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Application Note AN1601

Effect of Current Transformer Phase Shift On Metering Accuracy – Phantom Energy

Associated Product: WattsOn Family

Summary

Current transformers (CTs) are key components in power metering applications. The current transformer isolates and scales the line current to a level that can be safely measured by a power meter.

The accuracy of current transformers is a critical factor in determining entire metering system performance. Overall CT accuracy is a dynamic function of ratio, linearity and phase shift errors. This application note focuses on the effects of phase shift error.

Phase shift has always played a role in metering accuracy, however its effect is now more noticeable in applications where purely reactive loads are present. Idling solar inverters, permanently connected to the grid are an example of such a case.

Introduction

Electrical power (P) is a product of voltage (V) and current (I): P=V*I. This simple definition is true for DC (direct current), however AC (alternating current) systems are more complex. The AC voltage alternates (sine wave) and this effectively forces the current to flow back and forth through the conductor. In addition, any capacitive or inductive loads change the timing relation between voltage and current. Both of these load types store and release energy by constantly "charging" and "discharging" it. As a result the current "ebbs and flows" in the conductor but there is no power consumption.

The power associated with this current is referred to as "reactive" and is measured in VAR (Volt-Ampere Reactive). The power that does actual work in a load (light, motor, heater, etc.) is referred to as "real" (or "active") and is measured in W (Watts).

The AC power relationship is usually represented by a vector diagram using two axes (shown in figure 1). The 'x' axis (real) represents real power (W), which performs useful work at the load, while the 'y' (imaginary) axis represents reactive power (VAR) - power that flows but does not contribute to real work.

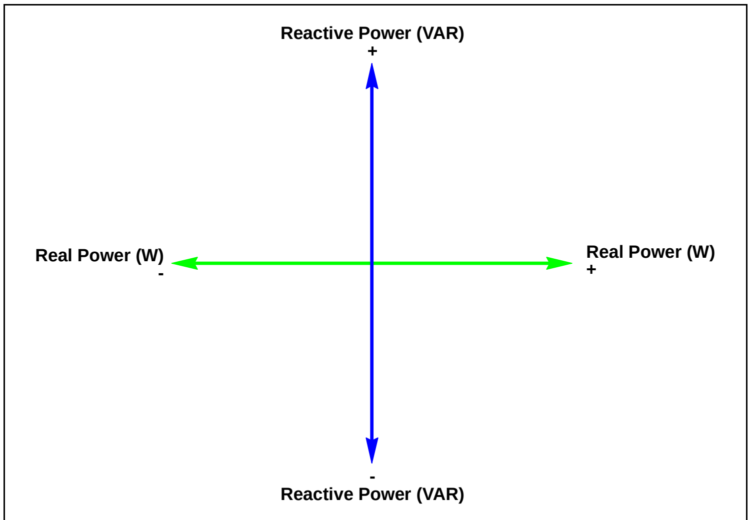

Figure 1

Power Triangle

The "power triangle" represents the real and reactive power relationship on the power axis. *Real power* can flow in two directions (import/export, +/-). *Reactive power* can also flow in two directions (inductive and capacitive). Additionally, the perspective of the measurement is important (i.e. your "import" is my "export") so the installation point and reference bears significance in how a meter perceives energy flow. It should be mentioned that the sign of the power in a system (+/-) and how it relates to import/export is arbitrary, and depends on the chosen convention.

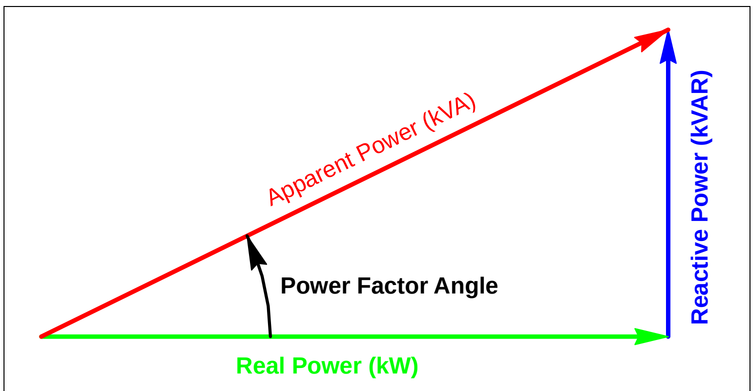

Figure 2

The relationship between *real power* and *reactive power* is determined by the nature of the load. If the load is purely resistive, then voltage and current are perfectly in sync (referred to as "in phase") with each other, and only real power flows.

