SECTION 15

MEASUREMENT SYSTEMS

Measurement circuits are critical in the analysis, design, and maintenance of electronic systems. For those who work in electronics, these circuits and systems become the eyes into the world of the electron that cannot be directly seen. The main objective of such systems is to not influence what is being measured or observed. This is accomplished by a range of types of measurement circuits. All of these are considered in this section.

A key element of systems that measure is how the measurement is actually made. Without an understanding of how the measurement is made, one cannot understand the limitations. It is possible to make a measurement and be off by several orders of magnitude. We look at the process of making measurements and what to look for so that one can have a level of confidence in the measurement.

Substitution and analog measurements have been an important mainstay of this field. Unlike measurements that involve some digital systems, the accuracy and precision of the measurements depend totally on the precision of elements used in the measurement systems. We look at a variety of measurement techniques using substitution and look at analog devices like ohmmeters. Digital instruments have many advantages especially when used in data acquisition systems.

An important component of measurement systems is the transducer. The transducer converts a physical quantity into an electrical signal that can be measured by a measurement system. Knowing the characteristics, especially its limitations, helps in understanding the precision with which measurements can be made. It is in the area of transducers and sensors that we have seen some of the most dramatic advances.

Bridge circuits gave us the first opportunity to actually make measurements without "loading" the circuit being measured. The accuracy of the measurements merely depended on the precision of the elements used in the bridge.

We need AC impedance measurements to develop the small signal characteristics of a circuit or system and to evaluate the stability of the circuit or system. These kinds of measurements are important in a variety of applications from the space station to how well your television works. C.A.

In This Section:

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CHAPTER 15.1
PRINCIPLES OF MEASUREMENT CIRCUITS

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DEFINITIONS AND PRINCIPLES OF MEASUREMENT

Precision is a measure of the spread of repeated determinations of a particular quantity. Precision depends on the resolution of the measurement means and variations in the measured value caused by instabilities in the measurement system. A measurement system may provide precise readings, all of which are inaccurate because of an error in calibration or a defect in the system.

Accuracy is a statement of the limits that bound the departure of a measured value from the true value. Accuracy includes the imprecision of the measurement along with all the accumulated errors in the measurement chain extending from the basic reference standards to the measurement in question.

Errors may be classified into two categories, systematic and random. *Systematic errors* are those which consistently recur when a number of measurements are taken. Systematic errors may be caused by deterioration of the measurement system (weakened magnetic field, change in a reference resistance value), alteration of the measured value by the addition or extraction of energy from the element being measured, response-time effects, and attenuation or distortion of the measurement signal. *Random errors* are accidental, tend to follow the laws of chance, and do not exhibit a consistent magnitude or sign. Noise and environmental factors normally produce random errors but may also contribute to systematic errors.

The arithmetic average of a number of observations should be used to minimize the effect of random errors. The arithmetic average or mean X of a set of n readings $X_1, X_2, \ldots, X_n$ is

$$X = \sum X_i / n$$

The dispersion of these reading about the mean is generally described in terms of the standard deviation σ, which can be estimated for n observations by

$$s = \sqrt{\frac{\sum (X_i - X)^2}{n-1}}$$

where s approaches σ as n becomes large.

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A *confidence interval* can be determined within which a specified fraction of all observed values may be expected to lie. The *confidence level* is the probability of a randomly selected reading falling within this interval. Detailed information on measurement errors is given in Coombs (Chap. 15.5).

Standardization and calibration involve the comparison of a physical measurement with a reference standard. Calibration normally refers to the determination of the accuracy and linearity of a measuring system at a number of points, while standardization involves the adjustment of a parameter of the measurement system so that the reading at one specific value is in correspondence with a reference standard. The numerical value of any reference standard should be capable of being traced through a chain of measurements to a National Reference Standard maintained by the National Institute of Standards and Technology (formerly the National Bureau of Standards).

The range of a measurement system refers to the values of the input variable over which the system is designed to provide satisfactory measurements. The range of an instrument used for a measurement should be chosen so that the reading is large enough to provide the desired precision. An instrument having a linear scale, which can be read within 1 percent at full scale, can be read only within 2 percent at half scale.

The resolution of a measuring system is defined as the smallest increment of the measured quantity which can be distinguished. The resolution of an indicating instrument depends on the deflection per unit input. Instruments having a square-law scale provide twice the resolution of full scale as linear-scale instruments. Amplification and zero suppression can be used to expand the deflection in the region of interest and thereby increase the resolution. The resolution is ultimately limited by the magnitude of the signal that can be discriminated from the noise background.

