Fast digital calibration procedure
for STPM01 based energy meters

Introduction

This document describes the fast digital calibration procedure enabled by STPM01 in solid state energy meters.

Based on energy meter measurements the customer gets a bill and has to pay for energy consumption. It is in the interest of the customer and the electricity company that the meter, which counts the energy consumption, is working properly and accurately.

The quality control of the meters therefore is highly important, since the main requirements that a meter needs to fulfill are accuracy, cost, manufacturability and reliability. This explains the trend of moving from traditional mechanical solutions to solid state ones (electronic meters). Electronic meters allow high accuracy over a wide current dynamic range, low power consumption, reliability, robustness and gearless. They do not require precision mechanics and easily enable new functionalities (AMR: automatic meter reading, multi tariff billing, tamper proofing, prepayment meters, load shedding, power outage detection…).

Special care must be dedicated to the calibration procedure, because it impacts directly on many key features of the meter, such as accuracy, cost, manufacturability and reliability.

Due to its internal structure and features, STPM01 allows a more effective and innovative calibration procedure, which will be explained in this document.

Advantages of this procedure are:
● reduced calibration time
● no need for re-calibration (calibration parameter can be written in a permanent way)

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1 Calibration principles and underlying theory

1.1 Measuring principle of a digital energy measurement system

Modern digital energy measuring systems, such as STPM01, are usually constituted by an analog section with high-resolution Analog/Digital converters (ADCs) and a digital section with powerful Digital Signal Processors (DSPs) to perform the measurement of power and energy together with a variety of secondary parameters. The main scheme of such a system is indicated in *Figure 1.*

Figure 1.   Principle of a digital power and energy measurement system
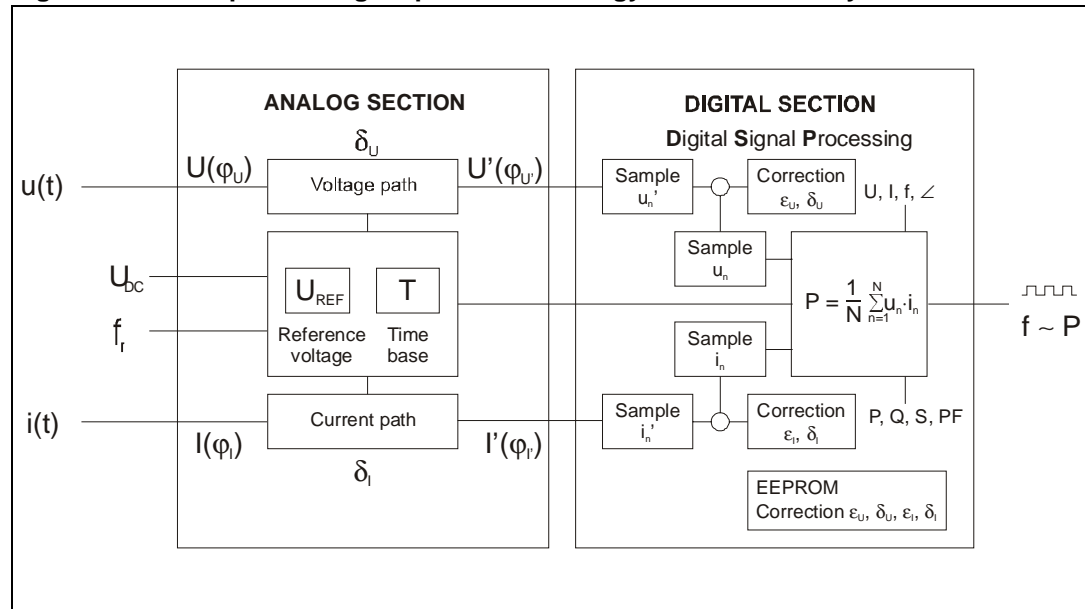
The **analog section** consists of voltage and current paths for each phase, and a common area with system DC reference voltage and the system time base.

Voltage and current paths include the following blocks:

● sensors for voltage and current
● signal conditioning (to optimize signals to match the required input level of the ADC)
● ADC

Common section consists of the following elements:

● system DC reference voltage
● system time base, provided by a quartz crystal oscillator or by an internal RC oscillator

The reference voltages and sample clocks used for the different ADC in the voltage and current paths are synchronized to these basic quantities.

The **digital section** consists of a DSP providing real time calculation based on the samples to carry out power, energy and all other parameters through standard mathematical formulas.

The A/D converters collect samples of phase current and phase to neutral voltage synchronized to the sample clock. Sample clock and reference voltages of the A/D converters are based on two fundamental quantities for amplitude and time, namely a DC reference voltage and a time base.

Outputs of the analog section are samples of voltage and current in digital form with an exact time relationship to each other.

The measured samples are corrected for amplitude and phase angle errors. The correction algorithm is defined during manufacture and is hardwired in DSP, while the correction parameters are calculated during the calibration phase and are stored in non-volatile memory (antifuse OTP cells).

Active energy and all other parameters are calculated in real time through standard mathematical formulas from the same set of corrected samples, and are stored in 32-bits registers, from which impulses are generated, with frequency proportional to measured power.

