Applied Power Electronics In The Field Of Voltage Dip-Proofing.

By:F V Fischer

1. Introduction

The purpose of this paper is to introduce and present a history and case for using voltage dip-proofing to provide ride-through for facilities using a specific technique and specially developed equipment. The effectiveness of this technique and associated equipment is discussed.

Dip-Proofing Technologies Inc. is the U.S. representative for Switching Systems, an international company specializing in the design and manufacture of industrial electronics products. Operation began in 1971 with the development and production of ground continuity monitoring systems for the mining industry and subsequently, the company became the leading manufacturer in this field. In the early 1980's it was realized that there was a growing need for a device that would harden the control gear used in continuous industrial processes against the disruptive effects of momentary voltage dips and outages. It was during this period that the technology known as Voltage Dip-Proofing was developed.

As an industry leader in industrial electronics, Switching Systems was approached in 1989 by Southern Africa's major utility, ESCOM (Electricity Supply Commission), to develop a solution to problems they were encountering within their *own* power plants due to voltage dips. Currently ESCOM is the fifth largest utility in the world. Major problems were caused by short circuits in the 22kV switch yard that supplied power to the plant controls. The depression in supply voltage to the auxiliary system resulted in the contactors dropping out, stopping drives which are critical to the continuous running of the generators. During the early 1970's ESCOM installed auto re-close systems on auxiliary system drives but found them ineffective, and although they had UPS's on their computer equipment, wanted application specific protection for the sensitive equipment in their motor control centers and switchboards. Subsequently, over a two year period, a unique custom solution was developed and successfully installed during 1990 and 1991 in all the large fossil power stations. Originally only available in one configuration, various versions were introduced to accommodate different applications in a variety of industries.

2. Problem Identification

Once various power quality monitoring reports and case studies were published and scrutinized, it was established that under voltage conditions constitute major power quality problems. The majority of these events are of short duration, ranging from a few cycles to around one second, see Fig 1, p2. They may occur naturally as a result of lightning strikes, flash overs, snow storms, or artificially due to heavy load switching, internally generated short circuits and recloser operations clearing line faults caused by overgrown vegetation. Regardless of cause, they affect industrial and large commercial facilities by interrupting critical and continuous processes, which invariably results in monetary loss. Fig 2, p2, lists examples of affected equipment in a chip making facility. Naturally, the causes and effects must be investigated before solutions can be recommended.

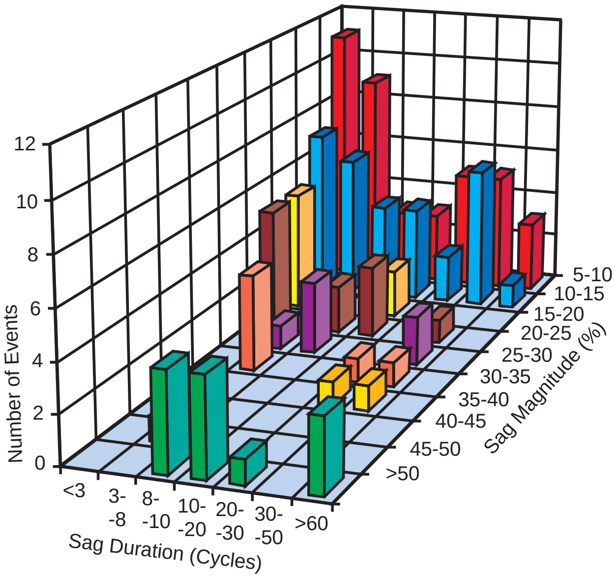

Fig 1

Distribution power quality monitoring data

Outage Duration (sec)	% of All Outages	Equipment Affected
< 0.05	21.875	Build up hydraulic pumps - Build up coolant pumps Termination ovens - Build up machines
0.05≤ < 0.1	37.5	Tin treatment controls - Termination ovens Build up hydraulic pumps - Build up coolant pumps Central plating exhaust - Termination exhaust Scrubber - Rotaries
0.1 ≤ < 0.5	21.875	Build up hydraulic pumps - Build up coolant pumps Central plating exhaust - Termination exhaust Build up & Cutting machines - Plating tank heaters 75hp Compressor - Scrubber - Termination ovens Build up hvac - Brandson Hook BTU's Hvac #1 - Thermo shock chamber
0.5 ≤ < 1	9.375	Central plating exhaust - Termination exhaust 75hp Compressor - Termination ovens - BTU's Tin treatment controls - QE chambers - Plating tank heaters Lasers - Rotaries - Cutters - Burn in voltage alarms
1 ≤ < 1.5	9.375	Central plating exhaust - Termination exhaust 75hp Compressor - Termination ovens - BTU's Tin treatment controls - Plating tank heaters Hvac #1 - Barber Colman controls
≥ 1.5	0	

Fig 2

Affects of momentary outages on semiconductor production equipment.

