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Enabling Grid Resilience and Efficiency - EDGE Device for Power Grid analysis and Asset Monitoring

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Abstract

The integration of renewable energy sources (RES) into power distribution grids is crucial for achieving global green energy objectives. However, RES power inverters can adversely impact power quality, increase losses, and lead to power interruptions due to issues such as harmonics, frequency deviation, and grid fault response limitations. To address these challenges, this paper presents an innovative solution combining hardware and software components based on Phasor Measurement Unit (PMU) and EDGE processing technologies that provide the ultimate tools for real-time monitoring of the distribution power grid. The proposed solution, designed for research and innovation activities, features a low-cost, high-performance architecture that facilitates real-time monitoring of secondary distribution substations.

1 Introduction

Today, various devices and equipment are used to monitor the power grid key assets to provide operators with a detailed picture about the state of their grid. Phasor Measurement Units (PMUs) play a significant role in acquiring and digitizing the voltage and current phasors with high sampling frequencies. By using advanced signal processing and correlation techniques on the data received from several PMUs, a high-quality analysis of the dynamic behavior of the electric power grid can be performed. Moreover, EDGE computing paved the way for de-centralized operation in distribution power grid application.

This integrated solution described is based on an open PMU architecture with EDGE processing capability (Nikolaos-Antonios I. Livanos, 2023) and it offers significant advantages in enhancing grid resilience, efficiency, and eventually CO2 reduction. By leveraging the EDGE processing capability of the PMU platform, real-time asset monitoring and diagnostics are achieved. The device offers continuous monitoring of key parameters and enables the detection of grid anomalies, facilitating fast and automated fault detection, isolation, and recovery. Moreover, the solution supports state estimation, power quality monitoring, and dynamic events analysis, among other data-driven valueadded services.

The hardware device is equipped with a Digital Signal Processor, a high-end processor capable of running a Linux OS, and a phasor measurement unit. It is deployed at secondary distribution substations to enable comprehensive analysis of the grid's performance and to facilitate proactive maintenance strategies. The use of EDGE computing capabilities and cloud technologies allows for scalable deployment and efficient management of the system. A pilot implementation of the prototype design has been successfully deployed in multiple medium-to-low-voltage substations across Cyprus.

This paper showcases the successful implementation of the solution, highlighting its potential to revolutionize power grid analysis and diagnostics. The combination of hardware, software, and advanced monitoring capabilities demonstrates the effectiveness of the solution in achieving the goals of grid resilience, efficiency, power theft detection, and CO2 reduction. The results obtained from the pilot demonstration phase validate the performance and value of the proposed system, paving the way for future research, development, and widespread adoption in the energy sector.

2 System Overview

The overall system consists of the following four major components:

1. Secondary Transformer Monitoring (STM) devices, which serve as a data acquisition point for measuring various variables related to the grid and the transformer.
2. The central application (SCADA), which takes on the role of managing and coordinating the operations of these edge devices. It oversees their operations, retrieves the acquired data from each device, stores them in the central database, and handles tasks that demand more computational resources.
3. The graphical user interface is a web-based environment that provides real-time monitoring representation of the system using graphs, time plot elements, alert notifications as well as the option to view past stored data.
4. The AI-based algorithms are fed with the updated data and executed iteratively to provide more accurate results. These algorithms are mainly specialized for power theft detection, but other applications are also supported, like load prediction, islanding, power flow, and optimal power flow.

Figure 1 illustrates the top-level design of the overall system, providing a visual representation of its high-level structure and functionality.

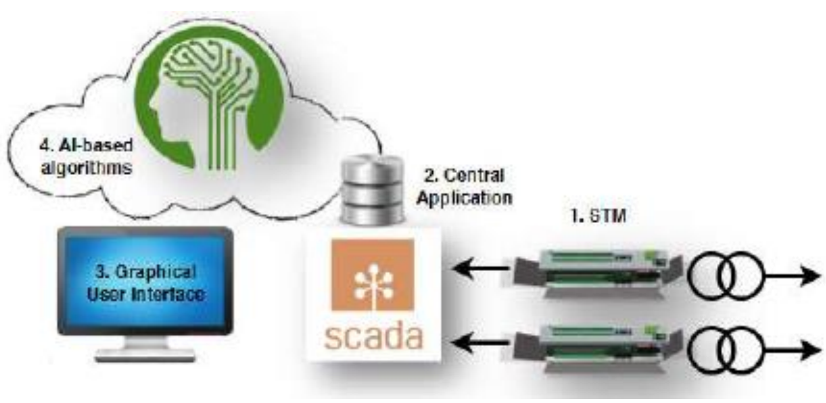

Figure 1: Top-level logical diagram of the solution

3 Hardware Description

The STM device supports easy installation through non-invasive and non-disruptive means. It is divided into two parts: the primary part housing the main components, and the secondary part housing external sensors mounted on the transformer. Figure 2 illustrates the logical structure of the STM device, providing a visual representation of its components and their relations. Specifically, the following components comprise the hardware device:

1 **Gateway (GW):** this is essentially the module that provides the EDGE capability, which is based on the OSD3358 System-in-Package (SiP) developed by Octavo Systems (Octavo systems; Rev, I.N.D. 2022). It can run a Linux operating system and it is responsible for collecting the measurements from the PMU and the RTU, storing them into its database, handling requests from the central application, and synchronizing all the data between the device and the server.