The following basic definition and formulas for power with amplitude and phase angle errors are derived from the scheme reported in *Figure 1.*

1.2 Basic definition

● Active Power

$$P = U \bullet I \bullet \cos\Phi$$

Eq. 1

● Apparent Power

$$S = U \bullet I$$

Eq. 2

● Reactive Power

$$Q = \sqrt{S^2 - P^2} = U \bullet I \bullet \sin\Phi$$

Eq. 3

● Power factor PF

$$PF = \cos\Phi = \frac{P}{S}$$

Eq. 4

where:

U, I effective values of voltage and current;

ϕ current to voltage phase angle $\phi = \varphi_U - \varphi_I$;

φ_U, φ_I voltage and current to common reference phase angles.

● Measured value of active power

$$P' = U' \bullet I' \bullet \cos\phi' = U' \bullet I' \bullet \cos(\varphi U' - \varphi I')$$

Eq. 5

where:

P' measured active power;

$U'=U(1+\varepsilon_U)$;

$I'=I(1+\varepsilon_I)$;

$\varphi_U{}`=\varphi_U+\delta_U$;

$\varphi_I{}`=\varphi_I+\delta_I$;

$\phi`=\varphi_U{}`-\varphi_I{}`=\varphi_U-\varphi_I+\delta_U-\delta_I=\phi+\delta$

ε_U voltage amplitude error;

ε_I current amplitude error;

δ current to voltage phase angle error $\delta=\delta_U-\delta_I$;

δ_U voltage phase angle error;

δ_I current phase angle error.

Then, neglecting the term $\varepsilon_U{}^*\varepsilon_I$:

$$P' = U \bullet I \bullet (1 + \varepsilon_U + \varepsilon_I) \bullet \cos(\phi + \delta) \qquad\qquad Eq. 6$$

1.3 Accuracy and stability influence factors

Even in a digital measuring system, all components which have any influence on the system accuracy and stability are located in the input analog section.

Generally, there are only a limited number of internal components which determine the accuracy characteristics of the system:

● voltage and current sensors

● signal conditioning section

● oscillator frequency

● internal reference voltage source

● analog to digital converters' gain

The components used must be of highest quality to reach the desired stability and linearity. The circuit must be carefully designed to minimize any influences on these components which could degrade short time repeatability, linearity or immunity.

Also external influences can affect the meter accuracy, such as:

● capacitive and inductive coupling to the inputs and between the phases (cross talking[1])

● influences of high frequency electrical and magnetic fields (EMC)

● common mode voltage between inputs and to earth

● influence of low frequency magnetic fields

● measuring setup (wiring, earth connection ground loop)

● influence of source (stability of U, I, ϕ, signal quality)

● long-time drift

● humidity

Unwanted external influences must be minimized. This can be achieved by careful shielding of the analog part or by compensating for the influences in hardware or software.

If the system is not immune to the external influences, it can only be operated under very special conditions and the results are impossible to reproduce in other locations, where there may be a different measuring set-up. Also short time repeatability due to noise and the resulting statistical effects will be bigger.

The external influences on total system accuracy can be as big as or even bigger than the basic specified error.

Note: *Please note that the voltage front end handles voltages of considerable amplitude, which makes it a potential source of noise. Disturbances are readily emitted into current measurement circuitry, where it will interfere with the actual signal to be measured. Typically, this shows as a non-linear error at small signal amplitudes and non-unity power factors. At unity power factor, voltage and current signals are in phase and crosstalk between voltage and current channels merely appears as a gain error, which can be calibrated. When voltage and current are not in phase, crosstalk will have a non-linear effect on the measurements, which cannot be calibrated. Crosstalk is minimized by means of good PCB planning and the proper use of filter components.*

2 An innovative STPM01 approach to calibrate the energy meter: fast digital calibration

The calibration procedure is a key feature among the main meter requirements. In fact, it impacts directly on accuracy, cost, manufacturability and reliability of the meter.

After the final assembly phase, an energy meter requires a calibration procedure due to unknown sensitivities of its following blocks:

- built-in voltage and current sensors
- oscillator frequency
- internal reference voltage source
- analog to digital converters' gain

assuming that the above listed values will not significantly change with environment temperatures changes and/or by aging.

2.1 Digital calibration procedure: traditional approach

The frequency of the output pulse signal is proportional to active energy.

As shown in *Figure 2.*, the error on the frequency is weighed up by the following equipments:

- Precision current and voltage source (Gen)
- High class precision energy meter (EMp)
- Meter under calibration (EM)

Figure 2.   Meter calibration set-up
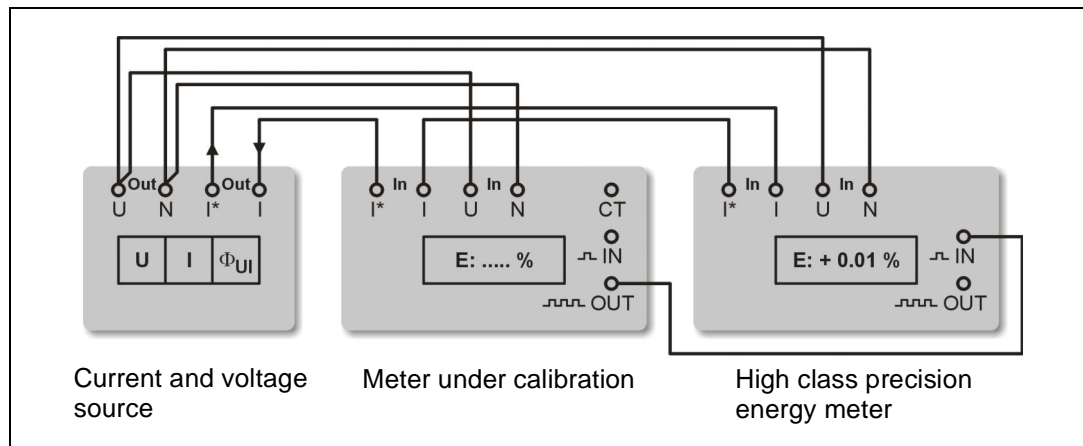
Gen equipment generates the line signals at the same frequency and well known phase between them. EMp and EM equipments measure the same line signals, but EMp computes the error by comparing those readings (energy, voltage and current RMS) with the measured frequency of the EM output pulse signal.

