APPLICATION NOTE

AN_65XX_052 **FEBRUARY 2011**

71M65XX with VITROPERM CTs

Introduction

Affordable current transformers that compete in price with hall sensors or even shunt resistors have been developed by Vacuumschmelze GmbH, Germany (VAC, www.vacuumschmelze.com). The latest development by VAC is the VITROPERM® series of DC-tolerant CTs capable of measuring 60 A (P/N T60404-E4624-X131) or 100 A (P/N T60404-E4626-X131), and exposing slightly higher sensitivity to temperature changes than CTs based on the well-known VITROVAC® material.

The advanced features of the metering ICs made by Teridian make it possible to compensate nonlinear phase behavior over current as well as signal magnitude and phase error changing with temperature.

This Application Note describes the steps necessary in order to successfully integrate VITROPERM® CTs made by VAC into a poly-phase meter operating with any Teridian poly-phase IC (71M6513, 71M6533, 71M6534, and 71M6543).

Properties of the VITROPERM® CTs

The primary factors influencing the accuracy of electricity meters using CTs are magnitude and phase error over current. While being of benign importance at zero degree load angle, phase error becomes a large influence at higher load angles. For example, at 60° load angle (PF = 0.5), a phase error of 1% (0.6°) results in a magnitude error of the real energy (Wh) measurement of almost 2%. Teridian electricity metering ICs using compensation mechanisms implemented in CE code can easily deal with large positive and negative phase errors, as long as they are constant. However, as Figure 1 shows, the phase error of the VITROPERM® CTs can change significantly and rather unpredictably over current.

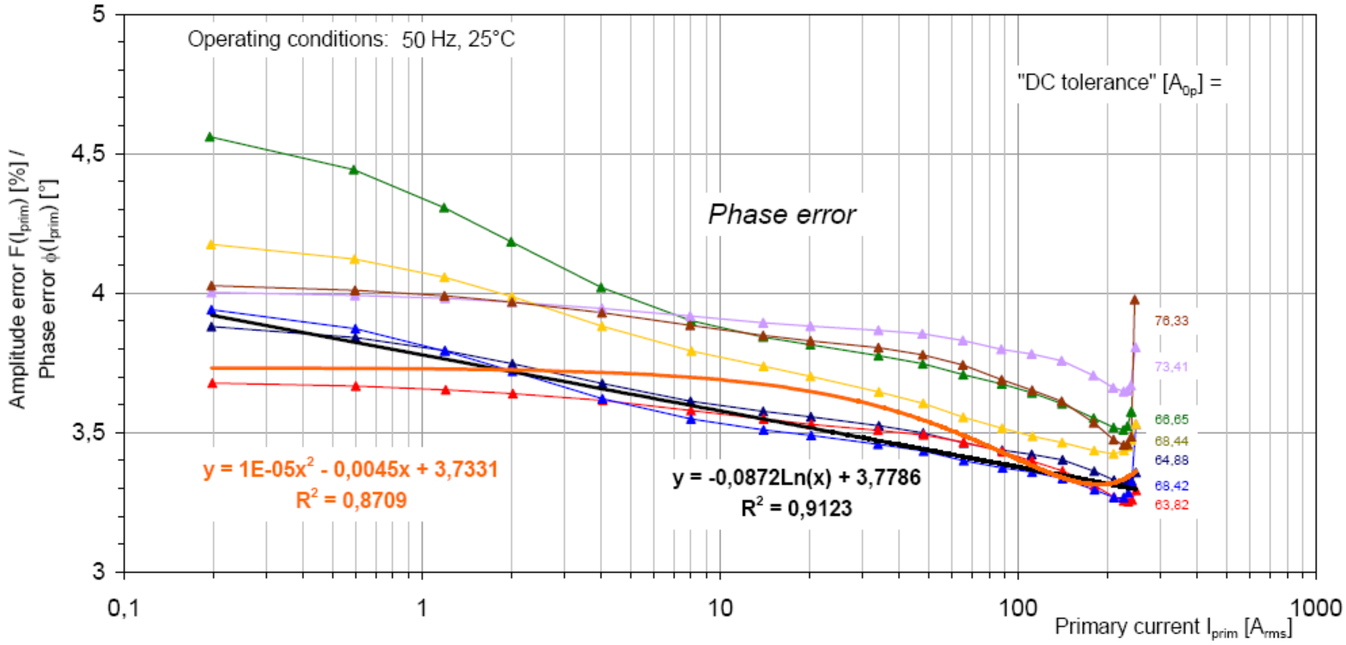


Figure 1: VITROPERM® (60 A) Phase Error over Primary Current

Figure 1 shows some examples of phase-angle distribution that VAC encounters with VITROPERM® CTs at their production test:

- The CT characterized by the orange line measured 3.7° phase error at 0.2 A and 3.3° at 100A, which is not a large variation.
- In comparison, the atypical CT characterized by the green line measured almost 4.6° at 0.2 A and 3.7° at 100A, which is a significant. CTs with large parameter variations are screened out by VAC during production. However, this CT was included in the set of tested CTs to show how Teridian metering ICs can successfully adapt to even atypical CTs
- Further inspection of Figure 1 shows that phase error at low currents will not predict the development of phase error at higher currents, which means that every CT has its own unique characteristics.

Furthermore, the amplitude of the output of the secondary winding of the VITROPERM® CTs has large variations over current and also varies significantly with the individual sample, as shown in Figure 2. The magnitude error of the CT shown in the orange line stays within a 0.1% error band, whereas the error of the atypical CT shown in green exceeds 0.25%.

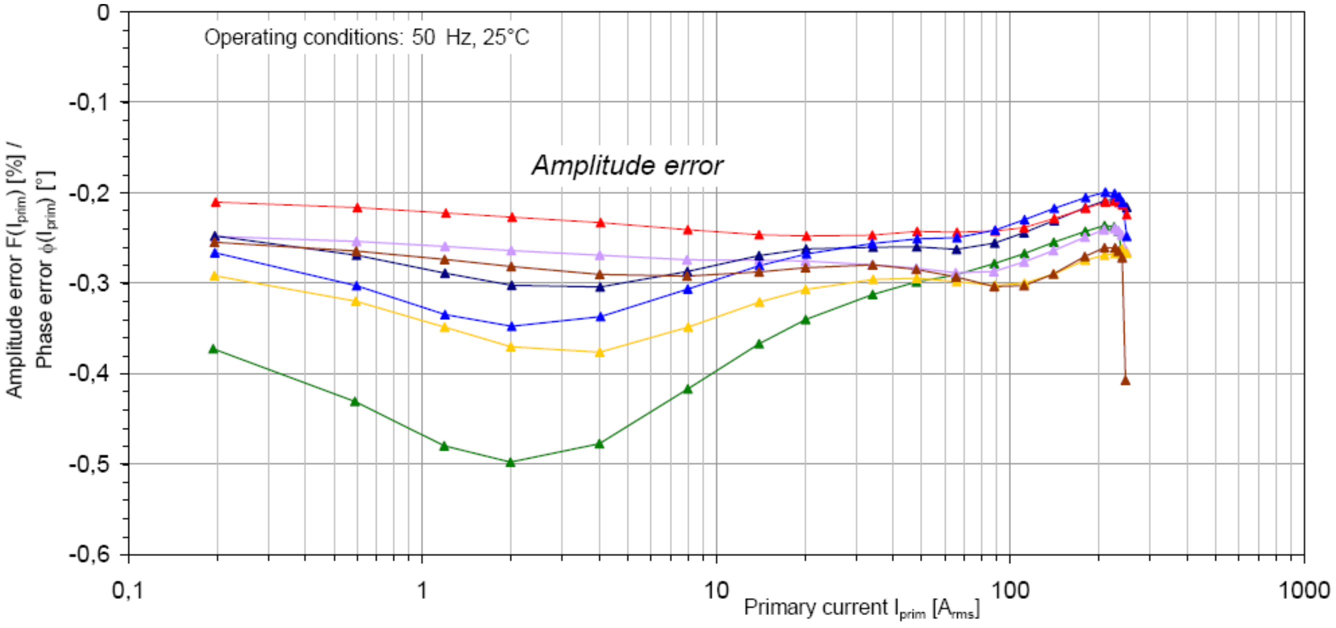


Figure 2: VITROPERM® (60 A) Amplitude Error over Primary Current

More errors are introduced on top of phase and amplitude errors by the temperature characteristics of the VITROPERM® CTs, as shown in Figure 3. Phase errors between lowest and highest temperature differ by as much as 2.1°, which would result in almost 4% magnitude error at 60° load angle. Fortunately, for constant temperatures, the amplitude errors over current are in a relatively narrow band between 0% and -0.5%, if higher currents above 100 A are ignored).

