SAGs and SWELLs

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ABSTRACT

Sags and swells are the most common types of power quality disturbances. Millions of dollars are lost in productivity each year in the United States due to these disturbances. A simple understanding of the causes will allow for effective solutions to mitigating these disturbances in most applications.

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DEFINITIONS

The definitions of sags and swells have evolved over the past fifteen years, as have the power quality instruments that measure them. Sags, or dips as they are referred to in the European communities, were initially any reduction in voltage below a user- defined low limit for between one cycle and 2.55 seconds. Swells, originally referred to as surges, were similar to sags, except that the voltage exceeded a user-defined high limit. While various definitions relative to the amplitude and duration are still in use, the IEEE 1159-1995 Recommended Practice on Monitoring Electric Power Quality has defined them as follows:

> Sag (dip) a decrease to between 0.1 and 0.9 pu in rms voltage or current at the power frequency for durations of 0.5 cycles to 1 minute.
>
> Swell - an increase to between 1.1 pu and 1.8 pu in rms voltage or current at the power frequency durations from 0.5 to 1 minute.

A sag is differentiated from an outage or interruption by the amplitude being greater than or equal to 0.1 per unit (of nominal voltage). In addition to the above definitions, the IEEE 1159 document further classifies the duration values into three categories: instantaneous, momentary, and temporary, as illustrated in the following table from Table 4-2.
Categories and Characteristics of Power Systems Electromagnetic Phenomena:

Categories		Typical Duration	Typical Magnitude
2.1 Instantaneous			
	2.1.1 Sag	0.5-30 cycles	0.1-0.9 pu
	2.1.2 Swell	0.5-30 cycles	1.1-1.8 pu
2.2 Momentary			
	2.2.1 Interruption	0.5-3 seconds	<0.1 pu
	2.2.2 Sag	0.5-3 seconds	0.1-0.9 pu
	2.2.3 Swell	0.5-3 seconds	1.1-1.8 pu
2.3 Temporary			
	2.3.1 Interruption	3 sec-1 minute	<0.1 pu
	2.3.2 Sag	3 sec-1 minute	0.1-0.9 pu
	2.3.3 Swell	3 sec-1 minute	1.1-1.8 pu

Table 1

The limits and values defined in both the ANSI C84.1-1989 Utility Power Profile and the CBEMA (Computer and Business Equipment Manufacturers Association) curve have both set limits as to the duration and amplitude values that are likely to cause problems with equipment powered by such. The lower the amplitude of a sag or higher the value of a swell, the shorter the duration should be for equipment to ride through the disturbance, as in the following table derived from such. The typical industrial utility power after building line losses is in the range of +6%, -13% from the nominal value.

DURATION	AMPLITUDE LIMITS
8-50 msec:	-30%, +20%,
50ms-500 msec:	+15%, -20%;
longer than .5sec:	residential +/-5%;
	industrial +/-10%

Table 2

For purposes of consistency with IEEE 1159, the magnitude of the sag is expressed as a percentage of the nominal value. The expression "a sag of 80% of nominal" on a 120 Vrms nominal system refers to a reduction to 96 Vrms. Some publications will refer to the percentage reduction instead, where an 80% sag on a 120Vrms system would be a reduction to 24 Vrms.

Figure 1 shows an example of a sag on a three phase circuit, monitored by PTs with a 120 volt nominal output. The sag initiated on Phase A, and involved Phase B 3 cycles later.

A number of well-known studies have been conducted in the past concerning frequency and extent of power quality disturbances. Two recent studies have been conducted by the Electric Power Research Institute (EPRI) and the National Power Laboratories (NPL) on the distribution and point-of-use levels, respectively. The EPRI sponsored program has used 300 power quality monitoring nodes on the distribution systems of 24 utilities through US, which was undertaken by Electrotek Concepts, Inc. Monitoring units were placed at the distribution substation, at a point near the middle of the feeder, and at a point near the end of the feeder. It has been reported that approximately 42% of the sags observed to date were outside CBEMA limits.

