VOLTAGE CONDITIONING TO MAINTAIN PRODUCTION

Avoid Many Unplanned Production Stoppages

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Abstract - Electrical power supply voltage disturbances, particularly voltage sags, have been identified as a major cause of unplanned production stoppages in continuous process-based industries. Electricity network operators are frequently unable to provide the level of power quality demanded by these industries using traditional techniques. Power electronic technology has allowed the development of new high performance power conditioning equipment that can mitigate problems with the incoming power supply at the point of interface with the utility or within the plant internal electrical distribution system

This paper reviews the types of problems frequently encountered and solutions using active voltage conditioning to perform high speed voltage correction and discusses an actual operational case study.

I. INTRODUCTION

In 2003 EPRI published a report [1] which stated that the cost of unplanned production interruption to US industry due to variations in electrical power supply was of the order of U$100 billion per annum. EPRI forecasts that this cost will grow as the use of power electronic devices in industry increased.

The replacement of conventional motor starters by variable speed drives and the widespread use of power electronic devices has provided industry with much greater process control, but these devices have proved much more susceptible than traditional equipment to power variations and particularly to voltage disturbances.

Unfortunately even in 2003 many industrial and commercial facilities have installed little, if any, sophisticated metering equipment.
Frequently they cannot determine the nature or the magnitude of the voltage variation. What they do know is that for some reason the production process was interrupted and this has cost them money.

The common first assumption (albeit frequently incorrect) is that there has been some interruption to the utility supply and the first call is to the utility to complain and request an explanation

Studies [2] have concluded that less than 10% of all production stoppages relating to electrical power are actually due to a true persistent power interruption, or black-out.

The balance of production stoppages is due largely to voltage variations and of these by far the most common are voltage sags.

In order to provide some means of correction it is important to determine the true cause of the problem. Data should be recorded for voltage levels over a period of time using suitable metering equipment to make an accurate diagnosis of the problem. Once the nature of the problem is understood then the most effective and economical solution can be proposed.

Many electrical utilities in North America are willing to assist customers identify problems which can cause production stoppages and sometimes will install meters for a limited period.

II. VOLTAGE DISTURBANCE PROBLEMS

Voltage variations occur in several forms as shown in Table 1 and can have many causes.

Type of Variation	Duration
Persistent Overvoltage	Few Seconds – Several Hours
Short term Overvoltage - Surges	Half a Cycle – Few Seconds
Transient Overvoltages - Spikes	Microseconds but typically < 1 cycle
Voltage Sags	Half a Cycle – 30 seconds
Multiple Voltage Sags	Several Cycles per sag but several sags within a few seconds
Long term Undervoltage	Few Seconds to Several Hours
Voltage Phase Unbalance	Typically long periods Hrs – Days or longer
Voltage Harmonics	Few Cycles to a persistent continuous condition.

Table1: Voltage Disturbances

1.0) PERSISTENT OVERVOLTAGES

This phenomenon usually affects all three phases simultaneously and can persist from several seconds to several days. Persistent overvoltages typically may occur at particular times or seasons.

1.1) Causes of Overvoltage

a) Site supply transformer taps are set for higher than nominal voltage value to accommodate large seasonal loads such as air conditioning. This will result in overvoltage on other equipment if these loads are not running (e.g. in winter or during cold weather periods).

b) Utilities, particularly local utilities in rural areas, sometimes leave capacitors on line during periods of low load demand e.g. evenings and week-ends. This can cause overvoltages of the order of 10% or more.

c) Utility transformers can feed one or more manufacturing facilities and transformer taps can be adjusted to accommodate large connected loads on one site. If these large loads are off-line for any reason, adjacent customers or other loads in the same facility can experience overvoltage conditions.

1.2) RESULT

i) Variable speed drives experience fail (burn out)
ii) Motors fail earlier than expected
iii) Damage to sensitive electronic equipment
iv) Insulation systems overstressed
v) Current carrying conductors overheated as overvoltages will cause excess current to flow in resistive components for extended periods
vi) In some circumstances can cause failure of UPS systems

2.0) VOLTAGE SURGES

These can be single phase or multi-phase phenomena. Typically they persist for several cycles and are shown in Fig.1.

