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 have various nature and characteristic. They also differ in the frequency range and spectral content from dc up to tens GHz and the level range from nano and micro units up to mega and giga units, No single instrument satisfies 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 well knowledge of the quantities, measure units and theory of electrical circuits.

Definitions of basic electric quantities and measure units are presented in chapter 2. Only the most common quantities such as voltage, current, power, resistance, capacitance and inductance are discussed. Some time and frequency aspects of electric quantities required for correct measurement and related parameters and characteristics are depicted in chapter 3 and 4 respectively. Chapter 5

gives overview of basic measurement techniques and instrumentation for electrical quantities and their characteristics. The glossary and bibliography in appendix summarises short explanation of essential terminology and refers additional reading for deeper study respectively.

1. Introduction

Nowadays the measurement of electrical quantities is an essential part of nearly any measurement. It could be realized as a measurement that 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 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 the place with their excess (place with negative charge) to the place with their deficiency (place with positive charge).

2.1. Electrical current and charge

According the convention, the positive direction of electric current is opposite, i.e. the positive direction of electric current is from the place with positive charge to the place with 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 international convention (SI), which 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”.

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 trough a surface, the current of 1 amper 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 measure charge 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 basic electrical quantities it is measured very rarely in praxis and if needed usually only calculated from measurement of other electrical quantities.

2.2. Electrical voltage

Electrical 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 quantities) and the unit of measure 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".

Electrical voltage and current are manifestation of electrical charge movement and the can be suppose to be "active" quantities. They can carry information in electronic circuits and systems or they can be supposed to be only expression of supplied and consumed electrical energy. Measurement methods and instrumentation as well as measured parameters differ from a point of view where and why the voltage and current are measured.

2.3. Resistance, capacitance, inductance and impedance

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

Resistance (symbol *R*) is 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 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".

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

$$i(t) = C \frac{\mathrm{d}v}{\mathrm{d}t} \tag{3}$$

The unit of measure capacitance 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".

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

$$v(t) = L \frac{\mathrm{d}i}{\mathrm{d}t} \tag{4}$$

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

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

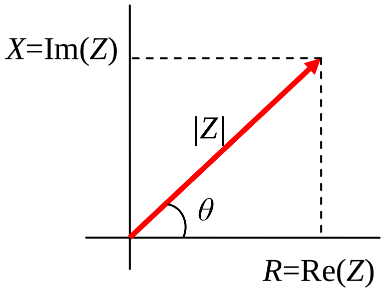

Figure 1. Expesions of complex impedance Z

In some cases, using the reciprocal of impedance is mathematically expedient. In which case $1/Z = 1/(R + \mathrm{j}X) = Y = G + \mathrm{j}B$, where Y represents admittance, G conductance, and B susceptance. The unit of admittance is the siemens (S). Impedance is a commonly used parameter and 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 is 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 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 change of electrical energy E in a time t:

$$p(t) = \frac{\mathrm{d}E}{\mathrm{d}t} \tag{6}$$

If a signal containing many frequency component is to be measured, the total power is 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 measure power 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":

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

Electrical energy describes the ability of electricity to perform a work and the unit of measure 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 its multiplications, e.g. kWh, MWs, etc., are formally more often used than J and its multiplications.

Except here above shortly described electrical quantities one can meet also with various other quantities, which full list, explanation and measurement method description would require much more place 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 multiplication equals to power can vary in time. To describe the time behaviour 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 Eolss encyclopaedia.

3. 1. Time domain

Time behaviour of electrical quantities affects methods and determines instrumentations convenient for the measurement. The simplest circumstance is when voltage and current are steady in time. 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., *Vac*. Shape and repetition frequency of variations can be nearly any. According to the signal theory the time varying voltage and current can be deterministic, which 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), which 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 impossible to perform absolutely precise and accurate measurement. The theory of uncertainties and errors in measurement is out of the scope of this chapter and can be found in another chapter of EOLSS encyclopaedia and in some referred 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 exactly repeat. 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 characterise shape, distortion, imperfection and other properties of time varying real electrical quantities.

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

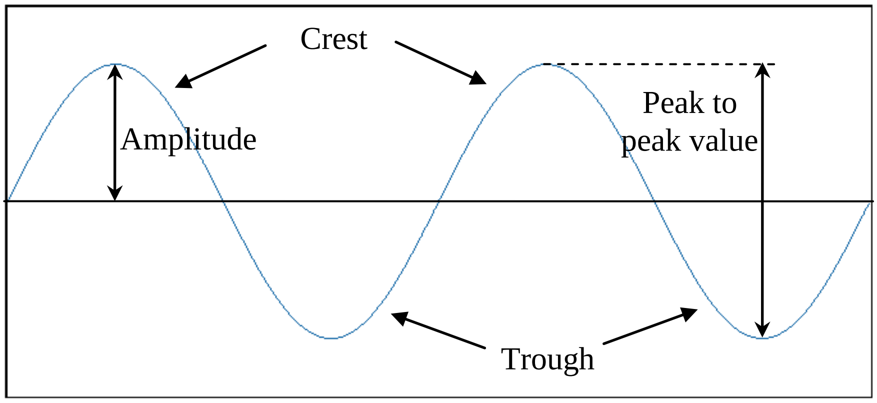

Figure 2. Common used parameters of ac quantity

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

$$V_{rms} = \sqrt{\frac{1}{T}\int_0^T v^2(t)\mathrm{d}t} \qquad (9)$$

The abbreviation RMS or sometimes TRMS comes from form of eq. 5: “Root Mean Square” or “True Root Mean Square”. RMS value of time varying quantity depends not on its amplitude about also on shape of quantity time variation (waveform). Figure 3 depicts a few simple examples of some common waveforms.

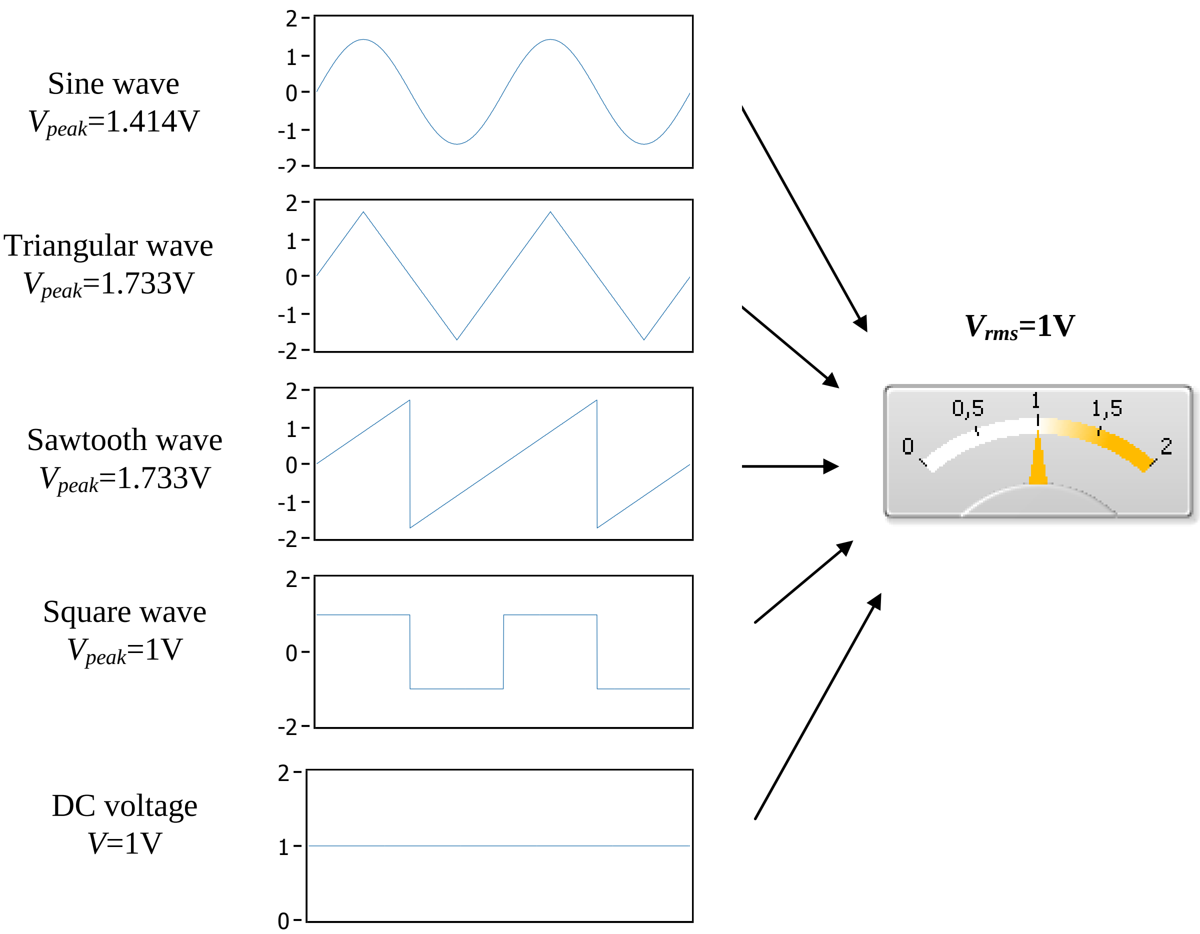

Figure 3. Example of common waveforms with RMS value equal to 1V.