Capacitive and inductive loads change the timing between voltage and current. The more "reactive" (capacitive or inductive) the load is, the greater the reactive power component in the power triangle. To deliver both real and reactive power, the amount of current in the conductor must increase (as per the hypotenuse of the triangle). The power flow associated with this current is represented by the *apparent power* vector.

A cosine of the angle between vectors of real power and apparent power is referred to as Power Factor (PF). Power Factor may be considered as the "efficiency" of the power delivered, and/or as the degree of utilization of the current, or its ability to deliver real power. (In a purely resistive load VAR = 0, power factor angle =0 thus its cosine =1 and apparent power equals real power – the triangle has no vertical (blue) component).

Current Transformer Role in Measurement

The CT scales down and isolates the current signal to the meter. Current transformers work on the principle of magnetic coupling (like any other transformer), therefore their accuracy is affected by the following errors:

- *Ratio error*: the effective input to output ratio (the output is a scaled down version of the input)
- *Linearity*: the input to output ratio error over the input range of the CT
- *Phase Shift*: the input to output current shift introduced by the CT

Typically, focus is placed on ratio error as it can be easily measured. It is the difference of the actual output signal magnitude compared to the theoretical value. The timing relationship between the input and output (phase shift) is often ignored.

Every current transformer introduces a phase shift. Furthermore, it is a dynamic and non-linear characteristic (figure 3). It depends on the type and construction of the CT (core material, size, winding, full scale rating, solid or split core). It also depends on the actual current being metered and the load (burden) on the CT presented by the meter. A typical characteristic of current transformer phase shift is represented by the graph below.

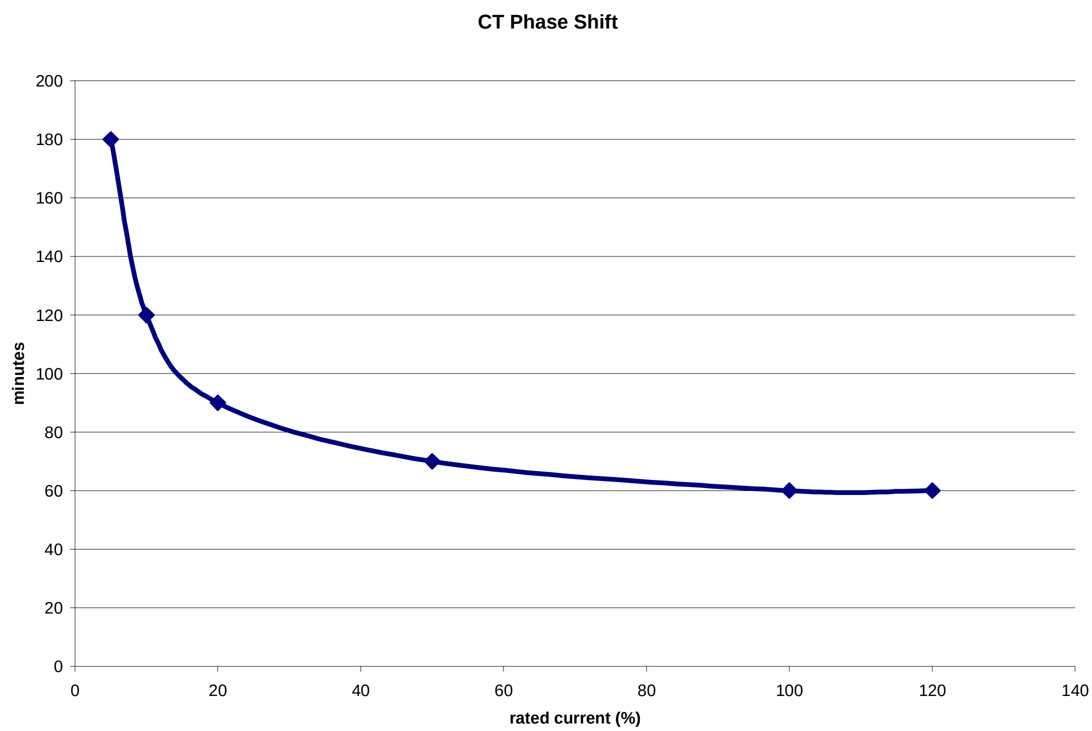

Figure 3

The phase shift introduced by a CT is exhibited as a leading phase angle. This means that the output current signal from the CT leads the actual current being measured.

