Electricity Meter in the age of Photovoltaic

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Introduction

In this article we will learn how the electronic Energy Meter can "deal" with the massive penetration of renewable Photovoltaic energy to the grid. The Meter handles measurements of environmentally friendly energy, but **hostile** to the meter itself.

Due to a shortage of conventional energy sources and increasing environmental pollution in recent years, as an alternative Photovoltaic (PV(solar energy has been put in use.

A key component in solar photovoltaic generation systems is the DC/AC converter. These converters are widely used in solar photovoltaic energy. Solar photovoltaic systems are connected to the electricity grid through a DC/AC voltage converter. These converters cause power quality problems, the harmonic distortion levels in distribution systems are increasing. Measurements on distribution network disturbances show high levels of voltage distortion, although the emission level of a single DC/AC converter meets the quality standards, a large number of DC/AC converters cause harmonic interference to the distribution (low voltage) network. DC/AC inverters penetrate mass harmonic emission, causing poor power quality.

Power companies and end users of electricity are becoming more and more concerned about the quality of the electrical network which can affect the performance of measurement equipment such as energy Meter that can affect the client's billing as well as affect the electrical appliances in the home. It is known that the interference caused by harmonics level of 8% of THD (Total Harmonic Distortion) can damage electrical household appliances.

Figure 1 shows Photovoltaic system for home; solar photovoltaic panels, electronic charge controller, batteries, DC to AC converter, service boxes and electricity meter.

A significant number of electronic energy meters in the market today are not suitable to deal with massive installations of solar photovoltaic systems; meters were not designed to deal with the harmonics distortion emitted from solar PV inverters. I am not sure that electric companies are aware of such problems; I doubt if they install the right type of meters that are developed to cope with photovoltaic "hostile" environmental?

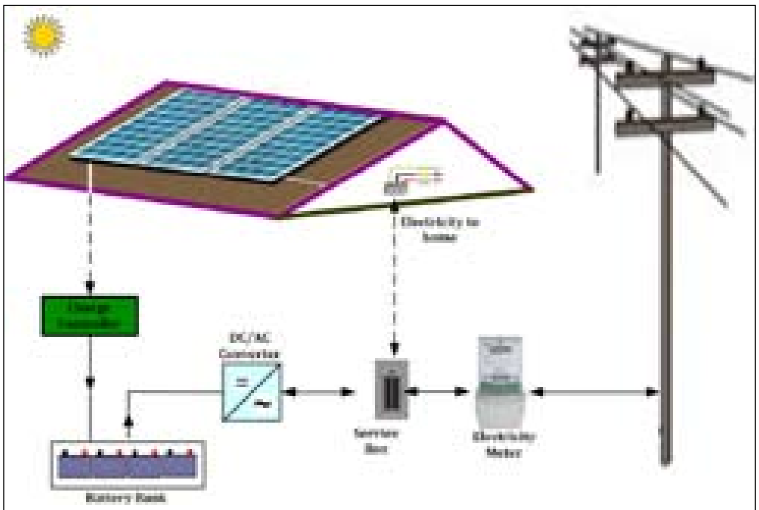

Figure 1: Photovoltaic system

The Meter

Our subject is the electronic energy Meter in renewable energy era, so we will concentrate here mainly on it.

Electricity meters measure current (amperes) and voltage (volts) and calculate the product of these values to determine electrical power (watts). Power integrated over time then provides the energy that is used (typically expressed as watt hours) and also measures the Power Factor (PF) of the load, Time of Use (TOU) of electricity consumption, and other things like: instantaneous parameters Voltage (t) and Current (t) per phase, etc. Power is measured by instantaneous values of voltage and current for each phase are converted to digital using precision A/D converters, a powerful DSP performs digital samples of voltage and current, processing V_{RMS} , I_{RMS} calculates Active power (P), Reactive power (Q) and Apparent power (S) and integrates the measured power quantities over time in order to measure the energy quantities. V_{RMS} and I_{RMS} are very important quantities for energy measurement and therefore disturbance of those values will cause incorrect measurement of Power: $P = V_{RMS} \cdot I_{RMS} P = V_{RMS} \cdot I_{RMS}$, and hence Energy: $E = V_{RMS} \cdot I_{RMS} \cdot t E = V_{RMS} \cdot I_{RMS} \cdot t$, also those formulas do not deal with the disturbances caused by harmonics to the voltage and current as a function of time. In this article we will see how harmonics distortion can affect V_{RMS} and I_{RMS}.

