PSerc: 97-05
Proceedings, 30th Annual Hawaii International Conference on System Sciences, Jan. 7-10, 1997

Unbundling Power Quality Services: Technical Issues

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Abstract

The modern industrial facility depends on sensitive electronic equipment that can be shut down suddenly by severe power system disturbances. A large number of these disturbances on the power system are a result of line faults which can cause momentary voltage sags. This results in equipment malfunctioning and high cleanup cost. This papers describes some of the emerging opportunities for new services to users of electrical power. In particular the focus is on the need for improved quality of power and methods for providing this new service.

1. Introduction

One of the driving forces behind change in the power industry has been customers seeking variety in terms and conditions of electric service. The distribution system can greatly facilitate this customer choice, because it affects the quality and nature of service. This includes a choice of generation, demand side technologies, level of power quality and tools for risk management.

In the past, to the electrical power user, power quality implied that power was available when needed at an acceptable voltage level. Today the definition of power quality depends on the user's load and it's sensitivity to voltage changes. These changes are a result of the introduction of equipment based on adjustable speed drives (ASD) and complex control systems.

In this paper the details of power quality are discussed along with methods to measure the quality of power. The last sections discuss power electronics based solutions which can be supplied by the distribution company.

2. Forces of Change

There a many forces encouraging change in the distribution system. These include new marketplace opportunities, change in the character of customer's load and the need for power quality services.

2.1 Marketplace

Most of forces for change acting on the distribution system are driven by technology. Technological changes in the nature of available generation, the growing potential of several distributed storage technologies, methods for effective application of electrical power and power quality controllers suggest that the power delivery system could change dramatically. Most of these technologies utilize power electronics.

If current trends continue, it may make more economic sense to place small scale generation and storage units at the distribution system level. Clearly, with an appropriate level of local generation and storage it is possible to achieve competitive energy prices for customers. There is an option to contract the level of power from the wholesaler which includes "time-of-purchase" rates rather than "time-of-use" rates. For example storage allows purchase of power at low demand times for use during peak periods. This flexibility to negotiate for lowest cost energy is expanded using efficient distributed generation. The basic operational task is to find the best mix between wholesale power, locally generated power based on available fuel source, and level of power quality required by the customer.

The growth of demand side technologies is driven through the need for effective consumption of electricity. This implies not only greater efficiencies but greater control of energy intensive process. Prime examples are heavy robots, machine tools, compressors, microelectronics processing and other automated precision processing systems. However this technology has an adverse impact on the power system and the user. To the power system, there is a degradation of power quality due to harmonic current. A second issue is the change in the complexity of system load which could have a major impact on the voltage stability. From the user perspective, power disturbances that once were barely noticed now produce costly malfunctions in customers' equipment. This change in the nature of the load demands more flexibility in power quality services.

Risk management is not only a hedge against the cost of power, but protection against costly loss of production due to a short or long loss of power. For example, a recent agreement between Detroit Edison Company and manufacturers of motor vehicles reimburses the customer for defects in the supplier's product. This contract embraces both traditional reliability and power quality. In France, Electricite de France (EDF) now provides power quality services with a performance guarantee to its customers.

These technological changes suggest the possibility of an integrated, customer centered electrical energy supplier which has the ability to provide extra user services in addition to low cost power.

2.2 Changes in Load Characteristics

Manufacturers want faster, more efficient machines that are more productive. The electrical utilities encourage this because it reduces the aggregate rate of growth of electrical load and helps defer large investment for substations and generation.This results in systems which depend on precise control of motors through adjustable speed drives (ASD) and complex control systems.

This trend towards greater control of energy intensive process is supported by the rate of growth in the AC and DC drives market as shown in Figure 1. In 1988 DC drives held close to 60% of the market. Between 1988 and 1995 there has been a 50% increase in the number of drives with most of the growth in AC drives. Equivalent growth can be found in the use of programmable logic controllers.

