Analysis of Harmonics, Flicker and Unbalance of Time-Varying Single-Phase Traction Loads on a Three-Phase System

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***Abstract*— The system impact of a new transit substation may include harmonic distortion, voltage unbalance and flicker. The Metro North commuter train system in Connecticut is powered from 27 kV single-phase transformers through overhead trolley conductors with a return through the rail and a separate feeder conductor. The single-phase transformers are tapped from three-phase 115 kV transmission lines. The planned installation of a new train substation made a power quality study necessary. Measurements of harmonics, flicker and voltage unbalance were taken at a similar substation over a 24 hour period, and at a nearby transmission substation over a month. Statistical analysis of the measurements showed that the Metro North train load produced significant levels of third harmonic current, in excess of IEEE 519 limitations. System simulations were performed to determine the harmonic resonance points of the power system at the planned substation. Simulation results showed that installation of a third harmonic filter would reduce harmonics to within acceptable levels. The decision as to whether to install a harmonic filter is a difficult one. Unbalance and flicker were found to be negligible.**

Keywords-- Rail transportation power systems, Harmonic analysis, Power quality.

I. Introduction

THE impact of a single-phase nonlinear load on a three-phase high voltage transmission system has been extensively studied. [1,2,3] Nonetheless, the evaluation of individual cases is necessary due to the wide variety of loads and the power systems to which they are connected. The system to be discussed in this paper is an ac railway line used primarily for commuter trains out of New York City (Metro North), as well as intercity trains (Amtrak) between New York and Boston. The railway load is characterized by three factors:

1. Harmonics produced by power converters on the trains.
2. Phase unbalance caused by the single-phase nature of the load.
3. Flicker, caused by the rapidly varying load as trains accelerate.

Solutions to harmonics problems are either active [1,3] or passive [4] filters, which are applied on the supply to the train load. Transformer connections [2] or Static Var Controllers (SVC) may be applied to limit unbalance. Flicker can also be controlled by SVC application.

The Metro North lines in Connecticut [5] are configured as a three-wire trolley-feeder-rail system Fig. 1. The single-phase taps are connected the same two phases for each substation feeding the same section of track. Where sections meet which are fed by different phases, there is an insulated "phase break" in the track. The autotransformers are designed to reduce the flow of return current in the rails and ground and confine it to the areas around the trains. From the point of view of the power system, the load is carried between the trolley and feeder.

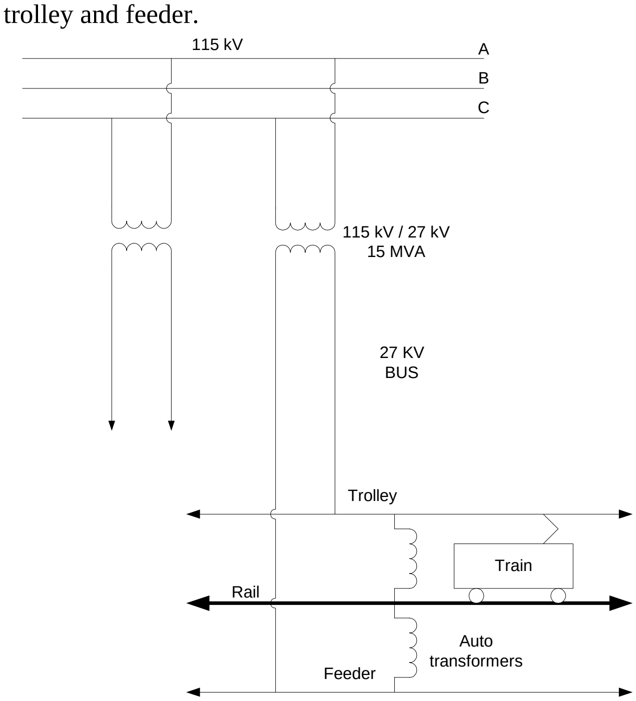

Fig. 1. Typical three-wire distribution substation and structure of rail line distribution. Circuit breakers and switches are omitted for clarity.

