HARMONIC FILTER APPLICATION CRITERIA

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Abstract-This paper discusses the criteria for applying a passive three-phase, shunt harmonic filter for use on an electrical power system. Passive means that the filter is predominantly made up of inductors, capacitors, and resistors rather than electronically controlled devices. Shunt means that the device is connected from the three phases to the neutral or ground of the power system. Harmonic filter means that it is designed to reduce harmonic distortion on the power system. No specific standard exists for harmonic filters. This document is a guide for applying harmonic filters. It references standards where they exist and gives typical criteria where appropriate standards do not exist.

I. INTRODUCTION

Sources of harmonic distortion on the power system include devices which produce distorted or non-sinusoidal waveforms. Examples include electronically controlled devices (such as rectifiers and power controllers), arcing loads (such as arc furnaces and arc welders), and magnetic devices to a lesser degree (such as rotating ac machinery and transformers).

One of the common ways of controlling distortion is to place a passive shunt harmonic filter between the harmonic producing load(s) and the rest of the power system. The harmonic producing device can generally be viewed as a source of harmonic current. The objective of the filter is to shunt some of the harmonic current from the load into the filter and, therefore, to reduce the amount of harmonic current that flows into the rest of the power system as illustrated in Figure 1. The simplest type of shunt harmonic filter is a series LC circuit as illustrated in Figure 2a. More complex filter arrangements may involve multiple LC circuits of which some may also include a resistor, as illustrated in Figure 2b.

The objective of this paper is to define the criteria which should be considered in designing, controlling, and protecting a harmonic filter.

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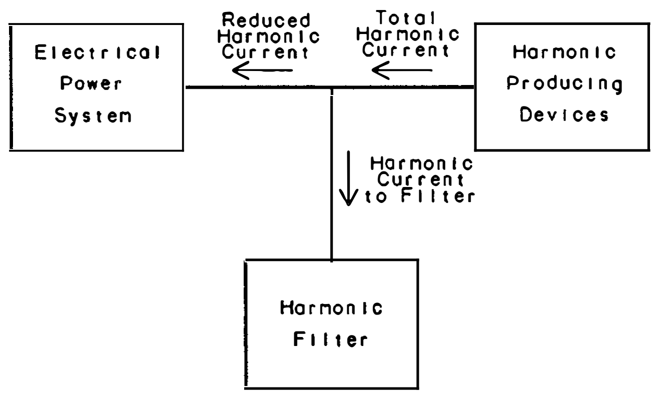

Fig. 1: Applying Harmonic Filters

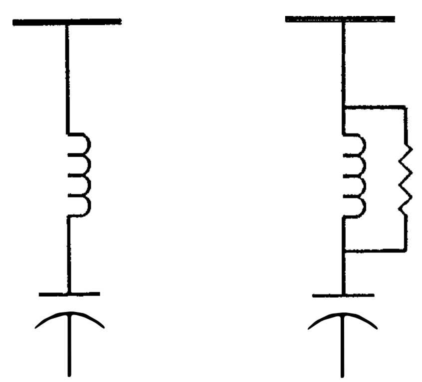

Fig. 2a: Single Tuned Filter

Fig. 2b: High Pass Filter

II. FILTER DESIGN CONSIDERATIONS

The key filter design considerations include the following:

A. Kvar requirements
B. Harmonic limitations
C. Normal system conditions
D. Normal harmonic filter conditions
E. Contingency system conditions
F. Contingency harmonic filter conditions

These considerations can be grouped into performance and rating criteria. The performance criteria relates to normal expected operating conditions and includes kvar requirements, harmonic limitations, normal system conditions, and normal harmonic filter conditions. The rating criteria relates to unusual conditions which may place a more severe duty on the equipment. This includes contingency system conditions and contingency harmonic filter conditions. Under the contingency conditions, it may be acceptable to have a more relaxed harmonic limitation. These six design considerations are discussed below.

