Plug & Play Monitoring for Distribution Substations

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Abstract—**New decentralised and mostly renewable energy sources and the increase in the e-mobility domain cause new challenges for the grid infrastructure. Especially, the low-voltage grid will be affected. A necessary step towards a resilient operation of future grids is to equip the low-voltage grid with sensors, which will provide sufficient monitoring data for the implementation of intelligent planning and control algorithms. Since the infrastructure is very durable and not all distribution substations are equipped with sensors, this paper presents a Plug & Play monitoring system that can be easily integrated into existing substations. The system consists of a local controlbox and fully wireless, energy self-sufficient current sensors. The sensors are attached to the individual phases of secondary feeders, measure the line current and transmit the data to the controlbox using a time synchronized wireless communication protocol. The controlbox measures the secondary voltage directly, calculates all relevant power values of the substation and transmits them to a backend (e.g., SCADA). In order to demonstrate the functional principle of the proposed monitoring system, a prototype of the current sensor and the backend is presented in this paper.**

Index Terms—**Smart Grid, Plug and Play, Monitoring Systems, Wireless Time Synchronisation, Energy Harvesting, Power Quality, Low-voltage Grid**

I. INTRODUCTION

The growing diversity of decentralized energy consumers and producers poses a great challenge for the future power grid. E-mobility, demand-response applications or intelligent prosumers as well as the increasing generation of renewable energy require intelligent planning and controlling of the low voltage grid. To efficiently facilitate the grid by preventing from overloads and outages, new control and protection concepts must be developed [1].

According to [2] (among others) these future challenges can not be addressed by using existing static plans and strategies (e.g., pricing policies and load shedding schedules) but have to include dynamic control algorithms. New monitoring concepts must ensure a continuous resilient monitoring of the grid status, while being able of handling a variety of different sensors in terms of data quality, temporal resolution, communication protocols and reliability. If these problems are not addressed early enough by either pushing ahead with appropriate grid expansion or designing new and intelligent control concepts, supply failures and associated costs can occur. For example, if we look at the costs of congestion management, we can already see an alarming increase. According to [3], the the congestion management costs in Austria in August 2019 were higher than for the entire year 2015.

One major problem with the necessary evolution of the smart grid is that the transition from the traditional to the new intelligent grid lacks a exhaustive availability of measurement data. Sufficient data is needed to support and control the grid operation and to optimize planning activities.

Currently, reliable monitoring data is only available up to the medium-voltage outputs of the substations. The future challenges, however, also require measurements in (distribution-) substations and possibly even in distribution boxes in the low-voltage grid. The infrastructure installed there is very long-lasting. Due to the relatively constant load increase in the past, planning of reserves during the construction of substations (e.g., n-1 redundancy for urban distribution grids) was therefore the reason why no monitoring had previously been necessary in the low-voltage grid. The challenge to create a sufficient sensor density in the low-voltage grid therefore lies not only in the fact that an appropriate monitoring system must be provided when planning future stations, but especially in the fact that many of the currently active stations do not have such a system, but still have an expected service life of several decades.

In order to enable exhaustive data collection in the distribution grid, a retrofittable monitoring system for the existing infrastructure is necessary. Here the problem is that this system needs to be installed cost-effectively, fast and without interrupting the supply. In the case of maintenance work following faults, the issue of additional cables to instrument transformers etc. is also an issue, as these are very obstructive for the grid technicians.

In order to address these challenges, we propose a Plug & Play monitoring system with which existing distribution substations can be cost-effectively retrofitted. The system consists of a *central controlbox* and a number of *current sensors* per substation with the following key objectives:

A A noninvasive measuring method must be used to reduce installation effort and avoid the need for shutdowns during installation.
B Wireless communication is required to avoid additional cables inside the substation.

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C Energy Harvesting is needed to allow for autonomous measurements without built-in batteries (reduce maintenance effort).

D Current and voltage measurements must be synchronized to allow calculating accurate power and phase values.

The rest of this paper is organized as follows: After a review of related work (section II) the proposed monitoring system is introduced in section III. The single current sensor and the data transmission are further discussed in section IV. Results of the proposed system are shown in section V and finally conclusions and an outlook are given in section VI.

