An Inductively Powered Line-Mounted Time-Synchronized Micro Point-on-Wave Recorder

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***Abstract*— The distribution system is an integral component of the electric power system, but not much is known about how it behaves in real-time. To address this knowledge gap, a low-cost, time-synchronized, micro point-on-wave (PoW) recorder is designed, built, and characterized in this paper. The inductively powered recorder operates wirelessly by using the current flowing through a typical distribution conductor. The recorder is designed to be small, lightweight, and is intended to be installed directly on the power line. To validate the performance of this recorder, tests of measurement accuracy, electric current requirements, and susceptibility to electromagnetic interference from both steady-state and arc-induced sources are performed. The results indicate that the proposed recorder satisfies both the technical as well as the economical constraints required for bulk deployment in an actual distribution network.**

***Index Terms*-- Electric distribution system, Inductive energy harvesting, Hardware design, Point-on-wave recorder, Time synchronization.**

I. Introduction

Although the electric power transmission system has a high penetration of time-synchronized fast speed measurement devices, such as phasor measurement units (PMUs), the penetration of such measurement devices in the electric power distribution system is much lower [1]. Since power outages may occur disproportionately in certain areas of the distribution system [2], and particularly in light of concerns about the role of electric power infrastructure in fire outbreaks [3], it would be extremely valuable to collect real-time, time-synchronized, electrical measurements throughout the distribution system.

A significant barrier to the widespread installation of measurement devices in the distribution system is their relatively higher cost, and to an even greater extent, the cost of the communication and support infrastructure [4]. In part, the high cost of these devices results from the need for robust electrical isolation between medium-voltage power lines and the measurement hardware, which is typically ground-referenced and coupled through instrument transformers [5]. Sourcing on-site power for these devices is also costly, due to the need for suitable low-voltage electrical sources for the operation of the measurement hardware [6]. Finally, the use of dedicated communication infrastructure to relay measurements back to the control center incurs additional cost to the operation of measurement devices throughout the distribution system [7].

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The cost of installation of each of these devices could be drastically reduced if the need for electrical isolation of the devices from the medium-voltage lines which they monitor could be eliminated. Costs could be further reduced if the power needed to operate the devices could be directly obtained from the power lines themselves. Finally, the need for dedicated communication infrastructure for these devices could be eliminated fully or in part by leveraging mature and robust wireless communication networks, including the cellular network and 5th-generation (5G) technologies.

This paper documents the development, physical construction, and characterization of a global positioning system (GPS)-synchronized, point-on-wave (PoW) recorder that is inductively powered from the current flowing through a typical distribution conductor. The proposed PoW recorder is designed to be sufficiently small and lightweight to be installed directly on a power line conductor and is therefore called a micro-PoW recorder. Furthermore, as an added feature to leverage the increasingly bandwidth-capable cellular network infrastructure, the recorder is designed to communicate wirelessly with a base station, and in the future may be equipped with a cellular radio in order to transmit recorded data wirelessly to an operations center or the cloud for real-time analysis/storage purposes.

II. Design Methodology

A. Hardware Selection and Design

The first step in constructing a successful micro-PoW recorder prototype is the identification of the required capabilities of such a device. In order to obtain the design objectives described in Section I, the selected hardware elements must have the following features: (1) onboard analog-to-digital converter (ADC) unit(s), (2) wireless communication capability, (3) ability to simultaneously perform data acquisition and reporting in real-time, (4) GPS timestamp acquisition, (5) ability to measure the current flowing in a conductor, (6) ability to derive sufficient power from the current flowing in a typical distribution conductor to operate all onboard electronics, and (7) protect internal electronics from the effects of transients.

The first design decision involved the selection of the digital components, which would provide the backbone around which all other parts of the micro-PoW recorder would be constructed. The ESP32 system-on-a-chip (SoC) by Espressif Systems fulfills all the microcontroller-related requirements excluding GPS synchronization. The ESP32 SoC features an onboard 12-bit ADC capable of measurement rates in excess of 3,000 samples per second, onboard IEEE 802.11N wireless communication capability, and a dual core processor [8]. In order to furnish the capability of GPS synchronization to the design, the NEO-6M GPS module was selected due to its compatibility with the UART serial interface provided by the ESP32 SoC [9].

