Power System Harmonic and Transient Measurements - Know What to Expect

W. Edward Reid
Member, IEEE
Qual-Tech Engineers, Inc.
201 Johnson Road – Suite 203
Houston, PA 15342

Kevin A. Puskarich
Non-Member, IEEE
Qual-Tech Engineers, Inc.
201 Johnson Road – Suite 203
Houston, PA 15342

Abstract - Technology advancements in measuring equipment have made it possible to easily obtain a wealth of information about events on the power system. Coincidentally, it is possible to easily obtain inaccurate information or to misapply it. To solve problems efficiently and accurately this information must be obtained and used wisely. This paper discuses and illustrates the importance of knowing what to expect when making power system harmonic and transient measurements. Since these types of measurements are often associated with problem solving, it is important to combine the measurements with other information and analysis to obtain the maximum benefit. This includes obtaining as much historical documentation of the events of concern and the system as possible. In addition, it is essential to know what to expect when making the measurements and, then, to understand the measurements once they are made. Simulations coupled with the measurements can add a high degree of confidence to the analysis of the problem at hand. Case histories are given to illustrate the benefit and the importance of knowing what to expect when making power system harmonic and transient measurements.

1. INTRODUCTION

Knowing what to expect is important both for making field measurements and simulations. It is especially beneficial when the measurements and simulations can be tied together such that one verifies the other. A number of examples are given in this paper where this has been done.

Power system electrical measurements are usually made for one of the following reasons:

1. There has been a problem which is often associated with equipment failure or equipment misoperation.
2. It is planned to make changes to the system, and documentation of the existing conditions is desired before the changes are made.
3. Documentation of existing system conditions is made as a part of general maintenance and planning.

The most common reason for making power system measurements is generally to investigate a problem associated with equipment failure or misoperation. The failure or misoperation of electrical equipment can have a significant effect on production and the revenues generated by a given facility. When the same or similar problem appears to be reoccurring periodically, it may be a system problem rather than one associated with a particular piece of equipment. Sometimes a more in-depth analysis indicates that there are repetitive problems with other equipment as well. Repetitive problems could include any number of different events, but some of those are: scr failures, spurious fuse blowings, unexplained circuit breaker trips, transformer overheating when the load does not appear to be excessive, motor overheating, motor contactors dropping out, misoperation of electronic equipment, and equipment failures.

[Presented at a panel session at the 1999 IEEE/PES Transmission and Distribution Conference, New Orleans, Louisiana, April 15, 1999]

System conditions that may cause some of the above problems are: momentary low voltage, excessive voltage or current distortion, capacitor bank switching, switching of other equipment, lightning surges, misoperating switches or circuit breakers, and inadequate grounding.

In trying to solve a failure or misoperation problem, documentation is very important. The key parts of the documentation are (1) the details of the problem and (2) the details of the system.

2. EVENT DOCUMENTATION

When a problem occurs, there is usually a lot of information available. The key is to document that data and combine it with experience and analytical capabilities to solve the problem. The following guidelines can help to expedite this process:

1. The person who has been most directly involved in the problems knows a lot of information, but he or she may not always realize the importance of some of those facts. It is important to get as many details as are available.
2. Write down as much information as possible about a problem soon after it occurs. As time passes, the facts tend to change. Include such information as time of day, date, weather, and any other event which happened simultaneously, such as the opening or closing of a certain switching device. When events occur in fractions of a second, it is not necessarily obvious what occurred first.
3. In piecing together the facts, what overcurrent devices operated or didn't operate can be very important. That should be noted at the time of the event.
4. If an experienced person is to be brought in to help in solving the problem, it is best to do that as soon after a problem has occurred as possible. If equipment damage has occurred, it is desirable for that person to inspect the

damage prior to it being cleaned up and repaired. (Pictures of the damage can be invaluable.)

5. If the problem is repetitive and does not cause significant damage, field measurements may be appropriate. If the event causes severe damage every time it occurs, trying to record it again may not be desirable or practical.

3. SYSTEM DOCUMENTATION

It is important to define the details of the electrical system. The following guidelines can help to expedite the process:

1. Obtain, update, or create an accurate one-line diagram of the electrical system and nameplate data of key equipment. This is essential information to efficiently determine a solution to the problem.
2. Obtain schematic drawings for any piece of equipment that misoperated or failed.
3. Determine what has changed about the system that may have coincided with the beginning of the problem.

4. INDUSTRY STANDARDS AND PRACTICES

Knowing industry standards and practices can be helpful in solving a problem. Some references which may be helpful in this area are listed at the end of this document. Some references to key standards are also given in those documents. [1 to 7]

5. SIMULATIONS

Depending upon the information available, it may be helpful to simulate what has occurred to attempt to explain the problem. This may involve harmonic simulations and/or transient simulations. The combination of simulations and field measurements can vary from problem to problem. In a given case, it may be necessary to only do simulations or to only make field measurements. Doing simulations can be helpful in knowing what to expect when making field measurements. It could also determine how the measurements are made and with what equipment.

6. FIELD MEASUREMENTS

If after evaluating the available information, it is not clear exactly what happened and it is reasonable to believe that the event could occur again, then making field measurements could be helpful in solving the problem. It is helpful to have an idea of what to expect before measurements are made. If something different occurs, it is advisable to take time to understand why there is a discrepancy. Sources of discrepancies can include instrumentation problems, power system equipment misoperation, and lack of understanding of the event. Making measurements, collecting a wealth of information, and determining what it means at some later time can be risky. It is generally not reasonable to analyze every piece of information while the measurements are being made; however, some checking should be done to have reasonable assurance that the information being collected is accurate. The key is to be thinking during every step of the process. Do not just take data without thinking.

7. HARMONIC CASE HISTORIES

Several case histories are given below to illustrate the benefit of making accurate power system harmonic measurements and the importance of knowing what to expect. This includes understanding the system as well as what distortion levels to expect to see during the measurements. Simplified example one-line diagrams are given to illustrate the key points of each case where it is appropriate. Detailed discussions of each case are not given in this paper. Cases A, D, E, and F illustrate conditions where accurate field measurements helped in developing good system models to be used in solving problems. Cases B and C describe conditions where knowing what to expect led to an awareness that the measurements were not reflecting true system conditions.

