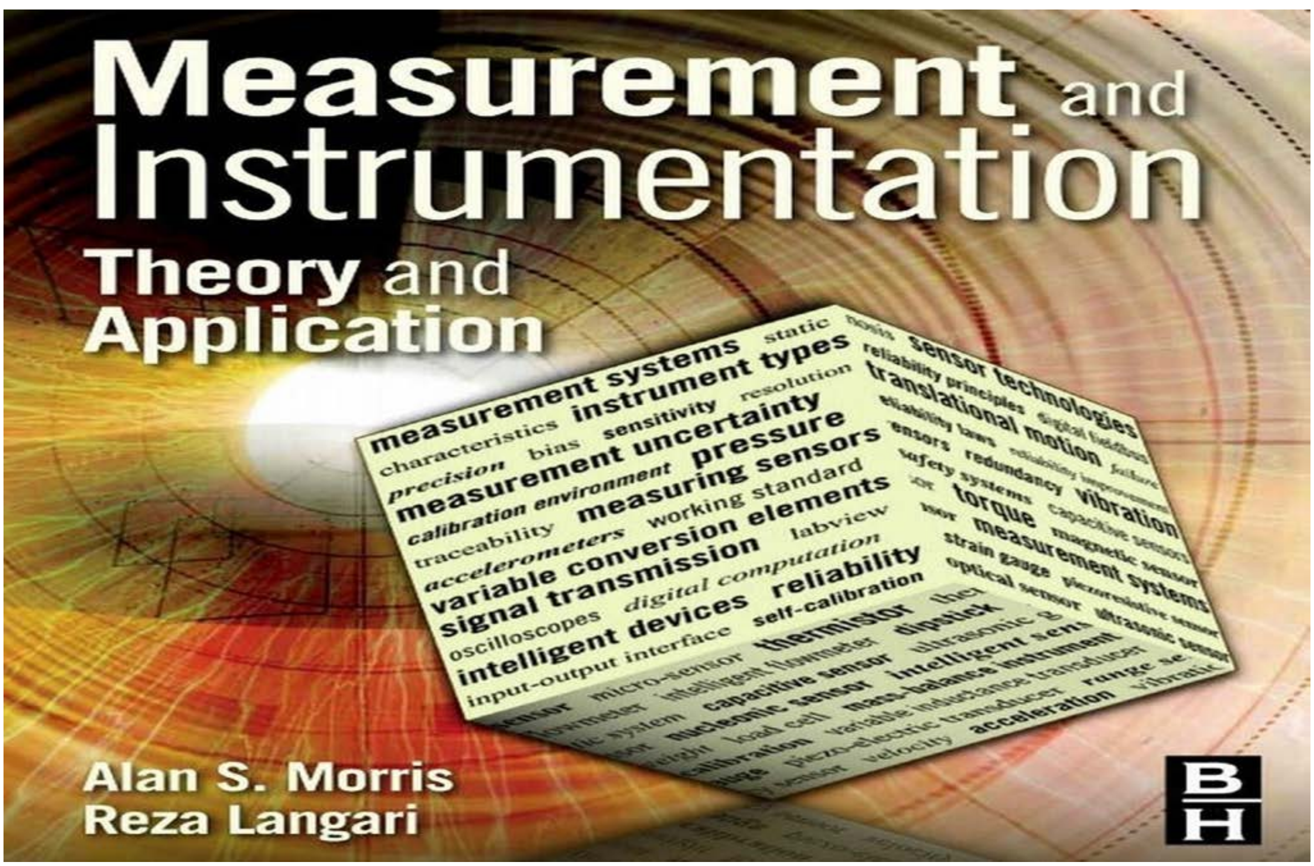
Course: 236CCE

Electronic Measurements

Lectures Notes of Chapter 1

Measurements and Instrumentations Fundamentals

This lectures notes are extracted from the text book: " Alan S Morris and Reza Langari, Measurement and Instrumentation: Theory and Application, Second edition, Academic Press, 2015. ISBN-13: 978-0128008843. From CHAPTER 2: Chapter 2 Instrument Types and Performance Characteristics (From page11 to page 22)



Measurements and Instrumentations Fundamentals

Basic Electrical Quantities

1. **Passive quantities**: resistance, capacitance and inductance
2. **Active quantities**: electrical charge, electric current, electric voltage, electric power

Electricity

It is the flow of electrons from a place of their excess (the place with negative charge) to the place of their deficiency (the place with positive charge).

Electric Charge

The only charge that occur in nature are integral multiple of the electron (proton) charge.

$$e = 1.602 \times 10^{-19} C$$

Electric Current

It is the movement of elementary electric charges carried by electrons. Mathematically, electric current is the time rate of change of charge measured in Ampere.

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

Electric Voltage (Electromotive Force)

الفرق · مكانين · بشحنتين مختلفة

It is a difference of potential between two places with different charges. Voltage provides the ability to move charges and hence do a work. ⇒ الفولتج يحرك الشحنة ويسبب شغل

TF Electric current and voltage are manifestation of electric charge movement. a current can only flow as long as a potential difference is sustained (The following charge must be replenished).