Industrial systems that depend upon programmable logic controllers and AC adjustable speed drives are the most sensitive to the quality of power. This type equipment can experience costly malfunctions due to minor power disturbances. For example, constant speed induction motors and DC drives can hold their torque during voltage dips by drawing more current. On the other hand, AC drives require a diode rectifier, a DC bus, and an inverter, which results in a system that is much more sensitive to AC voltage dips. In a like manner, programmable logic controllers require a stable DC voltage source which in many cases is supplied by a single phase diode rectifier. The DC voltage supplied by the rectifier will track the fluctuations of the AC voltage resulting in the controller misoperation during voltage dips. The result is the malfunction of critical process at a large cost to the industry. This trend has resulted in an emerging market for solutions from both the supplier of equipment and the electrical utility. The solutions to these malfunctions range from designing equipment with greater ride-through capability to new power electronic equipment designed to enhance the quality of the distribution system power.

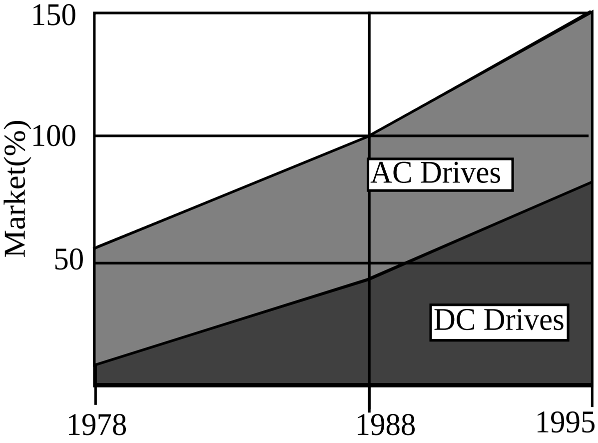


Figure 1. Market Growth (%)of AC, DC Drives [1].

2.3 Power System Quality Enhancement

Today's power electronic technology allows for solutions that can be beneficial to both the customer and the distribution company. This technology enables the supplier to provide different levels of power quality to the end user at a cost reflecting the users needs. For example, premium power to the sensitive loads would warrant higher tariffs than a thermal load that is willing to lose service in exchange for lower energy costs. This ability to provide a range of quality of power is becoming a distinct competitive advantage as utilities face increasing competition through deregulation of retail markets.

About 90% of disturbances affecting customers originate on the distribution system. One principle sources of customer disturbances are lightning and line faults. Disruptive loads such as whole-log chippers, rolling mills etc., and harmonics due to rectifier based loads are another important source of problems. The equipment available today to mediate these problems are; solid-state switches for transfer between feeders or for fast isolation of a problem line; series injected voltages to isolate critical loads; shunt voltages controllers to isolate disruptive load, and active filters to control harmonics penetration in the distribution system.

3. Load sensitivity and the quality of power

The key to understanding load sensitivity and its relationship to quality of power centers around the response of diode rectifiers to changes in AC voltage. Sensitive load will malfunction during voltage sags and momentary interruptions, depending on the duration and the magnitude of the voltage sag. These events are usually associated with a fault or rapidly changing load somewhere on the distribution system. Actual interruption occurs when the fault is on the circuit supplying the customer.

3.1 Sensitivity of Load

A distinction needs to be made between single phase loads and three phase loads. Many sensitive industrial processes depend upon adjustable speed drives. These are three phase loads with a diode rectifier providing the interface between the AC system and the drive. On the DC side there is a capacitor to provide an interface between the rectifier and the load. During an AC voltage sag the DC voltage across the capacitor will also sag. The magnitude is dependent upon the average of the AC voltage present, while the rate of drop is dependent upon the size of the DC capacitor and the nature of the load. Controllers such as programmable logic controllers are typical single phase loads. They also rely on diode rectifiers to provide a DC voltage for the controller.

Figure 2 shows sensitivity of equipment as a function of duration of the sag and the magnitude of the DC voltage. The figure shows the difference between an old and a new version of the same programmable logic controller[2]. The new, Type 1 controller will trip at 60-75% voltage with no ride-through capabilities. The older, Type 2, PLC could ride through zero voltage for 10-15 cycles with no problems. Voltage dips are becoming a greater problem for electronic controllers due to this increased sensitivity. CBEMA limits, developed by the Computer Business Manufacturers Association, are a possible standard for equipment sensitivity. They set the allowable sag as a function of the duration. Allowable sags range from 0% voltage for 1/2 cycle to 87% voltage at steady state.

