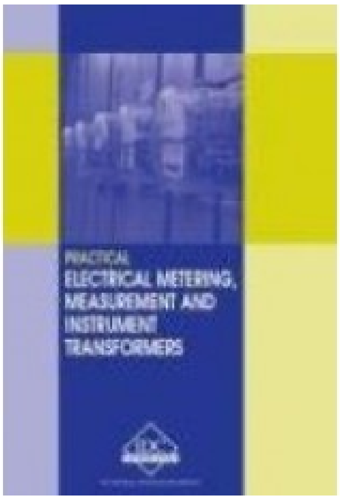
# MI-E - Practical Electrical Metering, Measurement and Instrument Transformers




**Price: $139.94**

**Ex Tax: $127.22**

## Short Description

This manual discusses the details of instrument transformers including their construction, ratings and specifications. Various measuring devices such as instruments and transducers, their operating principles and applications are be covered as well.

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**Introduction to Electrical Measurement**

# 1 Introduction to Electrical Measurement

*Electrical energy is one of the most widely consumed forms of energy by the industrial, residential and commercial applications. It is therefore necessary to measure and monitor various important electrical parameters at the source end as well as at the consumption points of electrical systems for purposes of monitoring, calculating consumption, billing and protection. In this chapter we will review the various basic electrical parameters that get measured and the kind of accuracies needed for such measurements. A brief introduction on the basic principles of operation of instruments and the different types of electrical devices used for such measurements will also be covered. We will also discuss the purpose and importance of instrument transformers used in electrical measurements.*

**Learning objectives**

- Introduction to electrical measurements
- Need of measurements in electrical installations
- Why accuracy is important in measurement?
- Different types of measuring devices
- Transducers and their principle of operation
- Instrument transformers and principles
- Purpose of instrument transformers

## 1.1 Electrical systems and measurements

All electrical systems are individually identified in terms of their typical characteristics namely voltage, current, power factor, energy, power, etc to distinguish each system from others. The above electrical units defining the characteristics of an electrical system depend on the two main basic parameters of these systems namely, voltage and current. The various other electrical units can be derived and ascertained using these basic two parameters.

Table 1.1 gives the various parameters that are commonly used to define the characteristics of an electrical system along with the main inputs used for measuring the values of these characteristics/ units.

**Table 1.1**

*Inputs needed for electrical measurements*

| Parameter | Inputs for measurements | Electrical Units |
|---|---|---|
| Potential difference | Voltage | Volt or kilo Volt |
| Load | Current | Ampere |
| Frequency | Voltage | Hertz |
| Resistance | Voltage, Current | Ohm |
| Angular difference | Voltage, Current | Power factor |
| Active Power | Voltage, Current | kilo Watt |
| Reactive Power | Voltage, Current | kilo VAr |
| Active Energy | Voltage, Current | kilo Watt hour |
| Reactive Energy | Voltage, Current | kilo VArH |
| Apparent Power, Maximum demand | Voltage, current | kVA |

There are also some other electrical units like capacitance, inductance, etc that are dependent on the properties of the material of conductors and construction/application of equipment. These affect the main parameters voltage and current and hence all the other parameters indicated above.

It is well known that electrical power is normally consumed in the form of AC or DC (Alternating Current and Direct Current). Hence measurements are required for both AC and DC systems. The following paragraphs give a brief on the fundamentals of these two systems.

### 1.1.1 Alternating current system

The power generators in power stations generate AC voltages, which follow sinusoidal waveforms alternating between positive and negative values around a zero (X) axis, due to the angular movement of rotors and the magnetic field. In simple terms, if Vp is the maximum voltage attained at a generator terminal then –Vp is the minimum voltage attained at the same terminal with respect to zero in one complete cycle. The magnitude of voltage V at any time t alternating at a frequency ‘f’ cycles/second, can be mathematically expressed as

$V = V_p \text{ Sin } (2p \times f \times t)$ ……………………. (1.1)

This follows the curve as shown in Figure 1.1.

**Figure1.1**

*Typical AC sinusoidal wave*

Figure 1.1 shows the waveform of a single phase AC system. Three phase systems have their phases exhibit similar waveform, but shifted by 120° from each other. As the characteristic curve is continuously varying over time, it means that the measurements (along the curve) are also continuously varying in all these three phases over time, based on the system behaviour as well as load characteristics.