Capacitance

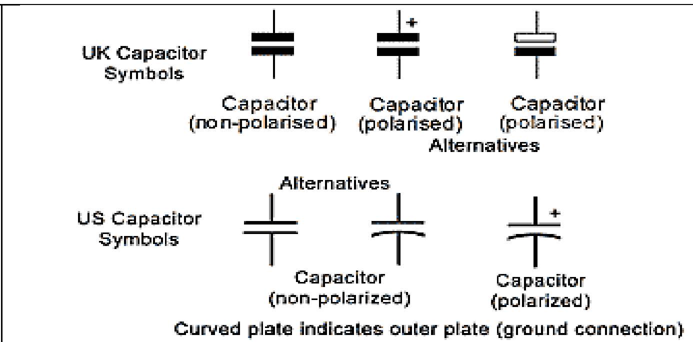
تجميع ~~تخزين~~ · الطاقة الكهربائية · مجال كهربائي

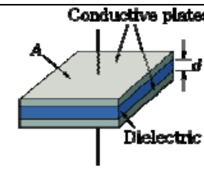
It expresses the ability to accumulate electrical energy in the form of electric field. The charge stored in the capacitor is directly proportional to the applied voltage. TF

$$q(t) = Cv(t)$$

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

$$v(t) = \frac{1}{C}\int_{-\infty}^{t} i(\tau)d\tau$$





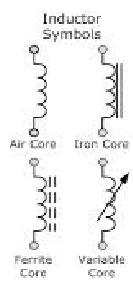
Inductance

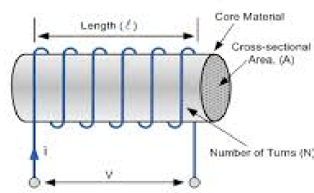
مجال مغناطيسي على شكل الطاقة الكهربائية تجمع

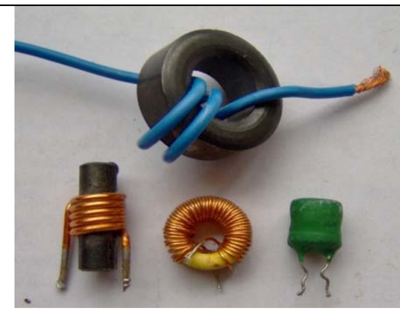
It expresses the ability to accumulate electrical energy in the form of magnetic field as long as the source is connected measured in Henry. Inductance of the inductor oppose the change of current flowing through it.

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

$$i(t) = \frac{1}{L}\int_{-\infty}^{t} v(\tau)d\tau$$







Electric Energy

It describes the capacity of electricity to perform a work ($1Wh = 3600J$). The energy absorbed or supplied by an element from time t_0 to time t is

$$\boxed{E = \int_{t_0}^{t} i(t)v(t)dt = \int_{t_0}^{t} p(t)dt}$$

Electric Power

It is the time rate of expending or absorbing electric energy measured in Watt.

