Smart grids: improve monitoring, increase revenue, and achieve compliance

Electrical power consumption is measured and monitored far beyond the electricity meter in your utility cabinet. A combination of factors has driven growth in applications that want to or must monitor power consumption and quality. So, while utility-to-consumer metering remains a key application today, others including EV chargers, solar inverters, lighting, smart plugs, servers, industrial load monitors, and home appliances are also important and quickly ramping up. In addition, these applications require both accurate energy consumption measurements and power quality monitoring. EV chargers are a symbol of the two-way nature of the system, going beyond the typical charging mode. In order to accurately measure the energy returned to the power network through vehicle-to-grid (V2G) demand services, it is necessary to measure the energy that is billed to the consumer, especially when supporting the demand for peak shaving.

This paper focuses on exploring the diversity and complexity of metrology in electrical applications. It delves into the various approaches that can be employed to meet different requirements, ensure compliance, and enhance revenue in fiscal metering. Additionally, the paper also highlights the significance of guaranteeing repeatability and trustworthiness in non-fiscal metering. Finally, it spotlights some innovative, scalable semiconductor metering technologies that offer varying levels of integration and system partitioning.

THE GROWTH IN METROLOGY IN ELECTRICAL APPLICATIONS

Monitoring electrical energy consumption has been part of demand measurement since the late nineteenth century. The British engineer John Hopkinson recognized that electrical energy (kilowatt hours) consumed formed a sound basis for charging consumers. However, there was also the power component (kilowatts). He argued that, for example, a business using 20 kW in thirty minutes should surely be charged more than a business consuming the same amount of power over several hours. Combining energy used with peak power demand led to the Hopkinson Rate for fiscal charging and the beginning of the need for metering.

Consumer electricity is typically charged for electrical energy used, with billing based upon annual kilowatt hour (kWh) readings. Early electromechanical induction meters utilized a disc rotating proportionally to the power passing through the meter to record consumption on a mechanical counter.

However, with the advancement of semiconductor technology and wide area networks, more intelligence is integrated into today's meters. Some offer prepayment. Others transmit readings back to the utility provider, avoiding sending meter readers door-to-door. Consumers benefit, too, with real-time electrical energy consumption visible on the web or smartphone apps. Such consumption awareness encourages a reduction in energy usage and pushes us toward purchasing more efficient home appliances.

Figure 1: A typical electromechanical power supply meter

SMART GRIDS: CHANGE IN ELECTRICITY CONSUMPTION AND GENERATION

Who generates electricity is also changing. Long being the domain of utility providers, a centralized approach to generation and distribution can't respond rapidly to changing energy needs and the transition to green energy. This has allowed property owners to become energy providers, installing solar panels and selling the energy generated. Accurate metering is required to ensure correct billing while sharing generation data via apps and public display systems promotes clean energy contributions to the Green Deal.

In this scenario, electric vehicles (EVs) are also changing our relationship with energy consumption and generation. According to a report by McKinsey[1] , Germany is expecting 8 million EVs (including commercial vehicles) on the roads by 2030. They claim that charging will add a 4% increase in load to the electrical network. Most of this load takes place in the evening, when owners return from work, which is already a time of peak usage in winter. However, it doesn't all have to be challenges.

Using vehicle-to-grid (V2G) technology, EVs can support electrical utility providers (Figure 2). Short periods of high demand can be bridged by EVs injecting energy back into the grid. Coupled with intelligent charging, this approach ensures that an owner's vehicles remain ready for use when required. It's been in operation at a small scale since the mid-2010s[2] and was included more recently in the Human 1st Vision project[3] . Thus, with suitable metrology in place, owners can earn from their electrical contributions.

Then there are Industry 4.0 applications, where reducing energy usage contributes to the UN's Sustainable Development Goal (SDG) of sustainable industrialization[4]. Furthermore, the gut instinct of the maintenance team is being replaced by measurements and IIoT data networks. Energy consumption changes, measured using sub-metering, are a good indicator of wear, changes in operational function, and pending maintenance needs.

Figure 2: V2G in EV chargers ensures vehicles are always ready to drive but also helps smooth out power grid peaks.

MODERN ELECTRONIC ELECTRICITY METERING

Today's metrology solutions result from advancements in analog sensing technology, analog-to-digital conversion, and a growth in low-cost, high-performance application-specific computing. However, the measurement principles remain the same. As in the older electromechanical meters, a magnetic field induced an eddy current in an aluminum disk that, in turn, rotated proportionally to the power consumed (P = V · I).

Modern electronic meters use an analog-to-digital converter (ADC) front-end to measure the voltage, with a resistor divider reducing the voltage to a level suited to the ADC's input specification (Figure 3) to deliver up to ±300 mV to the ADC's input.