The resulting error has to be minimized acting on some design parameters, known as calibrators.

This traditional power calibration procedure for STPM01 based meters is described in detail in Appendix A.

2.2   Fast Digital calibration procedure: new approach

Energy meters based on STPM01 ASSP device allow a different kind of calibration due to the following important facts:

● The device is compound of two independent meter channels for line voltage and current respectively. Each channel includes its own 8 bits digital calibrator to adjust the signal amplitude, and digital filter to remove any signal DC component.

● The device computes RMS values of measured voltage and current, and from such corrected signals it calculates all different kind of energies (active, reactive, apparent and active energy of the 1st harmonic) through mathematical modules which are implemented with hardwired digital structures and therefore, are not objects of calibration.

● The device produces an output pulse signal but information can also be read through Serial Port Interface, SPI, communication channel.

● The device has an embedded memory, 56 bits, used for configuration and calibration purposes. The value of these bits can be read or they can be changed temporarily or permanently through SPI communication channel.

According to what pointed out above, it is possible to calibrate STPM01 based energy meters by calibration of voltage and current channels rather than of output pulse signal frequency. Since any energy measure performed by the device (active wide band and active fundamental, reactive or apparent) is calculated digitally (without error) from current and voltage calibrated signals, it means that every measure is automatically calibrated if current and voltage channels are calibrated. Calibration of both channels is performed in such way to achieve also the target value of power sensitivity constant of meter.

For the calibration procedure described above, it could even be possible to use two independent line signal generators, because to a certain extent line frequency and phase between line signals are not of high significance, observing RMS values.

Even more, if the line generator used is precise and stable enough, theoretically, it is not necessary to have any additional precision energy meter (EMp) to perform the calibration because only signal amplitudes (voltage and current RMS value) are calibrated and any DC offset is rejected, thanks to the almost ideal linearity of STPM01. Meter calibration is achieved by calibrating the device at just one measuring point (fast digital calibration), most often at nominal values, let's say, 230 V_{RMS}, 5 A_{RMS}, 50Hz.

This may simplify the generation of reference line signals of accurate output values. If accuracy is not guaranteed, the reference values of line signals for a calibration system can be obtained by precision RMS meters.

Calibrating only voltage and current in a single operating point led to a very short (4-5 sec. in an automated environment) calibration time.

If an application uses both current channels, they must both be compensated with the same procedure. This cannot be done at the same time, due to multiplexed implementation of two channels. In this case calibration time is increased (see paragraph "Two current channels calibration").

3 Fast digital calibration procedure

The following paragraphs describe the important items of fast digital calibration procedure.

3.1 System description

The fast digital calibration system is composed by the following parts:

Table 1.   Calibration equipment

Item	Description
CPC	Calibration Process Controller
Interface	serial communication to energy meter under calibration
EM	energy meter under calibration
Gen	line voltage and current reference generators

While the following parts are optional:

Table 2.   Optional calibration equipment

Item	Description
M1, M2	line voltage and current RMS meters
EMp	precision energy meter

Figure 3.   Fast digital calibration system. The equipments marked by (*) are optional
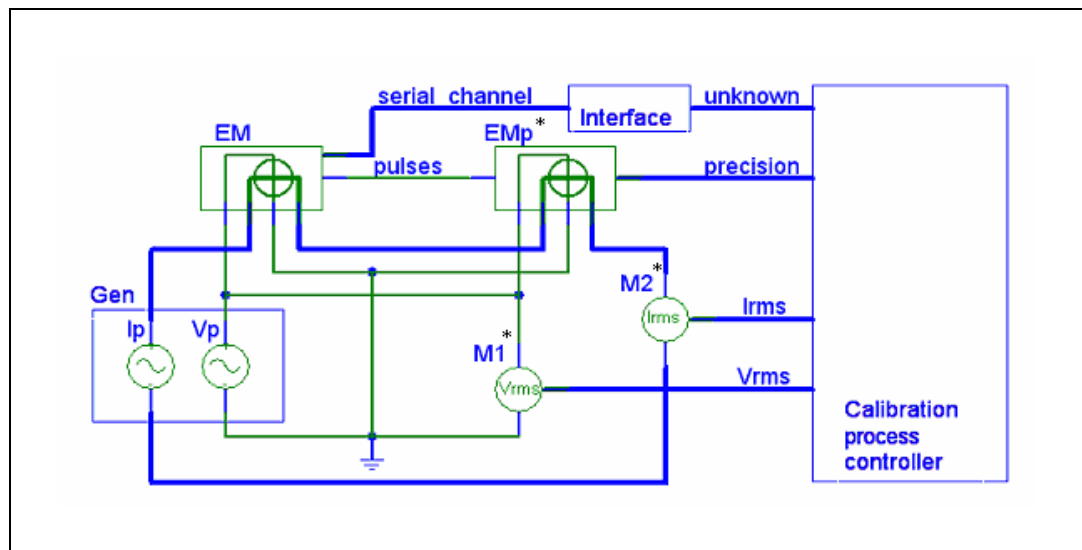
Often the Calibration Process Controller (CPC) is implemented with a Personal Computer (PC) which runs calibration software. The PC should have enough RS232C ports in order to communicate with other calibration system units.

