DISTRIBUTION SYSTEM VOLTAGE SAGS: INTERACTION WITH MOTOR AND DRIVE LOADS

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Abstract - Several papers have been written on the response of directly connected induction motors or adjustable speed drive (ASD) connected motors to unbalanced and balanced voltage sags caused by faults on the power system. This paper will detail the interaction between the motors and drives and the supplying distribution system both during and after the voltage sag. In addition, the system effect of transferring the loads during the sag to an alternate feed with solid-state switching is evaluated. The Electro-Magnetic Transients Program (EMTP) was used for the analysis.

INTRODUCTION

Voltage sags are generally caused by faults on the supplying power system. A voltage sag is a reduction in rms voltage, and not the complete loss of ac power. Voltage sags are characterized by magnitude and duration [1] and are very important to industrial customers because they can cause tripping of important equipment and processes [2]. The sensitivity of an industrial customer's equipment to voltage sags dictates the severity of the problem. Some equipment has been shown to be sensitive for voltage sags as little as 10% in magnitude, and can result in thousands of dollars in lost product and many hours of equipment downtime when tripped [3].

Voltage sags can be caused by faults on the transmission and/or distribution system, and characterizing the performance at an industrial facility usually involves power quality monitoring and computer simulations. Figure 1 is an example of one year's worth of monitoring at an industrial facility fed from a distribution system. This monitoring data includes voltage sags caused by faults on the supplying distribution and transmission systems. The monitoring results show that the great majority of the voltage sags that occurred lasted 10 cycles or less and were 20-30% in magnitude. Similar results are being obtained from EPRI's nationwide Distribution Power Quality monitoring project [4].

Reference [5] presents the results of computer simulations run to determine the effect of voltage sags on motors and drives, and to determine the effectiveness of solid-state load transfer. The basic conclusions from that paper were:

1. Unbalanced voltage sags caused by single-line-to-ground fault (SLGF) conditions should not result in any significant motor speed variation for practical inertia values. The results indicate that it should not be necessary to trip motors during most voltage sag conditions, and that maintaining motor connection is very important.

2. For drive-connected motors, the speed and torque of the motor fed by the drive are less sensitive to the dc bus voltage variation than directly-connected motors are to the ac voltage variation. This implies that it should not be necessary to trip drives during most voltage sag conditions. However, undervoltage protection in the drive often trips the device.

3. Transferring the load to an emergency feed can protect the load for almost all cases of utility faults.

This paper presents the results of EMTP simulations run to determine the impact a customer with a large collection of motors and drives has on a utility distribution system, namely, voltage sag magnitude and duration (both during and after the event). Both SLGF and three-phase fault induced sags were modeled. Finally, the power system impacts of transferring the motor or drive load to an alternate feed with solid-state switches was simulated and is discussed.

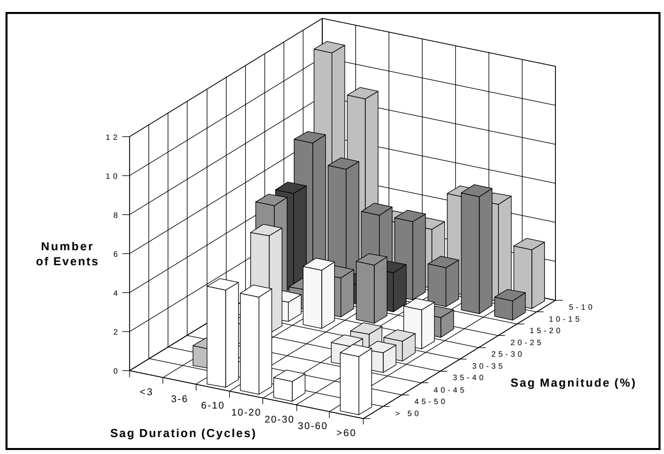

Figure 1. Distribution Power Quality Monitoring Data

EXAMPLE SYSTEM DESCRIPTION

The example system for this study is shown in Figure 2. The critical motor loads are fed at 480 volts from a 24 kV distribution system. The distribution system is supplied from a 100 kV transmission system. The transmission network beyond the substation high voltage bus has been reduced and represented by a single equivalent voltage source. The short circuit capacity at the 100 kV substation bus is 2400 MVA. The substation transformer is connected delta/wye-ground.

