MEASUREMENTS OF ELECTRICAL QUANTITIES

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Contents

Summary

In this work, a fundamental overview of measurement of electrical quantities is given, including units of their measurement. Electrical quantities are of various properties and have different characteristics. They also differ in the frequency range and spectral content from dc up to tens of GHz and the level range from nano and micro units up to Mega and Giga units. No single instrument meets all these requirements even for only one quantity, and therefore the measurement of electrical quantities requires a wide variety of techniques and instrumentations to perform a required measurement. The measurement is unimaginable without sound knowledge of the quantities, measurement units and the theory of electrical circuits.

Definitions of basic electric quantities and measurement units are presented in Section 2. Only the most common quantities, such as voltage, current, power, resistance, capacitance and inductance are discussed. Several time and frequency aspects of electric quantities required for correct measurement and related parameters and characteristics are depicted in Section 3 and 4, respectively. Chapter 5 gives an overview of basic measurement techniques and instrumentation for electrical quantities and their characteristics. The glossary and bibliography provide a brief explanation of the essential terminology, and refers to additional readings for a deeper study, respectively.

1. Introduction

Nowadays, the measurement of electrical quantities is an essential part of almost any measurement. It can be realized as a measurement, whose results indicate directly a value of measured electric quantities, such as voltage, current, resistance, etc., or a measurement, where measurement of electrical quantities is only an internal function of an electronic measurement system measuring any other physical quantity.

2. Basic Electrical Quantities

The basic electrical quantities are electrical current and voltage, electrical charge, resistance, capacitance, inductance and electric power. Electricity is a flow of free electrons carrying negative electric charge from a place of their excess (the place with negative charge) to a place of their deficiency (the place with positive charge).

2.1. Electric Current and Charge

According to the convention, the positive direction of electric current is opposite, i.e. the positive direction of electric current is from the place with a positive charge to the place with a negative charge. The symbol for electric current is I (or i, if the current is time varying), and the basic unit of measure is ampere (symbol A) after André-Marie Ampère. The ampere is one of seven basic units according to the international convention (SI), and its definition is: "the ampere is that constant current which, if maintained in two straight parallel conductors of infinite length, of negligible circular cross-section, and placed 1 meter apart in vacuum, would produce between these conductors a force equal to 2 x 10^{-7} newton per meter of length". Although ampere is the basic SI units, its definition is not convenient for metrological applications and construction of calibrators. In practice ampere is maintained via Ohm's Law from the units of electromotive force and resistance, the volt and the ohm (see below), since the latter two can be tied to physical phenomena that are relatively easy to reproduce, the Josephson junction and the quantum Hall effect, respectively.

Another more simple definition comes from the fact that electric current is movement of elementary electric charges carried by electrons. When there is a constant flow of approximately $1.602176487 \times 10^{19}$ electrons per second through a surface, the current of 1 ampere is flowing. The mathematical representation is

$$i(t) = \frac{dq}{dt} \qquad (1)$$

where q is the charge and t the time. The unit of charge measurement is coulomb (symbol C), after Charles Augustin de Coulomb. One coulomb is approximately $1.602176487 \times 10^{19}$ of elementary charges. The SI definition of coulomb is "the coulomb is the quantity of electricity carried in 1 second by a current of 1 ampere". Although electrical charge is one of the basic electrical quantities, it is measured very rarely in practice and, if needed, it is usually only calculated from measurement of other electrical quantities.

2.2. Electric Voltage

Electric voltage is a difference of potential between two places with different charges. Voltage provides the ability to move charges and hence do a work, and therefore voltage is also sometimes called electromotive force (EMF). The symbol for voltage is V or sometimes U (v or u, if the voltage is time varying quantity) and the measurement unit of is volt (V) after Alessandro Volta. The SI definition is: "The volt is the potential difference between two points of a conducting wire carrying a constant current of 1 ampere, when the power dissipated between these points is equal to 1 watt".