The first interface port should be dedicated to communication with the energy meter under calibration (EM).

If EM does not have some Automatic Meter Reading (AMR) capability, a SPI to RS232C interface must be located between CPC and EM.

There are some RS232C ports that could be optional in the following conditions:
● if only calibration is required, the EMp and "precision" port can be omitted but Ip current path must not be broken,
● if Gen unit is accurate enough (< ±0.05%), the RMS meters M1 and M2 and corresponding "V_{RMS}" and "I_{RMS}" ports can be omitted.

3.2 Calibration flow chart

The calibration procedure can be summarized in the following steps, which will be examined in section 3.3:

Figure 4. Calibration flow chart
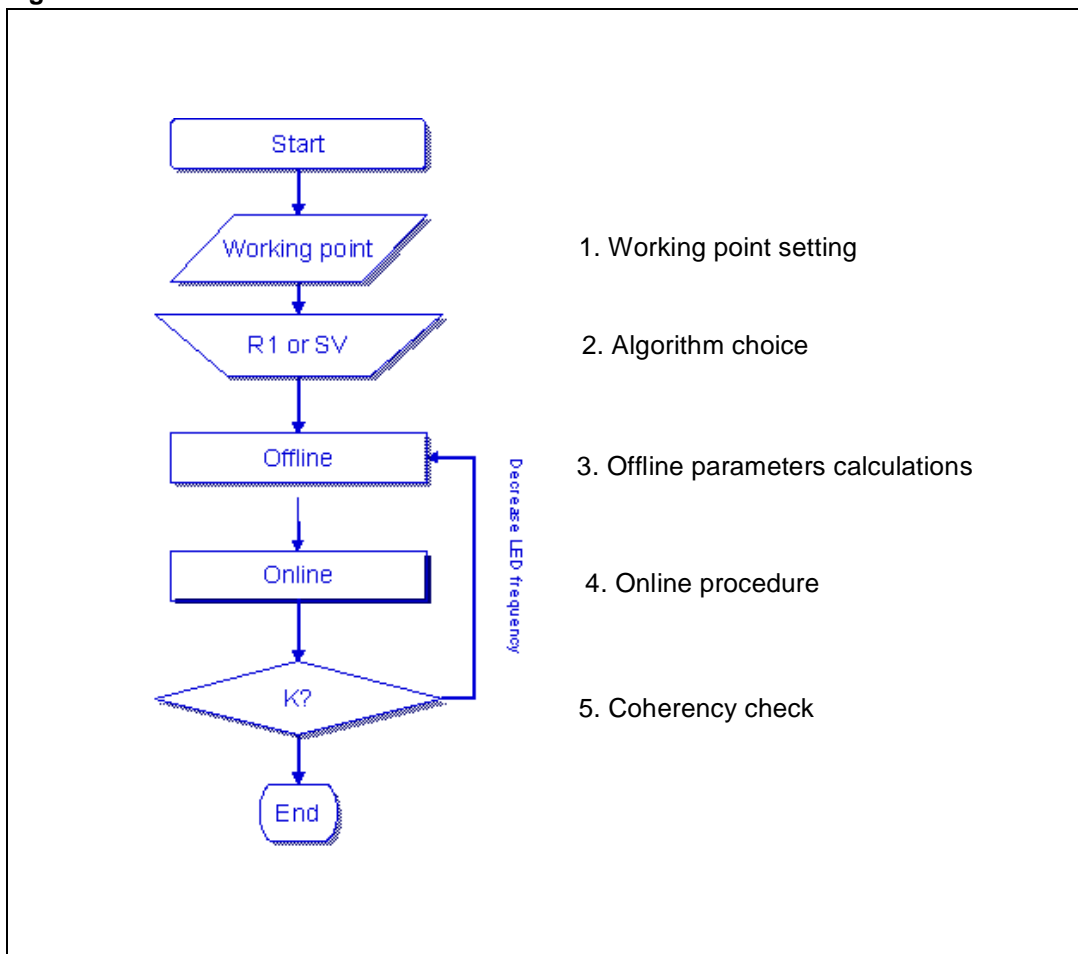
3.3 Calibration procedure

3.3.1 Working point setting

According to what pointed out previously, the device can be calibrated in a single point. Thus, voltage and current nominal values must be defined before running the calibration procedure, for example:

● Line RMS voltage:
  – Vn=230V
● Line RMS current:
  – In=5A

The following other parameters and constants of STPM01 (and relative tolerances) are also known:

Table 3.   Metering constants

Parameter		Value	Tolerance
Internal reference voltage	V_{BG}	1.23V	±2%
Internal Calculation Frequency	f_M	2^{23}HZ	±50 ppm
Amplification of voltage ADC	A_V	4	±1%
Amplification of current ADC	A_I	8, 16, 24, 32	±2%
Gain of differentiator	G_{DIF}	0,6135	
Gain of integrator	G_{INT}	0,815	
Gain of decimation filter	G_{DF}	1.004	
RMS Voltage register length	B_V	2^{11}	
RMS Current register length	B_I	2^{16}	
Constant	D_{UD}	2^{17}	

As shown in *Table 3.*, only analog parameters are object of calibration because they introduce a certain error. Voltage ADC amplification Av is constant, while Ai is chosen according to used sensors.