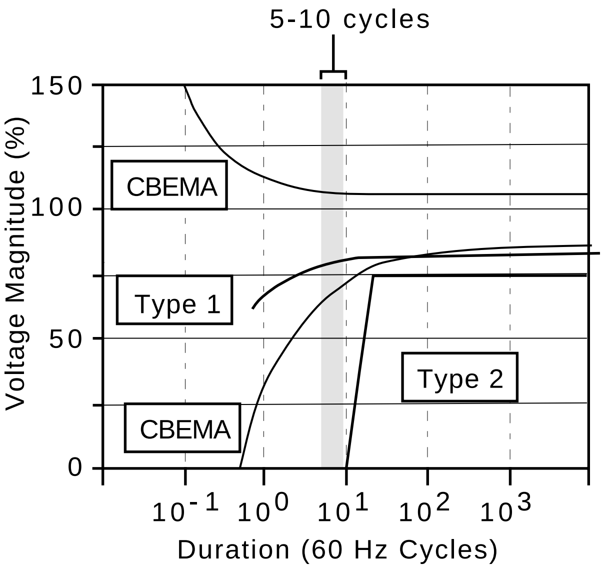
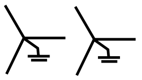
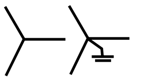
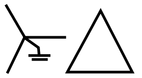
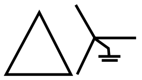


Figure 2. Equipment Sensitivity to Voltage Sags

Motor drives voltage sag trip-out levels range from a poor 85% voltage for 3 cycles to 70% voltage drop for 30 cycles [4]. All drives could be designed to meet the CBEMA standard or higher with careful power supply design and correct sizing of the DC bus capacitor.

Table 1: DC and Secondary Transformer Voltages During a Shorted Phase on the Primary

Transformer Connection	Secondary Voltage		Diode Rectifier's DC Voltage		
	L-L	L-G	3Ø	L-L	L-G
	0.58 1.0 0.58	0.0 1.0 1.0	.72	1-.58	1-0.0
	0.58 1.0 0.58	0.33 0.88 0.88	.72	1-.58	1-.33
	0.33 0.88 0.88	_ _ _	.70	.88-.33	------
	0.88 0.88 0.33	0.58 1.0 0.58	.70	.88-.33	1.-.58

3.2 Importance of Transformers

Voltage disturbances that occur close to a customer's transformer can cause the most problems. In Table 1 the effect of a line-to-ground fault on a primary phase is shown. The first column shows a set of possible transformer connections, followed with the change in the secondary voltage measured line-to-line and line-to-ground. For example, the line-to-line secondary voltages can never be less than 33% and in most cases will be 88% or higher during the fault.

The last three columns of Table 1 look at the DC bus voltage change from nominal. It is apparent that a three phase rectifier sees a much smaller DC voltage drop than that seen by a single phase rectifier. Some single phase loads will be unaffected and other single phase loads may drop out, even though their sensitivities to voltage sags may be identical. For example consider a Type 1 controller connected line-to-line. Table 1 indicates that for all connections shown a line-to-ground fault on the primary would result in a trip average of 50%.