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In the system to be studied, a new substation is to be added at New Haven, which will be similar to the existing substation at Devon in terms of loading, as it will be on the same phase section of track. In order for the utility connection to be approved, the new substation must not introduce harmonic, voltage unbalance or flicker problems. The first step in the project was to take measurements at the existing 27 kV substation in order to ascertain the harmonic characteristics of the train load, as well as the load variation. Additional measurements were taken at 115 kV to obtain the background system levels of harmonics, unbalance and flicker. The analytical work consisted first of constructing a harmonic model of the power system. From this, frequency scans were used to ascertain the impedance vs. frequency characteristics and thus the resonance points. Harmonic voltage and current calculations were made to determine whether the injected harmonic currents from the train loads caused unacceptable overvoltages at the point of common coupling (PCC). The simulations were carried out for full load conditions, 50% and 25% load, and with existing harmonic filters at Branford RR and the Cross Sound Cable on and off-line.

II. Measurements

A. Harmonic Measurements

The power quality measurement instrument was connected to record both current and voltage on a single-phase branch at the Devon substation. The Point of Common Coupling (PCC) for IEEE 519 analyses is the 115 kV bus where the single-phase transformers for Metro North are connected. The 15/20/25 MVA single-phase transformer is connected phase-phase on the 115 kV line. Measurements were taken at the 27600:115 VTs and 1200/5 CTs on the transformer secondary circuit. Measurements were in place for approximately 24 hours. This enabled capture of both the morning and evening rush hours and the nighttime storage of trains at New Haven.

The rms harmonic current I_{HRMS} stayed below 73 A 95% of the time (Fig. 2 and Fig. 3). The harmonic current injections used in the simulation were based upon the 73 A I_{HRMS}.

The Voltage THD at 27 kV stayed below 3.3% 95% of the time (Fig. 4 and Fig. 5). Because individual harmonic currents were only sampled, the maximum sampled currents were used in this evaluation. Measurements taken at a nearby 115 kV bus showed Voltage THD below 1% for all days measured. An example histogram from a 24-hour period is shown in Fig. 6. Neither of these measurements was at the PCC, but the 115 kV measurements were electrically closer to it. These results indicate that there are no concerns about pre-existing harmonics in the transmission system.

In order to apply IEEE 519 current limits, the base load current I_L must be determined. This is defined as the average of the maximum monthly demand over the previous 12 months. The value used was taken from projected 2010 load demand values.

The other factor required for IEEE 519 current comparisons is the short circuit ratio, I_{SC}/I_L, where I_{SC} is the minimum three-phase fault current. In this system, the short circuit ratio was calculated to be nearly 400.

The results of this comparison indicate that the third harmonic limit is substantially exceeded (16% vs. 6%), which would continue to be the case under any reasonable variations of the values of I_{SC} and I_L. This, in turn, drives the TDD (17% vs. 7.5%).

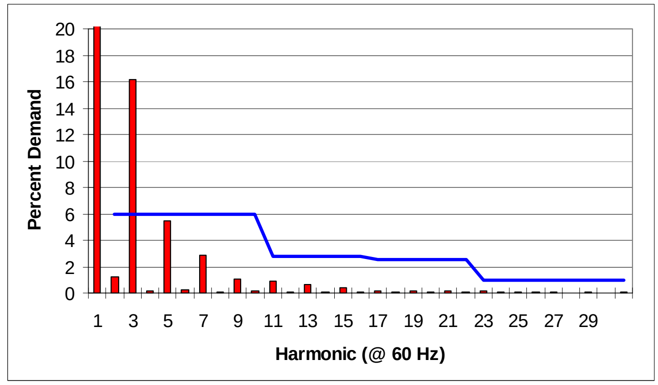

Fig. 2. Harmonic current measurements of railway load compared to IEEE 519 limits.

