 to 10 A plus impulse noise current	0.001 to 0.5 A or more	0.0035 A or less

EPS Case Study – Cellular Phone Company

A monitoring system was installed to measure and record the EPS performance at a number of switching installations at a cellular phone operator. The data from the different sites was sent to a central database at the national operations centre. The monitoring system measured voltage and current on the LV busbar as well as the UPS powered loads.



Simplified Single Line Diagram of Cellular Switch Supply

The above diagram is typical of the power supply to a switching site. These installations are located in major cities in South Africa. The cell phone provider's business system requires the network to be continuously available. Any interruption in the network results in a loss of revenue that cannot be recovered. This consequently requires the power supply to be uninterrupted. All critical loads such as cellular RF, network equipment and computers are supplied by the uninterrupted power supplies (UPS). Equipment has a redundant backup, which reflects the mission critical nature of the operation. The loads are relatively small (30-60 kVA). In some of the smaller exchanges, use is made of banks of batteries which are constantly charged. These supply DC power to certain equipment. Inverters provide AC power to the other critical loads.

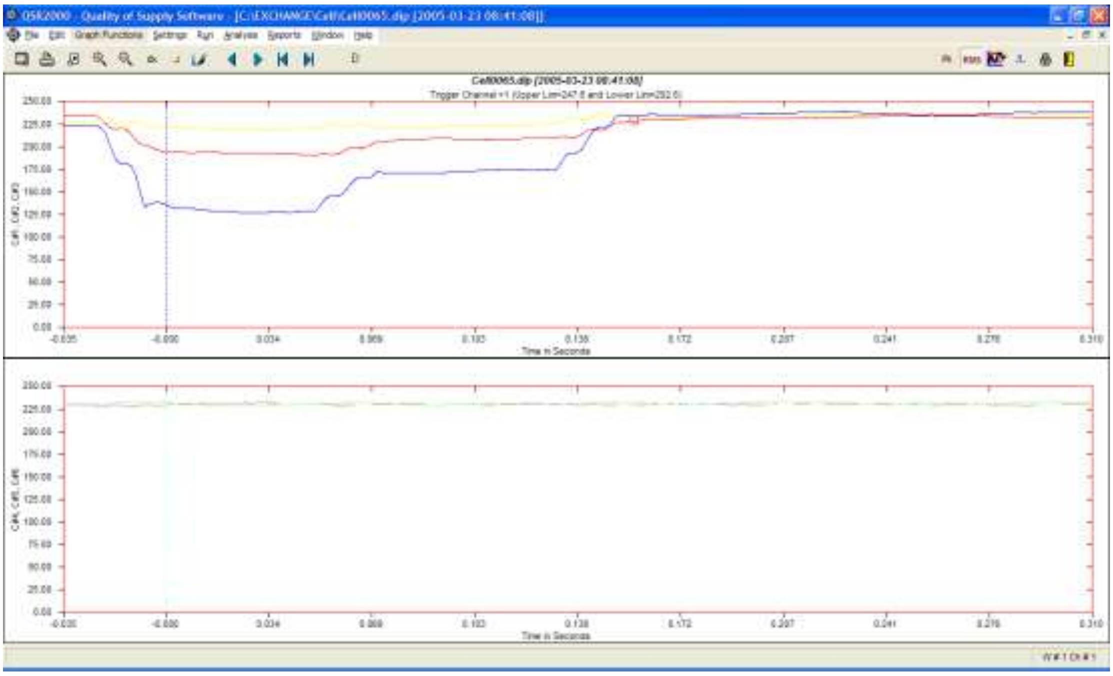
In the event of a supply interruption, the UPS, batteries or inverters supply power to the critical loads. Standby generators start up and once their supplies have been synchronized and are stable, an automatic changeover occurs and the supply is restored. This takes around one to two minutes to occur. The system can operate for several hours in this mode if required. A recent fire at a Johannesburg substation left the supply to the exchange off for over a week. The limiting factors are fuel supply, heat generation and noise pollution.

During normal service the UPS equipment is subjected to lightning and switching surges from the supply. Surge suppression equipment is fitted at the supply to reduce the magnitude. Monitoring equipment was installed to monitor the performance of the surge suppression equipment and the quality of the UPS supply to the critical equipment. This has been highly successful in detecting early failures that could consequently lead to equipment damage and failure.

Some examples of power quality measurements taken at these sites are illustrated below.