Designing a class 1 meter with this type of CT requires careful adjustment of magnitude and phase angle depending on primary current, as well as efficient compensation of the temperature characteristics. The compensation methods must be efficient for all possible variations of CT parameters as they occur in production.

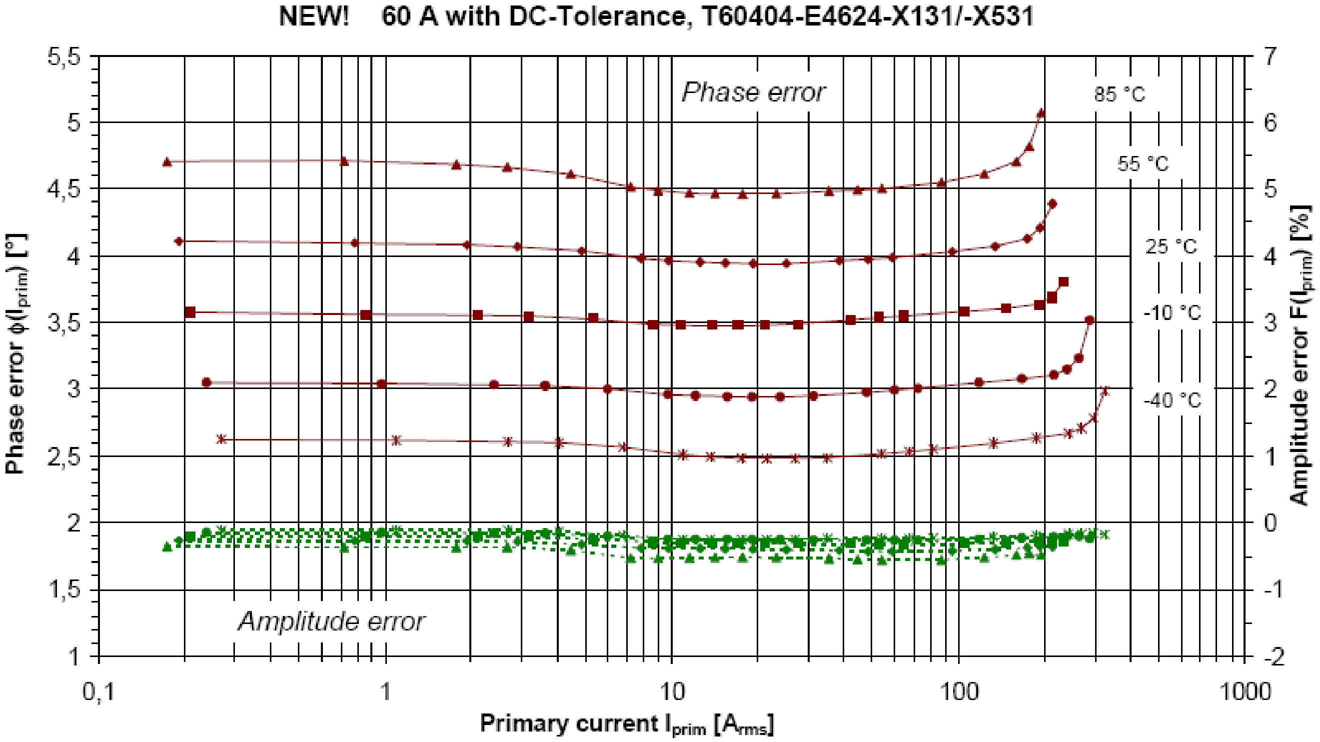


Figure 3: VITROPERM® (60 A) Phase Error over Temperature

The Teridian Poly-Phase ICs

In the 71M65XX ICs, magnitude adjustments are made to current and voltage inputs on a phase-by-phase basis by changing the values for the current and voltage CE calibration coefficients *CAL_IAn* and *CAL_VAn* (16384 applies unity gain). Similarly, the values applied in the phase compensation coefficients *PHADJ_n* adjust the phase error compensation.

All ICs of the 71M651X series (except for the 6515H, which has fixed code), as well as all ICs of the new 71M653X family are capable of implementing advanced mechanisms for compensation of nonlinearities and temperature effects.