II. RELATED WORK

Conventional measurement systems are usually limited to the measurement of current and voltage using wired solutions. Typical devices include individual measuring units which are connected to the measuring device via a cable (e.g., [4]). In order to simplify retrofitting, wireless sensors are preferred that are able to independently generate energy for their operation are preferred. In addition to the reduced maintenance costs due to the absence of a battery, such a system has lower installation costs, since the subsequent professional (and therefore time-consuming) wiring is no longer necessary. The monitoring system presented in this paper therefore includes radio sensors for autonomous measurement and data transmission.

Nowadays, more and more research work is focusing on the topic of radio communication in autonomous measurement sensors. In [5] a system is described, which uses a current transformer for the combined measurement and energy harvesting of household cables and transmits the measured current values using the IEEE 802.15.4 standard. With a connected load of 300 W, the sensor can measure and transmit data every 60 seconds. However, the sensor requires a backup battery to start properly. In [6] a similar sensor is presented, which in contrast to the previous work can also be mounted around a double line (N+L) and does not require a battery. With a line current of 4 A, up to 1.89 mW of energy can be harvested by this system. However, the sensor must be mounted in a certain and rigid position on the cable. Another concept from [7] also requires a correct and fixed installation. This monitoring sensor is able to measure voltage and current non-invasively and to transmit the data. With a line current of 170 A, data can be transmitted every 2 minutes. The current measurement sensor presented in [8] also does not require a backup battery. Here, two separate modules are used for energy harvesting and measurement. The current is measured using a Rogowski coil and a current transformer is used for energy generation. This allows an individual adaptation of the two elements and an optimized operating range, but increases the hardware and cost. The system is designed for medium-voltage lines and achieves a power consumption of 0.3 W for sensor operation in an operating range from 1 A to 1000 A line current. Furthermore, in [9] a sensor is presented which extracts sufficient energy for current and temperature measurement from the stray field of an power line by means of a flux concentrator. With a line current of 50 A to 1000 A, the sensor is active, measures the line current periodically and transmits the data wirelessly. At 100 A, the sensor can start a measurement once per minute and transmit the result. However, current measurement via the stray field also requires a precise mounting or calibration of the attached sensor and is therefore not suitable for simple installation.

The mentioned systems generally require either a backup battery for black start, use separate technologies for measurement and harvesting modules, or require precise placement and installation. The system presented in this paper is designed to overcome these disadvantages and can be flexibly attached to the lines of any (local) network station using only one technology and without a backup battery.

III. MONITORING SYSTEM

The main concept of the Plug & Play monitoring system is shown in Figure 1. The currents of the individual low-voltage feeder phases of a substation are measured by autonomous sensors. The sensors, hereinafter referred to as ”nodes”, consist of a current measurement module, an energy harvesting module, a microprocessor for data processing and a wireless transceiver for communicating with the central node in the substation, hereinafter referred to as a ”controlbox”.

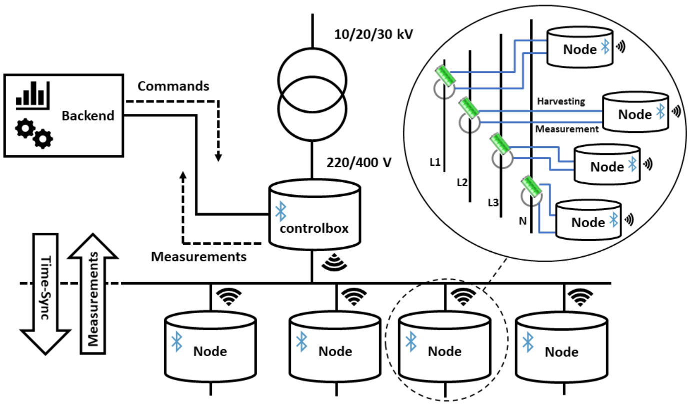

Fig. 1. Plug & Play Monitoring System

One single commonly-used current transformer with a split core is used for both current measurement and energy harvesting. On the one hand, the sensors can therefore work autonomously and without batteries. On the other hand, they can be easily attached to the secondary feeder phases without having to interrupt the station operation. As the current transformers can be easily attached to the existing cables (due to the divisible core), neither precise mounting nor destructive manipulation on the cables are necessary. This reduces effort during operation and installation, thus reducing costs over the entire product cycle compared to other solutions discussed in section II.