Because the current transformer slightly skews the relationship between the voltage and current measured, it invariably changes the "picture" of the power triangle as seen by the meter.

Let us assume a perfectly resistive load, which consumes only real power on the power vector diagram (Figure 4).

Now, let us assume that we measure this load using a current transformer with a slight phase shift (Figure 5). Again, the phase shift induced by a CT is typically leading, which will shift the output signal CLOCKWISE on the power vector diagram.

It is clear from the diagram that the phase shift of the CT has skewed the output signal (which would be seen by the meter). Consequently the resulting measurement will have both real and reactive power components.

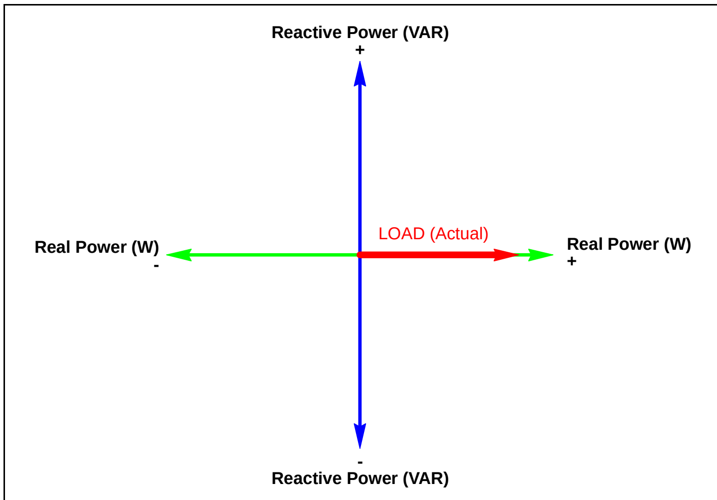

Figure 4

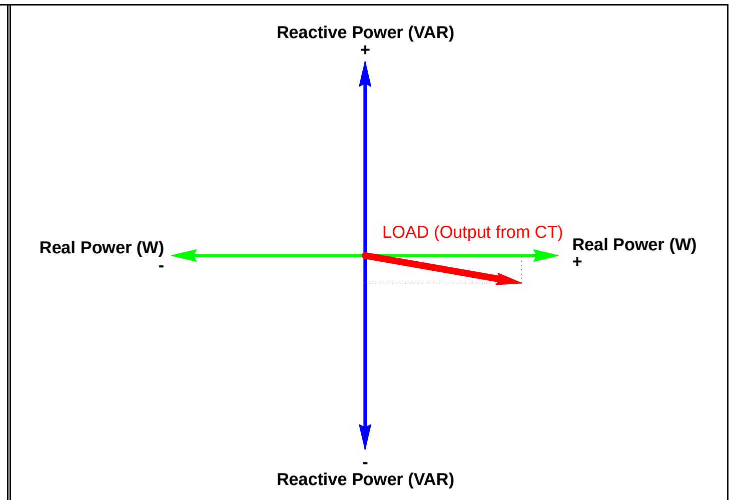

Figure 5

In an extreme situation, where the load is purely reactive (figure 6), it can be seen that the skew caused by the CT yields a real power component to the signal seen by the meter (figure 7)

