HIGH-VOLTAGE MEASUREMENTS

Rastko Zivanovic
Technikon Pretoria, South Africa

Keywords: measurements, high voltage, measuring transducer, current transformer, voltage transformer, signal conditioning, signal processing, power quality, state estimation, disturbance recorders, synchronized measurements

Contents

Summary

This article presents a summary of the modern technology for electrical measurements in high-voltage transmission and distribution systems. The progress in high-voltage measurements is in a transition period due to the rapid growth of digital technology, more computing power, better communication capabilities, and the use of modern signal-processing technology at the device and system levels. Also, change in the power industry is an ongoing process driven by the need to increase efficiency and profits while maintaining the reliability and stability of system operation. These necessitate

accurate and timely measurements to provide comprehensive control of power systems and reliability.

1. Introduction

Since the early 1980s all concepts and technological developments in the field have been influenced primarily by the rapid growth of digital technology. The exponential trend of having more computing power and more capacity in communication links for less money has ultimately led to the integration of measurement devices into systems, as well as the use of modern signal-processing technology at the device and system levels. For example, improved communication capabilities are necessary for many demand-side management services. These services include the automation of the distribution of meter reading, as well as other services for information exchange between customers and the utilities. Improved communication capabilities are also necessary for monitoring and controlling transmission and distribution systems. Optical fibers are promising as transducers in electrical environments because they are nonconducting, capable of linear sensing, versatile in the number of parameters they can measure, and sensitive. Satellites are already being used for timing control in power networks and may increase in importance as wide-area, high-voltage measurement networks, in particular, emerge.

In parallel with the development of new technologies, the ongoing process of changing the electric power industry is on the way. This process is driven by the need to increase efficiency and profits while maintaining the reliability and stability of system operation. Wide-area measurement and disturbance-recording systems are used to provide comprehensive real-time data access and the integration necessary to control and operate fully the wide areas of a power system. Power-quality and condition-monitoring systems are used to increase reliability. Specific requirements for high-voltage measurements in the electric power industry are presented in Section 2.

The instrumentation components that are required to accomplish high-voltage measurements are voltage and current transducers, signal conditioning equipment, and signal analysis and monitoring equipment. Voltage and current transducers are required to convert the system voltage and current to acceptable levels for input to the signal-conditioning equipment. Details about measuring transducers are presented in Section 3. Traditional and modern signal-conditioning and data-transmission techniques are presented in Section 4.1. Modern digital devices for processing and monitoring high-voltage measurements use highly accurate analog-to-digital converters (ADCs) and, in many applications, synchronization devices based on global positioning system (GPS) receivers. Various methods for signal processing are used to transform sampled data into frequency domain. Measuring techniques and algorithms for primary quantities, such as voltage, current, power, energy, and frequency, are presented in Section 4.2. Additionally, in Section 4.3, specialized measuring algorithms and devices used to analyze power-quality problems are presented. In Section 5 systems for integrated high-voltage measurements are presented. The role of state estimation in modern energy-management systems (EMS) is explained. In addition to classical data-acquisition systems, utilities are installing disturbance recorders with synchronization capability. These devices provide additional information to EMS that could speed-up system restoration after large disturbances and monitor system power quality during normal operation.

2. Requirements for High-Voltage Measurements

It is recognized that the most important forces that drive changes in the electric power industry today are deregulation, economic competition, efficiency, reliability, stability, and power quality. The process of changing the power industry is complicated by the following emerging problems:

- The emergence of additional suppliers of electric power increases the complexity of the power system.
- The growth in demand is being met without significant construction of new transmission systems.
- The economic pressure on the providers of electricity prompts them to use aging equipment longer.
- The environmental restrictions on rights of way encourage the sending of more power down existing rights of way; and
- The emergence of wide-area power sharing and power wheeling complicates control and stability issues.

It is clear that these changes will give rise to a broad spectrum of technical needs and to related requirements for new high-voltage measurement capability.

High-voltage measurements are used in bulk power transmission systems, for control and protection, monitoring, and metering. There is a need both for primary instruments that measure voltage and current, and for secondary instruments that compute other quantities, such as power, energy, and frequency, from the measurements made by the primary instruments. High-voltage measurement instruments are used throughout the electric power system for limited monitoring of power system equipment. However, as attempts to control the operating parameters of power networks increases, the installation of many more instruments will probably be needed to monitor system disturbances.

