Power Monitoring Applications

Introduction

Monitoring momentary power and energy use becomes increasingly important in data centers, industrial equipment, power distribution units (PDUs), household appliances and other applications.

In data centers, techniques such as smart cooling based on measured energy consumption are used to minimize cooling cost, whereas energy monitoring can be used to bill customers for the use of servers or server clusters based on consumed energy.

TERIDIAN energy metering chips are ideal for all above-mentioned applications since they provide all functions to efficiently and accurately measure the relevant energy-related values.

This application note describes how the various TERIDIAN energy metering chips can be used to display, record and monitor a variety of power-related items such as voltage, current, real, reactive and apparent energy, as well as phase angle, power factor, and frequency.

Topologies of Energy Monitoring Systems

Energy monitoring and display systems may be classified into the following categories:

- Stand-alone systems
- Systems with communication capabilities

The stand-alone systems are independent self-contained units that are mainly used for display purposes. They can be designed with a variety of TERIDIAN energy metering chips (71M6511, 71M6512, 71M6513, 71M6521, 71M6523, 71M6531, 71M6533, or 71M6534) combined with external sensor(s) for current and voltage, a display, and an optional user interface. Since there is no recording or communication component, these systems are limited to singular installations. The application of the TERIDIAN chips in these systems is very similar to applications in electricity meters. Important meter-related topics are covered by the data sheets and by several TERIDIAN Application Notes published for electricity meter designers.

Power-monitoring systems with communication capabilities are of increasing importance. They are used in data centers ("server farms") with smart cooling capabilities, installations where billing is based on energy usage, wind mills and applications where a large number of electrical outlets or power distribution units (PDUs) have to be monitored by a central processor. These types of applications are addressed in this Application Note.

TERIDIAN Metering ICs - Comparison

Since all TERIDIAN electricity metering chips have high-resolution ADCs, an independent compute engine (CE), and a 80515 microprocessor with communication capabilities, they are useable in the context of energy monitoring systems. Table 1 lists some of the features important for smart energy monitoring systems.

As indicated in Table 1, almost any TERIDIAN energy meter chip can be used for the task at hand. The 6515H has a special status, however: It is shipped pre-programmed with a versatile metering program and requires an external master to function as a host controller. It does not directly support LCD displays.

Chip	Number of measurement inputs	Flash memory (KB)	Communication ports	Other
6511	3	64	2 x UART	Single-phase (1 voltage, 2 currents)
6512	4	64	2 x UART	Single-phase (2 voltages, 2 currents)
6513	6	64	2 x UART	Poly-phase
6515H	6	64	1 x UART	Intelligent front end, poly-phase, no LCD pins
6521	4	8, 16, 32	2 x UART	Single-phase (2 voltages, 2 currents)
6523	(6)	32	2 x UART	External multiplexer, no VARh output
6531	4	128, 256	2 x UART, SPI	Single-phase (2 voltages, 2 currents), advanced RTC
6533	7	128	2 x UART, SPI	Poly-phase, advanced RTC, differential inputs
6534	7	256	2 x UART, SPI	Poly-phase, advanced RTC, differential inputs

Table 1: TERIDIAN Chip Comparison

Circuit Topologies of Energy Distribution Systems

Various configurations for power sources exist for industrial and PDU applications. Most of them are used in energy metering and thus are directly compatible with the TERIDIAN energy metering chips. In the dual-processor architecture of the TERIDIAN energy metering chips, the computation engine (CE) processor implements the equation representing the energy calculations of specific meter configurations. For example, in a 3-phase, 4-wire WYE configuration, where the total energy is the sum of the individual phase energies, the CE directly computes the total momentary power using equation 5, i.e. $P = VA*IA + VB*IB + VC*IC$ along with the power of the individual phases. The power is multiplied with the incremental time taken per sample (usually 400µs) to yield an energy quantum. Energies for all phases are continuously summed up over an accumulation interval (usually one second) by the CE and then handed over to the MPU for long-term accumulation, post-processing, display and storage.

Four-Wire Three-Phase Y

This configuration is very common in industrial environments. It is important to notice that the common reference for the phase voltage (neutral) is directly connected to the V3P3 (supply) voltage of the Teridian meter chip.
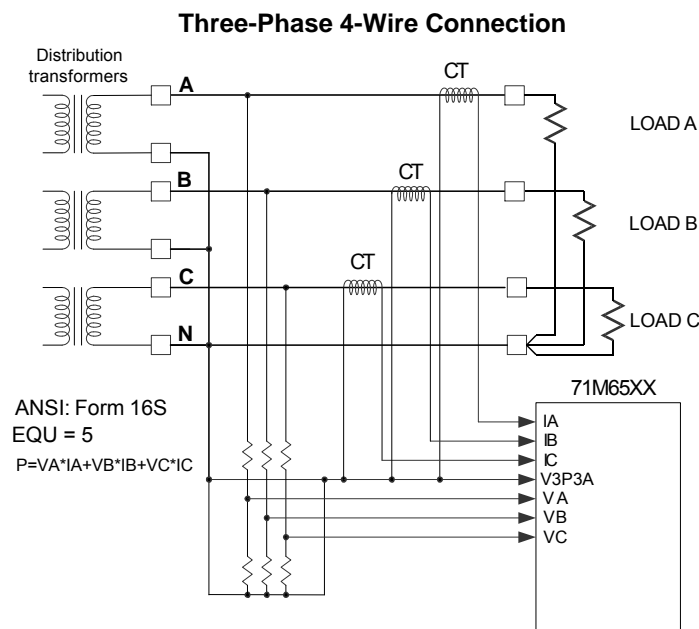
Three-Phase 4-Wire Connection

Figure 1: 3-Phase, 4-Wire Y Configuration

Single-Phase 2-Wire

This configuration is very common in residential environments. Only one voltage is present, and only one current is measured. The energy is calculated using equation 0, i.e. P = VA*IA. Single-phase energy metering chips such as the 6511, 6521, or 6531 are typically used for this configuration. The remaining inputs of the energy meter chip (IB, VB) may be used for a secondary channel.
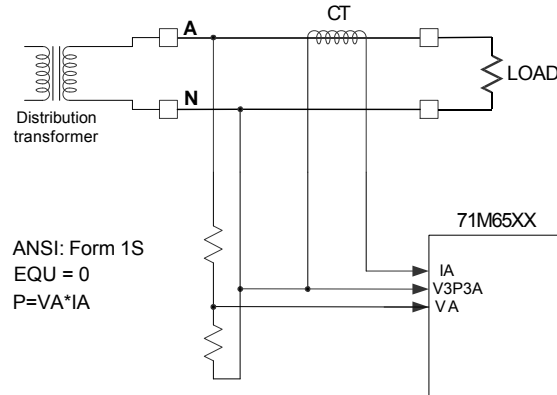