$$P = IV = \frac{V^2}{R} = RI^2$$

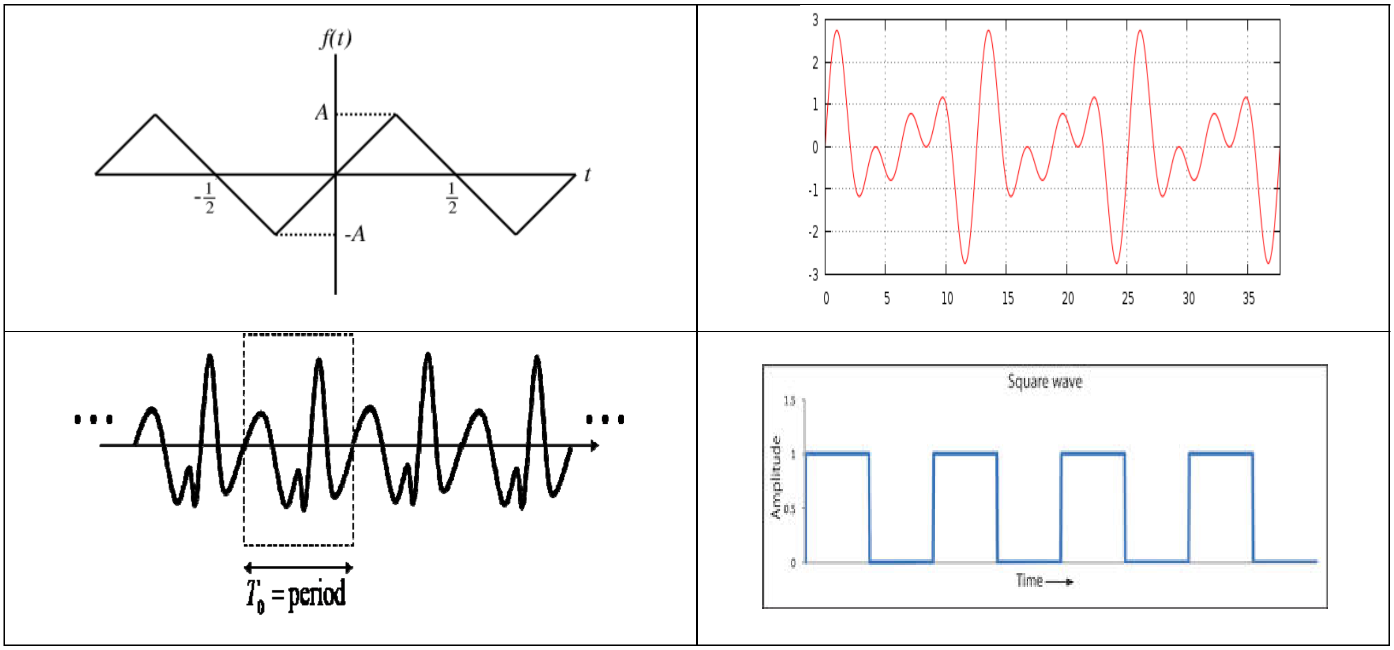
مجموع

If a signal contains many frequency components, then the total power is the sum of power of all frequency components.

$$P = \sum_{n=0}^{N} P_n = \sum_{n=0}^{N} \frac{V_n^2}{R}$$

Periodic Signal

It has a minimal time period after which the signal repeat itself exactly.



Important Parameters of AC Signal

1. Amplitude and Peak value
2. Peak-to-peak value
3. Effective value.

Average Value of a Signal

A periodic signal $v(t)$ with a period T has an average value V_{ave} given by

$$V_{ave} = \frac{1}{T}\int_0^T v(t)dt$$

Effective Value of a Signal (Root Mean Square)

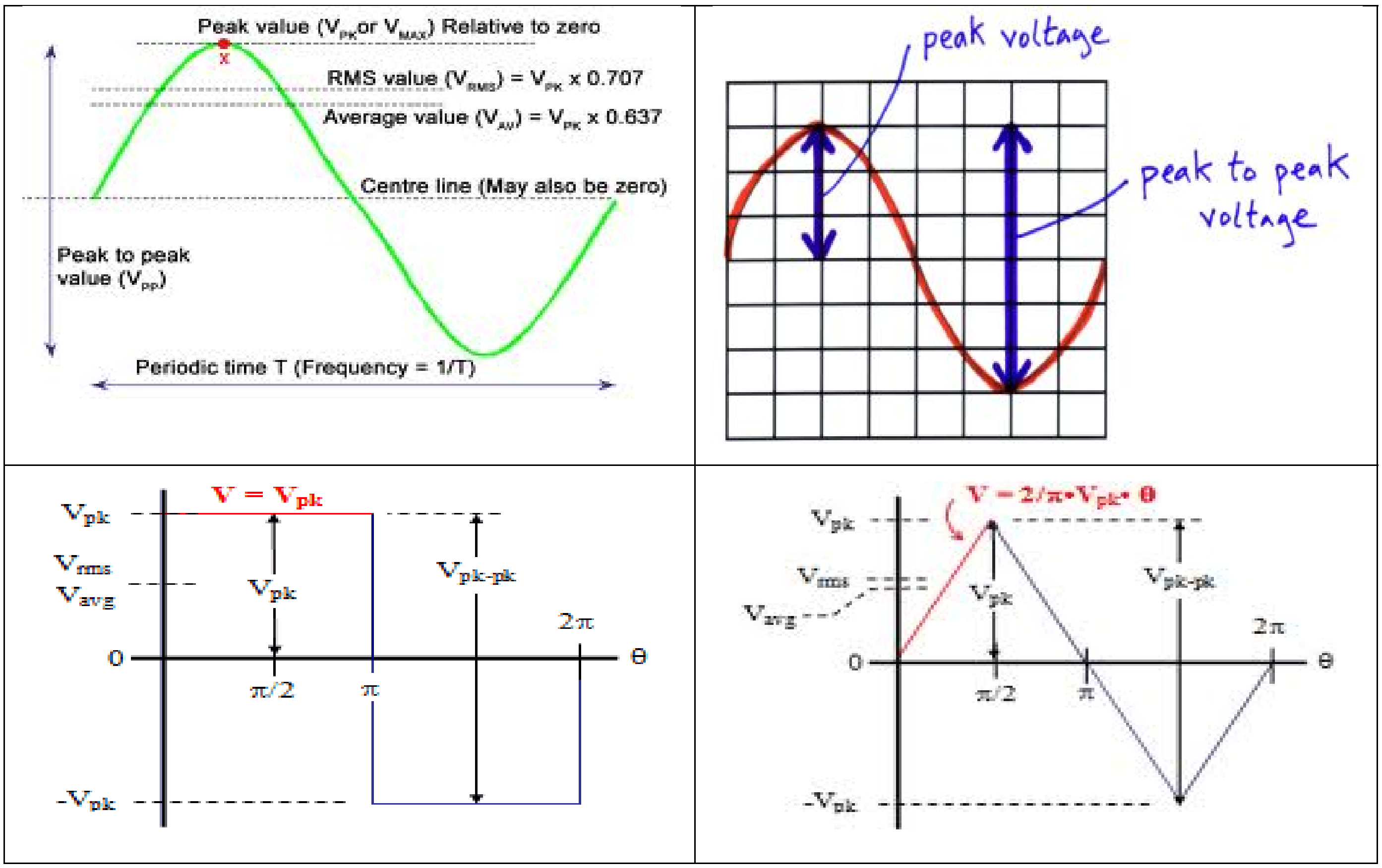
A periodic signal $v(t)$ with a period T has an effective value V_{rms} given by

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

It is called effective because it corresponds to the same amount of DC voltage in heating power.