3.3 Frequency of Voltage Dips

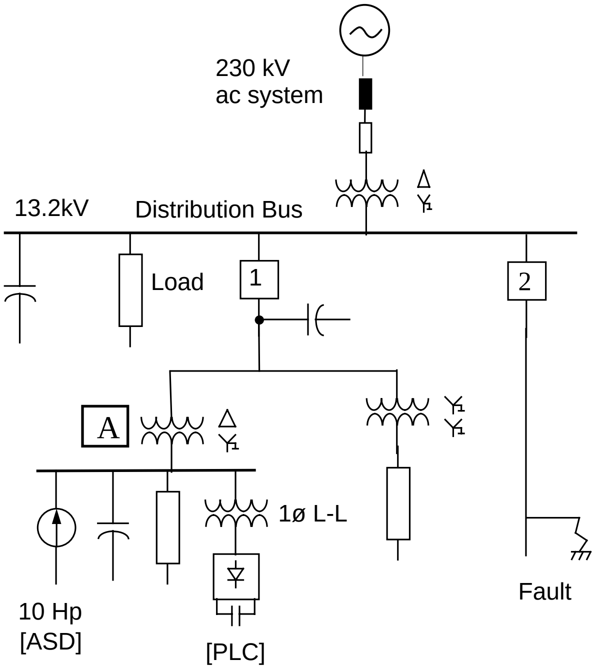


Figure 3. Example Distribution System

Voltage sags are typically caused by fault conditions. These faults can occur on the transmission system or on the distribution system. Figure 3 illustrates a typical distribution system with a number of feeders supplied from a common 13.2 kV bus. This bus is feed through a step-down transformer connected to the 230 kV transmission system. A fault on the high voltage transmission system or on any feeder of the distribution system will cause an interruption that will affect customers.

Faults on the transmission system can affect customers on other distribution systems. Customers hundreds of miles from the fault location can experience a voltage sag resulting in equipment misoperation. Faults on the distribution system are usually limited to the feeders of the faulted distribution system.

The majority of faults on a utility are line-to-ground faults (SLGF). Three phase faults cause more problems, but are less frequent. SLGF's can result from lightning, wind, animal contact, contamination of insulators, trees, accidents, etc. Lightning is the most common cause of faults. Fortunately these are temporary, clearing in a few cycles

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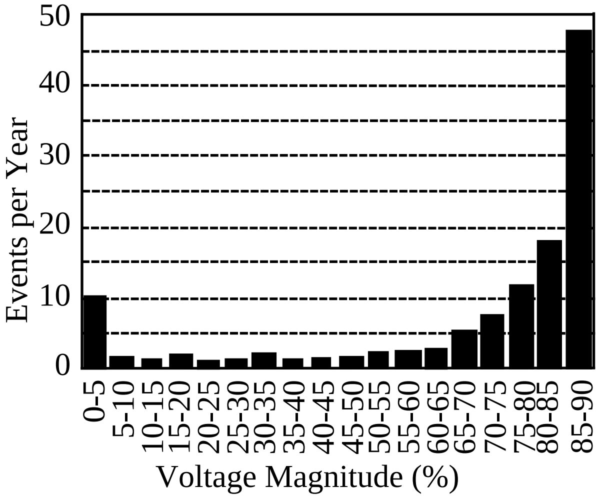

Figure 4. Frequency and Severity of Voltage Sags

The last remaining question is frequency and magnitude of voltage dips at a customer's site. Figure 4 shows frequency and magnitude of voltage dips at a typical site. This site experiences close to 40 events per year with voltages below 75%. Of these 40 events around 1/3 are expected to be due to three phase faults, the remaining events are line-to-line and line-to-ground voltage dips. An ASD would see close to 13 trips due to the 3 phase faults. A type 1 controller will trip out on the same 13 events plus an average of 13 tips due to single phase faults. This results in 26 events per year. Most critical processes are completely automated and dependent both on ASDs and PLC controllers. These interruptions can cause very expensive cleanups and restarting requirements. Financial losses per event can be very high.

4. Example System

. The example distribution system shown in Figure 3 will be used to demonstrate the response of the loads connected to transformer A to faults on Feeder 2. Both single line-to-ground and three phase faults will be simulated. This model system includes three phase ASD loads and single phase PLC controllers connected line-to-line. The faults introduce a 50% reduction in phase voltage at the distribution bus.

Simulation results due to a single phase fault and a three phase fault are shown in Figure 5. The top trace is the line-to-line voltage at the 13.2 kV distribution bus. At 120 milliseconds there is single phase fault held for 100 milliseconds followed by 100 milliseconds of restored voltage and a second fault which is three phase.

The middle trace of Figure 5 shows the response of the DC capacitor voltage for a single phase diode bridge. The DC bus voltage dips to 65% during the single line-to-ground fault and 50% for the three phase fault. In both cases a Type 1 controller would trip. A Type 2 controller would also trip if the faults lasted for more than 600 milliseconds.