3. Frequency domain

Measurement of electrical quantities in frequency domain (spectrum) is often required to determine some quantity parameters. The spectrum describes distribution of the quantity to its frequency components (harmonics) and it can be calculated by applying 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 all components with the parameters together we will get the origin shape of the quantity (Figure 4).

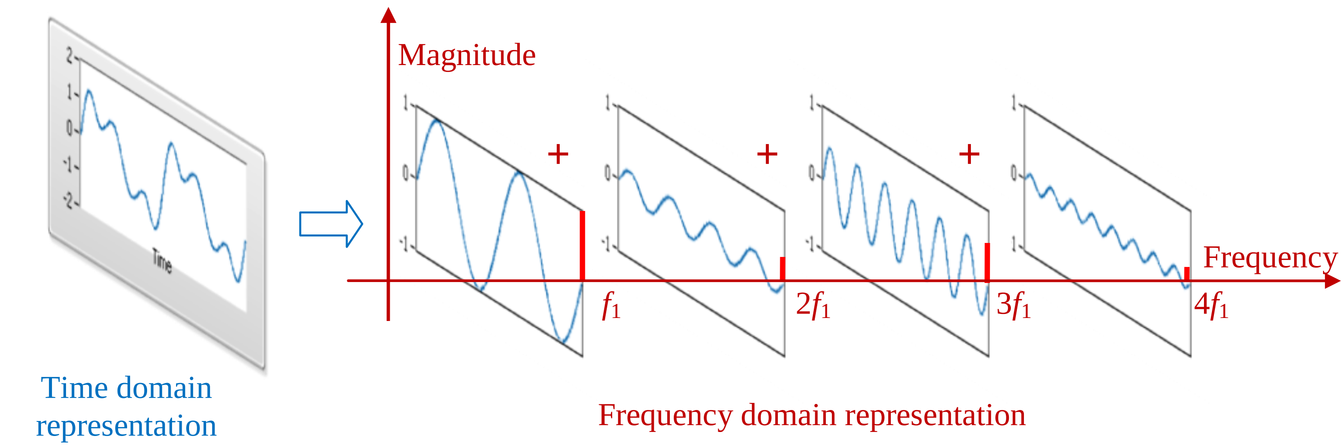

Figure 4. Signal representation in time and frequency domain.

Spectrum is usually plotted in two graphs: magnitudes of the frequency components versus frequency and phase shifts versus frequency (phase spectrum). Magnitude is mathematical term for a 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 logarithmic relative unit derived from ratio of powers and defined as follows:

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

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. The reference values may be chosen formally, e.g. 1A, 1V, 1W, etc., or they may be taken from a measurement, e.g., magnitude of 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).

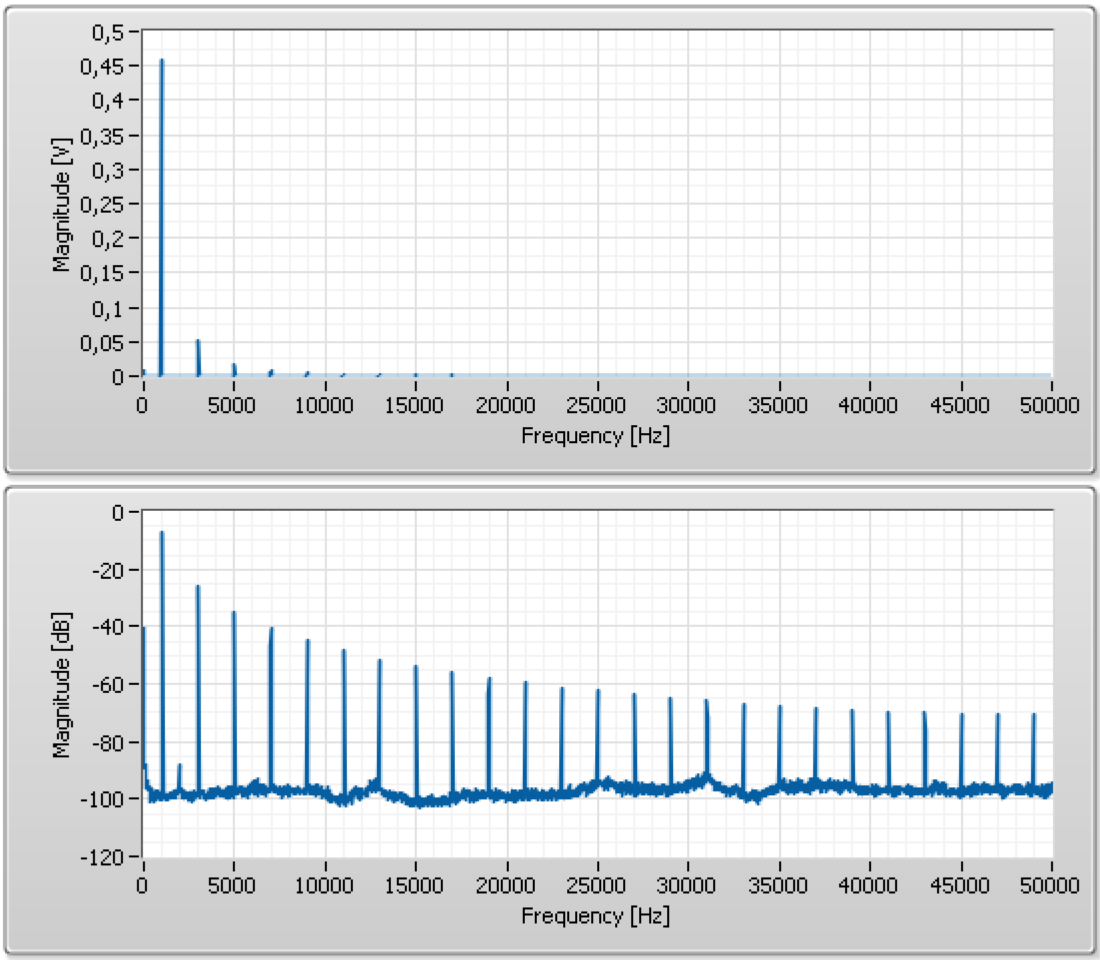

Figure 5. Example of magnitude spectrum of real triangle signal in linear scale and in dB.

Spectrum can be also expressed in the form of power spectrum describing power distribution of the signal on its frequency components. Power spectrum can be simply calculated from magnitude and phase spectrum and presented in one plot power in dB versus frequency. Very similar forms of displaying spectrum is power spectral density describing power distribution for 1Hz bandwidth and its integral called distribution function of power spectrum that expresses the total power in signal spectrum in range of frequencies from 0 up to given frequency.

Knowledge of frequencies of important components and frequency bandwidth determined from spectrum of a quantity are also very important. The different instrumentations and methods must be used for low frequency measurements and different for radiofrequency or even for ultra high frequency measurements. In general we can say that the higher frequencies are measured the more complex and expensive methods and instrumentations are needed.

We recommend being familiar with the signal theory fundaments at least from Eolss encyclopedia before reading the next paragraphs on measurement of electrical quantities.

4. Parameters of electrical quantities

Engineers and scientists utilize a huge number of characteristics that are typical for various fields of exploitation of electricity and characterize electrical quantities from various points of view. It is impossible to introduce all used parameters and to describe all methods and instrumentation for their measurement in this chapter. The interested reader is recommended for more details to read at least other chapters of EOLSS encyclopedia and the referenced books.

Measured characteristics of electrical quantities can be simple numeric values (scalar parameters) or functions (plots, dependence of measure parameter on other quantities, etc.). Value of dc voltage or current, resistance of conductor at a constant temperature, amplitude or RMS value of sine wave ac voltage, shape distortion of a quantity from required reference shape, noise disturbance, time jitter, phase noise, etc. are examples of simple scalar parameters

Functional parameters are, for example, the course of measured electrical quantity (ac voltage, current), in time or its spectrum (voltage, current), dependence of capacitance of a capacitor or inductance of a coil on temperature, frequency, or voltage , dependence of current on voltage in a nonlinear electronic component, etc.