Figure 2: Single-Phase, 2-Wire Configuration

Single-Phase, Three-Wire

This configuration is used in the US and in some South-American markets. Load currents may flow from A to neutral, from B to neutral, or from A to B. Using equation 1, two current sensors are used, their measurements are subtracted and the result is divided by two.
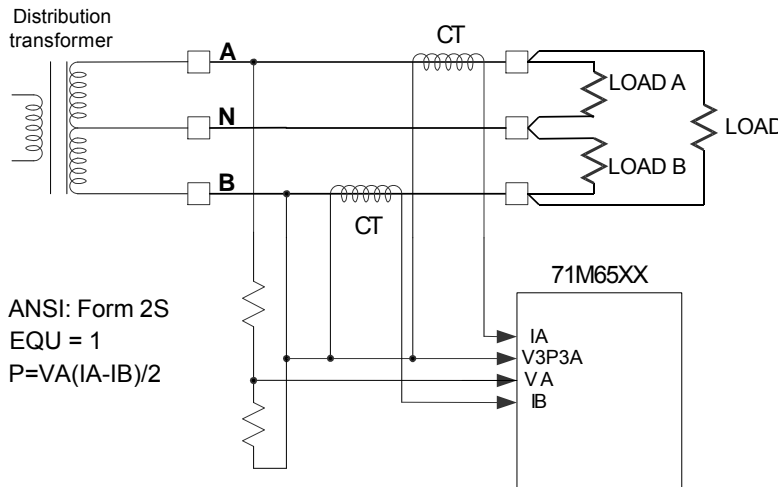

Figure 3: Single-Phase, 3-Wire Configuration

Two-Phase, Three-Wire

This configuration is used in Japan. Phases A and B may be independent and not in phase, they may for example be two phases out of a three-phase system. This is why both voltages and both currents have to be measured. The energy is calculated using equation 2, i.e. P = VA*IA + VB*IB.
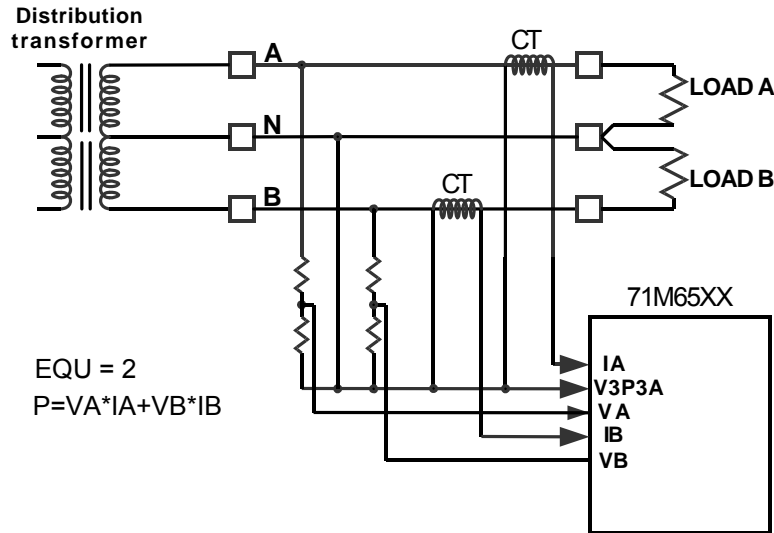
Figure 4: Two-Phase, 3-Wire Configuration

Three-Phase, Three-Wire Delta

This configuration provides three symmetrical phases in delta arrangement. Since the system is floating (isolated from ground) it is permissible to connect one phase (C, in this example) to ground or neutral. This way, only two phase voltages and two phase currents are used for the loads, and the power calculation is reduced to equation 2.
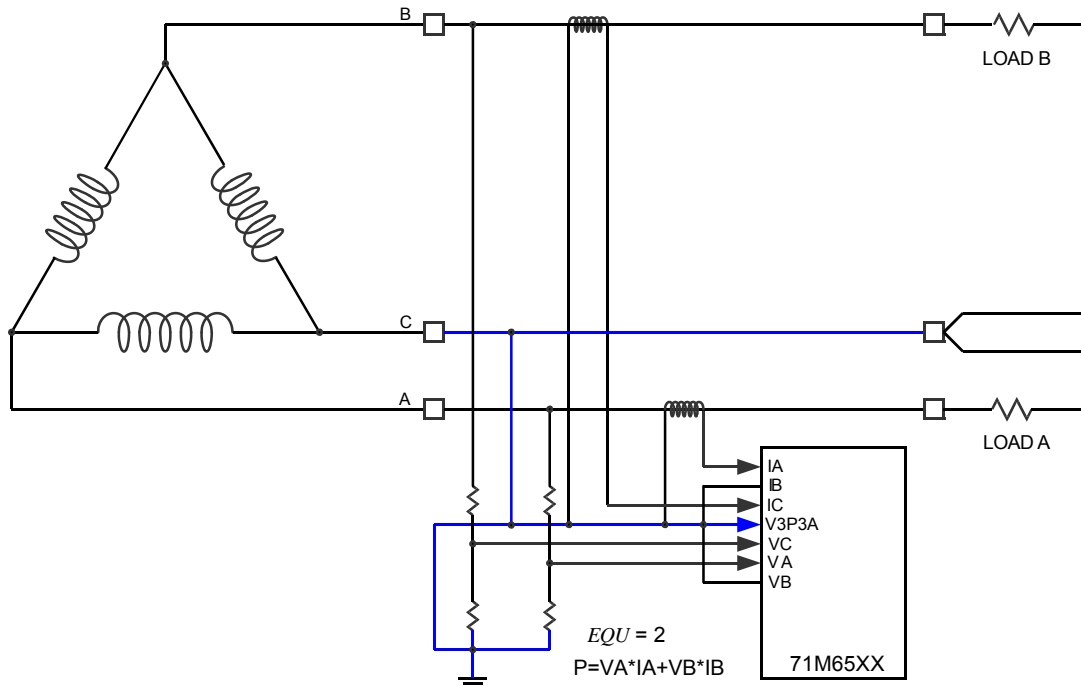

