Freescale Semiconductor, Inc.
Design Reference Manual

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Kinetis-M Three-Phase Power Meter Reference Design

1 Introduction

This design reference manual describes a solution for a three-phase electronic power meter based on the MKM34Z128CLL5 microcontroller. This microcontroller is part of the Freescale Kinetis-M microcontroller family. The Kinetis-M microcontrollers are especially designed for electronic power meter applications. Thus the Kinetis-M family offers a high-performance analog front-end (24-bit AFE) combined with an embedded Programmable Gain Amplifier (PGA). In addition to high-performance analog peripherals such as an auxiliary 16-bit SAR ADC, these new devices integrate memories, input-output ports, digital blocks, and a variety of communication options. Moreover, the ARM® Cortex®-M0+ core, with support for 32-bit math, enables fast execution of metering algorithms.

The commonly used three-phrase meter topology is based on the six or seven channels of sigma-delta (SD) ADC converters. Kinetis-M microcontrollers use different topology because of the 24-bit AFE (four channels of the 24-bit SD ADC) convertors and the 16-bit successive approximation (SAR) ADC converter with an input analog multiplexer.

Contents

The main purpose of a three-phrase meter implementation on the KM3x devices is based on the signal's dynamic range analysis. The current signal in metering is typically from 50mA to 120A, thus the current must be digitalized by a very precise and linear ADC with wide dynamic range, typically 24 bits. The SD method is an ideal solution to solve current dynamic range requirements. On the other hand, the voltage signal in metering is in the range of 80V to 280V. So the voltage dynamic range is approximately 60 times smaller than current dynamic range. The voltage requirements can be easily solved by a high-resolution SAR converter.

The common reason for using six or seven independent ADC channels is for easier converter synchronization—that is, all channels are able to begin precisely at the defined time. The KM3x devices solve this problem by the peripheral called XBAR. The XBAR is an internal connection matrix among of the peripherals. Internal signals such as conversion complete from the SD converter can be used for starting SAR conversion. So the complete signal sampling process based on the combination of three or four SDs and one SAR with an input multiplexer is fully supported by the device's hardware and only the conversion results must be read by the microcontroller core or by DMA.

The three-phase power meter reference design is intended for the measurement and registration of active and reactive energies in three-phase four-wire networks. It is pre-certified according to the European EN50470-1, EN50470-3, classes B and C, and also to the IEC 62053-21 and IEC 62052-11 international standards for electronic meters of active energy classes 2 and 1.

The integrated Switched-Mode Power Supply (SMPS) enables an efficient operation of the power meter electronics and provides enough power for optional modules, such as non-volatile memories (NVM) for data logging and firmware storage, a low-power magnetic field sensor for electronic tamper detection, and an RF communication module for AMR and remote monitoring. The power meter electronics are backed-up by a 3.6 V Li-SOCI2 battery when disconnected from the power mains. This battery activates the power meter whenever the user button is pressed or a tamper event occurs. The permanent triggers for tamper events include two tamper switches protecting the main and terminal covers. An additional optional tamper event is generated by a low-power 3-axis magnetometer sensor. The 3-axis magnetometer is useful to check for magnetic field changes which is important because current sensing is widely used with current transformers. This type of sensor guarantees the static magnetic field generated by the permanent magnet.

The power meter reference design is prepared for use in real applications, as suggested by its implementation of a Human Machine Interface (HMI) and communication interfaces for remote data collecting.

1.1 Specification

As already indicated, the Kinetis-M one-phase power meter reference design is ready for use in a real application. More precisely, its metrology portion has undergone thorough laboratory testing using the test equipment ELMA8303 [1]. Because of intensive testing, an accurate 24-bit AFE and 16-bit SAR ADC, and continual algorithm improvements, the three-phase power meter calculates active and reactive energies more accurately and over a higher dynamic range than required by common standards. All information, including accuracies, operating conditions, and optional features, are summarized in Table 1.

Table 1. Kinetis-M one-phase power meter specifications

Feature or Condition	Description or Parameter
Type of meter	Three-phase residential
Type of measurement	4-Quadrant
Metering algorithm	Filter-based
Precision (accuracy)	IEC50470-3 class C, 0.5% (for active and reactive energy)
Voltage range	90–265 V_{RMS}
Current range	0–120 A (5 A is nominal current, peak current is up to 154 A)
Frequency range	47–53 Hz
Meter constant (imp/kWh, imp/kVArh)	500, 1000, 2000, 5000 (default), 10000. Note, that pulse numbers 10000 are applicable only for low-current measurement.
Functionality	V, A, kW, kVAr, kVA, kWh (import/export), kVARh (lead/lag), Hz, time, date
Voltage sensor	Voltage divider
Current sensor	Current transformer (tested with different CT`s types)
Energy output pulse interface	Two red LEDs (active and reactive energy)
Energy output pulse parameters: • Maximum frequency • On-Time • Jitter	 • 600 Hz • 20 ms (50% duty cycle for frequencies above 25 Hz) • ±10 is at constant power
User interface	LCD, one push-button, one user LED (red)
Tamper detection	Two hidden buttons (terminal cover and main cover)
IEC1107 infrared interface	4800/8-N-1 FreeMASTER interface
Optoisolated pulse output (optional)	optocoupler (active or reactive energy)
Isolated RS232 serial interface (optional)	19200/8-N-1
RF interface (optional)	2.4 GHz RF 1322x-LPN internal daughter card
External NVMs (optional) • EEPROM	 AT24C32D, 32 KB
Electronic tamper detection (optional)	MAG3110, 3-axis digital magnetometer
Internal battery	1/2AA, 3.6 V Lithium-Thionyl Chloride (Li-SOCl2) 1.2 Ah
Power consumption @ 3.3V and 22°C: • Normal mode (powered from mains) • Standby mode (powered from battery) • Power-down mode (powered from battery)	 • 18.4 mA • 260 µA • 6.5 µA (both cover closed), 4.9 µA (covers opened)

2 MKM34Z128 microcontroller series

The Freescale Kinetis-M microcontroller series is based on the 90-nm process technology. It has on-chip peripherals, and the computational performance and power capabilities to enable development of a low-cost and highly integrated power meter (see Figure 1). It is based on the 32-bit ARM Cortex-M0+ core with CPU clock rates of up to 50 MHz. The measurement analog front-end is integrated on all devices; it includes a highly accurate 24-bit Sigma Delta ADC, PGA, high-precision internal 1.2 V voltage reference (VRef), phase shift compensation block, 16-bit SAR ADC, and a peripheral crossbar (XBAR). The XBAR module acts as a programmable switch matrix, allowing multiple simultaneous connections of internal and external signals. An accurate Independent Real-time Clock (IRTC), with passive and active tamper detection capabilities, is also available on all devices.

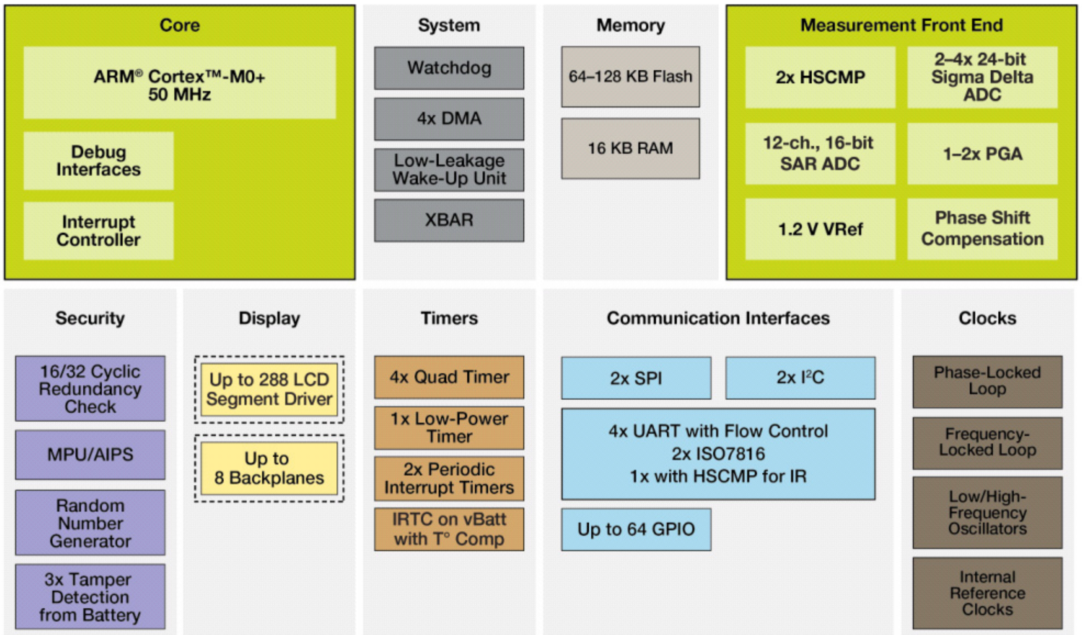

Figure 1. Kinetis-M block diagram

In addition to high-performance analog and digital blocks, the Kinetis-M microcontroller series has been designed with an emphasis on achieving the required software separation. It integrates hardware blocks supporting the distinct separation of the legally relevant software from other software functions. The hardware blocks controlling or checking the access attributes include:

- ARM Cortex-M0+ Core
- DMA Controller Module
- Miscellaneous Control Module
- Memory Protection Unit
- Peripheral Bridge
- General Purpose Input-Output Module

The Kinetis-M devices remain first and foremost highly capable and fully programmable microcontrollers with application software driving the differentiation of the product. Nowadays, the necessary peripheral software drivers, metering algorithms, communication protocols, and a vast number of complementary software routines are available directly from semiconductor vendors or third parties. Because Kinetis-M microcontrollers integrate a high-performance analog front-end, communication peripherals, hardware blocks for software separation, and are capable of executing a variety of ARM Cortex-M0+ compatible software, they are ideal components for development of residential, commercial, and light industrial electronic power meter applications.

3 Basic theory

The critical task for a digital processing engine or a microcontroller within an electricity metering application is the accurate computation of the active energy, reactive energy, active power, reactive power, apparent power, RMS voltage, and RMS current. The active and reactive energies are sometimes referred to as the billing quantities. The remaining quantities are calculated for informative purposes, and they are referred to as non-billing.

3.1 Active energy

The active energy represents the electrical energy produced, flowing or supplied by an electric circuit during a time interval. The active energy is measured in the unit of watt hours (Wh). The active energy in a typical one-phase power meter application is computed as an infinite integral of the unbiased instantaneous phase voltage u(t) and phase current i(t) waveforms.

$$Wh = \int_0^{\infty} u(t) i(t) dt \qquad \textbf{Eqn. 1}$$

3.2 Reactive energy

The reactive energy is given by the integral, with respect to time, of the product of voltage and current and the sine of the phase angle between them. The reactive energy is measured in the unit of volt-ampere-reactive hours (VARh). The reactive energy in a typical one-phase power meter is computed as an infinite integral of the unbiased instantaneous shifted phase voltage u(t-90°) and phase current i(t) waveforms.

$$VARh = \int_0^{\infty} u(t - 90°) i(t) dt \qquad \textbf{Eqn. 2}$$

3.3 Active power

The active power (P) is measured in watts (W) and is expressed as the product of the voltage and the in-phase component of the alternating current. In fact, the average power of any whole number of cycles is the same as the average power value of just one cycle. So, we can easily find the average power of a very long-duration periodic waveform simply by calculating the average value of one complete cycle with period T.

$$P = \frac{1}{T} \int_0^{\infty} u(t) i(t) dt \qquad \textbf{Eqn. 3}$$

3.4 Reactive power

The reactive power (Q) is measured in units of volt-amperes-reactive (VAR) and is the product of the voltage and current and the sine of the phase angle between them. The reactive power is calculated in the same manner as active power, but in reactive power the voltage input waveform is 90 degrees shifted with respect to the current input waveform.

$$Q = \frac{1}{T}\int_{0}^{\infty} u(t - 90°)i(t)dt$$ **Eqn. 4**

3.5 RMS current and voltage

The Root Mean Square (RMS) is a fundamental measurement of the magnitude of an alternating signal. In mathematics, the RMS is known as the standard deviation, which is a statistical measure of the magnitude of a varying quantity. The standard deviation measures only the alternating portion of the signal as opposed to the RMS value, which measures both the direct and alternating components.

In electrical engineering, the RMS or effective value of a current is, by definition, such that the heating effect is the same for equal values of alternating or direct current. The basic equations for straightforward computation of the RMS current and RMS voltage from the signal function are the following:

$$IRMS = \sqrt{\frac{1}{T}\int_{0}^{T} [i(t)]^2 dt}$$ **Eqn. 5**

$$URMS = \sqrt{\frac{1}{T}\int_{0}^{T} [u(t)]^2 dt}$$ **Eqn. 6**

3.6 Apparent power

Total power in an AC circuit, both absorbed and dissipated, is referred to as total apparent power (S). The apparent power is measured in the units of volt-amperes (VA). For any general waveforms with higher harmonics, the apparent power is given by the product of the RMS phase current and RMS phase voltage.

$$S = IRMS \times URMS$$ **Eqn. 7**

For sinusoidal waveforms with no higher harmonics, the apparent power can also be calculated using the power triangle method, as a vector sum of the active power (P) and reactive power (Q) components.

$$S = \sqrt{P^2 + Q^2}$$ **Eqn. 8**

Due to better accuracy, we prefer to use Equation 7 to calculate the apparent power of any general waveforms with higher harmonics. In purely sinusoidal systems with no higher harmonics, both Equation 7 and Equation 8 will provide the same results.

3.7 Power factor

The power factor of an AC electrical power system is defined as the ratio of the active power (P) flowing to the load, to the apparent power (S) in the circuit. It is a dimensionless number between -1 and 1.

$$\cos\varphi = \frac{P}{S}$$ **Eqn. 9**

where angle φ is the phase angle between the current and voltage waveforms in the sinusoidal system.

Circuits containing purely resistive heating elements (filament lamps, cooking stoves, and so forth) have a power factor of one. Circuits containing inductive or capacitive elements (electric motors, solenoid valves, lamp ballasts, and others) often have a power factor below one.

The Kinetis-M one-phase power meter reference design uses a filter-based metering algorithm [2]. This particular algorithm calculates the billing and non-billing quantities according to formulas given in this section. Because of the use of digital filters, the algorithm requires only instantaneous voltage and current samples to be provided at constant sampling intervals. After a slight modification to the application software, it is also possible to use FFT based algorithms [3].

4 Hardware design

This section describes the power meter electronics. The power meter electronics are divided into three parts:

- Power supply
- Digital circuits
- Analog signal conditioning circuits

The power supply part of the hardware design is comprised of an 85–265 V AC-DC SMPS, a low-noise 3.6 V linear regulator, and a power management block. This power supply topology has been chosen to provide low-noise output voltages to supply the power meter electronics. The simple power management block works autonomously—that is, it supplies the power meter electronics from either the 50 Hz (60 Hz) mains or the 3.6 V Li-SOCI2 battery, which is also integrated. The battery serves as a backup supply in cases when the power meter is disconnected from the mains, or the mains voltage drops below 85 V AC. For more information, refer to Section 4.1, "Power supply."

The digital part can be configured to support both basic and advanced features. The basic configuration comprises only the circuits necessary for power meter operation—these are, the microcontroller (MKM34Z128MCLL5), debug interface, LCD interface, LED interface, IR (IEC1107), isolated open-collector pulse output, isolated RS232, push-button, and tamper detection. In contrast to the basic configuration, all the advanced features are optional and require the following additional components to be populated: 32 KB I^2C EEPROM for data storage, 3-axis magnetometer for electronic tampering, and UMI and RF MC1323x-IPB interfaces for AMR communication and remote monitoring. For more information, see Section 4.2, "Digital circuits".