From the other point of view the parameters can be divided according their sense to a few groups: parameters describing a size of the quantity, e.g. amplitude, peak value, RMS value, power etc., parameters characterizing ac quantities in time such as period, frequency, rise time, fall time, phase, etc., parameters characterizing quality and distortion of ac quantities such as *THD*, *SINAD*, *SNR*, etc. (see below) and a group of special parameters describing, for example, glitches and other short time fluctuations, various types of noise and its parameters, jitter, etc.

Except the basic parameters mentioned in the previous chapter such as amplitude, peak value, RMS value, etc., parameters describing quality and shape deterioration of time varying electrical quantities are very often used. Most of them have been defined in frequency domain.

Parameter "Total Harmonic Distortion" (*THD*) is used to quantify the distortion of real signal in relation to exact sine wave. *THD* in dB is defined in spectrum as follows:

$$THD_{dB} = 10\log\frac{\sum_{h=2}^{N} P_h}{P_1} = 20\log\frac{\sqrt{\sum_{h=2}^{N} A_h^2}}{A_1} \qquad (11)$$

where P_h and A_h are powers and magnitudes of higher harmonics, respectively and P_1 and A_1 is power and magnitude of the basic harmonic, respectively (see Figure 6).

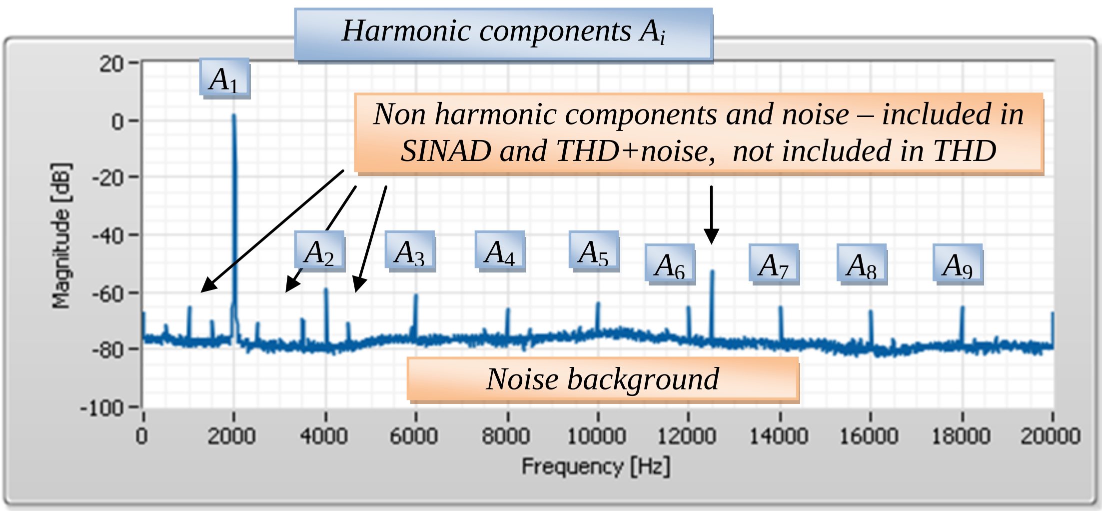

Figure 6. Signal components covered by definition of THD, SINAD, and THD+noise.

Another parameter is "Signal to Noise and Distortion ratio" (*SINAD*), which is defined as follows:

$$SINAD_{dB} = 10\log\frac{P_1}{\eta_{rms}^2} = 20\log\frac{A_{1rms}}{\eta_{rms}} \qquad (12)$$

where P_1 and A_{1rms} is power and RMS value of the first harmonic, respectively and η_{rms} effective value of total noise and distortion in the signal including random noise, higher harmonics, non harmonic components and other disturbances presented in the measured signal.

Reciprocal value of *SINAD* is parameter "Total Harmonic Distortion + noise (*THD* + *noise*).

$$THD + noise_{dB} = -SINAD_{dB} = 10\log\frac{\eta_{rms}^2}{P_1} \qquad (13)$$

SINAD is sometime mislead with *SNR* ("Signal to Noise Ratio"), which is commonly used to characterise quality of electrical signal at the presence of random noise. The main difference is that *SNR* definition does not cover the higher harmonics of signal:

$$SNR_{dB} = 10\log\frac{P_1}{\eta_{rms}^2 - \sum_{h=2}^{N} P_h} \qquad (14)$$

These and also other parameters can be simply measured by spectrum or signal analysers – see chapter 5.1.3

5. Measurement methods and instrumentations

We mentioned here above that electrical quantities measuring instruments and methods of measurement differs according to measurement quantity, required parameter, its size and frequency range, required uncertainty, etc. Many measurement methods are very complex. Therefore only a short overview of basic electrical quantities measured method and instrumentation is presented in following chapters. The interested reader can find more in some referred books and in other chapters of the EOLSS encyclopaedia.

5.1. Voltage, current and resistance measuring instruments

5.1.1. Meters

Voltage, current (both ac and dc), and resistance are probably the most common measured electrical quantities. Meters are the easiest to use instruments for performing these measurements. In the simplest case, each measurement type is performed by an individual instrument – a voltmeter measures voltage, ampermeter measures current and ohmmeter measure resistance. These instruments have many components in common that enable very effective integration of a few measurements into one instrument – multimeter.

Multimeter is general purpose meter that combines measurement instruments into simple general-purpose instrument. Multimeters often offer also other measuring functions such as capacitance and inductance measurement, measurement of frequency, temperature, etc. Classical instruments very equipped by analogue electromechanical indicator. Modern digital multimeters (DMM) convert analogue measurement quantity to number indicated on a digital display. On the other hand, presence of many display digit does not automatically means that multimeter has such a high accuracy, Meters often display more digits than their accuracy specification supports. This can be very misleading to the uninformed user.

Thank to digitalisation of measurement quantity and built-in microcontroller many modern DMM are also equipped by additional functions such as averaging, standard deviation calculation, memorising measured values (maximum, minimum), communication interfaces, etc. and they are even able to display the measured quantity in time and calculate spectrum.

Typical generalised block diagram of modern digital multimeter is shown in Figure 7. The input measured signal must first pass through signal conditioning and switching circuits comprising ranging, attenuation or amplification of signal and if the measured quantity is not voltage also its conversion to voltage. Current can be converted to voltage by simple known resistor or more accurate by active convertor with amplifier. Resistance measurements are performed by supplying a known dc current to an unknown resistance – converting the unknown resistance to an easily measured dc voltage according to Ohm law.