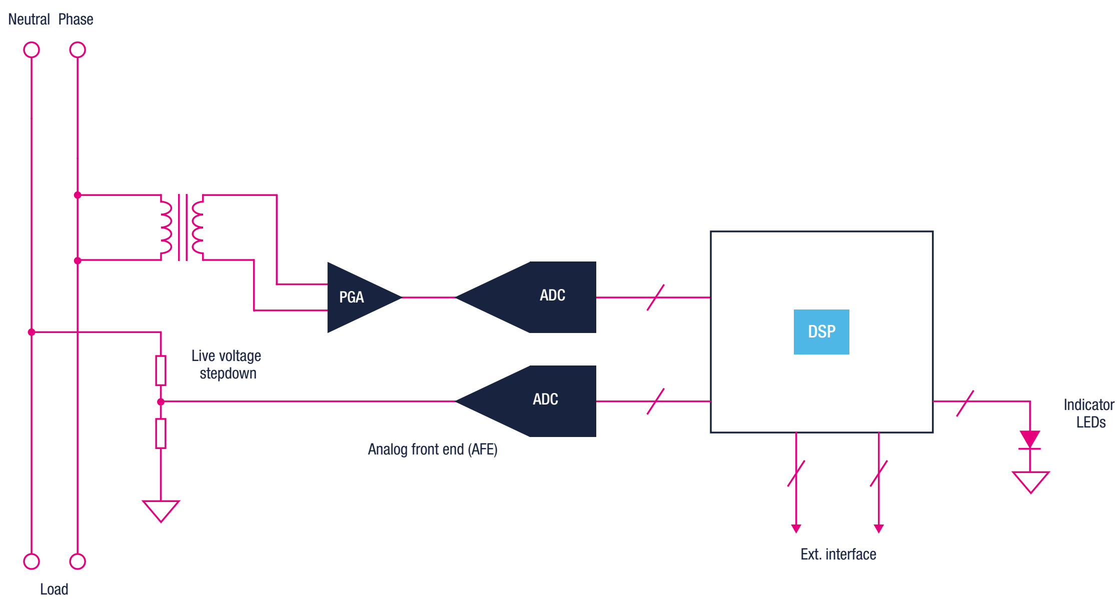


Figure 3: Block diagram of single phase electricity meter based on STPM32 architecture.

Current can be acquired using several approaches ranging from low cost but lower accuracy, such as a shunt resistor (Figure 4), to higher cost but more accurate methods, such as current transformers or Rogowski coils. One of the many challenges here is the dynamic range of this signal as well as the system's measurement accuracy over its lifetime that can be impacted by intrinsic characteristics including high temperature variations, external electro-magnetic fields and sensor linearity.

For the purpose of power grid utility billing, your meter will need to measure a wide power range with the required accuracy either at very low or high energy levels. A handful of household appliances in standby mode may consume just 10 W combined, drawing 41 mA at 240 V_{AC}. But turning on the kettle, air-conditioner, TV, fridge, oven and vacuum cleaner can easily increase this to over 4,000 W, drawing 16.6 A. And while the continuous 10 W draw may not seem like much, that's 87 kWh of annual billable energy usage per household.

Figure 4: Evaluation board (EVALSTPM32) for a single-phase shunt-based energy meter

The engineering challenge revolves around accurately sensing the current in such way as to not introduce an error and an error drift over temperature that cannot be compensated.

Along with selecting the correct current sensors and all discrete companion chips, the role of the analog front-end (AFE) is to ensure the measured voltages and currents are passed accurately to the computation engine. Additionally, the AFE must offer suitable resolution and bandwidth to determine low and high power consumption to allow the computation of additional fundamental quantities (harmonics content, power factor, THD, FFT, etc.) accurately.

The impact of the interference in these measurements is inevitable, especially at low voltages and currents. While printed circuit board (PCB) layout and overall design minimize the introduction of measurement inaccuracies, a certain amount of filtering in the digital domain must be applied.

Furthermore, metrology isn't solely about power consumption. Sub-metering applications also focus on power quality, monitoring RMS and instantaneous voltage and current, line voltage frequency, and information on sag and swell events. All data measured will need to be stored for a defined timeframe for detecting load anomalies and preventing unexpected conditions and as well as for checking in the event of a complaint regarding accuracy.

All these aspects push the engineer toward a higher-end microcontroller (MCU) that offers real-time, complex and accurate computations, either within its instruction set or through a hardware accelerator, coupled with plenty of volatile and non-volatile memory.

Power in DC circuits is easy to calculate ($P = V \cdot I$) but is split into active, reactive, and apparent parts in AC circuits. Inductive and capacitive loads cause the voltage and current to move out of phase (θ). Active power ($P = V \cdot I \cdot \cos\theta$) is doing useful work in the system, e.g., turning the motor, and is measured in watts (W). Reactive power ($Q = V \cdot I \cdot \sin\theta$) is 'useless' energy released back from inductors/capacitors magnetic/electric fields measured in volt-ampere reactive (VAR). Apparent power is the sum of the two, expressed in volt-ampere (VA).

Power Factor (PF) describes the relation between active and apparent power. Unity PF (1.0) indicates voltage and current are in phase, and 100% of the power is performing useful work. Typically, PF is less than 1.0. A value of 0.95 indicates that 95% of the power is active and 5% is reactive. Lower PF also means higher currents and larger conductor sizes. Industrial consumers, who typically have many inductive loads, use correction systems featuring banks of capacitors to improve their PF. Utility providers also place limits on allowable PF.

INTEGRATED SOLUTIONS FOR SMART GRID METROLOGY

Bringing all the aforementioned required elements into a single device is critical to optimizing electrical metering designs. High integration levels help designers by providing reusable blocks that can solve common challenges in metrology. These challenges are similar regardless of the number of phases being monitored or the application type. The challenges include tolerances, thermal drift, inaccuracy, noise, reliability issues, and cost. By eliminating redundant components, high integration levels further improve the design process.