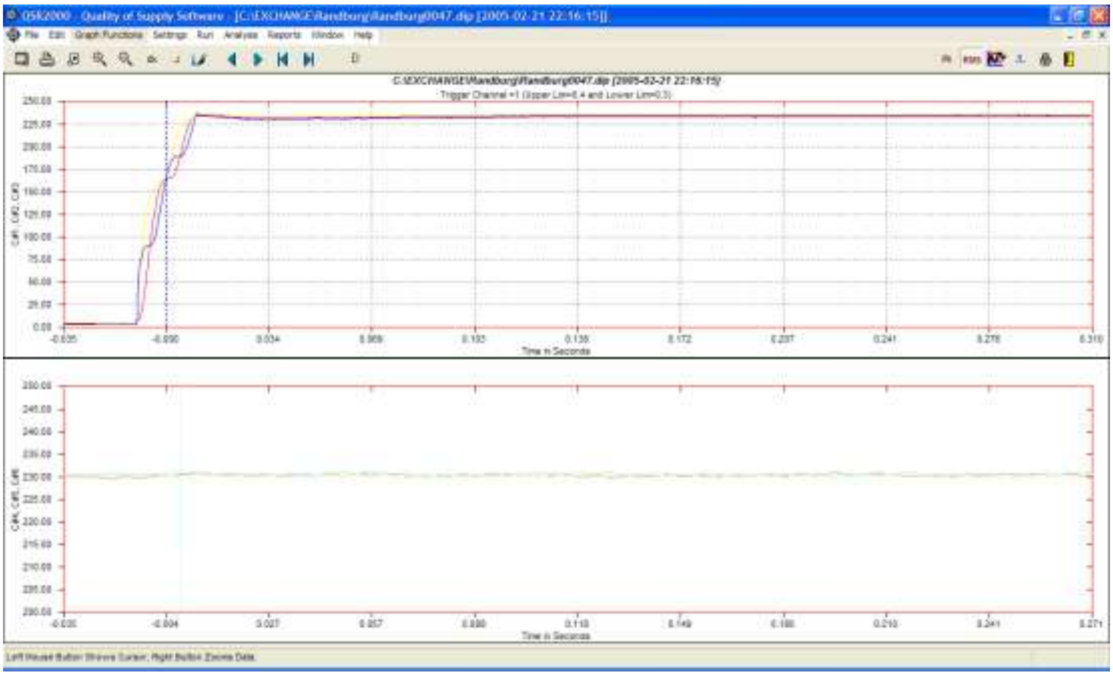
Power Quality Measurements on Utility and EPS Supply

As discussed above, it is imperative to ensure no interruption of the power supply to any critical loads occurs. As the following figures illustrate, the simultaneous measurement of incoming supply voltage and UPS output voltage. A severe voltage dip, total interruption and restoration of the incoming supply do not affect the UPS output voltage. The top trace is the supply voltage to the UPS while the bottom trace is the output voltage to the equipment.



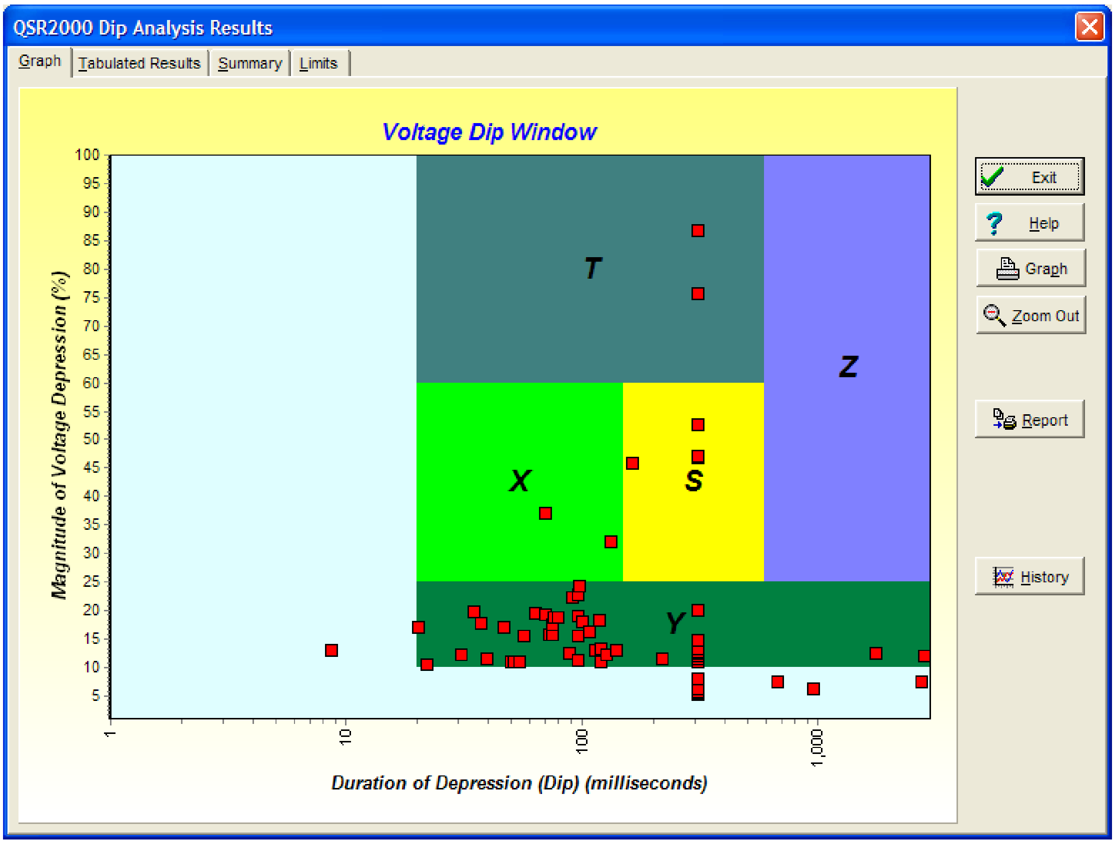
Severe Voltage Dip on the Supply has no effect on the UPS output