B. Voltage unbalance

Negative sequence voltage unbalance can be calculated from measurements by taking the ratio of negative sequence to positive sequence voltage. The negative sequence voltage unbalance derived from measurements can be compared to calculated values. Fig. 7 shows the characteristics of negative sequence voltage unbalance at 115 kV, where the average value is 0.3%, and the maximum 0.8%. The recommended limit for voltage unbalance (defined as the ratio of maximum deviation over average voltage) is 3%, according to ANSI C84.1-1995. Although the standard uses a different definition than the measurement data is framed in, the difference between the two is normally slight, and these results can safely be compared to the 3% standard. The measured voltage unbalance is well within acceptable limits.

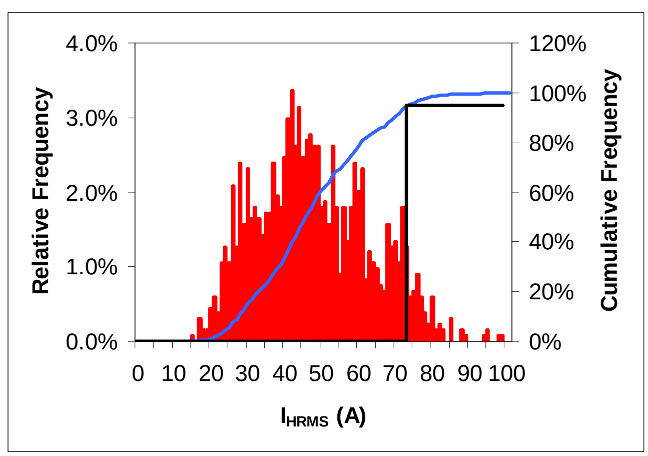

Fig. 3. Histogram of 24 hours measurement of I_{HRMS} showing 95% probability of at least 73 Amperes rms harmonic currents.

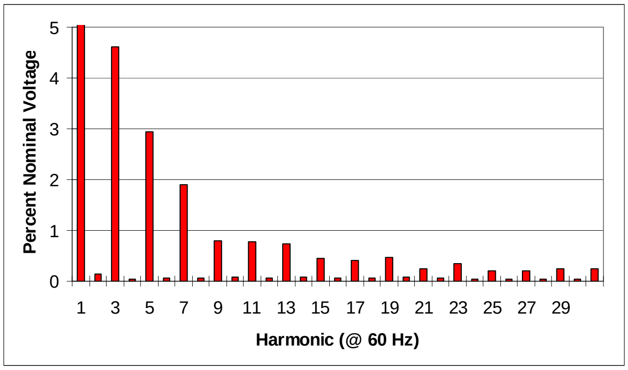

Fig. 4. Harmonic voltage measurement results at 27 kV railway bus.

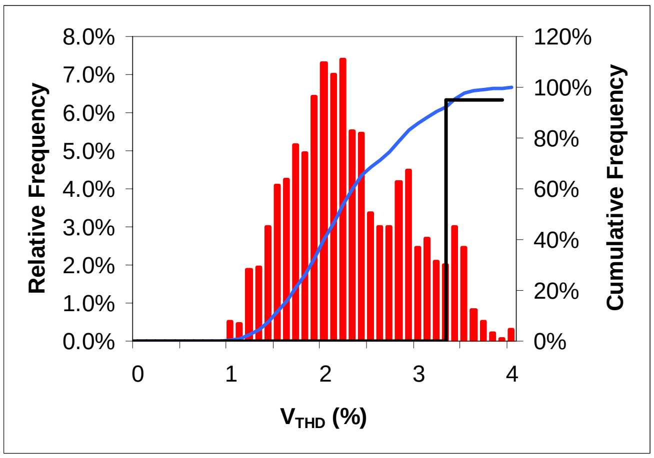

Fig. 5. Histogram of 24 hours measurement of Voltage THD at 27 kV showing 95% probability of THD being as much as 3.4%.