2 **Phasor Measurement Unit (PMU):** this includes an analog front-end that interfaces with the transformer to acquire the voltage and the current measurements. It is comprised of an analog-todigital converter (ADC) for signal sampling and a Digital Signal Processor (DSP, based on TI's low-power C55x fixed-point DSP TMS320C5517) (Texas Instruments. TMS320C5517 Fixed- Point Digital Signal Processor) that executes its own firmware regarding data acquisition, storage, and processing.

3 **Remote Terminal Unit (RTU):** this includes a simple 8-bit microcontroller running its own firmware for handling the communication between the external sensor and the gateway via the RS-485 interface, regarding data transfer and control.

4 **Power supply:** this includes two AC/DC converters to distribute power to the internal components. One converter supplies power to the 4G modem (12V DC), and the other powers the remaining components (5V DC). Additionally, a UPS is utilized to ensure uninterrupted operation during power outages.

5 **4G Modem:** configured with a static IP SIM card, this is used for remote communication and control of the STM device from the central application. It also establishes a local network in the installed substation, to provide seamless connectivity with external devices when it is necessary.

6 **GPS:** this is utilized for enabling synchronized data sampling across multiple STM devices by using the pulse-per-second (PPS) signal.

7 **External Sensor:** this is the secondary part, which includes a set of board sensors for measuring the temperature, humidity, magnetic field, and acoustic noise. It utilizes a microcontroller that interfaces with each sensor, and it is responsible for collecting the measurements and handling the data requests from the RTU via the RS-485 interface.

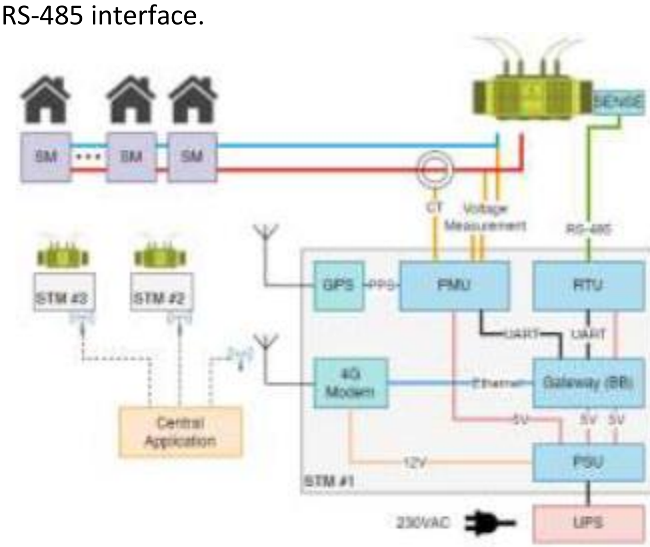

Figure 2: Logical structure of the STM device.

4 Application Results

One of the outcomes of the application is the demonstration of power theft detection. Specifically, two power theft detection methods were utilized, both based on analyzing the collected measurements and identifying discrepancies in technical losses. The first method is done by examining the statistical characteristics of technical losses for a given secondary substation within a certain period to identify potential instances of power theft. Essentially, a set of measurements from both the STM device and the smart meters must be made available to perform the analysis.

The calculation of technical losses is performed using the equation (1) outlined below:

$$E_{STM} = \sum E_{SMi} + E_{TL} \qquad (1)$$

The calculated energy by the STM device (E_{STM}) is equal to the sum of each smart meter energy (E_{SMi}) plus the energy of the technical losses (E_{TL}). Given that E_{STM} and E_{SMi} are known quantities, equation (1) can be solved to calculate the energy of the technical losses.

In general, the energy of the technical losses remains around the same average value, but even if it changes, it happens due to factors unrelated to power theft (e.g., seasonal weather, equipment wearing, etc.). However, if a sudden difference is observed, then this may be considered a potential instance of power theft, in which case further investigation must be performed to confirm or rule out the possibility.

Figure 3 below shows a plot depicting the energy measurements from the STM device, the smart meters, and the technical losses. Two distinct periods are highlighted where abrupt changes in the technical losses' values were detected. These discrepancies indicate the potential occurrence of power theft and showcase the capability of the method to detect such events.