Figure 5: Three-Phase, 3-Wire Delta Configuration

Three-Phase, Four-Wire Delta

In this configuration, the center tap of transformer A-B is connected to ground, while the phases A, B, and C are still available to provide load currents. The energy calculation uses equation 3, i.e. P = VA*(IA-IB)/2 + VC*IC.
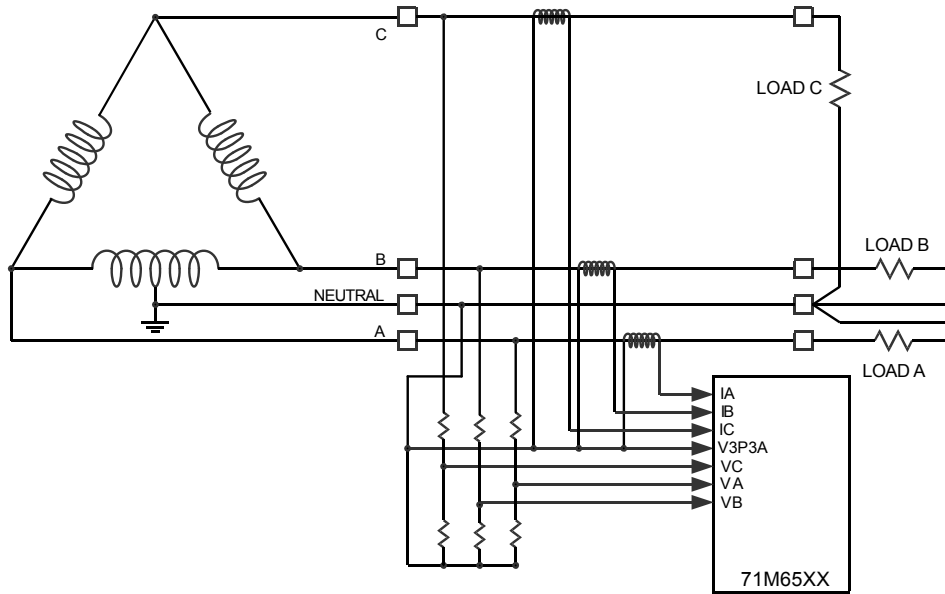
Figure 6: 3-Phase, 4-Wire Delta Configuration

Three-Phase, Three-Wire Delta, Isolated

Sometimes a 3-phase, 3-wire delta configuration is given, but, as opposed to the 3-phase, 3-wire and 3-phase, 4-wire delta configurations, it is not permitted to ground any phase. This configuration is not too common in the metering world, but frequently encountered in the context of PDUs (see Figure 7). The application requires measurement of the phase voltages V_{AB}, V_{BC}, and V_{CA}, which in turn would require a truly differential configuration of the meter chip. However, like all ADCs and mixed-signal chips, metering chips have single-ended topologies, i.e. they use ground or the DC supply voltage as reference points. This means that the delta configuration has to be converted to a ground-referenced configuration.
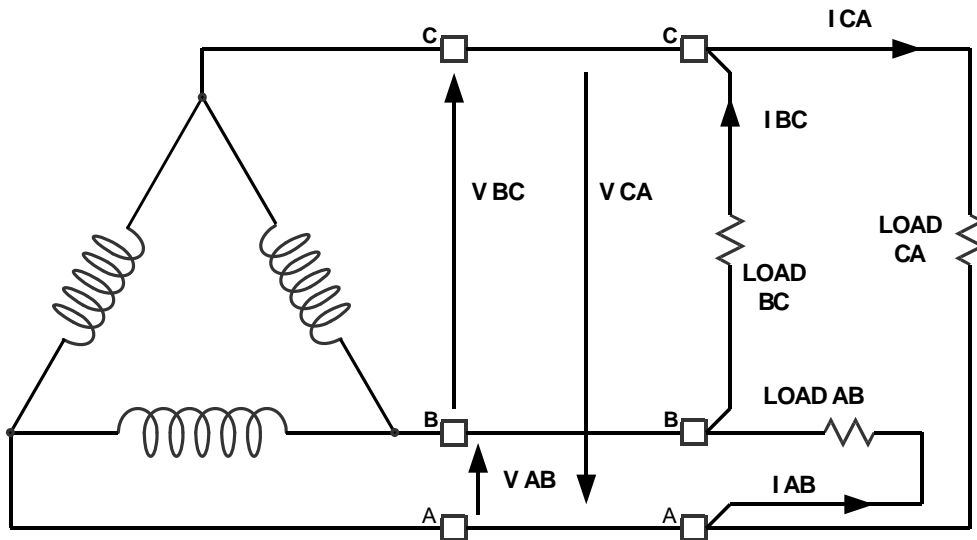

Figure 7: 3-Phase, 3-Wire Delta Configuration, Isolated

Two methods can be used to successfully convert the isolated 3-phase, 3-wire delta configuration to a configuration that can be processed by TERIDIAN metering chips:

1. If a "virtual neutral" is introduced, the voltages from the phases A, B, and C can be measured to neutral and then converted to delta voltages using calculations based on simple trigonometry.

2. If no "virtual neutral" is introduced, the phase-to-phase voltages can be converted to phase-to-neutral voltages using voltage transformers, as shown in Figure 10.

In both cases, the energy can be computed using equation 5:

$P = V_{AB}*I_{AB} + V_{BC}*I_{BC} + V_{CA}*I_{CA}$

Virtual Neutral and Conversion Using Trigonometry

To create a virtual neutral that can serve as a reference voltage for the metering chip, it is usually sufficient to tie three resistors each with one terminal to the phase voltages and to connect the other terminals, as shown in Figure 8. The center connection point will be neutral. If the resistors have the same value, and if the phase voltages are symmetrical, the phase-to-phase voltages can be determined using the following formula:
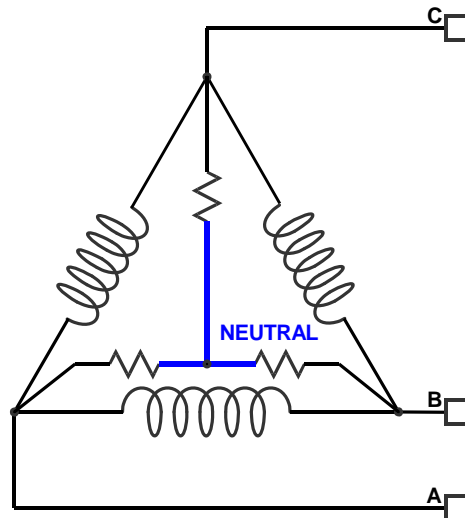
$$V_{AB} = \sqrt{A^2 + B^2 - AB\cos\phi}$$

Figure 8: Virtual Neutral for 3-Phase, 3-Wire Delta

A circuit using the virtual-neutral technique is shown in Figure 9. The overall power has to be calculated with the following formula:

$$P = I_{AB}\sqrt{V_A^2 + V_B^2 - V_A V_B \cos\phi_{AB}} + I_{BC}\sqrt{V_B^2 + V_C^2 - V_B V_C \cos\phi_{BC}} + I_{AC}\sqrt{V_A^2 + V_C^2 - V_A V_C \cos\phi_{AC}}$$

In most systems, the phase angles stay constant at 120°, so cos(Φ) is –0.5, which simplifies the equation to:

$$P = I_{AB}\sqrt{V_A^2 + V_B^2 + \frac{V_A V_B}{2}} + I_{BC}\sqrt{V_B^2 + V_C^2 + \frac{V_B V_C}{2}} + I_{AC}\sqrt{V_A^2 + V_C^2 + \frac{V_A V_C}{2}}$$

One caveat when using the virtual neutral method is that the voltage measurements depend on the phase voltages being balanced. Imbalanced phase voltages or a disconnected phase will move the neutral voltage from its midpoint and thus affect the phase voltage measurements. The Teridian energy meter ICs have mechanisms that detect missing voltages enabling them to take proper action. For example, with phase A missing, the virtual neutral moves to the half-point between phase B and phase C where it provides a new reference point for the measurement of phase B and phase C.