In addition to the current measurements, the controlbox itself measures the voltage directly at the busbar or similar existing tapping points (with state-of-the-art voltage sensors) locally and temporally independent of the nodes. In order to measure phase angle and power parameters, current and voltage measurements are synchronized. Since the data from the sensors are transmitted wirelessly to the controlbox, the selected wireless technology must ensure sufficient synchronicity. The controlbox is on the edge to the outside world and exchanges operational and management data with the external backend (e.g., SCADA or other tools for grid operators).

IV. NODE

Figure 2 shows the structure of a single node. The main element is a current transformer with a split core, which can be mounted in any position on the cable to be measured. This core is used for both current measurement and energy harvesting. The necessary measuring and harvesting circuit as well as the microcontroller and the radio module are mounted together on the current transformer and result in a fully wireless and compact module. A current transformer was chosen because it is well suited for the combined use of measurement and harvesting. Its bandwidth is sufficiently high for power analysis in the low voltage grid and the high power transmission (compared to, e.g., a Rogowski coil) enables a long measurement and transmission (=active) phase.

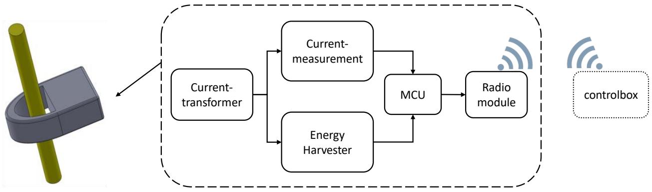

Fig. 2. Node overview

A. Energy Harvesting and Measurement

For the design of the harvesting and measuring circuit, a simulation model of the current transformer was initially created and verified in *LTSpice*® according to the nonlinear transformer model presented in [10]. A commercially available *60/1* current transformer (*Gossen Metrawatt SC30 60/1*) was selected for the first laboratory prototype. Based on this simulation model, various harvesting and measurement circuits were analyzed in *LTSpice*®. A super-capacitor (super-cap) was chosen as energy storage. In order not to influence the measurement by the harvesting circuit, the sensor always changes between harvesting and measuring phase. In the harvesting phase, the microcontroller and the radio module are not powered and deactivated. The current transformer charges the super-cap up to a target voltage (*VT,HIGH*) and then automatically switches to the measurement mode. In this phase, the capacitor is no longer charged and the harvesting circuit is disconnected from the converter in order to generate a measurement signal that is as accurate as possible. As long as the energy in the capacitor is high enough, the sensor measures the line current, preprocesses the measurement data (e.g., low-pass filter, offset-correction, etc.) and transmits it to the control box. If the voltage at the super-cap drops below a target value (*VT,LOW*), the sensor automatically switches back to harvesting mode. In other words, the black start case (= energy is exhausted) is part of normal operation and therefore no additional backup batteries are required. Figure 3 shows the complete analog circuit design of the designed sensor including the primary line and the current transformer model (CT) in *LTSpice*®. This circuit changes independently between harvesting and measuring phase without backup battery and provides a stable 3.3 V supply (*Vs*) and an amplified measuring signal (*M1*) for a microcontroller and the radio module during the measuring phase. The upper and lower target voltages (*VT,HIGH* and *VT,LOW*) are set by the resistor network *R1*, *R2*, *R3*, *R4* and *R5*. Thus, depending on the voltage range and capacitance of the super-cap, the charging time and the available energy in the measuring phase can be varied on the one hand and the minimum required primary current (line current) for sensor operation can be adapted on the other hand. With an upper target voltage (*VT,HIGH*) of 2.5 V, a minimum primary current of approximately 22% rated current of the current transformer is required.