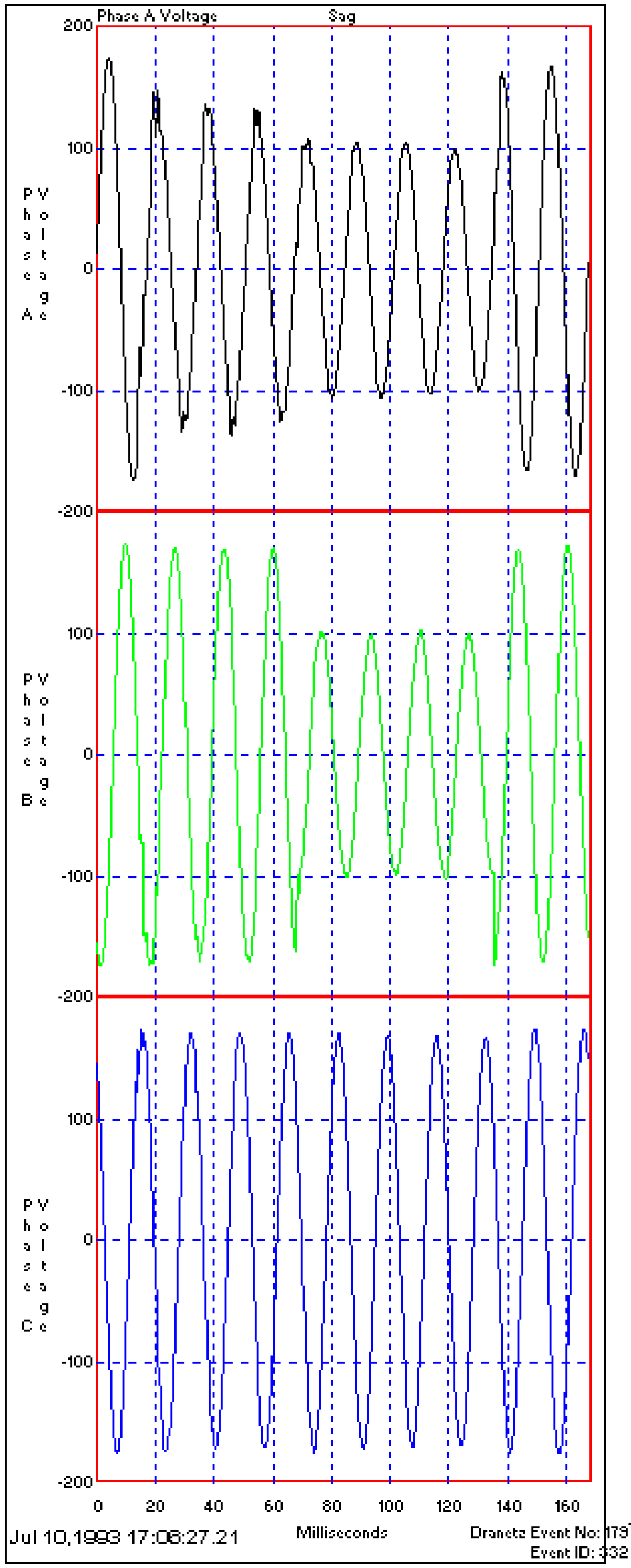
Phase A Voltage
Sag
Phase A Voltage
Phase B Voltage
Phase C Voltage
200
100
0
-100
-200
0 20 40 60 80 100 120 140 160
Milliseconds
Jul 10,1993 17:06:27.21
Dranetz Event No: 179
Event ID: 332

Figure 1

The NPL study was a four year study between 1990 and 1994 of point-of-utilization power quality monitoring at 112 North American locations. Single phase, line-to-neutral data was collected at the standard wall receptacle. Monitors were placed for varying lengths of time at the site, depending on the need to determine climatic effects and other correlating factors. Sites included: a climactic and geographic cross section of the US, cross section of major types of utility loads (heavy industry, light industry, office and retail stores, residential, mixed); and, a broad range of building locations, building types, building ages, and population areas.

A 104 Vrms limit for sag, and 127 Vrms limit for a swell was used, as per the ANSI C84.1-1989 limits and CBEMA curve. A quantity of 1057 site months of data was collected, which yielded over 160,000 power disturbances during the monitoring period. Sags were the most prevalent type of events, averaging 27.9 per month, with an average sag amplitude of 99.3 Vrms. The median duration of sag was 0.26 sec, versus a 2.1 sec average, which the result of several long-term sags (beyond the IEEE 1159 duration limit). Figure 2 shows a graph of the distribution by duration of sags below 90 Vrms.