Electric voltage and current are manifestations of electric charge movement, and they can be considered "active" quantities. They can carry information in electronic circuits and systems or they can be considered only an expression of supplied and consumed electrical energy. Measurement methods and instrumentation as well as measured parameters differ depending on where and why the voltage and current are measured.

2.3. Resistance, Capacitance, Inductance and Impedance

The following electrical quantities: resistance, capacitance and inductance are "passive" quantities. They describe behavior and manifest properties of material and electrical components in the presence of voltage and current.

Resistance (symbol R) is a very important electrical quantity that indicates how much voltage is necessary to create a certain amount of current in a component. The relation among voltage, current and resistance is given by the Ohm's law:

$$R = \frac{V}{I} \tag{2}$$

Resistance is measured in ohms (symbol Ω) after Georg Simon Ohm. The SI definition of ohm is: "the ohm is the electric resistance between two points of a conductor when a constant potential difference of 1 volt, applied to these points, produces in the conductor a current of 1 ampere, the conductor not being the seat of any electromotive force".

Capacitance expresses the ability to accumulate electrical energy in the form of electric field. Capacitance is the basic required property of a capacitor. The simplest capacitor consists of two isolated conductive plates. The general relation among current i and voltage v across the capacitor and capacitance C is given by:

$$i(t) = C\frac{dv}{dt} \tag{3}$$

The unit of capacitance measurement is farad (symbol F) after Michael Faraday. The SI definition is: "the farad is the capacitance of a capacitor between the plates of which there appears a potential difference of 1 volt when it is charged by a quantity of electricity of 1 coulomb".

Inductance is the ability to accumulate electrical energy in the form of magnetic field. Inductance is the fundamental property of an inductor. The simplest inductor is a coiled wire optionally equipped with a core. The general relation among current i and voltage v across the inductor and inductance L is given by:

$$v(t) = L\frac{di}{dt} \tag{4}$$

The unit of inductance measurement is henry (symbol H) after Joseph Henry. The SI definition is: "the henry is the inductance of a closed circuit in which an electromotive force of 1 volt is produced when the electric current in the circuit varies uniformly at the rate of 1 ampere per second".

Capacitance, inductance, and resistance are electrical quantities that characterize an ideal simple electronic circuit, component, and materials used to make components, and determine a relation between ac voltage and current (see Eq. (2), (3), and (4)). To express the relation between ac voltage and current (sine waves of a frequency) in a complex electronic component that contains a combination of capacitance, inductance, and resistance in its structure, the complex quantity "impedance" is used. The unit of impedance measurement is ohm – the same as for resistance. Impedance is a function of frequency.

Mathematically, impedance is expressed by a complex number $R + jX$ or in the polar form as a magnitude and phase angle: $|Z|\angle\theta$. It describes the coordinates of an impedance vector in a complex plane; the impedance vector consists of a real part (resistance, R) and an imaginary part (reactance, X) – see Figure 1.
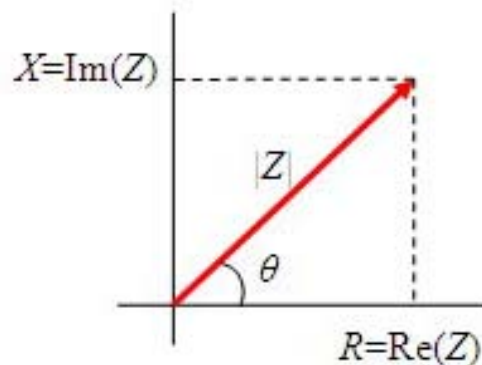

Figure 1. Expressions of complex impedance Z.

In some cases, using the reciprocal of impedance is mathematically expedient. In such case, $1/Z = 1/(R + jX) = Y = G + jB$, where Y represents admittance, G conductance, and B susceptance. The unit of admittance is the siemens (S). Impedance is a commonly used parameter, and it is especially useful for representing a series connection of resistance and reactance, because it can be expressed simply as a sum, R and X. For a parallel connection, it is better to use admittance. Impedance and admittance are frequency dependent electrical quantities.