The last trace in figure 5 is for the three phase rectifier. In this case we see a reduced sensitivity if the rectifier can operated in a single phase mode during single phase voltage dips. In both cases the measure of the effects of different types of faults and transformer connections on is equipment is the response of the related D.C. bus voltage.

5. Solutions

Understanding the relationship of system disturbances to tripping of rectifier type loads described, the next step is to describe the range of solutions for avoiding power quality problems.Solutions may be implemented by the customer or by the utility. Of the many utility based solutions, two Custom Power devices will be described in greater detail.

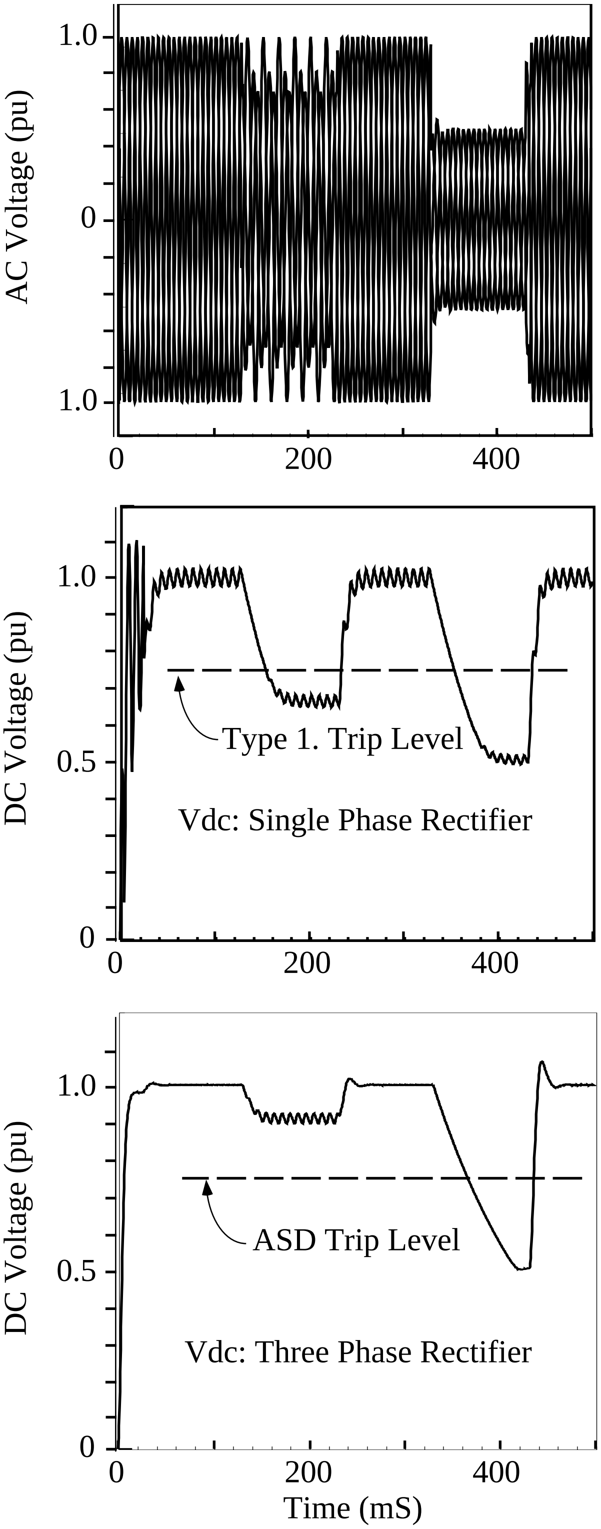

Figure 5. Response of Rectifiers to Voltage Dips.

5.1 Customer

The customer can take measures to reduce productivity losses caused by power disturbances. Equipment sensitivity can be reduced by specifying, at the time of acquisition, that equipment must have a certain level of sag ride-through capability. For equipment already in place, small scale power conditioning equipment can be applied first to controllers and then to ASDs. Constant voltage transformers, uninterruptible power supplies, and motor-generator sets are examples customer based power conditioning equipment. Besides dealing with power disturbances that come from the utility, customers may also have to take measures to prevent harmonics originating in their plant from propagating back to the utility. Passive and active filters may used to avoid exceeding harmonic current limits set out in proposed IEEE 519-1992 standard. Another option is to purchase power quality services from the distribution company.