The **STPM3x family of metering ICs** is designed to deliver the quality and accuracy levels desired of an AFE coupled with the computation capability of a DSP (Digital Signal Processor) in a single package (Figure 5). This allows the use of a simple and low-cost companion MCU that optimally meets the application's remaining requirements. The designer also has the choice between shunt, Hall sensor, current transformer, or Rogowski coil for current measurement, ensuring that system cost can always be balanced against the required accuracy and target physical volume of the end product.

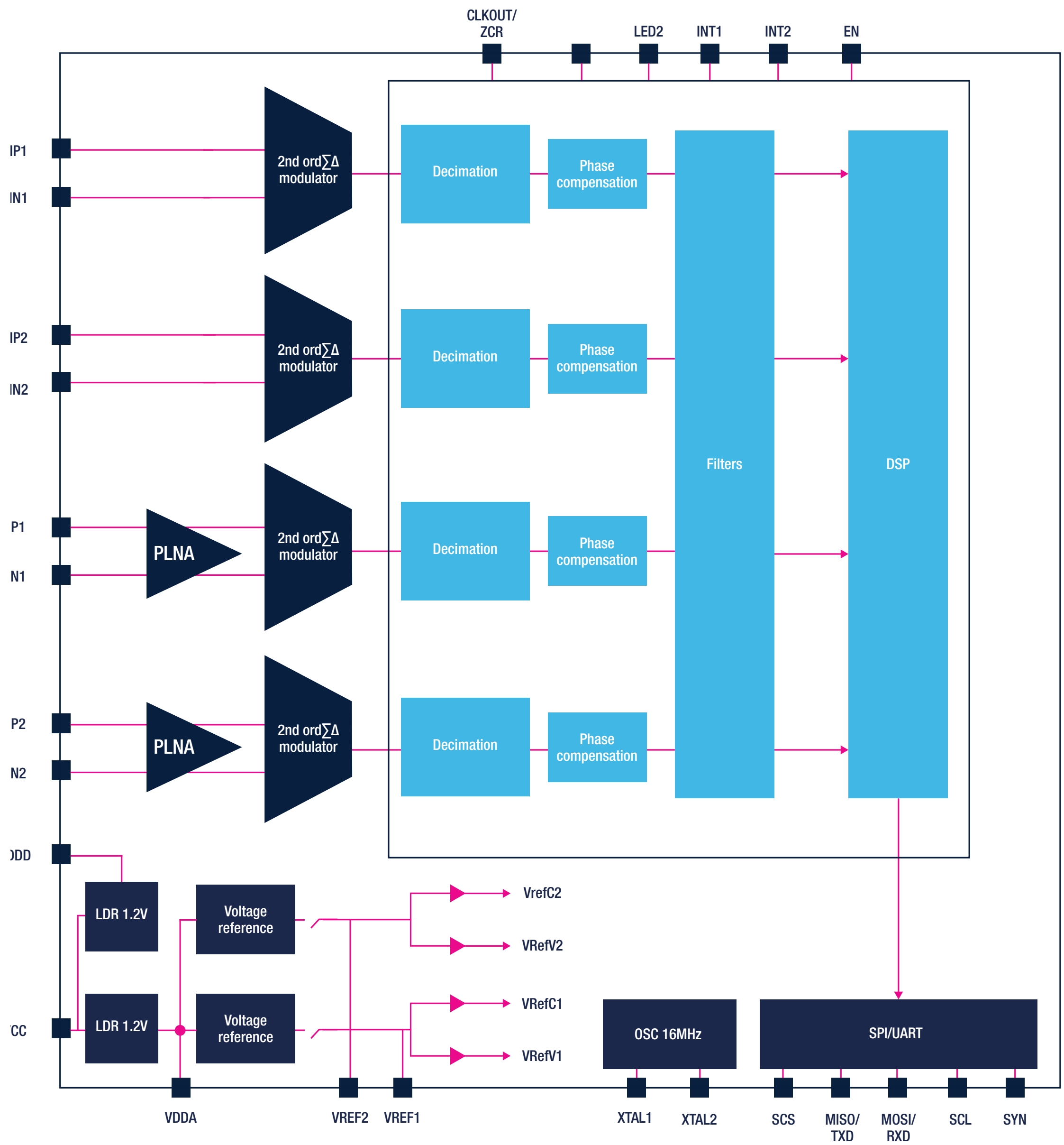


Figure 5: Block diagram of the superset STPM34 with four inputs and DSP for multi-phase metrology

Three devices are available:

- **STPM32 with two input channels** (V1, I1) for single-phase metrology; no anti-tamper support.
- **STPM33 with three input channels** (V1, I1, I2) for split single-phase metrology; anti-tamper support.
- **STPM34 with four input channels** (V1, I1, V2, I2) for multi-phase metrology; two independent anti-tamper support.

Integrated within these mixed-signal ICs are between two and four 24-bit, second-order sigma-delta ADCs. The technology and optimal design, along with very tight internal temperature compensated bandgap voltage references, achieve a very high performance at low power levels and against temperature variations typical of shunt sensors. An accuracy of < 0.1% error over a dynamic range of 5,000:1 and < 0.5% error over 10,000:1 is attainable for active power measurements, exceeding standard requirements for AC watt meters (EN 50470, IEC 62053-2x, ANSI 12.2x). Furthermore, reactive power accuracy is < 0.1% error over the 2,000:1 dynamic range.

Tampering with utility meters is undertaken to reduce billable usage. Methods range from connecting loads to ground, bypassing the neutral current path, reversing current, and disconnecting the neutral to physical manipulation[5] . Anti-tamper mechanisms record tampering events and, if possible, attempt to compensate for them.

