Application Note

User Guide for E-Metrology Library for Digital Power Applications with F28P55x and F28P65x

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ABSTRACT

Modern electrical systems demand high-precision metrology and comprehensive power quality (PQ) analysis, tasks that challenge conventional microcontrollers with real-time processing of complex waveforms and computationally intensive algorithms. This application note introduces a tailored metrology software library designed for Texas Instruments C2000™ real-time microcontrollers, specifically leveraging their integrated 32-bit Floating Point Unit (FPU32), trigonometric math unit (TMU), and inherent DSP capabilities to overcome the challenges. The library delivers a rich set of high-accuracy measurements—including true RMS voltage and current, multi-phase active, reactive, and apparent power and energy, power factor, line frequency, sag/swell detection, and precise FFT-based total harmonic distortion (THD)—all performed using high-precision 32-bit floating-point arithmetic. The efficient split-architecture, separating time-critical background data accumulation (conceptually driven by ADC interrupts) from complex foreground calculations, maintains optimal performance. This work highlights the distinct advantages of C2000 MCUs, such as native floating-point FFT execution and dedicated DSP instructions, offering superior performance and accuracy for demanding metrology and PQ applications compared to general-purpose MCUs.

Table of Contents

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1 Introduction

The evolution of modern electrical infrastructure, including smart grids, renewable energy integration, and sophisticated industrial automation, places increasingly stringent demands on the accuracy and comprehensiveness of electrical parameter measurement. Precise metrology—the science of measurement—is no longer just about basic energy consumption; metrology now encompasses detailed power quality (PQ) analysis, crucial for maintaining grid stability, equipment longevity, and operational efficiency. Parameters such as RMS voltage and current, active and reactive power, power factor, frequency, and harmonic distortion provide vital insights into the health and performance of electrical systems. However, implementing robust metrology and PQ analysis designs presents significant technical hurdles. Modern electrical loads are often non-linear, leading to distorted current and voltage waveforms rich in harmonics. Accurately processing these complex signals in real-time, while performing computationally intensive algorithms like fast Fourier transforms (FFTs) for harmonic analysis or precise dot-product accumulations for true RMS and power calculations, strains the capabilities of traditional microcontrollers. Furthermore, achieving the high-precision required by metrology standards, often necessitating floating-point arithmetic, adds another layer of complexity, particularly on resource-constrained embedded platforms.

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2 Library Architecture

To meet the stringent real-time requirements of continuous power monitoring and maintain that no critical data is lost, the metrology library employs an efficient split-processing architecture. This design decouples time-sensitive tasks from less frequent, more computationally intensive calculations, optimizing resource utilization and maintaining system responsiveness. The architecture is broadly divided into two main processing layers - background processing and foreground processing.

Background Processing:

Executed at a high frequency, typically synchronized with the analog-to-digital converter (ADC) sampling rate, the background processing tasks are handled within an Interrupt Service Routine (ISR). The primary responsibilities of this layer include:

1. *Raw Sample Acquisition*: Reading the latest voltage and current samples from the ADC.
2. *Essential Pre-processing*: Performing minimal, time-critical operations on the raw samples, such as DC estimation and filtering to remove any DC bias.
3. *Core Accumulations*: Calculating and accumulating fundamental dot products (for example, sum of squared voltage samples, sum of squared current samples, sum of voltage-current products) over a defined measurement window (typically one or more mains cycles). These accumulations form the basis for most subsequent metrology calculations.
4. *Data Buffering and Synchronization*: Managing data buffers and preparing accumulated data for safe transfer to the foreground tasks.

The key design principle for background processing is to keep the ISR execution time as short as possible to maintain high sampling fidelity and allow the system to respond to other critical interrupts.

Foreground Processing:

Operating at a lower frequency within the main application loop, the foreground tasks are triggered once the background process has accumulated a complete block of data. This layer handles the more computationally intensive calculations, including:

1. *Retrieving Accumulated Data*: Safely reading the consistent set of dot products and other relevant data logged by the background task.
2. *Applying Calibration*: Correcting the raw accumulated values using pre-determined calibration coefficients to compensate for sensor inaccuracies and analog front-end variations.
3. *Calculating Final Parameters*: Computing the full suite of metrology parameters, such as RMS voltage and current, active, reactive, and apparent power, power factor, frequency, THD, and sag/swell events, using the calibrated data.
4. *Energy Accumulation*: Integrating power values over time to calculate energy consumption. Updating Results: Making the final, calibrated measurements available to the application for display, logging, or communication.

Data Transfer Mechanism:

A crucial element of this split architecture is the robust data transfer mechanism between the background ISR and the foreground tasks. The library employs a synchronized hand-off technique, often referred to as double-buffering, to maintain data integrity. The process is as follows:

1. The background ISR continuously updates a primary set of accumulators with per-sample data.
2. Once a complete measurement block (for example, a defined number of samples or mains cycles) is accumulated, the background task copies the current values from these primary accumulators to a secondary, "logged" set of variables.
3. A status flag is then set by the background task, signaling to the foreground task that a new, consistent block of data is ready in the logged variables.
4. The foreground task, running in the main application loop, periodically checks this status flag. Upon detecting that the flag is set, it knows that a complete and consistent set of data is available in the "logged" accumulators. It then proceeds to use this data for its calculations.