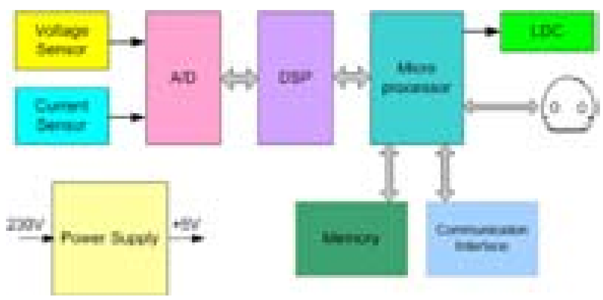

Figure 2: Energy Meter block diagram

For sampling the Current and Voltage an electronic meter requires Current and Voltage sensors. These sensors are interfaced to the meter's input circuitry, and therefore the linearity and behavior of the sensors as a function of time is the most important for the meter measurement, we will see how the harmonic disturbances can affect those sensors and hence the results of energy measurement.

Meter Sensors

There are two common methods for sensing the amount of current flowing in a wire (see figure 3):

1. Method uses an Isolation **Current Transformer** (CT) that indirectly measures current through the secondary winding.

The Current Transformer (CT) is a device offering isolation through transfer of current from the primary to the secondary side. The CT can handle higher currents than the shunt and also consumes less power. The nonlinear phase response of the CTs can cause power or energy measurement errors at low currents and large power factors and also problems of DC tolerance.

2. Method uses a **Shunt Resistor** to directly measure the amount of current.

The current sensing shunt is a small piece of metal, typically made of manganin and copper. It acts as a simple resistor with the voltage drop across it proportional to the current flowing through it. The shunt is ultimately limited by its own self-heating and is typically not used in meter designs with large maximum current requirements $I_{MAX} > 100A$.

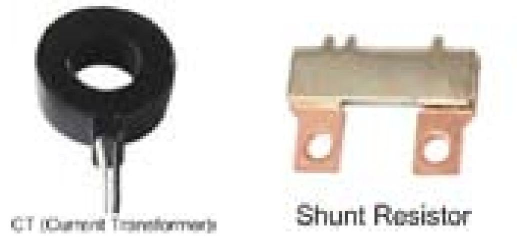

Figure 3: Current Sensors

Photovoltaic DC/AC converter's Harmonic distortion

The DC/AC converter is a critical component of a solar photovoltaic system; it converts DC (Direct Current) to AC (Alternating Current). The result is not a pure Sin wave and therefore contains harmonics. Any waveform that is not sinusoidal contains harmonics; any distortion or harmonic content will cause displacement of the Power Factor (PF) of the network and therefore reduce the efficiency of energy transfer from source to load, means that more current has to be generated at source to deliver the power to the load. Figure 4 shows the location of two direction (import & export) energy meter, from one side it is connected to the DC/AC converter and from the other side it is connected to the Grid.

When PF < 1 we need to modify the formulas of Power and Energy calculation by adding the PF quantity as follows: Power:

$P = V_{RMS} \cdot I_{RMS} \cdot \cos \emptyset P = V_{RMS} \cdot I_{RMS} \cdot \cos \emptyset$ à Energy:

$E = V_{RMS} \cdot I_{RMS} \cdot \cos \emptyset \cdot tE = V_{RMS} \cdot I_{RMS} \cdot \cos \emptyset \cdot t$

, also as direct result of the PF displacement it will produce Reactive Energy as well. Accordingly for three phase system:

$$P_t = V_{RMS1} \cdot I_{RMS1} \cdot \cos \emptyset_1 + V_{RMS2} \cdot I_{RMS2} \cdot \cos \emptyset_2 + V_{RMS3} \cdot I_{RMS3} \cdot \cos \emptyset_3$$

$$P_t = V_{RMS1} \cdot I_{RMS1} \cdot \cos \emptyset_1 + V_{RMS2} \cdot I_{RMS2} \cdot \cos \emptyset_2 + V_{RMS3} \cdot I_{RMS3} \cdot \cos \emptyset_3$$

Figure 5 gives an example of Power Vectors for "Normal condition" and for displacement caused by harmonics.