The devices also feature up to two programmable gain chopper stabilized, low-noise, low-offset amplifiers (PLNA) at the current measurement inputs (Figure 6).

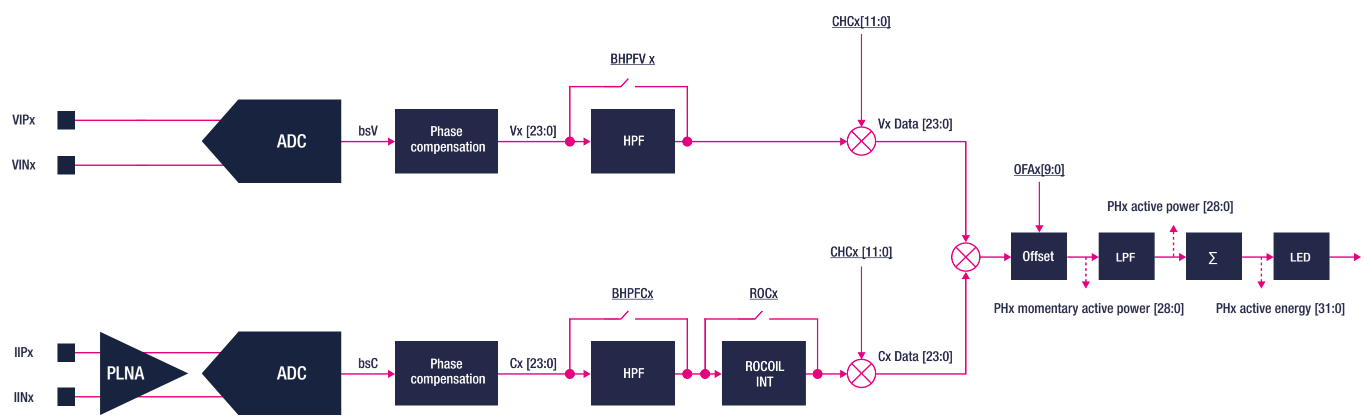


Figure 6: Signal path from voltage/current input through to an active energy measurement result.

The 3.6 kHz bandwidth of decimation filters downstream from the ADC stage, guarantees the harmonic signals are fully available for post-processing computation. After signal digitization, the data is passed through the digital front-end (DFE), i.e. decimation block, phase compensation, and calibration filters prior to processing by the dedicated hardwired DSP. Here, DC cancellation filters, a Rogowski coil integrator, and fundamental harmonic component filters can be configured.

Measurement results and device configuration are accessed through either SPI (five pins) or UART (four pins) interfaces. This provides design freedom when interfacing with the selected low-cost host MCU by optionally minimizing the number of required I/O pins and related components, including galvanic digital isolators when needed. Metrology data is generated by the hardwired DSP and stored in internal registers for easy access and use by the host MCU. Measurements are refreshed at 7.8125 kHz and include:

- Active power and energy wideband 0 Hz (4 Hz) to 3.6 kHz
- Active power and energy fundamental 45 to 65 Hz
- Reactive power and energy
- Apparent power and energy from RMS data
- Apparent power from vectorial calculation
- Other measurements, such as RMS, period, zero-crossing, phase-delay, sag and swell, tamper detection.

Fiscal meters feature an LED that typically blinks 1,000 times per kWh, providing a visual indication of correct operation. Configurable LED output pins are available to generate the required pulses to support this. Interrupt output pins are also available for asynchronous signaling of events, such as sag and swell, tamper, and energy register overflow, to the host MCU. For the STPM33 and STPM34 with tamper monitoring, differences above a predefined setting for the absolute value of two active energy values can trigger a detection. In the event of neutral wire disconnection tamper, the supply voltage is no longer available. In this case, current continues to be monitored with energy calculated based on a nominal voltage value.

SAG AND SWELL

Sag and swell are terms describing AC over- and undervoltage conditions, respectively. They are power quality disturbances that can result in incorrect operation in the event of a power outage or even damage to equipment caused by a voltage spike. Precise definitions for sag and swell are given in standards such as IEEE 1159-2019. A disturbance lasting longer than three cycles is typically visible in lamps that are switched on.

The **STPM3x family** also provides a range of single-point calibration registers. For example, with the application of a known voltage and current, all calculated values may be calibrated in a single point and ensure the target accuracy throughout the specified power range. Power calculations can also suffer from errors as small as 0.1° to 0.3° in the signal phase from the transducers and system components employed, such as current sensors and resistors tolerances and drifts, inductive PCB traces coupling, etc. Digital phase correction can be applied to compensate individually for each measurement channel. Each channel can also be corrected using a power offset compensation register for each power measurement result (active, active fundamental, reactive, and apparent).

Of course, some development teams may be looking to leverage the performance of the AFE and DFE to couple it with their own signal analysis. In such cases, the STPMS2 provides single-phase measurements that closely reflect the capabilities of the STPM32 without the hardwired DSP (Figure 7). Like the fully-featured sensing ICs, it also exceeds the IEC 687/1036 specification for class 1, class 0.5, and class 0.2 AC watt meters (50 to 60 Hz). Three such devices can be coupled to implement a poly-phase meter using shunts for current monitoring and linked to a powerful Cortex-M4 core **STM32F413 high-performance MCU** via three **STISO621 digital interface galvanic-isolators** when shunt sensors are used.