There is a need for automated transmission and distribution systems to provide adequate real-time control, as well as a need for real-time assessment of actual power flows and dynamic capacity. These automated systems employ advance measurement and control and protection devices, as well as solid-state devices for power-flow control, such as flexible AC transmission systems or FACTS. In implementing such systems there is a need for a large number of low-cost digital instruments that can be installed throughout the transmission system and accompanying communication systems to interconnect the instruments and coordinate the operation of the controllers, such as FACTS devices. Special signal-processing and mathematical-modeling software is required for extracting information from measurements. Communication links will provide high-performance support for the sharing of reference signals for wide-area correlation, automatic posting of disturbance directories on computer bulletin boards, exchanges of data records, and interactive assistance in measurement operations and analysis from remote locations. Additional measurements will also provide more information on the state of the system so that the proper operation of end-user equipment can be ensured. Improved diagnostic coverage of the system and individual components could perhaps have provided advance warning of the problems and would have been useful in determining the causes of the outages.

Two important factors that have an impact on large concerns about power quality problems today are the sensitivity of microelectronic devices and the emergence of power electronic devices. Microelectronic devices could malfunction or even be damaged as a consequence of some power quality problems. The question of who is responsible for the quality of the power used—the utility or the consumer—is an important one. Power electronic devices are increasingly used in electrical and electronic products to achieve high energy efficiencies and excellent control. In normal use, they switch on and off rapidly to control power flow. The resulting transients and harmonics can be propagated on power lines to other users and can degrade the smoothness—or quality—of the sinusoidal waveform. Special high-voltage measurements can help quantify the harmonics of the fundamental power frequency voltage and current, voltage dips, spikes, and other transients. The specific reasons for taking harmonic measurements include confirming the presence of harmonics, evaluating the severity of the problem relative to acceptable harmonic limits, establishing compliance with standards and guidelines, harmonic filter design, providing input data for harmonic software analysis programs, and designing an analytical model of the problem. The instruments and systems for power quality measurements can help identify the sources of power quality degradation and to protect customer equipment. Many power quality monitoring instruments are designed for input voltages of up to 600 V rms and current inputs up to 5 A rms. Voltage and current transducers must be selected to provide these signal levels. Two important concerns must be addressed in selecting transducers: signal levels should use the full scale of the instrument without distorting or clipping the desired signal, and the frequency response should be adequate for transient and harmonic distortion monitoring where high-frequency signals are particularly important.

Custom power devices, applied to the distribution system itself, can provide more global solutions to power quality problems. They are the dynamic voltage restorer, the solid-state breaker, and the distribution system version of the static compensator. Implementation requires numerous digital instruments to be installed throughout the systems to monitor power quality and disturbances. Communication systems should be put in place to interconnect the instruments and to coordinate the operation of the custom power devices. Custom power devices will rely on rapid and accurate fault location to respond correctly to disturbances and to maintain high power quality.

Demand-side management programs are becoming increasingly popular with the utilities to reduce the level of demand and the fluctuation in demand. Their purpose is to mitigate the need for the construction of new electrical generation and transmission systems. One type of demand-side management involves the direct real-time involvement of the utility, either by controlling electrical devices used by the consumer or by instituting real-time pricing. With real-time pricing the consumers are continuously informed of the instantaneous cost of electricity, and can adjust their use patterns accordingly. Implementation of such programs requires a large number of instruments and controllers installed at consumer sites and linked to the operator of the system.

Power system reliability is enhanced through the reduction of equipment failures. The failures can be reduced through predictive maintenance using advanced equipment monitoring technologies, and in particular, through more accurate on-line condition monitoring. The improved reliability of power system components results in the prevention of lost revenue by reducing power outages. Additional cost savings for utilities can be realized by extending the usable lifetime of expensive equipment, such as power transformers, beyond their design lifetimes, which delays the outlay of capital for replacing old equipment. Since lightning is a major cause of power system disturbances, electrical power equipment is subjected to testing with high-voltage impulses before being placed in service to ensure reliability. In these tests partial-discharge monitoring provides a measure of insulation integrity. Digital recording systems are required for both the laboratory and field testing of high-voltage apparatus. Under some conditions, online, real-time data recording may be advantageous and cost effective.

There is a definite need for the calibration of primary instruments in service. It is desirable that new digital instruments be self-calibrating, remotely calibrating, or have characteristics that change over time in a predictable manner, since the alternative of calibrating instruments in the field is so costly.

3. Voltage and Current Transducers

3.1. Current Transducers

For current measurements in high-voltage circuits it is not practical to allow primary current to flow directly through an instrument. One method is to divert a small current through a resistive shunt. A disadvantage of such devices is that, unlike transformers, they do not provide any insulation between the high-voltage side and the measuring system. More commonly used transducers are Rogowski coils, current transformers (CTs), and optical current transducers (OCTs).