PERCENTAGE OF SAGS OF GIVEN DURATION

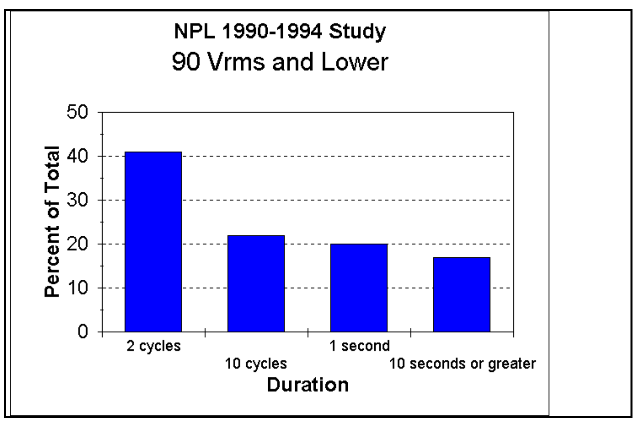

Figure 2.

The average number of swells per month was less than half of the sags, at 13.9, with

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an average swell amplitude of 127.8 Vrms. The median duration was 60.0 seconds, with some sites operating for extended durations in an overvoltage condition. The most prevalent occurrence for both sags and swells was during May through August.

Figure 3 shows the relative probabilities of sags of varying amplitudes. The data is combined from the NPL study, and a graph in an IEEE paper titled, "Predicting and Preventing Problems Associated with Remote Fault-Clearing Voltage Dips." Additional graphs of the amplitude and duration distributions of sags and swells can be found in Appendix A.

PROBABILITY OF SAGS OF
GIVEN AMPLITUDE

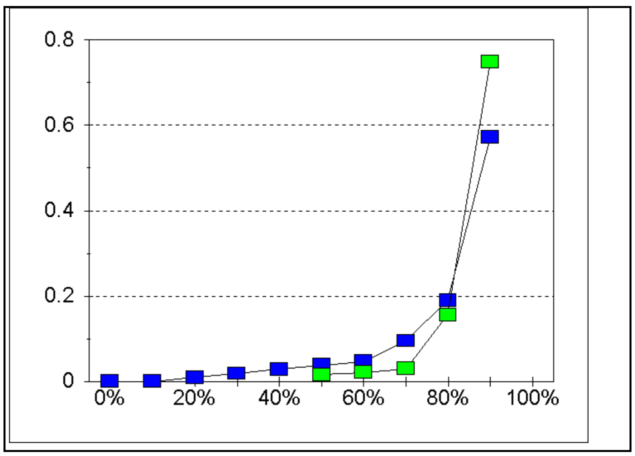

Figure 3.

SYMPTOMS

Equipment used in modem industrial plants (process controllers, programmable logic controllers, adjustable speed drives, robotics) is actually becoming more sensitive to voltage sags as the complexity of the equipment increases. The proliferation of microprocessor-based equipment continues in the office environment, industrial plants, and residential homes. As the speed that the circuitry operates at continues to increase (100 MHz clocks are becoming more prevalent), and the voltage supplies decrease (3Vdc logic is also becoming more prevalent), the vulnerability to such disturbances increases. Reduction in ride-through times of power supplies increases the vulnerability of the equipment to sags.

The effects of a sag are often more noticeable than those of a swell. A sag of duration longer than three cycles is often visible in a reduction in the output of lights. Sags often not distinguishable from momentary outages, as the effects to the equipment may be the same. Sensitive equipment, such as computers, may experience intermittent lockups or garbled data. Even relays and contactors in motor starters can be sensitive to voltage sags, resulting in shutdown of a process when the drop out occurs. A wide disparity has been found here, ranging from 20% to 65% sags for over 1000 cycles. For one industrial plant that extruded plastic pipe, voltage sags to 80% of the 480 V nominal line with durations of 40 msec or greater would affect the production line control electronics, resulting in one or more extruder lines being shut down, and several hours of clean up before production could start again.