A. Kvar Requirements

The passive shunt harmonic filter is basically a capacitor bank with reactor(s) and/or resistor(s) added to it to achieve acceptable harmonic control. As a result, it provides 60 Hz capacitive kvar to the system. In order to optimize the system costs, it is important to know how much capacitive kvar is needed (if any) and what savings can be obtained by adding the capacitive kvar. The kvar and voltage control requirements may dictate that the filter bank be switched in steps. Reference [1] indicates that the maximum kvar step size is typically limited to a value such that the fundamental frequency voltage change is no greater than 2% to 3% in order to have a minimal effect on system loads. Consequently, the total and step kvar sizes are generally determined by fundamental frequency load flow and voltage control requirements.

B. Harmonic Limitations

Harmonic limitations are defined in terms of system limitations and equipment withstand capabilities, as summarized below:

1) System Limitations: System harmonic limitations are generally defined to insure that equipment does not misoperate or fail due to excessive harmonic distortion. System limitations are recommended in sections 10 and 11 of IEEE Standard 519 [3]. This standard recommends that the total voltage distortion be kept to 5% or less, depending upon the system voltage level and other factors, and that the total current distortion at the point of connection to the utility be limited to the range of 2.5% to 20%, depending upon the size of the customer and other factors.. (See IEEE Std 519 for details.) This document gives higher limits for conditions lasting less than one hour.

2) Equipment Withstand Capabilities: Some of the withstand capabilities which are described in existing equipment standards are summarized in the following paragraphs.

Total harmonic current withstand for transformers is limited to 5% at full load as defined in ANSI/IEEE C57.12.00 [4] and C57.12.01 [5]. ANSI/IEEE C57.110 [6] defines the method for derating transformers when supplying nonsinusoidal loads. UL 1561 [7] and UL 1562 [8] define the transformer K-rating which is intended for use in high harmonic environments.

IEEE 18 [2] indicates that capacitors can be operated continuously within the following limitations, including harmonic components:

110% of rated rms voltage
120% of rated peak voltage
180% of rated rms current
135% of rated reactive power

In section 17A of NEMA MG-1 [9] a proposed derating curve for harmonic voltages is given for constant speed motors. Typically, this curve indicates that the derating of the motor occurs for voltage distortions greater than 5%.

C. Normal System Conditions

The normal system operating conditions are generally evaluated to assure that the final filter design will meet specific kvar and harmonic performance requirements for these conditions. These include the following:

1) System Voltage Variation: Overvoltages to +5% are typically considered for normal load conditions and +10% for unloaded system conditions. Undervoltage conditions are generally not critical for harmonic filter design, unless voltage is lost completely. In that case, the filters should generally be disconnected from the system immediately until the system is restored to normal conditions.

2) System Frequency Variation: On the interconnected power system frequency variations beyond +/- 0.1 Hz are rare. Larger variations may occur when the system is fed from a dedicated generator. This can affect the duty of a filter.

3) Power System Configurations: Possible variations in the power system configuration should be evaluated, including the interconnected power system if it is significant. For filter design, the impedance characteristic for all possible conditions is sometimes defined by an R-X envelope.

4) Loading Conditions: Variations in the system load, as it affects the harmonic filter bank design, should be considered. This includes variations in the harmonic producing loads, in the status of ac motors, and in the status of system capacitor banks and other harmonic filters.

5) Uncharacteristic Harmonics: Frequencies, which are not theoretically characteristic of a perfectly operating device, may sometimes occur. Analysis, experience, and field measurements will often help to quantify these values.

D. Normal Harmonic Filter Conditions

Filters are seldom tuned to their exact calculated values. It is necessary to allow for the following parameter variations when evaluating the performance of the filters:

1) Component Tolerances: Manufacturing tolerances must be allowed for the inductance, capacitance, and resistance.

2) Ambient Temperature Variation: Capacitor values vary with temperature. The appropriate temperature range depends upon the location. For example, in many areas of the United States temperature variations of -20^{o}C to +40^{o}C are typically considered for outdoor applications. Capacitance variation with temperature is typically in the range of .4% to .8% decrease per 10^{o}C rise in temperature.