The calibration procedure has as final result the correction parameters, called Kv and Ki, which applied to STPM01 voltage and current measures compensate small tolerances of analog components that affect energy calculation.

Since Kv and Ki calibration parameters are the decimal representation of the corresponding configuration bytes CHV and CHP or CHS[1] (respectively voltage channel, primary current channel and secondary current channel calibration bytes), at the end of calibration CHV and CHP or CHS (according to the current channel under calibration, primary or secondary respectively) bits values are obtained.

In the following procedure CHV, CHP and CHS will be indicated as Cv and Ci.

Note: *For more info see paragraph "Two current channels calibration".*

Through hardwired formulas, Kv and Ki tune measured values varying from 0,75 to 1 in 256 steps, according to the value of Cv and Ci (from 0 to 255).

To obtain the greatest correction dynamic, calibrators are initially set in the middle of the range, thus obtaining a calibration range of ±12.5% per voltage or current channel:

● **Calibrators' value**

– Kv = Ki = 0.875

– Ci = Cv = 128

In this way it is possible to tune Kv and Ki having a precise measurement: for example Cv=0 generates a correction factor of -12.5% (Kv=0.75) and Cv=255 determines a correction factor of +12.5% (Kv=1), and so on.

According to what pointed out above, the following formulas, which relate Kv,i and Cv,i are obtained:

$$K_{v,i} = \frac{C_{v,i}}{128} \bullet 0.125 + 0.75 \qquad \text{Eq.7}$$

$$C_{v,i} = 1024 \bullet K_{v,i} - 768 \qquad \text{Eq.8}$$

Indicating with I_A and V_A average values and with X_I and X_V ideal values of RMS current and voltage readings (as calculated in the next steps), from what explained the following can be written:

$$X_V = \frac{K_v \bullet V_A}{0.875} \qquad \text{Eq.9}$$

$$X_I = \frac{K_i \bullet I_A}{0.875} \qquad \text{Eq.10}$$

3.3.2 Algorithm choice

It is possible to use two different algorithms to calculate the parameters to be used during the calibration:

1. R1 and R2 constants in order to carry out the sensor sensitivity KS;

2. Current sensor sensitivity and R2 constants in order to carry out R1.

The methods are equivalent. The choice is left to the designer.

According to the algorithm chosen, the next calibration step will produce the value of sensor K_S or resistor R1 to be mounted in the measure board to achieve calibration.

Algorithms formulas are reported below for both current transformer/shunt and Rogowski coil current sensors.

3.3.3   Offline parameters calculations

First of all it is necessary to determine target power sensitivity to achieve with the calibration process:

● Power sensitivity (LED):

  – P=128000 pulses/kWh

From which:

● Power sensitivity (Stepper Motor)

  – PM=P/64=2000 pulses/kWh

The calibration procedure will output Cv and Ci values that will allow the above power sensitivity of the meter.

This sensitivity is used to calculate target frequency at the LED pin for nominal voltage and current values:

$$X_F = f \bullet 64 \qquad\qquad\qquad \text{Eq.11}$$

where:

$$f = \frac{PM \bullet In \bullet Vn}{3600000} \qquad\qquad \text{Eq.12}$$

● **Current transformer or Shunt - Constant R1**

In this algorithm, voltage divider sensitivity is fixed, thus resistor values R1 and R2 are known, for example:

  – Resistor R1=R1
  – Resistor R2=R2

From values above and for both given amplification factor A_I and initial calibration data, the following target values can be calculated:

Voltage divider output:

$$V_{DIV} = Vn \bullet \frac{R2}{(R1 + R2)} \qquad\qquad \text{Eq.13}$$

Target RMS reading for given Vn:

$$X_V = \left(\frac{V_{DIV}}{V_{BG}}\right) \bullet 2 \bullet G_{DIF} \bullet A_V \bullet K_V \bullet G_{DF} \bullet G_{INT} \bullet B_V \qquad\qquad \text{Eq. 14}$$

Target RMS reading for given In:

$$X_I = \frac{f \bullet B_V \bullet B_I \bullet D_{UD}}{f_M \bullet X_V} \qquad\qquad \text{Eq. 15}$$

From which current sensor sensitivity KS is obtained:

$$K_S = \frac{X_I \bullet V_{BG} \bullet 1000}{In \bullet A_I \bullet Ki \bullet G_{DF} \bullet G_{INT} \bullet G_{DIF} \bullet B_I} \quad [mV/A] \qquad\qquad \text{Eq. 16}$$

● **Current transformer or Shunt - Constant K_s**

In this case the type of current sensor and its nominal value of sensitivity must be known, for example:

- – Shunt sensor=K_S

From values above and for both given amplification factor A_I and initial calibration data, the following target values can be calculated:

Target RMS reading for given In:

$$X_I = \frac{In \bullet K_S \bullet A_I \bullet Ki \bullet G_{INT} \bullet G_{DF} \bullet G_{DIF} \bullet B_I}{V_{BG} \bullet 1000}$$ Eq. 17

Target RMS reading for given Vn:

$$X_V = \frac{f \bullet B_V \bullet B_I \bullet D_{UD}}{f_M \bullet X_I}$$ Eq. 18

Voltage divider output:

$$V_{DIV} = \frac{X_V \bullet V_{BG}}{2 \bullet G_{DIF} \bullet A_V \bullet Kv \bullet G_{DF} \bullet G_{INT} \bullet B_V}$$ Eq. 19