Case A

A simplified system diagram is given in Figure 1 for a system that has a significant number of 15 kV cables. The application of a large drive resulted in higher than expected voltage distortion on the system due to a system resonance with the cable capacitance. Harmonic measurements were made and simulations of the system were done to determine an appropriate method for reducing the harmonic distortion.[7]

The calculated impedance scan of the system is given in Figure 2. This was calculated based on a detailed model of the system. The system impedances calculated from the harmonic measurements are indicated by the x's. A good match was obtained which verified the accuracy of the computer model. To obtain a good match like this requires detailed knowledge of the system, especially the significant capacitances. In this case the impedance characteristic was significantly influenced by the 15 kV cable capacitance, several capacitor banks throughout the system, and the 138 kV transmission line capacitance.

An 11th harmonic high-pass filter was designed for this application. A comparison of the impedance scans without and with the filter are illustrated in Figure 3. Simulations of the voltage waveform without and with the filter are given in Figures 4 and 5 respectively. This was done using a transient analysis program. The comparison of the measured waveforms with the simulated ones is again quite good.

Case B

On one occasion, it was observed during the making of harmonic measurements that after a certain motor started, the system voltage dropped and the harmonic distortion increased. These are generally reasonable results except that the changes in voltage and distortion seemed to be excessive. After some investigation, it was determined that the PT, where the measurements were being made, was not making a good connection. The motor was near to where the PT was located and when it was running, it created enough of a vibration to vibrate the PT connection, resulting in erroneous results.

Case C

Existing bus PT's are commonly used for making harmonic measurements. Their frequency response is generally adequate beyond 3000 Hz. Occasionally, however, there may be devices fed by a PT which may affect the measured distortion values. It is important to keep this in mind and to be sure that what is being measured makes sense.

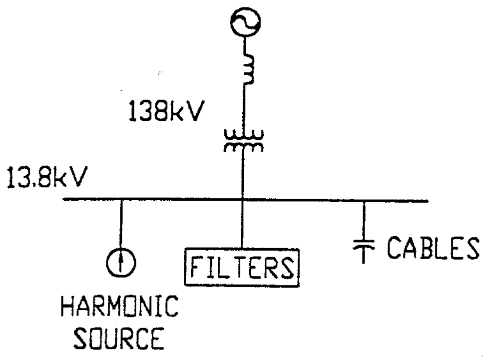


Figure 1: Case A - Simplified System Diagram

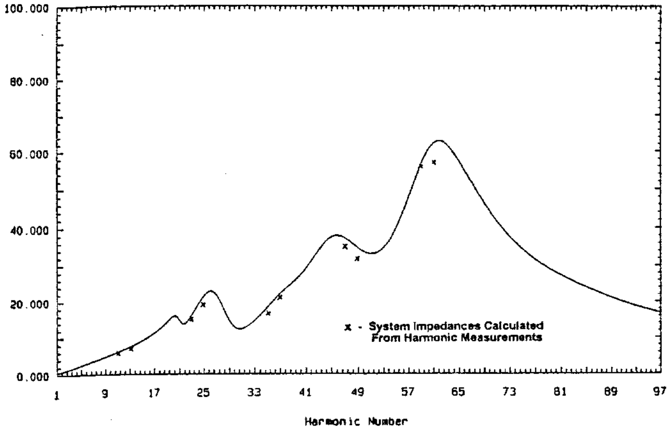


Figure 2: Case A - Impedance Scan & Measured Impedances

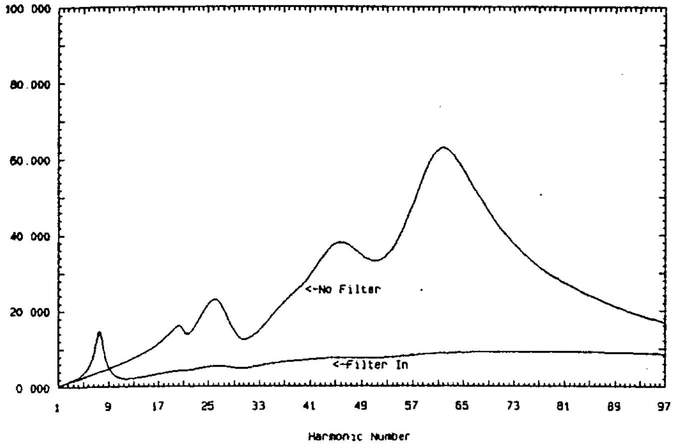
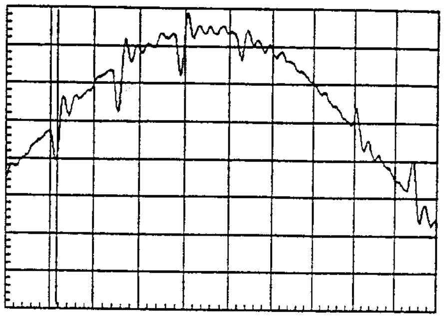
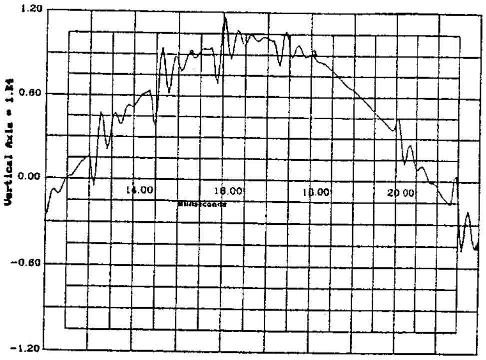