3) Reactor Taps: Where reasonable component tolerances may not result in acceptable filter performance, taps are often included in the reactors to finalize the filter tuning. If conditions in the application are not exactly as were anticipated, taps also allow for some last minute adjustments in the field. Sometimes it may be useful to make filter tuning adjustments by adding or removing capacitor units in the harmonic filter.

4) Capacitor Unit Outages: The outage of a limited number of capacitor units, typically one or two, may be considered for larger filters. For small filters, where capacitor unit outages are often not considered, the filters are often deenergized for the outage of a single capacitor unit.

5) Application of Filters Tuned to the Same Frequency: When filters are applied at the same location and are tuned to the same frequency, care must be taken to assure that there is acceptable sharing of the harmonic currents among the filters. This is a function of the differences in the actual tuned frequency of each filter.

E. Contingency System Conditions

The contingency system operating conditions are generally evaluated to assure that the final filter design will be rated adequately to handle these conditions although the normal system distortion limits may be exceeded. These include the following:

1) System Frequency Variation: Frequency variations greater than those for the normal system conditions are generally considered.

2) Power System Configurations: Single and double contingency conditions are evaluated which are more severe than the normal operating conditions. Sometimes it may be desirable that these conditions also meet the harmonic distortion criteria which were considered for normal operating conditions.

3) Characteristic and Uncharacteristic Harmonics: Higher values than those used to evaluate performance are typically used for the rating of the equipment.

4) Unknown Harmonic Sources: It is best to identify all of the significant harmonic sources on the power system. Sometimes this may be difficult and carefully conducted and documented field measurements may be helpful in resolving this issue. It is often advisable to add a factor, such as 20%, to the calculated harmonic duties to account for unknown harmonic sources when rating the equipment.

F. Contingency Harmonic Filter Conditions

When rating the filter components, the same factors which were given above for "Normal Harmonic Filter Conditions" are typically used, but with wider ranges. In addition, when multiple filters are applied at the same location, the outage of a complete filter is often considered in rating the filter components. In some applications, the outage of a single filter may require that the other filters be disconnected so that their ratings are not exceeded.

III. MAJOR COMPONENT SPECIFICATIONS

The major components of the harmonic filter bank generally include the capacitors, reactors, resistors (if any), and the main switchgear. In specifying this type of equipment, the normal standards generally apply with the added requirement of the harmonic current spectrum and tighter tolerances on component parameters, specifically capacitance, inductance, and resistance. The harmonic current spectrum implies the added considerations of higher peak voltage, increased heat generation, and higher noise generation than most other power system applications where these components are used. The applicable standards are noted below for each component with additional comments related to the filter application as needed.

A. Capacitors

IEEE Std 18-1992 [2] gives the following allowable overload limits for capacitors, including harmonic components:

110% of rated rms voltage
120% of rated peak voltage
180% of rated rms current
135% of rated reactive power

Section 6.1 of IEEE Std 1036-1992 [1] gives guidance on the application of power capacitors rated 2400 Vac and above used in a harmonic filter. Some of the key information related to capacitors is summarized as follows:

1) When designing a filter, the overload capabilities given above are generally used for contingency conditions while the normal duty is typically within the capacitor rating. The overload capabilities are used to cover system overvoltages, bank unbalance conditions, and other contingencies. The harmonic components may increase significantly for bank unbalance conditions.

2) The current limit is 180% by standards, but, individual capacitor units are usually fused at 125% to 165% of their current rating. Revised fuse ratings may be necessary in a filter bank compared to a normal capacitor bank application. The fusing criteria are described in detail in sections 4.4.1 and 5.6.1 of IEEE Std 1036-1992 [1]. Fusing for low voltage capacitors is often on the order of 200%.

3) In specifying capacitor equipment for these applications, the following information should be included:
   a) The system line-to-line voltage
   b) The bank capacitance (microfarads)
   c) The values of other relevant circuit components (R in ohms, L in microhenries or millihenries, etc.)
   d) The harmonic voltage or current profile for the capacitor bank for the range of required frequencies
   e) The expected duty cycle or repetition rate of the above currents and voltages.