The Kinetis-M devices allow differential analog signal measurements with a common mode reference of up to 0.8 V and an input signal range of ±250 mV. The capability of the device to measure analog signals with negative polarity brings a significant simplification to the phase current sensors' hardware interfaces. The phase voltage signal is simply connected to the SAR multiplexer, however, the external biasing circuits must be added externally (see Section 4.1, "Power supply").

The power meter electronics have been realized using a four-layer printed circuit board (PCB). We have chosen the more expensive four-layer PCB, comparing to a cheaper two-layer one, in order to validate the accuracy of the 24-bit SD ADC and 16-bit SAR ADC on the metering hardware optimized for measurement accuracy. Figure B-1and Figure B-2 show the top and bottom views of the power meter PCB.

4.1 Power supply

The user can use the 85–265 V AC-DC SMPS, which is directly populated on the PCB, or any other modules with different power supply topologies. If a different AC-DC power supply module is to be used, then the AC (input) side of the module must be connected to JP1, JP2, JP3, JP4, and the DC (output) side to JP1, JP5. The output voltage of the suitable AC-DC power supply module must be 4.0 V ±5%.

As already noted, the reference design is pre-populated with an 85–265 V AC-DC SMPS power supply. This SMPS is non-isolated and capable of delivering a continuous current of up to 80 mA at 4.125 V [4]. The SMPS supplies the SPX3819 low dropout adjustable linear regulator, which regulates the output voltage (VPWR) by using two resistors (R20 and R21) according to the formula:

$$VPWR = 1.235\left[1 + \frac{R20}{R21}\right] \qquad \text{Eqn. 10}$$

The resistor values R20 = 45.3 kΩ and R21 = 23.7 kΩ were chosen to produce a regulated output voltage of 3.6 V. The following supply voltages are all derived from the regulated output voltage (VPWR):

- VDD—digital voltage for the microcontroller and digital circuits
- VDDA—analog voltage for the microcontroller's 24-bit SD ADC and 1.2 V VREF
- SAR_VDDA—analog voltage for the microcontroller's 16-bit SAR ADC

The regulated output voltage also supplies those circuits with higher current consumption: Isolated RS232 interface (U301 and U302), Isolated pulse output (U303), and potential external modules attached to the RF MC1323x-IPB connector (J350). All of these circuits operate in normal mode when the power meter is connected to the mains.

The battery voltage (VBAT) is separated from the regulated output voltage (VPWR) using the D20 and D21 diodes. When the power meter is connected to the mains, then the electronics are supplied through the bottom D21 diode from the regulated output voltage (VPWR). If the power meter is disconnected from the mains, then D20 and the upper D21 diodes start conducting and the microcontroller device, including a few additional circuits operating in standby and power-down modes, are supplied from the battery (VBAT). The switching between the mains and battery voltage sources is performed autonomously, with a transition time that depends on the rise and fall times of the regulated output voltage supply (VPWR).

The analog circuits within the microcontroller usually require decoupled power supplies for the best performance. The analog voltages (VDDA and SAR_VDDA) are decoupled from the digital voltage (VDD) by the chip inductors L20 and L21 and the small capacitors next to the power pins (C26, C27, C28, C29, C30, and C31). Using chip inductors is especially important in mixed signal designs such as a power meter application, where digital noise can disrupt precise analog measurements. The L20 and L21 inductors are placed between the analog supplies (VDDA and SAR_VDDA) and digital supply (VDD) to prevent noise from the digital circuitry from disrupting the analog circuitries.

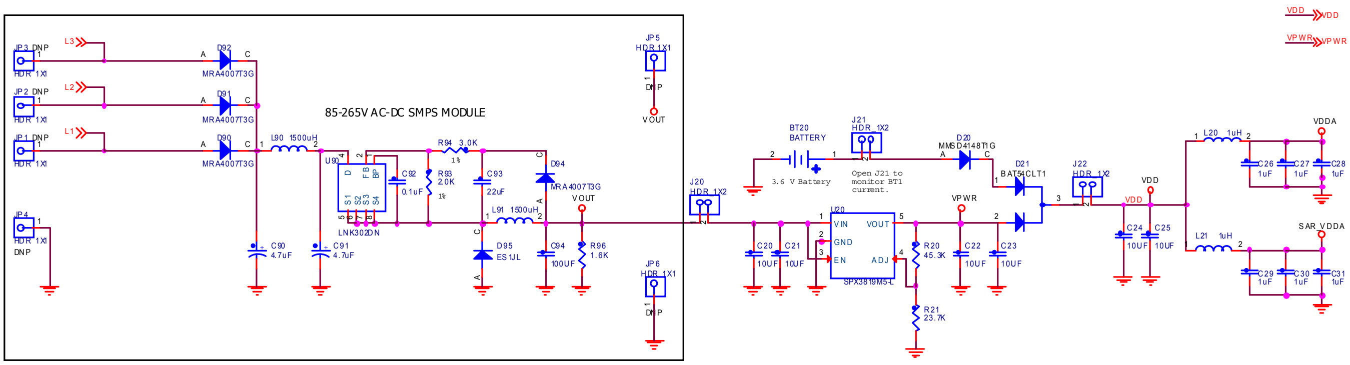

Figure 2. Power supply

NOTE

The digital and analog voltages VDD, VDDA and SAR_VDDA are lower by a voltage drop on the diode D21 (0.35 V) than the regulated output voltage VPWR.

4.2 Digital circuits

All the digital circuits are supplied from the VDD and VPWR voltages. The digital voltage (VDD), because it is backed-up by the 1/2AA 3.6 V Li-SOCI2 battery (BT200), is active even if the power meter electronics are disconnected from the mains. It supplies the microcontroller device (U1), 32KB EEPROM, and the 3-axis magnetometer (U381). The regulated output voltage (VPWR) supplies the digital circuits that can be switched off during the standby and power-down operating modes. These components are: Isolated RS232 interface (U303), Isolated open-collector pulse output interface (U301 and U302), RF MC1323x-IPB interfaces (J350), and the IR Interface (Q1), if in use.

4.2.1 MKM34Z128MCLL5

The MKM34Z128MCLL5 microcontroller (U1) is the most noticeable component on the metering board (see Figure A-1). The following components are required for flawless operation of this microcontroller:

- Filtering ceramic capacitors C1–C7 and C8–C11
- External reset filter C13 and R1
- 32.768 kHz crystal Y1

An indispensable part of the power meter is the Human Machine Interface (HMI) consisting of an LCD (DS300) and user push-button (SW371). The charge pump for the LCD is part of the MCU and it requires four ceramic capacitors (C8–C11) on the board. Two connectors (J361 and J362) are also populated to interface the terminal cover and the main cover switches to the MCU tamper detection circuit. Connector J1 is the SWD interface for MCU programming.

CAUTION

The debug interface (J1) is not isolated from the mains supply. Use only galvanically isolated debug probes for programming the MCU when the power meter is supplied from the mains supply.

4.2.2 Output LEDs

The microcontroller uses two GPIO pins or two timer channels to control the calibration LEDs (D351 and D352). The timers' outputs are routed to the respective device pins (QT2 and QT3). The LED's drive method is optional because the hardware supports both connections. The timer LED's drive method is usually chosen to produce a low-jitter and high dynamic range pulse output waveform; the method for low-jitter pulse output generation using software and timer is being patented.

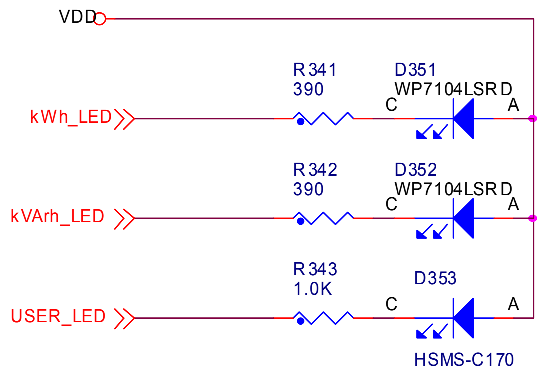

Figure 3. Output LEDs control

The user LED (D343) is driven by software through the GPIO output pin (PTD6). It blinks when the power meter enters the calibration mode, and turns solid after the power meter is calibrated and is operating normally.

4.2.3 Isolated open-collector pulse output interface

Figure 4 shows the schematic diagram of the open collector pulse output. This may be used for switching loads with a continuous current as high as 50 mA and with a collector-to-emitter voltage of up to 70 V. The interface is controlled through the GPIO (PTF0) pin of the microcontroller, and hence it may be controlled by a variety of internal signals, for example, the timer channels generate the pulse outputs. The isolated open-collector pulse output interface is accessible on connector J302.

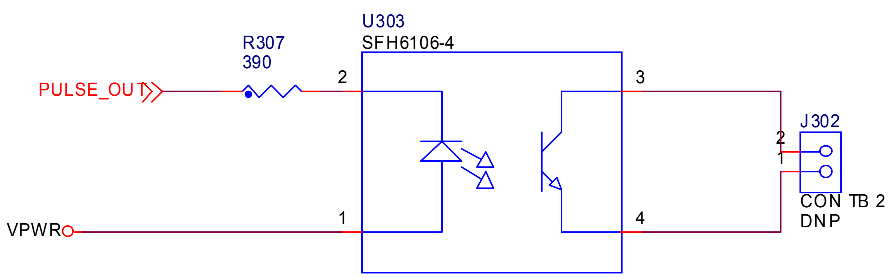

Figure 4. Open-collector pulse output control

The PTF0 pin also checks whether the VPWR is present. This use case is of PTF0 using the input mode.

4.2.4 IR interface (IEC1107)

The power meter has a galvanically isolated optical communication port, as per IEC 1107 / ANSI / PACT, so that it can be easily connected to a hand-held common meter reading instrument for data exchange. The IR interface is driven by UART3. The UART3 pins are shared with the isolated RS232 interface. IR interface selection is populated by R312 and R314. The IR interface schematic is shown in Figure 5.

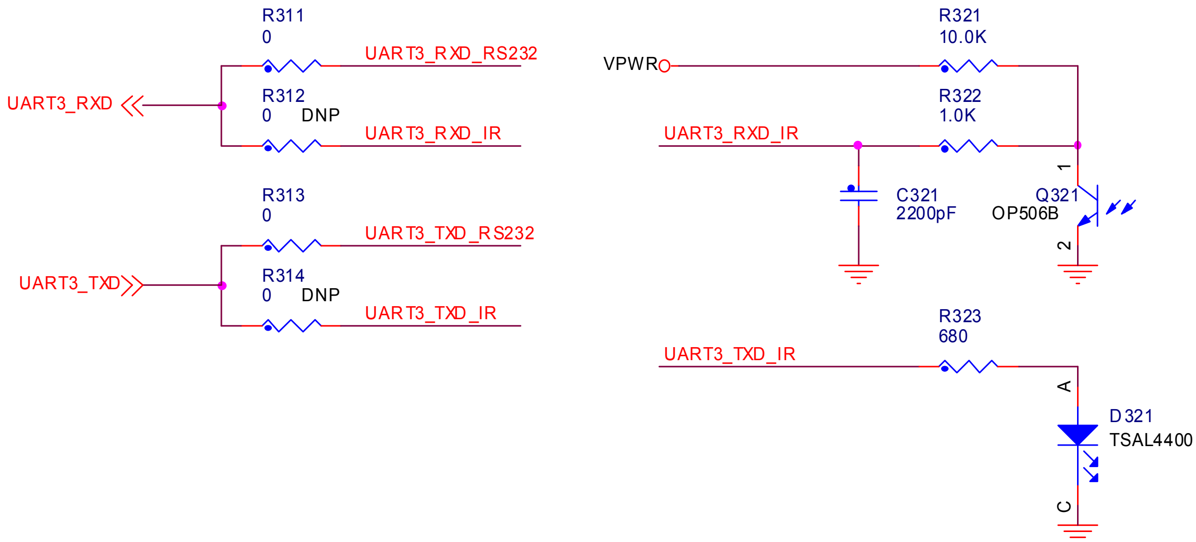

Figure 5. IR control

4.2.5 Isolated RS232 interface

This communication interface is used primarily for real-time visualization using FreeMASTER [5]. The communication is driven by the UART3 module of the microcontroller. Communication is optically isolated through the optocouplers U301 and U302. In addition to the RXD and TXD communication signals, the interface implements two additional control signals, RTS and DTR. These signals are typically used for transmission control, however, this function is not used within this reference design. Because there is a fixed voltage level on the control lines generated by the PC, the Isolated RS232 interface is used to supply the secondary side of the U4 and the primary side of the U3 optocouplers. The communication interface, including the D301–D302, C301, R305, and R306 components, that are required to supply the optocouplers from the transition control signals, is shown in Figure 6.

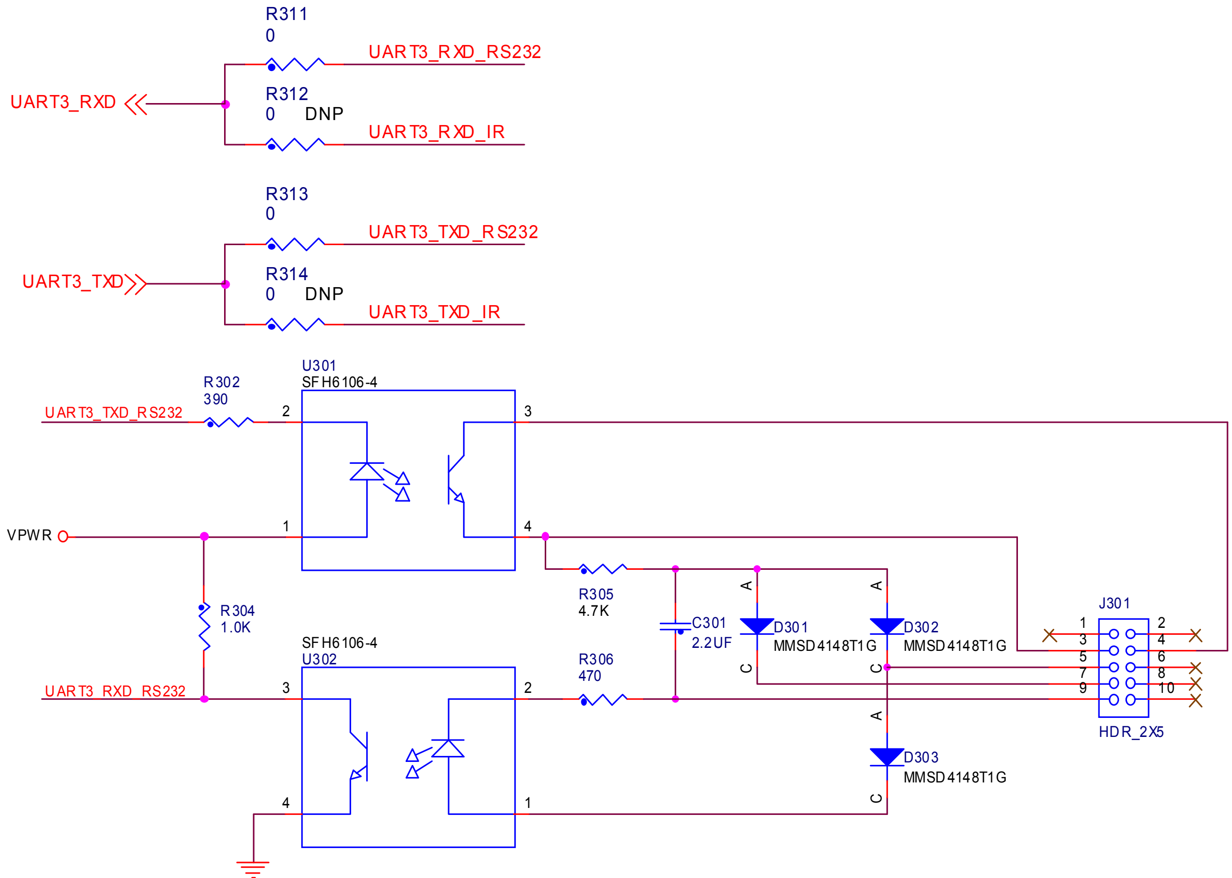

Figure 6. RS232 control

The UART3 pins are shared with the Isolated RS232 interface. The Isolated RS232 interface selection must be populated by R311 and R313.