When testing a virtual neutral configuration using a 6513, 6515H, 6523, 6533, or 6534 Demo Board, care should be taken to eliminate asymmetrical leakage currents. In the case of the 6513 Demo Board, for example, the jumper on JP16 should be removed to avoid a leakage path from phase A to the board ground via the power supply.
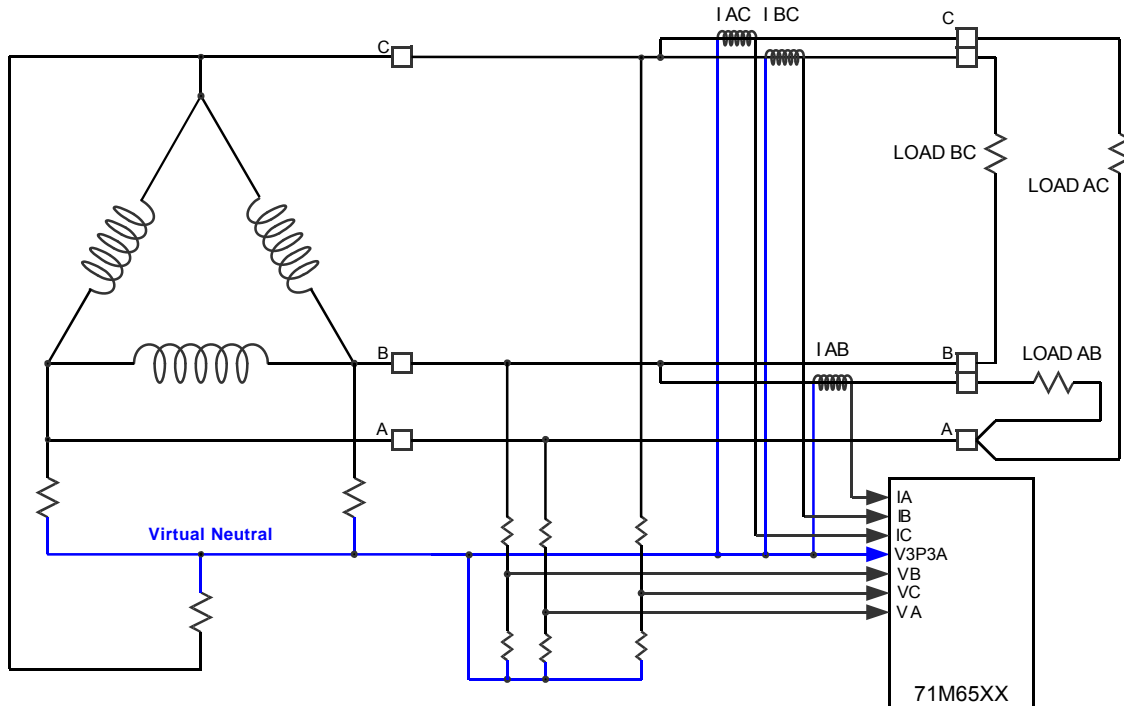

Figure 9: Circuit with Virtual Neutral for 3-Phase, 3-Wire Delta

Conversion Using Voltage Transformers

It is often required to maintain galvanic isolation between the high voltages and the power monitoring system. Voltage transformers, as shown in Figure 10 can provide this isolation while at the same time converting the configuration from delta to Y. The voltage transformers have to be chosen carefully. As opposed to general-purpose transformers that can introduce a substantial phase shift, voltage transformers (VTs) are designed for minimal phase shift and will introduce little phase error between each voltage and its associated current channel.

Typical phase shifts for general-purpose transformers are in the 20° range, too much to be compensated by the phase compensation mechanism of the standard meter CE code of the TERIDIAN energy meter ICs. For power monitoring systems that require phase-angle or power factor display, the phase shift is undesired, since the obtained phase-angles or power factors will be inaccurate.
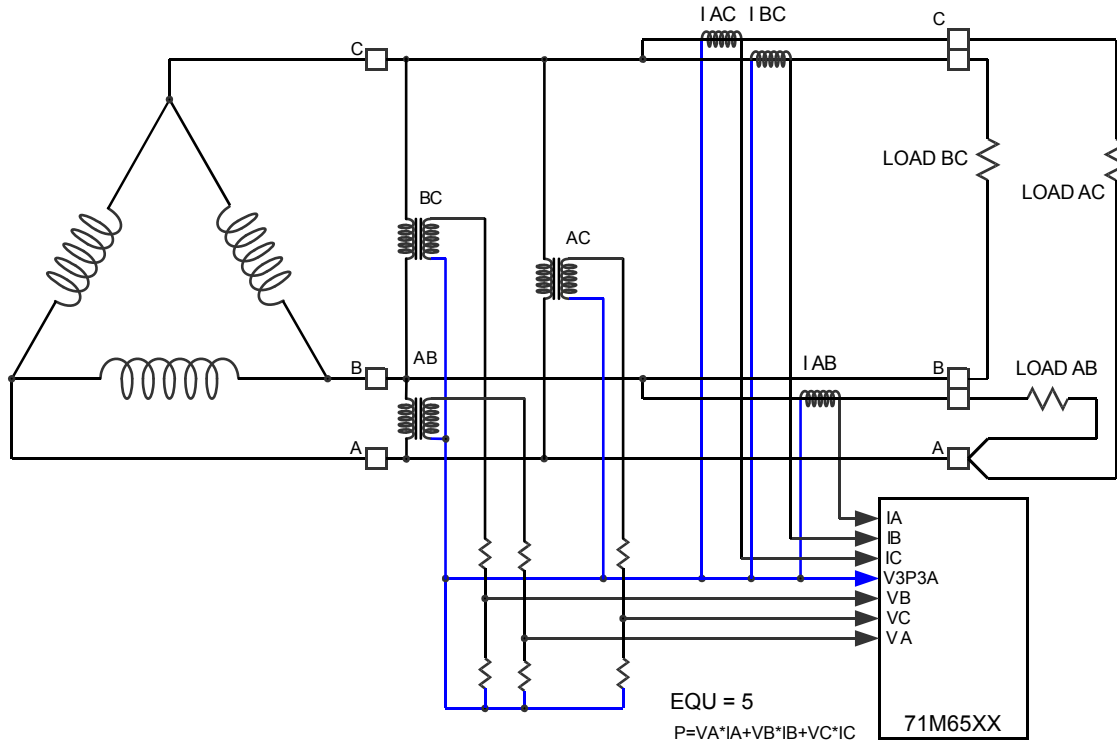
Figure 10: 3-Phase, 3-Wire Delta Configuration Converted