2.4. Electrical Power and Electrical Energy

Electrical power and electrical energy are quantities equivalent to power and energy known from other technical and scientific fields, e.g., mechanics, physics, chemistry, etc. The only formal difference is that electrical power and energy are related to electric circuits and other electrical quantities. For example, the power P in a circuit with a steady voltage V and current I and with application of Ohm's law can be simply calculated as:

$$P = V \cdot I = I^2 \cdot R = \frac{V^2}{R} \tag{5}$$

Electrical power can be also expressed as a change of electrical energy E in time t:

$$p(t) = \frac{dE}{dt} \tag{6}$$

If a signal containing many frequency components is to be measured, the total power is the sum of powers of all frequency components:

$$P_{tot} = \sum_{i=0}^{N} P_i = \frac{1}{R} \sum_{i=0}^{N} V_i^2 \tag{7}$$

The unit of power measurement is watt (W) after James Watt. According to Eq. (5) $W = V.A = A^2.\Omega = V^2/\Omega$, or according to SI definition "the watt is the power which in one second gives rise to energy of 1 joule":

$$W = \frac{J}{s} = \frac{N \cdot m}{s} = \frac{kg \cdot m^2}{s^3} \tag{8}$$

Electrical energy describes the ability of electricity to perform a work, and the unit of measurement is joule (J) after James Prescott Joule. According to Eq. (7) J is equal to W.s. and at measurement of electrical quantities Ws or their multiplications, e.g. kWh, MWs, etc., are formally used more often than J and its multiplications.

In addition to electrical quantities shortly described herein, one can also meet with various other quantities, the full list of which as well as explanation and measurement method description would require much more space than one chapter in this encyclopedia offers.

3. Voltage, Current and Power Representation in Time and Frequency Domain

Measured electrical quantities, particularly voltage and current as well as their product equals to power can vary in time. To describe the time behavior of electrical quantities and to define measured parameters and characteristics of the quantities the signal theory is applied. A deeper explanation of the theory is out of the scope of this chapter - the signal theory is well processed in many excellent books and some fundamentals can be found also in other chapters of the EOLSS.

3. 1. Time Domain

Time behavior of electrical quantities affects methods and determines instrumentation convenient for the measurement. The simplest circumstance is when voltage and current are steady in time. A label dc (Direct Current) is usually used for such quantities, and capital letters are used for symbols, e.g., V_{dc}.

If the quantities vary in time, the label ac (Alternating Current) is usually used, e.g., V_{ac}. Shape and repetition frequency of variations can be almost any. According to the signal theory, the time varying voltage and current can be deterministic, where each value of the signal is fixed and can be determined by a mathematical expression, rule, or table with complete confidence or stochastic (random, e.g. thermal noise), where future values cannot be accurately predicted, and they can usually only be guessed based on the averages of sets of signals. Real electrical quantities always contain a stochastic component (noise, disturbance, etc.), even if they are supposed to be strictly deterministic. This is one of phenomena that cause uncertainty of measurement and make it impossible to perform absolutely precise and accurate measurements. The theory of uncertainties and errors in measurement is out of the scope of this chapter, and can be found in another chapter of the EOLSS and in some reference books.

The deterministic voltage and current are very often periodic, i.e., there is a minimal time period (a cycle) after which the quantity values repeat exactly. Various mathematical functions such as sine, triangular, square, etc. are used to model and describe the course of periodic electric quantities in time. Moreover, many parameters have been specified and used to characterize shape, distortion, imperfection and other properties of time varying real electrical quantities.

Very important and commonly used parameters of ac electrical quantities are amplitude, peak or peak-to-peak value (Figure 2), and effective value (Figure 3).