4.2.6 MAG3110 3-axis magnetometer

This sensor is optional and can be used for advanced tamper detection for current transformers. In the schematic diagram, the MAG3110 3-axis magnetometer is marked as U381 (see Figure 7). The magnetometer communicates with the microcontroller through the I2C1 data lines; therefore, the external pull-ups R3 and R4 on the SCL and SDA lines are required.

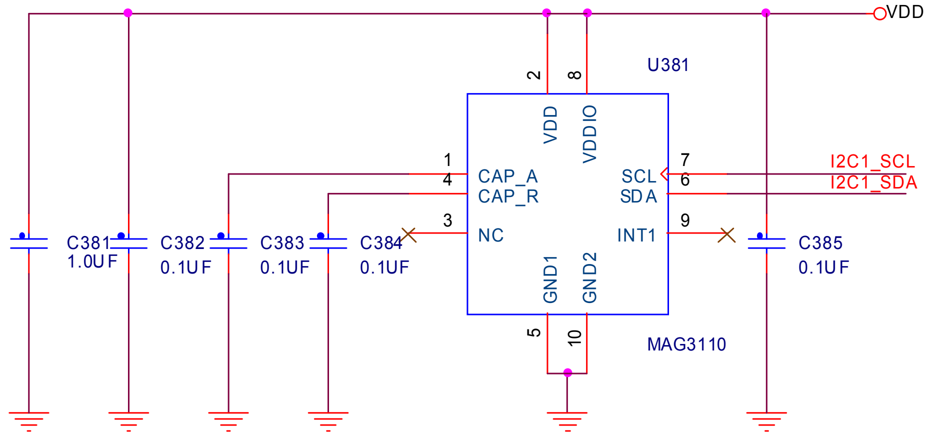

Figure 7. MAG3110 sensor control

4.2.7 4 KB I^{2}C EEPROM

The 32 KB I^{2}C EEPROM U391 (AT24C32D) can be used for parameter storage. The microcontroller uses I2C1 for communication with the EEPROM. The I2C1 is shared with a magnetometer sensor.

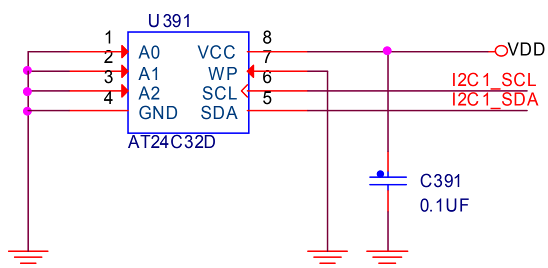

Figure 8. 32 KB I^{2}C EEPROM control

4.2.8 RF MC1323x-IPB interfaces

The RF MC1323x-IPB interface (J350) is intended to interface the power meter with the Freescale ZigBee small-factor modules. This interface comprises connections to UART1 and the I2C1 peripherals, as well as to several I/O lines for module reset, handshaking, and control.

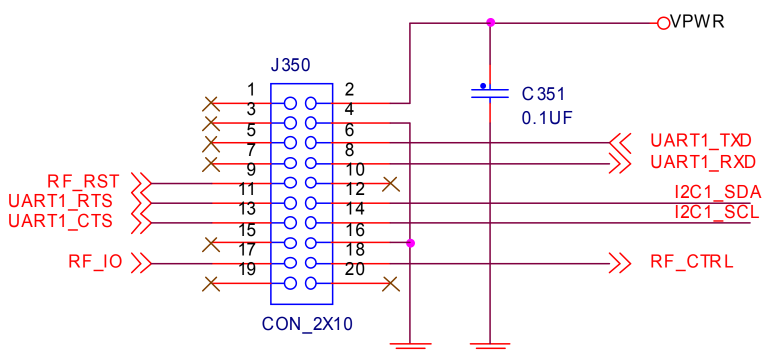

Figure 9. RF MC1323x-IPB interfaces control

NOTE

RF MC1323x-IPB interfaces are designed to supply the external communication modules from the regulated output voltage VPWR. Therefore, use only communication modules with a supply voltage of 3.6 V and a continuous current of up to 60 mA.

4.3 Analog circuits

Excellent performance of the metering AFE, including external analog signal conditioning, is crucial for a power meter application. The most critical performance aspect is the phase current measurement due to the high dynamic range of the current measurement (800:1 and higher) and the relatively low input signal range (from hundredths of millivolts up to volts). All analog circuits are described in the following subsections.

4.3.1 Phase current measurement

The Kinetis-M three-phase power meter reference design is optimized for current transformers, but a variety of Rogowski coils can also be used. The only limitations are that the sensor output signal range must be within ±0.5 V peak and within the dimensions of the enclosure. The interface of a current sensor to the MKM34Z128MCLL5 device is very straightforward; a burden resistor for current-to-voltage conversion and anti-aliasing low-pass filters attenuating signals with frequencies greater than the Nyquist frequency must be populated on the board (see Figure 10). The cut-off frequency of the analog filters implemented on the board is 72.3 kHz; such a filter has an attenuation of -33.3 dB at Nyquist frequency of 3.072 MHz. The burden resistor is a composite formed by two resistors with the same value. The middle point of this is connected to ground.

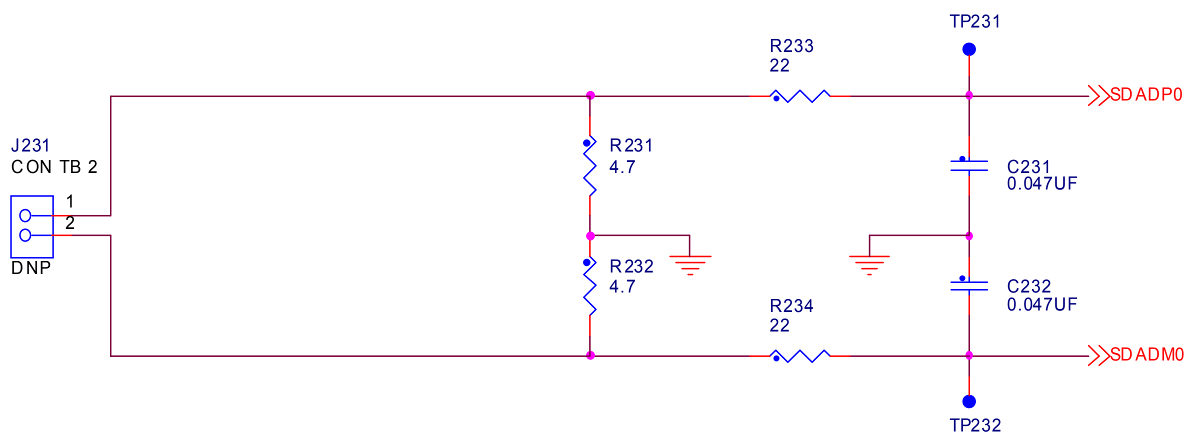

Figure 10. Phase current signal conditioning circuit

Each of the three (or four) current channels use the same topology.

Table 2. Current signal components

Channel	Component
1	R231, R232, R233, R234, C231, C232 and J231
2	R241, R242, R243, R244, C241, C242 and J241
3	R251, R252, R253, R254, C251, C252 and J251
4	R261, R262, R263, R264, C261, C262 and J261 neutral current measurement

4.3.2 Phase voltage measurement

A simple voltage divider is used for the line voltage measurement. In a practical implementation, it is better to design this divider from several resistors connected serially due to the power dissipation. One half of this total resistor consists of R201, R202, R203, and R204, the second half consists of resistor R205 (channel 1), R211, R212, R213, R214 and R215 (channel 2) and R221, R222, R223, R224 and R2025 (channel 3). The resistor values were selected to scale down the 325.26 V peak input line voltage to the 0.52272 V peak input signal range of the 16-bit SAR ADC. The SAR ADC input is unipolar different to bipolar SD ADC inputs, so for this case an external bias voltage must be added. External bias voltage is derived from the on-chip reference voltage (taken from the VREF pin) and the value is the half of reference voltage. The bias voltage is connected to the voltage diver through the *second half resistors* R205, R215 and R225. The voltage drop and power dissipation on each of the MELF02041 resistors are below 57.5 V and 22 mW, respectively. The anti-aliasing low-pass filter of the phase voltage measurement circuit is set to a cut-off frequency of 27.22 kHz. Such an anti-aliasing filter has an attenuation of -41.0 dB at Nyquist frequency of 3.072 MHz.

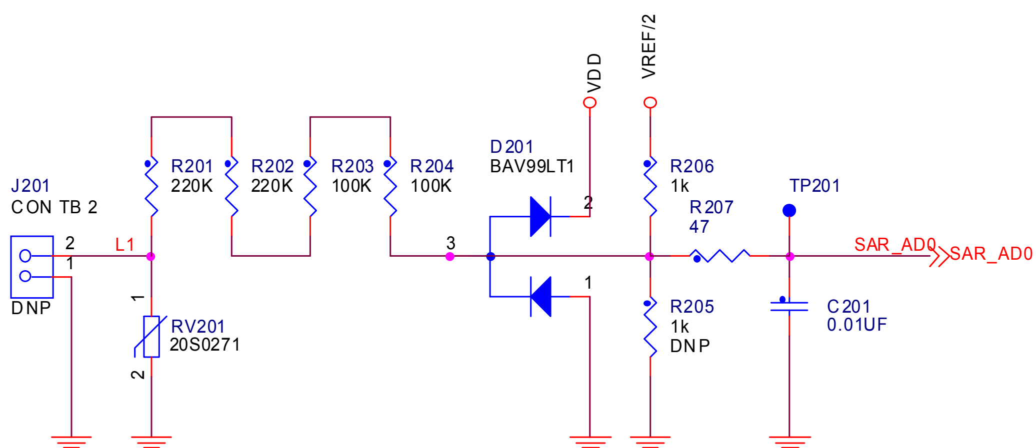

Figure 11. Phase voltage signal conditioning circuit

4.3.3 Half reference voltage level generator

The reference voltage half value is generated from internal voltage reference. Reference voltage 1.2V is available on the VREF pin. This voltage is simply divided by two through the voltage divider R281 and R282. The half reference voltage is connected to the unity gain buffer where the optional filter capacity C282 is added. The unity gain buffer is a low cost and simple instrumentation amplifier U281 LMV321.

A unity gain buffer is placed for phase voltage channel decoupling, therefore, the buffer works like an impedance transformer. Figure 12 shows the schematic diagram of the half reference voltage generator.

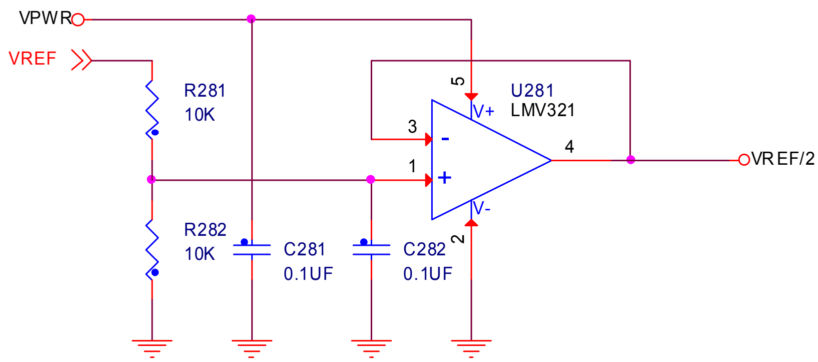

Figure 12. Half reference voltage level generator

4.3.4 Zero crossing circuits connection

The low level phase voltage from the voltage dividers is connected to the analog comparator inputs through R271, R272 and R273. Optional capacitors C271, C272, and C273 are added to the signal path for additional filtering.

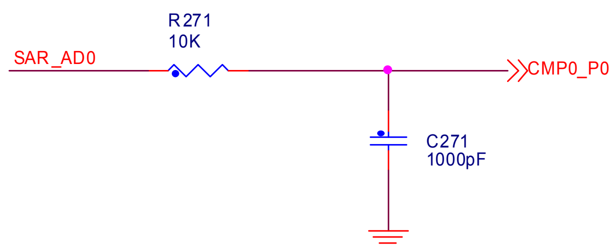

Figure 13. Zero crossing circuits

5 Software design

This section describes the software application of the Kinetis-M three-phase power meter reference design. The software application consists of measurement, calculation, calibration, user interface, and communication tasks.

5.1 Block diagram

The application software has been written in C-language and compiled using the IAR Embedded Workbench for ARM (version 6.60.0) with full optimization for execution speed. The software application is based on the Kinetis-M bare-metal software drivers [7] and the filter-based metering algorithm library [2].

The software features are as follows:

- Transitions between operating modes,
- Performs a power meter calibration after first start-up,

- Calculates all metering quantities,
- Controls the active and reactive energies pulse outputs,
- Runs the HMI (LCD display and button),
- Stores and retrieves parameters from the NVMs,
- Enables application remote monitoring and control.

The application monitoring and control is performed through FreeMASTER.

Figure 14 shows the software architecture of the power meter including interactions of the software peripheral drivers and application libraries with the application kernel.