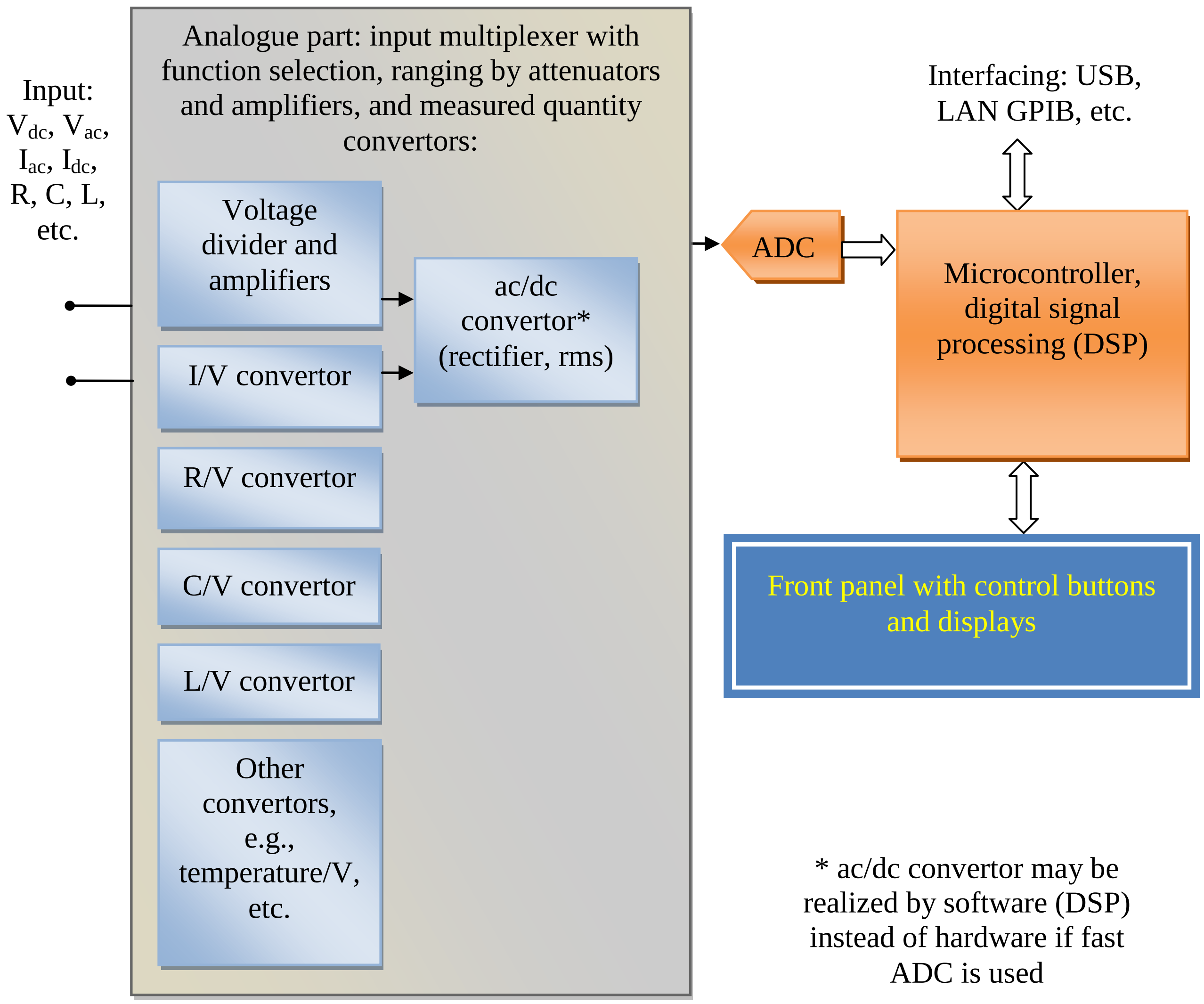

Figure 7. Principal block diagram of digital multimeter

Capacitance and inductance measurement are usually based on converting the quantity to the square pulses with mean (dc) voltage proportional to unknown measured capacitance or inductance. The conversion is based on monostable multivibrator that is triggered by low frequency oscillator (a few hundreds Hz). The time period of unstable state is given by known resistance and unknown measured capacitance or inductance. If amplitude of output signal from triggered monostable multivibrator is fixed, the mean value of the signal depends only on time constant of monostable multivibrator that is given by known resistance and unknown capacitance or inductance.

Measurement of ac quantities requires changing them into a dc voltage proportional to the measured parameter of ac quantities. This required parameter is usually effective value (RMS). The type of ac voltage to dc voltage converter employed in a meter is very critical. The most simple and cheap multimeters employ passive or active diode rectifiers with a low pass filtering (averaging). Output dc voltage of such rectifiers is proportional to mean value of rectified signal than cannot be simply recalculated to rms value. Therefore vendors calibrate these multimeters to indicate rms value for sinusoid shape of measured ac quantity by setting a convenient gain of internal circuit in multimeters although they measure the different parameter in principal. Such a multimeter measures and indicates correctly only sine wave (harmonic) signal. In case of measurement of non harmonic ac signal they measure with a systematic error that amount depends of difference of measured non harmonic signal from sine wave.

The higher quality DMM employs either integrated circuits that perform ac to rms conversion based on definition (eq. 5) with nonlinear operations (square/root or log/exp) or they sample and digitise the measured signal with a convenient high frequency and then calculate the rms values according to eq. (5) numerically from the digitised samples.

Many signals are combination of dc and ac component. Most DMM measure in ac mode only ac component (thank to ac coupling on input) and only dc component (mean value) in dc mode. On the other hand some rms DMM are dc coupled also in ac mode and measure true “heating value” of entire signal. Some have also user controlled switch between ac rms and ac+dc rms mode. The relation among dc, ac rms and total rms (ac and dc) is:

$$rms(ac + dc) = \sqrt{rms^2(ac) + dc^2} \qquad (15)$$

The common general purpose meters measure ac and dc voltage in ranges from milivolts to hundreds of volts and current from mikroampers to tens ampers. Nano and microvolmeters as well as nano and pikoampermeter are special meters to measure very small voltage and current. They require special technology and methods to reduce various interfering internal and external influences.

High currents are often measured by contactless clamp meters based on indirect measurement of magnetic field around the wire with measured current.

High voltage measurements (more than hundreds volts) require also specialised instrumentation and tools that have not only to perfume the measurement but also to protect person performing such a measurement against high voltage injury (see more in the referred bibliography.

Radio and high frequency ac current is not usually measured directly. Instead of current, high frequency voltage and power are measured. In the past frequency selective RF voltmeters were very popular but now they are obsolete. Selective voltmeters were very similar to RF receivers with a voltmeter on the output. Input RF signal is filtered by narrow bandpass tuneable filter. Frequency components of the input signal transferred thought the filter are rectified and measured by voltmeter. Step by step tuning enabled analyze spectrum and determine frequency components of measured high frequency signal. Nowadays powerful modern spectrum and signal analyzers are used instead of obsolete selective voltmeters.

5.1.2. Oscilloscopes

The word "oscilloscope" has evolved to describe any of a variety of electronic instruments used to observe, measure, or record time varying physical quantities and present the results in graphic form. The most typical application of oscilloscope is producing a two dimensional graphs with voltage presented at the input terminal plotted on the vertical axis and time plotted on horizontal axis. The measured voltage can be also something else than only a voltage directly scanned in an electrical circuit. Suitable transducers can change current, power, pressure, light, etc. into voltage. Oscilloscopes have multiple input channels (usually 2 – 4) so that simultaneous observation of multiple phenomena is possible. The key to any good oscilloscope system is its ability to accurately reconstruct a waveform – referred to as signal integrity.

The classical oscilloscope in analogue form, characterised by the use of a special tube (CRT) as a direct display device, is rather obsolete at the present. The modern digital oscilloscopes based on sampling, digitising, memorising, and digital processing of measured signals are more powerful, handy, and offers much wide variety of functions for user. Computer colour screen and soft buttons simplified meaningfully the analysis of measured signals and control of the scope. A conventional digital oscilloscope is known as a digital storage oscilloscope (DSO). The principal block diagram of DSO is shown in Figure 8.

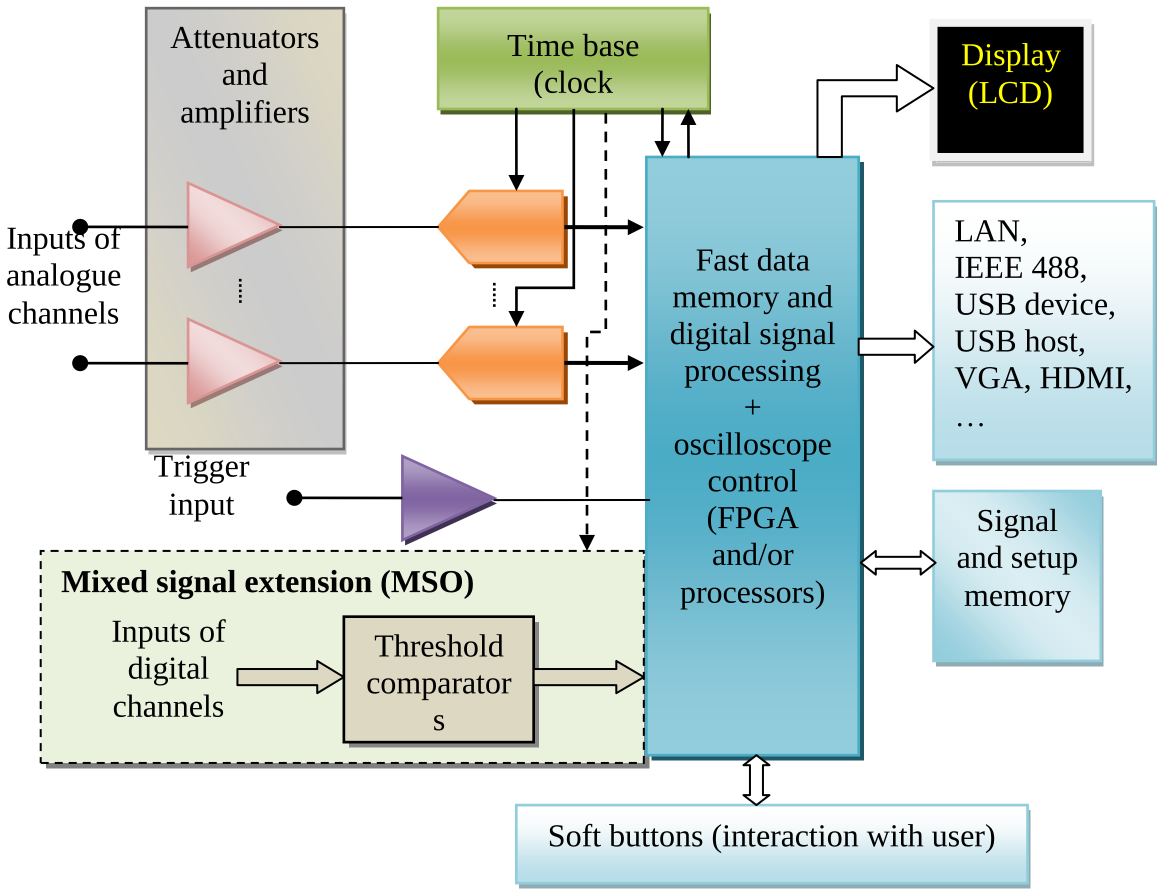

Figure 8. Principal block diagram of conventional digital oscilloscope (DSO) with optional extension for capturing signals on digital lines (MSO).