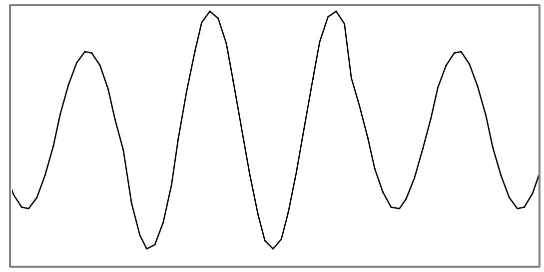

Fig.1: Voltage Surge

2.1) Causes of Voltage Surges

a) Disconnection of local large loads
b) Switching of line compensation capacitors by local utility
c) Switching of local capacitive loads
d) Ground faults particularly on ungrounded 3 phase delta systems or high resistance grounded systems

2.2) RESULT

i) Premature failure of variable speed drives and sensitive electronic loads
ii) Damage to motors
iii) Overstressed insulation systems

3.0) VOLTAGE TRANSIENTS

These can be single phase or multi-phase phenomena and can be very severe in magnitude. They have very short duration, as shown in Fig.2, measured typically in microseconds. Much of the damage caused by transients is due to the very rapid changes in voltage dv/dt.

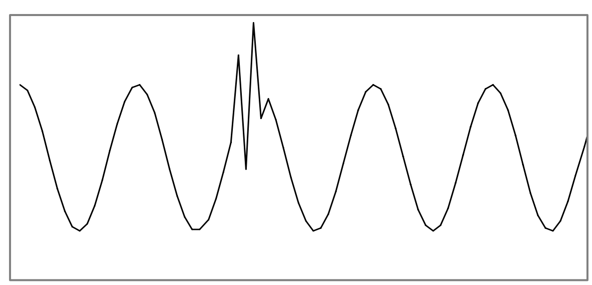

Fig. 2: Voltage Transient

3.1) Causes of Voltage Transients

a) Switching of high voltage capacitors at transmission voltages
b) Lightning strikes on overhead conductors
c) Major electrical short circuit on equipment connected to same distribution network

3.2) RESULTS

i) Destruction of sensitive electronic equipment, e.g. variable speed drives
ii) Damage to computers and electronic controls
iii) Damage to or destruction of motors
iv) Damage to transformers, capacitors
v) Damage to relay and contactor coils
vi) Damage to insulation systems

4.0) VOLTAGE SAGS

Voltage sags as shown in Fig.3 are the most common cause of production stoppage and typically these can last from a few cycles to several seconds.

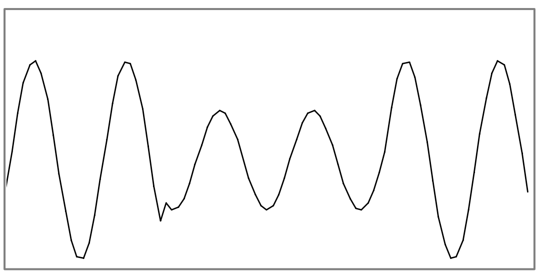

Fig.3: Voltage Sags

Figures published by EPRI [3] show that over 70% of voltage sags are single phase events and only some 10%-15% are balanced three phase sags. This can cause problems for motors due to unbalanced phase voltages (see 6.0 below) and in some cases premature failure.

4.1) Causes of Voltage Sags

a) Starting of large motors in same facility or by a neighbour on same distribution network
b) Operation of utility recloser
c) Ground fault on another part of distribution system
d) Transfer of loads by utility switching
e) Switching off capacitors either locally or on the network

4.2) RESULTS

i) Sensitive electronic equipment such as variable speed drives can stop
ii) Sensing devices such as photo-electric or proximity sensors cease to operate
iii) Contactor and relay coils drop out
iv) UPS systems will transfer to battery

5.0) MULTIPLE VOLTAGE SAGS

Typically caused by multiple operations of utility reclosers, the individual sags may only last for several cycles but there can be two or three consecutive sags as reclosers try to clear faults elsewhere on the system.