Figure 3: Case A - Impedance Scan Without & With Filter

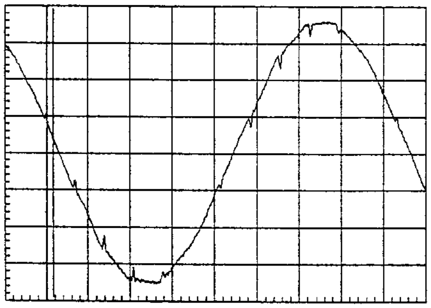


Measured Voltage Waveform

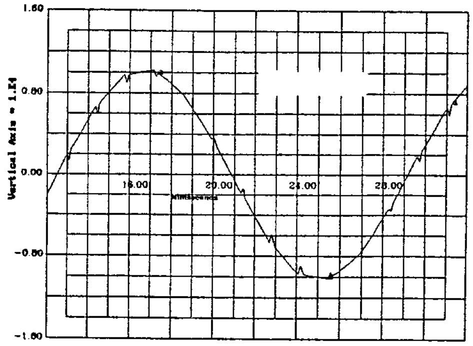


Simulated Voltage Waveform

Figure 4: Case A - Voltage Waveforms Without Filter



Measured Voltage Waveform



Simulated Voltage Waveform

Figure 5: Case A - Voltage Waveforms With Filter

Case D

A simplified system diagram is given in Figure 6 for a system that has a significant number of 15 kV and 138 kV cables. The application of large drives necessitated the application of harmonic filters to control the distortion to acceptable levels.

The calculated impedance scan of the system at Bus #1 without the filters is given in Figure 7. The two major resonances are evident. The system impedances calculated from the harmonic measurements are indicated by the x's. The lowest harmonic that was significantly above the background distortion was the 11th harmonic. A good match was obtained which verified the accuracy of the computer model. The calculated impedance scan at Bus #2 with the filters in is given in Figure 8. Again the impedance match is quite good between the measurements and the simulations which gives a high level of confidence to the analysis results. The analysis would include simulations of conditions that could not be measured, especially with regard to determining methods to reduce the harmonic distortion.

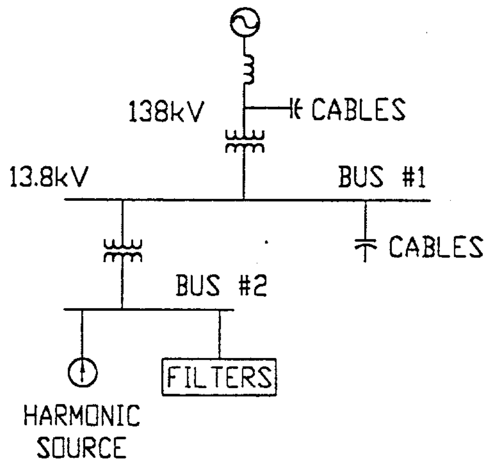


Figure 6: Case D - Simplified System Diagram

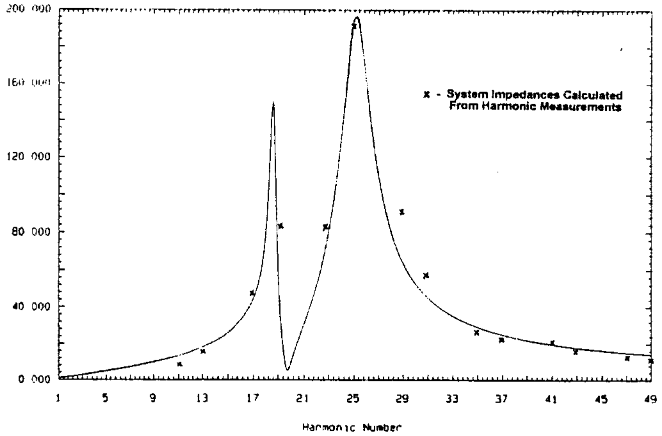


Figure 7: Case D - Bus #1 Impedance Scan Without Filters

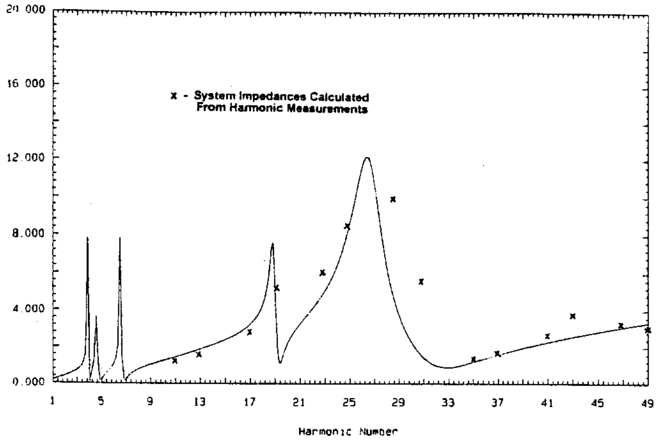


Figure 8: Case D - Bus #2 Impedance Scan With Filters

Case E

The example shown in Figure 9 is fairly complex with many capacitors throughout the system whose switching status may not always be known. An impedance scan at the location of the harmonic source without the filters is illustrated in Figure 10. The measured impedance ranges are indicated by the vertical lines.

The calculated system impedances for Cases A and D were very balanced among the phases. For Case E the variations are greater as indicated by the vertical lines in Figure 10. This is due to the unbalances of the untransposed transmission lines. This is especially evident at the resonance condition near the 47th and 49th harmonics.

Although the match between the calculated and measured impedances is good, it is not as good as it was for Cases A and D. This is due to some uncertainty in some of the system data, especially the status of the 13.8 kV capacitors. In this particular case, the match was quite adequate to solve the problem at hand. In some cases it is not reasonably possible to know all of the detailed information that one would prefer, and a judgment must be made with regard to what is adequate information to solve the given problem.