The measured voltage signal received on inputs is scaled in input analogue circuits to the amplitude range required by sampling ADCs. Signal can be also low pass filtered, dc component of the signal can be removed and offset positioning the signal in display in vertical direction can be added. The pre-processed signal is digitised by flash ADCs, memorised and processed by fast digital circuits (FPGA or digital signal processor). Digital processing enables to reconstruct the acquired signal for display, perform various automatic measurements in amplitude and time as well as to compare acquired parameters and measured signal with preset conditions and masks, perform sophisticated triggering, etc.

Sampling rate is controlled by time base of DSO. If the frequency of highest component of measured signal is less than half the oscilloscope's maximum sample rate, the real-time sampling is used. Here a complete record of samples is simultaneously captured on each channel in response to a single trigger event. Real-time sampling is the only way to capture fast, single-shot, transient signals with a digital oscilloscope. Equivalent Time repetitive sampling method, which is available in some oscilloscopes, enables measuring high frequency repetitive signals whose frequency exceeds half the oscilloscope's sample rate. The lack of equivalent time sampling method is requirement that the input signal be repetitive.

An oscilloscope's trigger function synchronizes the horizontal sweep at the correct point of the signal, essential for clear signal characterization. Trigger controls allow you to stabilize repetitive waveforms and capture single-shot waveforms. Edge triggering, available in analogue and digital oscilloscopes, is the basic and most common type. Many digital oscilloscopes offer numerous specialized trigger settings not offered by analogue instruments. These triggers respond to specific conditions in the incoming signal, making it easy to detect, for example, a pulse that is narrower or wider than it should be. Such a condition would be impossible to detect with a voltage threshold trigger alone. Advanced triggering capabilities in some oscilloscopes give you highly selective control. You can trigger on pulses defined by amplitude (such as runt pulses), qualified by time (pulse width, glitch, slew rate, setup-and-hold, and time-out), and delineated by logic state or pattern (logic triggering). Continual sampling and storing signal in FIFO memory buffer in parallel with signal processing for triggering enable user to capture and display what a signal did before a trigger event. Pre-trigger Viewing determines the length of viewable signal both preceding and following a trigger point.

Captured data and control button status (setup) can be stored in embedded memories and later recalled for comparison with measured signal and fast setup for a particular measurement. Information can be also copied to external USB memory. External monitor with lager screen can be used better displaying measured signals. Communication interfaces of DSO such as USB, IEEE 488, LXI (Ethernet) and RS232 give to DSO capability of control by a remote computer and integration to large, fully automated measurement and test systems.

Some modern digital oscilloscope can capture also data from digital lines in parallel with analogue channels. This is very similar to integration of a logic analyser and oscilloscope in one instrument called Mixed Signal Oscilloscope (MSO) – see Figure 8.

The essential condition for correct measurement by oscilloscope is to connect properly input of oscilloscope with a measurement point by a probe. The simplest passive probe also known as a "one-to-one or 1x probe is just a short shielded cable with coaxial connector at one end and sharp insulated metal point or tiny probe fix system at the other end. The 10x attenuator passive probe reduces circuit loading in comparison to a 1x probe and is an excellent general-purpose passive probe. Circuit loading becomes more pronounced for higher frequency and/or higher impedance signal sources, so be sure to analyze these signal/probe loading interactions before selecting a probe. The 10x attenuator probe improves the accuracy of your measurements, but also reduces the signal's amplitude at the oscilloscope input by a factor of 10. The 10x attenuation probe should be frequency compensated a oscilloscope before the first using. Frequency compensation balances probe's electrical properties to a particular oscilloscope and improves accuracy of measurement especially for high frequency components.

Increasing signal speeds and lower-voltage logic families make accurate measurement results difficult to achieve. Active and differential probes use specially developed integrated circuits to preserve the signal during access and transmission to the oscilloscope, ensuring signal integrity. Newer probe types provide the advantage of being able to use one setup, and get three types of measurements without adjusting probe tip connections.

5.1.3. Spectrum and signal analyzers

Traditionally, when you want to look at an electrical signal, you use an oscilloscope to see how the signal varies with time. This is very important information; however, it doesn't give you the full picture. To fully understand electrical signals and the performance of device, you also need to analyze the signal in the frequency domain and determine its frequency component. The spectrum analyzer is to the frequency domain as the oscilloscope is to the time domain. The separation and visualisation of the frequency components of signals may be attained in several ways.

5.1.3.1. Discrete Fourier spectrum analyzers

The Fourier analyzer basically takes a time-domain signal, digitizes it using digital sampling, and then performs the mathematics called Discrete Fourier transformation (DFT) required to convert it to the frequency domain, and display the resulting spectrum (Figure 9). Its fast mathematical form is called Fast Fourier transformation – FFT

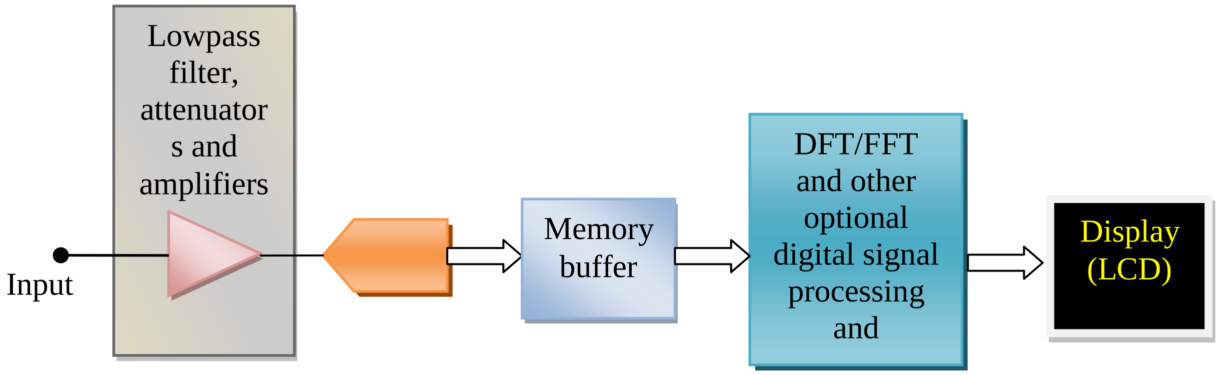

Figure 9. Principal block diagram of FFT spectrum analyzer.

It is as if the analyzer is looking at the entire frequency range at the same time using parallel filters measuring simultaneously. It is actually capturing the time domain information which contains all the frequency information in it. With its real-time signal analysis capability, the Fourier analyzer is able to capture periodic as well as random and transient events. It can measure very fast and even in real time not only magnitude but also phase spectrum as well as it can perform additional signal analysis such as analogue and digital demodulation, THD and SINAD analysis, etc. by application of various discrete mathematical algorithms and formulas. Spectrum analyzer equipped additional signal analysis function is called signal analyzer. However DFT analyzer has its limitations, particularly in frequency range (limited to a few hundred MHz), sensitivity, and dynamic range that are given primarily by ADC speed and resolution.

5.1.3.1. Swept spectrum analyzers and vector signal analyzers

These analyzers "sweep" across the frequency range of interest, displaying all the frequency components present. The swept receiver technique enables frequency domain measurements to be made over a large dynamic range and a wide frequency range, thereby making significant contributions to frequency-domain signal analysis for numerous applications, including the manufacture and maintenance of microwave communications links, radar, telecommunications equipment, cable TV systems, and broadcast equipment; mobile communication systems; EMI diagnostic testing; component testing; and signal surveillance.