From which R1 resistor value is obtained:

$$R1 = R2 \bullet \frac{Vn - V_{DIV}}{V_{DIV}} \quad [\Omega]$$ Eq. 20

● **Rogowski coil - Constant R1**

As previously mentioned, voltage divider sensitivity is fixed, thus resistor values R1 and R2 are known, for example:

- – Resistor R1=R1
- – Resistor R2=R2

From values above and for both given amplification factor A_I and initial calibration data, the following target values can be calculated:

Voltage divider output:

$$V_{DIV} = Vn \bullet \frac{R2}{R1 + R2}$$ Eq. 21

Target RMS reading for given Vn:

$$X_V = \frac{V_{DIV}}{V_{BG}} \bullet A_V \bullet Kv \bullet G_{DF} \bullet B_V$$ Eq. 22

Target RMS reading for given In:

$$X_I = \frac{f \bullet B_V \bullet B_I \bullet D_{UD}}{f_M \bullet X_V}$$ Eq. 23

From which current sensor sensitivity K_S is obtained:

$$K_S = \frac{X_I \bullet V_{BG} \bullet 1000}{In \bullet A_I \bullet Ki \bullet G_{DF} \bullet G_{INT} \bullet B_I} \quad [mV/A] \qquad \text{Eq. 24}$$

- **Rogowski coil - Constant K_s**

Sensor nominal value of sensitivity again must be known, for example:

    –   Rogowski coil=K_S

From values above and for both given amplification factor A_I and initial calibration data, the following target values can be calculated:

Target RMS reading for given In:

$$X_I = \frac{In \bullet K_S \bullet A_I \bullet Ki \bullet G_{INT} \bullet G_{DF} \bullet B_I}{V_{BG} \bullet 1000} \qquad \text{Eq. 25}$$

Target RMS reading for given Vn:

$$X_V = \frac{f \bullet B_V \bullet B_I \bullet D_{UD}}{f_M \bullet X_I} \qquad \text{Eq. 26}$$

Voltage divider output:

$$V_{DIV} = \frac{X_V \bullet V_{BG}}{A_V \bullet Kv \bullet G_{DF} \bullet B_V} \qquad \text{Eq. 27}$$

From which R1 resistor value is obtained:

$$R1 = R2 \bullet \frac{Vn - V_{DIV}}{V_{DIV}} \quad [\Omega] \qquad \text{Eq. 28}$$

3.3.4   Online Procedure

According to the used current sensor and the chosen algorithm, a component (resistor or current sensor) of the value calculated through Eq. 16, Eq. 20, Eq. 24 or Eq. 28 respectively must be mounted on the board.

To start online calibration procedure, the following has to be verified:

- EM is connected into the calibration system and it is properly configured according to the chosen application
- EM calibrators parameters are preset to initial data
- Target values of line signals are stable

When the system is connected and powered on, a certain number of readings of RMS values must be performed.

Due to the fact that 0.4% of ripple is present in the measured RMS values, more than ten readings of these values should be gathered each cycle (20ms at 50Hz) and average values of RMS current and voltage readings I_A and V_A should be computed. Consequently, from

Eq. 8, Eq. 9 and Eq. 10 a pair of final 8-bits calibration data can be calculated as shown below:

$$Ci = 896 \bullet \frac{Xi}{I_A} - 768 \qquad \text{Eq. 29}$$

$$Cv = 896 \bullet \frac{Xv}{V_A} - 768 \qquad \text{Eq. 30}$$

where X_V and X_I are those calculated in one of the four previous cases.

3.3.5 Coherency check

One assumes that the EM works correctly and that built-in voltage and current sensors allow the target power sensitivity constant to be achieved, because the correction parameters Ki and Kv can tune measured values within the calibration range of ±12.5% per voltage or current channel.

If after the calibration, calculated values for Cv or Ci are out of range (less than 0 or more than 255), it could mean that the application cannot reach the target value of power sensitivity. In this case, steps 3 and 4 have to be repeated choosing a smaller power sensitivity value. If the values of Cv or Ci are out of range even for small values of PM it could mean that the energy meter board is not good enough to perform such measurements, maybe because the tolerance of the components is too big, or no care has been taken in the layout phase, so the application has to be re-designed.

Otherwise, if calibrators values are written into STPM01, the average RMS readings will be very close to target values X_I and X_V and the frequency of LED output will be very close to target value f.

3.4 Two current channels calibration

If the meter uses two current sensors, calibration procedure must be repeated twice, one for each current channel calibration.

Steps 1 to 3 of fast digital calibration procedure (working point setting, algorithm choice and calculation of offline parameters) must be followed as explained before and they are common for both channels.

Before running the online procedure, configuration bit 7 must be cleared (PST2 = 0) to disable tamper function, then calibration is split for the two channels:

● **Primary channel calibration**: mode signal CSEL must be cleared to select primary channel, then step 4 and 5 (online measure and coherency check) must be executed. If Cv and Ci are valid values they can be written in bytes CHV and CHP.

● **Secondary channel calibration**: mode signal CSEL must be set to select secondary channel, then step 4 and 5 (online measure and coherency check) must be executed. This time only Ci, if valid, should be written in byte CHS.

For more info see STPM01 datasheet, "Configuration bytes" paragraph.