The effects of a swell can often be more destructive than those of a sag. The overvoltage condition may cause breakdown of components on the power supplies of the equipment, though the effect may be a gradual, accumulative effect. The increase in output from incandescent lighting may be noticeable, if the duration is longer than three cycles.

Various organizations have been testing the susceptibility of various types of equipment to voltage sags and swells. PEAC, PowerCET and various IEEE groups have conducted such studies of the past several years. In a study entitled "Voltage Sags in Industrial Systems" in 1993 [13], it was found that motor contactors and electromechanical relays: would drop out with a sag of 50-70% for greater than 1 cycle. High intensity discharge lamps would require restriking for sags below 80%. The ride-through of adjustable speed drives (ASDs) varied 0.05 to 0.5 seconds, though some were effected by a 90% sag for 3 cycles. The remote I/O units of some programmable logic controllers (PLCs) were found to trip on a reduction to 90% of nominal for just a few cycles.

In a paper entitled "The Impact of Voltage Sags on Industrial Plant Loads" [14], the results were reported of several different models of various types of equipment which were similarly tested. For process controllers, the results were quite varied. Where one would only withstand 70-80% of nominal for greater than 1 cycle, another could withstand 0V at 10 cycles, 35% sag up to 40 cycles, and 75% for 40 cycles and beyond. Like with other equipment, the PLCs tested found some of the newer equipment is more sensitive than older models. A newer model PLC would tolerate a

50-60% sag for 1-20 cycles, while an older model from the same manufacturer would ride through 0 Vrms for up to 10 cycles.

The effect on personal computers to sags is often the loss of any data stored in volatile memory (such as RAM). This problem is not very prevalent in the newer lap-top computers, which often run off of a internal battery, making them more immune to the effect of sags. Destruction of non-volatile memory (such as disk drive media) has also been experienced, particularly in older models, where the read/write head would be susceptible to contact with the media in the event of an uncontrolled shut-down.

A power interruption of 30% voltage sag for several cycles can reset programmable controllers for an assembly line. One glass plant estimates that a five-cycle interruption can cost about $200k. The cost to a major computer center of a 2-second outage was $600k. Following a voltage sag, an auto manufacturer indicated that the restarting of the assembly lines may required clearing the lines of damaged work, restarting boilers, and reprogramming automatic controls, for a typical cost of about $50k per incident. One automaker estimated that the total losses from momentary voltage sag at all its plants runs to about $10M a year. [6]

CAUSES

The causes of sags have been broken into three areas of occurrence: the transmission system (typically above 65kV); distribution systems (65kV to 12 kV); and, point-of-utilization (120-480V). Swells are treated under a single category. A common, underlying cause of sags and swells in all three areas is a sudden change of current flow through the source impedance. An understanding of Ohm's Law and Kirchoff's Equations, as they relate to real-life, non-ideal sources, is necessary to understanding the effects of such. In the case of a sag, the sudden, large increase in the current required from a source will cause a larger voltage to be developed across the source impedance. This will result in a reduction in the voltage, as seen by the load. Likewise with a surge, a sudden reduction in the current flow will cause an increase in voltage in inductive/capacitive impedances, which the load may experience.

Voltage sags have be linked to the most common cause of power-related computer system failure. This was confirmed in a 1976 study in Northern Virginia [1], where there were an average of 40 thunderstorms/year. The effect in high-incidence areas of lightning strikes, such as Florida, is even more pronounced. Table 2 shows the results from that study. Overhead lines had over three times the number of occurrences as underground lines.

CAUSE OF SAGS ON DISTRIBUTION SYSTEM

CAUSE	# of OCCURRENCES	PERCENTAGE
Wind and lightning	37	46%
Utility equipment failure	8	10%
Construction or traffic accident	8	10%
Animals	5	6%
Tree limbs	1	1%
Unknown	21	26%
TOTAL	80	

Table 3.

SAG CAUSES - TRANSMISSION SYSTEMS

The causes of voltage sags on a transmission level system are similar to those on a distribution system. They include the weather (especially lightning), construction accidents, transportation accidents (helicopter or light planes are common culprits), animals or a fault on another part of the system causing "sympathetic" sags. There have been recorded instances of the nesting habits of large birds in the towers resulting in phase-to-ground faults when the insulators were "shorted out" by bird droppings that were made into a conductive path during rain storms.