5.2 Utility

The utility's range of power quality enhancing measures go from creation of a more robust power system with fewer opportunities for disturbances to application of power electronic devices for meeting the needs of specific sensitive customers.

The first step is for the utility to reduce the number of sags and interruptions by improved practices. Vigilant tree trimming and insulator washing will reduce the number of faults. Additional reclosers can be placed on distribution feeders and fast tripping practices can be modified to reduce the number of interruptions. Parallel feeders can be used to stiffen the supply to a particular load and reduce the chance of a complete outage.

When power electronics are brought to bear, the primary features is fast subcycle control. Momentary voltage dips as brief as one cycle can be prevented from getting through to sensitive loads. This means that sags that might otherwise have tripped a controller or ASD will go unnoticed, reducing product defects and production downtime. Using modern self commutating power devices such as Insulated Gate Bipolar Transistors, compensators can be built with ratings of 20 MVA or more, a level suitable for distribution applications.

By using power electronics, the utility can provide a range of additional functions. A Solid State Breaker SSB can be used to isolate a faulted feeder in less than a cycle, thereby avoiding a sag on adjacent feeders. If parallel feeders are available to a load, a Solid State Transfer Switch SSTS can provide an instantaneous transfer between feeders, decreasing the likelihood of a complete outage or transferring the load away from a sagging feeder. A Static Var Compensation SVC can compensate for the effect of widely varying loads. Finally, a Battery Energy Storage System BESS can be used to provide completely uninterruptible power.

For removing sags at a customer's bus, the Dynamic Voltage Restorer DVR and the Static Compensator STATCOM are the most appropriate devices. These two compensators are now discussed in more detail.

6. Shunt and Series Compensation

Compensators typically employ a controlled fundamental frequency voltage source, synthesized by a converter. The voltage may be inserted in series or in shunt with the line. The series configuration has been referred to as a Dynamic Voltage Restorer or DVR while the shunt configuration has been referred to as a Static Compensator or STATCOM.

6.1 Description of Series Compensator

In the DVR, a transformer is placed in series with the feeder. The converter generates a voltage across the transformer that is in quadrature with feeder current. The series transformer appears as a variable impedance, either inductive or capacitive, which adds to or subtracts from line impedance.

By changing the total apparent feeder impedance, the voltage drop across the line can be controlled and the load bus voltage increased or decreased. For example, when the incoming voltage sags, the transformer can produce capacitive voltage canceling some of the voltage drop in the line. In this normal mode of operation, the DVR does not have to supply real power to achieve voltage control. During power interruptions, the DVR can perform a UPS function if it has energy storage capability.

The severity of voltage sag that can be handled with a DVR without real power flow is dependent upon the characteristics of the distribution system and the power factor of the feeder load. The limit for a given system can be determined from the power flow equations using the assumption that the line impedance can take on any value, either inductive or capacitive.

6.2 Description of Shunt Compensator

In the STATCOM, a converter synthesized shunt voltage source is connected to the feeder by a reactance. This shunt voltage is in phase with the feeder voltage but can be higher or lower in magnitude, resulting in capacitive or inductive vars being supplied to the line. The injected reactive current interacts with the primarily inductive feeder impedance causing the line voltage to increase or decrease.

The range of STATCOM voltage control depends upon the line impedance and the amount of reactive current it can supply. With energy storage, the STATCOM can also perform a UPS function.

One difference between the two compensators is that the DVR can provide improved power quality only to loads that are downline from it. This is because the DVR is in series with the feeder. It provides no voltage regulation benefit to any upline loads or adjacent feeders. The STATCOM, on the other hand, provides some measure of voltage support to loads upline from the regulated bus. The STATCOM can also reduce voltage flicker along the entire distribution system when it is placed near a variable load that is causing the flicker.