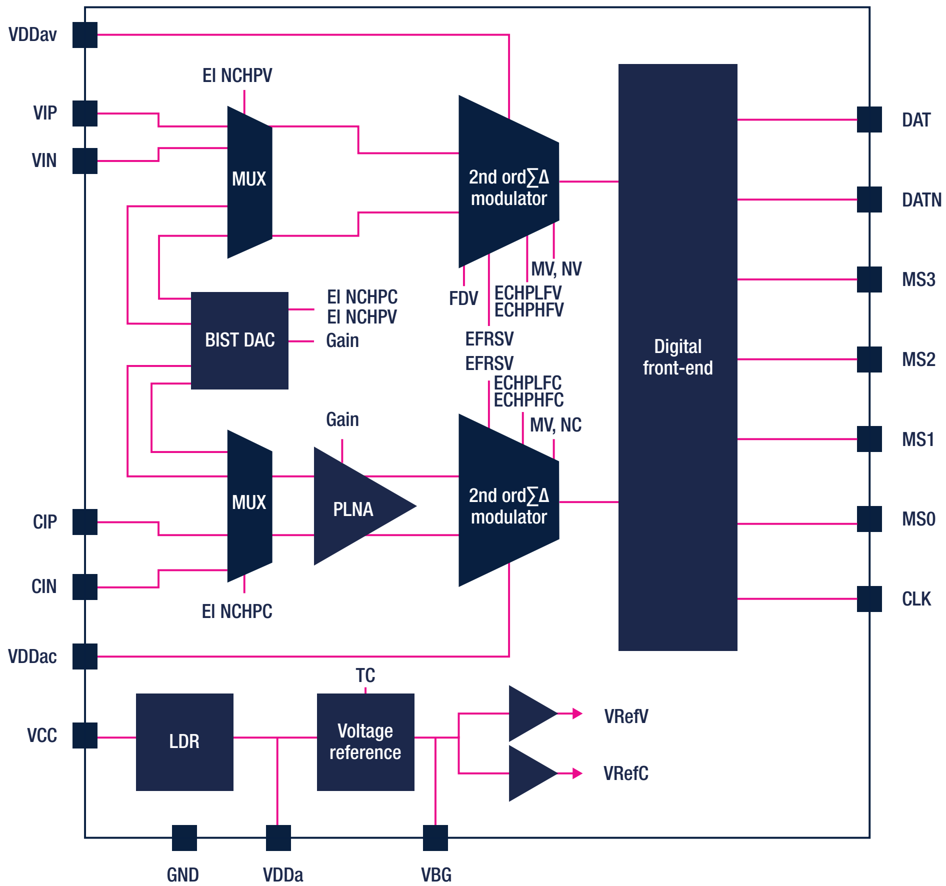


Figure 7: Block diagram of the cost-optimized STPMS2 that provides highly accurate, digitized voltage and current measurement for integration with application-specific data analysis at the MCU side.

SCALABLE TO VARYING METERING APPLICATIONS

To appreciate the scalability of the STPM3x family, various evaluation boards are available. The **EVALSTPM34 evaluation board** provides a class 0.2, dual-phase meter with two CTs for voltages of 140 to 300 V(RMS) and an Inom/Imax of 5/100 A(RMS). The board provides an isolation UART-to-USB interface, allowing connection to a PC. UART and SPI interfaces are also brought out to headers to connect with a host MCU for rapid application development. Configuration is simplified thanks to the evaluation software, a graphical user interface (GUI) providing quick access to the on-chip configuration, calibration, and measurement registers. The **EVALSTPM33** and **EVALSTPM32** evaluation boards offer the same functionality for the remaining family members (Figure 8).

Figure 8: Evaluation boards of the STPM3x family.

Coupling two EVALSTPM34 boards forms the basis of a three-phase energy meter, targeting applications such as high-end EV charging stations (Figure 9). Beyond power and energy measurement on each phase, the data collected can also provide grid status (over- and under-voltage), overcurrent detection on phase and neutral, and failure situations such as current flowing through the earth conductor. The electrical energy metering and STPM34 monitoring circuitry is simply replicated twice and interfaced with a low-end, low-pin-count, host MCU.