The 24 kV distribution feeder characteristics are based on an existing utility circuit. The backup feeder has similar characteristics as those of the normal feeder. As shown in the one-line diagram, this backup feeder is connected to an isolated 24 kV equivalent source.

Faults considered in this study are located at the end of the 100 kV transmission line. A SLGF and three-phase fault are simulated to generate unbalanced and balanced distribution system sags, respectively. The primary loads consisting of motors or ASDs are located six miles away from the transmission substation as shown in the figure.

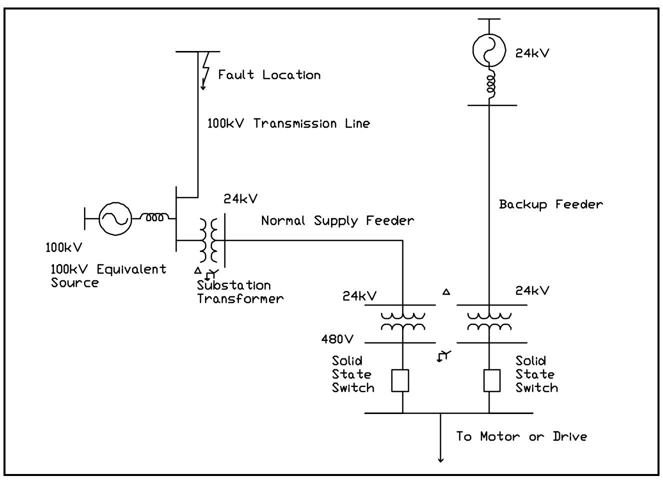

Figure 2. One-line Diagram of the Example System

For simulation purposes, the induction motors at the customer location are lumped together and represented as a single equivalent 4-pole induction machine. The full load rating of this equivalent machine is 3.0 MW. This machine can be either delta-connected or wye-connected with a ungrounded neutral. A constant mechanical torque corresponding to the full load rating of the equivalent machine is used to represent the mechanical load on the rotor shaft.

A single equivalent diode-bridge front-end, pulse-width modulated (PWM) voltage source inverter (VSI) is used to represent the adjustable speed drives connected at the customer 480 volt bus. The dc capacitance used in the simulation is about 0.5 F. The PWM switching frequency of the VSI is 420 Hz.

The backup 24 kV voltage source is synchronized with the normal supply feeder voltage. It was assumed that gate-turnoff (GTO) based devices are used for the feeder load transfer. This enables a phase current to be interrupted within a 1/4 cycle.

RESPONSE FOR UNBALANCED VOLTAGE SAGS

Unbalanced voltage sags on the 24 kV distribution system and 480 volt customer system were simulated by placing a SLGF on the 100 kV transmission system.

System Impacts with Motor Load

When a SLGF occurs on phase a of the transmission system as shown in Figure 2, a 30% sag (70% nominal voltage remains) was observed on the transmission substation 100 kV bus. The voltage is reduced across windings a-b and c-a of the 100 kV transformer. The voltage across winding b-c is not affected.

Through the delta-wye transformer, the 24 kV line-to-ground voltages of phase a and b are reduced, resulting in all three phase-to-phase voltages at 24 kV being affected. The voltage across phases a-b of the feeder is the lowest, which correspondingly made the phase b voltage on the 480 volt side the lowest. The phase-to-ground voltage waveforms at the three voltage levels are shown in Figures 3, 4, and 5.