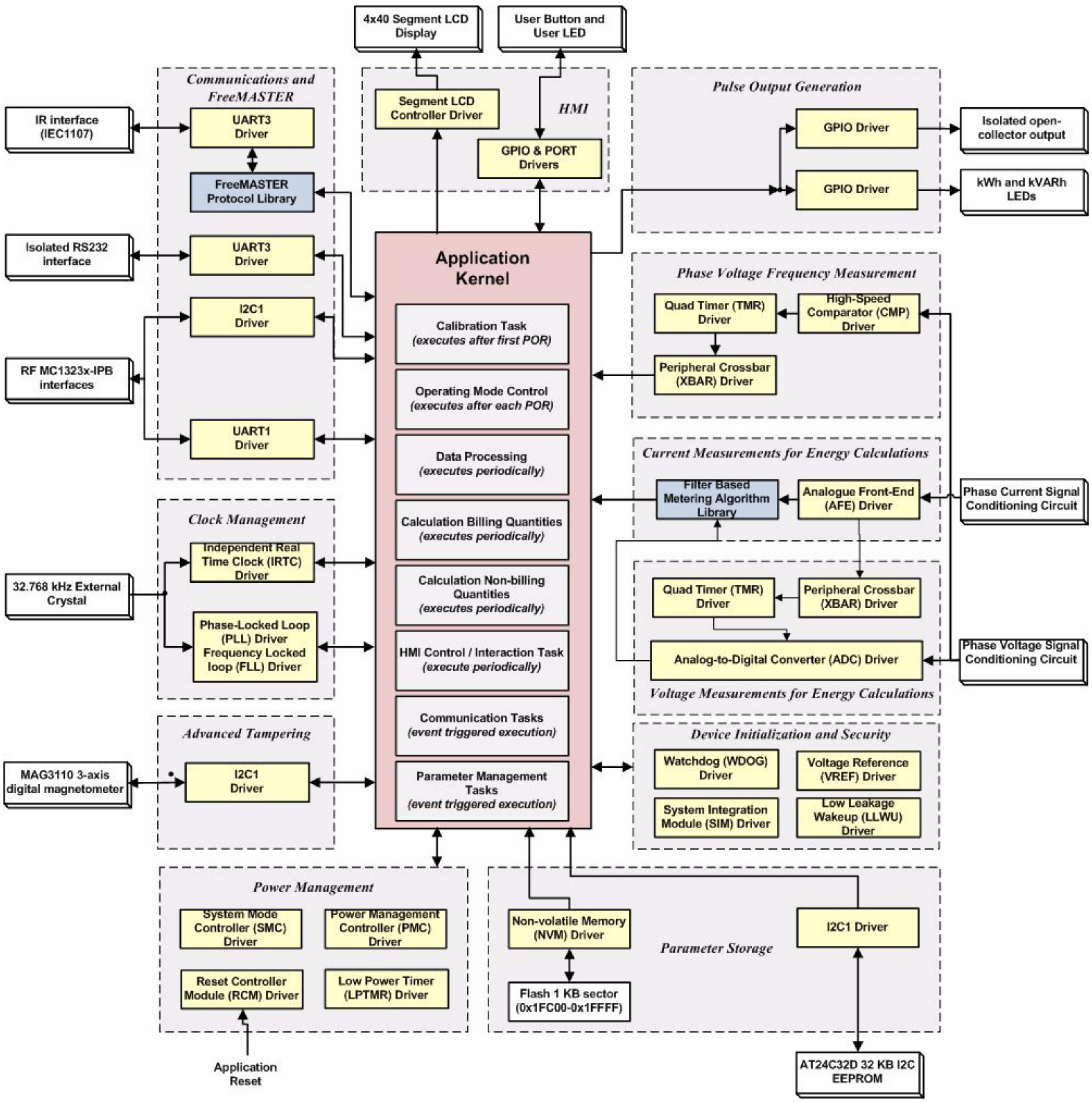

Figure 14. Software architecture

All tasks executed by the Kinetis-M one-phase power meter software are briefly explained in the following subsections.

5.2 Software tasks

The software tasks are part of the application kernel. They're driven by events (interrupts) generated either by the on-chip peripherals or the application kernel. The list of all tasks, trigger events, and calling periods are summarized in Table 3.

Table 3. List of software tasks

Task name	Description	Source file(s)	Function name	Trigger source	Interrupt priority	Calling period
Power meter calibration	Performs power meter calibration and stores calibration parameters	config.c config.h	CONFIG_UpdateOffsets CONFIG_CalcCalibData	device reset	—	after first device reset, and a special load point is applied by the test equipment
Operating mode control	Controls transitioning between power meter operating modes	mk341ph.c	main	device reset	—	after every device reset
Data processing	Reads digital values from the AFE, SAR, and performs scaling	main.c	afech0_callback afech1_callback afech2_callback	AFE CH0 AFE CH1 AFE CH2 conversion complete interrupt	Level 0 (highest)	periodic 166.6 µs
Calculation; billing quantities	Calculates billing and non-billing quantities	—	auxcalc_callback	—	Level 1	periodic 833.3 µs
Calculation; non-billing quantities	—	—	—	—	—	—
HMI control	Updates LCD with new values and transitions to new LCD screen after user button is pressed	—	display_callback	—	Level 3 (lowest)	periodic 250 ms
FreeMASTER communication	Application monitoring and control	freemaster_*.c freemaster_*.h	FMSTR_Init	UART3 Rx/Tx interrupts	Level 2	asynchronous
	Recorder	—	FMSTR_Recorder	AFE CH2 conversion complete interrupt	Level 1	periodic 833.3 µs
Parameter management	Writes/reads parameters from the Flash	config.c config.h	CONFIG_SaveFlash CONFIG_ReadFlash	after successful calibration or controlled by user	—	—

5.2.1 Power meter calibration

The power meter is calibrated with the help of test equipment. The calibration task runs whenever a non-calibrated power meter is connected to the mains. The running calibration task measures the phase voltage and phase current signals generated by the test equipment; it scans for a 230 V phase voltage and 5.0 A phase current waveforms with a 45 degree phase shift. If the calibration task detects such a load point, then, after 35 s of collecting data, the calibration task calculates the calibration offsets, gains, and phase shift using the following formulas:

$$gain_u = 230/URMS \quad \textbf{Eqn. 11}$$

$$gain_I = 5.0/IRMS \quad \textbf{Eqn. 12}$$

$$\theta_{comp} = 45° - \tan^{-1}\left(\frac{Q}{R}\right) \quad \textbf{Eqn. 13}$$

where $gain_u$, $gain_I$ are calibration gains, θ_{comp}, is the calculated phase shift caused by current transformers, and *URMS*, *IRMS*, *Q*, *P* are quantities measured by the non-calibrated meter.

Contrary to the gain and phase shift calculations that are based on RMS values, the calibration offsets are calculated from instantaneous measured samples, as follows:

$$offset_u = \frac{max\left(\sum_{k=0}^{n} u(k)\right) - min\left(\sum_{k=0}^{n} u(k)\right)}{2} \quad \textbf{Eqn. 14}$$

$$offset_I = \frac{max\left(\sum_{k=0}^{n} i(k)\right) - min\left(\sum_{k=0}^{n} i(k)\right)}{2} \quad \textbf{Eqn. 15}$$

where $offset_u$, $offset_I$ are calculated calibration offsets, $u(k)$, $i(k)$ are respectively the instantaneous phase voltage and phase current samples in measurement steps k=0,1, … n.

The calibration task terminates by storing calibration gains, offsets and phase shift into the flash and by resetting the microcontroller device. The recalibration of the power meter can also be initiated from FreeMASTER.

5.2.2 Operating mode control

The transitioning of the power meter electronics between operating modes helps maintain a long battery lifetime. The power meter software application supports the following operating modes:

- Normal (electricity is supplied, causing the power meter to be fully-functional)
- Standby (electricity is disconnected, and the user navigates through menus)
- Power-down (electricity is disconnected, but there is no user interaction)

Figure 15 shows the transitioning between supported operating modes. After a battery or the main power is applied, the power meter transitions to the device reset state. If the mains have been applied, then the software application enters normal mode and all software tasks including calibration, measurements, calculations, HMI control, parameter storage, and communication are executed. In this mode, the MKM34Z128MCLL5 device operates in run mode. The system clock frequency is generated by the FLL and is 48 MHz. The power meter electronics consume 18.4 mA.

If the mains have not been applied, then the software application enters standby mode. In this mode, the power meter runs from battery. All software tasks are stopped except HMI control. In this mode, the MKM34Z128MCLL5 device executes in VLPR mode. The system clock frequency is downscaled to 125 kHz from the 4 MHz internal relaxation oscillator. Because of the slow clock frequency, the limited number of enabled on-chip peripherals, and the Flash module operating in a low-power run mode, the power consumption of the power meter electronics is 260 µA.

Finally, when the power meter runs from battery but the user does not navigate through the menus, then the software transitions automatically to the power-down mode. The MKM34Z128MCLL5 device is forced to enter VLLS2 mode, where recovery is only possible when either the user button is pressed or the mains is supplied. The power-down mode is characterized by a current consumption of 6.5 µA.

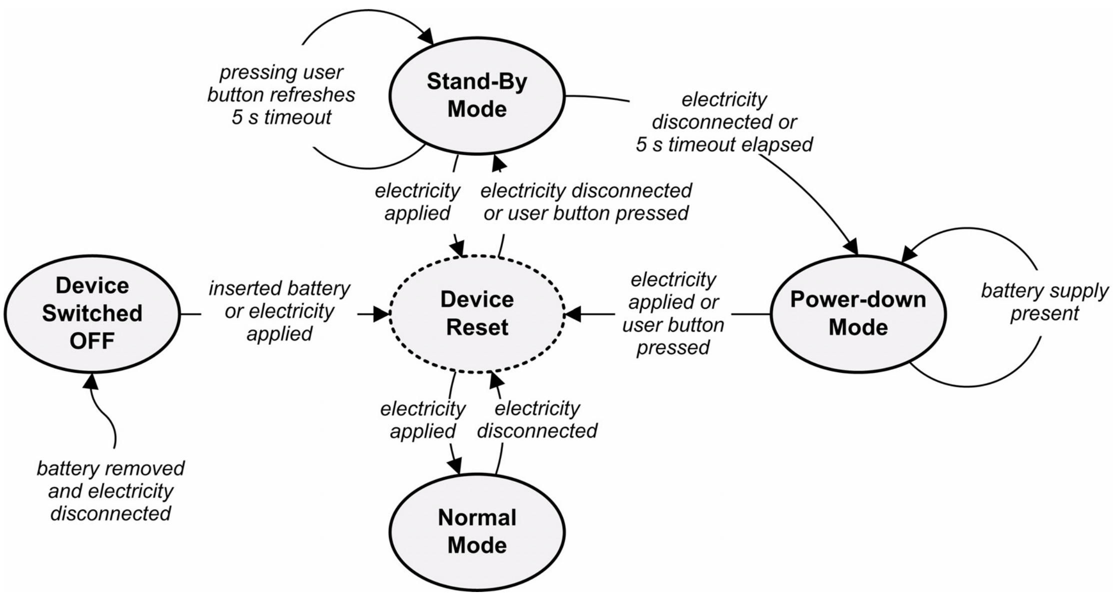

Figure 15. Operating modes

5.3 Data processing

Reading the phase voltage from the SAR ADC and phase current samples from the analog front-end (AFE) occurs periodically every 166.6 µs. This task runs on the highest priority level (Level 0) and is triggered asynchronously when the AFE result registers receive new samples. The task reads the phase voltage and phase current samples from the AFE result registers, scales the samples to the full fractional range, and writes the values to the temporary variables for use by the calculation task.

5.3.1 Data sampling

The phase voltage and phase current must be sampled at the same time, because the power calculations are defined as are the multiplication of the immediate voltage and current values in Equation 7 and Equation 8. The voltage signal is sampled by the one SAR ADC with an input multiplexor, because of this, all six signals (3x phase voltage and 3x phase current) cannot be sampled at the same time. The sampling of the different phase signals must be time shifted. This can be easily implemented by using the AFE delay start function. Each AFE channel start is delayed from the previous channel. CH0 begins conversion at the time

0 × FDL, CH1 begins conversion at the time 1 × FDL, and CH2 begins conversion at the time 2 × FDL. The FDL (Fix Delay) constant is longer than the SAR conversion time plus multiplexor switching time. The internal interconnection between AFE and SAR is implemented through the XBAR peripherals. The AFE COCO CHx (COCO—conversion complete, for continued AFE mode conversion start) is used for the hardware trigger conversion start for SAR. Typically, current sensors generate phase shift between phase voltage and phase current, because current signal is converted on the voltage signal. Voltage signal is needed for ADC. The voltage to current conversion takes time, called phase shift error. The sensor phase shift error can be compensated to add delay time between the AFE COCO signal and the SAR hardware conversion trigger. This requirement can also be resolved through the XBAR. The signal chain AFE COCO and SAR hardware trigger should be extended by adding the next block between AFE and SAR to generate the time delay. The ideal hardware resource for this task is a Quad Timer, because it can operate in One-Shot mode. The signal chain for the sensor's phase shift compensation is; AFE connected to the TMR which is connected to the SAR. AFE COCO signal begins the TMR and then TMR, after a delay, passes the signal to SAR which generates the hardware trigger signal. The three phase application uses three current sensors with different phase shift errors, for this reason, it is during the calibration process that the three compensation times for each channel are calculated.

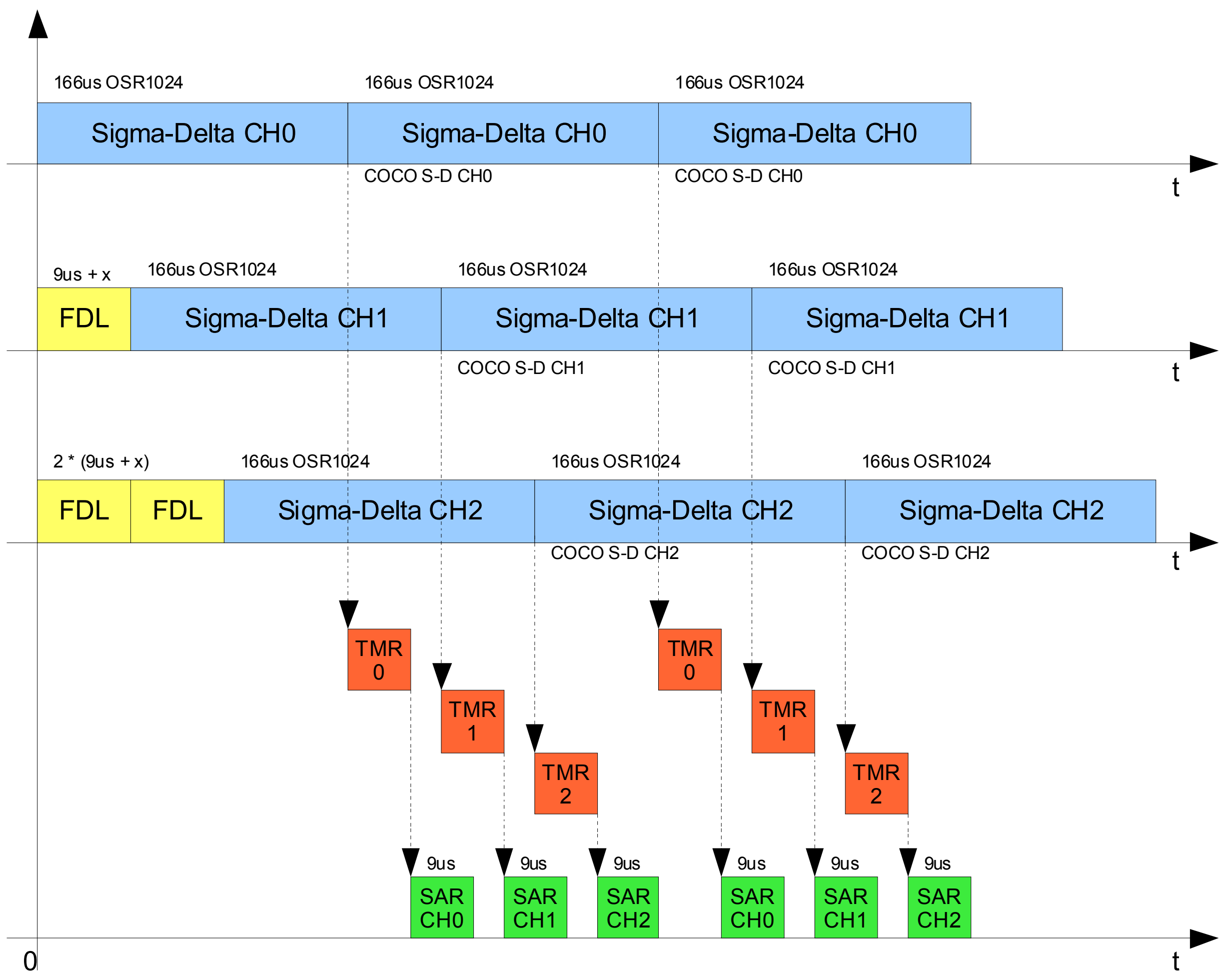

Figure 16. Three-phase sampling signal chain with HW based phase shift error compensation

The other possible method to compensate for current sensor phase shift error is a software based solution. The sample's value is scaled with respect to the phase shift error. This correction algorithm can also be implemented in the time and frequency domains.