Peak-to-Peak Value of a Signal

It is the net difference between the positive peak amplitude and the negative peak amplitude.



Duty Cycle of a Square Signal

It is the percentage of one period in which a signal is active.

$$D = \frac{T_{ON}}{T = T_{ON} + T_{OFF}} \times 100\%$$

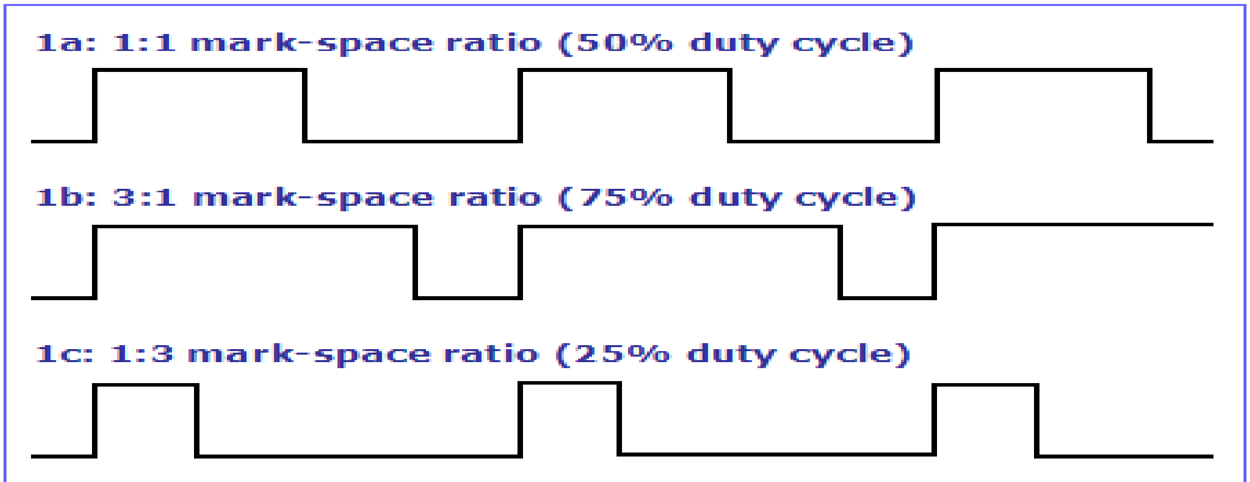


Figure 1: Pulse width modulation waveforms

International System of Units

It is a set of definitions to overcome the many different units used throughout the world. there are seven base units, meter (m) for Length, Kilogram (Kg) for Mass, second (sec) for Time, Ampere (A) for Current, Kelvin (K^0) for Temperature, mole (mol) for Matter, candela (cd) for Luminous intensity.

TABLE 1.1

Common physical variables	Typical signal variables
• Force	• Voltage
• Length	• Displacement
• Temperature	• Current
• Acceleration	• Force
• Velocity	• Pressure
• Pressure	• Light
• Frequency	• Frequency
• Capacity	
• Resistance	
• Time	
• …	

"I often say that when you can measure what you are speaking about and can express it in numbers, you know something about it; when you cannot express in it numbers your knowledge is of meager and unsatisfactory kind"