The cumulative effect of sequential sags may cause more problems than a single sag.

5.1) Causes of Multiple Voltage Sags

a) Multiple utility recloser operations
b) Sequential starting of large motors

5.2) RESULT

i) As 4.2 above but equipment that can ride through a single sag may not be sustainable under multiple sag conditions

6.0) PHASE VOLTAGE UNBALANCE

A common but frequently overlooked condition that may occur in conjunction with other voltage variation phenomena.

6.1 Causes of Voltage Unbalance

a) Load unbalance between phases frequently found in commercial buildings with large numbers of single phase loads, e.g. lights and computers etc.
b) Presence of an uncorrected ground fault – most frequently found on ungrounded or high resistance grounded systems.
c) Frequently occurring single phase sags even when these are of insufficient magnitude to create a production stoppage
d) Use of 3 single phase transformers connected in delta to supply 3 phase system if impedances are not matched precisely.

6.2 RESULTS

i) A major cause of premature motor failure
ii) A NEMA rated motor will exceed its nameplate capacity when phase voltage unbalance exceeds 2%
iii) Damage to sensitive power electronic equipment

7.0 VOLTAGE HARMONICS

There is still limited understanding in many manufacturing plants of the causes and results of harmonic voltages but they are now found in many industrial and commercial buildings.

Although power supply utilities do not generate harmonics, these can appear on the network. Many utilities are now working to prevent individual customers from back-feeding harmonics onto utility systems.

7.1 CAUSES

a) Harmonic currents are generated by electronic devices, the very same sensitive loads such as variable speed drives, UPS systems, power rectifiers and computers which contribute to improved productivity. These currents create harmonic voltages which spread through a distribution network.

b) Power electronic equipment using six pulse rectifiers typically generate 5^{th} and 7^{th} harmonic currents with smaller quantities of 11^{th} and 13^{th}. Equipment using 12 pulse rectifiers generate 11^{th} and 13^{th} harmonic currents with smaller proportions of $17^{th}$and 19^{th} and higher harmonics.

c) The harmonic currents generate harmonic voltages which can appear at the point of common coupling to the utility supply.

d) It is possible for harmonic currents created in one facility to create harmonic voltages which appear in a neighbouring facility connected to the same branch of the distribution network.

7.2 RESULTS

Harmonics distort the sine wave so that it can have two or more peaks per half cycle. Harmonics create heat in conductors and in some cases this can be excessive causing damage to insulation etc.

This can cause havoc to equipment such as variable speed drives. The result can be seen when multiple drives are in the same facility and for no apparent reason suddenly unexpected stoppages occur. The harmonics have combined to create a distorted voltage wave form and this can occur apparently at random.

III. ACTIVE VOLTAGE CONDITIONING (AVC)

It has already been stated that modern power electronic equipment is more sensitive to voltage variations than traditional induction motors. The availability of precisely controlled power electronics has enabled the development of solutions to many of these voltage variation problems.

A recent solution is the **Active Voltage Conditioner (AVC)**. In its simplest form this device was developed for the correction of voltage sags and comprises an injection transformer with power electronics incorporating a rectifier, an inverter and a high speed processor.