3. Solutions

In order to run an industrial plant through power dips and sags or voltage interruptions, either the stored kinetic energy of the plant must be utilized or standby power must be supplied. Four levels of protection in order of increasing cost can be identified; the first two using stored kinetic energy and the second two using standby power, see Fig 3, p3. The feasibility and cost of implementing each depends on practicality, economics and the losses incurred due to downtime. The less expensive solutions are considered first.

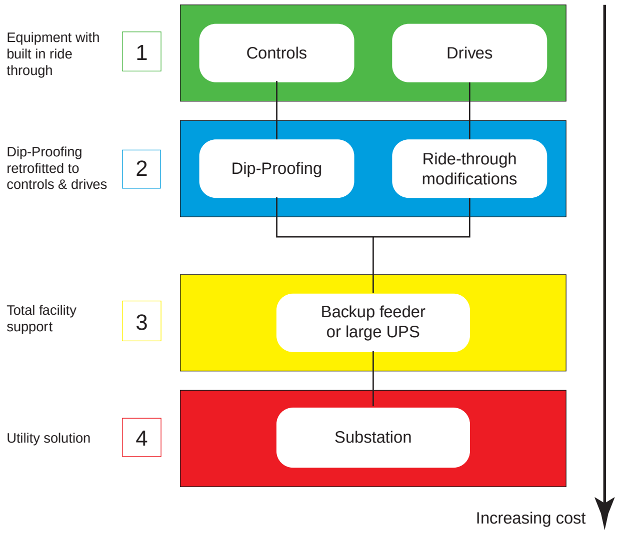

Fig 3

Levels of facility protection.

1) The installation of equipment with ride-through already incorporated.

2) The protection of the sensitive devices, equipment and controls in the plant.

3) The use of large and expensive devices to protect the entire facility.

4) The use of a utility solution such a new nearby substation or new feeder system.

Using the stored kinetic energy of the plant, only short interruptions of one second or less can be catered for. Considering that most voltage dips (approx. 90%) are of short duration, using the inertia of the plant is a distinct possibility. With the aid of individual monitoring studies and some ‘in-plant micro-surgery’, the sensitive equipment and controls can be identified and only these items protected, thereby reducing equipment and retrofit costs as well as enhancing reliability.

Next, the dynamic response of the electrical equipment in a plant is analyzed and divided into three distinct groups;

1. *Very low inertia, from 5 to 30ms;* ***the controls.***

Typically contactors, relays, PLC’s, electronic relays and similar sensitive auxiliary equipment. In general all controls either drop out or switch off within a 5 to 30 millisecond period.

2. *Low inertia, less that 350ms;* ***motors and drives.***

Compressors or pumps may drop in speed to a level where they have to be switched off. Small motors driving spinning or CNC machines could also come to a standstill within this period.

3. *High inertia;* ***motors and drives.***

Conveyers and fans can run for seconds after the power is removed.

From the above, it becomes clear that the first line of attack when dip-proofing a plant is to supply the very low inertia equipment, i.e. controls, with standby power. This can be done with CVT’s, which have a limited support time and are not ideally suited to variable loads (such as those with high inrush currents) or with standard UPS’s which are designed primarily for computer type loads and environments. However, a device which has been specifically designed to supply switchboards and motor control centers which represent a radically different kind of load, is a much more desirable solution.

With this in mind, the knowledge that most industrial plants have enough stored mechanical and magnetic energy to ride through power interruptions of one second or less and the fact that process controllers, relays and contactors would drop out in less than 10 milliseconds, the development of a custom uninterruptable power supply was justified. The design criteria for this specialized device were as follows: (details of how they were accomplished are discussed in section 4.)