Each point of the sine wave represents a unique value in terms of its magnitude and angular position, though these values repeat over and over again for each cycle. Hence the measurements made shall be such as to truly represent these constantly varying parameters. In AC systems it is quite common to come across the following parameters to be considered for measurements.

- Voltage and current – Average, peak, Root mean square (RMS[GVR1] )*.
- Power – peak or maximum, average.
- Energy – Active energy, Reactive energy.
- Powerfactor – lagging, leading, unity.
- Frequency – Normal, Harmonics.

* The RMS value is the effective value of a varying voltage or current. It is the equivalent to the steady DC (constant) value which gives the same heating effect.

All the above measurements require a good understanding of electrical systems and the way electricity is distributed to the various consumers – industrial, commercial, etc.

### 1.1.2 Direct current system

Direct current (DC) system is defined by the polarities positive and negative with a definite, constant difference of potential between the polarities. A DC system can be feeding a load in one of the following combinations.

- Positive and negative not connected to ground potential (Floating).
- Positive connected to ground (zero) potential.
- Negative connected to ground (zero) potential.

Based on the method of connection, the current flow can be different and therefore it is necessary to ensure correct polarity connection methods to perform measurements in a DC system.

In electricity transmission systems, HVDC (High Voltage Direct Current) technology is gaining importance on account of the reduced transmission losses. While the normal DC systems used in many industrial and commercial applications are usually in the range of 3V to 220V, HVDC systems are generally rated above 400kV. HVDC systems consequently require different types of instruments for measurements and monitoring.

Most electrical systems employ AC voltage and therefore we will deal with the measurements carried out in ac systems in this chapter.

## 1.2 Need for measurement in electrical installations

As already noted, measurements basically help to distinguish the characteristics of various electrical systems. This however is only the very basic purpose. Measurements are also needed by the utility companies as well as the end users for the following reasons:

- Utility companies need to continuously monitor the quality of electricity supplied in order to ensure that the electrical parameters are within the defined limits so that, their consumers are not affected.
- It is necessary for the utility companies to charge the consumers for the amount of electricity supplied to them and hence need to measure the energy supplied to their consumers. The consumers shall also be convinced on the methods used for the measurement of electricity consumption. A well defined and uniform method of measuring the consumption is therefore necessary to help both the producers and consumers of electricity. Energy meters thus constitute the basic instrument in any electrical system for measuring the quantum of energy consumed.

- With increasing electricity consumption, it is also necessary to monitor the increase in demand of electricity consumption so that action plans can be initiated by the utility companies and Governments for enhancement of generating capacities, transmission and distribution systems, etc to meet the future demands. The measurements of consumption patterns at various consumer points help to take decisions on enhancement/ strengthening of the electrical systems.
- Some of the changes in electrical parameters are transient in nature but repetition of such transients can affect the reliability of the system in the long run. Transient changes need to be continuously recorded and analysed to curtail the abnormal factors responsible for such short time adverse phenomenon. This is essential to avoid costly damages to the systems in service.
- The sizing of electrical equipment is affected by the powerfactor of the system. Sizing can be optimized by monitoring and keeping the powerfactor close to unity. Powerfactor also affects the capacity of the generating plants on account of the need to supply reactive power.
- Harmonics is another phenomenon that affects upstream sources and also downstream power systems. Measurement of harmonics is gaining importance due to increasing use of power semiconductor devices in equipments like UPS, VFDs etc.
- Energy conservation is gaining importance, as the energy savings in a system can more than compensate for the efforts needed to generate the additional electricity for energy that is wasted.
- The efficiencies of different systems can be evaluated by correct measurements at the appropriate points.
- Measurements help to check the status of deterioration of equipment due to aging, and help the consumers take decisions on replacements and renovations of equipment.
- Alarms can be generated through detection of abnormal electrical parameters in the system, so that corrective actions can be taken to avoid failure and damage to the connected equipment either by prompt isolation or shut down.

Thus, a well designed good measurement system can contribute to a reliable and optimal electrical system that is beneficial both for the Electricity producers and the consumers.