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3 Metrology Calculations

The actual metrology calculations take place in the *meterology_caluclations.c* file.

1. This module contains the library of mathematical functions that implement the metrology algorithms.
2. The module takes inputs such as accumulated dot products, sample counts, and calibration data.
3. The module outputs the calculated electrical parameters (for example, calculateRMSVoltage, calculateActivePower, calculateFrequency_PLL).

4 Configuration and Data Structures

1. These files define constants (for example, nominal voltage/frequency, sample rates), preprocessor macros for feature enablement (for example, HARMONICS_SUPPORT, NEUTRAL_MONITOR_SUPPORT), and the critical data structures that hold all metrology-related information.
2. *metrologyData*: The top-level global structure, an instance of which holds all data for all phases, neutral, totals, and system status.
3. *phaseMetrology / neutralMetrology*: Structures within metrology data containing parameters (params) and readings (readings) for each phase and the neutral line.
    a. params: Stores configuration, intermediate accumulations from background (like dotProd arrays), calibration-derived values, and state variables (for example, for PLL, sag/swell).
    b. readings: Stores the final calculated metrology values (RMS, power, PF, and so on).
4. *calibrationData* (metrology_nv_structs.h): Holds the calibration coefficients.

5 Calibration Module

1. Manages the loading, application, and storage (conceptual) of calibration data.
2. *Metrology_setup_init* (or similar in metrology_setup.c) initializes data structures and applies initial calibration settings like phase corrections.

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6 Applications and Use Cases

Calculation of metrology parameters using this C2000-based library finds applications in multiple areas of digital power industry and beyond. The following are some examples of these applications.

1. **Smart Electricity Meters**
    - *Billing Accuracy*: High-precision measurement of RMS voltage, current, active power (Wh), reactive power (VARh), and apparent power (VAh) across multiple phases maintains fair and accurate billing for residential, commercial, and industrial consumers.
    - *Power Quality Monitoring*: Integrated sag/swell detection and THD analysis provide valuable data for utilities to monitor grid health and for consumers to understand the quality of power supplied. This data can be logged and reported.
    - *Load Profiling*: Detailed energy consumption patterns can be recorded, helping utilities with demand-side management and consumers to optimize their energy usage.
2. **Power Quality Analyzers (PQAs)**
    - *Comprehensive Event Detection*: The library's sag, swell capabilities are fundamental to PQAs. The logging of event duration and magnitude allows for detailed event analysis.
    - *Harmonic Analysis*: The FFT-based THD calculation (vTHDfft, iTHDfft) and the underlying find_harmonics function (from metrology/metrology_calculations.c) provide the spectral data needed to identify specific harmonic orders and their magnitudes, crucial for diagnosing issues like equipment overheating or interference.
3. **Industrial Automation and Control**
    - *Motor Monitoring and Protection*: Monitoring current, power, power factor, and THD for large motors can predict failures, optimize efficiency, and protect against adverse conditions like phase imbalance or overload.
    - *Energy Management Systems (EMS)*: In factories and large facilities, the library can be the core of sub-metering units, providing granular data on energy usage by different sections or machinery, enabling targeted energy-saving initiatives.
4. **Renewable Energy Systems**
    - *Solar Inverters*: Monitoring AC output voltage, current, frequency, power, and THD is essential for grid-tied solar inverters to maintain compliance with grid codes and optimize power injection.
    - *Energy Storage Systems*: Measuring power flow (import/export, as supported by the energy accumulation logic) and quality is vital for battery management and grid interaction in energy storage applications.
5. **Electric Vehicle (EV) Charging Stations**
    - *Accurate Energy Dispensing*: Precise measurement of energy delivered to the EV is critical for billing.
    - *Power Quality Impact*: Monitoring the impact of off-board EV charging on the local grid, including harmonic injection and voltage stability, can be achieved using the library's THD and sag/swell features.
    - *Smart Charging*: Real-time power data can enable smart charging algorithms that adjust charging rates based on grid conditions or electricity prices.
6. **Data Centers**

- *Power Distribution Unit (PDU) Monitoring*: PDUs in data centers require accurate monitoring of power consumption at the rack or server level for capacity planning, billing, and efficiency optimization (e.g., Power Usage Effectiveness - PUE).
- *Input Power Quality*: Maintaing the quality of power supplied to sensitive IT equipment is crucial. The library can monitor sags, swells, and harmonics that can affect server reliability.

The combination of the C2000™ MCU's real-time processing capabilities and the comprehensive algorithms within this metrology library provides a versatile platform for these applications.

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7 Helpful Links

Please find some links that are relevant to the E-Metrology library *here*. Details on user configurations, memory usage of the library, theory behind how these metrology parameters are calculated and so on are discussed here. This page also provides a link to download the E-Metrology library.

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