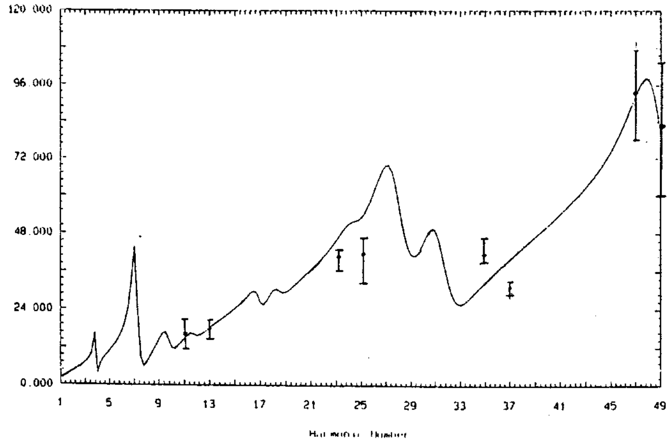


Figure 10: Case E - Impedance Scan

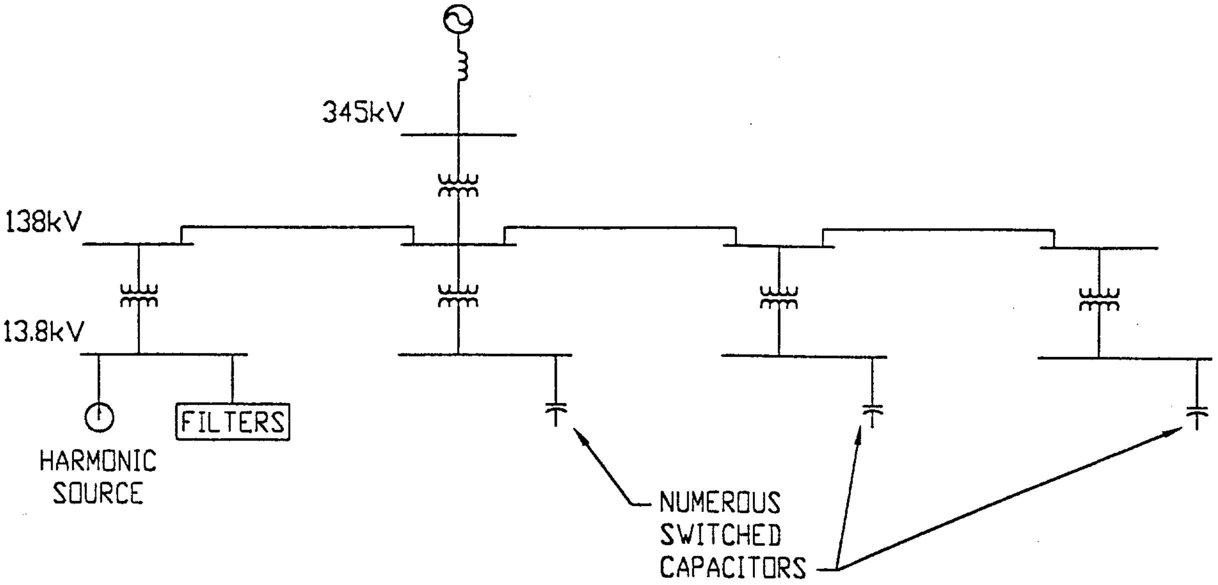


Figure 9: Case E - Simplified System Diagram

Case F

In Figures 11 and 12, harmonic currents are illustrated for two 5th harmonic filter banks that were connected to the same system. Each filter bank had three steps. The voltage distortion on the system was quite low at less than 2.5%, and the system was operating normally. There was no indication of a problem. The measurements given in Figures 11 and 12 were made during the course of taking background measurements for consideration in making future changes to the system. The predominant harmonic current for filter bank #1 is the 5th harmonic. The predominant harmonic current for filter bank #2 is the 17th harmonic. The distortion level was quite low; however, this difference in currents was not expected. The filter banks were deenergized, inspected, and tested. It was found that several of the reactors in filter bank #2 were shorted. With the reactors shorted, the result had been a resonance near the 17th harmonic. If this condition had continued to go on undetected, it could have led to a more significant failure event in the future.

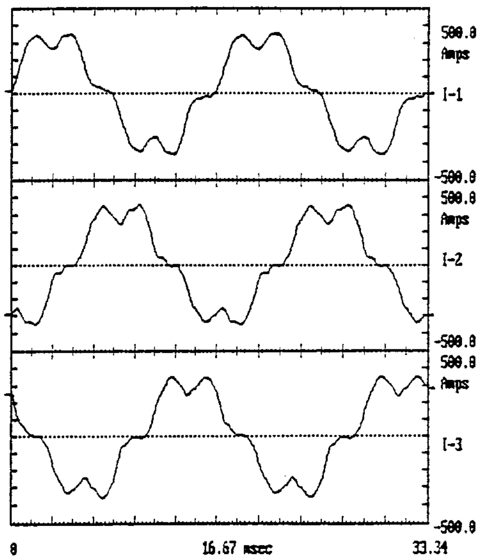


Figure 11: Case F - Filter Bank #1 Currents

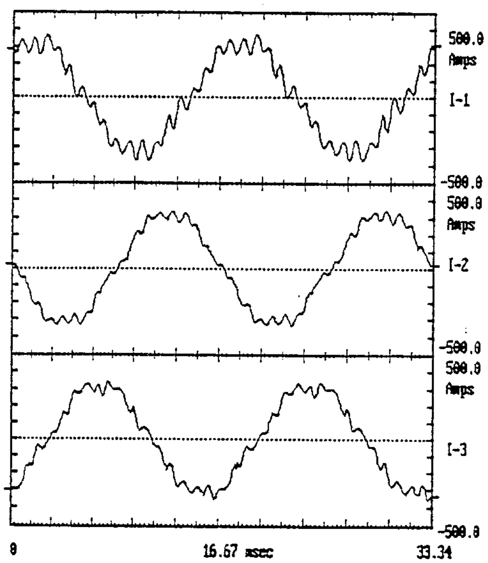


Figure 12: Case F - Filter Bank #2 Currents

8. TRANSIENT CASE HISTORIES

Several case histories are given below to illustrate the benefit of making accurate power system transient measurements and the importance of knowing what to expect. This includes understanding the system as well as what transient levels to expect to see during the measurements. Simplified example one-line diagrams are given to illustrate the key points of each case where it is appropriate. Detailed discussions of each case are not given in this paper. Cases G, I, and J illustrate conditions where accurate field measurements helped in developing good system models to be used in solving problems. Cases H describes a condition where knowing what to expect led to an awareness that the measurements were not reflecting true system conditions.