4) Capacitor units used in filter banks are commonly overrated in voltage by 10% to 25% to account for the higher 60Hz voltage on the capacitors and the harmonic components.

5) IEEE Std 18-1992 [2] requires a tolerance of 0% to +15% for the capacitance. This wide range is often unacceptable for many filter applications. Most capacitors are actually in the range of 0% to +8%, and specifying a range of 0% to +4% is generally reasonable. An appropriate tolerance on the capacitance coupled with taps on the filter reactor will allow for the desired tuning once the equipment is manufactured.

6) As given in IEEE Std 18-1992 [2], capacitors have a short time overload capability which may be useful in cases where short time high harmonic conditions occur:

   2.20 perunit rms voltage for 6 cycles
   2.00 perunit rms voltage for 15 cycles
   1.70 perunit rms voltage for 1 second
   1.40 perunit rms voltage for 15 seconds
   1.30 perunit rms voltage for 1 minute
   1.25 perunit rms voltage for 30 minutes

   If this capability is needed in a particular application, it is important to be sure that the other equipment also has this short time overload capability including the reactors, resistors, fuses, switchgear, etc.

B. Reactors

There is no current ANSI or IEEE standard specifically related to filter reactors. The closest document to that is ANSI C57.16. That document is currently being revised and is in the draft stage [10]. The referenced draft includes an appendix that provides guidance for applying dry-type air-core filter reactors. Filter reactors generally fall into three categories:

- Dry-type iron-core reactors - These are generally used in low and medium voltage applications.
- Dry-type air-core reactors - These are generally used in medium and high voltage applications.
- Liquid-immersed iron-core reactors - These may be used in high voltage applications.

Some of the key information related to applying filter reactors that is different from applying other series connected reactors is summarized as follows:

1) The harmonic current spectrum must be defined. This spectrum determines the heat/losses and vibration/ noise considerations for the reactors. If this is not taken into account in the design, the reactor may overheat and/or be excessively noisy. It is generally desirable to have low losses; but, where low component tolerances are important, low losses can sometimes result in increased distortion and filter duties.

2) The impedance tolerance given in ANSI C57.16 is -3% to +7%. This wide range is often unacceptable for many filter applications. Specifying a tolerance of -2.5% to +2.5% is generally reasonable. An appropriate tolerance on the reactor coupled with reactor taps will allow for the desired tuning once the equipment is manufactured.

3) When iron core reactors are used, it is important that they not saturate during the various system operating conditions. Specifying a saturation level that is 250% of the nominal fundamental current will usually eliminate this potential problem by allowing for some temporary overcurrent conditions without going into saturation.

4) In configuring the harmonic filter, the following items are noted:
   a) For low and medium voltage applications, the filter is generally connected in an ungrounded wye configuration with the reactor on the line side as illustrated in Figure 3a. The neutral connection is generally conveniently made within the capacitor equipment. The reactor limits the available fault current for a fault in the capacitor bank. The ungrounded configuration is used to avoid the tripping of any ground relays when energizing the capacitor bank.
   b) For high voltage applications, the filter may be connected in a grounded wye configuration with the reactor on the ground side as illustrated in Figure 3b. This allows the basic impulse insulation level (BIL) of the reactor to be less than the system BIL. This can be a significant cost savings in these larger applications. In that case an appropriately rated surge arrester should be placed across the reactor.

C. Resistors

The standard which relates most to resistors in filter applications is ANSI/IEEE Std 32 [11]. Some of the additional considerations for filter banks are summarized below:

1) The harmonic current spectrum must be defined. As with the reactors, this spectrum determines the heat/losses and vibration/noise considerations.

2) It is generally required that the resistor have very low inductance.

3) If the resistor is not in a grounded configuration, then the insulation requirements need to be taken into account.

D. Switching Devices

In general, ANSI/IEEE C37 standards [12] include guides and standards for circuit breakers, switchgear, relays, substations, and fuses. ANSI/IEEE C37.012 [13] provides guidance on applying high-voltage circuit breakers in switching capacitor banks. In sections 460-8 and 460-24 of the National Electrical Code [14], there is also information on switching devices for capacitor switching. These documents generally recommend that the device be capable of switching a capacitive current and that the device be rated for at least 135% of the rated current of the capacitor. With high harmonic currents in a filter, the current rating needs to be adjusted accordingly.