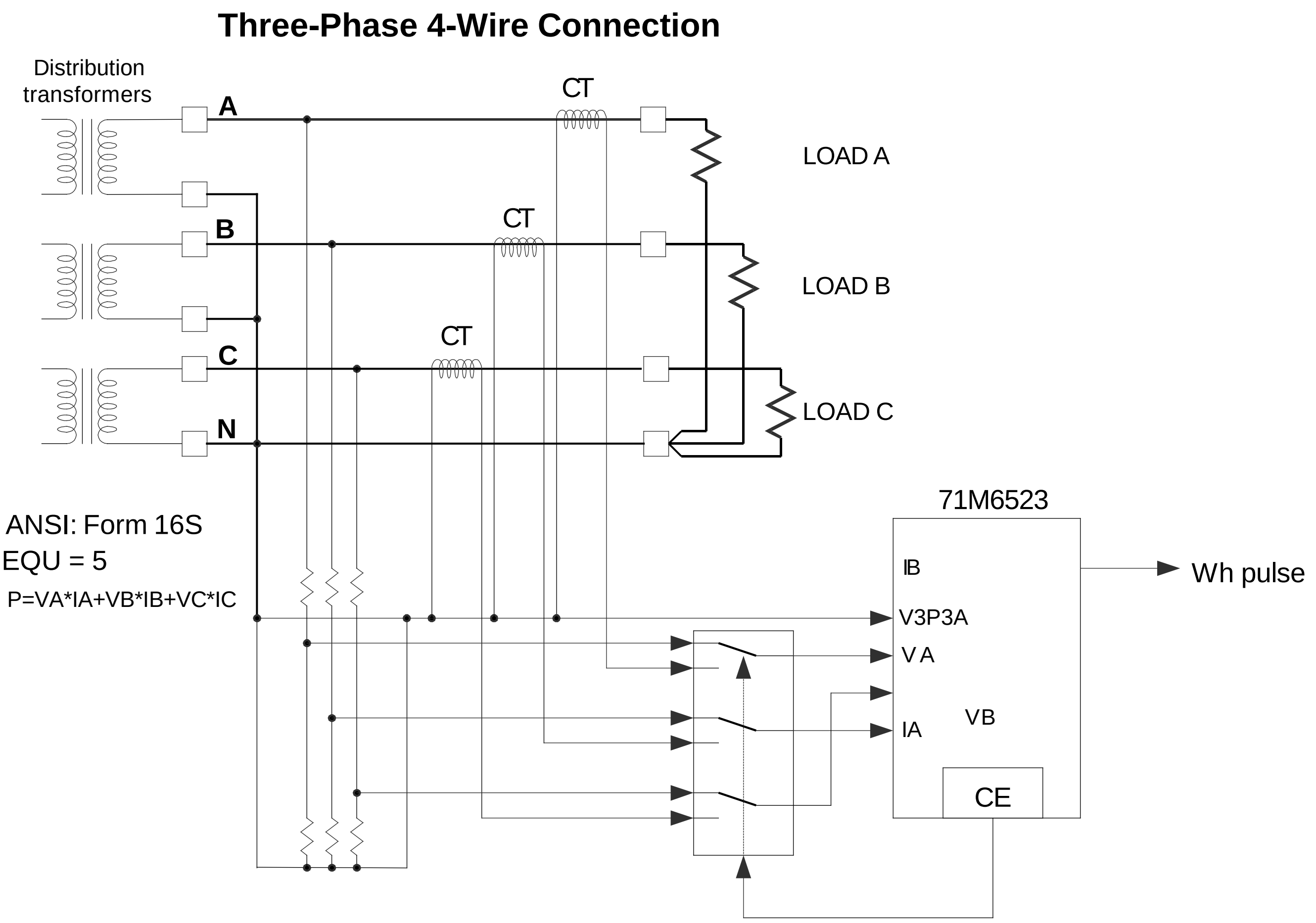


Figure 4: TERIDIAN 71M65XX Block Diagram

Linearizing the Load Line with the Teridian 71M65XX

Initial measurements without any type of compensation or consideration for the nonlinearities of the VITROPERM® CTs will yield the expected non-optimal results. As Figure 5 demonstrates, the Wh magnitude errors are very large for a CT that exposes large phase error and large phase error variation over current when operated without phase compensation. Even after calibrating for magnitude and phase-compensating at 10 A, the load line tends to be very inaccurate at currents other than 10 A, as shown in Figure 6. More errors can be expected when the meter is exposed to changing environmental temperatures.

Linearity over current can be greatly improved by multi-point calibration. It is up to the meter designer to decide how many points should be used. There will be a trade-off between achieved accuracy and the time that must be used for each meter for the calibration process. The 71M65XX imposes no restrictions on the number of calibration points.

A good first approach is to choose calibration points far apart where the raw load line is relatively flat and to move them closer where the load line shows a larger variation.

The MPU will have to take an active role in assigning calibration coefficients depending on the momentary current. A suggested approach is to update coefficients, if necessary, at a rate of about one per second during the XFER_BUSY interrupt, i.e. when metering data are exchanged between CE and MPU.

If calibration points are arbitrarily chosen at 0.5 A, 5 A and 20 A, and if the load line is separated into three segments around each calibration point, each calibration point yields three different calibration coefficients per phase n, providing a matrix of coefficients that is shown in Table 1.

To test this calibration approach without having to modify MPU code, the calibration coefficients can be manually applied to the CE using the command line interface of the standard 71M65XX Demo Code.

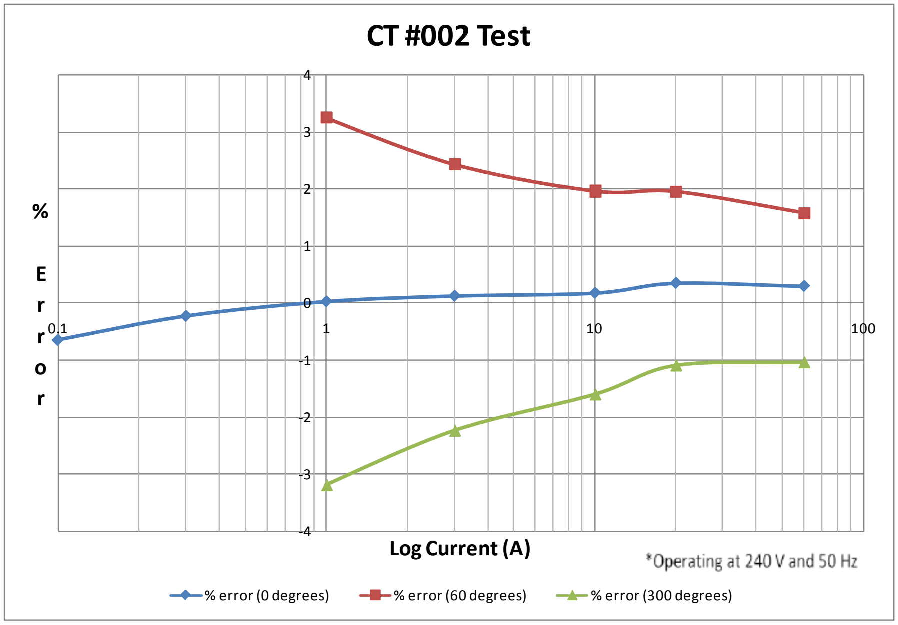


Figure 5: Load Lines for CT #2, Uncalibrated (blue: 0°, green: 300°, red: 60°)

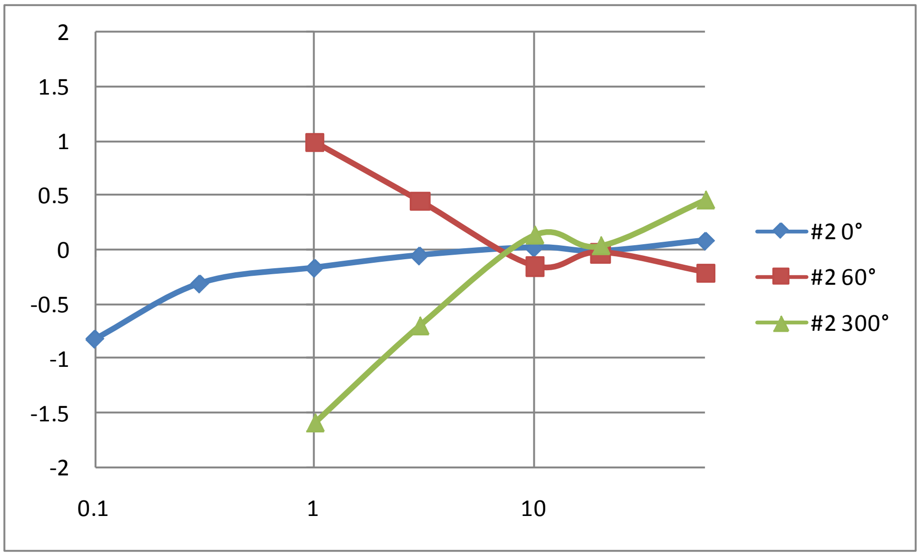


Figure 6: Load Lines for CT #2, calibrated (blue: 0°, green: 300°, red: 60°)

Current	V Magnitude	I Magnitude	Phase
0.5 A	*CAL_Vn_0*	*CAL_In_0*	*PHADJ_n_0*
5 A	*CAL_Vn_1*	*CAL_In_1*	*PHADJ_n_1*
20 A	*CAL_Vn_2*	*CAL_In_2*	*PHADJ_n_1*

Table 1: Calibration Coefficients for Phase n

The three-point calibration can improve results significantly, as shown in Figure 7 and Figure 8. The waviness of the load line in Figure 8 reflects the abrupt transitions from one set of calibration coefficients to the next set when the borders between current segments were crossed.

The waviness seen in Figure 8 can be improved, if desired, by interpolating the calibration coefficients in between the three calibration currents and by extrapolating for the currents outside the current range (see Table 2, calibration currents 20 A, 5 A, 0.5 A and corresponding coefficients highlighted). Figure 9 shows much smoother load line obtained by manually applying a different set of calibration coefficients to each phase at every incremental current.