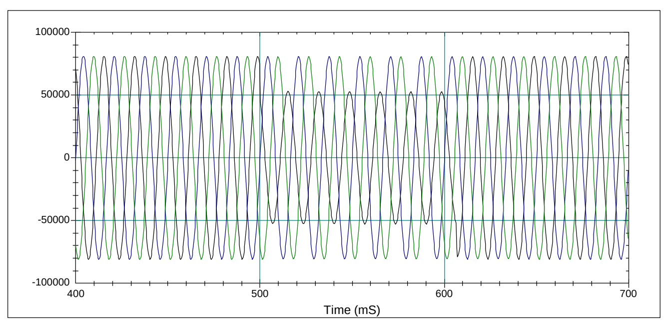

Figure 3. V_{lg} at 100 kV Side of Substation Transformer

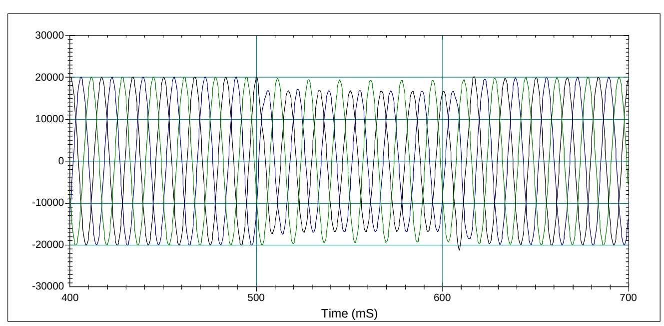

Figure 4. V_{lg} at 24 kV Side of Distribution Transformer

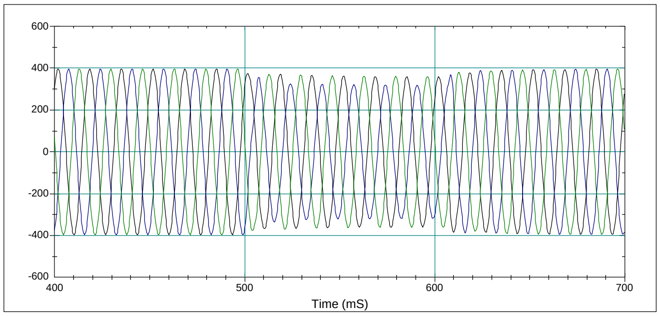

Figure 5. V_{lg} at 480 Volts with 30% Sag at 100 kV Bus

Figure 3 shows that at the moment the fault occurs, the phase-a voltage magnitude at the 100 kV bus dropped to 70% of nominal voltage. It remained constant at this level until the fault was cleared and normal system voltage was restored. However, this is not the case at the 24 kV and 480 volt levels. Figures 4 and 5 illustrate that the voltages at the distribution and, especially, at the customer level gradually reduces when the fault is initiated and the low voltage remains for a couple of cycles after the fault is cleared.

The gradual change of the voltage magnitude is a result of the interaction between the system and the induction motor. At the start of the voltage sag, the back electromotive force (EMF) of the induction motor provides voltage support for the system which prevents the customer bus voltage from dropping instantaneously. The motor starts to slow down, as the low voltage remains, and more current is drawn from the system. This tends to drag the system into a deeper sag. When the fault is cleared, motor inrush prevents the customer bus voltage from returning to normal instantaneously. The significance of the system impacts depend on the strength of the supplying system, characteristics of the sag, and characteristics of the machine and its shaft load.

Motor Load Transfer via Solid-State Switching

When a load transfer is incorporated, the motor load supplied by the normal feeder is switched to the backup feeder in a quarter-cycle after the fault occurs. In this study, it is assumed that two sets of solid-state switches are operated simultaneously; one interrupts the normal feeder and the other connects the backup feeder to the motor load. Since the sources are synchronized, the solid-state switching results in only a minor voltage transient. The phase-a voltages supplied by the normal and backup feeders around the switching point on the 480 volt side are shown in Figure 6. However, no measures were taken to reduce the current transient as shown in Figure 7. The current transient causes motor speed and torque transients but the magnitudes of these transients are small and they are damped quickly.