The effective value has been defined as equivalent dc value of the quantity that produces the same heating effect in the load as the measured ac quantity. For a periodic signal, e.g., voltage $v(t)$, with period T, the effective value V_{rms} is:

$$V_{rms} = \sqrt{\frac{1}{T} \int_0^T v^2(t) \, dt} \tag{9}$$

The abbreviation "rms" or sometimes "trms" comes from form of Eq. 5: "Root Mean Square" or "True Root Mean Square". The rms value of time varying quantity does not depend only on its amplitude, but also on a shape of the quantity time variation (waveform). Figure 3 depicts a few simple examples of some common waveforms.
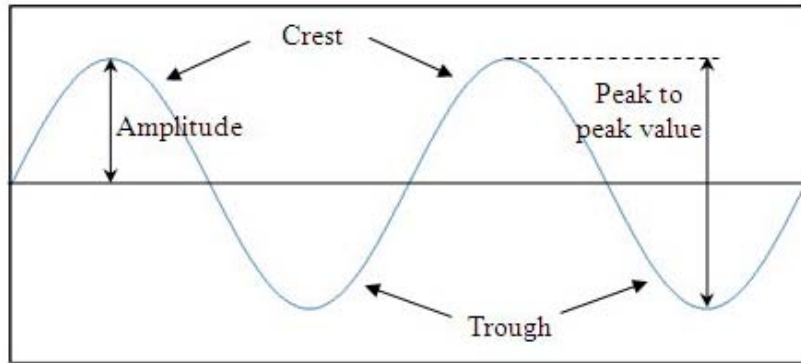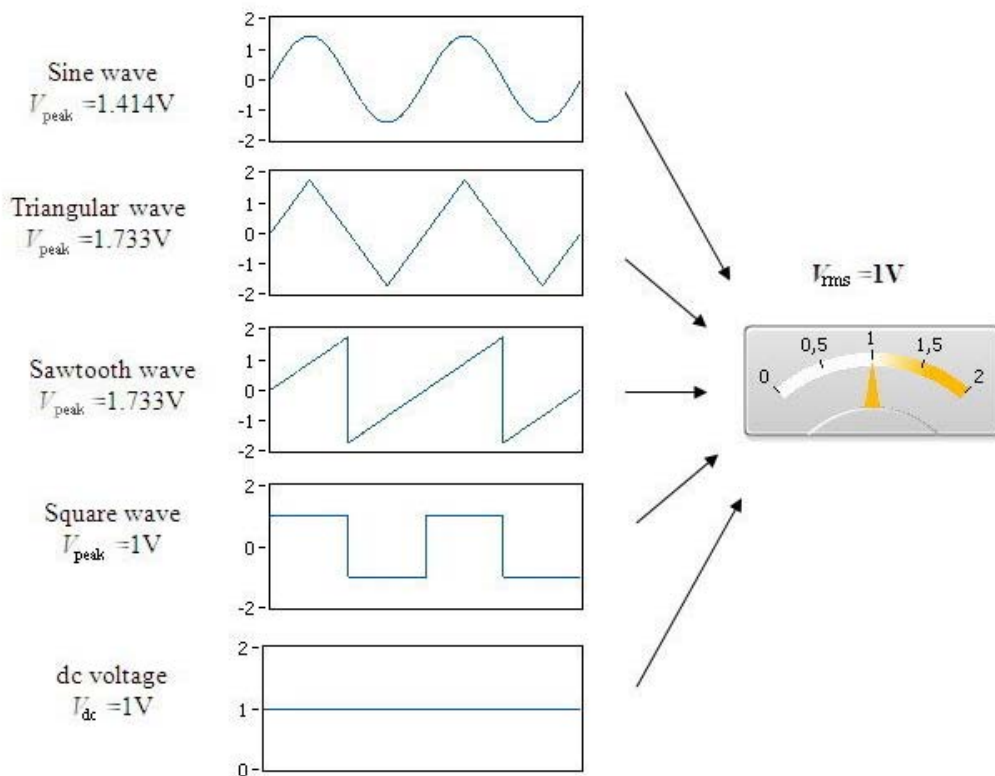

Figure 2. Commonly used parameters of ac quantity.

Figure 3. Example of common waveforms with rms value equal to 1V.