It is possible to avoid the V/I phase shift by either using special voltage transformers (VTs) or by applying post-processing in MPU code. Since good VTs are expensive due to the required high permeability of the magnetic cores, post-processing may be considered a good alternative. Figure 11 shows the relationship between the applied (primary) phase angle and the measured (secondary) phase angle, as measured with a standard 71M6513 using a general-purpose transformer (Pulse type EE20/4). As can be seen, the relationship is linear and changes slightly with frequency.
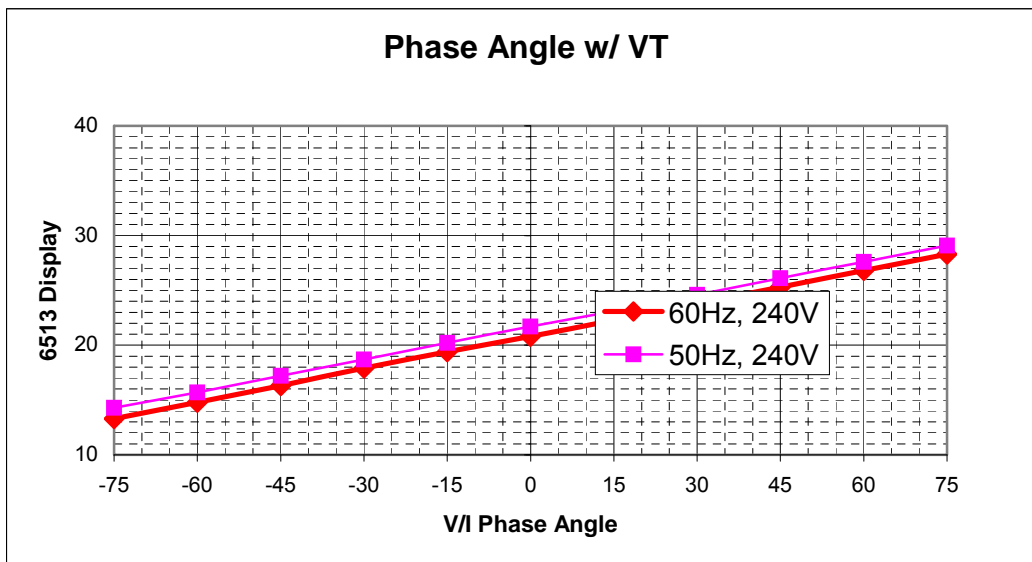

Figure 11: Measured V/I Phase Angle vs. Applied V/I Phase Angle

The effects of the primary voltage magnitude are a little bit more pronounced, as shown in Figure 12. With voltage and frequency known, it is possible for the MPU to calculate the original V/I phase angle.
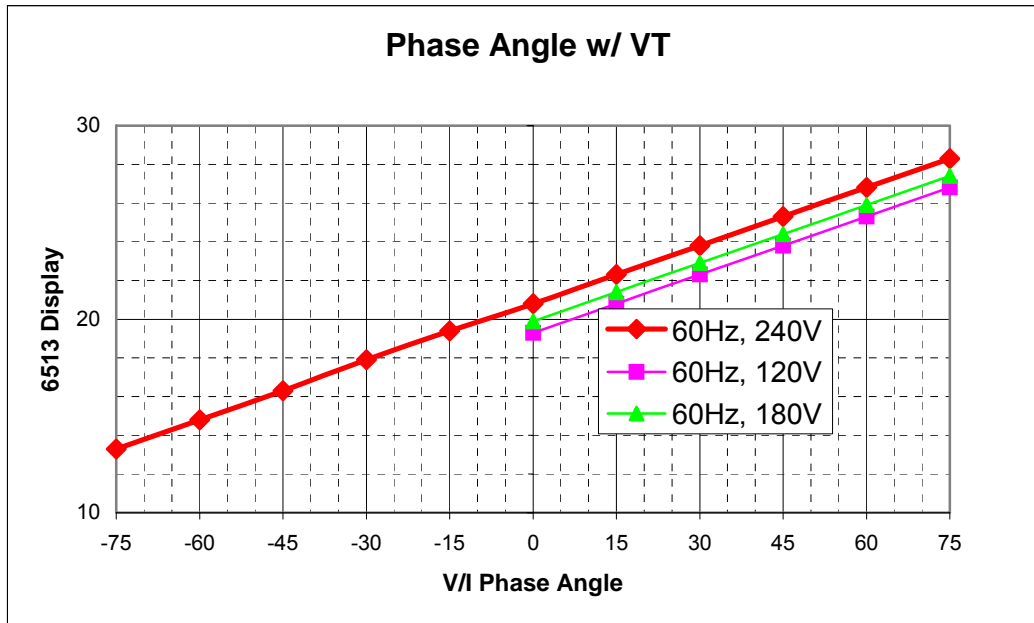
Figure 12: Measured V/I Phase Angle vs. Applied V/I Phase Angle

Current Sensors

A variety of current sensors has been developed over the years, among them:

- Current transformer (CT)
- Resistive shunt sensor
- Rogowski coil
- Hall effect sensor

Of the mentioned sensors, only the current transformer (CT) and the resistive shunt sensor are widely used in industrial or residential meters.

Current Transformers (CTs)

Current transformers are a subset of general transformers. For a CT, the number of primary windings is only one, while the number of secondary windings can be several thousand. Typically, the primary winding is the wire that is routed through the center hole of the transformer (see Figure 13).

Figure 13: CT

Function and Use of CTs

A CT with a winding ratio of 1:2,000 will yield a secondary voltage of 2,000 times the primary voltage and a secondary current of 1/2,000 of the primary current. In a typical application, the secondary current is applied to a resistor ("burden resistor") of a few Ohms in order to generate a voltage signal (see Figure 14).
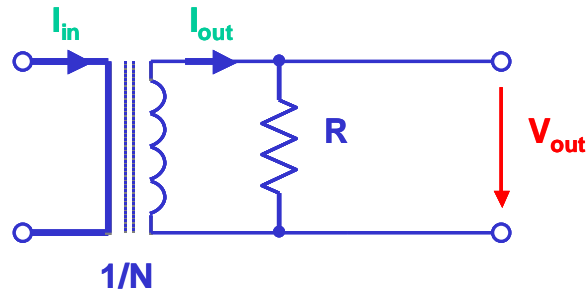
Figure 14: CT with Burden Resistor

Following Ohm's law, the resulting voltage V across the burden resistor R is:

$$V = N \frac{I_{IN}}{R}$$

In this formula, N is the winding ratio and I_{IN} is the primary current.

The optimum burden resistor is specified by the manufacturer of the CT. If the burden resistor is too high, the output becomes non-linear. When used with a TERIDIAN meter chip, it is important to dimension the burden resistor for optimum signal magnitude. At maximum current (I_{MAX}), the voltage built up across the burden resistor should not exceed 176mV RMS (±250mV peak). It is useful to provide a margin in order to be able to measure currents above I_{MAX}. This makes it often necessary to dimension the burden resistor value lower than the recommended value by the manufacturer. For most CTs, this will not pose a problem.