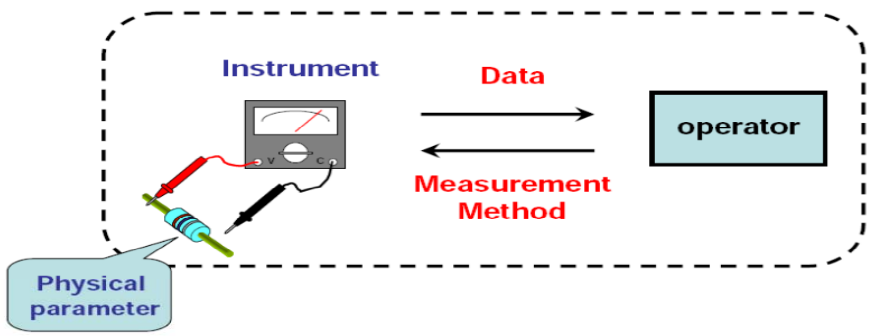
Lord Kelvin

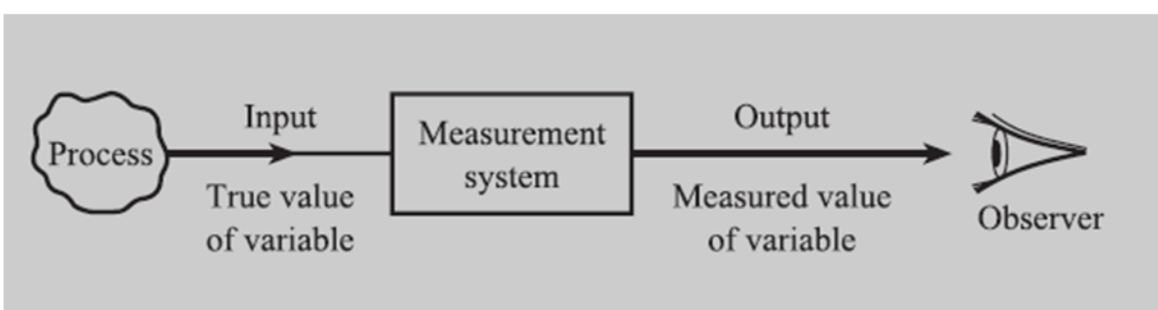
Physical Quantity

It is a variable that represent a physical case like pressure, temperature, mass, length, current, voltage, etc. In electrical circuits, voltage is a common signal variable. In mechanical systems, displacement or force are commonly used as signal variables.

Measurement

It is a method to obtain information regarding the values of a physical variable of interest (the *measurand*) using a measurement device. The display or recording device of a measurement system allows a human observer to read the measurement.





measurand   Sensor, signal conditioning, display   Man, tracking control etc

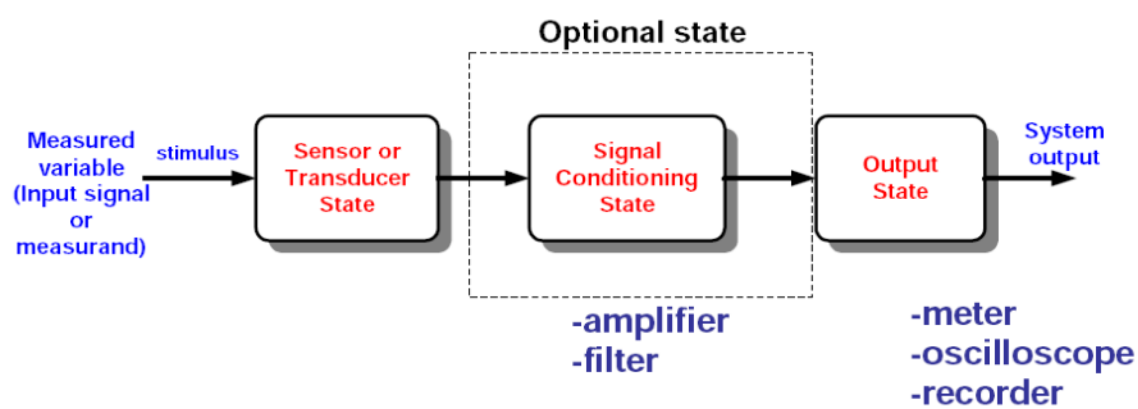
Transducer (Energy Converter)

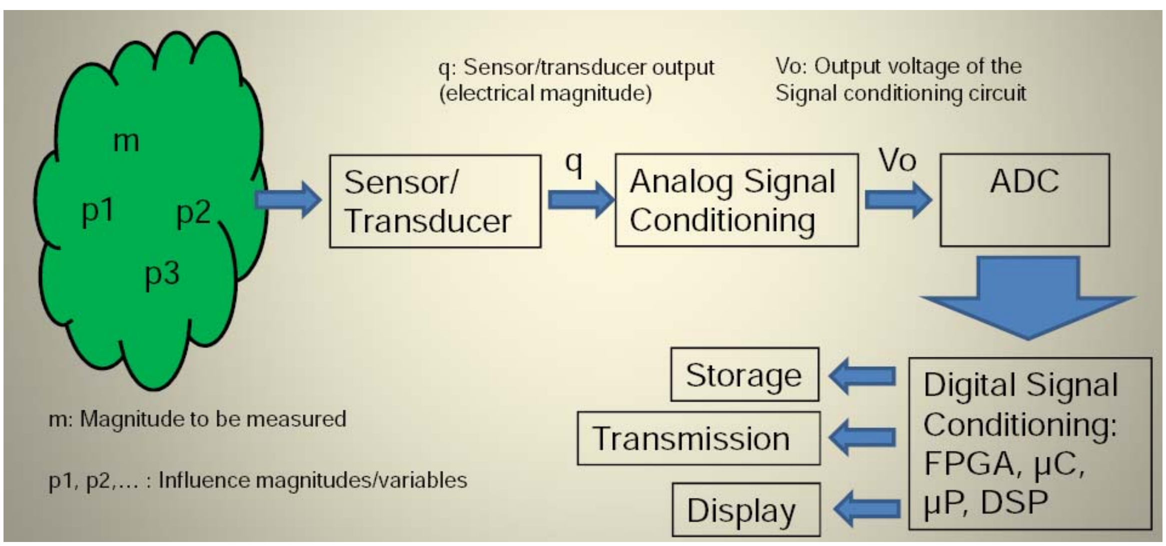
It is device which converts a signal from one physical (energy) form to a corresponding signal having a different physical (energy) form.