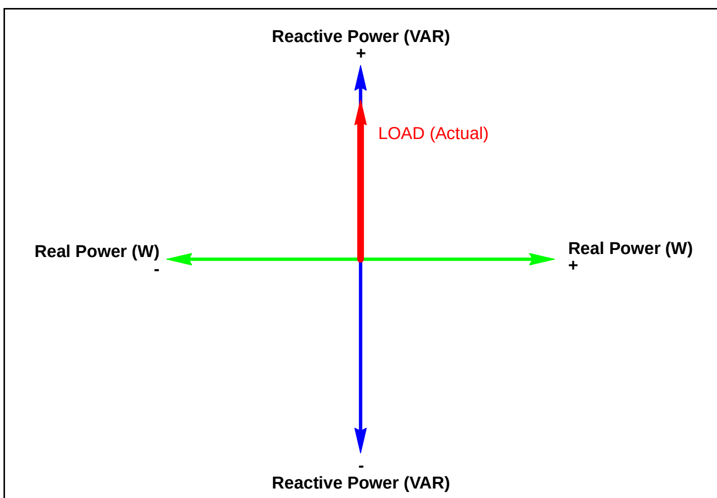

Figure 6

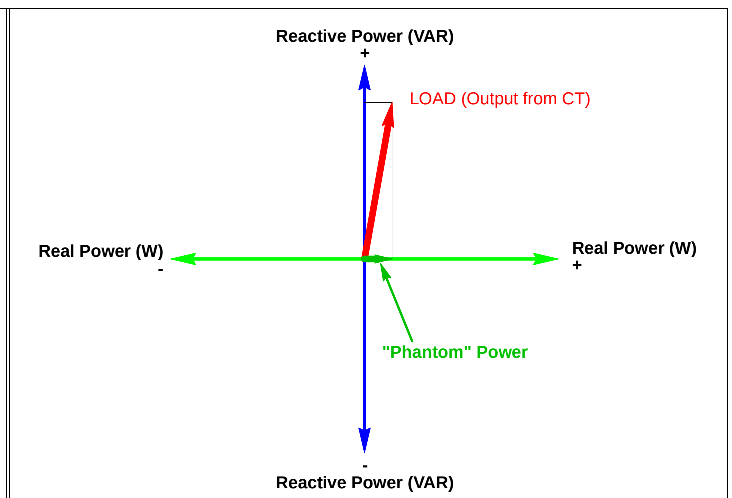

Figure 7

Effect on Measurement Accuracy at different Power Factors

Most current transformer specifications list the accuracy performance between 10% and 110% of the rated input current. Within this range, the phase shift is usually small and mostly constant. Addionally, most loads consume little reactive power in comparison to real power (their power factor is high, meaning small phase angle). In such situations, the CT phase shift plays a small role in the overall accuracy of the real power measurement, as demonstrated in the below examples.

The error increases when measured current is low because the phase shift of the CT typically deteriorates as load current drops. More importantly, the effect of CT phase shift is amplified when reactive loads are present (low power factors are involved). While the power factor of the load does not change the CT phase shift specification, the phase shift of the CT influences the measurement error more significantly when the power factor decreases.

This is best demonstrated by examples:

If we assume a 100V, 10A (1000VA) load that is purely resistive (1000W, no reactive power), being measured by a CT with 2° phase shift then:

Actual Load		As seen through the CT	
Phase Angle [Θ]	0°	Measured Phase Angle [Θ]	**2°**
Power Factor [cos(Θ)]	1.00 (resistive)	Power Factor [cos(Θ)]	0.9994 (mostly resistive)
Actual Real Power [P_a]	1000 W	Measured Real Power [P_m]	999.39 W
Actual Reactive Power [Q_a]	0 VAR	Measured Reactive Power [Q_m]	34.90 VAR
		Relative Error [(P_m – P_a) / P_a]	**-0.061 %**

The resulting error in real power measurement is small and well within specifications for any system.

Now, let us assume a load with similar magnitude (1000VA), however having a poor power factor (0.7). This could be a load such as a motor (which has both real and reactive components due to the inductance of the windings).

Actual Load		As seen through the CT	
Phase Angle [Θ]	45.573°	Measured Phase Angle [Θ]	45.573° + **2°** = 47.573°
Power Factor [cos(Θ)]	0.7000	Power Factor [cos(Θ)]	0.675
Actual Real Power [P_a]	700.00 W	Measured Real Power [P_m]	674.65 W
Actual Reactive Power [Q_a]	714.14 VAR	Measured Reactive Power [Q_m]	738.14 VAR
		Relative Error [(P_m – P_a) / P_a]	**-3.62 %**

It can be seen from this example that the error grows significantly, even though the magnitude of voltage (100V) and current (10A) has not changed. The current transformer is performing identically, with an identical phase shift influence on the current signal. Only the load type (power factor) has changed. This demonstrates that the effect of the CT phase angle causes a non linear error - it is a factor of the cosine of the resulting angle.