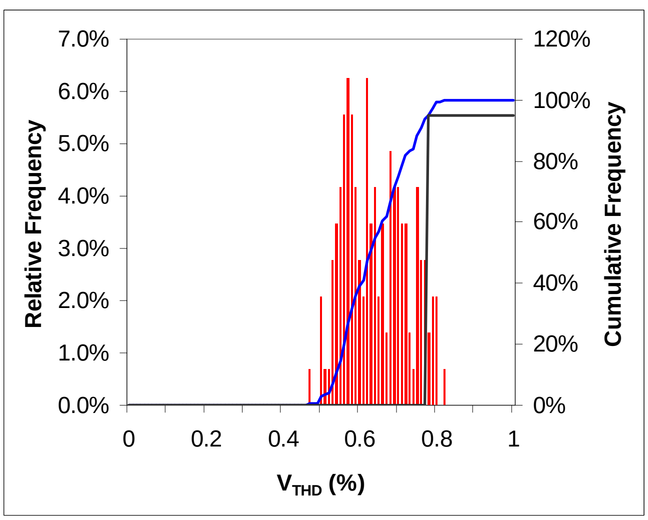

Fig. 6. Histogram of 24 hours measurement of Voltage THD at 115 kV showing 95% probability of THD being as much as 0.78%.

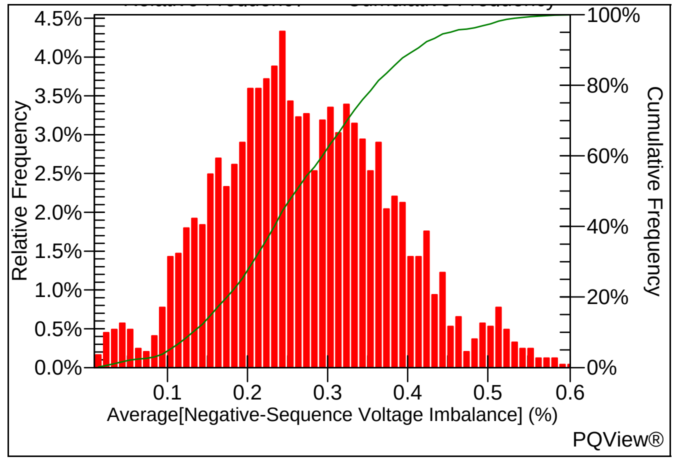

Fig. 7. Histogram of 17 days measurement of Voltage unbalance showing 95% probability of unbalance being as much as 0.45%.

C. Flicker

Flicker is a voltage variation over time, which results in undesirable changes in the intensity of electric lights. Short-term flicker (Pst) covers variations over a ten-minute interval. The normal criterion for evaluating these results is that the Pst should be less than 1.0 (usually evaluated at either the 95% or 99% probability level). Fig. 8 shows that the flicker levels are very low.

Some of the individual 10 minute Pst values are caused by voltage sags or other disturbances, that may not be associated with load variations. These points would normally not be included in the evaluation but they are not affecting the 95% or even the 99% probability level values of the Pst. Pst at the 99% probability level is only 0.13.

Long-term flicker (Plt) covers variations over a two-hour interval. The normal criterion for evaluating these results is that the Plt should be less than 0.8. Fig. 9 shows that the Plt levels are very low, corresponding to the Pst values.

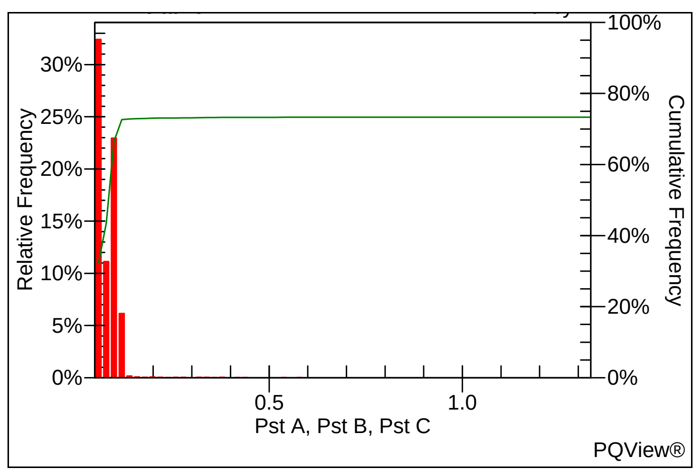

Fig. 8. Histogram of 17 days measurement of short term flicker showing 95% probability of Pst being as much as 0.1%.