- The ability to handle highly inductive loads as motor control centers are made up mainly of electromagnetic devices.
- The ability to withstand the inrush or energizing current of contactors, starters and relays which can be more than 10 times larger than their holding current.
- The use of an ultra-fast off line system as the device is only required to run for short periods of time.
- Inherent reliability is of utmost importance as failure of the device would mean involuntarily shutting down the plant.
- The device should be maintenance free. If adjustment or routine testing is required, it must be possible to by-pass it without dropping the switch-board and load.
- The device should be small, light weight and easy to install In new or existing switchboards.
- The incorporation of an adjustable timer to provide ‘pre-set’ ride through to loads deemed unsafe to keep connected beyond a certain point.
- The transfer level is adjustable to accomodate differing load conditions.

The desirability of maintaining motor connection as well as when to disconnect, needs to be evaluated and justified. Keeping the controls energized only solves part of the problem and the actual motors and drives must also be analyzed.

Rotating loads can be grouped into three categories:

1. Induction Motors
2. Synchronous Motors
3. Variable Speed Drives

If the inertia of *induction motors* is used for dip-proofing, the motor can either be disconnected during a voltage dip or it can remain connected.

If it is disconnected, no currents can flow in the stator, and the existing magnetic field can only be maintained by currents flowing in the rotor. As the resistance of the rotor is very low, the flux will decay slowly, as will the residual voltage on the terminals, see Fig 4, p5. If the supply voltage is now reconnected and is out of phase by more than 180°, the motor will decellerate until it is synchronized with the supply before reaccellerting to normal speed. During this period the motor shaft is subjected to very high peak torques, up to 18 times the normal value, that can cause mechamical damage to the motor and the load. At the same time, twice the nominal voltage appears on the motor windings and this can lead to insulation breakdown. Proposed standards recommend that the total residual voltage combined with the oncoming supply voltage should not exceed the rated voltage by more than 35% and should not be out of phase by more than 90°.

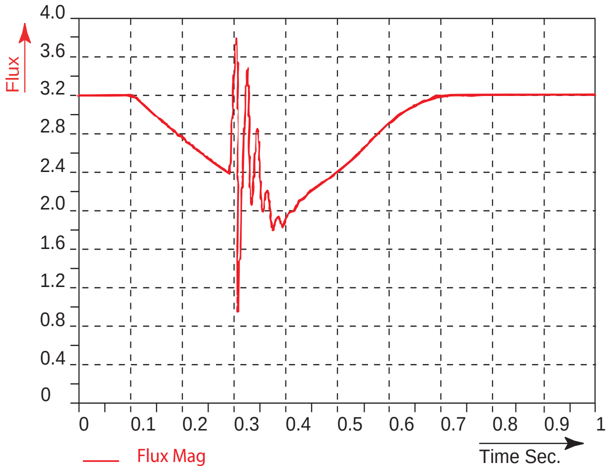

Fig 4

Induction motor flux decay when open circuited.

However, if a motor is kept connected during a voltage dip, current can still flow in the stator, either through other loads parallel to the motor or the secondary of the supply transformer. Current flows in the stator and rotor, and torque is created that uses the energy of the magnetic field. Therefore the voltage on the motor terminals will decrease much faster than in a disconnected motor.

Voltage dips of a duration of 100ms and less would not matter because the motor voltage would only phase shift by less than 30° during this period and the load and supply would not be significantly out of sync. Dips longer than this have the effect of quickly reducing the induced voltage to acceptable levels, thereby reducing stress to the system. Typically, the flux will decay rapidly to less than 30% of the rated value within 5 - 6 cycles, see Fig 5 below.

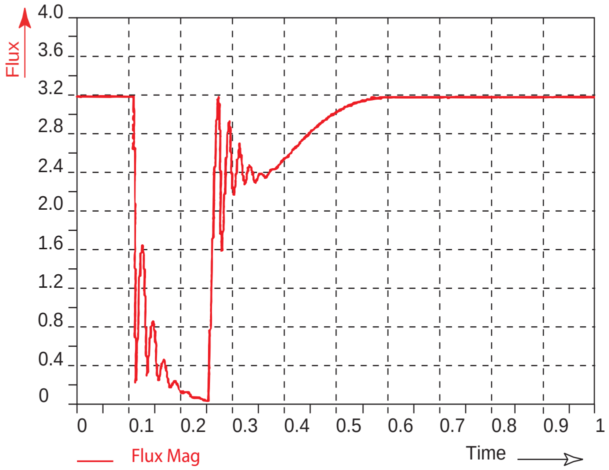

Fig 5

Induction motor flux decay when short circuited.