Lightning is often attributed with being the most common cause of faults on overhead transmission and distribution lines. The fault can occur by lightning directly striking a phase conductor, or by striking a grounded object, such as shield wire or tower, which is called a backflash. A flashover develops from the voltage path across the phase conductors to ground or to another other phase, resulting in flow of fault current.

Transmission-related voltage sags are normally shorter in duration than distribution voltage sags. This is attributed to the fact that the fault clearing mechanisms (the relay/breaker schemes) must react faster, because of the large amount of energy in transmission faults. Total time for fault detection and breaker operation is 3-6 cycles on older systems, with newer breakers having fault clearing times within a cycle.

Another reason for the shorter duration is that transmission systems are looped or networked, versus radial for distribution systems. This means that when a single line trips, the remaining system can still handle the load, including the fault current. However, the larger currents involved can have further reaching effects. The effects of sag to 90% have been found to be experienced up to 700 miles away from the fault, while a sag to 75% have effect up to 300 miles away. [11]

SAG CAUSES - DISTRIBUTION SYSTEMS

Similar to the transmission system causes, weather (lightning, wind, ice), animal contact, contamination of insulators, construction accidents, motor vehicle accidents, falling or contact with tree limbs can result in voltage sags. Such faults may be 3-phase, line-to-line, or single line-to-ground. The 3-phase faults are the most severe, but are relatively unusual. "Single line-to-ground faults on the utility system are the most common cause of voltage sags in an industrial plant". [9]

Preliminary results from the EPRI study indicate that most important cause of momentary voltage sags is lightning strikes. In the majority of sags, the voltage drops to about 80% of nominal value on the parallel feeders, while the faulted feeder may have a lower sag value, or may result in an outage if the fault cannot be cleared. Distribution system sags tend to cluster around several duration ranges, based on the fault protection schemes: 6-20 cycles (typical distribution fault clearing times, 30-60 cycles (the instantaneous reclosing time for breakers) or 120-600 cycles (the delayed reclosing time for breakers).

A typical distribution substation is show in Figure 4. A fault on the 115KV primary side of the transformer (transmission level) will effect all of the feeders, as the 13.8KV bus voltage will be lowered. A fault on a single feeder will most likely cause an outage to loads on that feeder, as well as sag on the parallel feeders. The closer the fault is to the substation bus, the more of an effect it will have on the parallel feeders.

DISTRIBUTION SUBSTATION LAYOUT

Figure 4

When the breaker opens or the fuse blows, clearing the fault, the system current and bus voltage will return to normal. Distribution breakers typically allow faults to remain longer than transmission breakers and typically reclose slower, in order to allow time for the protective equipments (such as fuses) that are downstream to function. The recloser will open, and then reclose into the fault after about 1-10 seconds (depending on type of recloser scheme), after which time the breaker is either locked out, or the fault has been cleared. Depending on the number of reclosers before lock-out, parallel feeders can experience as many as four voltage sags in succession.

When the fault occurs on a fused branch of a distribution feeder, the fuse blows and customer located on that branch will experience an outage, which will last until which time that the fuse is replaced. If the breaker/reclose operates during the fault, all the customers on that feeder experience an interruption of a duration that depends on the recloser setting.

SAG CAUSES - POINT OF UTILIZATION (LOADS)

In the NPL study, 50% or more of the recorded low/high RMS events were caused by load equipment in the same building. Sudden increases in the current requirement can have the same effect within a facility's wiring as on a utility distribution system. Voltage sags can be caused by fault conditions within the building, or the start up of large inductive loads, such as motors, that create a temporary in rush current condition. The starting of large horsepower motors that would draw adequate current are typically longer in duration than 30 cycles, and the associated voltage magnitudes are not as low as with a utility fault. The voltage sag condition lasts until the large current demand decreases, or the fault is cleared by a protective device. In the plant, this will typically be a fuse or a plant feeder breaker.