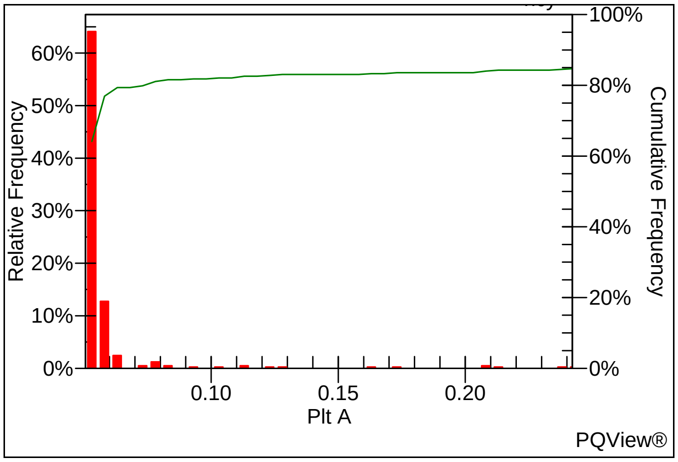

Fig. 9. Histogram of 17 days measurement of long term flicker showing 95% probability of Plt being as much as 0.1%.

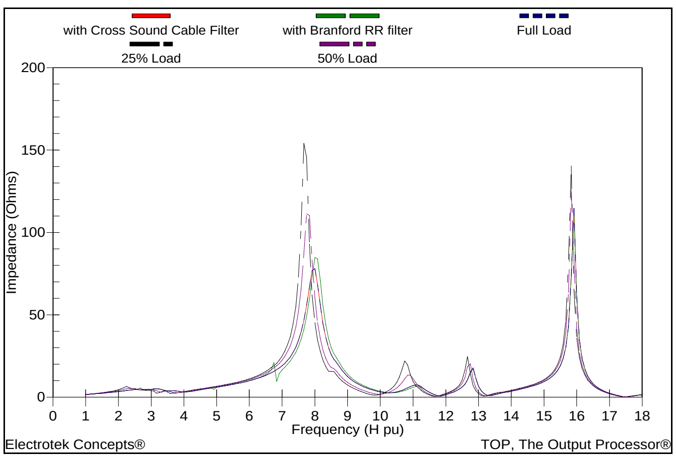

Fig. 10. Harmonic Frequency scans of 115 kV transmission system from point of common coupling.

III. System Modeling

A. Harmonic Analysis

Harmonic frequency scans are used to detect resonance points of the power system. This is usually done in terms of a range of scenarios in order to capture any variations that may significantly affect the results. The frequency scans were performed using the positive sequence impedance network and the loads and capacitors listed above. Five different scenarios were run. (Fig. 10) In all cases, harmonic resonances were found at the 8^{th} and 16^{th} harmonics, with smaller peaks near the 11^{th} and 13^{th} harmonics. The major resonances occur at even harmonics where there is very little current injection from the Metro North load (approximately 0.1%). The effect of the Branford Railroad filter is to shift the 8^{th} harmonic peak upwards, while decreasing load shifts it downwards and increases its magnitude. The 16^{th} harmonic resonance is shifted downwards and increased slightly when the load is decreased. The Cross Sound Cable filter does not appear to have a visible effect on the resonances. Fig. 11 shows the harmonic voltages at the PCC with the above-defined injections.