Case G

The phase shifting transformer shown in Figure 13 failed coincident with the energization of the 50 Mvar capacitor bank which was 34.5 miles away.[2] The inspection of the phase shifter indicated that the failure was a phase-to-phase fault. Simulations of the system and subsequent measurements indicated that transients in access of the 650 kV BIL rating of the transformer were possible. A comparison of simulations and measurements is given in Figures 14 and 15, respectively. To accomplish a duplication of this accuracy required a good model of the 500 kV system as well as the 230 kV system. This good duplication allowed solutions to be evaluated with a high degree of confidence in the results. (See Reference 2 for the detailed evaluation.)

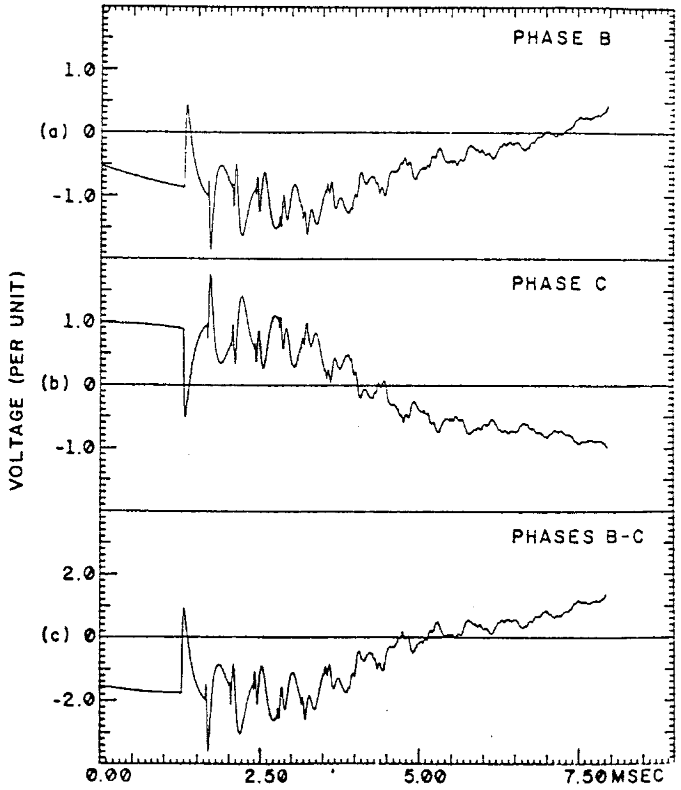


Figure 14: Case G - Simulated Voltages at Phase Shifter

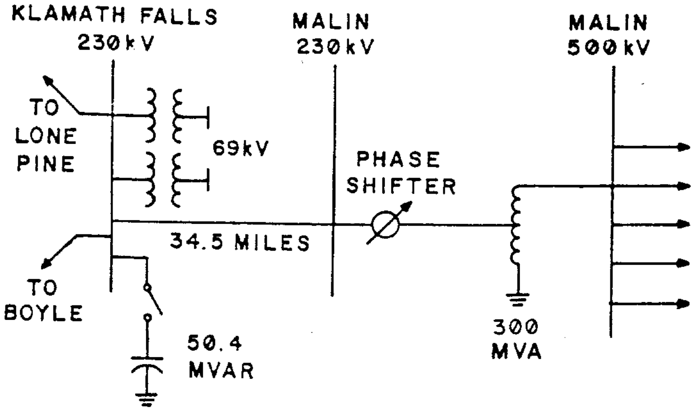


Figure 13: Case G - System Diagram

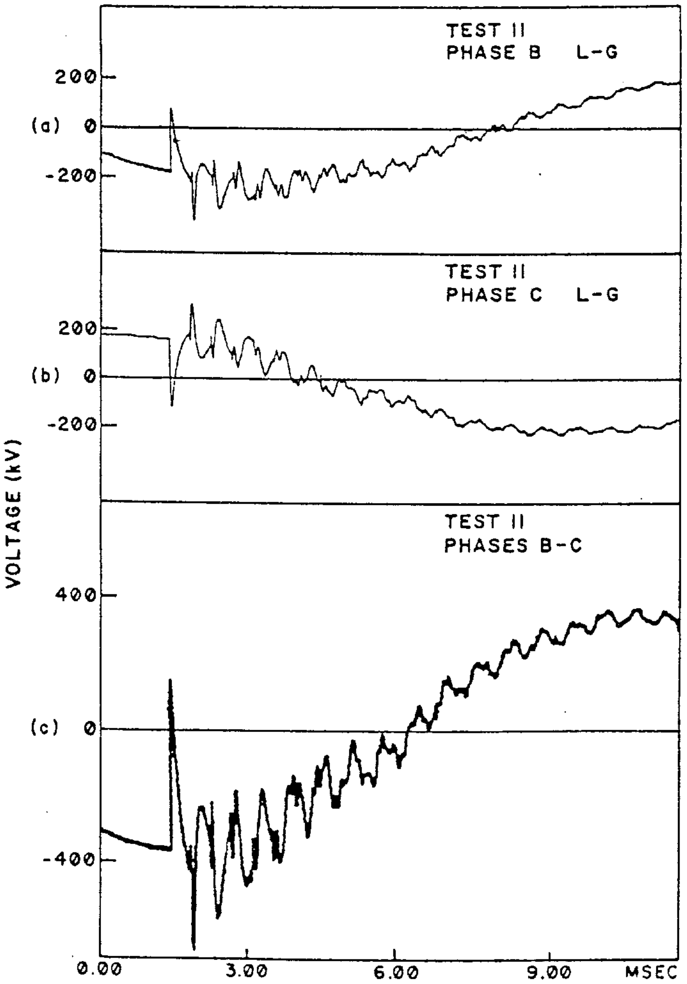


Figure 15: Case G - Measured Voltages at Phase Shifter

Case H

For the system shown in Figure 16, a large motor was connected to Bus #1. That motor was experiencing unexplained undervoltage trips. Measurements were made at Bus #1 and Bus #2. An example of a measured voltage dip is given in Figure 17. An example of the bus voltage and the motor current during the dip is shown in Figure 18. The motor current did not change although the voltage change was quite significant. Measurements at Bus #2 did not show any evidence of the voltage dip measured at Bus #1. The measurements seemed to point to a problem with the metering circuit. In fact, it was determined that the PT feeding the undervoltage relay from which the measurements were made had a loose connection which was causing the erroneous trip of the motor.