## 1.3 Importance of accuracy

Any method of measurement is subject to some degree of error and electrical measuring devices are no exception. While measurements provide the various benefits enumerated above, they may not serve the purpose without adequate accuracy in the measurements. This is particularly true for electricity which is a costly commodity and which has become an integral/ basic need in today's world.

Nevertheless the level of accuracy can differ from location to location and it is necessary to install instruments of correct accuracy based on the location and the kind of application.

For example, the power consumption of an installation served by the utility company is measured at the service entry point of the consumer. Since this instrument decides the amount payable by the consumer and receivable by the utility, this shall have the highest possible accuracy so that both the parties are reasonably convinced of the reliability of the measurements made by these instruments that decide their expense/ income. However, there can be many other branch consumption points within the consumer premises, which may either be important or unimportant depending on the time period of use, power rating of the equipment, etc. In these branch measurements the user shall judiciously decide the level of accuracy needed to serve the purpose, because higher the accuracy higher will be the cost. Hence the requisite type of instruments shall be selected by the user based on the capital cost and the likely benefits achievable from such instruments.

We saw earlier, that measurements are also performed to give timely alarms to the users so as to take corrective action and avoid shutdown or failure of a costly process or equipment. It goes without saying that the accuracy levels employed for such critical alarm devices shall be quite high to avoid unnecessary shutdown or catastrophic failures.

Energy conservation study is another area that requires reasonably good and accurate measuring devices because the recommendations and decisions on energy conservation will depend on the quality of data collected from these devices. Poor quality measuring instruments may lead to wrong and costly decisions which may finally give no appreciable benefits and savings.

Hence it is necessary to evaluate the benefits and returns from an instrument and decide on the required accuracy specifications for the instrument. An instrument without proper accuracy may remain only as an ornamental piece and may not give any benefit to the user.

## 1.4 Types of measuring devices

The types of electrical measuring devices can be broadly classified based on the types of outputs derived for a particular measurement. These devices can be further subdivided based on the type of construction.

Based on the types of measurement outputs to be derived from the instruments, following are the broad classifications of the instrument types:

- Indicating instruments.
- Integrating instruments.
- Recording instruments.

## 1.5 Transducers

Today, many process industries are remotely controlled by monitoring various parameters like pressure, temperature, liquid levels, etc through computer monitors. All these are possible, thanks to the advances in electronics and sensors. The sensors are used in conjunction with instruments called transmitters to basically produce electrical outputs for the convenience of measurements. In some cases the transmitters are integrated with the sensor. A typical process transmitter is shown in figure 1.3.

**Figure1.3**

*Typical transmitter block diagram*

In a similar way, remote electrical measurements are achieved by use of transducers. A transducer arrangement is analogous to the above and has an input parameter coming from an electrical device to a "black box" called the transducer. The transducer changes the received electrical parameter quantity such as voltage, current, power or frequency into a proportional DC output for measurement, control and protection purposes. The outputs are basically DC signals like 0 to 20mA, 4 to 20mA[GVR2] , 0-5V etc which are directly proportional to the magnitude of the input parameter.

By adopting such transducers in an electrical circuit, a complex electrical quantity, such as active power (watts), reactive power (vars) etc measured at the load point can be converted into a load independent DC current signal and transmitted using just two wires over long distances for display, recording or control.  Thus the values obtained from transducers can be used for monitoring as well as for control purposes, so that the desired predetermined output value can be achieved. Apart from the requirement of fewer wires for transmission of the signal, the transducer output wires can have small cross section and need to be insulated only for low voltage.

Transducers can be broadly classified into two types, “Active transducers” and “Passive transducers”. "Active" Transducers need external auxiliary supply for their working. "Passive" Transducers can be powered with the input signal itself without an external auxiliary supply[GVR3] .  Modern digital measuring instruments have the additional advantage of communicating the measured data to remote control systems using digital communication networks without the need for transducers.