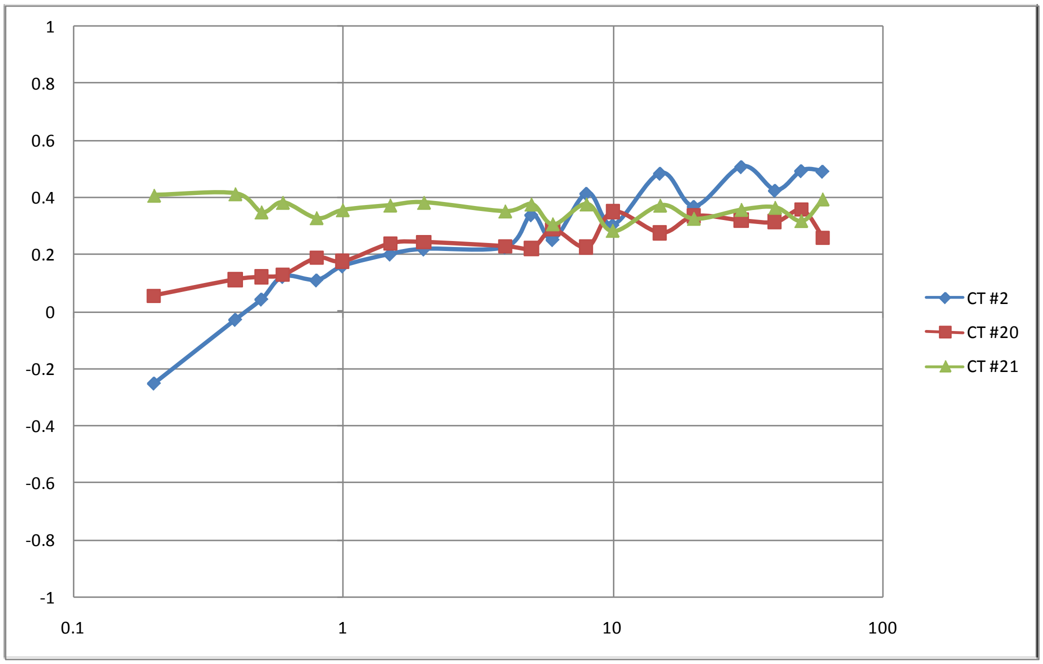


Figure 7: Load Lines for Tested 60 A CTs after 3-Point Calibration (0° Load Angle)

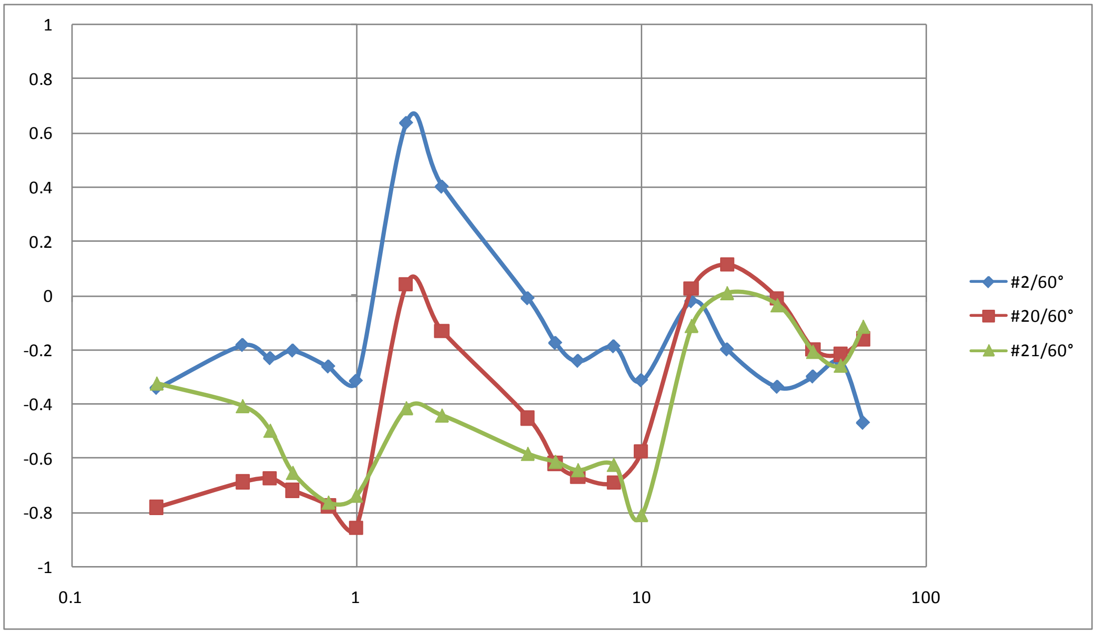


Figure 8: Load Lines for Tested 60 A CTs after 3-Point Calibration (60° Load Angle)

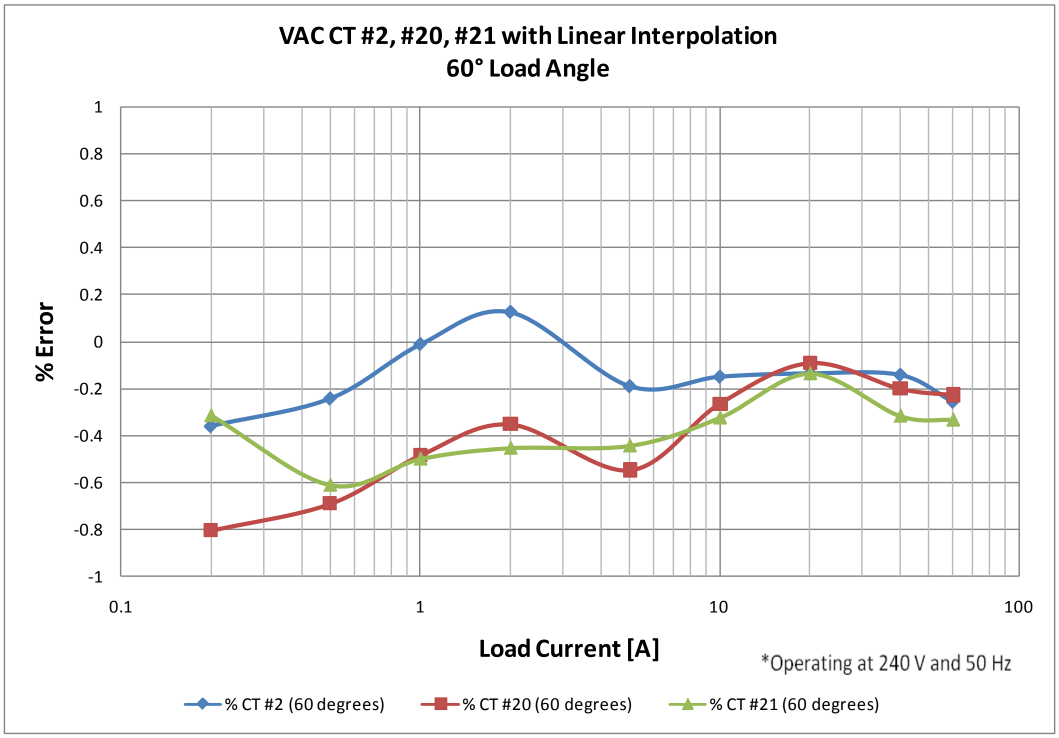


Figure 9: Load Lines, 3-Point Calibration with Interpolation (60° Load Angle)