Noise may be defined as any signal that does not convey useful information. Noise is introduced in measurement systems by mechanical coupling, electrostatic fields, and magnetic fields. The coupling of external noise can be reduced by vibration isolation, electrostatic shielding, and electromagnetic shielding. Electrical noise is often present at the power-line frequency and its harmonics, as well as at radio frequencies.

In systems containing amplification, the noise introduced in low-level stages is most detrimental because the noise components within the amplifier passband will be amplified along with the signal. The noise in the output determines the lower limit of the signal that can be observed.

Even if external noise is minimized by shielding, filtering, and isolation, noise will be introduced by random disturbances within the system caused by such mechanisms as the Brownian motion in mechanical systems, Johnson noise in electrical resistance, and the Barkhausen effect in magnetic elements. Johnson noise is generated by electron thermal agitation in the resistance of a circuit. The equivalent rms noise voltage developed across a resistor R at an absolute temperature T is equal to $\sqrt{4kTR\,\Delta f}$, where k is Boltzmann's constant (1.38×10^{-23} J/K) and Δf is the bandwidth in hertz over which the noise is observed.

The bandwidth Δf of a system is the difference between the upper and lower frequencies passed by the system (Chap. 15.2). The bandwidth determines the ability of the system to follow variations in the quantity being measured. The lower frequency is zero for dc systems, and their response time is approximately equal to $1/(3\Delta f)$. Although a wider bandwidth improves the response time, it makes the system more susceptible to interference from noise.

Environmental factors that influence the accuracy of a measurement system include temperature, humidity, magnetic and electrostatic influences, mechanical stability, shock, vibration, and position. Temperature changes can alter the value of resistance and capacitance, produce thermally generated emfs, cause variations in the dimensions of mechanical members, and alter the properties of matter. Humidity affects resistance values and the dimensions of some organic materials. DC magnetic and electrostatic fields can produce an offset in instruments which are sensitive to these fields, while ac fields can introduce noise. The lack of mechanical stability can alter instrument reference values and produce spurious responses. Mechanical energy imparted to the system in the form of shock or vibration can cause measurement errors and, if severe enough, can result in permanent damage. The position of an instrument can affect the measurements because of the influence of magnetic, electrostatic, or gravitational fields.

TRANSDUCERS, INSTRUMENTS, AND INDICATORS

Transducers are used to respond to the state of a quantity to be measured and to convert this state into a convenient electrical or mechanical quantity. Transducers can be classified according to the variable to be measured. Variable classifications include mechanical, thermal, physical, chemical, nuclear-radiation, electromagnetic-radiation, electrical, and magnetic, as detailed in Sec. 8.

Instruments can be classified according to whether their output means is analog or digital. Analog instruments include the d'Arsonval (moving-coil) galvanometer, dynamometer instrument, moving-iron instrument, electrostatic voltmeter, galvanometer oscillograph, cathode-ray oscilloscope, and potentiometric recorders. Digital-indicator instruments provide a numerical readout of the quantity being measured and have the advantage of allowing unskilled people to make rapid and accurate readings.

Indicators are used to communicate output information from the measurement system to the observer.

MEASUREMENT CIRCUITS

Substitution circuits are used in the comparison of the value of an unknown electrical quantity with a reference voltage, current, resistance, inductance, or capacitance. Various potentiometer circuits are used for voltage substitution, and divider circuits are used for voltage, current, and impedance comparison. A number of these circuits and the reference components used in them are described in Chap. 15.2.

Analog circuits are used to embody mathematical relationships, which permit the value of an unknown electrical quantity to be determined by measuring related electrical quantities. Analog-measurement techniques are discussed in Chap. 15.2, and a number of special-purpose measurement circuits are described in Chap. 15.4.

Digital instruments combine analog circuits with digital processing to provide a convenient means of making rapid and accurate measurements. Digital instruments are described in Chaps. 15.2 and 15.4. Digital processing using the computational power of microprocessors is discussed in Chap. 15.3.

Bridge circuits provide a convenient and accurate method of determining the value of an unknown impedance in terms of other impedances of known value. The circuits of a number of impedance bridges and amplifiers and detectors used for bridge measurements are described in Chap. 15.4.

Transducer amplifying and stabilizing circuits are used in conjunction with measurement transducers to provide an electric signal of adequate amplitude, which is suitable for use in measurement and control systems. These circuits, which often have severe linearity, drift, and gain-stability requirements, are described in Chap. 15.3.