SWELL CAUSES

As discussed previously, swells are less common than voltage sags, but also usually associated with system fault conditions. A swell can occur due to a single line-to-ground fault on the system, which can also result in a temporary voltage rise on the unfaulted phases. This is especially true in ungrounded or floating ground delta systems, where the sudden change in ground reference result in a voltage rise on the ungrounded phases. On an ungrounded system, the line-to ground voltages on the ungrounded phases will be 1.73 pu during a fault condition. Close to the substation on a grounded system, there will be no voltage rise on unfaulted phases because the substation transformer is usually connected delta-wye, providing a low impedance path for the fault current.

Swells can also be generated by sudden load decreases. The abrupt interruption of current can generate a large voltage, per the formula: $v = L\, di/dt$, where L is the inductance of the line, and di/dt is the change in current flow. Switching on a large capacitor bank can also cause a swell, though it more often causes an oscillatory transient.

MONITORING & TESTING

As with other technology-driven products, the power quality monitoring products have rapidly evolved in the last fifteen years. Increased complexity and performance of VLSI components, particularly microprocessor, digital signal processors, programmable logic, and analog/digital converters, have allowed the manufacturer's of power quality monitoring instruments to include more performance in the same size package for the same or reduced price.

Different types of monitoring equipment is available, depending on the user's knowledge base and requirements. The four basic categories of power quality monitors (also known as power line disturbance monitors) are: event indicators, text monitors, solid state recording volt/ammeters, and graphical monitors. While all of these devices can be used to measure/monitor sags and swells, the effectiveness of each depends on what information the user wants to gain. Since sags and swells are relatively slow events (as opposed to microsecond duration transients), the wide variety of instruments are generally capable of capturing a sag or swell with reasonable reliability.

Event indicators are usually on the lower price end of the market. They indicate to the user that a sag or swell has occurred through visual means, such as indicator lights or illuminated bar graphs. Some products will store the worst case amplitudes of such and/or the number of occurrences of the type of event. Most such device do not provide an indication of the time of occurrence or the duration. The voltage limit detectors may be preset or programmable, with the accuracy being in the 2-5% range. Textual-based monitors were actually the first dedicated power quality monitors, produced back in 1976. The function of these instruments is similar to the event indicators, except the output is in alphanumeric format Additional information, such as duration and time-of-occupance is often included. Some of these products allow for the correlation of other information (such as environmental parameters and system status levels) to assist the user in determining the cause of the event.

Solid state recording volt/ammeters have replaced the older pen-and-ink chart recorders as a means of providing a graphical history of an event. These devices typically lack the resolution necessary for monitoring fault-clearing sags. Sampling techniques range from average of several cycles to samples over 2-30 cycles. The averaging over several cycles may mask the sag or swell, as well as result in misleading amplitudes. Sampling over multiple cycles will not properly represent the event either.

Graphical monitors provide the most information about a sag or swell. Most graphical monitors provide a cycle-by-cycle picture of the disturbance, as well as recording minimum/maximum values, duration, and time-of-occurance. The three-phase voltage graphs, coupled with graphs of neutral to ground voltage, phase currents, neutral current (in wye), and ground currents, will usually provide the user with enough information to determine if the fault occurred upstream or downstream. The timing and magnitude information can often identify the source of the fault. For example, if the phase current levels of the load did not change prior to the voltage sag, the fault is more likely upstream. If the magnitude of the sag is down to 20% of nominal, it is likely that the fault was close by. If the sag duration was less than four cycles, it was most likely a transmission system fault. If the swell waveform is preceded by a oscillatory transient, it may be the result of a power factor correction capacitor being switched on. A line-to-neutral voltage sag is often accompanied by a neutral-to-ground voltage swell.

The location of the monitor, power supply wiring, measurement input wiring, and immunization from RFI/EMI is especially critical with the higher performance graphical monitors. The monitor itself must also be capable of riding through the sag and surviving extended duration swells. The functionality of the monitor should be thoroughly evaluated in the laboratory, under simulated disturbances, before placing out in the field. Just because it didn't record it, does not mean it didn't happen.

Unless there is significant information pointing to the cause of the disturbance before the monitoring begins, it is common practice to begin at the point of common coupling with the utility service as the initial monitoring point. If the initial monitoring period indicates that the fault occurred on the utility side of the service transformer, then further monitoring would not be necessary until attempting to determine the effectiveness of the solution. If the source of the disturbance is determined to be internal to the facility, the placing multiple monitors on the various feeds within the facility would most likely produce the optimal answer in the shortest time period. Otherwise, the monitor must be moved from circuit to circuit, with particular attention to circuits powering suspected sources, and the circuits of the susceptible devices.