B. Digital Logic and Data Transmission

The system as sketched in Figure 1 is composed of n nodes attached to the different feeder phases and a controlbox, which aggregates and preprocesses incoming data from the nodes and forwards them to a backend. In the context of smart grid operation, a number of wireless protocols, such as IEEE 802.11/Wi-Fi [12], Bluetooth IEEE 802.15.4/ZigBee [13], Bluetooth Low Energy (BLE) [14] or 6tisch [15] have been investigated [16]. As sensor nodes are distributed in a substation only a few meters apart and provide only a limited energy budget for communication, the system proposed in this study, requires the application of a wireless protocol, suitable for indoor communication which exhibits a very low energy footprint (increased energy consumption on the communication side would decrease the awake time of the sensors and decrease the number of available measurements). In addition BLE supports over the air updates via consumer grade mobile phones, which is another important factor for a plug and play monitoring system.

Given these requirements, the communication between the sensor nodes (controlbox and nodes) was realized using the BLE protocol [17]. For the proof-of-concept the communication system was realized with Nordic nRF52840 dongles (for implementing the nodes) and a nRF52840 development board for the controlbox. Nordic chips were chosen due to the fact that the Nordic framework already provides out of the box solutions for over the air (OTA) updates and a white-paper time synchronization (which is outlined in more detail below), which speed up the development.

Within the system one can distinguish between controlbox and nodes. The controlbox is responsible for measuring the supply voltage (which is required to compute the cos ϕ of the nodes), acts as a master for time synchronisation (required to calculate time-consistent zero-crossings at the nodes) and collects, preprocesses and forwards measurement data received from the nodes towards a backend, where the data is stored in