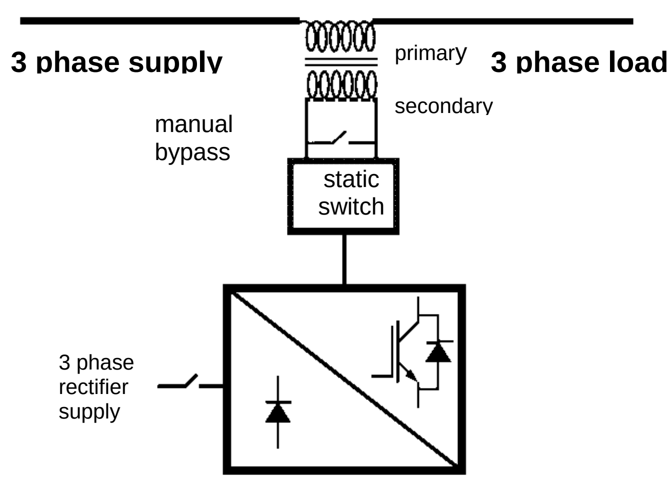

Fig. 4: AVC system one-line diagram

8.1 Basic AVC Concept

One set of transformer windings (primary) is connected in series with the load and the secondary windings are connected to the power electronics as shown in Fig. 4. When a voltage sag occurs this is detected by sensors on the line (supply) side of the transformer primary, current is drawn from the line, converted to DC by the rectifier, the inverter draws power from the rectifier and will inject voltage into the transformer secondary at the correct amplitude and phase angle to correct the voltage sag. Typical response times for correction are of the order of 2-10 milliseconds.

Active Voltage Conditioners are load specific devices and protect those loads which are sensitive to voltage variation and are considered to be essential parts of the production process.

8.2 AVC's With Capacitor Storage

Some manufacturers' designs incorporate capacitor storage so that they can provide a ride through capability of a few cycles in the event of a power loss and there are circumstances where this can provide benefits.

The use of capacitor storage requires that after correction of a sag a finite time is required to recharge the capacitors and typically this can be of the order of several seconds. The unit may not provide protection against sags from multiple consecutive recloser operations or similar such events.

Typically these designs are set to trigger a response once voltage levels drop to a pre-determined level e.g. 90% of nominal voltage. They can therefore be considered as off-line devices. Usually the voltage correction is applied in a single step and this can lead to system instability, especially with highly capacitive loads.

A negative of storage systems is that, in the event of a fault, the stored energy in the unit may feed the fault until the capacitors are discharged. Similarly, if the equipment to be protected is sensitive to overvoltage, the capacitor storage solution can create an overvoltage at the return to normal system voltage.

8.3 AVC's Without Capacitor Storage

Unlike the AVC's with storage these units are on line. Therefore this unit is not just a sag mitigation device but also a power conditioner and can either be positioned at the point of common coupling with the utility or dedicated to individual sensitive loads.

Several units can be connected to the same bus if required. In addition to correction of both single phase and three phase sags, the unit will correct phase voltage unbalance, flicker, voltage harmonics as explained in 8.6 and optionally 3 phase overvoltages.

AVC's without capacitor storage can be configured to work on a continuous basis. These AVC's are able to correct multiple sags such as those created by multiple recloser operations and in addition they can provide continuous phase voltage balancing.

This will reduce premature failure of electric motors.
In the event of a system fault the unit goes to internal bypass and the fault can then be cleared by existing system protection.
Unless there is some other external energy source they cannot usually handle any genuine blackout condition or the complete loss of one phase. In practice genuine blackouts often last for several seconds so offering protection for a few cycles may be of limited value.

8.4 AVC Operating Voltage

It is usually convenient and more cost effective to provide protection at low voltage (480V or 600V) for loads up to 5 MVA but for larger loads the AVC is available at medium voltage levels so that loads of the order of 10MVA or more can be conditioned at 2.4kV-36kV.

8.5 AVC Total Site Protections

Utilities are sometimes required to provide complete customer sites with conditioned power. In these cases it is perfectly feasible to use an AVC which can be supplied with an outdoor enclosure suitable for pad mounting and then be situated outside the customer's facility on utility property. In most cases these are larger loads, 1MVA or more, and it is more convenient to work at utility distribution voltage levels e.g. 4 - 36 kV.

8.6 AVC's And Harmonics

AVC's of larger kVA ratings are typically designed for 3 phase loads only. These loads may contain power electronics which can themselves create harmonic currents. In each case as the harmonic currents flow through the circuits they will create corresponding harmonic voltages.

The AVC will correct lower order, i.e. 5^{th},7^{th},11^{th} and 13^{th} voltage harmonics which would otherwise be seen be the load.

AVC's are not designed to provide overall system correction as they are load dedicated devices and are designed to correct voltage variations. Other technologies exist for correction of harmonic currents in large systems.