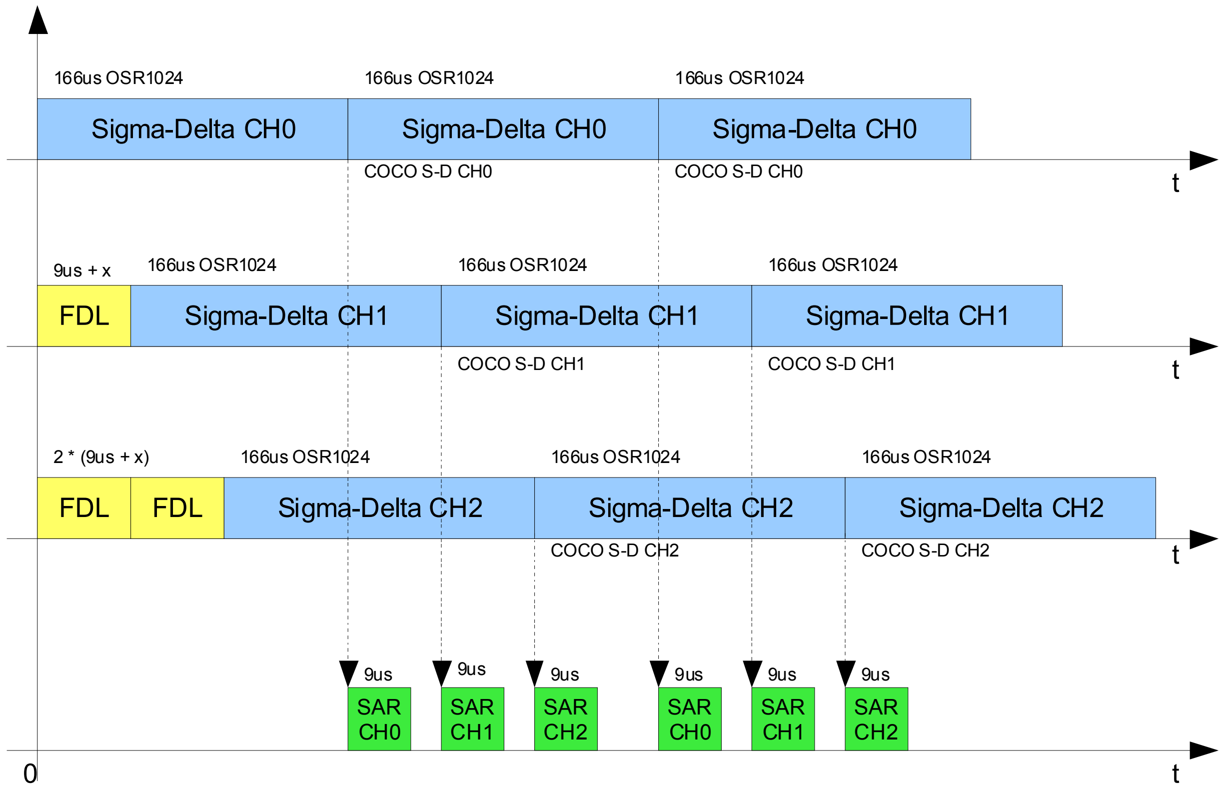

Figure 17. Two Three-phase sampling signal chain with SW based phase shift error compensation

Both methods offer advantages and disadvantages. The hardware based method uses pure sampling for the next calculation, therefore no calculation rounding error is incurred. The software based method saves the microcontroller's resources (three channels of TMR). For example, the TMRs can be used for direct drive output LEDs to produce very low jitter of the output pulses.

5.4 Calculations

The execution of the calculation task is carried out periodically every 833.3 µs. The calculation task scales the samples using calibration offsets and calibration gains obtained during the calibration phase:

$$u\_sample_{scaled} = gain_u(u\_sample - offset_u) \quad \textbf{Eqn. 16}$$

$$i\_sample_{scaled} = gain_I(i\_sample - offset_I) \quad \textbf{Eqn. 17}$$

where *u_sample* and *i_sample* are measured samples, $offset_u$, $offset_I$, $gain_u$, and $gain_I$ are calibration parameters.

The scaled samples are then used by the metering algorithm.

NOTE

We found experimentally that increasing the calculation update rate beyond 1200 Hz doesn't improve the accuracy of the measurement or calculations.

5.5 HMI control

The Human Machine Interface (HMI) control task executes in a 250 ms loop and on the lowest priority (Level 3). It reads the real-time clock, calculates the mains frequency, and formats data into a string that is displayed on the LCD. The interaction with the user is arranged through an asynchronous event, which occurs when the user button is pressed. By pressing the user button, you may scroll through menus and display all measured and calculated quantities (see Table 5).

5.6 FreeMASTER communication

FreeMASTER establishes a data exchange with the PC. The communication is fully driven by the UART3 Rx/Tx interrupts, which generate interrupt service calls with priority Level 2. The power meter acts as a slave device answering packets received from the master device (PC). The recorder function is called by the calculation task every 833.3 µs. The priority setting guarantees that data processing and calculation tasks are not impacted by the communication. For more information about using FreeMASTER, refer to Subsection 6.6-Error: Reference source not found.

5.7 Parameter management

The current software application uses the last 1024 bytes sector of the internal Flash memory of the MKM34Z128MCLL5 device for parameter storage. By default, parameters are written after a successful calibration and read following a device reset. In addition, storing and reading parameters can be initiated through FreeMASTER.

5.8 Performance

Table 4 shows the memory requirements of the Kinetis-M one-phase power meter software application[1].

Table 4. Memory requirements

Function	Description	Flash size [KB]	RAM size [KB]
Application framework	Complete application without the metering library and FreeMASTER	21.6	0.3
Filter-based metering algorithm library	Filter-based metering algorithm library	8.3	2.8
FreeMASTER	FreeMASTER protocol and serial communication driver	4.1	2.2
Total:		34.0	5.3

1. The application is compiled using the IAR Embedded Workbench for ARM (version 6.60) with full optimization for execution speed.

The software application reserves the 4.0 KB RAM for the FreeMASTER recorder. If the recorder is not required, or a fewer number of variables will be recorded, you may reduce the size of this buffer by modifying the FMSTR_REC_BUFF_SIZE constant (refer to the freemaster_cfg.h header file, line 72).

The system clock for AFE is generated by the PLL. In normal operating mode, the PLL multiplies the clock of an external 32.768 kHz crystal by a factor of 375, hence generating a low-jitter clock with a frequency of 12.288 MHz.

NOTE

The filter-based metering algorithm configuration tool estimates the minimum system clock frequency for the ARM Cortex-M0+ core to calculate billing and non-billing quantities with an update rate of 1200 Hz to approximately 8.4 MHz for one phase calculation. As shown in Figure 18, by slowing down the update rate of the non-billing calculations from 1200 to 600 Hz and further reducing the Hilbert-filter length from 49 to 39-taps, the required performance will eventually decrease by 32.14% to 5.7 MHz for one-phase calculation.

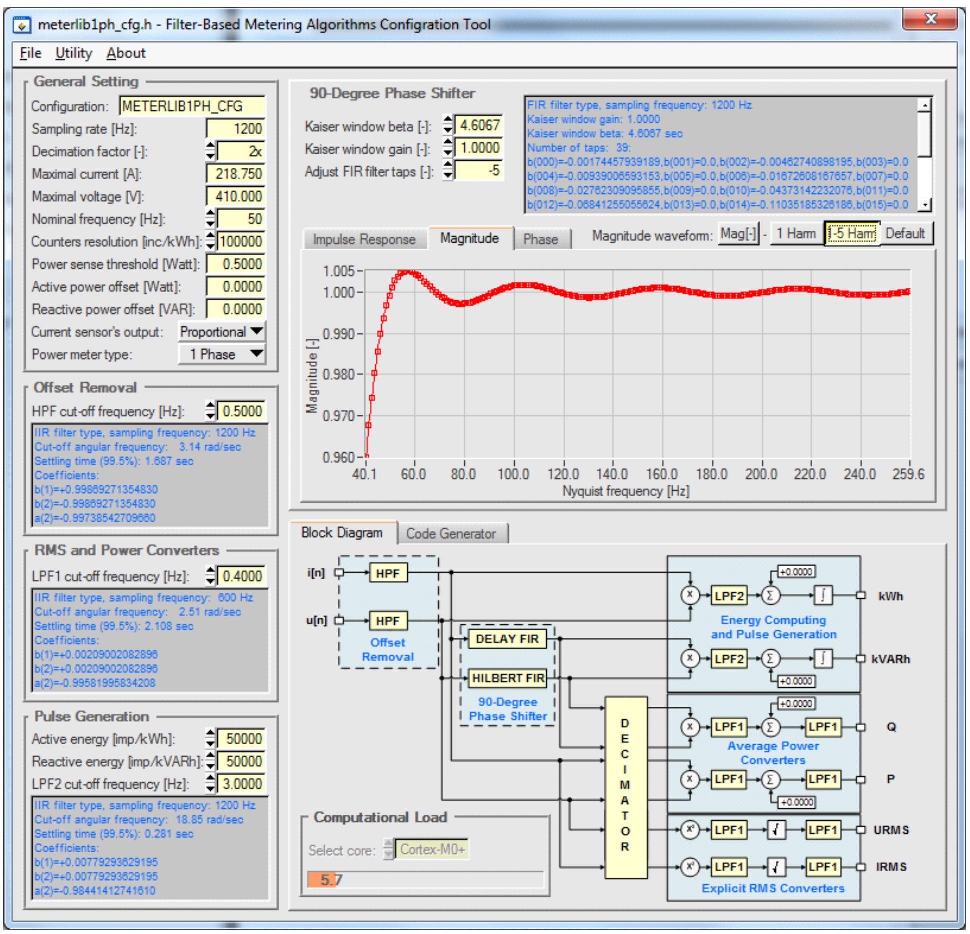

Figure 18. Minimum system clock requirements for the filter-based metering algorithm

6 Application set-up

Figure 19 shows the wiring diagram of the Kinetis-M three-phase power meter.

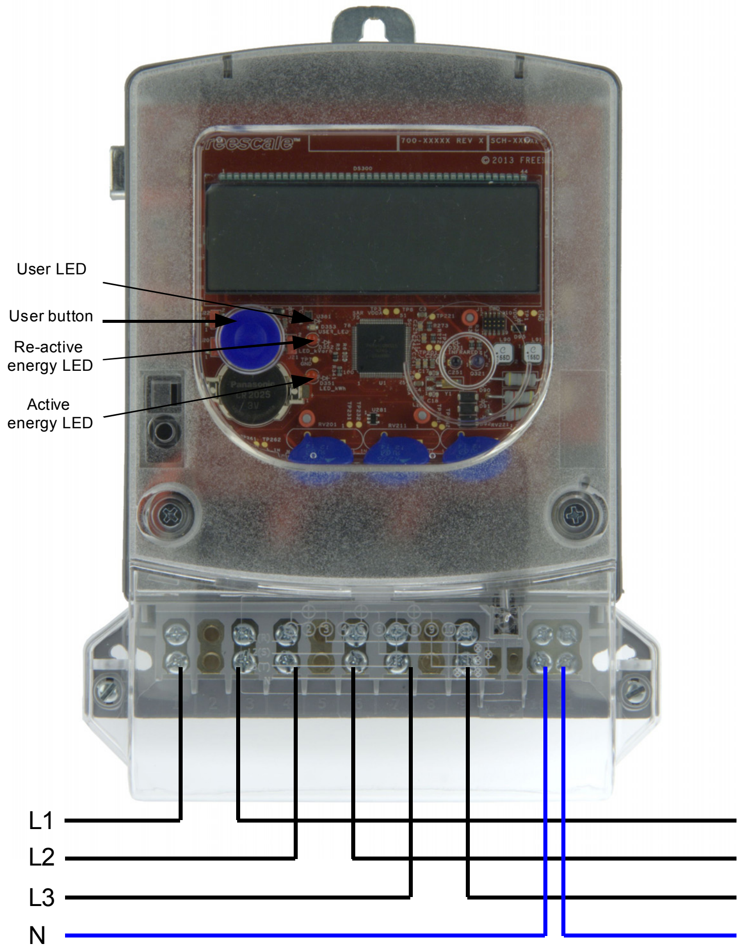

Figure 19. Kinetis-M Three-phase power meter – wiring diagram

Among the main capabilities of the power meter, is registering the active and reactive energy consumed by an external load. After connecting the power meter to the mains, or when you press the user button, the power meter transitions from the power-down mode to either the normal mode or standby mode, respectively. In normal and standby modes, the LCD is turned on and shows the last quantity. The user can navigate through the menus and display other quantities by pressing the user button. All configuration and informative quantities accessible through the LCD are summarized in Table 5.

Table 5. Quantities shown on the LCD

Value	Units	Format	OBIS Code
Date	year, month, day	YYYY:MM:DD	0.9.2
Time	hour, min, sec	HH:MM:SS	0.9.1
Line voltage; L1, L2, L3	V_{RMS}	#.# V	—
Line current; L1, L2, L3	I_{RMS}	#.### A	—

Table 5. Quantities shown on the LCD (continued)

Value	Units	Format	OBIS Code
Signed active power; L1, L2, L3	W	#.### W (+ forward, - reverse)	1.6.0
Signed reactive power; L1, L2, L3	VAr	#.### VAr (+ lag, - lead)	—
Apparent power: L1, L2, L3	VA	#.### VA	—
Signed active energy	kWh	#.### kWh (+ import, - export)	1.9.0
Signed reactive energy	kVArh	#.### kVArh (+ import, - export)	—
Frequency	Hz	##.# Hz	—
Software revision-product serial number	—	#.#.# - ### (revision – meter serial number)	—
Class according to EN50470-3	—	C # #-###A (example C 5-120A)	—

7 FreeMASTER visualization

The FreeMASTER data visualization and calibration software is used for data exchange [5]. The FreeMASTER software running on a PC communicates with the Kinetis-M three-phase power meter over an isolated RS232 interface. The communication is interrupt driven and is active when the power meter is powered from the mains. The FreeMASTER software enables remote visualization, parameterization, and calibration of the power meter. It runs visualization scripts which are embedded into a FreeMASTER project file.

Before running a visualization script, the FreeMASTER software must be installed on your PC. After installation, a visualization script may be started by double-clicking on the monitor.pmp file. Once started, the visualization script shown in Figure 20 will appear on your computer screen.