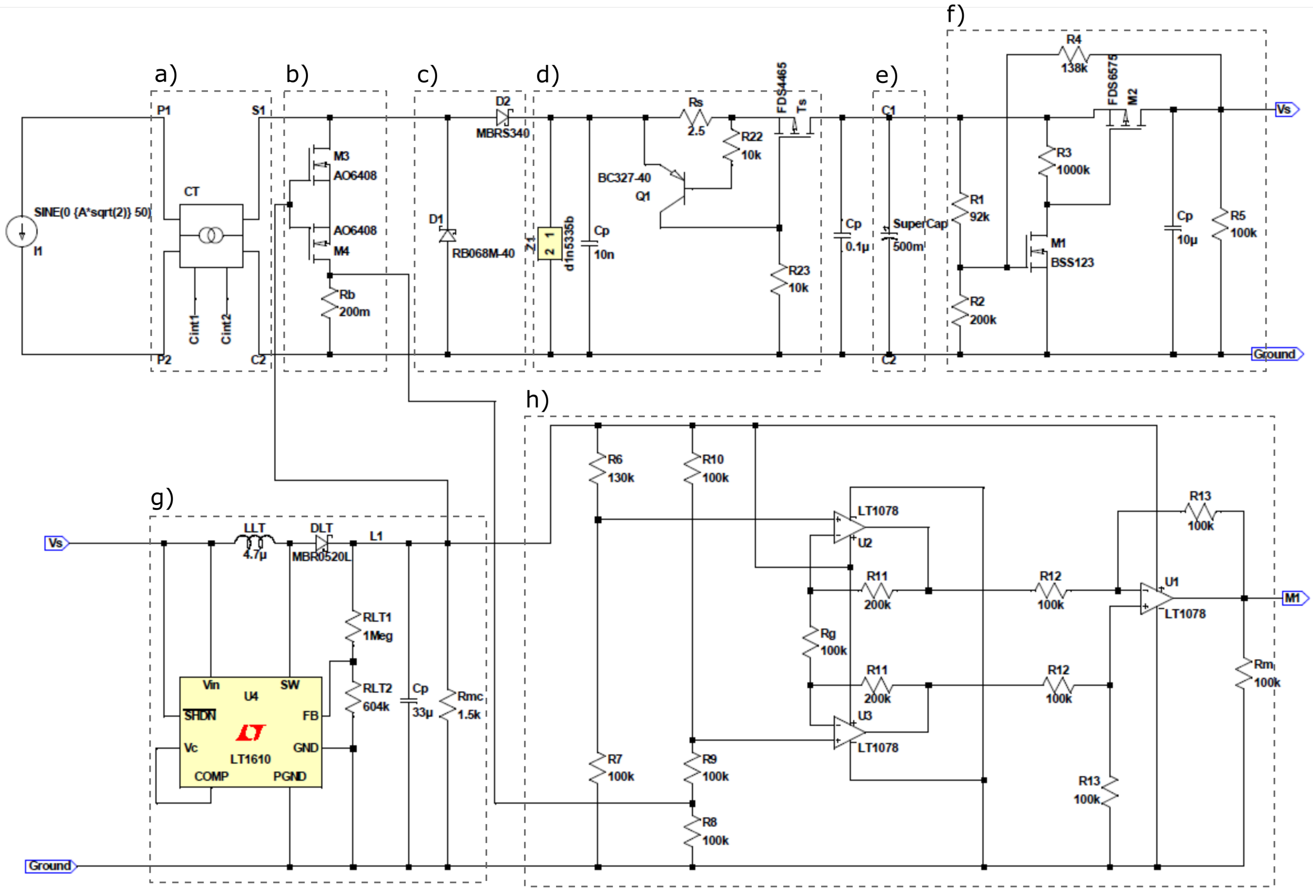

Fig. 3. Analog circuit design of one node: a): *LTSpice*® simulation model of the current transformer; b): switchable burden; c): rectifier; d): current and voltage limiter; e): super-capacitor; f): hysteresis switch; g): DC-DC converter and simulated microcontroller (average power consumption represented by *Rmc*); h): instrument amplifier providing measurement signal *M1* [11]

a database for further processing or depiction. To manage the system a serial connection between backend and controlbox is established and a simple UART protocol was implemented, which allows to control the controlbox from the backend. After establishing a connection with the controlbox and initializing the system, the backend will receive (and store) both data measured at the nodes as well as measured at the controlbox.

Communication between controlbox and nodes was tailored around standard GATT services with one or more characteristics. All characteristics support reading and notifications. The services available comprise of

- A service for the ADC measurements containing a
  - Characteristic for the samples [mV] (1k sample/s). This is done by measuring at a rate of 10k samples per second and averaging over 10 consecutive measurements.
- A service for the derived metrics containing a
  - Characteristic for Mean Voltage [mV] (updated 1/second, over 1k samples)
  - Characteristic for Frequency [mHz] (updated 1/second, only between last two zero-crossings)
  - Characteristic for Zero-crossings, timestamp [ticks]. 1/16000000 seconds per tick. (every zero-crossing from negative to positive)
  - Characteristic for RMS voltage over the first full period in the last 1k samples. [mV] (updated 1/second)

In order to calculate the phase angles based on the observed zero-crossings at the nodes and the controlbox time synchronization among controlbox and nodes is required. To achieve time synchronization a a broadcast type time synchronisation was realized, which is based on MAC time-stamping (Rx and Tx) [1]. The controlbox periodically sends out sync beacons to which all nodes adapt their clock. The sync packet contains the value of a 16 MHz 32 bit timer, a 32 bit counter and an unused field for the RTC (real timer counter) present in the NRF52 series of chips. The offset of the nodes clock (timer and counter) is computed from received packet (adjusting for the known delay from the transmission chain). The controlbox never adjusts its own timer, but broadcasts a synchronisation message with its own timer and counter value at a frequency of 20 Hz, while the nodes try to adjust their clock with 3 Hz. To realize time synchronization the radio uses the time slots

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[1] Technical details regarding the implementation can be found here https://tinyurl.com/yyjb7jpj

API to request a brief windows of dedicated access to the radio. This ”suspends” the BLE operation entirely and uses the simpler enhanced shockburst (ESB) mode. Currently the connection interval is 20 ms (interval between packets) for BLE and 50 ms for the timesync. In order to estimate the energy consumption of the nodes during the active phase, measurements in the various stages of the nodes were performed. The measurements suggest that communication takes around 7.7 mA, when including the ADC this results in a total of around 10.5 mA. To process and save the measured data the CPU requires around 5 mA.