The power line current signal was measured using a class 0.5 current transformer (CT) and suitable burden resistor [10]. The quality of the instantaneous line current measurements obtained by the recorder is directly dependent on the measurement accuracy of the CT selected; therefore, the selection of a CT capable of accurately transducing instantaneous current over a wide range of current magnitudes was crucial to the design of the micro-PoW recorder. The CT unit listed in Table I is a split-core unit capable of being installed on a distribution conductor without disconnecting or otherwise modifying it. Due to ease of availability, all testing described in this paper was performed on a comparably rated accuracy class 0.3 continuous-core CT, the 7ASHT-801; however, similar performance is expected from the split-core unit listed in Table I.

A second identical CT to the one in the measurement system was employed as the inductive energy harvesting element. The reason a separate CT was employed for this task was due to the high burden applied to the CT by the energy harvesting circuit, which would otherwise compromise the measurement accuracy of the CT. The raw output signal from the energy harvesting CT was rectified using a full-wave bridge rectifier, and a switching shunt-mode voltage regulator was designed to ensure that the voltage supplied to the rest of the circuit would remain within a safe range. The secondary voltage regulator module that was selected had an input voltage rating of 4.5-24 V [11]; to conservatively allow some overvoltage transients, a maximum output voltage of 22 V was designed into the shunt-mode regulator.

The design of the shunt-mode voltage regulator was crucial in ensuring the reliable operation of the micro-PoW recorder over a wide range of line currents. The IRLZ34PBF power transistor was selected due to its compatibility with 5 V control logic and its low cost [12]. A low-cost dedicated microcontroller was selected to measure the voltage of the recorder's main filter capacitor, and it was configured to switch the IRLZ34PBF on and off in order to maintain a suitable voltage range across the capacitor. Finally, a Zener diode-based regulator was employed to provide linear voltage regulation during the short period of time when the microcontroller first starts up and switched-mode regulation is not possible, as well as to protect the power supply from transients exceeding the response time of the microcontroller. A schematic of the shunt-mode voltage regulator stage of the micro-PoW recorder is depicted in Fig. 1, showing the key elements of the voltage regulation circuit.

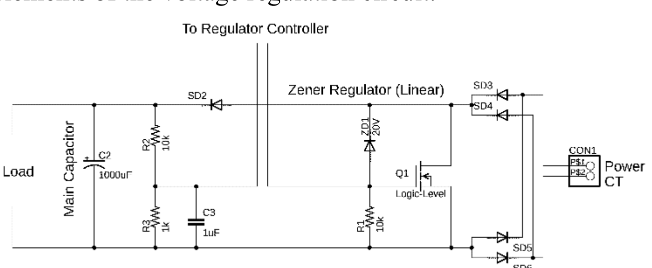

Figure 1: Schematic of the shunt-mode voltage regulator

Another key design parameter was *cost*, as the primary goal of the project was to develop a device that would be affordable and accessible to utilities in order to enable widespread installation. As such, the use of low-cost components was preferred during the selection process. The major components selected for use in the design of the micro-PoW recorder, with CTs priced separately, are listed in Table I. It can be observed that, even at low quantities this micro-PoW recorder is cost-effective to manufacture, and as such may be an attractive option for utilities wishing to expand their ability to monitor their distribution networks.