Electronic Transducer

It has an input or output that is electrical in nature (e.g., voltage, current or resistance).

General Measurement System





Sensor (Input Transducer)

It is an electronic transducer that receives a stimulus (physical quantity) and responds to it with an electrical signal which can be processed or transmitted electronically.

The signal output from the sensor can be displayed, recorded, or used as an input signal to some secondary device or system. The quality of performance of the system is directly related to the performance of the sensor. No sensor measures a process variable directly. Each sensor measures the effect of the process variable by physical position, force, voltage or some other more easily measured property. For example, when measuring temperature we are not directly measuring the temperature of an object, we are measuring a sensors change in resistance or the amount of voltage it produces from being exposed to a temperature. A modem automobile uses as many as 40 or 50 sensors in implementing various functions necessary to the operation of the car.

Signal Conditioning

It modifies the transducer signal into a desired form e.g. amplification, noise reduction. If the signal output from the sensor is small, it is sometimes necessary to amplify the output. The amplified output can then be transmitted to the display device or recorded, depending on the particular measurement application.

Analog to Digital Converter (ADC)

If the sensor does not inherently provide a digital output, then the analog output of the sensor is converted by an analog to digital converter (ADC) so that it can interface with a computer-based data acquisition or communications system. The digital signal is typically sent to a computer processor that can display, store, or transmit the data as output to some other system, which will use the measurement.

Output State

It provides an indication of the value of the measurement (readout device or recording).

Actuator (Output Transducer)

It is an electronic transducer that converts electrical energy into mechanical energy.

Measuring Instrument

It is a device that determines the value of a physical quantity or a variable. An example of a basic instrument is a ruler. In this case the measurand is the length of some object and the measurement is the number of units (meters, inches, etc.) that represent the length.

The observable physical variable need not necessarily be the measurand but simply related to the measurand in some known way. For example, the mass of an object is often measured by the process of *weighing*, where the measurand is the mass but the physical measurement variable is the downward force the mass exerts in the Earth's gravitational field.

Evolution of Instruments

1. **Mechanical Instruments:** They are unable to respond rapidly to measurements of dynamic and transient conditions.
2. **Electrical Instruments:** It depends on the mechanical movement of the meters. The response is 0.5 to 24 seconds.
3. **Electronic Instruments:** It is more reliable than other system. It uses semiconductor devices and weak signal can also be detected.

Analog Instrument

It gives an output that varies continuously as the quantity being measured changes. The output can have an infinite number of values within the input range.

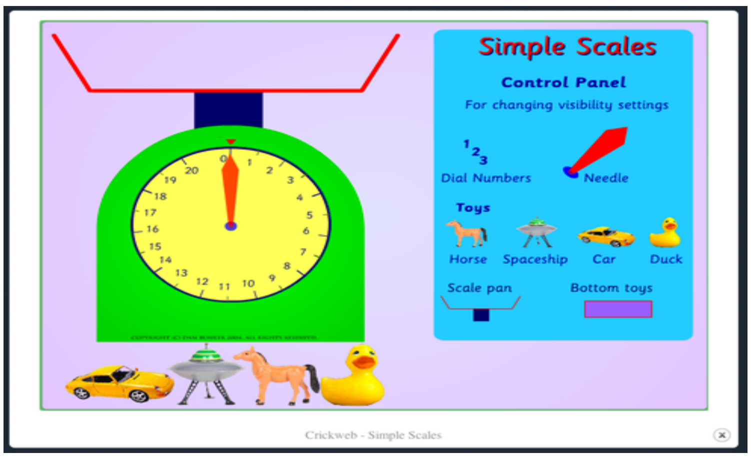


Digital Instrument

It has an output that varies in discrete steps and so can only have a finite number of values.

Display Devices

There are many types of display devices, Simple scales, Dial gages, and Sophisticated computer display systems.



Interference in the Measurement

It is an undesirable deterministic trends on the measured value because of the variables that can affected the value of the measured variable.

Noise in the Measurement

It is a random variation of the value of the measured signal as a consequence of the variation of the variables that can affected the value of the measured variable.