Due to this phenomenon, it appears that keeping the controls connected is preferable to reconnecting them. In certain cases where the above methods are still deemed unsafe, more sophisticated methods, like synchronized re-switching, can be employed where the supply remains connected for a period of time, is disconnected and then reconnected within a safe ‘window’. This is of no concern when the voltage has only sagged and not been totally interrupted as the supply and load would still be in sync.

Although low inertia drives can only be dip-proofed for relatively short periods of time using their inherent inertia, a fairly large percentage of problems will be overcome. For longer periods, external energy would have to be supplied in order to keep the drive running.

The second group is *synchronous motor* drives. They can also be dip-proofed by either removing the DC rotor field as fast as possible with the stator still connected, or disconnecting the stator and applying synchronized re-switching.

The last group is *variable speed drives***.** These can be divided into AC drives and DC drives. AC drives can be further divided into voltage driven and current driven types. Some, but not all, can tolerate voltage dips and various methods of providing ride-through can be considered.

The feasibility of each option will depend on practicality, economics and the type of drive installed. Briefly, they are as follows:

1) *Support the control circuitry and power supplies within the drive: (Assuming that there is no phase loss trip circuit.)*

Drives can be Dip-Proofed using standard DPI’s.

2) *The bypass of the power loss detection and trip circuitry:*

This requires careful investigation and should only be considered if damage is unlikely and/or warranties will not be voided. This will apply to older drives and has been implemented on plastic extrusion line drives.

3) *Increased energy storage capacity on the DC bus to provide ride-through:*

This can be achieved by adding extra capacitors on the DC side of the rectifier in the drive. The auxiliary or regulator supplies will probably also need support.

4) *The exchange of older drives for newer ones with limited ride-through:*

Instead of tripping and switching off, some newer drives are able to re-synchronize their output with the spinning load. This option is only feasible if the duration of the voltage dip is less than 500ms as most manufacturers only offer an average published ride-through of ± 500ms. However, this figure can be less if the motor is driving a low inertia load.

4. The Voltage Dip-Proofing Inverter: Its function, design and application.

The specially designed, custom uninterruptable power supply was named the VOLTAGE DIP-PROOFING INVERTER® and offers a number of advantages over current solutions and protective devices:

1. *Reliability* : The MTBF (mean-time-between-failures) is two to three times better. This is the result of using an off-line system, where the inverter is always on stand-by until a voltage-dip thereby developing little heat. The inverter employs a stepped square wave output that makes it simple and most importantly very robust. Also, a fail-to-safety design approach has been adopted.

2. *Maintenance* : By using capacitors for energy storage , battery maintenance and

hazardous waste disposal is eliminated. Typical voltage sag characteristics also tend to reduce battery life dramatically. Ideal for ultra clean environments as gaseous emissions problems are eliminated.

3. *Inrush currents* : The unit can tolerate between 10 and 20 times the nominal current. When choosing the correct size inverter, only the holding VA or continuous current needs to be considered, whereas a UPS's and CVT's must be laid out for maximum load.

4. *Speed* : An ultra-fast transfer time of approximately 700µs prevents extremely sensitive relays, starters, contactors and PLC's from dropping out. Small, cheap, off-line UPS's do not switch over fast enough.

5. *Low power factor tolerance* : In contrast to normal UPS's which specify power factors of 0.7 or higher, the DPI is suited to switchboards which generally have a power factor of 0.15 to 0.4.

6. *Size* : A 3kVA 120V unit measures only 555 x 311 x 162mm (21.85 x 12.25 x 6.4 in). Using capacitors for energy storage, batteries are eliminated and the DC voltage can be kept high which eliminates the need for transformers.

7. *Easy integration and monitoring:* Easy to retrofit into existing motor control centers by virtue of a simple '3 wire system' and small footprint. A status monitor provides visual front panel indication and an (optional) potential free relay contact output when the inverter is activated.

8. *Accurate application control* : All units incorporate a timer adjustable from 0.1 seconds to 3.1 seconds and offer a transfer level variable from 50% to 90% of nominal supply voltage.

9. *Industrial Robustness* : Unit has been designed for operation in harsh industrial environments with a robust enclosure that does not require ventilation or fans for cooling.

4.1 Theory of Operation.

The basic configuration is shown in Fig. 6, below. The use of an off-line system dictated the design of ultra-fast circuitry to avoid the sensitive control devices from dropping out during switch over as sometimes occurs with other stand-by equipment.