Figure 6: Shows two waves: one is pure sine wave, without distortion the results of V_{RMS1} / I_{RMS1} are maximum therefore the calculation of the Active Energy is maximum in this situation. The harmonics distorted wave V_{RMS2} / I_{RMS2} of this wave are reduced [see the blue lines $V_{RMS1} / I_{RMS1} > V_{RMS2} / I_{RMS2}$] and therefore the

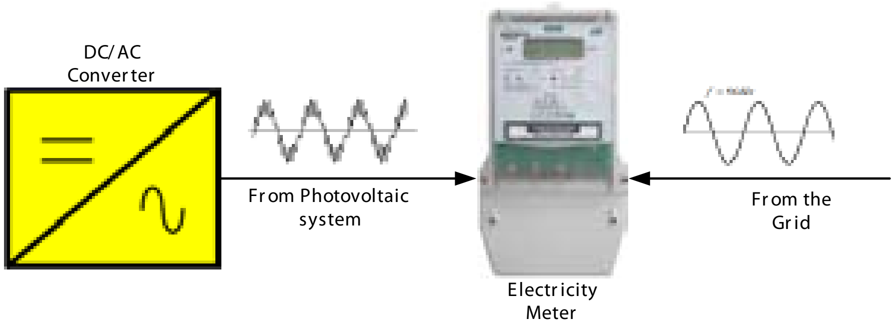

Figure 4: Location of Energy Meter

Figure 5: Displacement of PF (Power Factor) due to harmonic distortion

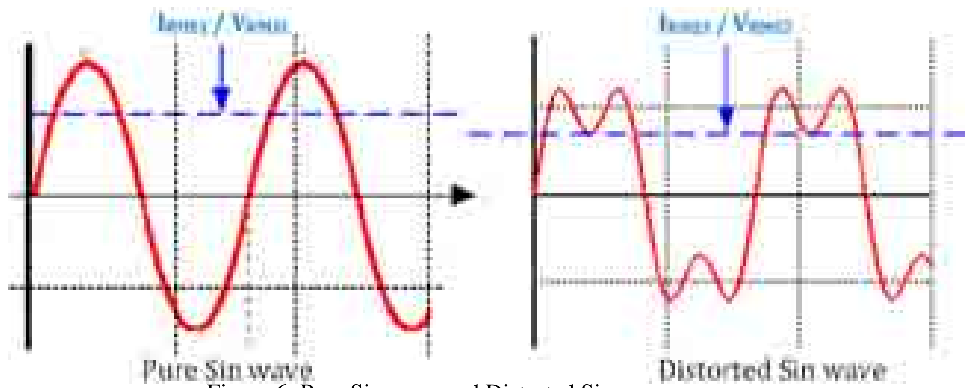

Figure 6: Pure Sin wave and Distorted Sin wave

calculation of Active Energy is also reduced, as affect of harmonic distortion.
Immediate conclusion is that harmonic disturbances will give a significant deviation calculations result of lower Active Energy (lower) measurement!

$$P1 = V_{RMS1} \cdot I_{RMS1} > P2 = V_{RMS2} \cdot I_{RMS2}$$

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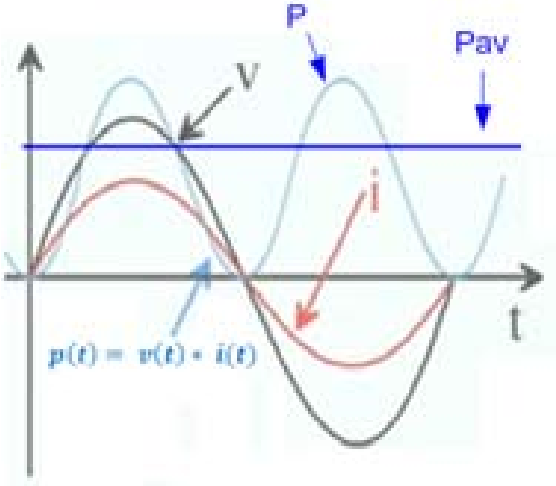


Figure 7: Pure sinusoidal wave quantities

Figure 7: Shows pure Sin voltage and current waves without angle shift between the current and voltage. Calculation of these waves will give only Active power $p(t) = v(t) \cdot i(t)$, the waveform of the Power P is all the way above Zero hence Pav (Average Power) is maximum in this situation.
Figure 8: Shows the effect of PF (power factor) displacement (phase shift ø between Voltage and current) the product of voltage and current $p(t) = v(t) \times i(t)$ there are parts (blue) of the result below zero, which means Reactive power is produced, and hence the Active power is reduced, Pav (average power) is lower in this situation.