## 1.6 Instrument transformers - principle

Ammeters used for current measurements in DC circuit are either connected directly to the circuit or by using shunts. When the measurements involve large magnitudes of current, say of the order of hundreds of amperes, it is a general practice to use low range ammeters in conjunction with suitable shunts. However, the measurement of large currents in AC circuits using shunts does not provide accurate results due to following reasons:

- In DC, resistance is the only parameter while in the case of AC circuits, reactance values also come in the picture. Division of current between a meter and its shunt when used in AC circuits would depend on the ratio of reactance values of the two paths. For proper measurement, the time constant of the meter and shunt should be the same, which is difficult to achieve.
- A shunt can be employed only up to a range of a few hundred amperes, because power consumed by shunts increases with increase in the magnitudes of current.
- Measuring circuit is not isolated from the power circuit.
- Insulation of the instrument and shunt is difficult in high voltage systems.

For measurement of large DC voltages a multiplier is used in conjunction with the measuring instrument. A ‘multiplier’ provides a high resistance connected in series with the instrument coil. A low range DC voltmeter with the help of a multiplier can measure a high value of DC voltage. However when measuring AC voltage using multipliers, the following problems could arise:

- For voltages more than 1000V, the power consumed by the multiplier becomes very high.
- Construction of multipliers for large voltages is very costly and complicated.
- Measuring circuit is not isolated from the power circuit.

Hence, use of shunts or multipliers is not a convenient method for measuring alternating currents and voltages. This is why, Instrument transformers are used when it comes to AC measurements.

The underlying principle of instrument transformers is same as that of power transformers. Transformer is the most common and widely used electrical equipment in AC installations. In its simplest form, a transformer basically consists of two windings for each phase, with magnetic linkage between the two windings. These windings are referred to as primary and secondary windings. The primary winding receives an AC voltage as input, transforms this input and delivers at its output a voltage that is of the same magnitude or of magnitudes that may greater than or lesser than the input magnitude (step up or step down).

Figures 1.4 (a) and (b) indicate in the simplest form, the typical transformation taking place between the two windings and the equations that subsequently follow provide the relationship between the input and output voltage magnitudes, with Ep as the voltage across the primary winding, Ip the current in the primary, Es as the voltage output across the secondary, Is as the current in the secondary and Np, Ns being the number of turns of these respective windings.

**Figure 1.4 (a)**

*Single phase transformer principle of operation*

**Figure 1.4 (b)**

*Single phase transformer principle of operation*

The relationship between the primary and secondary number of turns and voltages is given by the equation

$$\frac{E_p}{E_s} = \frac{N_p}{N_s}$$

There are three main types of Instrument transformers:

- Current Transformer (CT).
- Voltage Transformer (VT) or Potential transformer (PT).
- Combined Voltage and Current Transformer (CVCT).

The rating of instrument transformer is specified in terms of volt-ampere (VA) with values not exceeding 100VA. The latest numeric relays and electronic measuring instruments in fact, pose demands of less than 5 VA, compared to the earlier mechanical type relays and measuring instruments.

A current transformer has its primary winding directly connected in series with the main circuit which carries the main current of the system. A proportional lower magnitude current is produced in the secondary of the CT, which is made to flow through the protection relay or measuring instrument. The standard secondary currents used are 1 ampere and 5 amperes and the CTs producing these are referred to as 1 amp CT and 5 amp CT respectively.

All current transformers used in electrical circuits are basically similar in principle in that they all consist of magnetically coupled primary and secondary windings, wound on a common iron core. The primary winding of current transformers are connected in series with the main circuit and hence the primary of current transformers shall be capable of withstanding the system short-circuit currents.

The basic relationship underlying design of all current transformers is:

AMPERE TURNS in Primary = AMPERE TURNS in secondary

e.g. 100 amps x 1 turn = 1 amp x 100 turns.

Current transformers have much lower secondary currents than their primary currents implying that the number of turns on the CT secondary is always more than in its primary winding. The secondary turns requirements for 1 amp secondary CT is 5 times the corresponding 5 amp CT and that is one main reason for the higher price of 1 amp CT in comparison with a 5 amp CT.

A voltage transformer is basically one, whose primary winding is connected across the main electrical system voltage that is under measurement. A proportionate low magnitude voltage is generated in the secondary winding of the VT. The commonly used secondary voltages are 110 volts to 120 volts (as per local country standards) and 380 volts up to 800 kV or more for primary voltages.