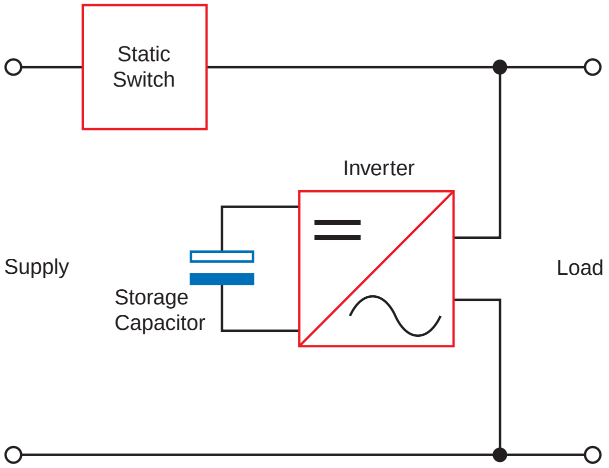

Fig 6
DPI block diagram.

The system consists of a static switch in series with the load, and an inverter parallel to it. For energy storage, long life computer grade electrolytic capacitors are used. This is possible due to the minimal “real power” component in motor control centers and switchboards, and the short period for which power is required.

Capacitors are available with high enough voltage ratings so that no transformers are necessary. They need no maintenance and are, in general, much more reliable than batteries. In this configuration the inverter and the capacitors only operate during dips so they work under ideal conditions by being always charged and carrying no ripple current. Subsequently no heat is generated and they are hardly stressed. Predicted life-time is approximately 12 years at 25°C/ 77°F, see Fig 7 below.

To predict the life of aluminum electrolytic capacitors at derated voltages, temperatures and ripple current the equation below is used.

$$Lifetime = L_S x2\left(\frac{\left(T_s-\left(T_a+5\left(\frac{I_a}{I_s}\right)^2\right)\right)}{10}\right)x\left(\frac{1}{\left(\frac{V_a}{V_s}\right)^2}\right)$$

Where:

Ls = Specified Load Life [Hours]	5000H
Ts = Specified Maximum Operating Temperature [˚C]	85˚C
Ta = Ambient Temperature (Capacitor Surface) [˚C]	40˚C (104˚F)
Ia = Applied Ripple Current At Operating Frequency [A rms]	0.07 @ 60Hz
Is = Specified Max Ripple Current Frequency Corrected [A rms]	8.6 (Ave.)
Va = Applied Voltage [Volts]	155V
Vs = Specified Maximum Voltage [Volts]	200V

Calculate at 40˚C (104˚F) average per year, probably the worst case:
Lifetime = 9 years

Calculate at 25˚C (77˚F) average per year, which is more common:
Lifetime = 12 years

Fig 7

Capacitor lifetime estimation.

The incoming sine wave is continuously monitored and should it deviate from the nominal value by a pre-determined percentage, the static switch is switched off and the inverter is switched on. The static switch is required, otherwise power flows back into the supply.

The voltage supplied by the inverter is synchronous with the supply voltage and is a *stepped* square wave, as can be seen in Fig 8, p9. This wave shape has various advantages, firstly the RMS and the peak value is the same as that of a sine wave, it can therefore be used with transformers and coils where RMS is important and with electronic relays using capacitor input filters where peak voltage is required. It can supply any inductive load without being distorted and the RMS voltage is regulated. Last not least, the electronic elements needed to create this wave shape are relatively simple and therefore less prone to failure. The only disadvantage is a higher harmonic content with an associated higher loss in the load. This is irrelevant as the inverter only operates for very short periods of time.

The only power device that Is constantly loaded is the static switch. This consists of a diode bridge and an IGBT, both extremely robust electronic components. To further enhance their reliability, they are greatly over designed. Should they malfunction it is probable that they fail to short circuit and would therefore not ‘drop’ out the load in the switch board.

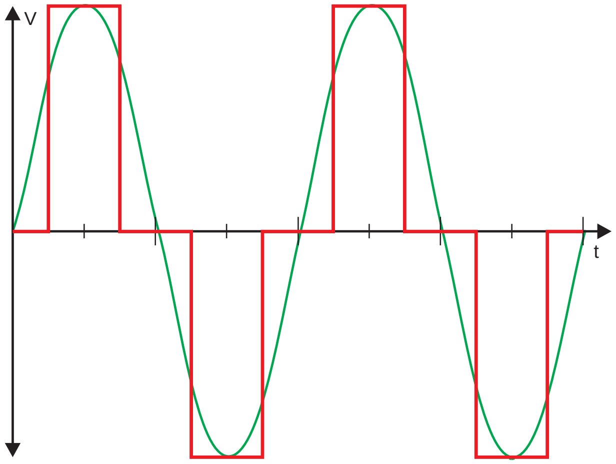

Fig 8

DPI waveform comparison.