TABLE I: HARDWARE COMPONENT SELECTION AND COST

Component	**Function**	**Cost**
ESP32-DevKitC-32D	Data Processing, ADC, Wireless Communication	$10.00
NEO-6M	GPS Receiver	$11.99
ATTiny85	Voltage Control	$1.20
IRLZ34PBF	Current Shunt Element	$1.62
DROK 2001708006	Voltage Regulation	$1.80
UB5C-0R2F1	Burden Resistance	$1.34
Circuit Board and Support Components	Component Support and Operation	$9.37
Lm201803261105	Plastic Enclosure	$13.99
	Total Excluding CTs:	**$51.31**
SC4-800/5A (2 Units)	CT (Price for 2 Units)	$119.80
	Total:	**$171.11**

In order to make the micro-PoW recorder easier to manufacture at scale, a printed circuit board (PCB) was designed. All the connections needed to enable the operation of the above-mentioned components, as well as the required support components for the energy harvesting, voltage regulation, and CT burdening circuits were also included on the PCB. Trace widths were selected to enable suitably low resistance to avoid overheating, and signal traces were routed away from the power traces in order to minimize interference. The PCB was installed in a plastic enclosure for mechanical protection as well as for protection from the elements, and the CTs were bolted to the enclosure and wired up internally. A picture of the finished micro-PoW recorder prototype is shown in Fig. 2. In this picture, the finished PCB is enclosed within the Lm201803261105 protective enclosure, and the two CTs are mounted so that their secondary output terminals are inside the protective enclosure. This enables the CTs to serve as mechanical support for the entire micro-PoW recorder assembly. The combined weight of the recorder was measured to be 1.91 kg, which is equivalent to the weight of just 2 m of additional 4/0 distribution conductor [13]. Thus, the addition of this recorder to a typical distribution line should pose minimal impact on its tensile loading.

B. *Software development: GPS and Wireless Configuration*

To ensure that the measurements obtained from one micro-PoW recorder can be correlated closely in time with those taken by other recorders or distribution-level PMUs, it is necessary to time-tag the measurements to a universally recognized timestamp. GPS can be used to provide extremely accurate and globally synchronized time stamps and is already used throughout the electric power industry [14]. Therefore, it was selected as the timing reference for the measurements taken by this micro-PoW system.

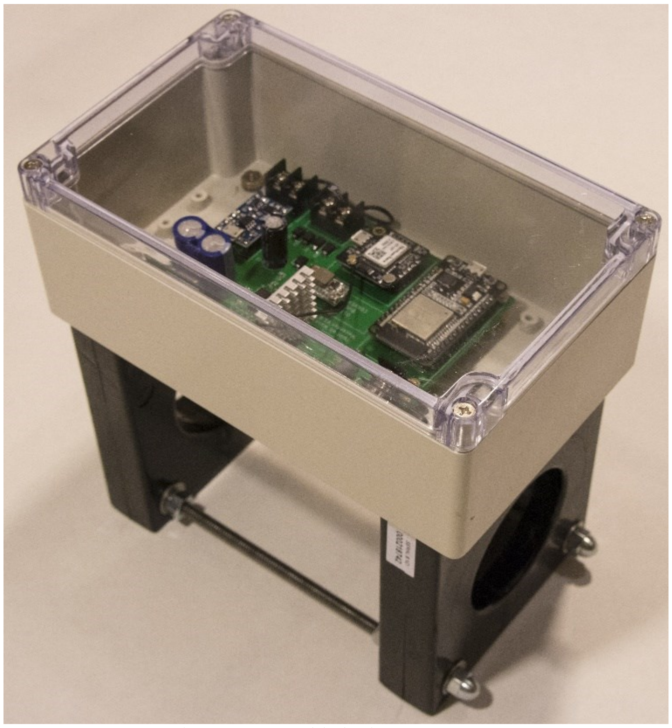

Figure 2. Assembled micro-PoW prototype

The NEO-6M GPS module provides timestamp data to the nearest centi-second via its serial interface, which can be read by the microcontroller. However, because the micro-PoW recorder was designed to capture data at a rate of approximately 3,000 samples per second, these synchronization timestamps were not sufficiently accurate for PoW data synchronization. Instead, the 1 pulse per second (1PPS) signal provided by the NEO-6M module was selected due to its typical accuracy of 30 ns [9], which is well within 1 sample taken by the micro-PoW system. In order to facilitate accurate timestamping of the samples, the Boolean state of the 1PPS pin is recorded alongside each ADC sample, thereby allowing measurement samples to be accurately tagged to within the typical accuracy of the 1PPS.