Since the development of CT output magnitude and phase error is not predictable, a simple linear interpolation is the most logical approach. The formula for the interpolated values is:

$$X = X_L + \frac{(I(x) - I_L)(X_R - X_L)}{(I_R - I_L)}$$

X_L = calibration value to the left of the segment
X_R = calibration value to the right of the segment
I (x) = current for which the interpolated value applies
I_L = current value to the left of the segment
I_R = current value to the right of the segment

I [A]	60	50	40	30	**20**	15	10	8	6	**5**	4	2	1.5	1	0.8	0.6	**0.5**	0.4
CAL_IA	16662	16690	16718	16746	**16774**	16788	16802	16808	16813	**16816**	16808	16793	16790	16786	16784	16783	**16782**	16781
CAL_VA	16742	16729	16716	16704	**16691**	16685	16678	16676	16673	**16672**	16680	16695	16698	16702	16704	16705	**16706**	16707
CAL_IB	16794	16789	16784	16780	**16775**	16773	16770	16769	16768	**16768**	16766	16762	16761	16760	16760	16759	**16759**	16759
CAL_VB	16673	16662	16651	16639	**16628**	16622	16617	16614	16612	**16611**	16612	16614	16614	16615	16615	16615	**16615**	16615
CAL_IC	16774	16763	16752	16740	**16729**	16723	16718	16715	16713	**16712**	16706	16695	16692	16689	16688	16687	**16686**	16685
CAL_VC	16677	16676	16675	16675	**16674**	16674	16673	16673	16673	**16673**	16673	16674	16675	16675	16675	16675	**16675**	16675
PHADJ_A	6911	7200	7489	7777	**8066**	8210	8355	8412	8470	**8499**	8741	9224	9344	9465	9514	9562	**9586**	9610
PHADJ_B	6346	6677	7008	7340	**7671**	7837	8002	8069	8135	**8168**	8342	8689	8776	8863	8898	8933	**8950**	8967
PHADJ_C	7187	7428	7669	7911	**8152**	8273	8393	8442	8490	**8514**	8563	8660	8684	8709	8718	8728	**8733**	8738

Table 2: Linear Interpolation of CE Calibration Coefficients

If the CE calibration coefficients for testing the interpolation method are generated in EXCEL or another spread sheet application, they can be easily converted to text strings that are compatible to the 71M65XX Demo Code command line interface format. For example, if the set of coefficients (*CAL_IAn*, *CAL_VAn* , *PHADJ_n*) to be applied at 8 A were 16808, 16676, 8412 for phase A, and 16769, 16614, 8069 for phase B, and 16715, 16673, 8442 for phase C, the resulting combined command string is:

```
]10=+16808=+16676=+16769=+16614=+16715=+16673=+8412=+8069=+8442
```

Linearizing the Meter Output over Temperature

In addition to linearizing the load line at room temperature, the temperature effects of the VITROPERM® CTs must be compensated in a production meter. It is important to understand the factors affecting the temperature performance of the meter. Granted, the temperature effects of the VITROPERM® are significant, but the other effects cannot be ignored. The temperature effects include the following:

1) Magnitude and phase variation of the VITROPERM® CTs
2) Reference voltage of the 71M65XX
3) On-resistance drift of the external multiplexer
4) Burden resistors and resistors associated with the voltage dividers

It would be straight forward to compensate just for the temperature effects of the VITROPERM® CTs. In a production meter, however, all temperature-related factors have to be considered. Combining the quadratic characteristics of the reference voltage with the more or less linear other effects, a quite nonlinear system temperature effect can be expected. Since the 71M65XX is entirely capable of performing complete system compensation over temperature, it is easy to implement a complete system temperature compensation mechanism.

The mechanism for temperature compensation involves the internal CE code variable *GAIN_ADJ*. *GAIN_ADJ* controls the gain of all current and voltage signals in the CE based on the following formula:

$$GAIN\_ADJ = 16385 + \frac{TEMP\_X \cdot PPMC1}{2^{14}} + \frac{TEMP\_X^{2} \cdot PPMC2}{2^{23}} \qquad \text{equation (1)}$$

TEMP_X is the deviation from nominal (calibration) temperature (measured in 1/10 °C), *PPMC1* is the linear coefficient, and *PPMC2* is the quadratic coefficient. A value of 16385 in *GAIN_ADJ* sets all channels to unity gain. Changing *GAIN_ADJ* by 1% will affect energy measurements by 2%.

In the 71M65XX Demo Code, the MPU controls *GAIN_ADJ*, once a reference temperature is provided in the memory location *TEMP_NOM* and values for *PPMC1* and *PPMC2* are provided.

Temperature compensation involving the VITROPERM® CTs consists of two steps:

1) Magnitude compensation: This type of compensation addresses variations of the 71M65XX reference voltage, of the burden resistors, of the external multiplexer, and of the magnitude variations of the VITROPERM® CT outputs.
2) Phase compensation: This type of compensation addresses variations of the phase error generated by the VITROPERM® CTs.

To determine the coefficients *PPMC1* and *PPMC2* for the magnitude compensation, a set of raw data must be obtained by locating the complete meter in a temperature chamber with temperature compensation disabled. The results for a sample measurement are shown in Figure 10. It is important to make this measurement with the previously determined calibration coefficients applied for each corresponding current.

In most cases, this test has to be performed only once on a prototype meter, whereas the multi-point calibration at room temperature will of course have to be performed for each meter that leaves production.

Since *GAIN_ADJ* applies to all phases of the meter simultaneously, it makes sense to base the determination of *PPMC1* and *PPMC2* on the average performance of all three phases.

Table 3 shows the errors at three primary currents averaged to yield an average error for each phase and each temperature. Note that the slopes of each phase for error over temperature are very similar.

	Phase A				Phase B				Phase C			
T [°C]	20 A	5 A	0.5 A	A average	20 A	5 A	0.5 A	B average	20 A	5 A	0.5 A	C average
-40	-1.408	-1.3288	-1.1501	-1.29563	-0.9241	-1.0365	-0.8757	-0.94543	-1.1177	-1.0675	-1.1662	-1.11713
0	-0.6494	-0.4964	-0.5059	-0.55057	-0.4349	-0.5311	-0.4628	-0.47627	-0.4404	-0.5626	-0.5973	-0.53343
22	-0.0347	-0.0338	-0.1043	-0.0576	-0.0372	-0.1737	-0.2746	-0.16183	-0.1148	-0.1526	-0.269	-0.1788
55	0.6633	0.7544	0.3094	0.5757	0.6478	0.4801	0.2437	0.4572	0.7658	0.5956	0.4432	0.601533
85	1.545	1.4543	1.0599	1.353067	1.3507	1.3234	1.1771	1.283733	1.4791	1.461	1.5515	1.4972
			slope	0.021			slope	0.018			slope	0.021