The most common type of swept spectrum analyzer is the RF swept-tuned receiver with heterodyne filtering technique. It is the most widely accepted, general purpose tool for frequency-domain measurements. Heterodyne means to mix (multiply) two signals with high frequencies, filter and demodulate the product. Figure 10 shows principal block diagram of a simple RF swept spectrum analyzer.

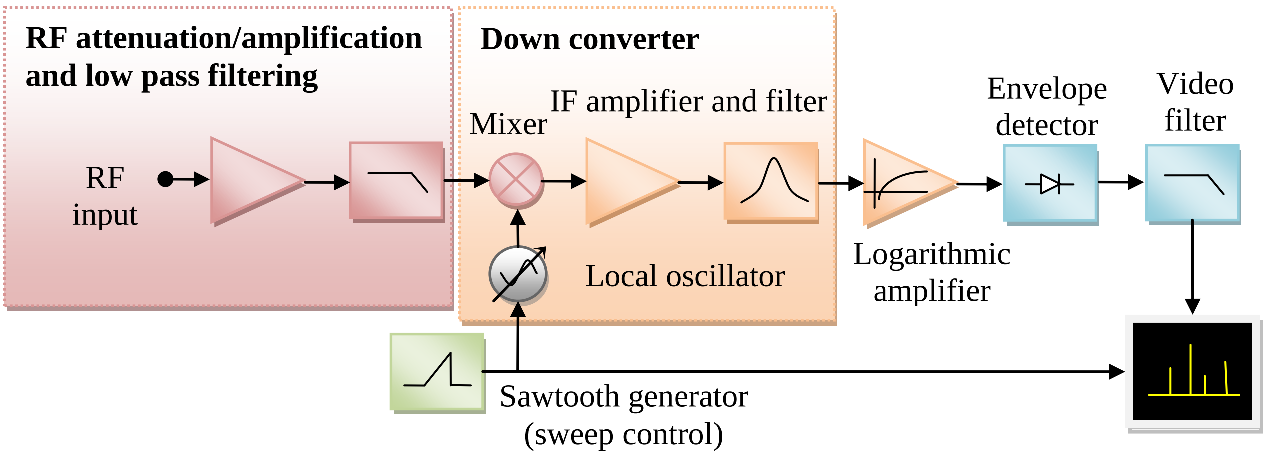

Figure 10. Principal block diagram of swept spectrum analyzer.

The analyzer converts the input signal with the aid of a mixer and a local oscillator to in intermediate frequency (IF). If local oscillator is tunable, the complete input frequency range can be converted to a constant intermediate frequency by varying the local oscillator frequency. The resolution of analyzer is then given by a filter at the IF with fixed central frequency.

To allow signals in a wide level range to be simultaneously displayed on the screen, the IF signal is compressed using of a logarithmic amplifier and its envelope is determined (rectification). The resulting signal is referred to as video signal. The video signal is applied to vertical axis and sweep control signal to horizontal axis simultaneously. Because the IF and local oscillator frequency are known, the input signal can thus be clearly assigned to the displayed spectrum.

In modern spectrum analyzers practically all processes are controlled by microprocessors and analogue functionality has been replaced by fast AD conversion and digital signal processing. These changes increased the accuracy of analyzers and allowed implementation of various advanced digital processing methods. A simplified block diagram is shown in Figure 11.

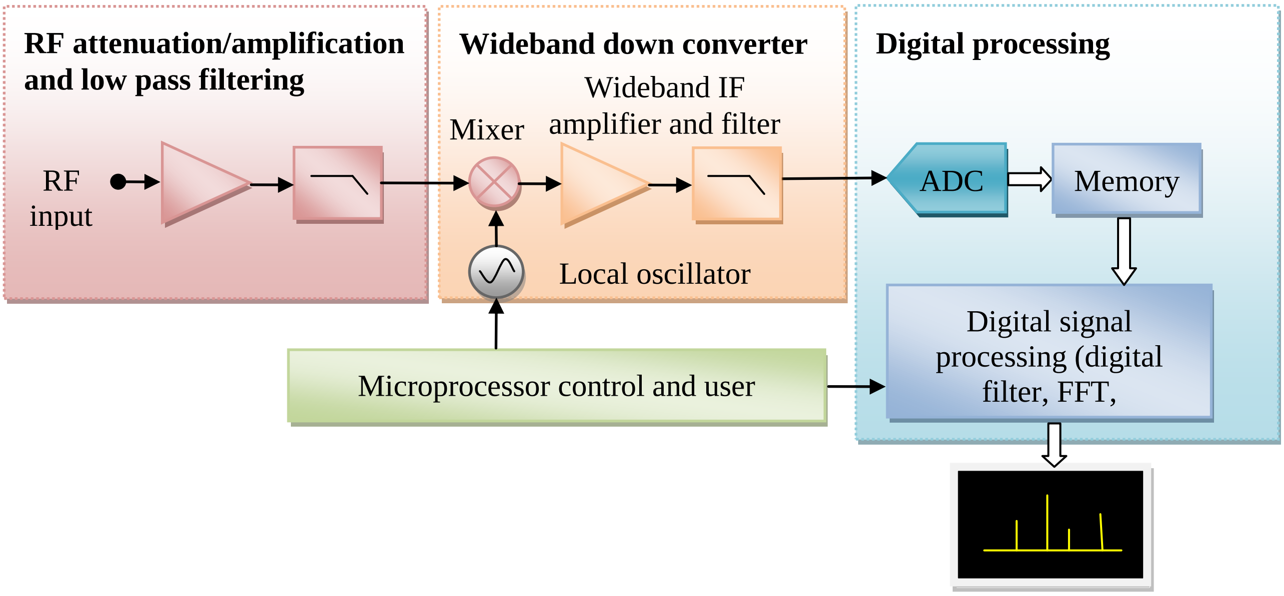

Figure 11. Principal block diagram of vector signal analyzer.

Analyzer digitizes and puts to memory all down converted RF signals in an instrument frequency range. The waveform in memory contains both the magnitude and phase information which can be used by digital signal processing for demodulation, measurements or display processing. Because of multifunctionality of such analyzers they are usually called vector signal analyzers (VSA). Within the VSA, an ADC digitizes the wideband IF signal with frequency band of tens MHz, and the downconversion, filtering, and detection are performed numerically. Transformation from time domain to frequency domain is done using DFT algorithms. The VSA can demodulate and measure parameters of analogue and digital modulations such as FM deviation, Code Domain Power, and Error Vector Magnitude (EVM and constellation diagrams). It also provides other displays such as channel power, power versus time, and spectrograms, etc. Real time vector signal analyzer perform signal acquisition and processing fast enough to continually process all signal components in the frequency band of interest. They employ parallel architecture for the continual signal digitalization and signal processing.

5.2. Electrical power and energy measuring instruments

Power meter called also watt meter may be used to measure the electrical power. Many factors influence he selection of a power measurement technique such as frequency range, power level, the spectral content of the signal, and the required accuracy. No single instrument satisfies all these requirements, and a wide variety of power meters and measurement methods are used by engineers.

5.2.1. Transition power meters

Transition power meter is to be connected between a source and a load. For low frequency application the meter contains voltage and current sensing elements. Outputs of sensing elements are processed (digitally in modern instrumentation) to produce the power measurement.

The simplest variant is measurement of dc power when instead of sensing elements a dc voltmeter and ampermeter may be used and dc power is then calculated according equation (5).

Transition power meters play very important role in producing, distribution, and consuming electrical energy. Here the voltage and the current vary in a low frequency sinusoidal manner and the voltage and current sine waves may have a phase shift (time shift). Three-phase power refers to three voltages that are offset from each other by 120° or one third of a cycle. These voltages (and currents) are usually carried on 3 wires. Three phase power is the standard throughout the world because it uses fewer and smaller conductors than multiple single phase systems to provide the same power. When we use electrical power we must connect a load. With ac power, the ideal configuration is when each of the three phases is connected to an equal load, also called a balanced load. Because the three phases are synchronized at 120° offset, you can connect all three of these wires together through equal loads to a fourth wire called neutral.

The maximum amount of work can be accomplished when the voltage and current are exactly in phase (zero phase shift). The more out of phase the voltage and current are, the less useful work can be accomplished. The degree to which the voltage and current are in phase is expressed by the power factor that cosine of phase shift between voltage and current. Apparent power is a power calculated simply by multiplication of rms voltage and current in ac power system. But the apparent power is not real active power that can perform a work. The active power can be calculated from equation (16):

$$P_a = V_{rms} \cdot I_{rms} \cdot \cos\phi \qquad (16)$$

where ϕ is the phase shift between the voltage and current sine waves. Nonworking power is the reactive power:

$$P_r = V_{rms} \cdot I_{rms} \cdot \sin\phi \qquad (17)$$

To measure active and reactive power the meter has to be phase sensitive or a phase metering component must be integrated in power meter.