E. Grounding Switch and Key Interlock

For servicing and maintaining the equipment a three-phase grounding switch is often included when using high-voltage capacitors. In addition, key interlocks are included which are tied to the main switch, the ground switch, and the enclosure doors if an enclosure is used.

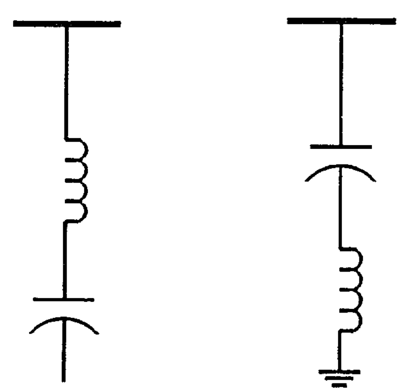

Fig. 3a: Typical Low & Medium Voltage Configuration

Fig. 3b: Typical High Voltage Configuration

IV. FILTER CONTROL AND PROTECTION

The filter control and protection considerations are discussed in this section.

A. Switching Control

The switching controls are similar to those used with standard capacitor banks. These are discussed in IEEE Std 1036-1992 [1]. The key factors and differences for harmonic filters are summarized as follows:

1) If the filter banks are switched, they are commonly controlled based on 60 Hz kvar and voltage requirements with consideration for harmonics as required.

2) Although inrush and outrush currents need to be taken into account, they are typically lower in filter applications due to the filter reactor than in standard capacitor applications.

3) To minimize closing transients, reenergization of a capacitor is generally delayed 1 minute for low voltage capacitors and 5 minutes for high voltage capacitors after deenergization to allow the capacitor trapped charge to decay adequately.

4) Undervoltage conditions are generally not critical for harmonic filter design, unless voltage is lost completely. In that case, the filters should generally be disconnected from the system immediately until the system is restored to normal conditions. This avoids dynamic overvoltage conditions that can occur when capacitors are energized with transformers. This can also occur when large transformers are energized after the filter bank is in service.

5) When a small kvar low tuned filter (such as a third harmonic filter) is switched with much larger higher tuned filters (such as fifth and seventh harmonic filters), the transient voltage in the third harmonic filter may be excessive resulting, in reactor or capacitor failures in that filter. This type of configuration should be evaluated carefully.

B. Overvoltage Protection

Overvoltage protection of capacitor banks is discussed in IEEE Std 1036-1992 [1]. The key points for harmonic filters are summarized as follows:

1) Surge protection of a filter bank is similar to that of a standard capacitor. Surge arresters connected to ground are sometimes applied at the terminals of the filter or between the reactor and the capacitor. Surge arresters may also be applied across the reactor if its BIL is not consistent with system requirements (see III.B above) or there are unusual switching transients (see IV.A above).

2) The application of capacitors inherently results in a voltage rise at that point in the system. To protect the capacitors and other station equipment against long-term overvoltage conditions, phase voltage relays are sometimes applied at the bus.

C. Overcurrent Protection

Overcurrent protection of capacitor banks is discussed in IEEE Std 1036-1992 [1]. The key points are summarized as follows:

1) Individual capacitor fuses are generally used to sense and indicate the failure of a single capacitor unit and remove the unit from service fast enough to prevent case rupture and damage to other units.

2) Capacitor unit fuses do not provide good overload protection. In standard capacitor banks, monitoring bank unbalance (see IV.D below) and possibly bus voltage (see IV.B above) generally results in adequate protection for long time overload conditions. Because of the high harmonic currents in filter banks, additional protection is sometimes included. This may involve a CT with a time delay relay in each phase or a temperature sensitive device in the reactor or in the reactor enclosure (if it is in an enclosure). The reactor is the component that will usually generate the most heat when an excessive harmonic condition occurs.

3) Major fault protection is generally provided by the main upline switching device or fuse.