Recent developments in artificial intelligence tools, especially fuzzy logic, have allow software vendors to develop products that allow knowledge and reasoning patterns to be stored in the software program. Further analysis of the event, beyond the IEEE 1159 classifications, is possible. These include the severity of the event, relative to the type of equipment that would be effected, and probability factors on the cause of the disturbance. Multiple, successive sags that return to nominal for an adequate time for the power supply capacitors to recharge may not be as severe as a longer duration sag of a higher amplitude.

SOLUTIONS

The first step in reducing the severity of the system sags is to reduce the number of faults.   From the utility side, transmission-line shielding can prevent lighting induced faults.   If tower-footing resistance is high, the surge energy from a lightning stroke is not absorbed quickly into the ground. Since high tower-footing resistance is an import factor in causing backflash from static wire to phase wire, steps to reduce such should be taken. The probability of flashover can be reduced by applying surge arresters to divert current to ground.

Tree-trimming programs around distribution lines is becoming more difficult to maintain, with the continual reductions in personnel and financial constraints in the utility companies. While the use of underground lines reduces the weather-related causes, there are additional problems from equipment failures in the underground environment and construction accidents.

The solutions within the facility are varied, depending on the financial risk at stake, the susceptibility levels and the power requirements of the effected device. Depending on the transformer configuration, it may be possible to mitigate the problem with a transformer change. "It is virtually impossible for an SLTG condition on the utility system to cause a voltage sag below 30% at the customer bus, when the customer is supplied through a delta-wye or wye-delta transformer." [13]

In a IEEE paper on "The Impact of Voltage Sags of Industrial Plant Loads" [14], the following table shows what the transformer secondary voltages would be with SLTG faults. The table shows the tradeoffs on the impact to the phase voltages that occur, based on the wiring configuration of the transformer.

TRANSFORMER SECONDARY VOLTAGES (pu) WITH SLTG FAULTS

TRANSFORMER CONNECTION	Phase-to-Phase			Phase-to-Neutral		
	Va	Vb	Vc	Van	Vbn	Vcn
Grounded wye - grounded wye	0.58	1.00	0.58	0.0	1.0	1.0
Grounded wye - ungrounded wye	0.58	1.00	0.58	0.0	1.0	1.0
Ungrounded wye - ungrounded wye	0.58	1.00	0.58	0.33	0.88	0.88
Ungrounded wye - grounded wye	0.58	1.00	0.58	0.33	0.88	0.88
Delta - delta	0.58	1.00	0.58	------	------	------
Ungrounded wye - delta	0.33	0.88	0.88	------	------	------
Grounded wye - delta	0.33	0.88	0.88	------	------	------
Delta to grounded wye	0.88	0.88	0.33	0.58	1.00	0.58
Delta - ungrounded wye	0.88	0.88	0.33	0.58	1.00	0.58

Table 4

For wye-wye and delta-delta connections two phase-to-phase voltages will drop to 58% of nominal, while the other phase-to-phase is unaffected. However, for delta-wye and wye-delta connections, one phase-to-phase voltage will be as low as 33% of nominal, while the other two voltages will be 88% of nominal. It is the circulating fault current in the delta secondary windings that results in a voltage on each winding.

Another possible solution is through the procurement specification. If a pre-installation site survey is done, the distribution curve and probability of the sags and/or swells can be determined. The user then specifies such information in the equipment procurement specifications. Only equipment with acceptable ride through characteristics would then be used.

When neither of the above solutions are practical or adequate, some form of additional voltage regulator are required to maintain constant output voltage to the effected device, despite the variation in input voltage. Each type has its own disadvantage and advantages for a given application. The utility companies can add dynamic voltage restorers, static condensers, fault current limiters, and/or high-energy surge arresters. Since these are beyond the control of the end user of the electricity, the following concentrates on "in-the-facility" solution. These include: ferroresonant transformers, magnetically controlled voltage regulators (3-10 cycle response); electronic tap-switching transformers (1-3 cycles); shielded isolation transformers; static transfer switches (within 4 milliseconds); static UPSs; and, rotary UPSs.