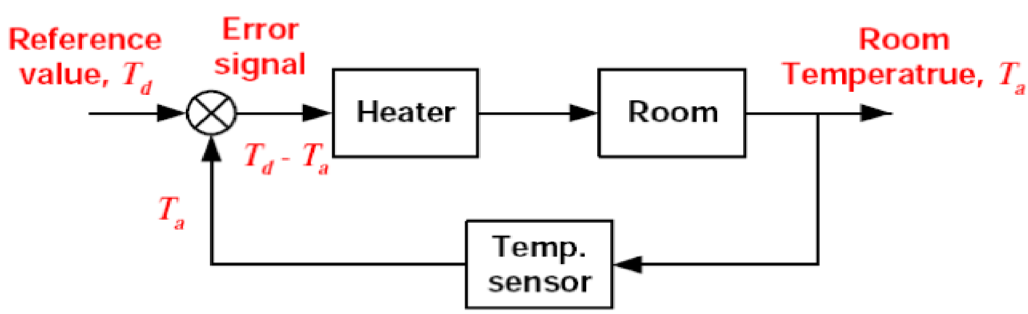
Calibration

Calibration is the process of making a measurement system reading agrees with the accepted and certified standard. This is done by applying known values (standard values) to a measurement system and observing the system (or sensor) output. Deviation between indicated values and their corresponding standard values constitutes the correction for inferring true value from indicated value thereafter. If the device is repaired, aged or modified then recalibration is carried out. The need for recalibration depends on the accuracy required, the measurement system stability, and the conditions to which the measurement system is subjected.

Applications of Measurement System

1. **Monitoring of processes and operations:** Here the measuring device is used to keep track of some quantity. The measuring device simply indicate the condition of the environment, and their readings do not serve any control functions in the ordinary sense. For example the thermometers and barometers for a weather bureau and the speedometer, fuel gage, and outdoor temperature sensor for a car.
2. **Recording of processes and operations:** Here we observe and save the measurement reading.

3. **Control of processes and operations:** This involves an automatic feedback control system. The design principle of all feedback control systems says that we should *measure* the variable which we want to control, compare it with its desired value, and then, based on the "error" between the two, manipulate the final control element in such a way as to drive the controlled variable closer to its desired value. For example the coolant temperature regulating system of a car.
4. **Experimental engineering analysis:** It is that part of engineering design, development, and research that relies on laboratory testing of one kind or another to answer questions. That is, as engineers, we have only two basic ways of solving engineering problems: theory and experimentation. The experimentation needs a measurement system.



A simple closed-loop control system

All measuring instruments should be regarded as guilty until proven innocent.

P.K. Stein

Instrument Performance Characteristics

They show the performance of an instrument. These characteristics allow users to select the most suitable instrument for a specific measuring jobs.

Measurand Range (Operating Range) (Full-scale Range)

It is the range of input variable that produces a meaningful output.

$$R = [x_{min}, x_{max}]$$

Measurement Span

It is the practical range of input variable that produces a meaningful output.

$$Z_i = x_{max} - x_{min}$$

Example 1

Find the operating range and span of

1. A pyrometer calibrated between 0^0C and 1000^0C?
2. A thermometer calibrated between 200^0C and 500^0C?

Solution 1

For pyrometer

$$R = [0^0C, 1000^0C]$$

$$Z_i = x_{max} - x_{min} = 1000 - 0 = 1000^0C$$

For thermometer

$$R = [200^0C, 500^0C]$$

$$Z_i = x_{max} - x_{min} = 500^0C - 200^0C = 300^0C$$

Full Scale Output (FSO)

It is the difference between the end points of the output scale. The upper limit of output over the measurand range is called the full scale (FS).

$$Z_o = y_{max} - y_{min}$$

Measurement Offset

It is the output of the measurement system, under room temperature condition unless otherwise specified, with zero measurand applied.

Measurement Accuracy

It is the closeness of the instrument reading (y) compared to the true (expected) value (y_t) of the quantity. Accuracy of a measurement means conformity to truth and can be quoted in as a fractional of the full scale output or a fraction of true value.

$$A_{FSO} = \frac{y - y_t}{Z_o} \times 100\%$$

$$A_{TRUE} = \frac{y - y_t}{y_t} \times 100\%$$

Example 2

The accuracy of a thermometer having a range of $[0^0C, 500^0C]$ is $\pm 0.5\%$ of FSO. What is the true value and the error percentage if the output is 500^0C and 25^0C?

Solution 2

$$A_{FSO} = \frac{y - y_t}{Z_o} \times 100\% \quad \rightrightarrows \quad y_t = y \pm Z_o A_{FSO}$$

$$\text{error percentage } = \frac{y_t - y}{y} \times 100\%$$

For $y = 500^0C$

$$y_t = y \pm Z_o \frac{A_{FSO}}{100} = 500 \pm 500 \times \frac{0.5}{100} = 502.5^0C \text{ or } 497.5^0C$$

$$\text{error percentage } = \frac{y_t - y}{y} \times 100\% = \frac{502.5 - 500}{500} \times 100\% = 0.5\%$$

For $y = 25^0C$

$$y_t = y \pm Z_o \frac{A_{FSO}}{100} = 25 \pm 500 \times \frac{0.5}{100} = 27.5^0C \text{ or } 22.5^0C$$

$$\text{error percentage } = \frac{y_t - y}{y} \times 100\% = \frac{27.5 - 25}{25} \times 100\% = 10\%$$

The error percentage for $y = 500^0 C$ is negligible while it is high for $y = 25^0 C$. That means the specification of accuracy in terms of FSO is misleading.