Table 3: Averaged Errors per Phase

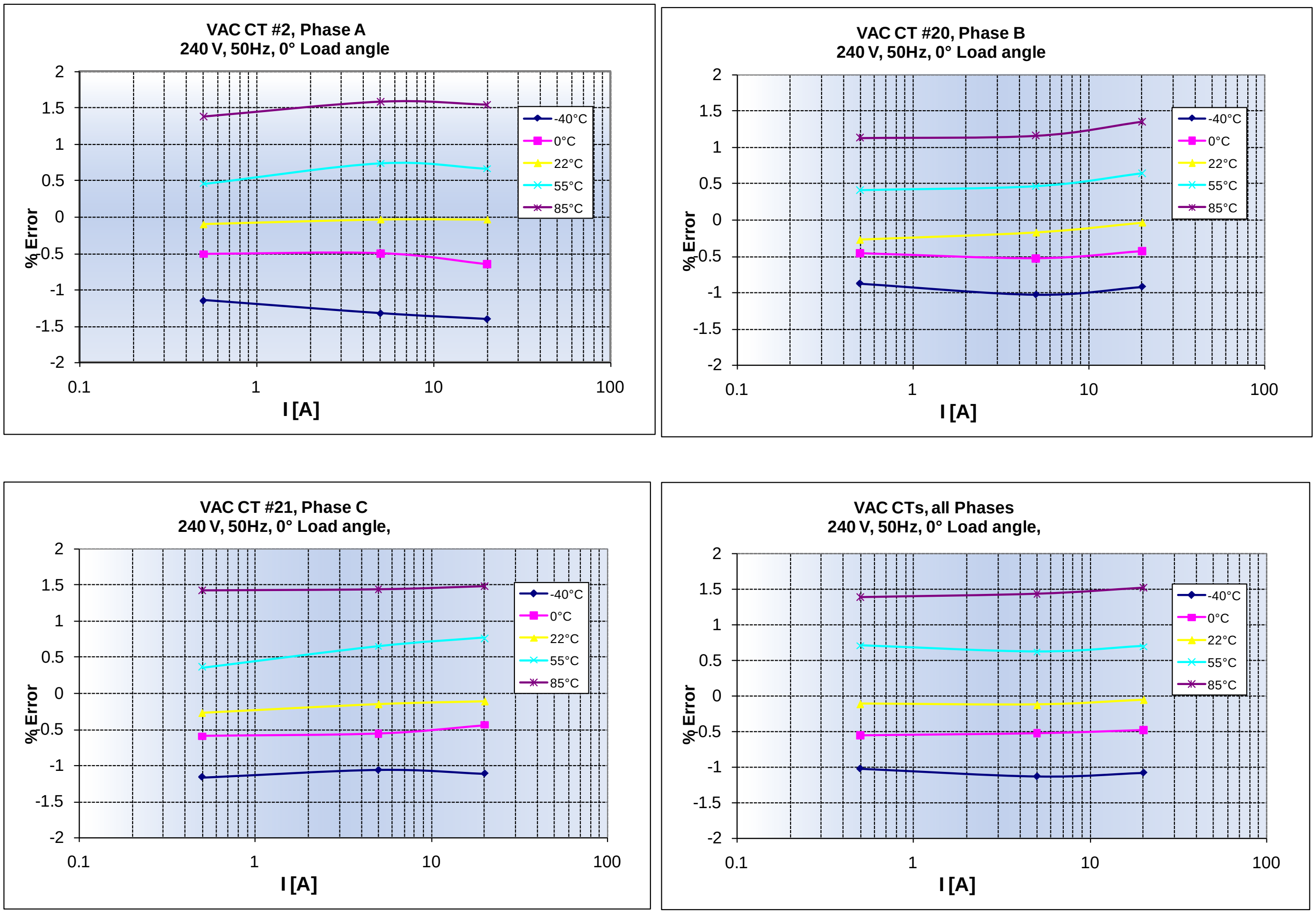


Figure 10: Load Lines at Various Temperatures, with 3-Point Calibration

The averaged errors must then again be averaged to yield an overall average, as shown in Table 4. The last column in Table 4 shows the normalized errors, i.e. with the error forced to zero at 22 °C.

The target *GAIN_ADJ* values can then be calculated, as shown in Table 5 for the tested VITROPERM® CTs. These are the values that compensate for the average error. Note that delta T is given in 1/10 °C.

	Phase A	Phase B	Phase C	All Phases	All phases
T [°C]	A average	B average	C average	average	normalized
-40	-1.29563	-0.94543	-1.11713	-1.119	-0.987
0	-0.55057	-0.47627	-0.53343	-0.520	-0.387
22	-0.0576	-0.16183	-0.1788	-0.133	0.000
55	0.5757	0.4572	0.601533	0.545	0.678
85	1.353067	1.283733	1.4972	1.378	1.511
slope	0.021	0.018	0.021	0.020	0.020

Table 4: Errors Averaged over all Phases

All phases normalized	delta T	Target GAIN_ADJ
-0.987	-620	16466
-0.387	-220	16417
0.000	0	16385
0.678	330	16330
1.511	630	16262

Table 5: Target *GAIN_ADJ* Values

The next task is to find the coefficients *PPMC1* and *PPMC2* that control *GAIN_ADJ* so it develops over temperature just like the target values. Using the values from Table 5 as an example, quadratic curve-fitting of the delta T values into the target *GAIN_ADJ* values yields:

PPMC1 = -1.609166
PPMC2 = -0.005297

These values have to be scaled by the factors of the 2^{14} and 2^{23} given in the formula for *GAIN_ADJ*, by equation(1). Using these scaling factors, we get:

PPMC1 = -2636
PPMC2 = -444

Feeding the calculated coefficients back into equation (1) shows that the synthesized *GAIN_ADJ* is very close to the target value, as demonstrated in Table 6. The largest deviation is -4, or -0.024%.

delta T	Target GAIN_ADJ	Synthetic GAIN_ADJ	Deviation GAIN_ADJ	Deviation in %
-620	16466	16464	-2	-0.012
-220	16417	16418	1	0.006
0	16385	16385	0	0.000
330	16330	16326	-4	-0.024
630	16262	16263	1	0.006

Table 6: Synthesized and Target *GAIN_ADJ* Values

Results of a temperature test of a set of VITROPERM® CTs with magnitude compensation applied are shown in Figure 11. The 71M65XX holds the magnitude below ±0.25% over temperature for all individual phases. Accuracy over temperature for all three phases combined is better than ±0.15%. The measured *GAIN_ADJ* values for this test are listed in Table 7. The values in this table show that the temperature measurement is sufficiently repeatable.

Temperature [°C]	Measured *GAIN_ADJ*	Target *GAIN_ADJ*
-40	16464	16466
0	16417	16417
+22	16385	16385
+55	16324	16330
+85	16258	16262

Table 7: Measured and Target GAIN_ADJ Values

It is important to note that the changes of *GAIN_ADJ* will affect both current and voltage channels of the 71M65XX. While this maintains accurate energy measurement, the voltage measurements will become inaccurate. For typical meters that do not measure or display the line voltage, this effect does not matter.