Incoming Supply Failure with Stable UPS Output



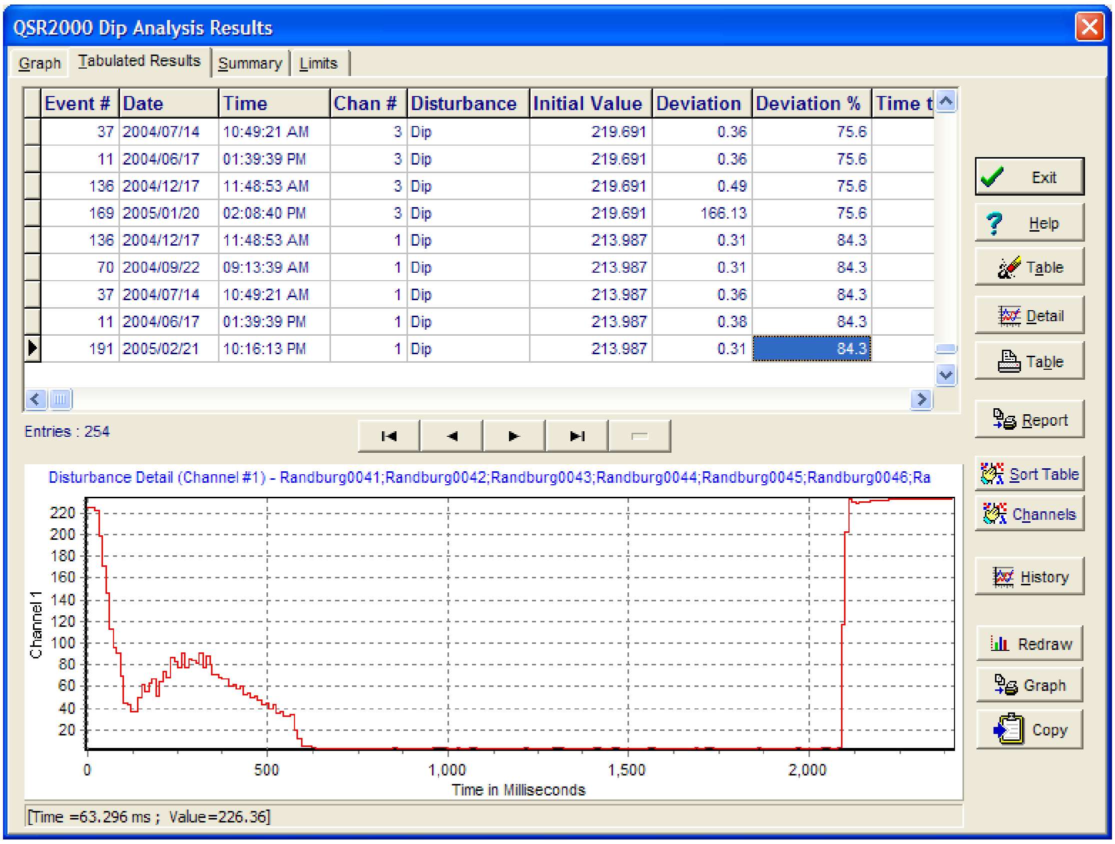
Incoming Supply Restored with Normal UPS Output to the Load

An example of dip information at the supply to the EPS at the site is shown below. The magnitude of the dip and its duration (up to 3 seconds) is indicated on the graph. The same graph can be drawn for the output from the EPS to the load. This can be used to determine if any disturbances are passing through the EPS. The EPS must eliminate any disturbances that may effect any sensitive equipment.