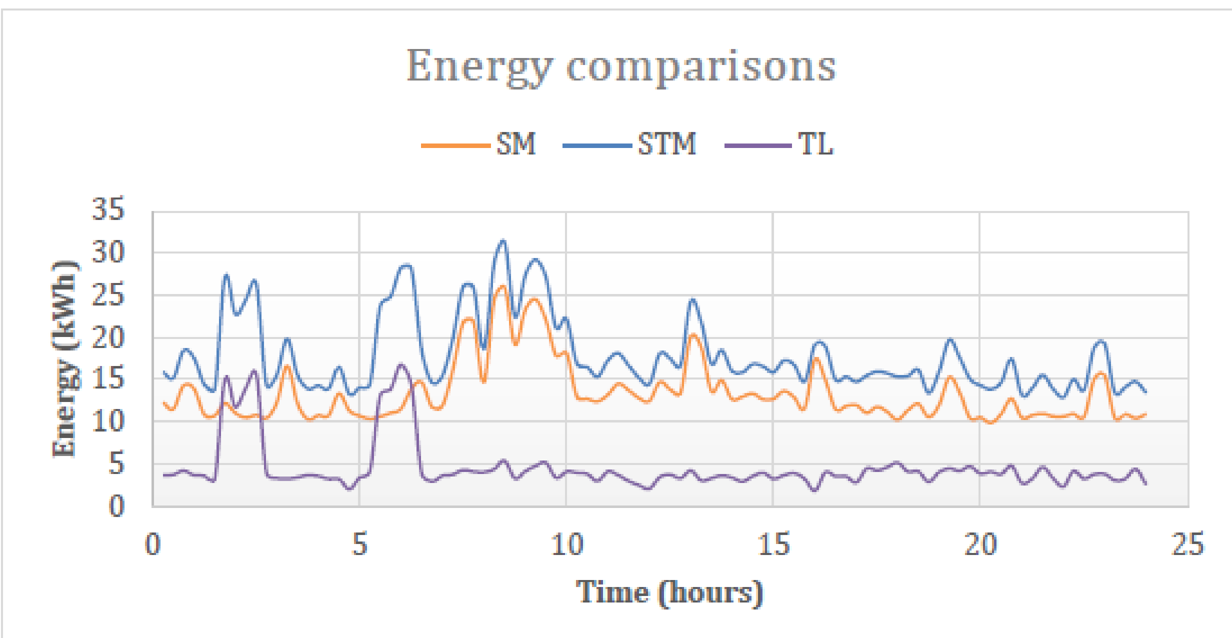

Figure 3: Energy measurements comparisons showing a case of power theft.

The other method to power theft detection involves using the same historical consumption data from the smart meters and comparing it to the values obtained through sequential power flow simulations. In these simulations, different consumers are selected as the slack bus each time. If there is a difference between the measured consumption from a smart meter and the simulated consumption, then this indicates the possibility of an electricity theft event occurring at that specific position in the grid. To perform the power flow method the Pandapower Python library is utilized, which is commonly used for power system modelling, analysis, and optimization (Thurner, et al., 2018), and it has been successfully applied in multiple grid studies (Menke, 2018) (Scheidler, Thurner, & Braun, 2018) (Thurner, Scheidler, Probst, & Braun, 2017) (Wang, 2017).

5 Pilot Operation

The implementation of the solution has been successfully carried out as part of the "Technorevmeta" project during the technology demonstration phase. This collaborative effort involved the Electricity Authority of Cyprus (EAC), the Frederick University in Cyprus, and the Photos Photiades Group, a beverage company, which allowed us to conduct a pilot demonstration at one of their production facilities.

The devices have been in operation for more than a year, continuously measuring the necessary parameters. The central application has been successfully deployed, enabling constant monitoring of communication with the edge devices. It efficiently retrieves data from them every minute and stores it in the central database.

Figure 4 shows its deployment in the secondary substation adjacent to the transformer, and Figure 5 shows the external sensor mounted on the transformer.

Figure 4: STM device installed at the pilot location

Figure 5: External sensor installed on the transformer.

6 Conclusion

In the context of digitizing electrical grids, various challenges emerge, including the need for effective asset monitoring, especially for transformers, and the detection of power thefts. This paper outlines the development of a comprehensive solution that addresses these challenges, making use of the processing capabilities and real-time communication facilitated by the Secondary Transformer Monitoring (STM) EDGE devices installed on secondary distribution transformers. The STM devices play a crucial role in enabling computationally intensive operations, allowing for the analysis of measured data through AI models. The primary objective of this analysis is to identify anomalies in energy generation and consumption that may indicate instances of power theft. A pilot demonstration has already been conducted, capturing, and storing valuable data to train the AI models. The initial results obtained for power theft detection show great promise, and as the training process continues and more data becomes available, these models are expected to exhibit even more significant improvements in the coming months.

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