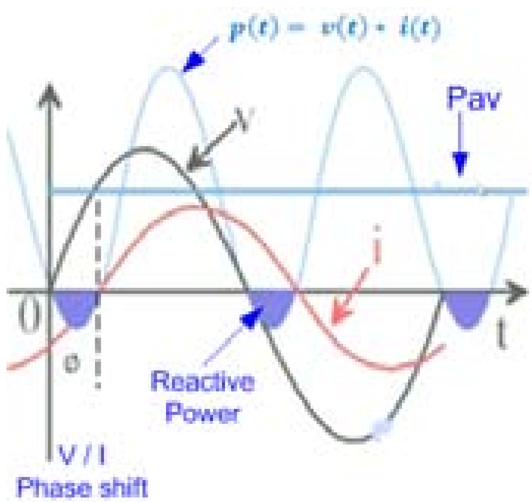


Figure 8: phase shift between current and voltage produces Reactive energy

Harmonics impact on Current sensors

Another result of harmonic disturbance is a negative impact on the Meter current sensors. "**Fourier transform**" of the distorted wave (in Figure 6) will show that there is a DC component in the current flow.
Input of DC current component to the CT sensor will shift the sensor "**working point**" toward saturation area which makes the sensor nonlinear component, and the current measurement result is seriously incorrect.
Figure 9: Shows B/H Hysteresis graph of the CT, the linear part of the CT is the Black line and this is the range where this component should be operated, when DC component penetrated to the Current flow this will shift the CT " working-point" to the Red line where the CT is totally nonlinear, then the relationship between input current and output current cannot be predicted.

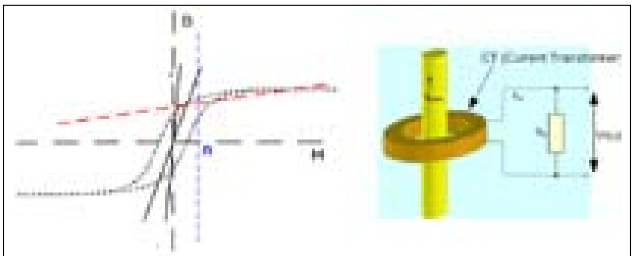


Figure 9: B/H Hysteresis graph of CT

There are CTs with DC tolerance however such CTs have a constant and inherent angle shift between input and output which will cause considerable error in the energy measurement, when designing the meter this issue must be taken into account and should be solved, otherwise the meter cannot be approved .
Due to harmonics DC component will appear in the current, DC component in the current also must be measured and added to the Active energy. CT sensor blocks the DC component therefore in this case DC component is removed by the CT and will not be calculated, Active energy result is seriously incorrect.
For Photovoltaic energy measurement I doubt if meters with CT as current sensor can be used?
Figure 10: Shows that DC component is only considered for measurement of Active Energy in "quadrant I", DC component does not appear in the Reactive Energy calculation (quadrants II, III, IV). So our concern for DC component measurement is only for Active Energy calculation and the CT as current has some disadvantages.