Nowadays the measurement of power in power distribution systems is bound with power quality measurement. Power quality measurement covers not only measurement of power factor but also various distortion, and imperfection in voltage and current sine wave such as harmonic distortion, short and long interruptions, dips and swells, flickers, transients surges, etc. Some of them can be measured by spectral methods; others require a special technique and instrumentation. Power quality measurement is out of scope of this article and the interested reader can find some recommended works in bibliography here below.

Instrumentation and technique of electrical power and energy measurement in power generating and distribution systems are well processed in other chapters of EOOLS encyclopedia and in referred bibliography sources and they are out of the scope of this article.

5.2.2. Absorption power meters

Absorption type of power meter generally comprises artificial load with power sensor and power meter. The load is connected instead of operating load. Dissipated power in the load is sensed by the sensor that produce dc or low frequency signal proportional to average power applied in the load. Power meter processes the sensor signal (amplifies and digitizes the signal) and produces readout of the power level. (Figure 12).

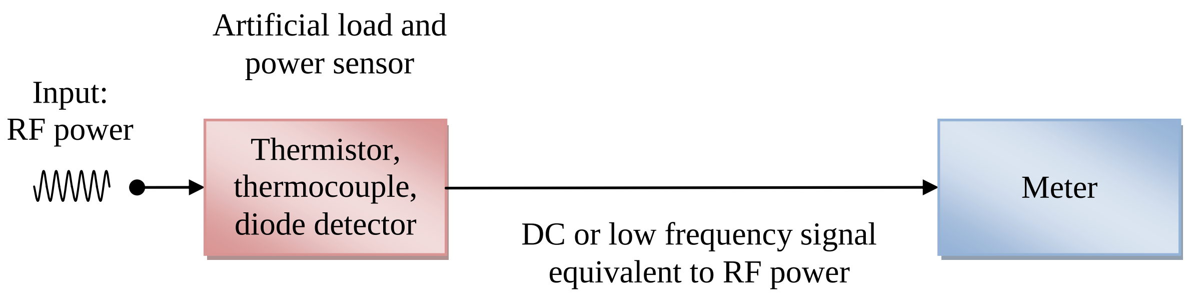

Figure 12. Principal block diagram of absorption power meter

This technique is typical for high frequency power measurements up to tens GHz. Because of load and sensor various imperfections the calibration of absorption power meter is required before each new measurement to ensure accurate results.

5.3. Resistance, capacitance, inductance, and impedance measuring instruments

Resistance can be simply measured by multimeters (see chapter 5.1.1. Meters). Because of dc test signal the measured resistance is also called dc resistance. The alternative method for dc resistance measurement is bridge method. The word "bridge" was originally used for a null indicator (*NI*) bridging the two points of balancing arms (Figure 13). The main advantages of the bridges are high accuracy, low costs, dependence of results only on passive reference components and independence of results on test signal source quality and nonlinearity of null indicator. The disadvantage of resistive bridges is need of manual balancing.

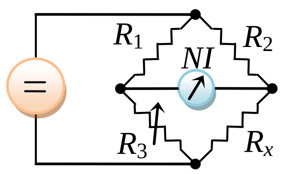

Figure 13. Principal resistance bridge with null indicator (*NL*).

Bridges operates on the principle of comparison. That is a known (standard) value is adjusted until it is equal to the unknown value. Then the unknown resistance can be simply calculated from three known resistances at the condition of bridge balance (zero current across null indicator):

$$R_x = R_3 \frac{R_2}{R_1} \qquad (18)$$

We can measure capacitance or inductance individually by simply technique at low frequencies using multimeter (see chapter 5.1.1. Meters) ignoring complex structure and behavior of real electronic component. Real-world devices have parasitic - unwanted inductance in resistors, unwanted resistance in capacitors, unwanted capacitance in inductors, etc. Different materials and manufacturing technologies produce varying amounts of parasitics. In real electric circuit especially on higher frequencies these parasitic quantities cannot be simply separated from the complex properties of an electronic element. Therefore the complex impedance is measured instead of simple capacitance, inductance, or resistance.

Impedance varies depending on the operating conditions of the components such as test signal frequency and level, temperature, dc bias, etc. Moreover measured value differs from real value by an error. The error reflects the instrument's inherent residuals and inaccuracies.

Traditional impedance test methods are based on bridges. A variety of bridges have been implemented depending on the applications. The main disadvantages are the need to be manually balanced and narrow frequency coverage with a single instrument. More over balancing is step by step process requiring iterative balancing manipulation of real and imaginary parts compensation components (see example of Schering bridge principal in Figure 14)

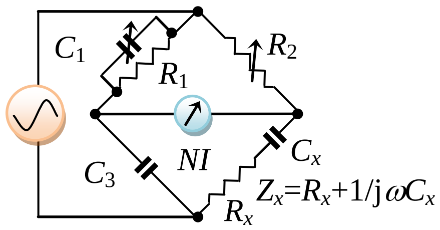

Figure 14. Example of impedance bridge – principal Schering bridge.

Nowadays auto-balancing bridge is probably the most often used method. A single instrument can cover wide frequency range from tens Hz up to hundreds MHz as well as wide range of measured impedances. The process of measurement is fully automated with digital readout not only in the form of complex impedance but result may be also recalculated to various equivalent circuits. The principal block diagram is shown in Figure 15.

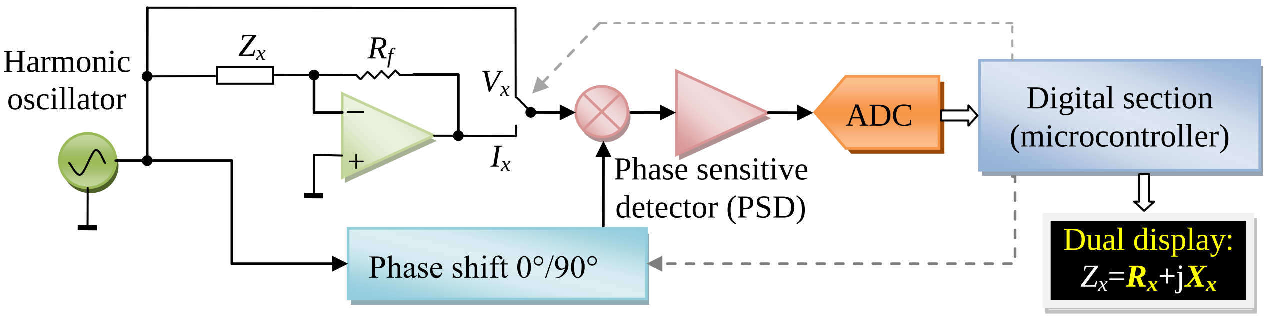

Figure 15. Principal block diagram of auto-balancing bridge.

In this block diagram, the reference resistor R_f is connected to the null point (P) and the residual voltage there is amplified to be fed back to the other end of the resistor to establish the null condition. Once null condition is achieved the impedance Z_x is calculated as follows:

$$Z_x = R_x + jX_x = \frac{V_x}{I_x} = \frac{V_x}{V_R / R_f} = R_f \frac{\mathrm{Re}(V_x) + j\,\mathrm{Im}(V_x)}{\mathrm{Re}(V_R) + j\,\mathrm{Im}(V_R)} \qquad (19)$$

where Re(.) and Im(.) is real and imaginary part respectively extracted by phase sensitive detector driven with 0° and 90° reference phase signals (*PSD* in Figure 16). The extracted signals are digitized and calculation is performed by a microcontroller. Results are usually presented in dual display that indicates real and imaginary component of measured impedance or values of equivalent resistance, capacitance, inductance in serial or parallel connection.

The alternate methods for measurements up to tens GHz are RF I-V method and network analysis method.

Connecting a tested component to the measurement terminals of the auto-balancing bridge instrument and DMM requires a test fixture or test cables. The selection of the appropriate test fixtures and cables as well as connection configuration is important for maximizing the total measurement accuracy. The most common two-terminal configuration is the simplest method of connecting a DUT but contains many error sources. Because of the same cables are employed for tests signal source connection to the tested device and for sensing voltage from it the result of measurement covers serial connection of device under test and connecting cable. For accurate low resistance and RF measurements the four wire connection is used. The current supply leads and voltage sensing leads are independently provided and they are connected together as close to measured device as possible.