6.3 Unbalance problem

One problem that needs to be addressed in the application of DVRs and STATCOM is imbalance. Long term voltage imbalance of a few percent is not uncommon in distribution systems. The STATCOM and DVR must be able to deal with these unbalanced conditions. The STATCOM is particularly sensitive to voltage imbalance. Even apparently small levels of imbalance can produce high current magnitudes in the compensator.

In addition to mild long term imbalance, severe momentary imbalance arises during asymmetrical power system faults. With advanced controls, a DVR or STATCOM can deal with imbalance and also prevent asymmetrical voltage disturbances from reaching sensitive loads. For example, single line voltage sags can be removed.[5,6]

Controls for dealing with imbalance have the added benefit of extending the compensator's range of compensation. In severely asymmetrical sags, the compensator may no longer be able regulate voltage through only reactive means. During a single line sag, for example, the converter can transition to a mode where real power is drawn from unfaulted lines and fed to the faulted line. By doing this, the low line can be supported beyond the normal compensation limit for a three phase sag.

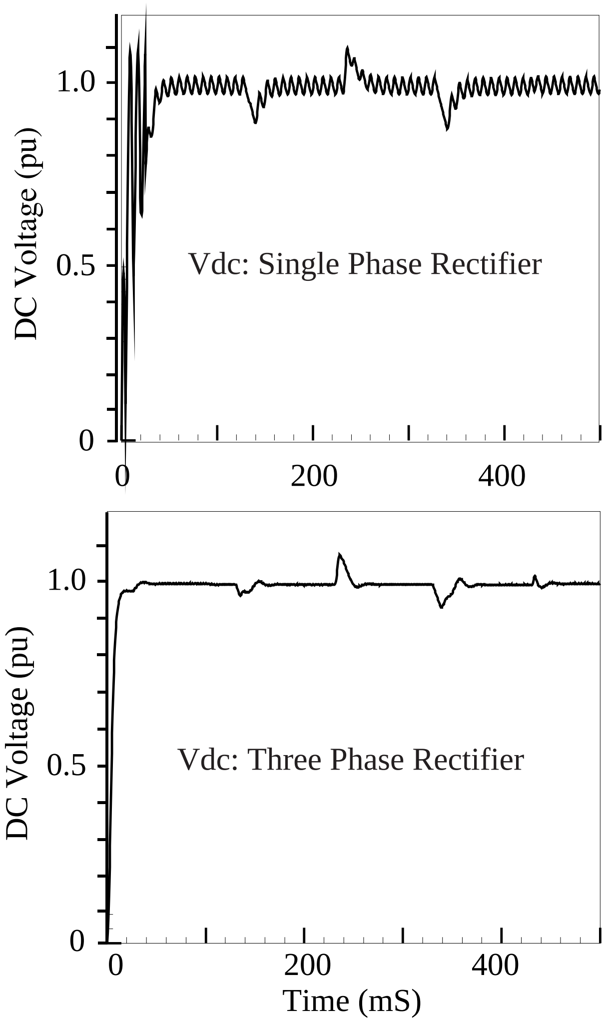

Figure 6. Response of Rectifiers to Voltage Dips with a DVR

The controls for removing imbalance operate by regulating the positive sequence component of the voltage in the usual fashion and rejecting or canceling the negative sequence component of the voltage. If needed, zero sequence voltage components can be eliminated as well, though special considerations must be taken in the converter design.

6.4 Examples

To demonstrate the effectiveness of the DVR and STATCOM in protecting sensitive loads, the distribution system of figure 3 is simulated with a compensator applied to the feeder with the sensitive load. The system