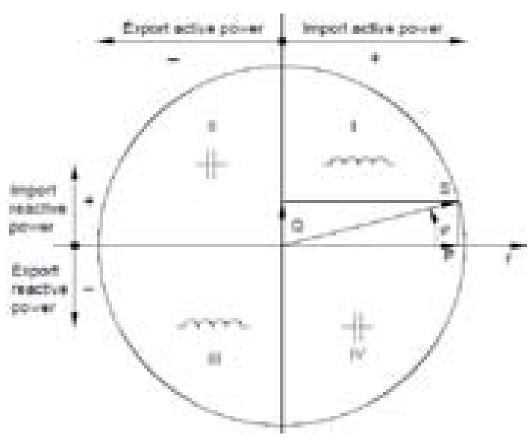


Figure 10: Quadrant definitions for active and reactive power

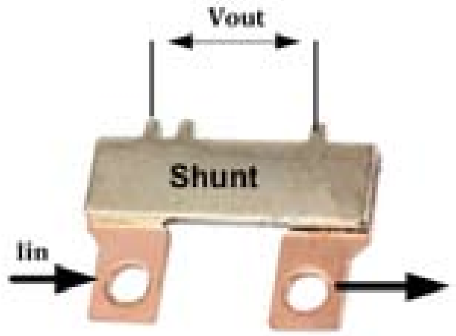


Figure 11: Shunt resistor as current sensor

Figure 11: Shows the Shunt as current sensor, this component does not suffer from some disadvantages of the CT as explained above, and it seems that it is better to use this component for photovoltaic meters, later we will see more. DC component will be developed on the Shunt and DSP with “All-Pass” function will calculate and add the DC component to the Active energy result.

Meter Power Supply

Another problem due to harmonic distortion is that damage can be caused to the meter power supply if it is not well designed.
Energy meter has an internal power supply to provide the necessary voltages to the meter parts. Electricity meter were designed and appeared in the market before the era of Photovoltaic energy systems, therefore meter manufacturers were not aware of the mass harmonics distortion circumstances. There are energy meters with different types of power supply such as:

1. “**Linear power supply**” providing a regulated DC output (3V÷5V) using a step-down transformer to reduce the 230 V AC to a desired level of low voltage AC. Usually when correctly designed this type of power supply does not “suffer” much from harmonic distortion.
2. “**Switched-Mode” Power Supplies** providing a regulated DC output (3V÷5V). Usually when correctly designed this type of power supply does not “suffer” much from harmonic distortion.
3. “**Capacitor Power Supply” using of a Voltage Dropping Capacitor. Meter that has such kind of power supply can be damaged significantly by harmonic distortion; mainly the voltage dropping capacitor can be destroyed. As a result the meter malfunctions and should be removed, in other cases the meter power supply performance is poor as a result a significant degradation of the meter energy calculations.**

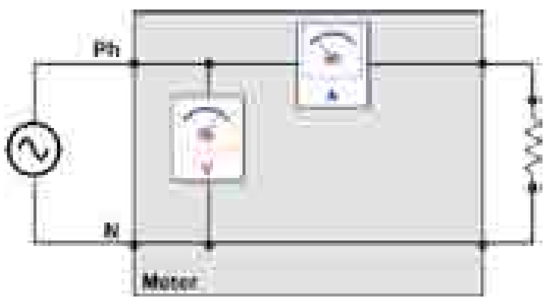


Figure 12: Meter using 1 Element (Blondel)

Current in the Neutral wire

Another problem we need to discuss due to the Harmonic distortion; Harmonics can nearly double the amount of current on the Neutral wire in three phase 4 wire distribution system.
[**Blondel theorem**] “In a system of N electrical conductors, N-1 electrical meter or wattmeter elements when properly connected, will measure the electrical power”. The majority (almost 95%) of energy meters in the market uses “**1 Element**” [One Volte meter & One Ampere meter] for power measurement see Figure 12. Most of the meters in the market measure the voltage and current of the phase, without measuring the current in the Neutral wire (using 1 Element method), in three phase balanced network no need to measure the current of the Neutral wire (it is zero).
Unfortunately the reality is that Photovoltaic solar energy DC/AC converters and other end user appliances emit harmonics resulting in unbalance of the electricity grid, Harmonics can nearly double the amount of current on the Neutral wire, no more balanced network, therefore energy meter should measure the current on the Neutral wire as well be of “**1.5 Element**” [One Volte meter and Two Ampere meters] type, see Figure 13.

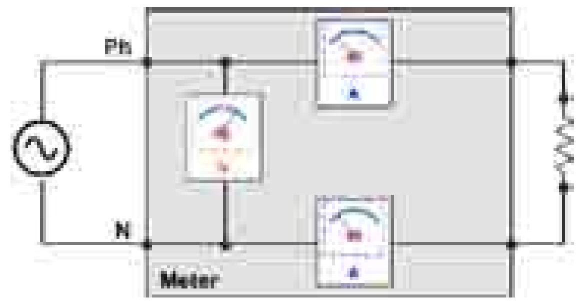


Figure 13 : Meter using 1.5 Element (Blondel)