6. Conclusions

In this work an overview of the essential principles of measurement of electrical quantities is presented. Particular attention has been dedicated to the definition of the quantities, units of measurement and instrumentations convenient for measurement in wide range of measured parameters, magnitudes and frequency. The state of art of instrumentation is explained using principal block diagram and essential mathematical formulas.

Glossary

Absorption power meter: An instrument measuring power by power sensor with artificial load. Absorption power meter are typical for radio frequency and microwave measurements.

Alternating Current (AC): A signal in which the current and voltage vary in a repeating pattern over time. Also used to indicate signal coupling type.

Amper (A): The basic unite of measure of electrical current.

Analogue-to-Digital Converter (ADC): A digital electronic component that converts an electrical signal into discrete binary values.

Analogue Signal: A signal with continuously variable voltages.

Attenuation: A decrease in signal amplitude during its transmission from one point to another.

Auto-balancing bridge: Fully automated electronic bridge to measure impedance.

Bandwidth: The range of frequencies that can be conducted or amplified within certain limits. Bandwidth is usually specified by the –3dB (half-power) points.

Bridge: An electronic circuit used for dc resistance and ac impedance measurements. It typically consists of two arms and null indicator.

Capacitance: In a capacitor or system of conductors and dielectrics, that property which permits the storage of electrically separated charges when potential differences exist between the conductors. Capacitance is related to the charge and voltage as follows: $C = Q/V$, where C is the capacitance in farads, Q is the charge in coulombs, and V is the voltage in volts

Coulomb (C): The basic unit of measure electrical charge. One coulomb is approximately 1.602176487×10^{19} of elementary charges.

Decibel (dB): The logarithmical unite to measure voltage, power, current, etc.

Digital Multimeter (DMM): an electronic instrument that measures voltage, current, resistance, or other electrical parameters by converting the analog signal to digital information and display. The typical simple five-function DMM measures dc volts, dc amps, ac volts, ac amps, and resistance.

Digital Oscilloscope: a type of oscilloscope that uses an analog-to-digital converter (ADC) to convert the measured voltage into digital information.

Digital Signal: A signal whose voltage samples are represented by discrete binary numbers.

Digital Signal Processing (DSP): The application of algorithms to improve the accuracy of measured signals.

Digital Storage Oscilloscope (DSO): A digital oscilloscope that acquires signals via digital sampling (using an analogue-to-digital converter). It uses a serial-processing architecture to control acquisition, user interface, and the raster display.

Digitize: The process by which an analogue-to-digital converter (ADC) in the horizontal system samples a signal at discrete points in time and converts the signal's voltage at these points into digital values called sample points.

Direct Current (DC): A signal with a constant voltage and/or current. Also used to indicate signal coupling type.

Effective value (RMS): The effective value is equivalent to dc value of the quantity that produces in the load the same heating effect as the measured ac quantity.

Electrical current: movement of electric charge from the place with positive charge to the place with negative charge

Electrometer: a highly refined dc multimeter. In comparison with a digital multimeter, an electrometer is characterized by higher input resistance and greater current sensitivity. It can also have functions not generally available on DMMs (e.g., measuring electric charge, sourcing voltage).

Electromotive force or voltage (EMF): EMF is generally used in context of a voltage difference caused by electromagnetic, electrochemical, or thermal effects

Error: The deviation (difference or ratio) of a measurement from its true value. True values are by their nature indeterminate. See also Random Error and Systematic Error.

Fall Time: The time required for a signal to change from a large percentage (usually 90%) to a small percentage (usually 10%) of its peak-to-peak value. See also Rise Time.

Farad (F): The basic unit of measure capacitance. 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.

Frequency: The number of times a signal repeats in one second, measured in Hertz (cycles per second). The frequency equals 1/period.

Four-Terminal Resistance Measurement: A measurement where two leads are used to supply a current to the unknown, and two different leads are used to sense the voltage drop across the resistance. The four-terminal configuration provides maximum benefits when measuring low resistances.

FFT analyzer: Spectral analyzer digitizing measured signal and calculating its spectrum using discrete (fast) Fourier transformation.

Glitch: An intermittent, high-speed error in a circuit.

Henry (H): The basic unit of measure inductance. 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.

Inductance (L): The inductance is ability to accumulate electrical energy in the form of magnetic field. Inductance is fundamental property of inductor.

Impedance (Z): the electrical quantity expressing relation between ac voltage and ac current in complex electronic component or structure

Logic Analyzer: An instrument used to make the logic states of many digital signals visible over time. It analyzes the digital data and can represent the data as real-time software execution, data flow values, state sequences, etc.

Magnitude: size of spectral component, e.g., peak value, rms value, peak to peak value, etc.

Mixed signal oscilloscope (MSO): A digital oscilloscope with option for measurement of digital signal (logic analyzer).

Nanovoltmeter: A voltmeter optimized to provide nanovolt sensitivity (generally uses low thermoelectric EMF connectors, offset compensation, etc.).

Noise: Any unwanted signal imposed on a desired signal.

Ohm (Ω): The basic unit of measure of resistance and impedance. 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.

Oscilloscope: An instrument that creates voltage changes visible over time by applying the input signal (conditioned and amplified) to the vertical axis of a screen (a cathode-ray tube – CRT or a computer screen – LCD) and the second signal usually linearly dependent on time to horizontal axis.

Phase: The amount of time that passes from the beginning of a cycle to the beginning of the next cycle, measured in degrees or radians.

Phase Shift: The difference in timing between two otherwise similar signals.

Picoammeter: An ammeter optimized for the precise measurement of small currents. Generally, a feedback ammeter.

Probe: An oscilloscope input device, usually having a pointed metal tip for making electrical contact with a circuit element, a lead to connect to the circuit's ground reference, and a flexible cable for transmitting the signal and ground to the oscilloscope.

Random Error: The mean of a large number of measurements influenced by random error matches the true value. See also Systematic Error.

Range: A continuous band of signal values that can be measured or sourced. In bipolar instruments, range includes positive and negative values.

Resistance (R): The electrical quantity that indicates how much dc voltage is necessary to create a certain amount of dc current in a component.

Resolution: The smallest portion of the input (or output) signal that can be measured (or sourced) and displayed.

Rise Time: The time required for a signal to change from a small percentage (usually 10%) to a large percentage (usually 90%) of its peak-to-peak amplitude. See also Fall Time.

RMS (TRMS): The abbreviation for effective value coming from mathematical equation: "Root Mean Square" or "True Root Mean Square".

Sampling: The conversion of a portion of an input signal into a number of discrete electrical values for the purpose of storage, processing and/or display.

Sample Rate: Refers to how frequently a device takes a sample of the signal, specified in samples per second (S/s).

Signal Integrity: The accurate reconstruction of a signal, determined by the systems and performance considerations of an oscilloscope, in addition to the probe used to acquire the signal.

Signal to Noise and Distortion ratio (SINAD): The parameter of measure signal distortion in comparison with ideal sine wave. The reciprocal value of THD+noise.

Sine Wave: A common curved wave shape that is mathematically defined by functions sine or cosine.

Spectrum: The spectrum describes distribution of the quantity to its frequency components (harmonics) and it can be calculated by applying Fourier transformation.

Swept spectrum analyzer: The spectrum analyzer that "sweeps" across the frequency range of interest (usually employing super heterodyne principle), displaying all the frequency components present.

Systematic Error: The mean of a large number of measurements influenced by systematic error deviates from the true value. See also Random Error

Time Base: Oscilloscope circuitry that controls the timing of the sweep. The time base is set by the seconds/division control.

Total Harmonic Distortion (THD): The parameter of measure distortion of real signal in comparison with ideal sine wave. Only the higher harmonics are taken in account.

Total Harmonic Distortion + noise (*THD + noise*): The parameter of measure distortion of real signal in comparison with ideal sine wave. All distrusting spectral components including noise are taken in account.

Transition power meter: An instrument measuring power by sensing transition current and voltage on load. Transition power meter are typical for low frequency measurements.

Trigger: The circuit that references a horizontal sweep on an oscilloscope or an external stimulus that initiates one or more instrument functions. Trigger stimuli include: an input signal, the front panel, an external trigger pulse, and IEEE-488 bus X, talk, and GET triggers.

Two-Terminal Resistance Measurement: A measurement where the source current and sense voltage are applied through the same set of test leads.

Vector signal analyzer (VSA): The spectrum analyzer that digitizes wide band IF signals and employs digital signal processing to analyze measured signal.

Volt (V): The basic unit of measure of electrical voltage. 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.