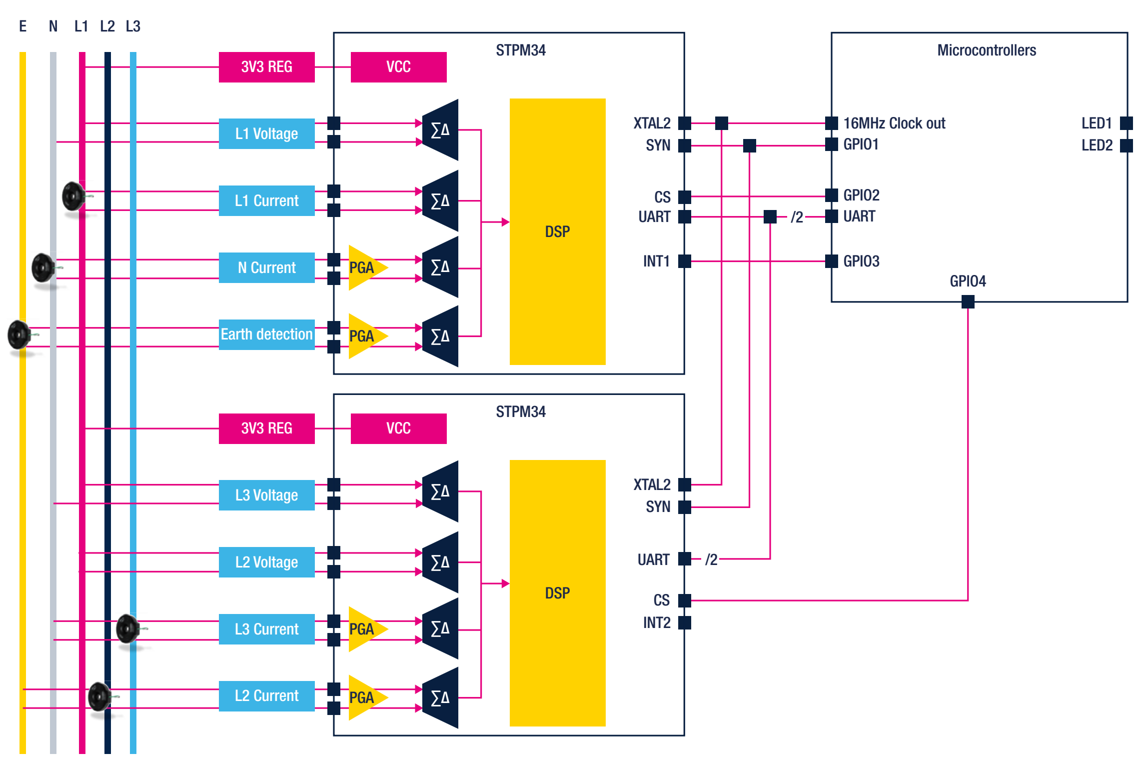


Figure 9: Example three-phase monitoring and energy metering solution for an EV charging station using two STPM34 devices.

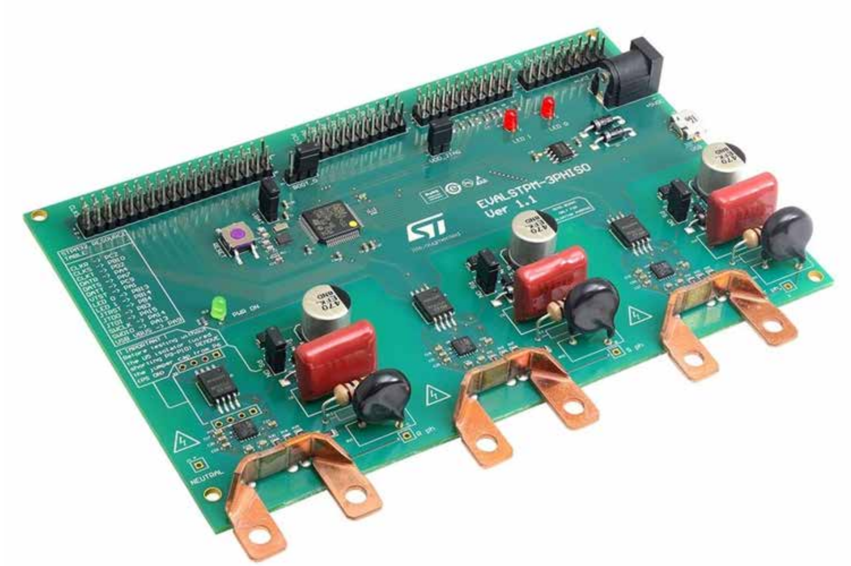


Figure 9 : Three-phase full shunt electricity meter reference design based on the STPMS2

At the simpler end of the spectrum, the **EVALSTPM32** can be deployed in a smart plug application for single-phase appliances (Figure 10). Here, the host MCU requirements can be even simpler, or the use of a highly integrated system-on-chip (SoC) may be considered to provide Wi-Fi or other Internet-of-Things (IoT) connectivity.

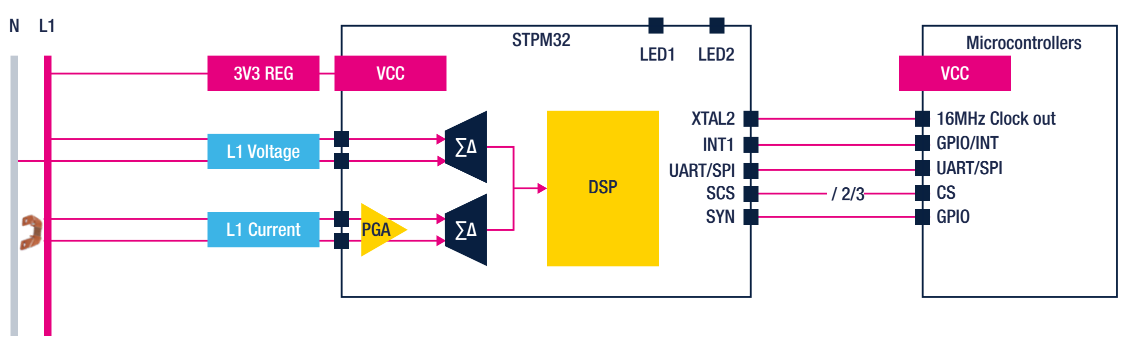


Figure 10: A smart plug application for single-phase home appliances is easily developed around the STPM32 and a low pin-count MCU.

Regardless of the application, the STPM3x family's high-performance AFE delivers accuracy that minimizes revenue losses in fiscal metering applications and provides sound, trustworthy power quality measurements in other sub-metering applications. In addition, the devices are fully compliant with applicable International Electrotechnical Commission (IEC), American National Standards Institute (ANSI) standards as adopted by regulatory authorities worldwide, and exceed State Power Grid Corporation of China (SGCC) requirements.