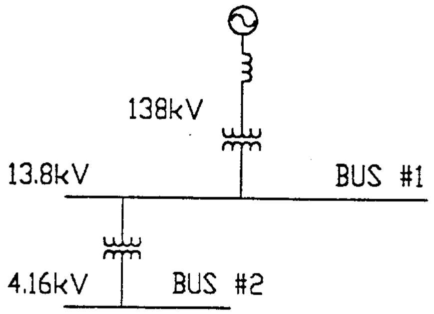


Figure 16: Case H - Simplified System Diagram

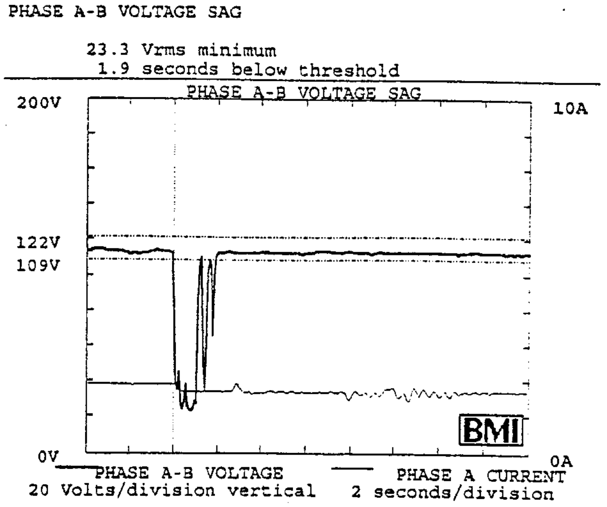


Figure 17: Case H - Measured Voltage Dip

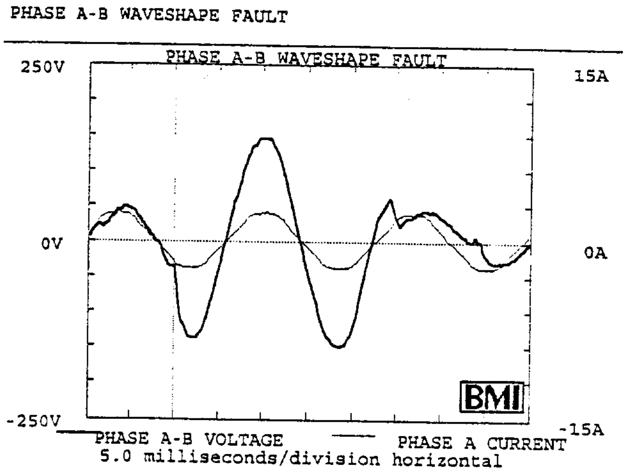


Figure 18: Case H - Measured Voltage & Current Waveforms

Case I

Figure 19 is an example of a surge protection circuit for an arc furnace application. Arc furnace transformers are often switched over 50 times per day. To minimize the transients upon opening, many arc furnace transformers are equipped with surge capacitors as illustrated in the figure.

An example of the measured transient recovery voltages (TRV's) in such an application is given in Figure 20. The phase C current extinguishes first, exhibits a reignition, extinguishes again, has another reignition, and then clears successfully in approximately another 5 msec. Phases B and A clear without reignitions. This sequence of events was simulated and is illustrated in Figure 21. From the simulations it is clear that the high magnitude transient that is evident in the measurements at the reignition is not a real power system transient. Being able to duplicate these types of measurements allows one to investigate other switching scenarios and system changes with a high level of confidence in the accuracy of the results.