To ensure that data is sent reliably and in a timely fashion to the control center or data storage site, data packets must be assembled that contain the ADC measurements for the most recent set of samples, the respective 1PPS pin state for each sample, and the most recent timestamp taken from the GPS serial output. These packets were chosen to be constructed as HTTP POST requests, owing to their universal use in existing network infrastructure [15] and ease of implementation on the ESP32-DevKitC-32D module.

III. Testing and Performance Evaluation

A. Accuracy Qualification

The Pal lab at Arizona State University is equipped with a Fluke 6135A high-precision calibration system [16] designed to test PMUs according to IEEE C37.118-2011 [17]. The electrical waveforms generated by this calibrator are guaranteed by the manufacturer to meet 0.007% accuracy when supplying up to 10 A of output current [18].

Since the typical operating current of the micro-PoW recorder is intended to range from 50 to 800 amperes, a typical operating current of 100 A was chosen as the current level at which the accuracy testing would be performed. A total of 10 turns of wire were wound through the CTs in order to simulate the effect of 10 times the applied current by the Fluke 6135A, which was set to an output current of 10 A. The measured ADC values, reported as integers by the ADC, were transformed into electric current values according to (1),

$$I = \left[\left(\frac{A}{2^b} * V_{ref}\right) - V_{offset}\right] * \frac{T_{CT}}{R_{burden}} \qquad (1)$$

where I is the current measured by the recorder, A is the integer value reported by the ADC, b is the number of bits of the ADC, V_{ref} is the voltage to which the ADC measurements are referenced, V_{offset} is the DC offset voltage against which the CT's output voltage is added in order to retain mesaurement of both positive and negative CT currents by the ADC, T_{CT} is the turns ratio of the CT, and R_{burden} is the burden resistance applied to the CT.

The output samples obtained from the micro-PoW recorder had a total harmonic distortion (THD) of approximately 0.55% and a measured current magnitude of 102% of the true value. The error in this value can be attributed to the effect of the CT, the 1% accuracy burden resistor, and the unspecified ADC and reference voltage errors. Actual PoW data obtained from this device are depicted in Fig. 3. Visual inspection of Fig. 3 confirms that the PoW data collected from this device is close to sinusoidal, giving additional confirmation of the low THD value reported. These metrics could be improved in future versions of the design by calibration of the unit at the time of manufacture and possible temperature compensation methods, such as ovenization of the ADC.

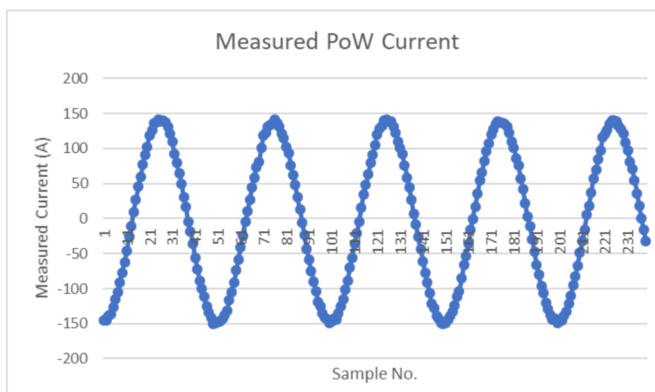

Figure 3. Point-on-wave measurements taken during accuracy validation

B. Minimum Supply Current Characterization

Power lines in the distribution system often carry highly variable electric current levels in the course of a typical day [19]. This means that at certain times of the day, the micro-PoW recorder may be forced to operate with a very low line current compared to its maximum rated line current. As such, it was deemed necessary to characterize the minimum current at which the recorder will initially start up, and the current at which it shuts down when in service.