Rogowski coils are specialized transducers usually used for the measurements of very large currents that last for a very short duration (e.g., hundreds of kiloamperes in less than a microsecond). The Rogowski coil is a solenoid air-core winding of a small cross-section looped around a conductor carrying the large primary current. The voltage induced on the terminals of the coil is proportional to the derivative of the primary transient current and number of turns. The coil is connected to an integrator. Integrated induced voltage gives a measure of the current in the primary conductor. Rogowski coils have the advantage of being free from saturation problems and of having a very fast response time.

3.1.1. Current Transformers (CTs)

CTs transform line current into values suitable for measuring instruments, meters, protective relays, and other similar apparatus. CTs also isolate instruments and relays from line voltages. A current transformer has two windings, designated as primary and secondary, which are insulated from each other. The primary winding is connected in series with the circuit carrying the line current to be measured, and the secondary winding is connected to instruments or protective devices. The secondary winding supplies a secondary current in direct proportion to the primary current almost without any difference in phase angle—there is a small phase error given in minutes. The four common types of CT design are wound type, bar type, window type, and bushing type.

The most important parameters that define CT performance requirements are the following:

- *Rated transformation ratio*. The ratio of the rated primary current to the rated secondary current.
- *Rated primary current*. The standard values of the rated primary currents are 10, 12.5, 15, 20, 25, 30, 40, 50, 60, and 75 A, and their decimal multiples or fractions.
- *Rated secondary current.* The standard values of the rated secondary currents are 1, 2, and 5 A. The preferred value is 5 A.
- *Ratio error*. This is the error that a CT introduces into the measurement of a current and that arises from the fact that the actual transformation ratio is not equal to the rated ratio. The error is expressed as follows:

  $$\text{Ratio error }\% = \frac{\left(K_n I_S - I_P\right)\times 100}{I_P} \tag{1}$$

  where K_n is the rated transformation ratio; and I_P and I_S are the actual primary and secondary currents, respectively. The accuracy requirements for current transformers used for measuring instruments and ones used for protective devices are different. For measuring instruments, the accuracy class of a CT is designated by the highest permissible percentage ratio error at rated current prescribed for the accuracy class considered. The standard accuracy classes are 0.1, 0.2, 0.5, 1, 3, and 5. In the case of a CT for a protective device the standard accuracy classes are 5 P and 10 P.
- *Rated output.* This is the value of the apparent power, in voltamperes at a specified power factor, which the CT is intended to supply to the secondary circuit at the rated secondary current, and with a rated burden connected to it. The standard values are 2.5, 5, 10, 15, and 30 VA.

The current in any system changes more often and with greater magnitude than the voltage. Hence, selecting proper transducers for currents could be difficult. The proper CT current rating and turns ratio depend on the measurement objective. In the case of disturbance recorders or protective devices, where fault or inrush currents are of concern, the CT must be sized in the range of 20–30 times the normal load current. This will result in low resolution of the load currents and the inability to accurately characterize load-current harmonics. Conventional current transformers are designed to operate within a frequency range of 15–100 Hz. With the need to measure the harmonic content of the primary current, the frequency response of current transformers is essential to the measurement process. The frequency response of current transformers is effectively determined by the capacitance present in the transformer and its relationship with the transformer inductance. Standard metering class CT is generally adequate for frequencies up to 2 kHz. Phase-angle shift between primary and secondary currents may start to become significant when the frequency is close to 2 kHz. For higher frequencies than 2 kHz, a window-type CT with a high ratio should be used. Higher ratios require lower magnetizing current and tend to be more accurate. Desirable attributes for a CT when harmonics are measured include large ratio, small remnant flux, large core area (the more steel used in the core, the better the frequency response of the CT), secondary winding resistance, and leakage impedance to be as small as possible.

The reactive component of the CT burden tends to increase with frequency. Hence, the associated power factor reduces with increasing frequency and the CT will produce a higher harmonic output voltage than it would for a purely resistive load. The increase in the voltage results directly in the increase of magnetizing current. This effect creates additional error in measuring harmonic currents. The practical suggestion is to use a low impedance burden with the maximal possible power factor to reduce the required CT voltage and, consequently, the magnetizing current.

In addition to harmonic frequencies it is also possible that the primary current will contain a DC component. This component will cause the core flux of the CT to become offset, and, hence, this could force the CT into saturation with a subsequent distortion of the secondary current. A similar condition could arise from remnant flux present in the CT core as a result of switching operations.