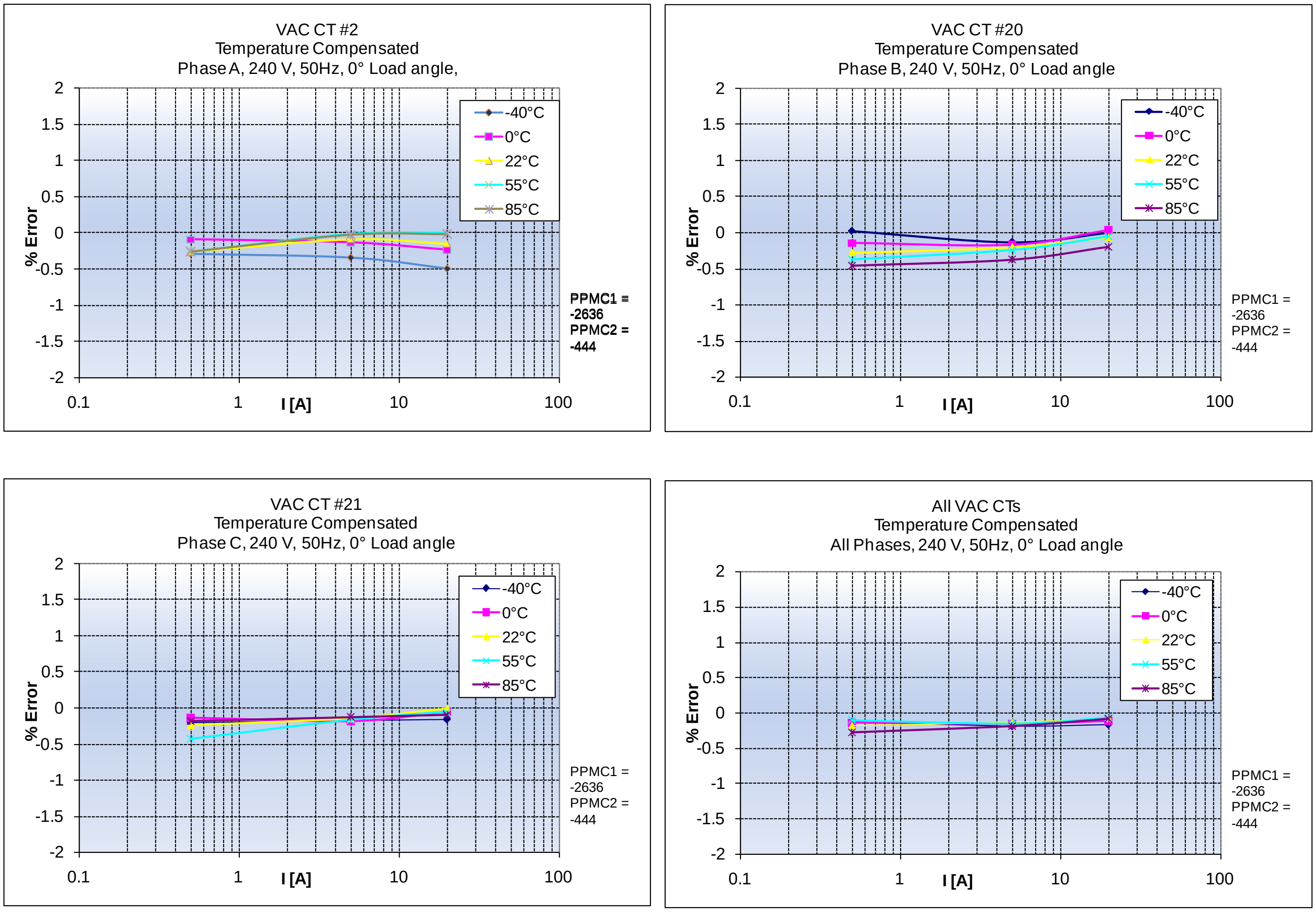


Figure 11: Load Lines with Magnitude Compensation over Temperature and 3-Point Calibration

The second step of linearizing the VITROPERM® CTs involves compensation for the phase error over temperature.

Fortunately, the development of the phase error for the VITROPERM® CTs is fairly linear over temperature, as shown in Figure 3. For a first, only linear approach, an approximation of +0.5° per 30 °C, or +0.0166° per °C can be used. If more accurate measurements are expected, quadratic or even 3rd order coefficients may have to be used.

As explained before, the CE code of the 71M65XX can compensate phase errors stemming from CTs or other influences on a phase-by-phase basis using the coefficients *PHADJ_n* stored in CE memory. The resulting phase angle compensation and the *PHADJ_n* value can be approximated by the following linear relation (see Figure 12):

$$PHADJ\_n = 2324 * \varphi \qquad \text{equation (2)}$$

In the interesting area around 4° (the average phase error of the VITROPERM® CTs), this approximation yields:

$$\Delta PHADJ\_n = 2324 * \Delta\varphi = \Delta T * 0.166 * 2324 = 38.75 * \Delta T \qquad \text{equation (3)}$$

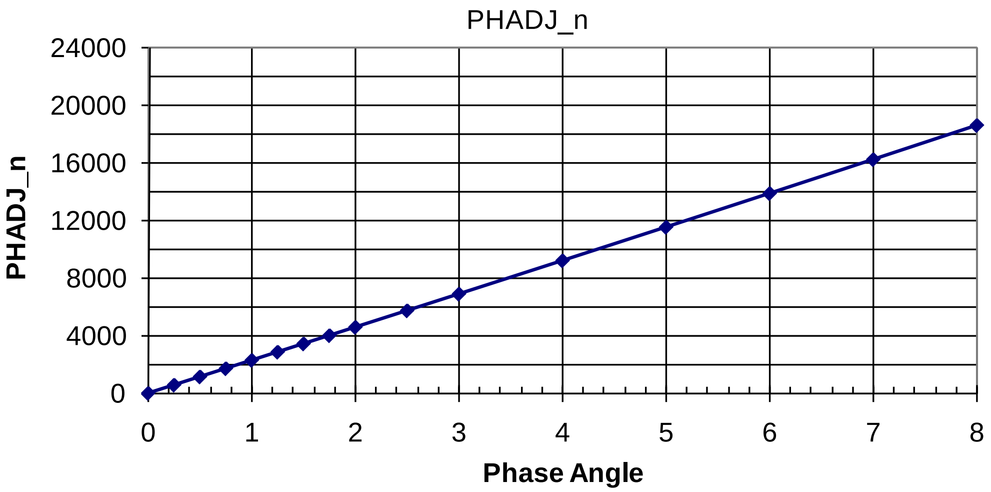


Figure 12: Relation of Phase Angle and *PHADJ_n*

In order to compensate phase error over temperature, a change of *PHADJ_n* with respect to the *PHADJ_ref_n* value used for calibration at 22 °C has to be applied:

$$PHADJ\_n(T) = PHADJ\_n\_ref + 38.75\Delta T \qquad \text{equation (4)}$$

For the VITROPERM® CTs, phase error increases with increasing temperature, requiring a higher *PHADJ_n* value for higher temperatures and a lower *PHADJ_n* value for lower temperatures.

Based on the approximation *ΔPHADJ_n* = 38.75 * ΔT made in equation (4) above, the correction values that have to be applied to *PHADJ_n* can be determined. Typical values are listed in Table 8.