The micro-PoW recorder was initially connected to a simulated power line capable of supplying between 0 and 100 A at 60 Hz. A picture of the simulated power line bench is depicted in Fig. 4. During the current characterization test, the line was operated in steady-state, and no disturbances or arcs were applied to the test bench setup. The current flowing through the simulated power line was gradually increased until the micro-PoW recorder started up and began sending data. Upon a successful startup, the current was then ramped down until the micro-PoW recorder shut down. This test was repeated three times for consistency, and the results are tabulated in Table II. Based on these results, it is realized that the micro-PoW recorder should be able to operate on any distribution conductor that consistently carries at least 25.0 A.

TABLE II: MINIMUM LINE CURRENT REQUIREMENTS

	Minimum Startup Current (A)	Minimum Shutdown Current (A)
Test 1	25.0	18.0
Test 2	24.0	18.3
Test 3	24.5	18.5
Average:	**24.5**	**18.27**

C. Simulated Power Line Tests and Arc Strike Testing

It can be argued that the most important time for a PoW recorder to operate is during fault conditions, when electric power utilities need immediate information about incipient asset failure. Post-mortem analysis of asset degradation and faults also depends on the integrity and performance of measurements taken before, during, and after these faults. In order to ensure the correct performance of the micro-PoW recorder in a realistic power system environment, the micro-PoW recorder prototype was placed on a test bench constructed to simulate the voltage and current conditions present in a real electric power distribution system.

The electric power line test bench depicted in Fig. 4 is equipped with an AC voltage source capable of delivering up to 4,400 V AC at up to 500 mA short-circuit current at the surface of the conductor. Although the fault current delivered in this small-scale bench is orders of magnitude lower than the fault currents present in actual power systems, it is capable of generating sustained electric arcs, which is one type of fault that occurs in the electric distribution system [3].

The micro-PoW recorder was mounted to the simulated power line, as shown in Fig. 4. The simulated power line was energized with a pass-through current of 100 A and an applied voltage to ground of 4,400 V. The performance of the micro-PoW recorder was evaluated by checking for dropped packets and monitoring the number of GPS satellites observed by the recorder during the testing. The results are shown in Table III. As a final test, an electric arc was instantiated on the simulated power line by a wire connected to an insulated "hot work stick" and was drawn across the micro-PoW recorder transformers in order to evaluate if damage to the device or to the power line was sustained. The measurements taken by the micro-PoW recorder during the arc were also scrutinized carefully in order to determine if any anomalous behavior was detected in response to the induced fault (see Table III and Fig. 5).

The packet drop-rate, minimum and maximum number of satellites visible by the GPS module during the steady-state and the repetitive arc striking tests are tabulated in Table III. A sample PoW data during an arc test, indicating the sags in current caused by voltage drop induced by the short-circuit of the 4,400 V AC supply and discharge-induced transients, is depicted in Fig. 5. The packet status and GPS satellite count for a 50-second repetitive arc test period are depicted in Fig. 6. Packets are sent approximately 3 times per second. Based on the results shown in Table III, it can be surmised that the effects of electrical arcs in close proximity to the micro-PoW recorder do not severely affect its performance.

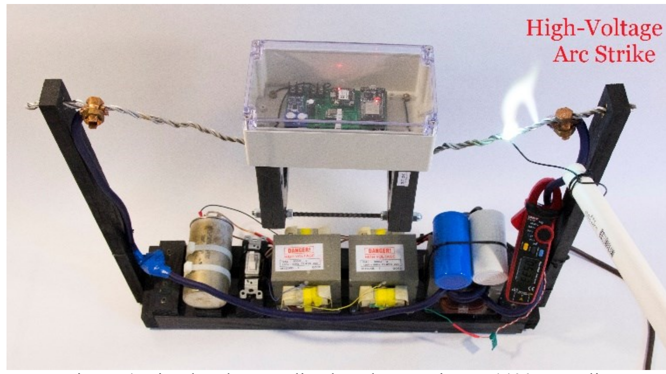

Figure 4. Simulated power line bench operating at 4400V AC line-to-ground and 100A through-current