B. Voltage unbalance

The voltage unbalance at the Metro North 115 kV bus was calculated as a line-line fault using the full system model. Using different values of fault resistance the variations in load were simulated. The voltage unbalance was calculated as the ratio of positive to negative sequence line-neutral voltage on the 115 kV Metro North Bus. These results show an unbalance of less than 0.25% for typical loads, in line with the measurement results.

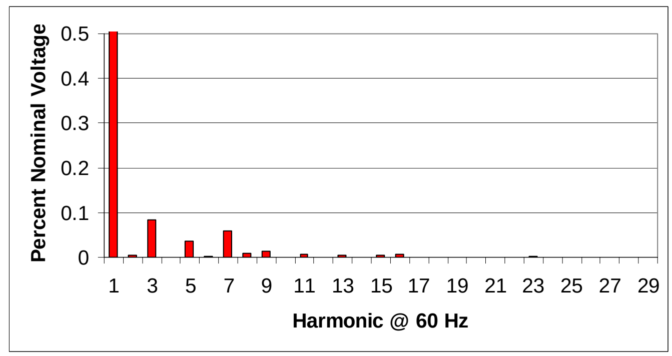

Fig. 11. Calculated Voltage at 115 kV bus as a result of harmonic current load from Metro North trains.

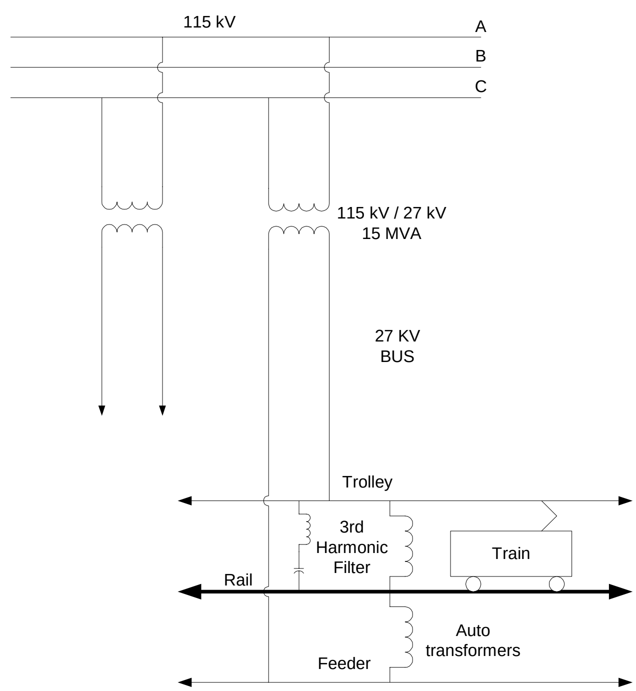

Fig. 12. Harmonic filter location for reducing third-order harmonics from trains on 27 kV system.

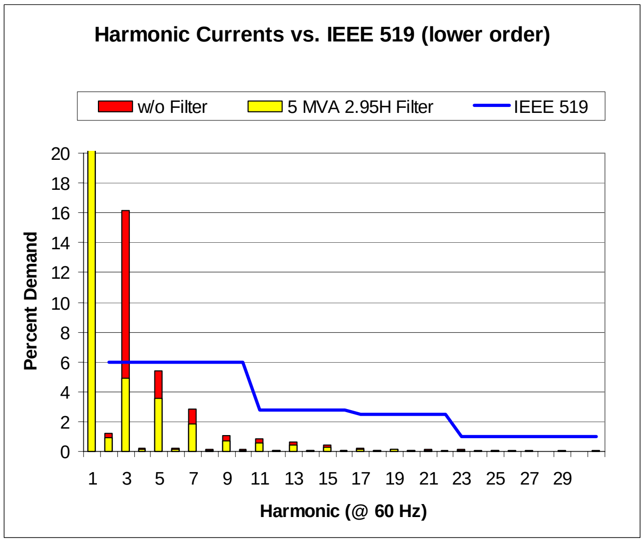

Fig. 13. Calculated harmonic currents with third harmonic filter and harmonic current measurements of railway load compared to IEEE 519 limits.