Most countries or trading zones define technical standards that utility meters must fulfill. There are also international standards that often form the basis of these documents. These can include IEC 62052-11 – Electrical Metering Equipment (AC); IEC 62053-21/23 – Particular requirements for active and reactive energy; IEC 61869-1– Instrument transformers; and IEC 62055-31 – Electricity metering – Payment systems.

IMPROVING MEASUREMENT ACCURACY AND EFT IMMUNITY

While the metering ICs provide high levels of measurement accuracy, this is only possible in combination with an appropriately designed PCB. Energy metering is a notoriously noisy and harsh environment, with the dangers of disruptions from the electrical grid on one side and energy impulses and high noise from industrial equipment or home appliances on the other.

To start, locate the critical blocks of the design, such as the voltage inputs, current inputs, and analog and reference pins of the metering IC[6] . At a higher level, both the analog and digital macroblocks have to be defined. Sensors, related components, and filtering capacitors should be located as close to the STPM3x/STPMS2 as possible. Furthermore, as much space should be placed between the analog and digital macroblocks as possible, including the separation of their ground planes. These can then be joined across the exposed pad of the metering IC (Figure 11).

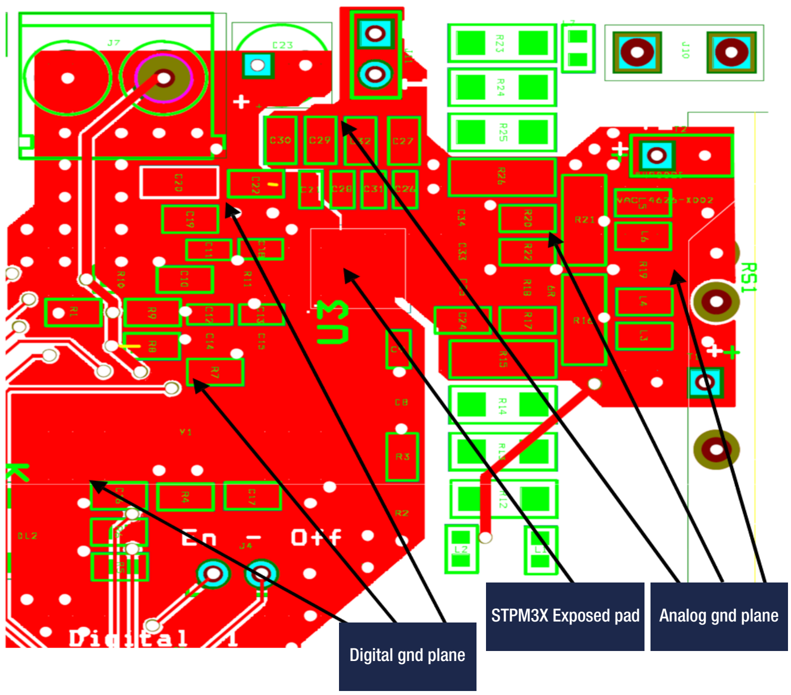


Figure 11: Ground plane design used on the STPM3x family evaluation boards to ensure accurate measurement.

Electrical fast transients (EFT), as defined in IEC-61000-4-4 tests, must also be withstood and not impact functionality or measurement accuracy. For the analog macroblock, low-value capacitors added to the voltage regulator and reference pins help minimize the impact of high-frequency EFT content. The digital macroblock benefits from R-C filters at the meter IC end of communication interfaces to remove high-frequency spikes. The same applies to the enable (EN) pin to avoid accidental reset.

Extensive testing has shown that the STPM3x demonstration boards, which follow these design rules, can attain a measurement accuracy of better than ±0.05%. This is comfortably within the margins of 0.5, 1, and 2 accuracy classes (Figure 11).