The construction features of current transformers and voltage transformers, the various types used and their methods of connections are covered in subsequent chapters.

## 1.7 Instrument transformers - advantages

Voltage transformers and current transformers continuously measure the voltage and current of an electrical system and provide corresponding low magnitude signals to protection relays to enable them to detect abnormal conditions. The low magnitude signals are also used by the analogue and digital measuring instruments for purposes of displaying and recording the system parameters. The values of actual currents in modern electrical systems vary from a few amperes in households, small industrial/commercial houses, etc. to thousands of amperes in power intensive plants, national grids, etc. Similarly the voltages in electrical systems vary from few hundreds of volts to many thousands of volts.

It is not practically possible to custom design measuring instruments and relays for every voltage/ current application. Voltage transformers and current transformers help to solve this issue by having standardized secondary output magnitudes. For example, the current transformers usually convert a primary current to either 1 ampere or 5 amperes and similarly voltage transformers convert primary voltages to around 110V. This kind of standardization helps meters to be manufactured for very low voltage and current applications making them light, transportable and cost effective. Hence the main purpose of the instrument transformers for metering applications is for standardization of the meters for all electrical applications with minimum time and cost spent in design, selection and manufacturing.  International standards have therefore evolved defining standard outputs for voltage transformers and current transformers.

These facilitate that only a minimum types of relays and meters need to be designed and manufactured for catering to the wide range of requirements of all types of electrical systems and consequently the selection and cost of relays and measuring instruments are brought within manageable means.

The main functions of instrument transformers are:

- Transform currents or voltages from usually high values to values that are easier to handle by relays and instruments
- Insulate the relays and instruments from the primary high voltage system
- Facilitate standardization of relays and instruments etc. to a few rated currents and voltages.

Current transformers and voltage transformers are extensively used for precise measurements as well as for routine measurements. They are also used for control and protection purposes. The main applications of instrument transformers are for the following:

- Metering - for energy billing and transaction purposes.
- Isolation - to insulate the metering circuit from the primary high voltage system.
- Protection - for system protection and protective relaying purposes.

## 1.8 Summary

Measurement of electrical parameters helps in distinguishing their characteristics and monitoring for any abnormal conditions. Electrical measuring instruments are used both in AC and DC systems. Most of the electrical parameters viz. active power, reactive power, power factor etc are dependent on two basic parameters namely voltage and current. All major electrical measurements require a good understanding of electrical systems and the way the electricity is transmitted and distributed to the various consumers – industrial, commercial, etc.

The purpose of performing measurements in electrical systems is not only for distinguishing their characteristics but also to help Utility companies to plan for their future growth and take strategic decisions regarding improvements/modifications needed for improving system reliability. Measurements also facilitate detection of abnormal behaviours in electrical systems, so necessary corrective steps can be taken to avoid costly interruptions and catastrophic failures. Measurement of energy is the main requirement from the commercial point of sale and purchase of electrical energy between the producer and the consumer of electricity.

The level of measurement accuracy needed, depends on the nature of returns and the benefits to the producer and consumer and hence accuracy shall be decided based on the requirement of the application.

Measuring devices can be broadly classified as indicating, integrating and registering types based on the kind of outputs obtained through them. The measuring instrument can be further sub divided as analogue (electromechanical) type and digital type based on the construction and operating principles. Electromechanical types generally incorporate moving needle mechanism for indication while digital meters provide the readings in the form of numerical displays. Transducers are yet another type of measuring devices used for providing low value signals to relays, control and measuring instruments.

Instrument transformers are essential devices in metering circuits. Voltage transformers and current transformers are used for providing voltage and current inputs to the measuring instruments, relays and control devices. They basically operate on the principle of electromagnetism similar to that of the standard power/distribution transformers. The current and voltage transformer outputs are standardized to ensure standardization of metering, protection and control devices. Typical outputs of current transformers are 1 amp or 5 amperes while voltage transformers usually produce 110V output.

[GVR1]It is necessary to explain RMS here

[GVR2]Also voltage based output?

[GVR3]Can we add here about digital instruments being able to communicate to a remote control system without having the transducer as an intermediary?