By employing an off-line system, should the internal regulator, the electronic control, or a power transistor fail, dip-proofing would be lost, but the load would not be dropped.

4.2 Implementation.

Fig. 9 shows a typical micro-interruption caused by a short circuit in the plant. The length of the dip is determined by how long it takes the protection equipment to clear the fault. Motors would hardly notice a 50ms interruption, but the contactors would all drop out.

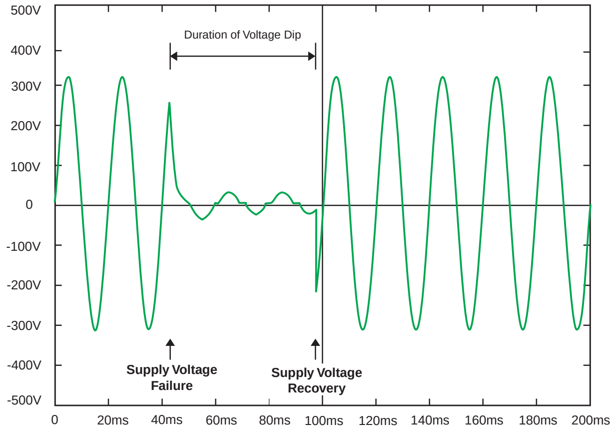

Fig 9

Supply voltage waveform during momentary outage.

Fig 10, p10, magnifies the point of failure. As can be seen, the voltage must drop below 65% of nominal in this case and must persist for longer than 700 µs. The static switch is then switched off and the inverter switched on. Power is then supplied by the capacitors via the inverter.

A timer, adjustable in increments of 100ms from 0.1 seconds to a maximum of 3.1 seconds, starts timing the inverter out. When the supply voltage is restored within the set time, the inverter output voltage is synchronized with the supply. This is important

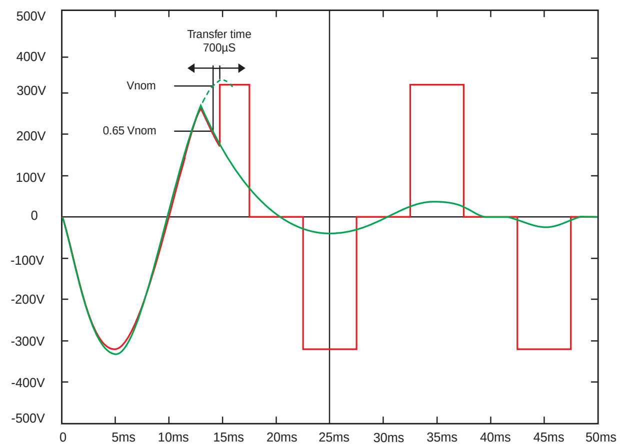

Fig 10

Supply & load waveforms at transfer.

because if it is not, contactors and relays will go into saturation and drop out anyway.

At this point the inverter is switched off and the static switch reconnects the supply. The output voltage can be seen in Fig 11, below. The capacitors are re-charged in approximately one second or less, depending on the load and the level to which they were discharged, and are then ready to compensate for the next voltage dip.

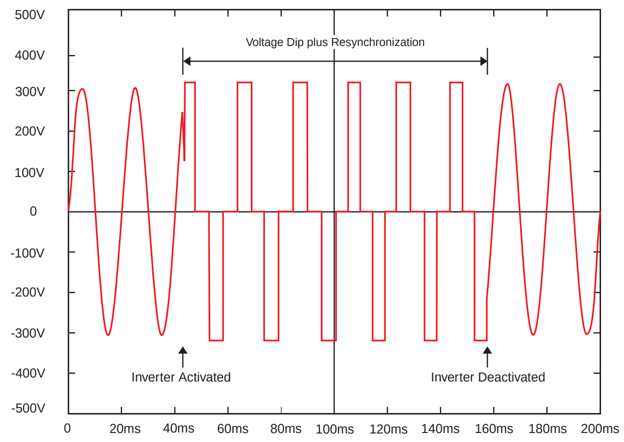

Fig 11

Load voltage waveform.