As the power factor worsens, this becomes an even larger issue. Let us assume the same load magnitude (1000VA), with an even more reactive power factor (0.100):

Actual Load		As seen through the CT	
Phase Angle [ϴ]	84.261°	Measured Phase Angle [ϴ]	84.261° + **2°** = 86.261°
Power Factor [cos(ϴ)]	0.1000	Power Factor [cos(ϴ)]	0.065
Actual Real Power [P_a]	100.00 W	Measured Real Power [P_m]	65.21 W
Actual Reactive Power [Q_a]	714.14 VAR	Measured Reactive Power [Q_m]	997.87 VAR
		Relative Error [(P_m – P_a) / P_a]	**-34.79%**

In this case, the error has grown almost exponentially.

In the worst case scenario (purely reactive load, no real power component) the theoretical error would be infinitely high:

Actual Load		As seen through the CT	
Phase Angle [ϴ]	90.000°	Measured Phase Angle [ϴ]	90.000° + 2° = 92.000°
Power Factor [cos(ϴ)]	0.0000	Power Factor [cos(ϴ)]	0.0349
Actual Real Power [P_a]	0.000 W	Measured Real Power [P_m]	34.90 W
Actual Reactive Power [Q_a]	1000.000 VAR	Measured Reactive Power [Q_m]	999.39 VAR
		Relative Error [(P_m – P_a) / P_a]	∞ %

Although the error with respect to power cannot be defined (a divide by zero in the error formula), this example shows that **the CT phase shift can lead to real power measurements when there is a purely reactive device connected in the system.** This Phantom Power and Phantom Energy will be measured and recorded by the meter.

The examples tabulated above show that similar errors exist in the VAR measurements as they do in the Watts, but on opposite ends of the power factor scale.

The diagrams in figure 4, 5, 6, 7 illustrate the phenomenon. It can be seen that although the actual load does not draw any real power, the effect of the CT phase shift presents a signal to the meter as if it does.

Why hasn't this issue been a problem in the past?

Historically, most measured loads have been resistive (PF better than 0.9). As shown earlier, the CT phase shift has a modest impact at high PF values. While the error due to phase shift is also present in VAR measurements, historically these have been ignored, and the resulting error to real power (W) measurements was too small to be noticed. Additionally, the other characteristics of the CT (ratio error, linearity) typically play a larger role in real power measurement error at high power factors.

Today's requirements for sub-meters and unique solid state power devices change the scenario.

Variable frequency drives and inverters have large reactive output stages (capacitors or inductors). In the case of an inverter, the output stage becomes a LOAD to the grid when the inverter is off but is not physically disconnected. As a result, this presents a reactive current draw on the grid, although no "real" power is consumed. However, if this inverter is monitored by a meter, the CT will invariably add a phase shift, and register a small amount of real power (and energy) flow.

Solutions

Although it is possible to compensate for CT phase shift in the meter, it is impossible to do so across the entire CT input range. This is because the phase shift is not constant or even linear. Moreover, most CT manufacturers do not list a phase shift specification and those which do, give the phase shift at the CTs "sweet spot", not outside the CT input ratings for accuracy (typically 10% to 110% of rated current).

The best solution is to use CTs with minimal phase shift. This is one of the reasons why Elkor promotes precision mA CTs. The mA CTs, combined with unprecedented dynamic input range and very low burden presented by Elkor meters, allow the CT to perform under preferred conditions, over a much larger input range. These factors offer the best system accuracy

As an alternative, additional logic in the metering and data acquisition systems may be considered to prevent measurement of certain quantities under specific conditions. Elkor's WattsOn-Mark II offers "PowFilter™", a proprietary feature to compensate for poor CT performance under these specific conditions.

Conclusion

A growing requirement for multi-point metering, stipulated by energy management and use of renewable sources has created a need for indirect (current transformer supplied) electricity meters. Most modern solid state meters can be designed as very accurate devices but they all rely on input signals from external CTs. It is a challenge to find appropriate CTs and to use them in such a way that their inherent errors will be minimized.

The CT phase shift is an important consideration for the overall metering accuracy. The type of load determines the resulting errors. In extreme cases, non-existing Watts (Phantom Power) may be measured because the CT presents a slightly shifted signal to the meter.

Although it is possible to compensate for phase shift, it is impossible to do so across the entire input range. There will always be some error, especially amplified at the very low end of the measurement range.

Choosing a quality CT will alleviate (although never fully eliminate) the issue. Additional logic in the metering and data acquisition systems can be used to mitigate the remaining issues.