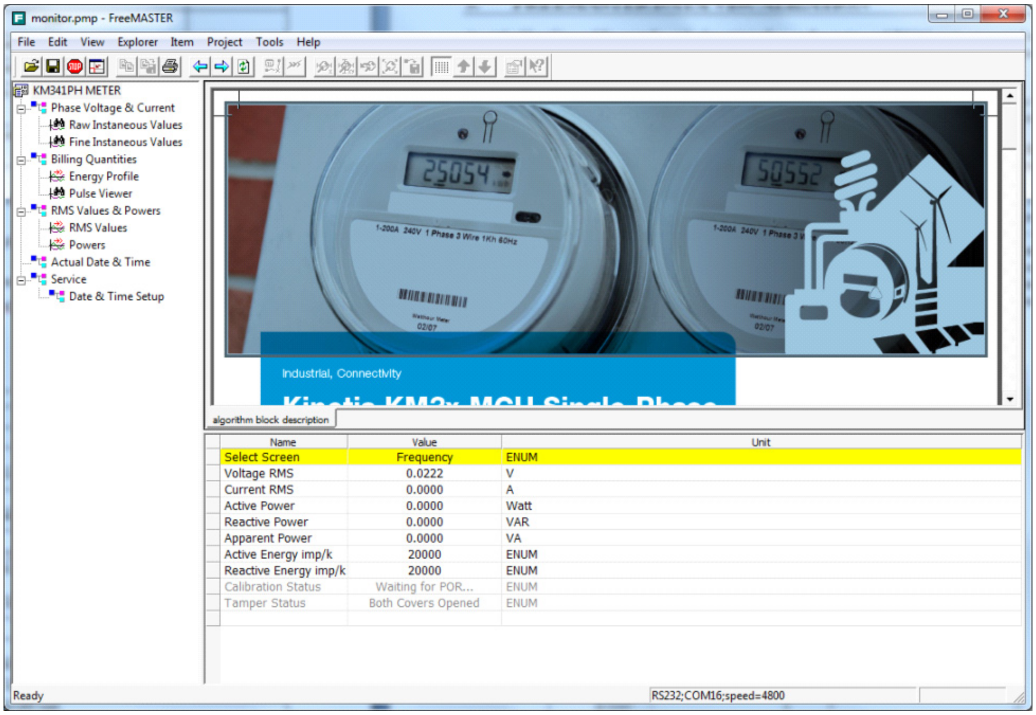

Figure 20. FreeMASTER visualization software

Next, you should set the proper serial communication port and communication speed in the Project/Option menu (see Figure 21). After communication parameters are properly set and the *Stop* button is released, the communication is initiated. A message on the status bar signals the communication parameters and successful data exchange.

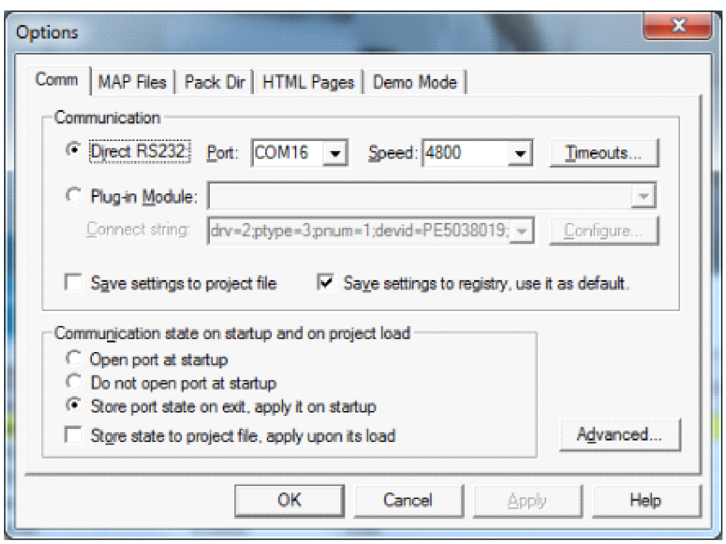

Figure 21. Communication port setting

Now you can see the measured phase voltages, phase current, active, reactive, and apparent powers, pulse numbers, and additional status information in FreeMASTER. You may also visualize some variables in a graphical representation by selecting the respective scope or recorder item from the tree.

The visualization script enables you to monitor and parameterize the majority of the power meter features. To eliminate inappropriate and unwanted changes, some key parameters are protected by a 5-digit system password. These key parameters are as follows:

- Set Calendar
- Set Imp/kWh
- Set Imp/kVARh
- Recalibration

All the remaining parameters and commands can be executed anytime, without the need for entering the system password:

- LCD Screen Select
- Software Reset
- Clear Energy Counters
- Clear Tampers

Most of all, FreeMASTER will be used for monitoring the power meter operation and analyzing the phase voltages and phase currents waveforms in real-time. The visualization script file contains the following visualization objects:

- Recorders (833 µs update rate, the number of samples is optional but limited to 4096 bytes)
  - — Raw instantaneous phase voltage and current samples
  - — High-pass filtered instantaneous phase voltage and current samples
- Scopes (10 ms update rate, the number of samples unlimited)
  - — Energy profile (kWh and kVARh counters with resolution 10-5)
  - — RMS voltage, RMS current, active power, reactive power, and apparent power.
  - — Power meter's actual date and time
  - — Mains frequency
- Variables and Enumerations (shown in text form)
  - — Password set-up
  - — Tamper status
  - — Remote command

Figure 22 shows the high-pass filtered phase voltage and phase current waveforms with shorted input terminals. The waveform samples are captured every 833 µs and stored in a dedicated buffer of the MKM34Z128MCLL5 device. When the buffer is full, the data is sent to the PC via the optical port interface. The FreeMASTER visualization tool then displays the data on the PC screen.

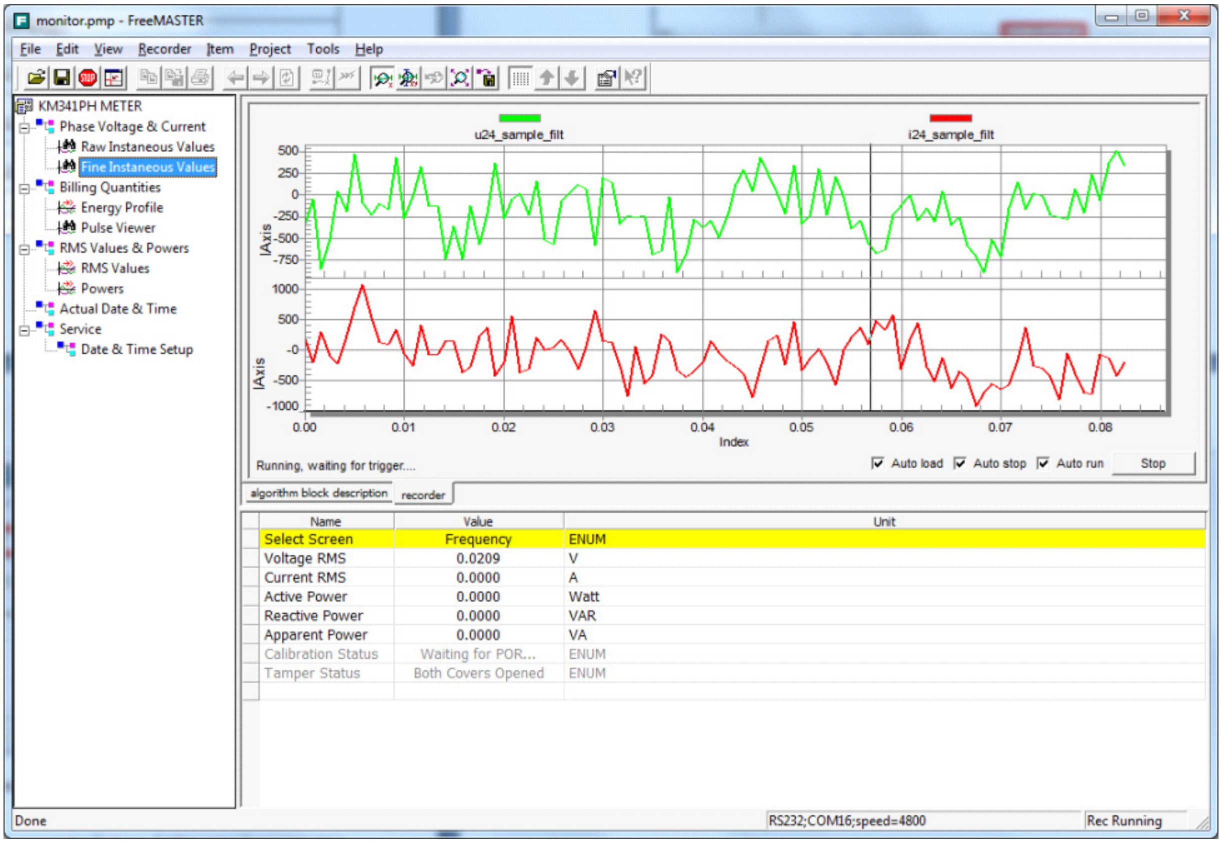

Figure 22. Recorded phase voltage and phase current waveforms

Advanced users benefit from FreeMASTER's built-in, active-x interface that serves to exchange data with other signal processing and programming tools, such as Matlab, Excel, LabView, and LabWindows.

8 Accuracy and performance

As already indicated, the Kinetis-M three-phase reference designs have been calibrated using the test equipment ELMA8303 [1]. All power meters were tested according to the EN50470-1 and EN50470-3 European standards for electronic meters of active energy classes B and C, the IEC 62053-21 and IEC 62052-11 international standards for electronic meters of active energy classes 2 and 1, and the IEC 62053-23 international standard for static meters of reactive energy classes 2 and 3.

During accuracy calibration and testing, the power meter measured electrical quantities generated by the test bench, calculated active and reactive energies, and generated pulses on the output LEDs; each generated pulse was equal to the active and reactive energy amount kWh (kVARh)/imp3. The deviations between pulses generated by the power meter and reference pulses generated by test equipment defined the measurement accuracy.

8.1 Room temperature accuracy testing

Figure 23 shows the calibration protocol of the power meter S/N: 35. The protocol indicates the results of the power meter calibration performed at 25°C. The accuracy and repeatability of the measurement for various phase currents and angles between phase current and phase voltage are shown in these graphs.

The first graph (on the top) indicates the accuracy of the active and reactive energy measurement after calibration. The x-axis shows variation of the phase current, and the y-axis denotes the average accuracy of the power meter computed from five successive measurements; the gray lines define the Class C (EN50470-3) accuracy margins.

The second graph (on the bottom) shows the measurement repeatability; i.e. standard deviation of error of the measurements at a specific load point. Similarly to the power meter accuracy, the standard deviation has also been computed from five successive measurements.

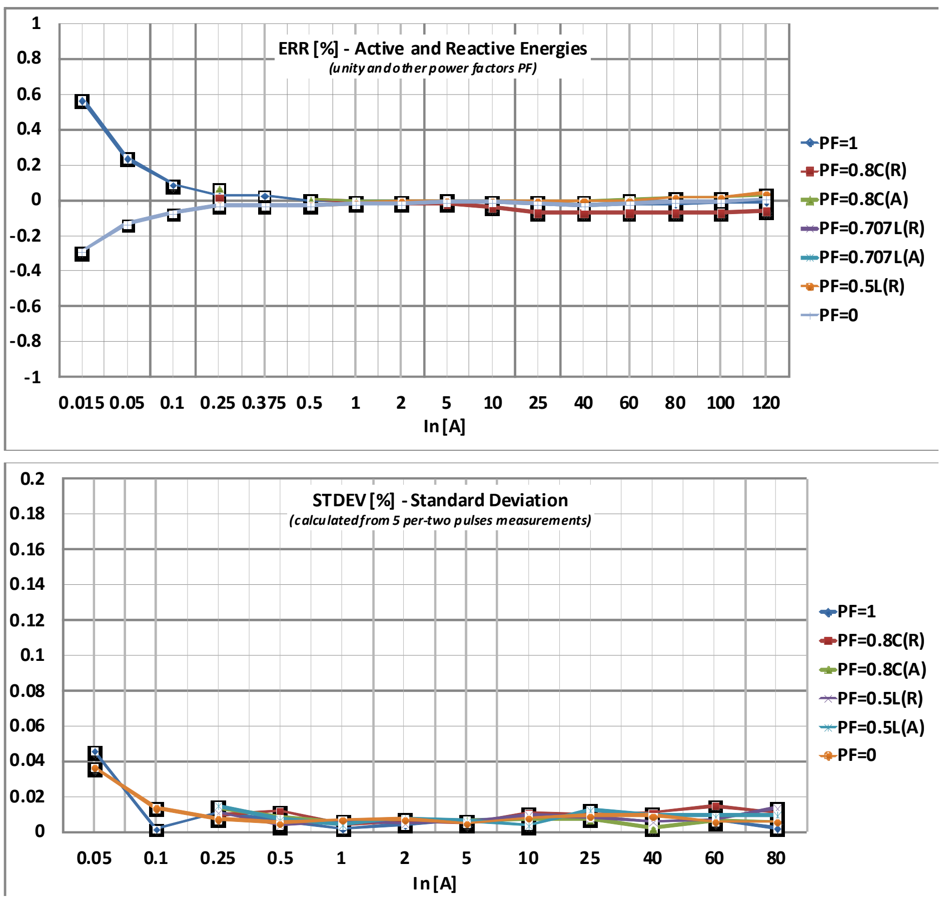

Figure 23. Calibration protocol at 25°C

By analyzing the protocols of several Kinetis-M three-phase power meters, it can be said that this equipment measures active and reactive energies at all power factors, at 25°C ambient temperature, and in the current range 0.25–120 A4, more or less with an accuracy range ±0.25%.

9 Summary

This design reference manual describes a solution for a three-phase electronic power meter based on the MKM34Z128CLL5 microcontroller.

Freescale Semiconductor offers filter and FFT based metering algorithms for use in customer applications. The former calculates metering quantities in the time domain, the latter in the frequency domain. This reference manual explains the basic theory of power metering and lists all the equations to be calculated by the power meter.

The hardware platform of the power meter is algorithm independent, so application firmware can leverage any type of metering algorithm based on customer preference. To extend the power meter uses, the hardware platform comprises a 32 KB I^2C EEPROM for data storage, an MAG3110 3-axis multifunction digital magnetometer for enhanced tampering, and RF MC1323x-IPB interfaces for AMR communication and monitoring.

The application software has been written in C-language and compiled using the IAR Embedded Workbench for ARM (version 6.60), with full optimization for the execution speed. It is based on the Kinetis-M bare-metal software drivers [7]. The application firmware automatically calibrates the power meter, calculates all metering quantities, controls active and reactive energy pulse outputs, runs the HMI (LCD and button), stores and retrieves parameters from Flash memory, and enables monitoring of the application, including recording selected waveforms through FreeMASTER. An application software of such complexity requires 29.9 KB of flash and 6.6 KB of RAM. The system clock frequency of the MKM34Z128CLL5 device must be 48 MHz to calculate all metering quantities with an update rate of 1200 Hz.

The power meter is designed to transition between three operating modes. It runs in normal mode when it is powered from the mains. In this mode, meter electronics consume 18.4 mA. The second mode, standby mode, is entered when the power meter runs from the battery and the user navigates through the menus. In this particular mode, the 3.6V Li-SOCI2 (1.2Ah) battery is discharged by 260 µA, resulting in 4,100 hours of operation (0.47 year battery lifetime). Finally, when the power meter runs from the battery but no interaction with the user occurs, the power meter electronics automatically transition to the power-down mode. The power-down mode is characterized by a current consumption as low as 6.5 µA, which results in 143,000 hours of operation (16.3 year battery lifetime).

The application software enables you to monitor measured and calculated quantities through the FreeMASTER application running on your PC. All internal static and global variables can be monitored and modified using FreeMASTER. In addition, some variables, for example phase voltages and phase currents, can be recorded in the RAM of the MKM34Z128CLL5 device and sent to the PC afterwards. This power meter capability helps you to understand the measurement process.

The Kinetis-M three-phase power meters were tested according to the EN50470-1 and EN50470-3 European standards for electronic meters of active energy classes B and C, the IEC 62053-21 and IEC 62052-11 international standards for electronic meters of active energy classes 2 and 1, and the IEC 62053-23 international standard for static meters of reactive energy classes 2 and 3. After analyzing several power meters, we can state that this equipment measures active and reactive energies at all power factors, a 25°C ambient temperature, and in the current range 0.25–120 A, more or less with an accuracy range ±0.25%.

In summary, the capabilities of the Kinetis-M three-phase power meter fulfill the most demanding European and international standards for electronic meters.