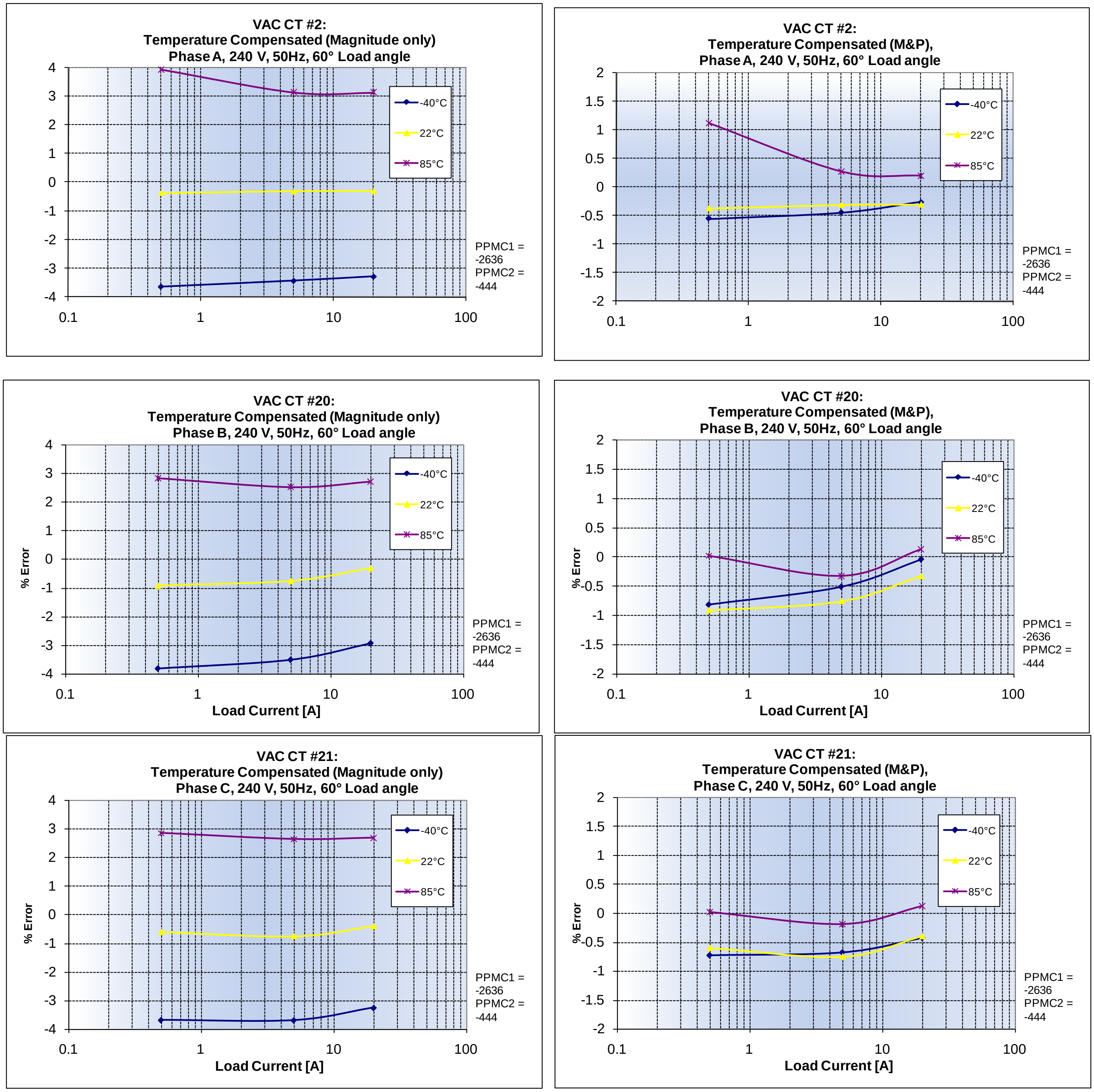
Temperature [°C]	-40	0	+22	+55	+85
delta T	-620	-220	0	+330	+630
Δ*PHADJ_n*	-2402	-852	0	+1279	2441

Table 8: Values Used for Temperature Correction of *PHADJ_n*

A 71M65XX meter with a set of three VITROPERM® CTs (60 A) was tested at 60° load angle at three different temperatures (room, -40 °C and +85 °C) with and without phase compensation. Magnitude compensation using *PPMC1* and *PPMC2* was always enabled. The phase compensation per Table 8 was manually applied to the phase angle compensation coefficients *PHADJ_A*, *PHADJ_B*, and *PHADJ_C*.

The results are shown in Figure 13. As can be seen in Figure 13, phase compensation improved the Wh error from 3% or 4% to well below 1% in all cases, except for the atypical CT #2, where the error at 0.5 A and -40°C is slightly above 1%.

Again, in a production meter, the MPU will have to change the values for *PHADJ_A*, *PHADJ_B*, and *PHADJ_C* based on IC temperature. This can be done in the same routine that changes the CE coefficients influencing voltage and current magnitude, but due to the nature of temperature changes, these updates will be necessary at much lower rates.



VAC CT #2: Temperature Compensated (Magnitude only) Phase A, 240 V, 50Hz, 60° Load angle

VAC CT #2: Temperature Compensated (M&P), Phase A, 240 V, 50Hz, 60° Load angle

VAC CT #20: Temperature Compensated (Magnitude only) Phase B, 240 V, 50Hz, 60° Load angle

VAC CT #20: Temperature Compensated (M&P), Phase B, 240 V, 50Hz, 60° Load angle

VAC CT #21: Temperature Compensated (Magnitude only) Phase C, 240 V, 50Hz, 60° Load angle

VAC CT #21: Temperature Compensated (M&P), Phase C, 240 V, 50Hz, 60° Load angle

Figure 13: Results of Phase Angle Compensation over Temperature

Conclusion

It has been shown that VITROPERM® DC-tolerant CTs made by VAC can be successfully used in an electronic electricity meter by applying advanced methods of calibration and temperature compensation.

The application of CE correction coefficients does not require special CE code but can rather be implemented in MPU code. Changes of the CE coefficients adjusting for voltage and current magnitude as well as for phase can be automated and made by the MPU in a centralized routine.

Further improvements of the load line are possible by applying the following measures:

1) Optimization of calibration points and careful selection of current segments.
2) Introducing temperature compensation that takes into account the quadratic and higher order component of the phase error over temperature.
3) Exclusion of CTs with atypical parameters.

The methods demonstrated in this document are easily transferable to the high-current VITROPERM® CTs and to the Teridian 71M651X or 71M653X families of electricity metering ICs.

Appendix

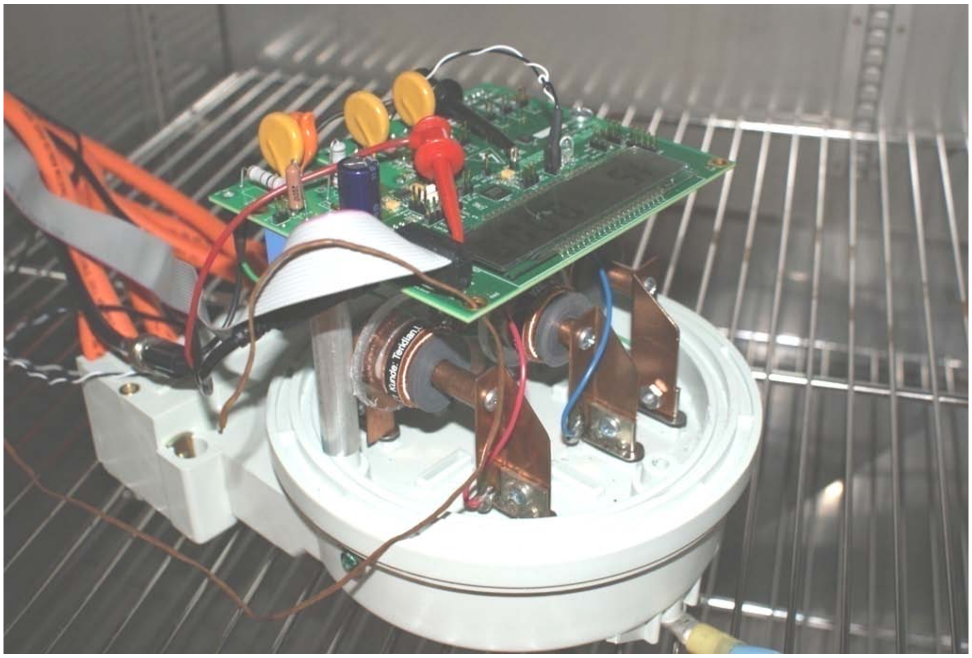


Figure 14: Meter Base with VAC CTs and Demo Board

Figure 15: Calibration System with Temperature Chamber

Figure 16: Meter Base with VAC CTs and Demo Board

Parameter	Location	Physical Value	Register Value
WRATE	CE	--	152
IMAX	MPU	260 A	2600
VMAX	MPU	600 V	6000
PPMC1	MPU	--	-2636
PPMC2	MPU	--	-444

Table 9: System Parameters Used with the VAC CTs

Revision History

Revision	Date	Description
Rev. 1.0	09/03/2008	First publication.
Rev. 1.1	09/26/2008	Fixed broken cross reference on page 12. Adjusted brightness and contrast of photos.
Rev. 1.2	02/01/211	Made the application note generic for all ICs in the 71M65XX family.

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