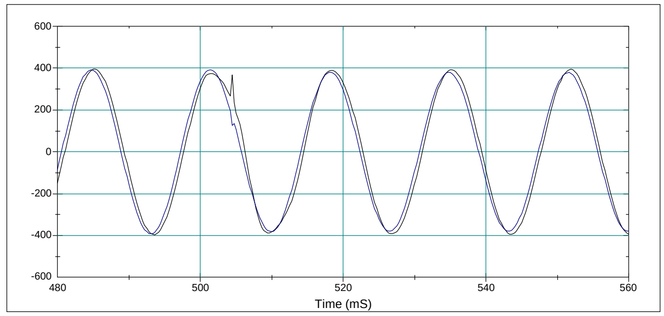

Figure 6. Motor V_{lg} Around Load Switching Point

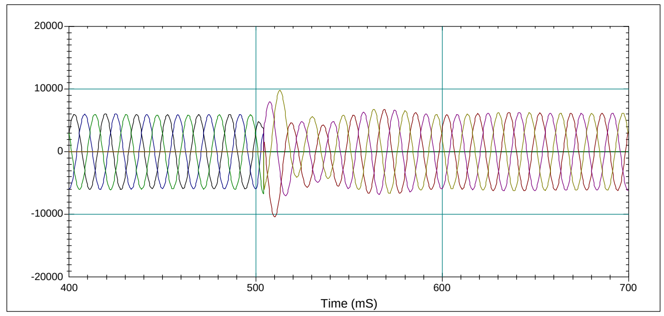

Figure 7. Motor Current Variation During Load Transfer

System Impacts with Drive Load

When the same motor is connected through a diode-bridge PWM adjustable speed drive with the same 30% transmission side sag, the 24 kV distribution system impacts are significantly different from that when the motor is directly connected. As shown in Figure 8, the same single-phase fault results in all three line-to-ground voltage peaks on the 24 kV bus to be reduced by approximately the same amount. This is one distinct impact of the drive load on the system.

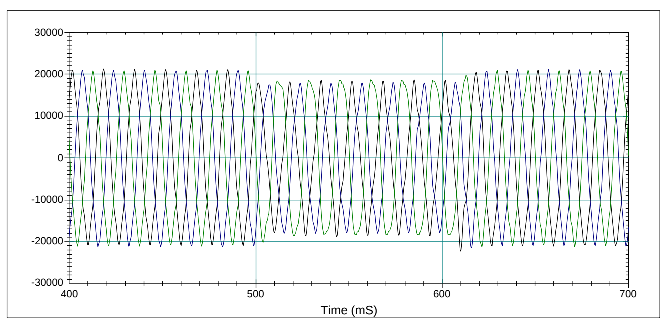

Figure 8. V_{lg} at the 24 kV Bus with Drive Load

The enlarged waveforms given in Figure 9 illustrate the distortion of the bus voltages, which increased during the voltage sags. Physically, the phase-a fault on the 100 kV system affects the 24 kV bus phase a and phase b voltages equally. It does not affect phase c. Through the 24kV/480V delta-wye transformer, phase b becomes the most affected and phase a and phase c are less affected. The dc capacitor charging current provided by each phase depends on both the magnitude of the phase-to-phase voltages and commutation timing among the phases.

Therefore, phase b contributes much less charging current than phase a or phase c does. This is clearly observed from the ac input currents given in Figure 10.

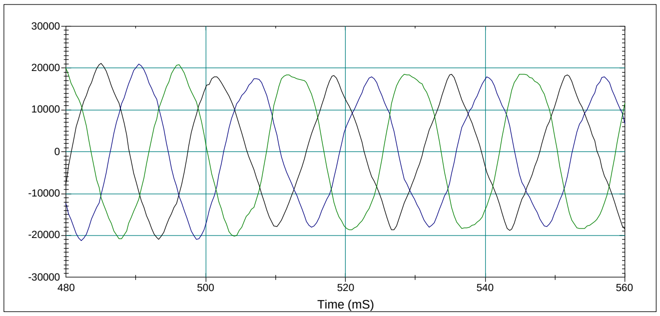

Figure 9. Enlarged Waveforms Around Sag Initialization

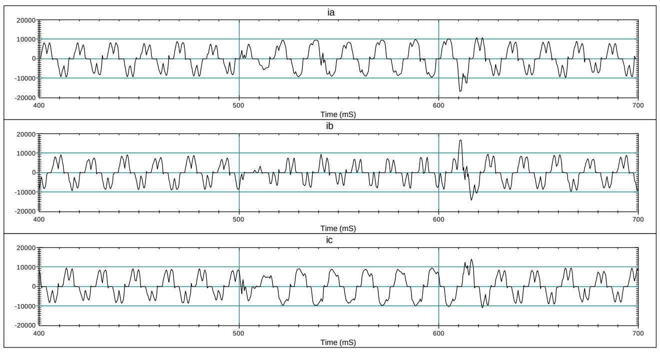

Figure 10. Waveforms of Input ac Line Currents

Hence, related by the basic rule of ampere-turn balance, on the 24 kV side of the transformer, the windings connected between phases a-c and phases b-c carry more current than the winding connected between phases a-b does. Consequently, it requires the unaffected phase c winding to supply more current compared with the other two phases. This heavy burden on phase c drags down its peak voltage. As a result, the difference in the voltage peaks between the affected and unaffected phases is reduced. It should be noted that the reduction in the rms value of the waveform of the phase-c voltage is not as great as in the waveform peak.