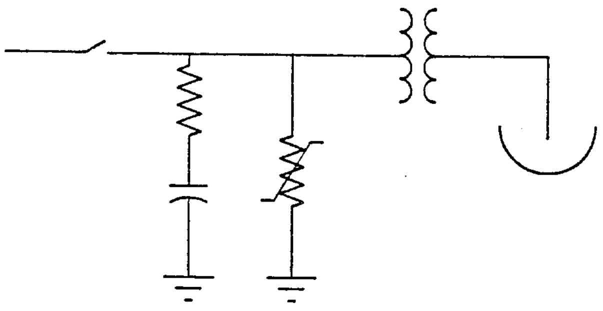


Figure 19: Case I - Example Arc Furnace System

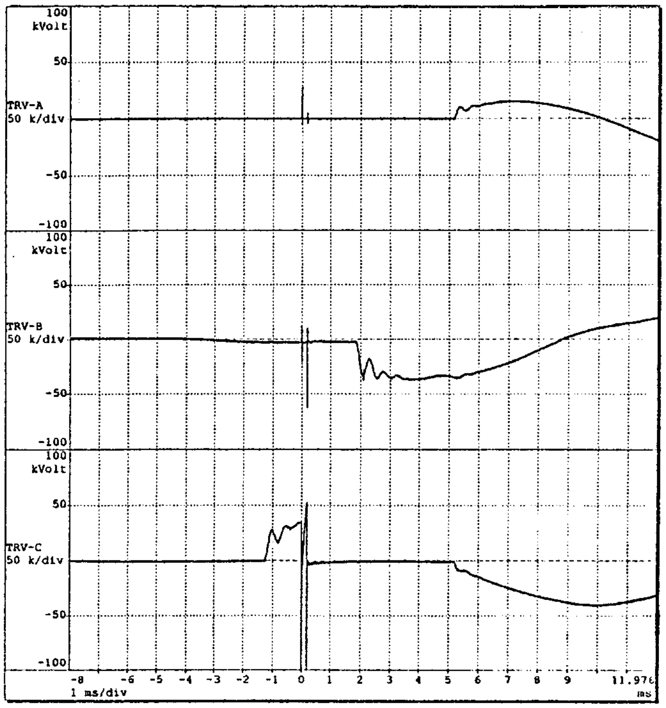


Figure 20: Case I - Measured Switch TRV

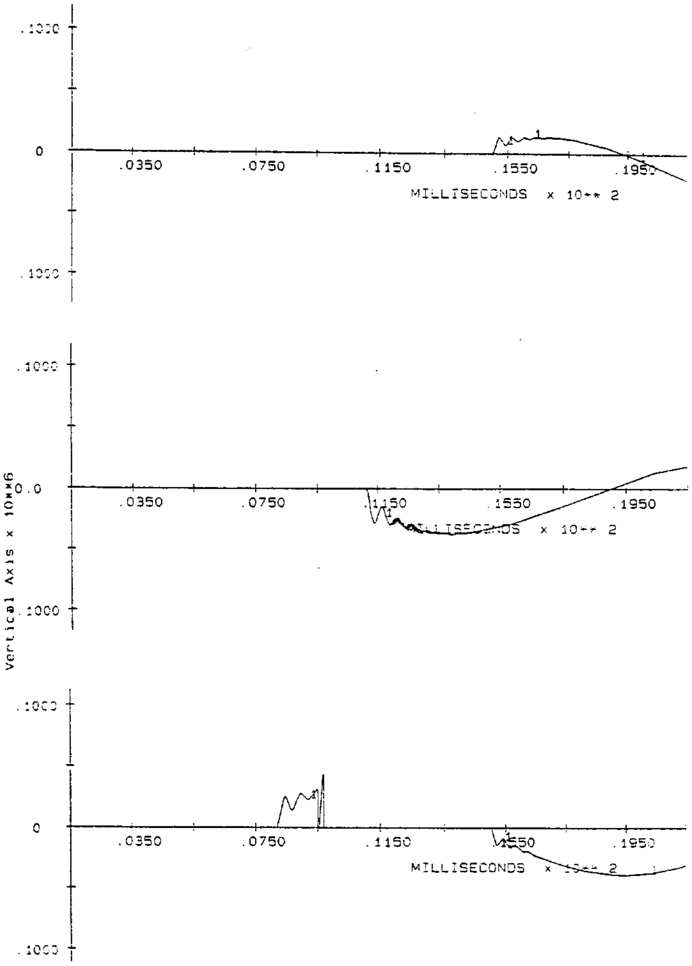


Figure 21: Case I - Simulated Switch TRV

Case J

In Figure 22 is a typical circuit for an ungrounded-wye, single-tuned filter bank. Currents which were measured during the opening of a switching device on a filter bank of this type are given in Figure 23. The 5th harmonic current content is evident in all three phases. The phase A current extinguishes for approximately 2 msec. and then it reignites. It conducts current for 2 cycles of the 5th harmonic current and extinguishes again. It reignites for the second time, conducts for 1/2 cycle of the 5th harmonic current, and clears successfully. Phases B and C clear successfully a short time later. The filter bank neutral voltage is plotted with each capacitor current.

A good simulation of the three currents is given in Figure 24. In this case the simulations were set up to determine the transient voltages on the capacitors and at other points on the system that were not monitored during the measurements.

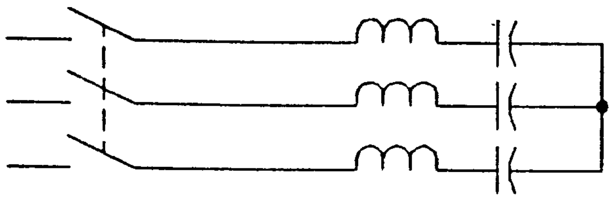
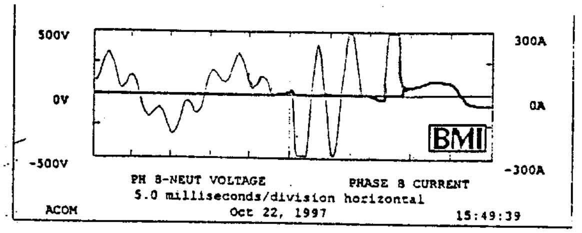
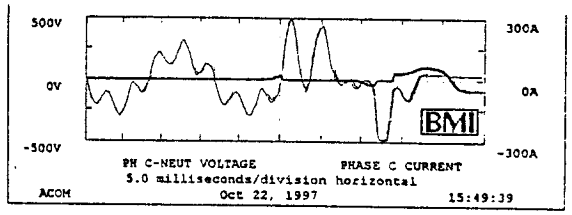