IV. Conclusions

The results of the harmonic measurements and analysis show that the only significant harmonic concern is the significant third harmonic current injected by the Metro North train loads. Both the third harmonic current and the TDD exceed the limits recommended by IEEE Standard 519-1992. Third harmonic currents are usually not as significant as fifth harmonic currents in utility transmission systems. Balanced third harmonic components from distribution loads do not reach the transmission system because of three-phase transformers with delta windings. These delta windings trap the zero sequence third harmonic currents. In this case, the load is single-phase, connected phase to phase. This results in an unbalanced third harmonic current flowing in the transmission system.

A third harmonic filter design was considered for the Metro North substation on the 27 kV side. This is similar to the third harmonic section of the Branford Amtrak substation, rated 5 MVA tuned at a harmonic order of 2.95. The filter would be located between trolley and rail (Fig. 12). The filter reduced the third harmonic currents to 5% of IL, just meeting the IEEE 519 limit. The fifth harmonic currents are also reduced to below the limit. (Fig. 13) While these calculations show the effectiveness of such a filter, a more detailed design study would be required to consider the filter's effectiveness under various contingencies.

Voltage unbalance and flicker were found to be within acceptable limits.

V. References

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VI. Biographies

Peter E. Sutherland (S'77–M'79–SM'97) received the A.S. degree in Electrical Engineering Technology and the B.S. degree in Electrical Engineering from the University of Maine, Orono, the M.Sc.E. degree in electrical engineering from the University of New Brunswick, Fredericton, N.B., Canada, and the Ph.D. degree in Electric Power Engineering at Rensselaer Polytechnic Institute, Troy, NY.

In 1987, he joined General Electric Company, Schenectady, NY, and held a variety of positions, becoming a Senior Engineer in the GE Power Systems Energy Consulting Department. In 2001, he joined SuperPower, Inc., Schenectady, N.Y., where he worked on applications of superconductivity to electric power systems. In 2003, Dr. Sutherland joined EPRI PEAC Corporation's Schenectady, NY office as a Consulting Engineer. Author of numerous technical papers, he is active in the IEEE Industry Applications Society, and in the IEEE Schenectady Section. Dr. Sutherland is a member of Phi Kappa Phi, Eta Kappa Nu and Tau Beta Pi. He is a Registered Professional Engineer in Pennsylvania, Maine and New York.

Marek Waclawiak is involved in a wide variety of engineering functions at the United Illuminating Company, ranging from power quality to transmission system engineering. He has implemented an advanced substation monitoring system that is used to characterize system performance on an ongoing basis, to evaluate operations during system disturbances, and to provide customers with power quality information to optimize their processes. He works with customers to help them improve their operations. He is actively involved in IEEE power quality standards activities and advises EPRI on their power quality research programs.

Mark F. McGranaghan (Member IEEE) is Vice President of Consulting Services at EPRI PEAC, Knoxville, TN. Mr. McGranaghan received his BSEE and MSEE from the University of Toledo and his MBA from the University of Pittsburgh.

Mr. McGranaghan is co-author of the book *Electrical Power Systems Quality*, considered to be the most complete reference in power quality issues for power systems He is influential in developing IEEE and international standards for harmonic limits on power systems and within facilities. He helped to achieve coordination between IEEE and IEC in a wide range of power quality standards-development activities He has taught seminars and workshops on power quality issues and power system analysis to electric utility engineers from around the world. His technical activities include: Vice Chairman, IEEE Power Quality Standards Coordinating Committee SCC22; U.S. National Committee of IEC, Technical Advisor for SC77A; Chairman, IEEE 519.1, Application Guide for Harmonic Limits; IEEE Power Quality Subcommittee, Chairman of Working Group on Standards.