Drive Load Transfer via Solid-State Switching

When the drive load was transferred to the backup feeder by solid-state switching, the current transient observed previously no longer existed (Figure 11).

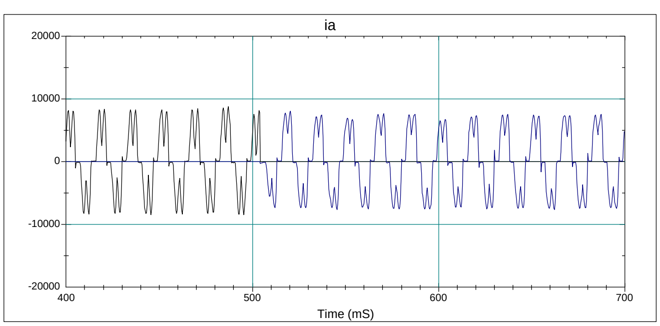

Figure 11. Drive AC Input Current

RESPONSE FOR BALANCED VOLTAGE SAGS

A three-phase transmission fault, lasting for six cycles and resulting in a voltage sag down to 50% of nominal on the 100 kV bus, can significantly affect the operation of the distribution system and motors. Results presented below address system and load impacts under balanced voltage sag conditions.

System Impacts with Motor Load

Within the six-cycle duration of the 50% transmission level voltage sag, the voltage on the 24 kV terminals of the distribution transformer decreases from 60% to 40% of nominal voltage as shown in Figure 12. The motor provides voltage support at the onset of the voltage sag but as the speed decreases, more current is drawn from the system resulting in a deeper sag on the feeder.

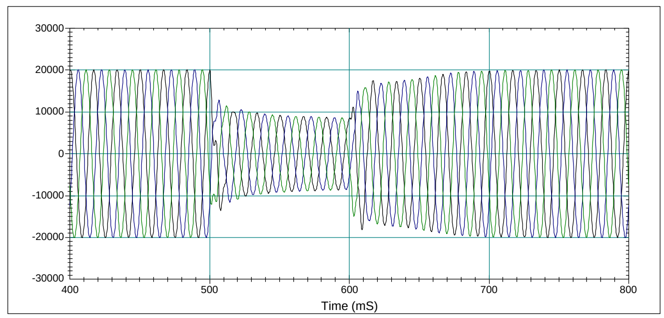

Figure 12. V_{lg} at 24 kV Side of Distribution Transformer

When the transmission fault was removed at the end of the six cycle duration, the distribution voltage took longer to recover back to its normal value. The motor inrush (Figure 13) caused the distribution sag to last longer and caused a two-stage sag as shown previously in Figure 12.

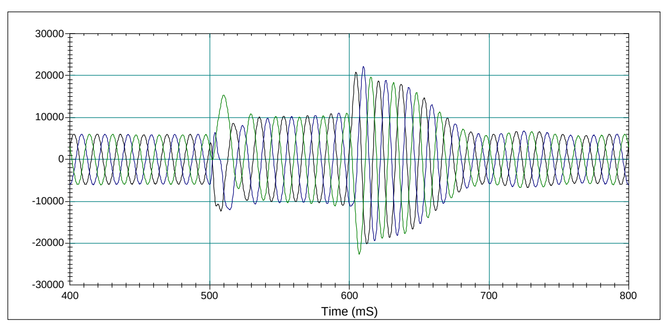

Figure 13. Induction Motor Current

Motor Load Transfer via Solid-State Switching

The transferring of the motor load under a three-phase fault condition is very similar to the transferring under the SLGF condition. The solid-state transfer is very effective even for three-phase sags if the transfer is accomplished rapidly.

System Impacts with Drive Load

When the motor is connected through a drive, the back EMF of the induction motor is separated from the ac system by the dc bus. Therefore, the 24 kV voltage sags shown in Figure 14 become very similar to that on the 100 kV bus. The phenomena of initial voltage sag support does not exist and ending voltage sag magnification is greatly restricted.