10 References

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5. *FreeMASTER Data Visualization and Calibration Software*, Freescale Semiconductor, www.freescale.com/webapp/ sps/site/prod_summary.jsp?code=FREEMASTER

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7. *Kinetis M Bare-metal Software Drivers*, from Freescale Semiconductor, September 2013, www.freescale.com/webapp/Download?colCode=KMSWDRV_SBCH

11 Revision history

Revision 0 is the initial release of this document.

Appendix A Board electronics

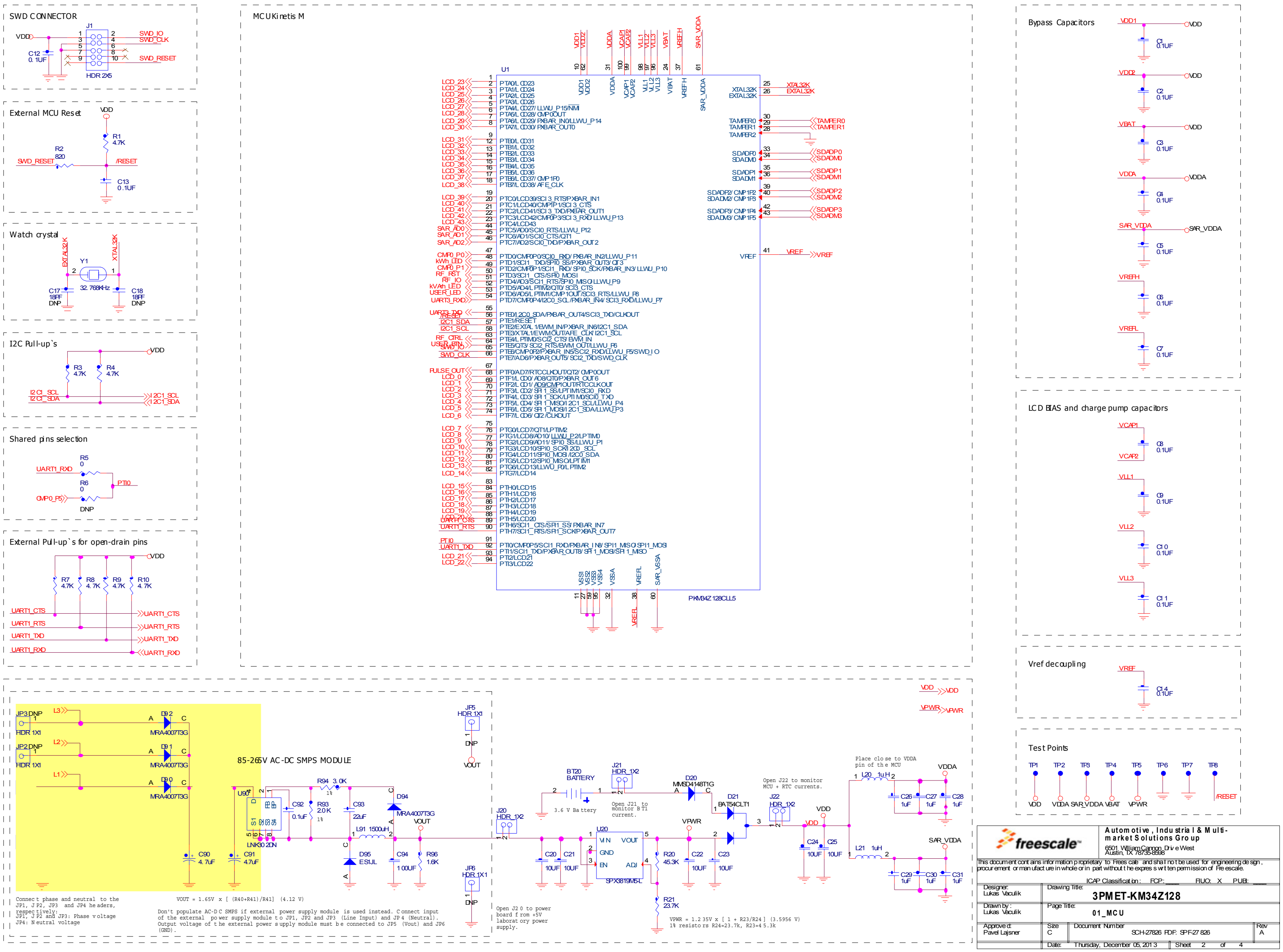

Figure A-1. Schematic diagram 01_MCU

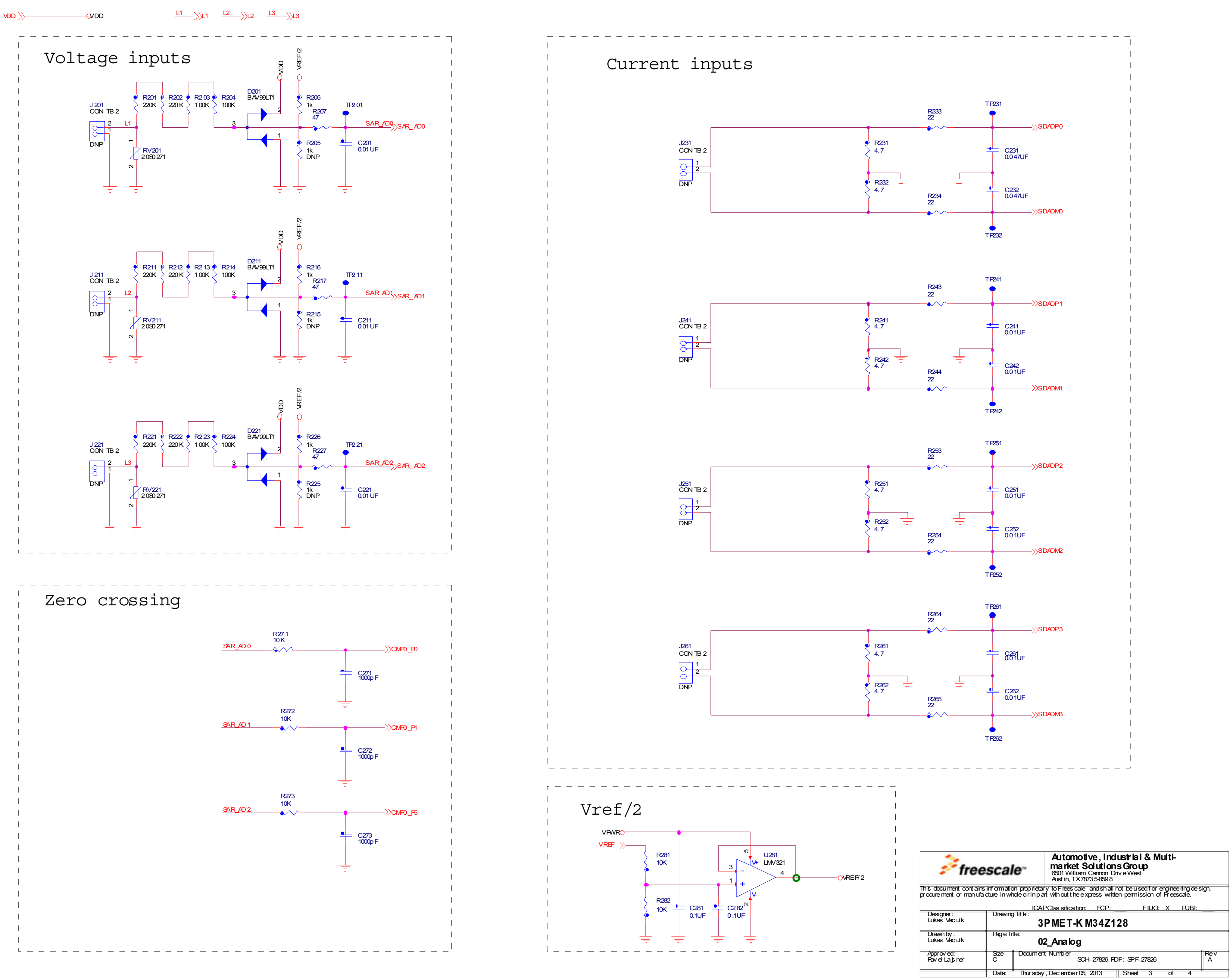

Figure A-2. Schematic diagram 02_ANALOG

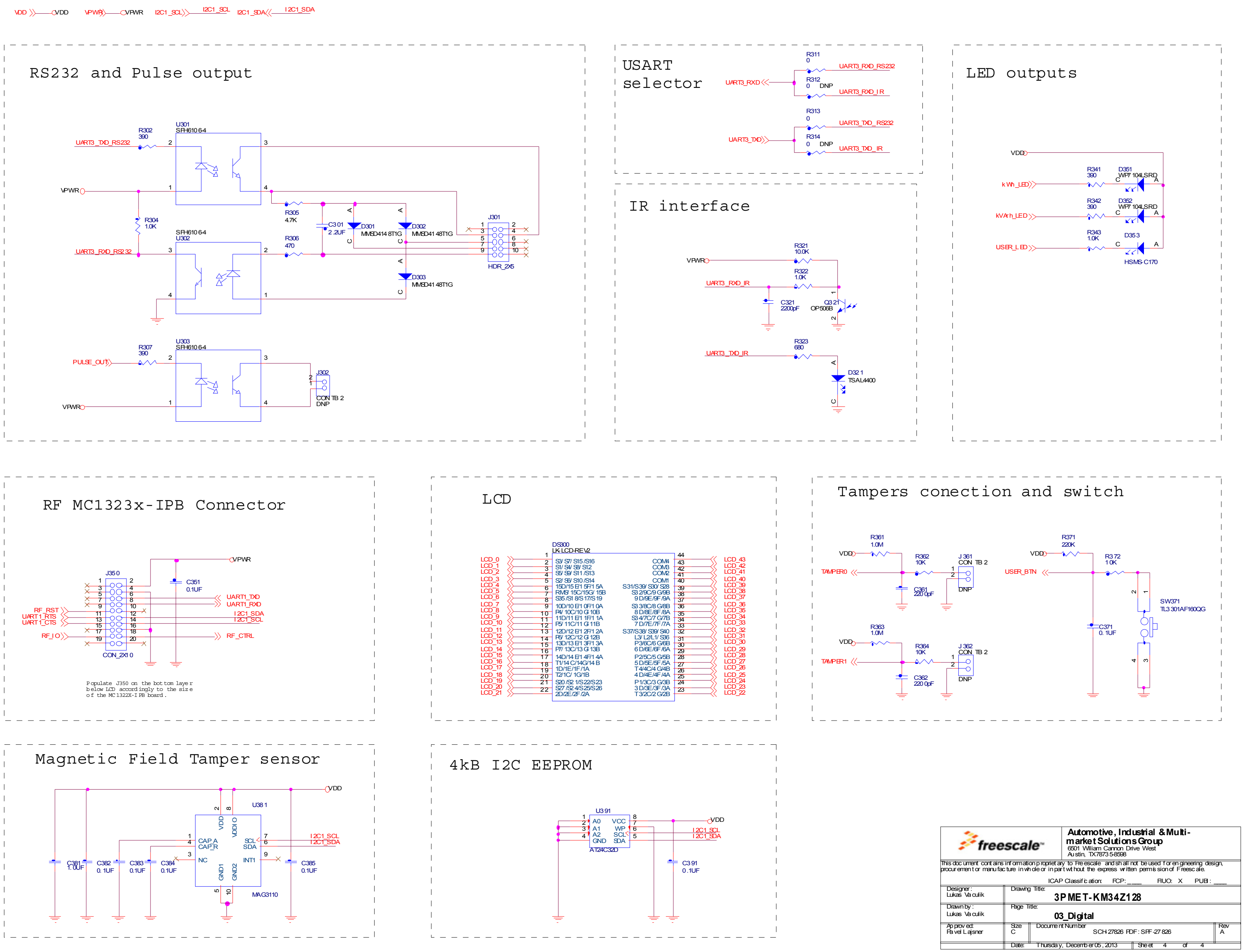

Figure A-3. Schematic diagram 03_DIGITAL

Appendix B Board layout

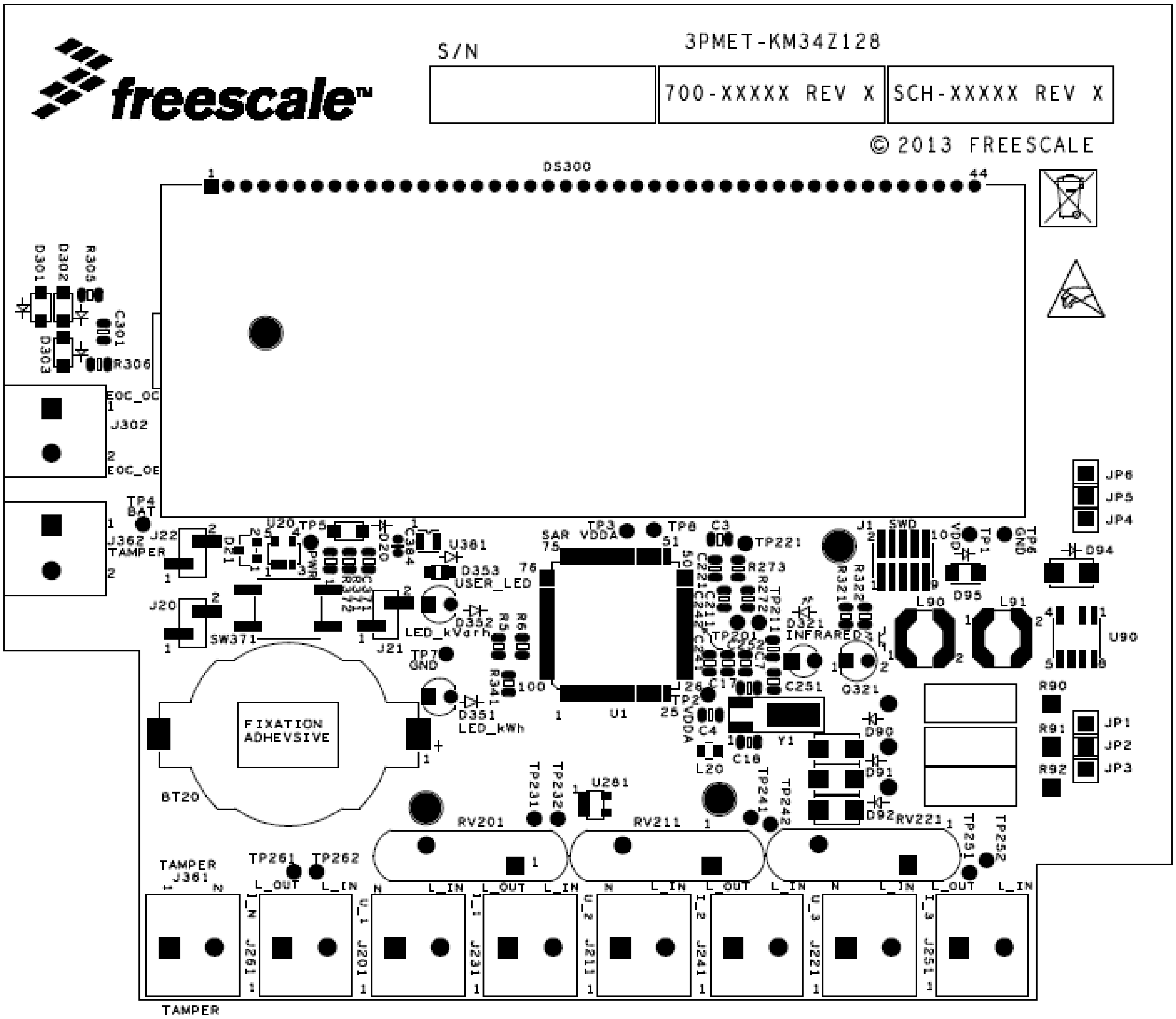

Figure B-1. Top side view

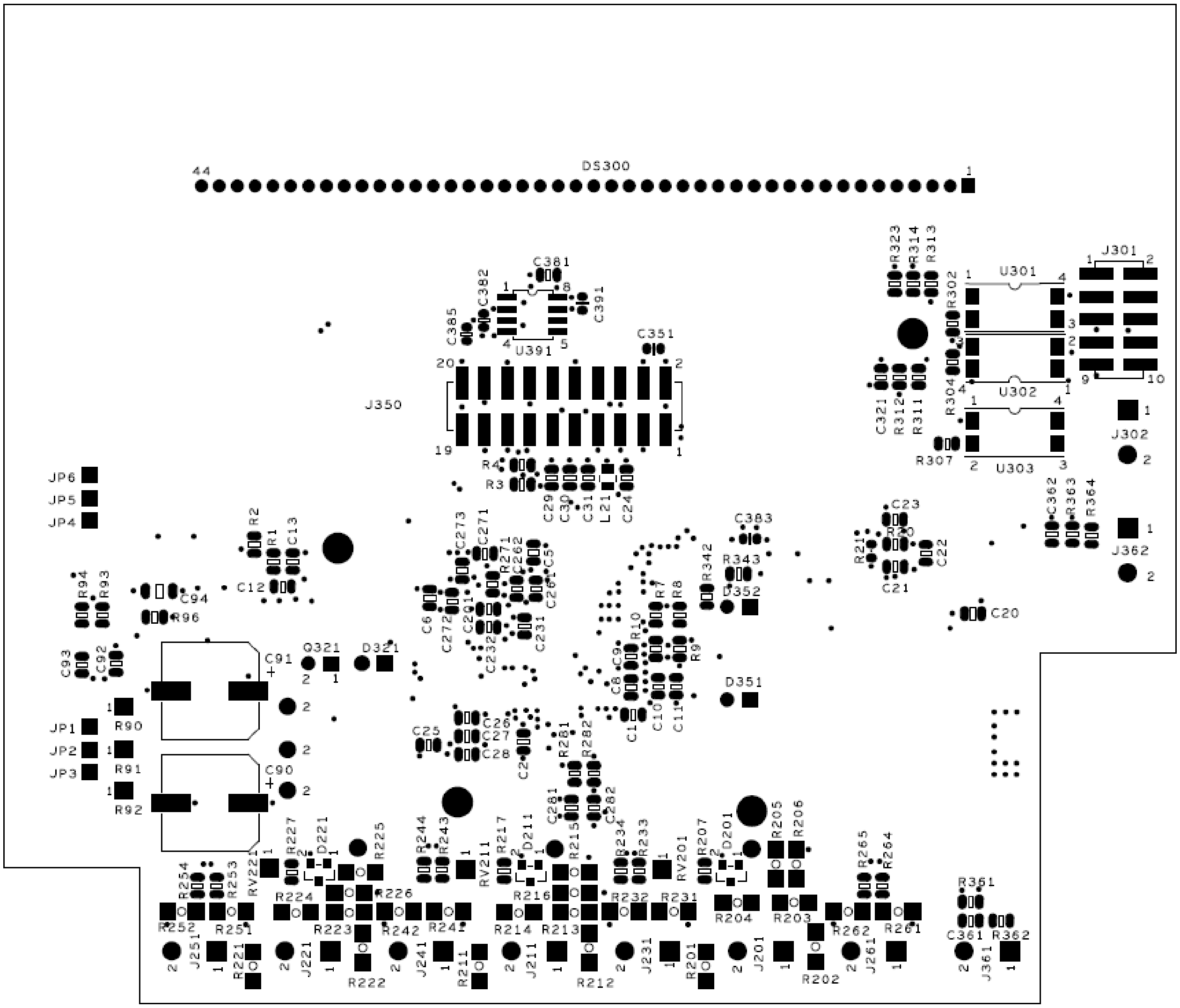

Figure B-2. Bottom side view

Appendix C Bill of materials

Table C-1. provides the Bill of Material report.

Table C-1. BOM report

Part Reference	Quantity	Value	Description	Manufacturer	Part Number
BT20	1	BATTERY	BATTERY HOLDER CR2032 3V ROHS COMPLIANT	RENATA BATTERIES	SMTU2032-LF
C1,C2,C3,C4,C5,C6,C7,C8,C9,C10,C11,C12,C13,C281,C282,C371	16	0.1UF	CAP CER 0.1UF 25V 10% X7R 0805	SMEC	MCCC104K2NRTF
C17,C18	2	18PF	CAP CER 18PF 100V 5% C0G 0805	KEMET	C0805C180J1GACTU
C20,C21,C22,C23,C24,C25	6	10UF	CAP CER 10UF 16V 10% X5R 0805	AVX	0805YD106KAT2A
C26,C27,C28,C29,C30,C31	6	1uF	CAP CER 1UF 50V 10% X7R 0805	SMEC	MCCE105K2NRTF
C90,C91	2	4.7uF	CAP ALEL 4.7uF 400V 20% -- SMT	NIC COMPONENTS CORP	NACV4R7M400V10x10.8TR13F
C92	1	0.1uF	CAP CER 0.10UF 50V 5% X7R 0805	SMEC	MCCE104J2NRTF
C93	1	22uF	CAP CER 22UF 16V 10% X5R 0805	TDK	C2012X5R1C226K
C94	1	100UF	CAP CER 100UF 6.3V 20% X5R 1206	Murata	GRM31CR60J107ME39L
C201,C211,C221,C241,C242,C251,C252,C261,C262	9	0.01UF	CAP CER 0.01UF 100V 5% X7R 0805	KEMET	C0805C103J1RACTU
C231,C232	2	0.047UF	CAP CER 0.047UF 50V 5% X7R 0805	KEMET	C0805C473J5RAC
C271,C272,C273	3	1000pF	CAP CER 1000pF 1000V 10% X7R 0805	Kemet	C0805C102KDRACTU
C301	1	2.2UF	CAP CER 2.2UF 10V 10% X5R 0805	AVX	0805ZD225KAT2A
C321,C361,C362	3	2200pF	CAP CER 2200PF 25V 10% X7R CC0805	VENKEL COMPANY	C0805X7R250-222KNE
C351,C382,C383,C384,C385,C391	6	0.1UF	CAP CER 0.10UF 25V 10% X7R 0603	KEMET	C0603C104K3RAC
C381	1	1.0UF	CAP CER 1.0UF 10V 10% X7R 0805	SMEC	MCCB105K2NRTF
DS300	1	LK-LCD-REV2	LCD 3-PHASE POWER METER	AR-ELEKTRONIK SRL	LK-LCD-REV2
D20,D301,D302,D303	4	MMSD4148T1G	DIODE SW 100V SOD-123	ON SEMICONDUCTOR	MMSD4148T1G
D21	1	BAT54CLT1	DIODE SCH DUAL CC 200MA 30V SOT23	ON SEMICONDUCTOR	BAT54CLT1G
D90,D91,D92,D94	4	MRA4007T3G	DIODE PWR RECT 1A 1000V SMT 403D-02	ON SEMICONDUCTOR	MRA4007T3G
D95	1	ES1JL	DIODE RECT 1A 600V SMT	TAIWAN SEMICONDUCTOR	ES1JL

Table C-1. BOM report (continued)

Part Reference	Quantity	Value	Description	Manufacturer	Part Number
D201,D211,D221	3	BAV99LT1	DIODE DUAL SW 215MA 70V SOT23	ON SEMICONDUCTOR	BAV99LT1G
D321	1	TSAL4400	LED IR SGL 100MA TH	VISHAY INTERTECHNOLOGY	TSAL4400
D351,D352	2	WP7104LSRD	LED RED SGL 30mA TH	Kingbright	WP7104LSRD
D353	1	HSMS-C170	LED HER SGL 2.1V 20MA 0805	AVAGO TECHNOLOGIES	HSMS-C170
JP1,JP2,JP3,JP4,JP5,JP6	6	HDR 1X1	HDR 1X1 TH -- 330H SN 115L	SAMTEC	TSW-101-23-T-S
J1	1	HDR 2X5	HDR 2X5 SMT 1.27MM CTR 175H AU	SAMTEC	FTS-105-01-F-DV-P-TR
J20,J21,J22	3	HDR_1X2	HDR 1X2 SMT 100MIL SP 380H AU	SAMTEC	TSM-102-01-SM-SV-P-TR
J201,J211,J221,J231,J241,J251,J261,J302,J361,J362	10	CON TB 2	CON 1X2 TB TH 200MIL SP 709H - 197L	PHOENIX CONTACT	1711725
J301	1	HDR_2X5	HDR 2X5 SMT 100MIL CTR 380H AU	SAMTEC	TSM-105-01-S-DV-P-TR
J350	1	CON_2X10	CON 2X10 SKT SMT 100MIL CTR 390H AU	SAMTEC	SSW-110-22-F-D-VS-N