A CT with an air-gap in the core could be used when the presence of DC component is expected in the primary current. An air-gap reduces the effect of saturation by increasing core reluctance, and in that way keeps the operating point in the linear range of the CT characteristic.

When digital instruments are used, careful consideration of the sizing of the CTs is required to take advantage of the full resolution of the instrument without clipping the measured signal. Digital instruments incorporate the use of ADCs. To obtain the most accurate representation of the signal being monitored, it is important to use as much of the full range of the ADC as possible.

3.1.2. Optical Current Transducers (OCTs)

Optical transducers represent one possible solution to the need for reliable and economical sensors in high-voltage measurement systems. Conventional transducers for voltage and current are expensive and require large volumes of electrical insulation when used on high-voltage lines. OCTs are designed with all-solid insulating materials and are, therefore, intrinsically safe. Because an OCT is an electronic device, a fundamental way it differs from a CT is in the signal power involved. In a CT, the secondary signal has a power level of several watts, while power in the OCT secondary is typically a few microwatts.

A number of quite different OCTs are available. Diversity is present in all elements of the system. The sensor may be optical or electronic. The insulator may be ceramic or polymer, and it may be used to support OCT or it may be suspended from it. All types of OCT use optics to isolate a high-voltage part of the system from a secondary side that carries information. The current being measured by an OCT is represented as modulated light. Typically, the link between sensor and user device—the measuring instrument—is an optical fiber. OCTs can be classified into five major classes, according to design:

1. Conventional CT with optical readout (an optical information channel replaces the copper wire output from the CT).
2. Magnetic concentrator with optical measurement (a magnetic circuit surrounds the conductor and the field inside is measured optically in an air-gap).
3. Bulk optics surrounding conductor (the optical path is inside a block of optically active material and encloses the conductor once).
4. Optical fiber surrounding conductor (the optical path is inside fiber that can be wound around the conductor an arbitrary number of times).
5. Witness sensor (the magnetic field at a point near where the conductor is sensed).

The Faraday effect is the effect commonly used in OCTs for high-voltage measurement systems. A typical arrangement of optical components in a Faraday sensor is presented in Figure 1. These OCTs utilize either optical crystals or fibers to induce a rotation in the plane of polarization of a light beam passed through the sensor head. The rotational change is linearly proportional to the current through the sensor. OCTs have the advantages of immunity to electromagnetic interference and wide dynamic range. Although saturation is not a problem, as with CTs, OCTs are linear over only a finite current range. This does not limit the usefulness of OCTs since their linear range is selected by appropriate sensor-head design. and since measurements of currents outside of their linear range are readily corrected by more complex signal-processing techniques. The wide bandwidth of OCTs, limited only by the optical detector, makes them applicable for both fundamental frequency metering and measurements of transient and harmonic currents. To summarize, the OCT has several advantages over a conventional CT device:

- light weight,
- better immunity to ambient electromagnetic and electrostatic fields,
- better linearity than CT,
- a high degree of isolation for the safety of instruments and personnel, and
- suitability for high-frequency and transient measurements.

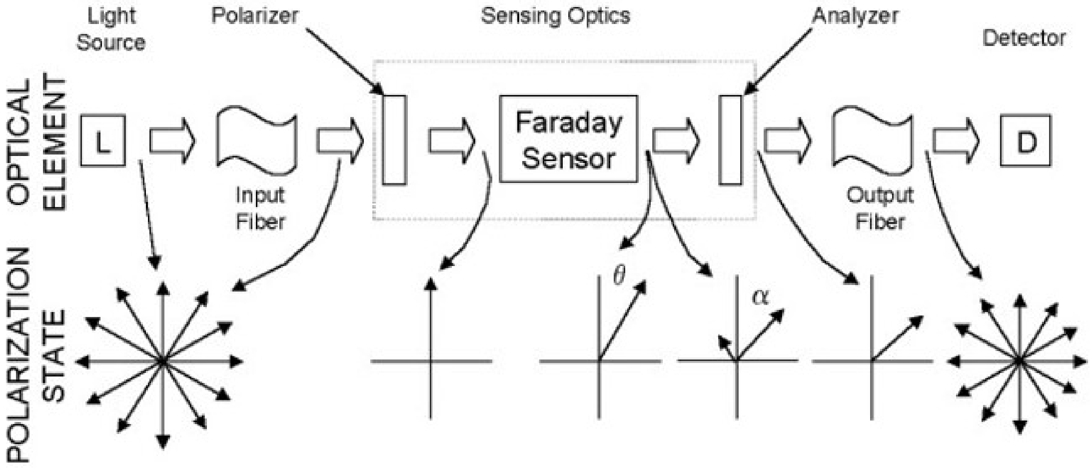

Figure 1. The arrangement of optical and polarization components in a Faraday sensor