4   Phase calibration

4.1   Phase error definition

STPM01 does not introduce any phase shift between voltage and current channel. However, voltage and current signals come from transducers, which could have inherent phase errors. Phase shift is usually introduced by the current sensor, since the voltage sensor, normally a resistor divider, does not introduce any delay. For example, a phase error of 0.1° to 0.3° is not uncommon for a current transformer (CT). These phase errors can vary from part to part, and they must be corrected in order to perform accurate power calculations.

At phase angle current to voltage $\phi = 0°$ (power factor PF = 1) the amplitude errors of voltages and currents determine the actual accuracy of the instrument.

In this case there is no phase shift between voltage and current and Eq. 1 becomes:

$$P = U \bullet I \qquad \qquad \text{Eq. 31}$$

This is the target measured power to reach with calibration.

At phase angles other than zero, e.g. ±60° (PF = 0.5) the phase angle errors between voltages and currents of each phase also affect the actual accuracy in addition to the amplitude errors described above.

Let us assume that voltage and current RMS values are already calibrated, so they do not introduce any error in measured power.

$P = U \bullet I\cos\phi$ real active power;

$P' = U \bullet I\cos(\phi + \delta)$ measured active power;

Figure 5.   Influence of phase angle errors in power measurement
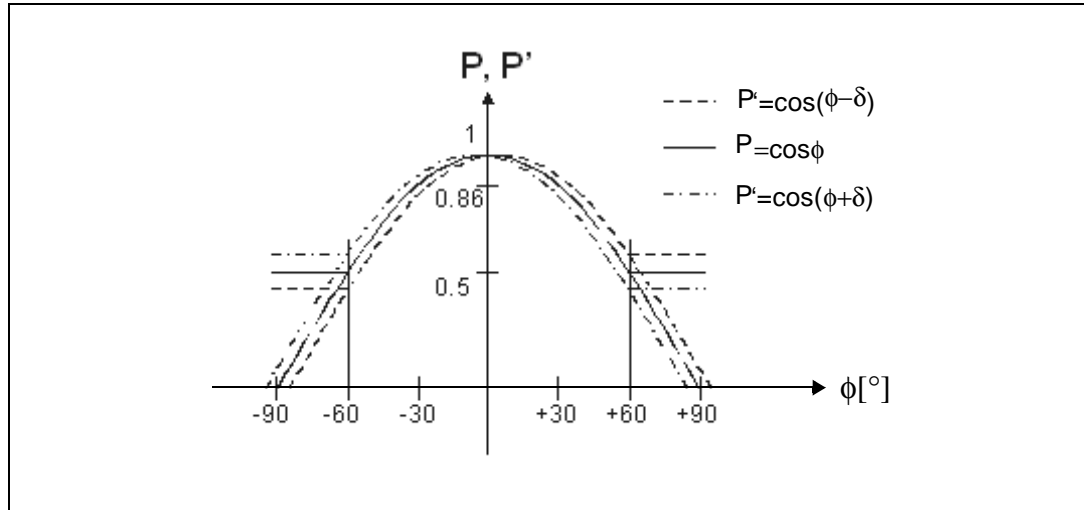
Formula for the relative error of power can be expressed as:

$$e = \left[\frac{P'}{P} - 1\right] \bullet 100 = \left[\frac{\cos(\Phi + \delta)}{\cos\phi} - 1\right] \bullet 100 \ [\%] \qquad \text{Eq. 32}$$

The relative error on power depends on phase angle ϕ and phase angle error δ, and it shows a symmetrical behavior regarding positive and negative phase angles (eg. +60° and -60°). The influence of δ is small at $\cos\phi = 1$, but becomes very big at small $\cos\phi$ values.

This additional contribution to the total error from the phase angle error is usually referred to as "related to apparent power" and can be expressed as follows:

$$e \ = \ e_{PF=\,1} \bullet \frac{S}{P} \ = \ \frac{e_{PF=\,1}}{PF} \qquad\qquad \text{Eq. 33}$$

As shown in Eq. 32 errors associated with phase mismatch are particularly noticeable at low power factors, e.g. with a specified error for power of ±0.01% the error tolerance for typical power factors will be:

Table 4.   Error tolerance vs. power factor

PF	E[%]
1	±0.01%
0.5	±0.02%
0.25	±0.04%

4.2   Phase error compensation in STPM01 based energy meters

A good Rogowski coil or Shunt would normally have a phase error small enough that there is no need for phase compensation. This also valid for the type of CT which are built on the ST measurement modules.

Otherwise, if the sensor is not very accurate also phase compensation needs to be performed. Since this process increases calibration time of at least 3 times more, it is advisable to find the best compensation value for a certain type of current sensor and then use such value for compensation of all modules.

STPM01 provides a means of digitally calibrating small phase errors. Calibration is obtained by introducing delays on voltage or current signal. The extent of phase compensation can be set using the 4 bits of the phase calibration register (CPH).

The default value of this register is 0, which gives 0° phase compensation. When the 4 bits are set (CPH = 15) the compensation is +0.576°. The resolution step of the phase compensation is 0.038°.

Phase calibration should be carried out after amplitude calibration. The method to follow is the same for both traditional power calibration and fast calibration approach.

As phase errors are amplified with power factor, to make them more evident a phase shift of 60° between line voltage and current is introduced.

In this case Eq. 1 becomes:

$$P \ = \ \frac{U \bullet I}{2} \qquad\qquad \text{Eq. 34}$$

CPH bits need to be changed in such a way to achieve this target power, either reading active power from DAP register (fast digital calibration approach) or measuring LED pin output frequency (traditional calibration approach).