3. Frequency Domain

Measurement of electrical quantities in frequency domain (spectrum) is often required to determine certain quantity parameters. The spectrum describes distribution of the

quantity to its frequency components (harmonics), and it can be calculated by applying the Fourier transformation. For example, any periodic quantity consists of a unique variety of sine waves (harmonics) with frequencies that are integer multiplications of frequency of the basic harmonic component, with some amplitudes and phase shifts. If we know the component parameters and if we sum up all components with parameters together, we will get the origin shape of the quantity (Figure 4).
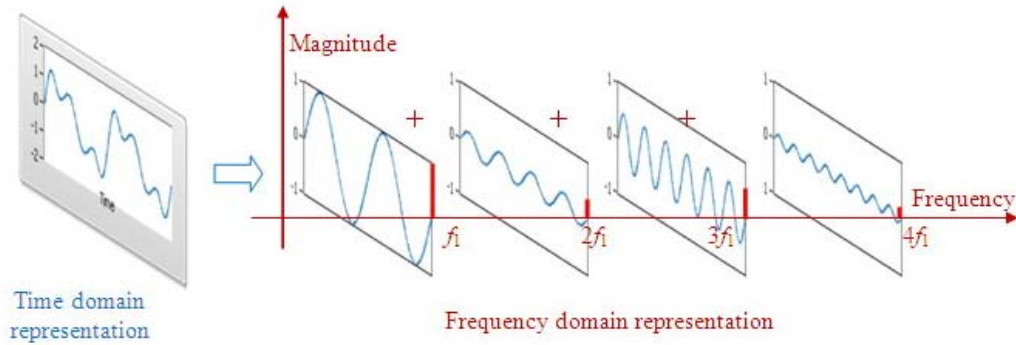

Figure 4. Signal representation in time and frequency domain.

Spectrum is usually plotted in two graphs: magnitudes of the frequency components versus frequency and phase shifts versus frequency (phase spectrum). Magnitude is a mathematical term for an object size. In case of spectrum, the magnitudes are sizes of spectral components, e.g., effective values, peak values, peak-to-peak values, etc. The magnitude spectrum is usually expressed in decibels (dB). The dB is a logarithmic relative unit derived from the ratio of powers and defined as follows:

$$P_{\mathrm{dB}} = 10\log\frac{P}{P_{\mathrm{ref}}} = 10\log\frac{V^2/R_Z}{V_{\mathrm{ref}}^2/R_Z} = 20\log\frac{V}{V_{\mathrm{ref}}} = 20\log\frac{I\cdot R_Z}{I_{\mathrm{ref}}\cdot R_Z} 20\log\frac{I}{I_{\mathrm{ref}}} \qquad (10)$$

Where P, V, and I are values to be recalculated to dB, P_{ref} is a chosen reference power, e.g., 1W, V_{ref} is a reference voltage, e.g., 1V, I_{ref} is a reference current, e.g., 1A and R_Z is a load resistance. Reference values may be chosen formally, e.g. 1A, 1V, 1W, etc., or they may be taken from a measurement, e.g., the magnitude of a basic component or carrier in spectrum. The main advantage of dB is that the logarithmic scale enables to present very small and very big values readably and at once (Figure 5).

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Biographical Sketch

Ján Šaliga, received his Degree (1982) and Ph.D (1995) in Radioelectronics at the Technical University of Kosice. He has been an associated professor of Electronics and Telecommunications at the Department of Electronics and Multimedia Telecommunication, Faculty of Electrical Engineering and Informatics, Technical University of Kosice, Slovakia since 2001. His teaching activities focus on Electronic measurement systems, Smart measurement systems, Data acquisition systems, and Software for measurement systems.

His present research interests cover the following areas: analogue to digital convertors and digital to analogue convertors, test methods, error correction methods, software for measurement systems, distributed measurement systems, and remote laboratories.

He is a co-author of more than 100 papers in proceedings of international scientific conferences and workshops and more than 10 publications in referred journals. He is a Member of Editorial board of two international journals and acts as a guest editor in Measurement Journal by Elsevier. He is a Member of International board IMEKO TC-4 Measurement of electrical quantities.