Due to their inductance, CTs will invariably introduce a slight phase shift between secondary current and secondary voltage. This phase angle can easily be compensated for by the CE of the Teridian meter chips, and becomes only a critical issue when it is not linear over current. Figure 15 shows the development of the phase angle between input current and output current of a CT.
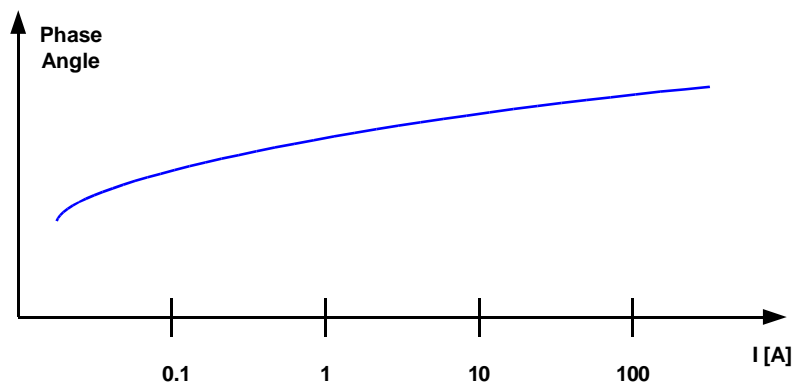

Figure 15: Phase Angle of a CT over Current

Typical values for the phase angle are in the 1° range, with some CTs reaching 4° and above. This angle is not a concern for a Wh measurement with load angles around 0, since the cosine of small angles is very close to 1. If the load introduces larger angles, the angular error of the Wh measurement becomes significant, as shown in Figure 16. Measurement errors will be noticeable If the phase angle added or subtracted by the CT is not constant over current.
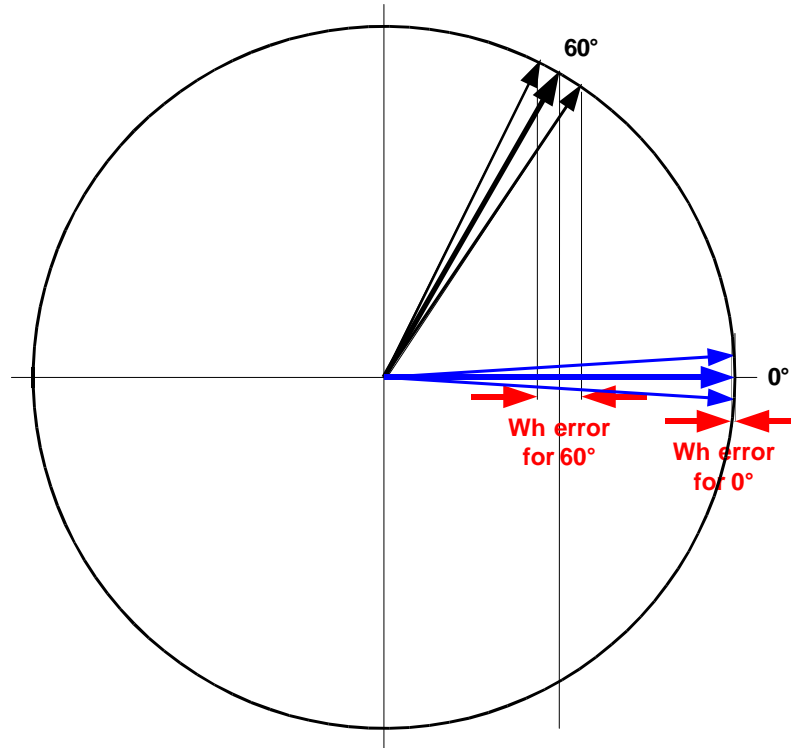
Figure 16: Wh Error due to Phase Angles of 0° and 60°

Apart from the factors mentioned above, CTs are characterized by a variety of parameters, some of which are listed below:

- Nominal and maximum primary current
- DC resistance of the secondary winding
- Isolation resistance and dielectric withstanding voltage
- Magnetic material

A CT should be selected in close cooperation with the CT manufacturer. The variety of types, materials, quality grades, and other selection criteria is beyond the scope of this Application Note.

Sources for CTs

Below is an incomplete list of some manufacturers of CTs, with URLs of CT-related web pages given in parentheses.

Amveco: http://www.amveco.com/acseries_current_transformers.htm

Coilcraft: http://www.coilcraft.com/sen60t.cfm

CR Magnetics: http://www.crmagnetics.com/newprod/ctransformersg.asp

Datatronics: http://www.datatronics.com/pdf/pt2190_series.pdf

Falco: http://www.falco.com/products/1/07-00.asp?Line=1&Family=07&Type=00

Taehwatrans, Korea: http://www.taehwatrans.com/english/pro_01_01.htm

Talema, India: http://www.talemaindia.com/en_products_ct.htm

Vacuumschmelze, Germany:
http://www.vacuumschmelze.de/dynamic/en/home/products/coresampinductivecomponents/applications/currenttransformers/accurrenttransformers.php

Zettler: http://www.zettlermagnetics.com/index.php?id=pf_standard_current_sensors

Shunt Resistors

Shunt resistors (see Figure 17) are the most basic current sensors since they directly implement Ohm's law:
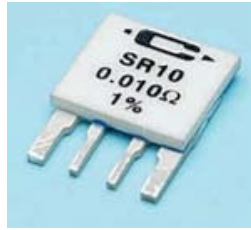
$$V = R * I$$

Figure 17: Shunt Resistor

This type of current sensor is very affordable, but has a few disadvantages:

- No galvanic isolation
- Self-heating
- Typically low-ohmic, resulting in very low output

The lack of galvanic isolation means that poly-phase meters typically do not contain shunt resistors. However, it is a common practice to isolate two shunt resistors in a two-phase meter using an isolation transformer. Some companies offer combinations of shunt and an isolation transformer in one package.

For a single-phase meter using a shunt resistor, certain precautions apply. No galvanic isolation implies that the meter parts are at mains voltage, which dictates the use of safety isolation against accidental touch and magnetic or optical isolators for any signals interfacing with the meter.

Self-heating is reduced by keeping the resistance of the shunt very low. For a shunt with 400µΩ operating at 30A, the power consumed by the shunt is 0.36W. The same shunt operated at 100mA has an output of only 40µV, which makes it hard to extract the signals from the noise present on the line. For that reason, wiring and PCB layout must be very carefully designed.

Lack of isolation also means that EMI carried on the mains grid directly accesses the vital parts of the meter. Again, careful design for EMI rejection is necessary for any shunt meter.

Shunt resistors are characterized by a variety of parameters, some of which are listed below:

- Current rating
- Initial accuracy
- Resistance drift with temperature
- Power de-rating depending on the environmental temperature

Connecting to Shunt Resistors

Regardless whether PCB-mounted shunt resistors or wired shunt resistors are used, it is important to connect the wires that pick up the voltage drop directly at the resistor. This type of connection is also known as "Kelvin connection". The purpose of this connection is to avoid measuring the voltage drop on the wires or traces to and from the resistor, which would introduce a measurement error. Figure 18 shows a typical shunt resistor that is mountable to terminal blocks. The large lugs carry the current, whereas the wires soldered to the resistor are used to pick up the voltage drop.