5 RC calibration

The purpose of RC oscillator calibration is to bring the working frequency into the band of interest (4.0 < F < 4.2MHz) in order to properly set some absolute definitions of time in the device. The calibration can be obtained either by changing the value of current settling resistor which should be connected between pin CLKIN and Vss or by programming of one or two OTP bits (CRC). The first possibility allows a precise calibration to a certain value while the second one allows only coarse calibration in few steps. In general, it is not so important to have a precise frequency of a certain value as long it stays stable under temperature variation or aging. On the other hand, the value of this frequency directly influences the power constant of the meter. For example, if Rogowski coil is used, the constant C changes twice as much as frequency F (dC/C = 2dF/F) but, if CT or shunt is used, the constant C changes as frequency F (dC/C = dF/F).

6 Temperature calibration

A calibration of Band Gap should be performed during EWS by means of production tester which could permanently write one or two OTP lower bits of TC. Namely, on the die, there is an additional test pad which enables the tester to measure the output of Band Gap generator. The upper two bits of TC are intended for compensation of temperature variation of the whole meter. We saw on some of our applications that we can rotate the temperature curve of the whole meter by changing the value of configurator TC. But, in practice, it is very difficult and time consuming to calibrate the temperature dependency of the meter. Therefore, it is advisable to control temperature dependency during the meter design phase. This would enable us to perform such compensation at the base.

6.1 APPENDIX A - Traditional calibration approach

It is possible to calibrate a STPM01 based energy meter also in a traditional way, setting the calibrators Cv and Ci in order to fix LED frequency rather than voltage and current values. The procedure requires an accurate frequency meter that allows reading frequency out of the LED pin.

LED pin outputs a pulse train with frequency that can be chosen proportional to wide band active power, 1st harmonic, reactive or apparent energy by setting a 2-bit configurator APL=0 (CFG03=APL0=0, CFG04=APL1=0) and then by setting another 2-bit configurator KMOT respectively to:

- 0 - Type 0 active energy - (CFG14=KMOT0=0, CFG15=KMOT1=0)
- 1 - Type 1 active energy - (CFG14=KMOT0=1, CFG15=KMOT1=0)
- 2 - Reactive energy - (CFG14=KMOT0=0, CFG15=KMOT1=1)
- 3 - Apparent energy - (CFG14=KMOT0=1, CFG15=KMOT1=1)

To perform the calibration, the following steps need to be performed.

6.1.1 Working point setting

Voltage and current nominal values must be defined before running the calibration procedure, for example:

- Line RMS voltage:
  – Vn=230V
- Line RMS current:
  – In=5A
- Active Power:
  – Pn=Vn*In=1150W

Target active power is calculated assuming no phase shift between line voltage and current.

Parameters reported in *Table 3.* are always valid for calculation.

In STPM01 active power is calculated from voltage and current registers. Eq. 9 and Eq. 10 show a proportional relationship between measured voltage and current and calibration

parameters. For this reason measured power will be proportional to the product of voltage and current calibrators, that will be defined as a "power calibrator" Kp:

$$P \propto V \bullet I \propto Kv \bullet Ki = Kp \qquad \text{Eq. 35}$$

$$Kv = Ki = \sqrt{Kp} \qquad \text{Eq. 36}$$

The minimum value of this new calibrator Kp is obtained with the minimum value of both calibrators Kv and Ki, and its maximum value from the maximum value of Kv and Ki:

$$0.5625 = Kv_{MIN} \bullet Ki_{MIN} < Kv_{MAX} \bullet Ki_{MAX} = 1 \qquad \text{Eq. 37}$$

In this way a power correction parameter related to Kv and Ki has been deduced.

This parameter has a correction dynamic greater than Kv and Ki. This this means that greater tolerances can be compensated, but in a single calibration point. In fact, with power calibration linearity cannot be guaranteed if calibration is performed in a single point, because power is calibrated, not voltage and current for which STPM01 has a great linearity. To find out Kv and Ki that compensate power in a certain range, it could be useful to perform the below procedure twice.

As done for Kv and Ki, to have the greatest correction dynamic, at the beginning of calibration procedure, Kp should be put in the middle of this interval:

● Calibrators' value
  – Kp = 0.78125
  – Kv = Ki = $\sqrt{Kp}$ = 0,88
  – Ci = Cv = 137

and since LED pin frequency f is proportional to measured power P, it is possible to write an equation analogous to Eq. 9 and Eq. 10 for the frequency:

$$X_F = \frac{Kp \bullet f_A}{0.78125} \qquad \text{Eq. 38}$$

where f_A is the measured frequency of the LED pin and XF is the target frequency calculated in Eq. 11.

b. Algorithm choice

This step is equivalent to that already explained for fast digital calibration procedure.

c. Offline parameters calculations

This step is equivalent to that already explained for fast digital calibration procedure.

d. Online Procedure

As done for fast digital calibration, before starting the online procedure it is necessary to verify that the equipment is properly configured and connected.

After system power on and frequency measurement, from Eq. 38 power calibrator Kp can be derived as follows:

$$Kp = 0.78125 \bullet \frac{X_F}{f_A}$$

Eq. 39

Then, from Eq. 36 and Eq. 8 Cv,i are calculated.

e. Coherency check

This step is equivalent to that already explained for fast digital calibration procedure.

7 Revision history

Table 5.   Document revision history

Date	Revision	Changes
25-Jan-2006	1	First issue
31-Jan-2006	2	Minor text revision

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