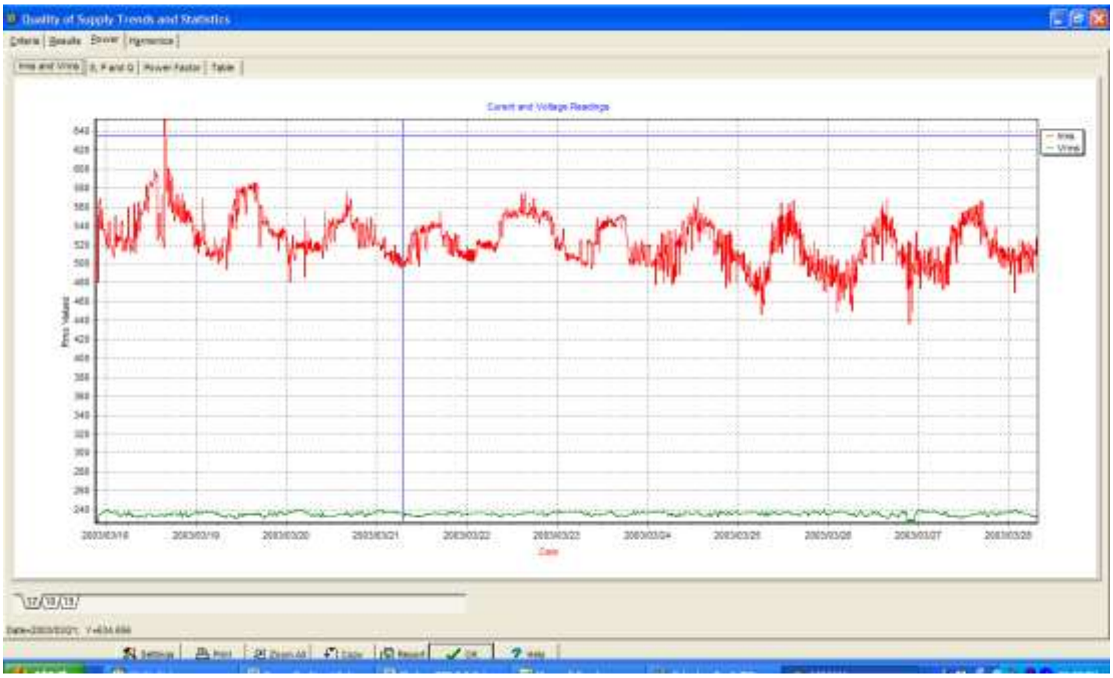
Voltage Dip-Duration Matrix on Incoming Supply

Each of the disturbance voltage waveform can be examined in detail if required. This is particularly useful when equipment fails to identify the nature of the power disturbance and its possible effects. An example of the disturbance voltage profile is shown below.



Voltage Dip-Profile on Incoming Supply

A useful measurement is the supply or load current to the EPS. This can be used to determine if the load current is normal or if the EPS is becoming overloaded. The graph below illustrates the cyclical nature of the load at the site. The red trace at the top is the rms load current. The installed equipment generates a significant amount of heat during operation. Air chillers are more active during the middle of the day when the ambient air temperature is higher. This increase in load is reflected on the current traces. The green trace at the bottom is the EPS output voltage. This can be used to determine if the load regulation of the EPS is operating correctly.



Load Current Profile on Incoming Supply

Conclusion

Mission critical equipment is connected to an EPS to ensure continuous operation. The power supply must be uninterrupted (or limited interruption) and of good quality to ensure there is minimum equipment downtime.

The monitoring and analysis of power quality can be used to ensure emergency power systems and their loads are operating correctly. This should be performed continuously so that a timeous alert can be provided to correct problems well before the power system fails.

Power systems consist of many complex interconnections and interactions between various supplies and loads. These complexities, sometimes frequent changes to the EPS loads, and EPS equipment degradation with time requires constant monitoring to ensure reliability. Continuous monitoring and analysis can be used to ensure peak performance from the Emergency Power System.

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