Sometimes it is necessary to power the monitoring device with the voltage applied to the shunt resistor. This technique requires a separate (third) wire at the resistor in order not to disturb the current measurement with the current feeding the power supply.
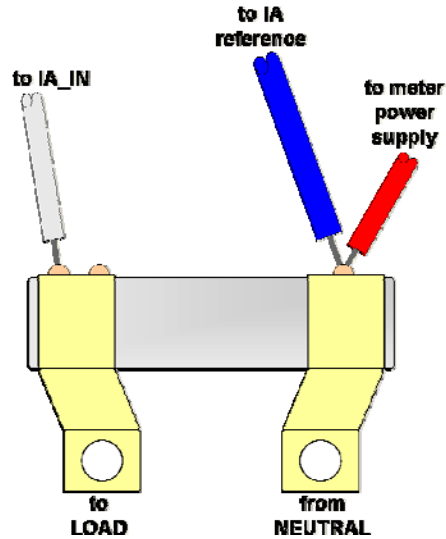
Figure 18: Wires on a Current Shunt

Using Shunt Resistors to Monitor Multiple Outlets

In single-phase systems or poly-phase systems where multiple outlets are connected to a single phase, shunt resistors can be used economically for the monitoring of current in individual outlets. Figure 19 shows the monitoring of the voltage and five currents using a poly-phase IC such as the 71M6513, 71M6515, or 71M6533. For the MPU, the current information is accessible in the CE registers I0SQSUM, I1SQSUM, I2SQSUM, V1SQSUM, and V2SQSUM of standard CE code. It is irrelevant that the pins VB and VC measure voltages in regular electricity meters. In the arrangement shown in Figure 19, the quantities in V1SQSUM and V2SQSUM associated with pins VB and VC are simply interpreted as currents.

Care has to be taken in designing this monitoring system, since there is no isolation between the meter IC and the high-voltage circuits.
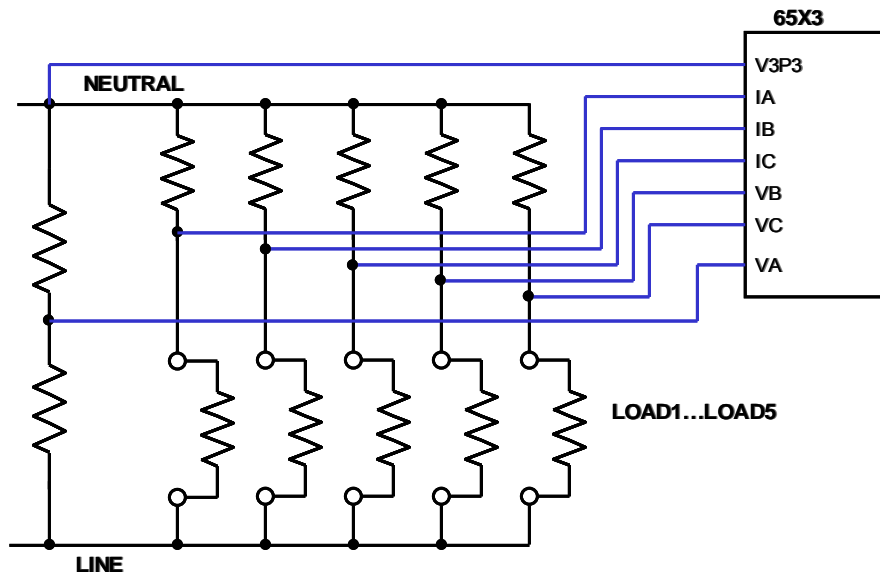

Figure 19: Current Monitoring of Multiple Outlets

Sources for Shunt Resistors

Caddock: http://www.caddock.com

IRC: http://www.irctt.com/products.aspx?frmCategory=22

Isabellenhütte, Germany: http://www.isabellenhuette.de/en/productoverview/

Isotek: http://www.isotekcorp.com/productDisplay.asp?CatID=1&SubCatID=

Vishay: http://www.vishay.com/resistors-discrete/current-sensing/metal-foil/

Zhejiang Chaoguang Meter Co., Ltd. (China): http://chog.en.alibaba.com/group/50158809/Shunt.html

Calibration for Energy Monitoring Systems

In general, all concepts presented in the Teridian Application Note AN_651X_022 (Meter Calibration) apply to energy monitoring systems. Most energy monitoring systems, however, will not have the energy pulse outputs used in electricity meters. In addition, calibration systems available for manufacturers may not provide flexible control of load angles.

These restrictions make it necessary to calibrate energy monitoring systems using displayed readings or indirect readings of current, voltage, power factor and/or reactive energy. The command-line interface available in the Demo Code for most Teridian Demo Boards allows the display of momentary RMS voltage, momentary RMS current, accumulated active energy (Wh), reactive energy (VARh) and power factor (PF). For prototypes and experimentation, this is usually sufficient. More accurate readings that are also accessible to the MPU are available in the form of various CE registers. A typical CE code provides the following values at the end of each accumulation interval (the LSB values are given in the data sheet for each IC):

1) Wh (real energy) per phase

2) VARh (reactive energy) per phase

3) ISQSUM (sum of squared currents) per phase

4) VSQSUM (sum of squared voltages) per phase

Example: For a meter equipped with a 71M6513, a value of N=255,650 (decimal) is obtained in the *W0SUM* register of the CE. Using the system constant given in the data sheet and the hardware constants *VMAX* (600V) and *IMAX* (208A), the measured energy is calculated as follows:

W = N*9.4045*10^{-13}*VMAX*IMAX Wh = 255650*9.4045*10^{-13}*600*208 Wh = 0.03 Wh

Given an accumulation interval length of one second, the momentary real power is 0.03 * 3600 Ws/s or 108 W.

Magnitude Calibration

Every electricity meter and every energy monitoring system will have to be calibrated to compensate for the tolerances of external components (burden resistors, voltage dividers) and for slight inaccuracies of the internal reference voltages of the Teridian electricity metering ICs (VREF is usually within <0.2%).

Typically, each phase is calibrated individually in multi-phase systems to achieve maximum accuracy. Teridian energy metering ICs provide the *CAL_In* and *CAL_Vn* calibration coefficients in CE data memory for proper adjustment of the current and voltage channels. *CAL_In* and *CAL_Vn* are set to the default values of 16384 for a gain of 1. If, for example, the voltage of channel B (phase B) has a positive error of 5% (i.e. reading high by 5%), *CAL_VB* is set to 16384/1.05 = 15604, which will accurately compensate for the error. The granularity of the calibration coefficients makes it possible to adjust the current and voltage measurements to 0.006% per LSB, which is beyond the accuracy of any calibration system.

Energy monitoring systems that process only RMS values (Vrms, Irms, apparent energy) function without phase information and require only calibration for magnitude, using the *CAL_In* and *CAL_Vn* calibration coefficients described above.