Example 3

The accuracy of a thermometer having a range of $[0^0 C, 500^0 C]$ is $\pm 0.5\%$ of true value. What is the true value and the error percentage if the output is $500^0 C$ and $25^0 C$?

Solution 3

$$A_{TRUE} = \frac{y - y_t}{y_t} \times 100\% \quad \rightrightarrows \quad y_t = y \pm y_t A_{TRUE}$$

For $y = 500^0 C$

$$y_t = \frac{y}{1 \pm 0.01 \times A_{TRUE}} = \frac{500}{1 \pm 0.01 \times 0.5} = 502.5^0 C \text{ or } 497.5^0 C$$

$$\text{error percentage } = \frac{y_t - y}{y} \times 100\% = \frac{502.5 - 500}{500} \times 100\% = 0.5\%$$

For $y = 25^0 C$

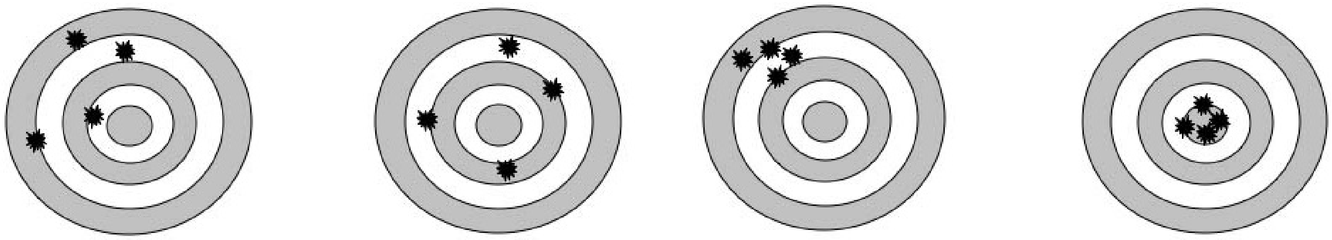
$$y_t = \frac{y}{1 \pm 0.01 \times A_{TRUE}} = \frac{25}{1 \pm 0.01 \times 0.5} = 25.125^0 C \text{ or } 24.875^0 C$$

$$\text{error percentage } = \frac{y_t - y}{y} \times 100\% = \frac{25.125 - 25}{25} \times 100\% = 0.5\%$$

This makes the same error percentage for any value. That means as the readings get smaller so do the errors.

Measurement Precision

It is the ability of the system to give always the same output upon repeated but independent applications of a specific value of input (stimulus). Precision of a measurement is associated more with its repeatability than its accuracy.



Indications of Precision

1. Conformity.
2. Number of significant figures in which the number is expressed. the more the significant figures, the greater the precision of measurement.

Example 4

A voltage is measured by two measurement systems as $256V$, and $256.0V$. Which one is more precise?

Solution 4

In the first value $256V$, there are three figures and this value may be $256.1V$ or $255.9V$. In the first value $256.0V$, there are four figures and this value cannot be $256.1V$ or $255.9V$. Thus the second value expresses a measurement of greater precision than the former.

Measurement Resolution

It is the smallest increment in input that produces a detectable increment in instrument output. Resolution is expressed in the percentage of the measurand range.

$$\text{Resolution} = \frac{\Delta x}{Z_i} \times 100\%$$

The precision, resolution, or both may be better than the accuracy. An ordinary six-digit instrument has a resolution of one part per million (ppm) of full scale. However, it is possible that the accuracy is no better than 25 ppm (0.0025%). Note that the practical resolution of an instrument cannot be any better than the resolution of the indicator or detector, whether internal or external.

Example 5

A voltmeter has a uniform scale with 100 divisions, the full scale reading is $200V$ and 1/10 of a scale division can be estimated with a fair degree of uncertainty. Determine the resolution of the instrument?

Solution 5

$$\text{One scale division} = 200/100 = 2V$$

$$\Delta x = \frac{1}{10} \times 2V = 0.2V$$

$$\text{Resolution} = \frac{0.2}{200} \times 100\% = 0.1\%$$

Example 6

A digital voltmeter has a readout range from 0 to 9999 counts. Determine the resolution of the instrument if the full scale reading is $9.999V$?

Solution 6

$$\Delta x = \frac{1}{9999} \times 9.999V = 1mV$$

$$\text{Resolution} = \frac{1m}{9.999} \times 100\% = 0.01\%$$

Measurement Reliability

It is the probability that an instrument's precision and accuracy will continue to fall within specified limits.

Measurement Stability

It is a quality of the system to maintain its characteristics under changes of the measurement conditions (e.g. Temperature) or aging.

Measurement Deviation

It is the difference between a single measured value and the mean (average) value of a population or sample.

$$\boxed{dev = y - m_y}$$

$$\boxed{m_y = \frac{1}{N}\sum_{i=1}^{N} y_i}$$

Measurement Standard Deviation

It is the square root of the average of the squares of the deviations from the mean (root mean square deviation). It is a measure of dispersion of a population.

$$\boxed{S = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(y_i - m_y\right)^2}}$$

Measurement Sensitivity

For linear instruments, sensitivity represents the change in output for a unit change in the input.