V. RESULTS

Figure 4 shows the designed sensor prototype, which records the measured value and transmits it via BLE communication. The analog measurement and harvesting circuit is framed in red. The orange framed area shows the SoC module nRF52840 from Nordic. The current transformer is connected to the prototype via a connector. The size of the board was chosen for debugging purposes, but basically it its to the size of the current transformer.

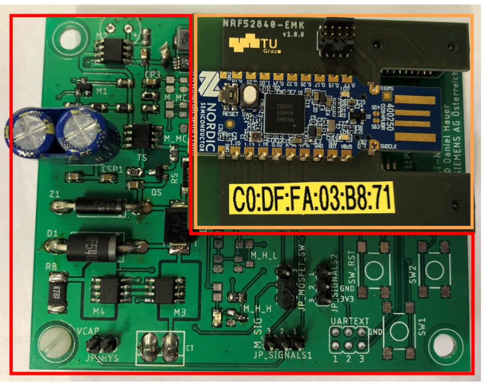

Fig. 4. Prototype of the node: (red) analog measurement and harvesting circuit, (orange) SoC chip and BLE module.

With a sufficiently large primary current (feeder phases current), the prototype is able to switch autonomously between harvesting and measuring phases and to preprocess the recorded current values in the measuring phase and transmit them via BLE. To verify the correct measurement function, the prototype was connected to a test cable in the laboratory. The comparison of the primary current (measured with a calibrated current clamp) with the measured value calculated by the sensor from *M1* is shown in Figure 5. The accuracy of the measurement result lies within the tolerance range of the used current transformer. The observed delay between both signals can mainly be traced back to the characteristics of the current transformer (more precisely its magnetizing current) and is therefore a known source of error for all sensors using current transformers.

The operation of one node can be seen in Figure 6. For this setup the signal from the current transformer was simulated by a comparable and expressive load profile, which was directly fed into the prototype (thus, simulation the secondary side of the current transformer). During the short harvesting mode (a few seconds), the super-cap (Capacitance = 1.5 F) gets charged ($V_{supercap}$ increases) and the microcontroller and measuring part are not powered ($V_{measurement}$ and V_{supply} decrease to Zero). As $V_{supercap}$ reaches the upper threshold (*VT,HIGH* = 2.5 V), the node autonomously switches into the active mode. Now the digital logic is powered with a stable supply voltage V_{supply} = 3.3 V and the measurement signal $V_{measurement}$ correlates to the cable current to be measured. According to the measurement circuit $V_{measurement}$ can be sampled by the microcontroller's ADC and converted back to the original cable current (as shown in Figure 5). During the active mode the super-cap provides the energy for the node's operation and its voltage therefore decreases until the lower threshold(*VT,LOW* = 1.5 V) is reached. With the given setup and parameters the node has an approximate operational life time of 2 minutes before it switches back to the harvesting mode. While the duration of the harvesting mode is related to the primary current (as described in section IV-A), the duration of the active mode is only defined by the power consumption and threshold values of the node itself. The active mode can therefore be optimized for a given use-case by changing the thresholds or adapting the measuring-, transmission- or synchronisation-frequency.

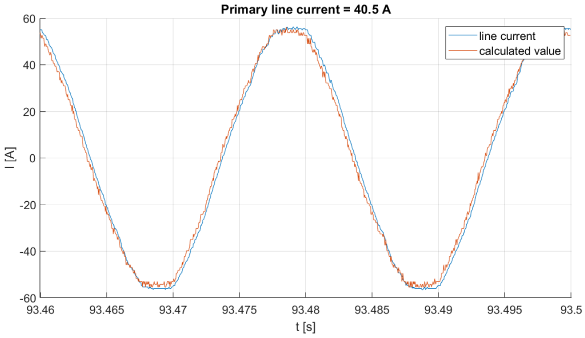

Fig. 5. Comparison of calculated current signal on the node and calibrated measurement of primary current.