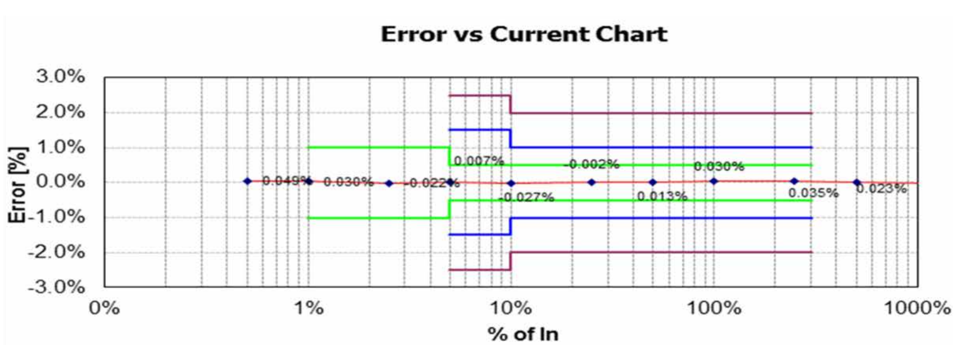
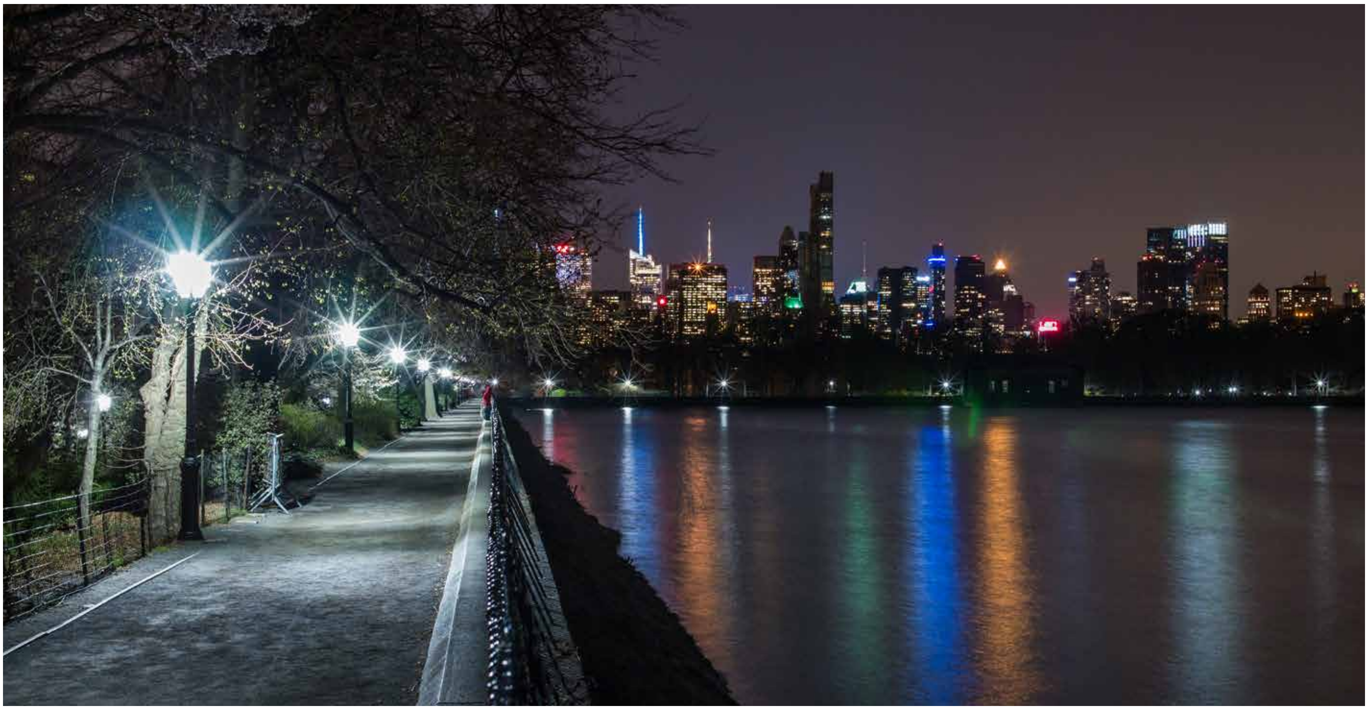


Figure 11: Accuracy of the STPM3x comfortably fulfills classes 0.5, 1, and 2 when good PCB design practice is followed.



CONCLUSION

Consumers with solar panels are becoming mini utility providers, EVs are balancing our power grids, and industry wants to understand their power usage better and protect their equipment from grid disturbances. As a result, metrology is no longer the purvey of utility providers but an integral part of a multitude of systems and applications. The availability of accurate, scalable metering ICs that can be deployed in single- through to poly-phase systems, and coupled with low-cost to high-performance current sensors, allows development teams to respond quickly to changing market needs while leveraging design experience from previous projects.

Devices such as the STPM3x family and STPMS2, with their high-quality AFEs, ensure that the system receives the best possible measurement data. Coupled with fine-tuning through calibration, this extracts the best from low-cost and high-end current sensors. STPM3x-based applications also benefit from the hardwired DSP that executes a plethora of typical power and quality measurements. This simplifies the BOM, design, and software development effort, and allows the use of a host MCU optimally dimensioned to the application’s other needs. Backed up by evaluation boards, development software and firmware, and design guides and documentation, development teams building metering applications are well supported throughout the design process of their electric meter applications.

ADDITIONAL RESOURCES

Improving measuring accuracy and EFT immunity for STPM3x applications
[Design tip DT0039]

Evaluation boards

Single-phase energy metering evaluation board based on the STPM32 [EVALSTPM32]

Single-phase energy metering evaluation board with tamper monitoring based on the STPM33 [EVALSTPM33]

Dual-phase energy metering evaluation board based on the STPM34 [EVALSTPM34]

USB interface tool between STPMxx energy meter evaluation boards and a PC running the user-friendly GUI [STEVAL-IPE023V1]

Three-phase full shunt electricity meter reference design based on the STPMS2 [EVALSTPM-3PHISO]

Evaluation software

STPM3x evaluation software with automatic calibration wizards for STPM32/33/34 evaluation boards [STSW-STPM001]

Graphical user interface for EVALSTPM-3PHISO reference design [STSW-STPM005]

Embedded firmware for EVALSTPM-3PHISO reference design with low-cost shunt current sensors [STSW-STPM004]

1. https://www.mckinsey.com/industries/electric-power-and-natural-gas/our-insights/the-impact-of-electromobility-on-the-german-electric-grid
2. https://europe.nissannews.com/en-GB/releases/nissan-enel-and-nuvve-operate-world-s-first-fully-commercial-vehicle-to-grid-hub-in-denmark
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5. https://www.eetimes.com/prevent-tampering-in-energy-meters/
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