8.7 AVC's And Flicker

Flicker is a phenomenon whereby a sub-harmonic frequency is generated by loads, typically in a manufacturing facility, and lights appear to vary in brilliance or flicker. The frequency is of the order of 7 - 9Hz and humans can experience significant physiological discomfort and in extreme cases this can cause seizures in people who are susceptible.

The sub-harmonic flicker frequency is usually created inside a manufacturing facility due to the interaction of harmonic and surge currents in the system and this in turn creates a voltage which causes the lighting level to vary. Introduction of a suitably sized AVC dedicated to protection of the lighting circuits can be a very cost effective solution to this problem.

8.8 AVC's For Overvoltage Protection

The principles of voltage sag correction incorporated in an AVC can equally be applied to protection against 3 phase over-voltage conditions whether these are of short duration, voltage surges, or long term overvoltage.

In this configuration a second inverter is used so that the AVC uses one inverter to provide conventional sag protection and the second one to provide overvoltage protection. In this format the AVC will protect both against voltage sags and overvoltage conditions.

Typically this is needed only when three phase overvoltages occur as the phase balancing capability of the conventional AVC can usually provide correction of single phase overvoltage

8.9 AVC's Subject To Transients

The AVC does not have transient suppression technology as part of its operation so it does not provide this protection to the load but where required a conventional TVSS device can be supplied with the AVC to provide transient protection also.

8.10 Economics Of AVC's

In high risk situations such as data centres, hospital laboratories and financial centres the effect of voltage variations or blackouts can be very severe. In many of these cases UPS systems have been installed and with suitable batteries these can provide extended ride through capability even in the event of a prolonged power failure.

UPS systems and their associated batteries may not be an economically feasible solution to voltage variation problems in many industrial applications and at higher MVA loads it may be necessary to parallel UPS systems to provide protection.

The AVC typically is both more compact in terms of space and less expensive than an equivalent size of UPS. It normally has very limited or **NO** ride through capability but typically it is a fraction of the cost of an equivalent UPS so in an industrial context where studies have shown that 11 out 12 electrical power production stoppages are due to voltage variations [D] and not to blackouts the AVC is frequently the economic solution of choice.

IV. CASE STUDY

9.1 Power Electronics Plant

The customer, located in the northern USA has a process which is sensitive to voltage sags. In a 12 month period several production stoppages occurred with a typical cost per occurrence of US $50k or more.

The customer had believed his production stoppages were due to black outs but, after the utility installed metering equipment, it was demonstrated that the stoppages were associated with single phase voltage sags.

In this area there are a large number of single phase reclosers on the network and single phase sags to 50% of nominal voltage occur quite frequently in stormy weather.

Working with the local utility, a 480 volt AVC with a capacity of 1.6 MVA was installed in the fall of 2002. In the following eight months the equipment protected by the AVC had ridden through some 18 major voltage sag events without causing any production disruption.

In this case the payback was less than 6 months. The price for a 30% 3 phase sag correction unit is in the range US $200 -$250 per kVA depending on kVA rating. Units with lower levels of performance, e.g. 20% 3 phase correction, are less expensive.

V. SUMMARY

AVC's are load dedicated devices designed to correct specific voltage variation problems in industrial and commercial buildings and greatly reduce the incidence of unexplained production stoppages due to variations in electrical supply voltages.

They are available to protect loads from a few kVA to 20MVA or more and can be produced to operate at low voltage (208V – 690V) or medium voltage (2kV - 36kV).

AVC's can be configured to deal with most types of voltage variation and several units can be installed on the same electrical network if required.

When used in conjunction with suitably rated devices to protect against transients they can provide a complete spectrum of voltage protection and can be applied at low voltage or at medium voltage.

The AVC's use well proven power electronic technologies and specially wound transformers to provide high reliability in service. They are highly efficient devices, typically of the order of 98% or better.

They can provide continuously conditioned voltage to sensitive loads to keep essential production processes running and avoid costly downtime and production losses.

Typically payback periods can be of the order of 12 months or less.

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