-
-
-

Bibliography

ANSI/IEEE Standard C57.13-1978 (1978). *IEEE Standard Requirements for Instrument Transformers*. Institute of Electrical and Electronic Engineers (IEEE). [This standard provides an overview of the instrument transformers for high-voltage measurements.]

Begovic M., Dunlap S., Djuric P., and Phadke A. (1993). Frequency tracking in power networks in presence of harmonics. *IEEE Transaction on Power Delivery*, **8**(2) 480–486. [This paper presents a number of algorithms for digital frequency measurement in high-voltage systems.]

Emerging Technologies Working Group and Fiber Optic Sensors Working Group (1994). Optical current transducers for power systems: a review. *IEEE Transaction on Power Delivery* **9**(4), 1778–1785. [This paper provides a review of the optical transducers for high-voltage measurements.]

EPRI Final Report TR-107903 (1997). *Assessment of Applications and Benefits of Phasor Measurement Technology in Power Systems.* US: Electric Power Research Institute. [This report describes some applications of phasor measurement technology.]

EPRI Final Report TR-112031 (1999). *A Dynamic Information Manager for Networked Monitoring of Large Power Systems.* US: Electric Power Research Institute. [This report provides details of information management for integrated high-voltage measurement systems.]

IEEE Power System Relaying Committee Report 87TH0195-8-PWR (1987). *Application of Fault and Disturbance Recording Devices for Protective System Analysis.* US: Institute of Electrical and Electronic Engineers. [A report describing disturbance recording devices and its applications.]

IEEE Standard 4-1995. *IEEE Standard Techniques for High Voltage Testing.* US: Institute of Electrical and Electronic Engineers [This standard provides information about high-voltage measurement systems for high-voltage laboratories.]

IEEE Tutorial Course Text 90EH0327-7-PWR (1990). *IEEE Tutorial Course on Nonsinusoidal Situations: Effects on Performance of Meters.* US: Institute of Electrical and Electronic Engineers [This tutorial describes the effects of nonsinusoidal situations on high-voltage measurement accuracy.]

MacDougall T.W., Lutz D.R., and Wandmacher R.A. (1992). Development of a fiber optic current sensor for power systems. *IEEE Transaction on Power Delivery* **7**(2), 848–855. [This paper provides a review of the optical transducers for high-voltage measurements.]

Monticelli A. (1999). *State Estimation in Electric Power Systems: A Generalized Approach.* US: Kluwer Academic Publishers. [A good book on the state estimation techniques for integrated measurement systems in power systems.]

US Department of Commerce, National Institute of Standards and Technology (1997). *Measurement Support for the U.S. Electric-Power Industry in the Era of Deregulation.* US: United States National Institute of Standards and Technology. [An extensive survey of requirements and possible solutions for measurement support systems of deregulated power systems.]

Biographical Sketch

Rastko Zivanovic was born in Belgrade, Yugoslavia, on January 26 1963. He received his Dipl.Ing. and Master’s degrees from the University of Belgrade in 1987 and 1991, respectively, and his Ph.D. degree from the University of Cape Town, South Africa, in 1997, all in Electrical Engineering. From 1987 until 1992, he held the positions of Research Assistant (University of Belgrade), Application Engineer (Jugohemija Company), Research Engineer (Electric Engineering Institute “Nikola Tesla”), and, finally, Lecturer (Higher School of Electrical Engineering), all in Belgrade, Yugoslavia. Since July 1992 he has been with the Faculty of Engineering at Technikon Pretoria, South Africa, where he has held the positions of Lecturer, Senior Lecturer, and currently Professor. He spent 1999 as Visiting Professor at Paderborn University, Germany. His teaching and research interests include power-system control, monitoring, and protection. He established the Centre for Electric Energy Systems at Technikon Pretoria in 1994. He received a research fellowship from the Ernest Oppenheimer Memorial Trust in 1995, the DAAD (Germany) lectureship grant in 1999, and a number of research grants from ESKOM, GENCOR, BILLITON, and the National Research Foundation of South Africa. He has also acted as consultant to ESKOM and NamPower. He has published more than 50 journal and conference papers.