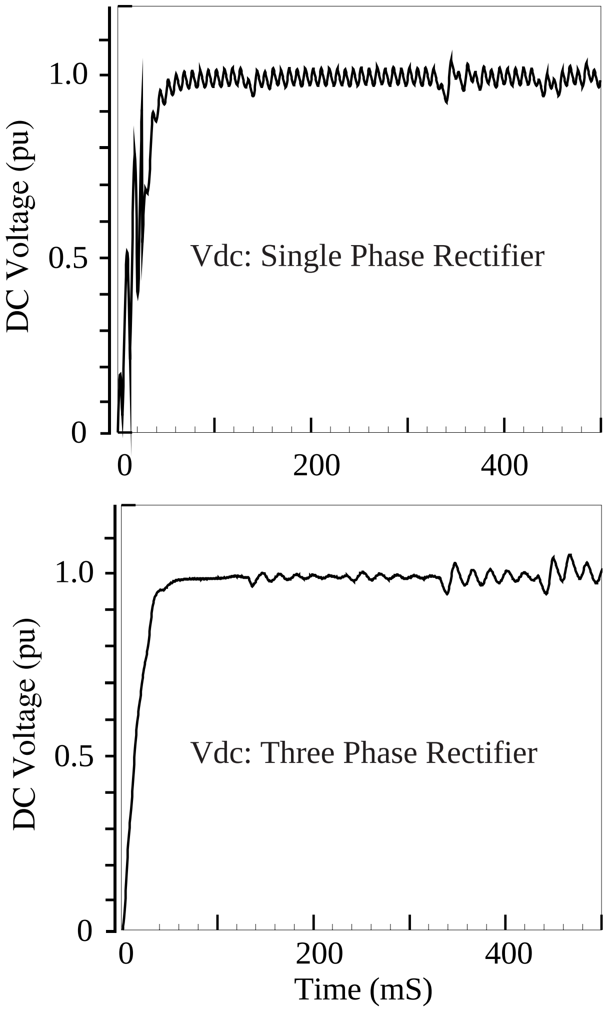

Figure 7. Response of Rectifiers to Voltage Dips with a STATCOM

is subjected to the same faults as appear in figure 5..

Top of figure 6 shows the DC bus voltage of a single phase rectifier used to model a PLC power supply when a DVR is used to isolate the feeder from upline faults. Single phase and three phase faults applied to an adjacent feeder do not disrupt the rectifier operation. The power supply voltage remains stable and well above the low voltage trip level. Without the compensator, the PLC fed from this rectifier would have tripped. Also shown in figure 6 is the DC bus voltage of a three phase rectifier in an ASD, which remains in a safe operating range during the faults.

When a distribution STATCOM is employed, the PLC and ASD responses are as shown in figure 7. Again, the sensitive loads are isolated from voltage disturbance caused by the fault.

By using a utility based solution for removing sags, all loads at the customer's site receive high quality power. This can greatly simplify the power conditioning problem when a large percentage of the load is sensitive voltage dips. In comparison to a full-time UPS, the DVR and STATCOM provide their power quality without requiring energy storage.

6.5 Compensation vs. Cost Trade-off

By using a DVR or STATCOM, load tripping can be reduced. As the severity of fault increases, so will the rating and cost of the compensator required for voltage restoration. The added cost of the compensator must be compared to the benefit of reduced downtime to determine the optimal compensator rating. The choice of which compensator to use, DVR or STATCOM, is dependent on the nature of the load and the distribution system characteristics.

7. Reference

[1] V. Hyvarinin and J.P. Makinen," Digital Drive Systems with Variable Speed AC Motors," ABB Review 4/90, pp. 3-10.

[2] J Lamoree, D Mueller, P. Vinett, W. Jones and M, Samatyj. "Voltage Sag Analysis Case Studies," IEEE Transactions on Industry Applications, Vol 30, No.4, July 1994.

[3] M. McGranaghan, D. Mueller and M. Samotyj, "Voltage Sags in Industrial Systems," IEEE Transactions on Industry Applications, Vol 29, No.2, July 1993.

[4] L. Conrad, K. Little and C. Grigg, "Predicting and preventing Problems Associated with Remote Fault-Clearing Voltage Dips," IEEE Transactions on Industry Applications, Vol 27, No.1, January/February 1991.

[5] R. Lasseter and C. Hochgraf, "Static Compensation for Unbalanced Systems Using a Voltage Sourced Inverter," The Future of Power Delivery Conference, April 9-11, 1996, Washington, DC.

[6] R. Lasseter and P. Cheng, 'Dynamic Voltage Restoration for Unbalanced Systems," The Future of Power Delivery Conference, April 9-11, 1996, Washington, DC.