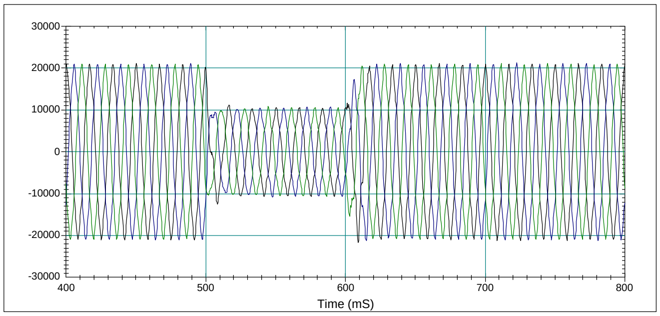

Figure 14. V_{lg} on 24 kV Side

At the onset of the sag, the drive input currents (Figure 15) discontinue for a short period of time. During this time, the dc bus voltage is always higher than the system phase-to-phase peak voltage. Therefore, all diodes of the rectifier bridge stop conduction. The input energy required by the motor is provided by the energy stored in the dc capacitor. The rectification resumes when the dc capacitor voltage is reduced to the system charging voltage level. In practice, undervoltage protection of the drive will trip the drive when its dc bus voltage goes down to a preset level. However, for the purposes of this investigation, it was assumed that the drive is maintained on-line for the entire disturbance duration.

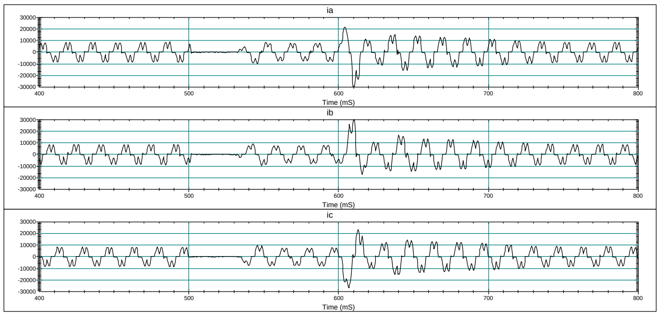

Figure 15. Drive Input Currents

Drive Load Transfer via Solid-State Switching

System load responses to the solid-state switching from the normal feeder to the backup feeder under balanced sag conditions are very similar to those under unbalanced sag conditions. The motor continues to operate smoothly and there is no significant speed or torque disturbances.

SUMMARY AND CONCLUSIONS

For Motor Load

Motors have an important effect on the voltage characteristics during a remote three-phase fault condition. Initially, the back EMF of the motors supports the voltage, reducing the severity of the sag in the vicinity of the motors. As the motors slow down, they draw increased currents that make the voltage sag more severe. When the sag ends, the motors draw an inrush current that prevents immediate recovery of the system voltage. This same phenomena also occurs for unbalanced voltage sag conditions, but not as severe. The exact response for a given system will depend on the sag severity and duration and number of phases affected.

For Drive Load

When motors are supplied through drives, the voltage support by the back EMF normally supplied by the motors does not occur because of the dc link separation. The high current draw during the sag and current inrush during recovery as seen for directly-connected motors are greatly restricted for drive-fed motors. Therefore, the drive-fed motors have less effect on system voltage sags.

However, a load consisting of drive-fed motors does have the tendency to equalize the distribution level phase voltage peaks under unbalanced voltage sag conditions. The sound phase is forced to provide more charging current than the affected phases.

Load Transfer via Solid-State Switching

For both motor and drive loads, 1/4 cycle load transfer can provide a very effective backup. For directly connected motors, this transfer can cause rotor speed and torque disturbances because of current transients. These transients should not be a concern in most applications due to their short duration. For drive loads, these problems do not exist. A successful load transfer needs a fast action and good synchronization.

REFERENCES

[1] 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, pp. 167-172, January 1991.

[2] M. McGranaghan, D. Mueller, and M. Samotyj, "Voltage Sags in Industrial System," IEEE Transactions on Industry Applications, vol. 29, no. 2, March/April 1993.

[3] J. Lamoree, D. Mueller, P. Vinett, and W. Jones, "Voltage Sag Analysis Case Studies," Paper presented at the IEEE I&CPS Conference, St. Petersburg, Florida, June 3-6, 1993.

[4] E. Gunther, J. Thompson, and H. Mehta, "Monitoring Power Quality Levels on Distribution Systems," Paper presented at the Second International Conference on Power Quality: End-Use Applications and Perspectives, Atlanta, Georgia, September 28-30, 1992.

[5] S. Chattopadhyay, and T. Key, "Predicting Behavior of Induction Motors During Electrical Service Faults and Momentary Voltage Interruptions," Paper presented at the IEEE I&CPS Conference, St. Petersburg, Florida, June 3-6, 1993.

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