Figure 7 finally shows the data of one node collected by the backend (here a Raspberry Pi 4). The voltage of the simulated load profile was measured by the controllbox (nRF52840) using its internal ADC and a self-designed instrument amplifier. The backend triggers the controlbox according to the commands given in section IV-B and thus the node is configured accordingly. Given the inertia of the underlying system RMS values are sent via a node each second (however the system supports a higher resolution, if required), the frequency of the zero-crossing timestamps sent by the nodes depends on the frequency of the underlying system. The left side of Figure shows the stored current RMS values and on the right side an extract of the received zero crossing timestamps can be seen. While the RMS represents the applied load profile, the 20 ms gap between the zero crossings confirm the correct function of the synchronisation process. In the current setup (i.e., using a timesync rate of 3 Hz) time-synchronization

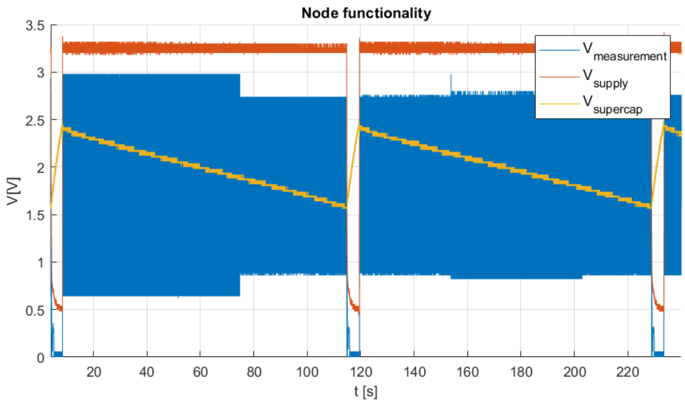

Fig. 6. Node operation: Autonomous switching between harvesting and active mode. Voltages of super-cap ($V_{supercap}$), supply unit V_{supply} and the measurement signal ($V_{measurement}$) are shown. The applied load profile are represented by the varying measurement signal.

achieves a synchronization among the nodes with a deviation of $< 1\mu s$, by increasing the timesync rate the deviation can be further reduced, with the trade-off of reduced sensor wake time.

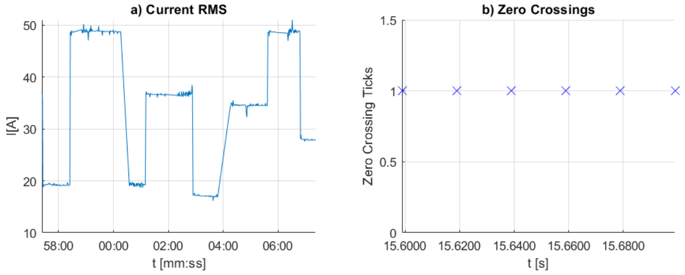

Fig. 7. Collected monitoring data at a backend (Raspberry Pi): a) shows the received current RMS values and b) zooms into the zero crossing timestamps to confirm the synchronisation process.

VI. CONCLUSION AND OUTLOOK

This paper introduced a new wireless Plug & Play monitoring system, which can be easily and quickly installed into existing grid infrastructure. The system uses fully wireless and non-invasive current sensors together with a controlbox to measure and calculate power data of a distribution substation. It can be used to upgrade existing stations which is the big step towards the digitalization of the power system.

The advantages of the presented system are the easy integration into existing distribution substations without the necessity of cost-intensive installation work and the elimination of batteries. This reduces personnel costs for installation and maintenance and increases data density in the low-voltage grid. Another advantage of the autonomously working sensors is the reusability of the monitoring system in different substations. This means that the sensor system can not only be used for permanent monitoring tasks in one substation but also for a temporary deployment in different stations. In addition, the maintenance personnel can access the sensors directly on site with a BLE-capable device and read out the measured values.

Wireless measurement sensors can accelerate the development of the smart grid in the future and therefore represent a promising field of research. The simple integration of Plug & Play sensors would increase the measurement data density and reduce the probability of grid failures.

In future work we will enhance our system by optimizing the harvesting circuit, so that even lower primary currents are necessary for the node's operation, and by synchronizing the active phases of the nodes to get complete substation measurements at once.

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