Phase Calibration

Current transformers introduce phase shifts that have to be compensated. Teridian energy metering ICs provide the *PHADJ_n* calibration coefficients for each channel in CE data memory for proper adjustment of the phase an-

gle. Figure 20 shows the relationship between the phase angle and the value that has to be written to *PHADJ_n* to compensate for that angle. CTs introduce a lag of the current signal behind the primary current. This lag is compensated with positive values of *PHADJ_n*. Some CE codes for Teridian energy metering ICs provide the ability to use much larger values *PHADJ_n* for the compensation of angles beyond 8° or the ability to even use negative values for *PHADJ_n*. Check with the applications engineers at Teridian if your application requires phase adjust values outside the standard range.
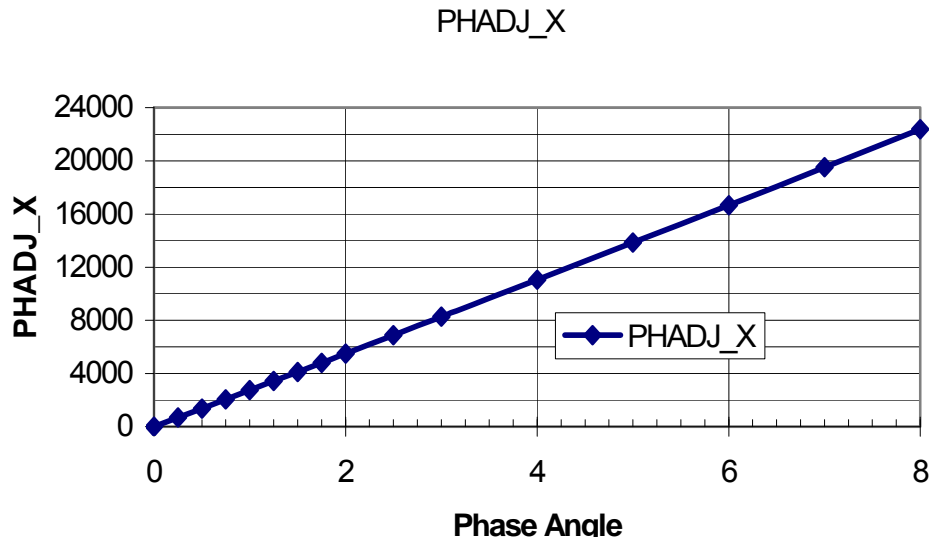
Figure 20: Phase Angle Adjustment Controlled by *PHADJ_n*

The following methods that can be used to determine the nominal value for *PHADJ_n*:

1) With a purely ohmic load applied to the energy monitoring system, the display for VARh or the display for PF can be used to find the best value for *PHADJ_n*. If the VARh display does not increase or decrease, or if the PF display is identical to 1.00, the phase adjustment is good. The command-line interface available in the Demo Code for most Teridian Demo Boards allows the display of reactive energy (VARh) or power factor (PF).

2) The 3-point of 5-point calibration methods described in Application Note AN_651X_022 can be used in conjunction with the calibration spreadsheet provided with the Teridian Demo Kits to determine the exact value of *PHADJ_n* for each channel (phase).

If voltage transformers are used, linearization of the phase angle as demonstrated in Figure 11 and Figure 12 can be implemented in MPU software. The coefficients for this linearization must be determined by tests.

Host Communication

Networks of Teridian energy metering ICs can be established using the TX and RX or OPT_TX and OPT_RX pins, as shown in Figure 21. This is useful when a multitude of channels must be monitored that exceeds the number of input pins available with the 71M65XX ICs.
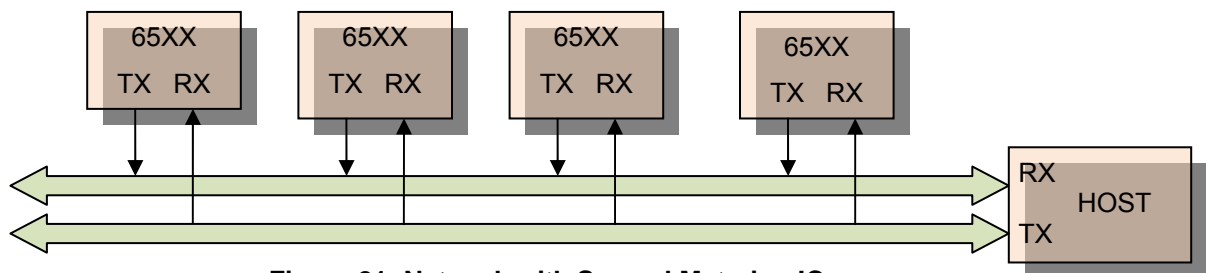

Figure 21: Network with Several Metering ICs

Since the TX and OPT_TX pins can be tri-stated (floated) it is possible to connect the TX pins of several Teridian metering ICs to a common TX bus that connects to the RX pin of the host. With proper MPU code, the metering ICs can be made addressable.
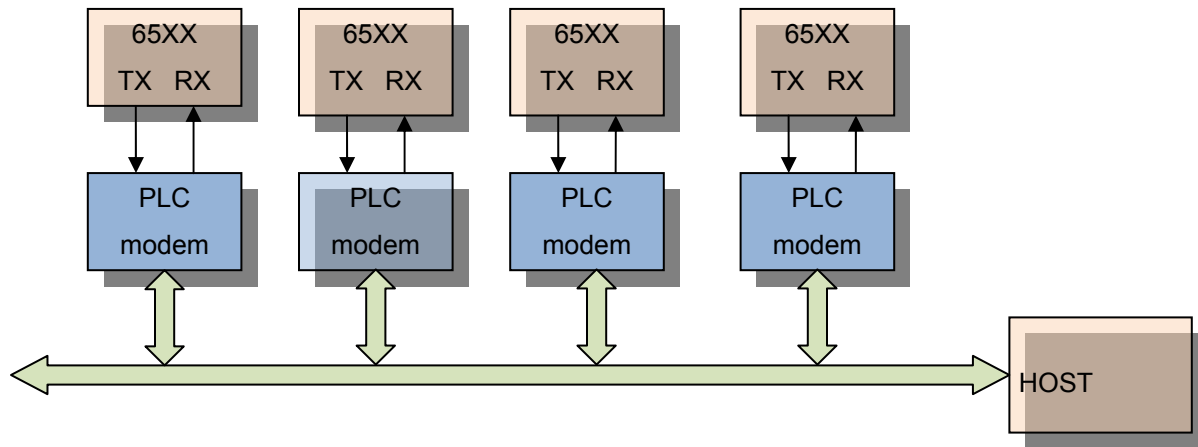

Figure 22: Network with Several Metering ICs

Communication does not have to be directly via the TX/RX pins. Level converters, such as RS-232 or RS-485 transceivers, PLC modems (as shown in Figure 22) or wireless modems can also be used to form networks.

In the case of the 71M6531, 71M6533, and 71M6534, the interface can also be the SPI port.

Revision History

Revision	Date	Description
Rev. 1.0	4/23/2008	First publication.
Rev. 1.1	5/5/2008	Corrected flash memory sizes in Table 1.