L20,L21	2	1uH	IND CHIP 1UH@10MHZ 220MA 25%	TDK	MLZ2012A1R0PT
L90,L91	2	1500uH	IND PWR 1500UH@100KHZ 130MA 20% SMT	Coilcraft	LPS6235-155ML
Q321	1	OP506B	TRAN PHOTO NPN 250mA 30V TH	OPTEK TECHNOLOGY INC	OP506B
RV201,RV211,RV221	3	20S0271	RES VARISTOR 275VRMS 10% 4.5kA 151J TH	epcos	B72220S0271K101
R1,R3,R4,R7,R8,R9,R10	7	4.7K	RES MF 4.70K 1/10W 1% 0805	SMEC	RC73L2A4701FTF
R2	1	820	RES MF 820 OHM 1/8W 5% 0805	BOURNS	CR0805-JW-821ELF
R5,R311,R313	3	0	RES MF ZERO OHM 1/8W -- 0805	YAGEO AMERICA	RC0805JR-070RL
R6,R312,R314	3	0	RES MF ZERO OHM 1/8W -- 0805	YAGEO AMERICA	RC0805JR-070RL
R20	1	45.3K	RES MF 45.3K 1/8W 1% 0805	BOURNS	CR0805-FX-4532ELF
R21	1	23.7K	RES MF 23.7K 1/10W 1% 0603	KOA SPEER	RK73H1JTTD2372F
R90,R91,R92	3	8.2	RES MF 8.2 OHM 2W 10% AXL	WELWYN COMPONENTS LIMITED	EMC2-8R2K
R93	1	2.0K	RES MF 2.00K 1/10W 1% 0805	SPC TECHNOLOGY	MC0805WAF2001T5E-TR
R94	1	3.0K	RES MF 3.00K 1/10W 1% 0805	SPC TECHNOLOGY	MC0805WAF3001T5E-TR

Table C-1. BOM report (continued)

Part Reference	Quantity	Value	Description	Manufacturer	Part Number
R96	1	1.6K	RES TF 1.6K 1/8W 5% 0805	VENKEL COMPANY	CR08058W162JT
R201,R202,R211,R212, R221,R222	6	220K	RES MF 220K 1/4W 1% 50ppm MELF0204	WELWYN COMPONENTS LIMITED	WRM0204C-220KFI
R203,R204,R213,R214, R223,R224	6	100K	RES MF 100K 1/4W 1% MELF0204	WELWYN COMPONENTS LIMITED	WRM0204C-100KFI
R205,R215,R225	3	1k	RES MF 1K 200V 0.1% 15PPM MELF0204	WELWYN COMPONENTS LIMITED	WRM0204Y-1KBI
R206,R216,R226	3	1k	RES MF 1K 200V 0.1% 15PPM MELF0204	WELWYN COMPONENTS LIMITED	WRM0204Y-1KBI
R207,R217,R227	3	47	RES MF 47 OHM 1/8W 1% 0805	YAGEO AMERICA	232273464709L
R231,R232,R241,R242, R251,R252,R261,R262	8	4.7	RES MF 4.7 OHM 1/4W 1% MELF0204	VISHAY INTERTECHNOLOGY	MMA02040C4708FB300
R233,R234,R243,R244, R253,R254,R264,R265	8	22	RES MF 22 OHM 1/8W 1% 0805	YAGEO AMERICA	RC0805FR-0722RL
R271,R272,R273,R281, R282,R362,R364,R372	8	10K	RES MF 10K 1/8W 5% 0805	VENKEL COMPANY	CR0805-8W-103JT
R302,R307	2	390	RES MF 390 OHM 1/8W 5% 0805	BOURNS	CR0805-JW-391ELF
R304,R322,R343	3	1.0K	RES MF 1.00K 1/8W 1% 0805	KOA SPEER	RK73H2ATTD1001F
R305	1	4.7K	RES MF 4.70K 1/8W 1% 0805	BOURNS	CR0805-FX-4701ELF
R306	1	470	RES MF 470 OHM 1/8W 0.5% 0805	KOA SPEER	RK73H2ATTD4700D
R321	1	10.0K	RES MF 10.0K 1/8W 1% 0805	VENKEL COMPANY	CR0805-8W-1002FT
R323	1	680	RES MF 680 OHM 1/8W 5% 0805	VENKEL COMPANY	CR0805-8W-681JT
R341,R342	2	390	RES MF 390 OHM 1/10W 1% 0805	SPC TECHNOLOGY	MC0805WAF3900T5E-TR
R361,R363	2	1.0M	RES MF 1.0M 1/8W 5% 0805	BOURNS	CR0805-JW-105ELF
R371	1	220K	RES TF 220K 1/8W 5% 0805	PANASONIC	ERJ6GEYJ224V
SW371	1	TL6700AF160QG	SW SPST PB 50mA 12V SMT	E SWITCH	TL6700AF160QG
TP1,TP2,TP3,TP4,TP5, TP6,TP7,TP8,TP201, TP211,TP221,TP231, TP232,TP241,TP242, TP251,TP252,TP261, TP262	19	70 MIL	TEST PAD 70MIL ROUND SMT; NO PART TO ORDER	—	—

Table C-1. BOM report (continued)

Part Reference	Quantity	Value	Description	Manufacturer	Part Number
U1	1	PKM34Z128CLL5	IC MCU FLASH 128K 16K 50MHZ 1.71-3.6V LQFP100	FREESCALE SEMICONDUCTOR	PKM34Z128CLL5
U20	1	SPX3819M5-L	IC VREG LDO ADJ 500MA 2.5-16V SOT23-5	Exar	SPX3819M5-L
U90	1	LNK302DN	IC VREG LINKSWITCH 65MA/80MA 85–265VAC/700V S0-8C	POWER INTEGRATIONS	LNK302DN
U281	1	LMV321	IC LIN OPAMP 130UA 2.7-5.5V SOT23-5	NATIONAL SEMICONDUCTOR	LMV321M5NOPB
U301,U302,U303	3	SFH6106-4	IC OPTOCOUPLER 100MA 70V SMD	VISHAY INTERTECHNOLOGY	SFH6106-4
U381	1	MAG3110	IC 3-AXIS DIGITAL MAGNETOMETER 1.95-3.6V DFN10	FREESCALE SEMICONDUCTOR	MAG3110FC
U391	1	AT24C32D	IC MEM EEPROM 4096X8 1MHZ 1.8-5.5V SOIC8	ATMEL	AT24C32D-SSHM-B
Y1	1	32.768 KHz	XTAL 32.768KHZ PAR 20PPM -- SMT	Citizen	CMR200T32.768KDZF-UT
BT20	1	BATTERY	BATTERY HOLDER CR2032 3V ROHS COMPLIANT	RENATA BATTERIES	SMTU2032-LF

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