Should more energy be required for a longer support time or to provide more ‘real power’ (i.e. watts), as in the case of PLC’s or power supplies connected to the same circuit, additional capacitors can be added.

Each unit is ‘burned in’ for 100 hours at full load and 50° C / 122° F. During this period it is subjected to more than 1000 dips.

Since being introduced into the market, the DPI has proved extremely reliable and a MTBF (Mean Time Between Failures) of well over half a million hours has been achieved. This bears out the careful design approach.

Bypass switches are available as an accessory for the DPI where no-break maintenance is required, see Fig 12, p11.

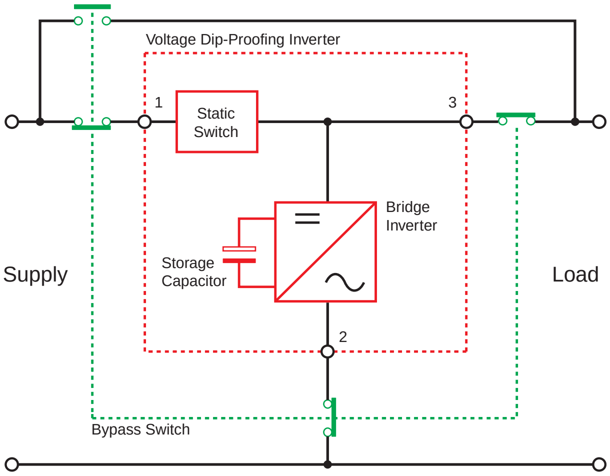

Fig 12

DPI bypass switch.

4.3 Application Examples.

The following is a list of applications and installations and the reasons the DPI was chosen:

a) Semiconductor wafer fab's: *Maintenance-free, adjustable timer* for accurate ride-through control, ability to *withstand variable loads* and *industrial robustness*. Used to support vacuum pump controls consisting of contactors, relays and PLC's.

b) Plastics facility producing body implants and prosthetics: *Maintenance-free* and *adjustable timer* for low inertia load applications. For use on oxidizers and blower MCC to support contactors, relays and logic.

c) Chemical processing and manufacturing plant: *Industrial robustness* and suitability to *inductive loads*. For use on 1500 HP booster blower MCC.

d) Plastic pipe extrusion plant: *Maintenance-free*; For use on extruder controls. UPS's were tried but because the plant often experiences numerous dips within a short period, battery life was diminished drastically. Maintenance and replacement became a nuisance.

e) Utility generation plant: *Maintenance-free, ease of retrofit, industrial robustness,* suitability to *inductive loads* and *adjustable timer* Used to support control starters on low inertia lubrication pumps on the diesel generators.

f) Fiberglass plant: *Maintenance-free* and suitability *to inductive loads.* Used on contactors and solenoids in motor control centers controlling 5kV blowers.

g) Crushing and separation plant: Harsh environment requiring a device that *does not have batteries* or need *ventilation*. Used to provide ride-through for conveyor and crusher controls.

h) Mines - For use on submersible pump controls in a harsh environment. *Maintenance-free,* and *adjustable timer* for low inertia load applications, *industrial robustness* and suitability to *inductive loads*.

i) Refinery - For use on main air blower and cooling pump controls. Ability to *withstand high energizing currents, batteryless,* inclusion of an *adjustable timer* for accurate control, and *bypass switch*.

Other types of industry either using the device or where it can be applied:

- Paper and Pulp
- Steel
- Rubber
- Food & Beverage
- Textiles
- Farming
- Packaging
- Printing
- Foundry
- Glass
- Semiconductor
- Automotive
- Refinery
- Plastics
- Chemicals

Can also be used for large commercial applications to protect HVAC equipment as well as elevator controls, ablution pumps and water chillers.

5. Conclusion

Providing ride-through for facilities is obviously not a simple task. Using the methods described in this paper involve more than just the installation of a ‘black box’ to support the system. The interaction between the controlling equipment and sensors, motors and drives along with power quality monitoring reports and studies needs to be evaluated before implementation can begin. Although this requires a combined effort from involved parties, investment return should be realized in a relatively short period of time and the costs involved are usually considerably lower than implementing huge and expensive solutions to protect an entire facility.

6. References

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[3] “Distribution Power Quality Monitoring Data” - EPRI, 1994

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