TABLE III: PACKET LOSS AND GPS SATELLITE VISIBILITY

	Steady-State 4400V/100A	Repetitive Arc Strike
Packet Loss (%):	1.23	1.31
Maximum No. of GPS Satellites:	10	8
Minimum No. of GPS Satellites:	5	6
Median No. of GPS Satellites:	7	8

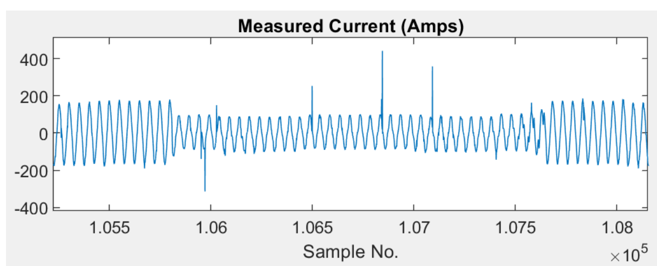

Figure 5. Sample PoW data during an arc striking test

IV. CONCLUSION AND FUTURE WORK

An inductively powered, line mounted micro-PoW recorder was successfully designed, constructed, and characterized in this investigation, and through the development of a PCB and standard list of components, prepared for commercial manufacture. The combination of wireless data communication, self-contained measurement hardware, GPS time-synchronization, and lack of need for an external power source is the salient contribution of the proposed micro-PoW recorder. The recorder designed here performs well over a wide range of line currents, exhibits high accuracy and low distortion, and remains reliable in the presence of nearby electric arcs. These features make this design of micro-PoW recorder an attractive option for electric power utilities looking to increase high-resolution measurement of their distribution systems, particularly in those areas where the safety and environmental risks associated with arc faults are of highest concern.

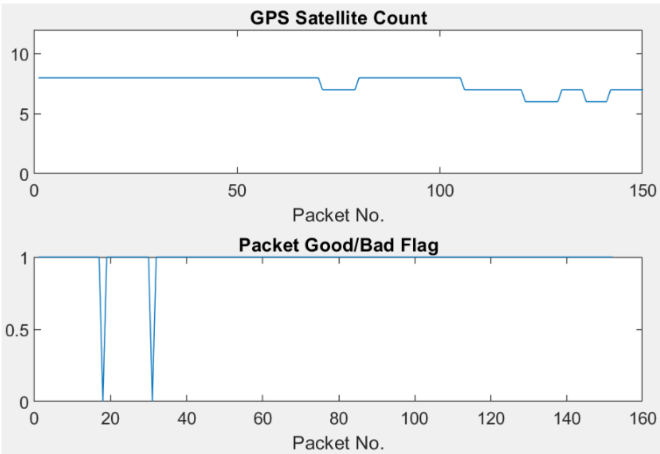

Figure 6. Received packet status and GPS satellite count

The performance of the recorder designed here can be improved in the following ways: Firstly, packet loss can be reduced by improving the software implementation of the HTTP POST request on the ESP32-DevKitC-32D. Secondly, the complete signal chain, including the ADC, CT, and burden resistor can be calibrated as a complete system in order to reduce the current magnitude error and THD in the current measurements. Future revisions of this design could also be configured to perform voltage measurements using capacitors, in a similar fashion to capacitively-coupled voltage transformers (CCVTs); however, further design and characterization is needed to implement this functionality.

Future work will also include the development of a data management backend, where data recorded by many of these micro-PoW recorders in the field can be consolidated and stored efficiently. The operation of a large number of micro-PoW recorders in the field would necessarily result in a very large influx of data, and a thorough investigation of the best methodology to manage and make the optimal use of this data would be in order. Opportunities exist to leverage advanced compression algorithms on the server-side to efficiently manage the large amounts of data that can be obtained by a fleet of micro-PoW recorders [20].

It is the authors' firm belief that the bulk deployment of the proposed low-cost, time-synchronized micro-PoW devices throughout the distribution system will enable utilities to understand, detect, and prevent failures, and as a result, greatly reduce the economic and safety risks associated with poorly observed distribution networks.

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