FERRORESONANT TRANSFORMERS

Ferroresonant transformers, also called constant-voltage transformers (CVT), can handle most voltage sags. Ferroresonant transformers can have separate input and output windings, which can provide voltage transformation and common-mode noise isolation as well as voltage regulation. While CVTs provide excellent regulation, they have limited overload capacity and poor efficiency at low loads. At a load of 25% of rating, they require an input of a minimum of 30% of nominal to maintain a +3/-6% output. At 50% load of rating, they typically require 46% of nominal input for regulation, which goes to 71% of nominal input at full load. Therefore, for maximum improvement of voltage sag ride through capability, CVT should be sized about four times greater than the load.

Ferroresonant CVTs are most effective for constant, low power loads, such as personal computers or process controllers. Variable loads present problems because of the tuned circuit on the transformer output. Ferroresonant transformers have a nonlinear response, similar to that of a regular transformer when excited high on its saturation curve.

MAGNETICALLY CONTROLLED VOLTAGE REGULATORS

Magnetic synthesizers use transformers, inductors and capacitors to synthesize 3-phase voltage outputs. Enough energy is stored in the capacitors to ride through one cycle. They use special autotransformers, with buck-boost windings to control the voltage. The effect of the buck-boost windings is varied by a control winding with DC current that affects the saturation of the core. The control-winding current is produced by electronic sensing and control circuits. The response time is relatively slow (3-10 cycles).

TAP SWITCHING TRANSFORMERS

Electronic tap-switching transformers have the high efficient, low impedance, noise isolation, and overload capacity of a transformer. These regulators use solid state switches (thyristors) to change the turns ratio on a tapped coil winding. The switching is controlled by electronic sensing circuits, and can react relatively quickly (1-3 cycle). Thyristor switching at zero voltage is easier and less costly than at zero current, but can cause transient voltages in the system, as the current and voltage are only in phase at unity power factor. Thus, switching at zero-current is preferred. The voltage change is in discrete steps, but the steps can be small enough so as not to induce additional problems.

STATIC UPS

A UPS can provide complete isolation from all power line disturbances, in addition to providing ride-through during an outage. A static UPS consist of a rectifier AC to DC converter, DC bus with a floating battery, DC to AC inverter, and solid state bypass switch. The rectifier converts the raw input power to DC, which keeps the floating battery fully charged and supplies power to the inverter section. The inverters generate 6 or 12 step waves, pulse-width modulated waves, or a combination of the two, to create a synthetic sine-wave output. Inverter output should be a stable, low-distortion sine wave, provided there is adequate filtering in the output stage. The batteries supply the DC bus voltage when the AC voltage is reduced.

There units range from a few hundred VA to 750kVA or higher. Since they are constantly running, there is no switch-over time, except when the bypass switch is activitated. The capacity of the battery banks determine the length of ride-through.

ROTARY UPS/MOTOR GENERATORS

Motor generator sets can also provide power conditioning by fully isolating the output power of the generator from disturbances of the input power (except for sustained outages). Various configurations are possible, including single shaft synchronous MG, DC motor driven MG, 3600 rpm induction motor with a flywheel driving a 1800 rpm generator, synchronous MG with an additional DC machine on same shaft, which powers AC generator with AC fails; or, variable speed,constant frequency synchronous MG (varies number of poles so that frequency remains the same. The inertia of an MG set, (especially if supplemented by a flywheel), can ride-through several seconds of

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input power interruption.   Since the generator output can be of different voltage and frequency from the motor input, conversion from 60 Hz to 400 Hz is possible.

NEWER SOLUTIONS

EPRI has been working with PSEG and Westinghouse Electric Corp to develop an active power line conditioner, which will combine active harmonic filtering, line voltage regulation and transient voltage surge protection in a single compact unit. To date, 5KVA, 50KVA and 150KVA units are available.

Several successfully applications of superconductivity magnetic-storage systems have been carried out in the United States. The stored energy that is provided by the batteries in a static UPS, or the inertia of the motor in a MG set, is instead provided by current stored in a superconductive magnetic system. This energy can be quickly coupled back into the system, when the AC input power is inadequate.

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