Meter inputs circuitry types

Figure 14: Shows the Voltage and Current sampling for meter’s measurement component. The input **Voltage** interfaces to the meter has a very large resistance (**Ra, Rb, Rc**) in series with the measurement component to reduce the amount of current coming from the network to the meter. The input **Current** interfaces to the meter by very small Shunt resistor (**Rai, Rbi, Rci, and Rni**) that allow most of the current being measured to flow from source to the load. The majority of meters do not have Shunt on the Neutral wire, due to Harmonic distortion a shunt has been added to the Neutral (see Yellow rectangle in Figure 14) to measure the unbalance current.
ITF Fröschl GmbH , from Germany has proven metering solutions for Photovoltaic energy measurement

If you wish to know more you are welcome to listen to my lecture in the Energy Metering & Management session SEEEI’s 2012, on Friday, November 16, 2012 directed by Mr. Mashiach.

Summary/Suggestions

1. Household Consumer’s billing that is based on the definitions of Active Energy only, must be changed to three basic electrical quantities: Active power (P), Reactive power (Q) and Apparent power (S).
2. The Photovoltaic Energy Meter should be with measurement of Active and Reactive Energy measurement. The difference in KVA meter measurement can be as large as 30% when the wave is distorted.
3. Electronic meter cannot resolve the problems caused to the voltage and current waveforms, the meter will use those waves to measure energy quantities.

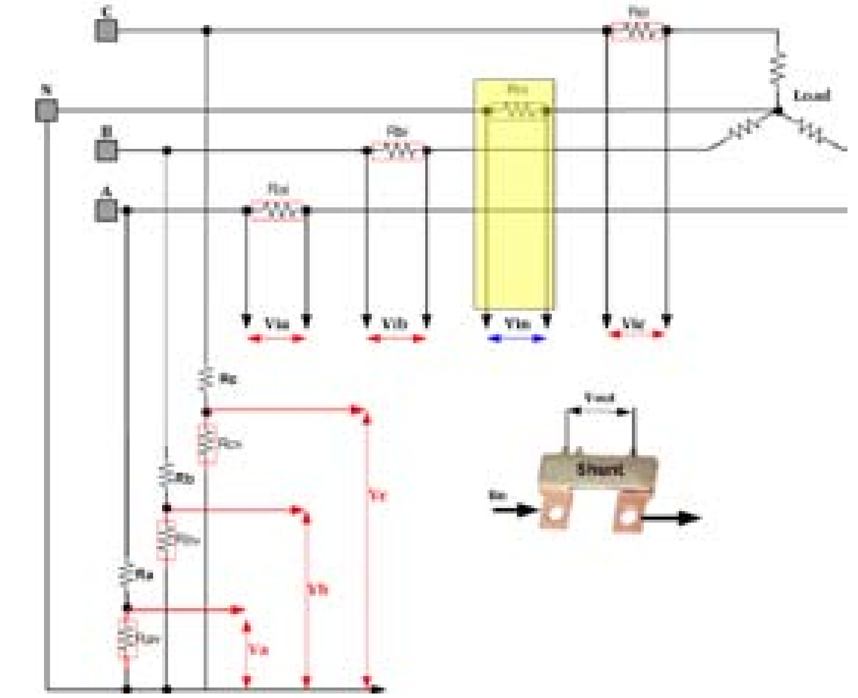
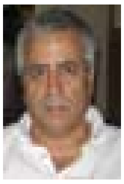


Figure 14: Three Phase Shunt Resistors circuitry input

4. It is known that photovoltaic DC/AC converter causes Reactive energy in the system, so with installation of the meter it is necessary to install Power Factor Correction Capacitors.
5. One problem is that there is no requirement in the International Standards (IEC) for testing Meter Reactive energy measurement under harmonic interference. Electric companies do not get test reports of reactive energy under harmonic distortion.
6. For Photovoltaic energy measurement I doubt if meters with CT current sensor can be used?
7. For Photovoltaic energy measurement I would suggest to use meters that use Shunt as current sensor, **provided** that the meter has DSP with "All-Pass" function.
8. Use of Meter that has Capacitor Power Supply, **only** if the meter power supply uses special Capacitors which are designed to overcome the harmonics distortion problems.
9. For 4 wire three phase system Harmonics can double the amount of current in the Neutral wire, therefore this meter must be of type of "**1.5 Element", measurement of the Neutral wire current as well.**



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2002 - 2004 Vice President at "Holley Metering" a Chinese company, and the largest metering company in the world providing: Electricity, Water, and Gas meters, and AMR systems
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