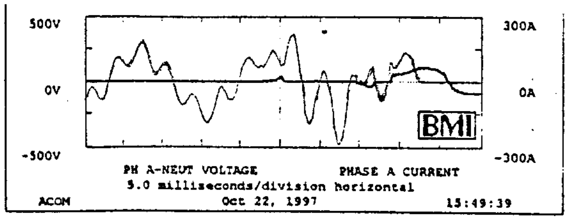
Figure 22: Case J - Example Filter Bank



Phase A

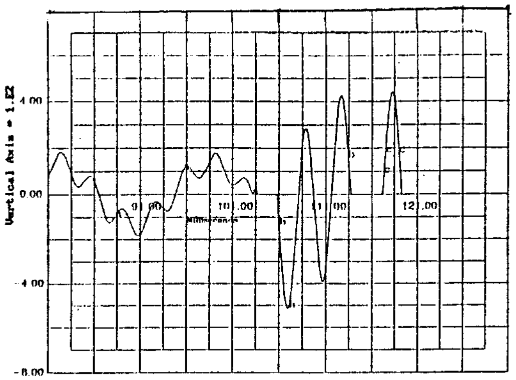


Phase B

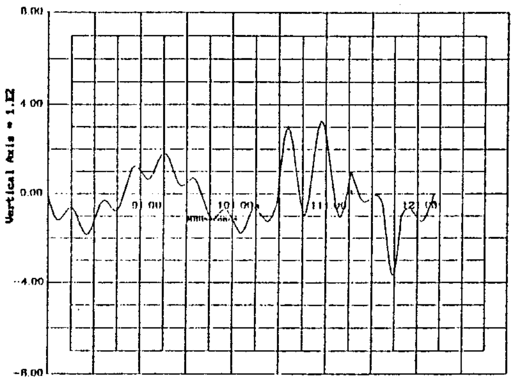


Phase C

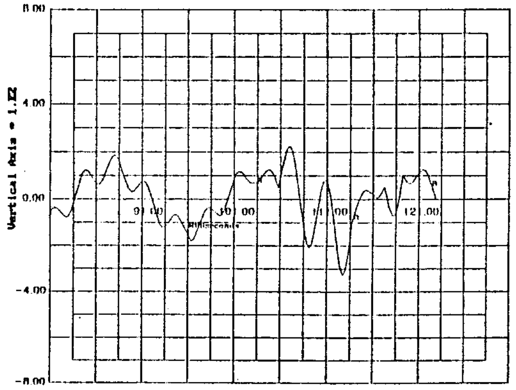
Figure 23: Case J - Measured Filter Currents



Simulated Current - Phase A



Simulated Current - Phase B



Simulated Current - Phase C

Figure 24: Case J - Simulated Filter Currents

9. CONCLUSIONS

Based upon the discussion given in this paper, the following guidelines are noted with regard to using field measurements to determine solutions for failure and misoperation problems:

1. Document the details of the problem and the details of the system.
2. Know industry standards and practices.
3. Use accurate field measurements to develop accurate system models to be used in solving problems where it is appropriate.
4. Prepare for field measurements by knowing what to expect in the measurements so that discrepancies and unusual findings can be quickly identified.
5. Understand the limitations of the simulation model and the measuring equipment. Know what you have assumed and what you have neglected.

10. REFERENCES

[1] M.F. McGranaghan, W.E. Reid, S.W. Law, D.W. Gresham, "Overvoltage Protection of Shunt-Capacitor Banks Using MOV Arresters", *IEEE Transactions on Power Apparatus and Systems,* Vol. PAS 103, pp. 2326-2336, August 1994.

[2] R.S. Bayless, J.D. Selman, D.E. Truax, W.E. Reid, "Capacitor Switching and Transformer Transients", *IEEE Transactions on Power Delivery*, Vol. 3, No. 1, pp. 349-357, January 1988.

[3] W.E. Reid, "Capacitor Application Considerations - Utility/User Interface", Panel Session on Capacitor Bank Design and Application, IEEE/PES T&D Conference and Exposition, New Orleans, LA, April 1989. Also presented at the 1991 Pulp and Paper Industry Technical Conference (Paper CH2973-6/91/0000-0070).

[4] P.B. Steciuk, K.A. Puskarich, W.E. Reid, "Harmonic Considerations on Low Voltage Systems", Proceedings of IEEE 1991 Textile, Fiber, and Film Industry Technical Conference, Also presented at the Fourth International Power Quality Conference, September 22-27, 1991, Universal City, California.

[5] W.E. Reid, K.A. Puskarich, "Harmonic Filter Application Criteria", Presented at Panel Sessions at the IEEE/PES 1994 Winter Power Meeting, New York, New York, February 2, 1994 and the 1994 Summer Power Meeting, San Francisco, CA, July 28, 1994.

[6] W.E. Reid, "Power Quality Issues - Standards and Guidelines", IEEE Transactions on Industry Applications, Vol. 32, No. 3, pp. 625-632, May/June 1996.

[7] K.A. Puskarich, W.E. Reid, P.S. Hamer, "Harmonic Experiences With A Large Load Commutated Inverter Drive", to be presented at the IAS Petroleum & Chemical Industry Technical Conference, San Diego, CA, Sept. 13-15, 1999.

11. BIOGRAPHIES

W. Edward Reid is Director, Analytical Studies with Qual-Tech Engineers, Inc. of Pittsburgh, PA. He has over 25 years of experience in electrical power system analysis. This has included system design, insulation coordination, harmonics, transients, load flow, short circuit, overcurrent coordination, and specialty field measurements. His experience has contained a special emphasis on problem solving including shunt and series capacitor applications, filter design from low voltage industrial to HVDC applications, equipment insulation failures, switchgear transient recovery voltage considerations, power quality and power outage problems, and equipment application considerations. He has taught seminars and undergraduate classes on several of these topics related to electrical power system applications. He has had extensive experience in series and shunt capacitor applications and was the Chairman of the IEEE Capacitor Subcommittee. He also is or has been a member of the IEEE Power Engineering Society, T&D Committee, IEEE Pulp and Paper Committee, Working Group on Transient Recovery Voltages, Harmonics Working Group, Transformer Task Force on External Clearance Requirements, Insulation Coordination Subcommittee, and Standards Coordinating Committee 22 on Power Quality. He has co-authored over 15 technical papers.

Kevin A. Puskarich is a Senior Power Systems Engineer with Qual-Tech Engineers, Inc. of Pittsburgh, PA. He has over 15 years of experience in the analysis of industrial and utility electrical power systems. His primary areas of experience have included transient and harmonic analysis to determine equipment ratings, operating procedures, and equipment protection schemes, as well as to perform equipment failure analysis. Analysis tools have included transient network analyzer, digital computer programs, and field measuring equipment. He has also been involved in the development of electronic models of power system equipment, electrical power system design, and software development. The power system studies have included harmonic filter design, harmonic and transient field measurements, short circuit and coordination analyses, arc furnace studies, shunt and series capacitor applications, static var systems, transmission line switching, and HVDC applications.