D. Filter Detuning Protection

When an individual capacitor fuse blows, an increase in the fundamental frequency occurs on the remaining units in that series group. An unbalance detection scheme is employed to monitor such conditions and to take action as required in terms of providing an alarm or tripping the filter bank out of service. The typical requirements are given in section 5.6.3 of IEEE Std 1036-1992 [1] and detailed methods are described in IEEE Std C37.99 [15] with specific comments on filter banks given in section 9.0. The key differences compared to standard capacitor banks are summarized as follows:

1) Generally, the same methods are used in filter banks as in standard capacitor banks, except that the relays

generally incorporate filtering or harmonic restraint such that the unbalance decisions are based on the fundamental frequency voltages or currents and not on the harmonic components.

2) The loss of a capacitor unit will detune the filter from its design point. This detuning may result in a significant increase in the harmonic current in the filter. Consequently, filter banks may be designed to trip for less units out of service than for a standard capacitor bank of comparable design.

3) Low voltage filters often do not include an unbalance detection scheme. In addition, some low voltage capacitor designs have a self healing capability that allows them to recover from partial failures. If this occurs, the capacitance will go down over time which will result in the tuned frequency of the filter increasing. For these applications temperature is often monitored in the reactor or in the enclosure to detect these types of problems.

V. CONCLUSIONS

Based upon the information given in this paper, the following conclusions are noted.

1) When designing a harmonic filter, it is important to define and consider both the performance criteria and the rating criteria.

2) The major components of the harmonic filter bank generally include the capacitors, reactors, resistors (if any), and the main switchgear. In specifying this type of equipment, the normal standards generally apply with the added requirement of the harmonic current spectrum and tighter tolerances on component parameters, specifically capacitance, inductance, and resistance. The harmonic current spectrum implies the added considerations of higher peak voltage, increased heat generation, and potentially higher noise generation than most other power system applications where these components are used.

3) The filter control and protection considerations are generally similar to those for a standard capacitor bank but with some variations as noted in this paper.

VI. REFERENCES

[1] IEEE Std 1036-1992, IEEE Guide for Application of Shunt Power Capacitors.

[2] IEEE Std 18-1992, IEEE Standard for Shunt Power Capacitors.

[3] ANSI/IEEE Std 519-1992, IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems.

[4] ANSI/IEEE C57.12.00-1987, IEEE Standard General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformers.

[5] IEEE C57.12.01-1989, IEEE Standard General Requirements for Dry-Type Distribution and Power Transformers Including Those With Solid Cast and/or Resin-Encapsulated Windings.

[6] ANSI/IEEE 57.110, IEEE Recommended Practice for Establishing Transformer Capability When Supplying Nonsinusoidal Load Currents (Dry-Type and Liquid-Immersed up to 50 MVA).

[7] UL 1561, Standard for Dry-Type General Purpose and Power Transformers.

[8] UL 1562, Standard for Transformers, Distribution, Dry-Type - Over 600 Volts.

[9] NEMA Publication No. MG 1, Motors and Generators.

[10] 1992 Draft #5 of ANSI C57.16, Requirements, Terminology and Test Code for Dry-Type Air-Core Series Connected Reactors.

[11] ANSI/IEEE Std 32-1972, IEEE Standard Requirements, Terminology, and Test Procedure for Neutral Grounding Devices.

[12] IEEE Std. C37, Guides and Standards for Circuit Breakers, Switchgear, Relays, Substations and Fuses.

[13] ANSI/IEEE C37.012-1979, IEEE Application Guide for Capacitance Current Switching for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis.

[14] NFPA 70, National Electrical Code, 1993 Edition.

[15] IEEE Std C37.99-1990, IEEE Guide for Protection of Shunt Capacitor Banks.

VII. BIOGRAPHIES

W. Edward Reid is Director, Analytical Studies with Qual-Tech Engineers, Inc. of Pittsburgh, PA. He has over 20 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 is 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 coauthored over 10 technical papers.

Kevin A. Puskarich is a Power Systems Engineer with Qual-Tech Engineers, Inc. of Pittsburgh, PA. He has over ten 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.