A Novel Technique for Residential System Power Monitoring with Magnetic Sensor Array Measurement (V1.0)

Pengfei Gao, Student Member, IEEE, Wilsun Xu, Fellow, IEEE

Abstract—This paper presents a new magnetic sensor array technique for real-time residential system power monitoring without invasive access to the home feed-in conductors. Our approach consists of three components: three magnetic field sensors are deployed in close proximity of the power conductors to provide array information; an active current pattern injection method is utilized to calibrate the sensor array; individual conductor current can be computed after the calibration is completed. The real-time power consumption data is transmitted via common home internet router to a cloud server to provide remote accessibility. The development, prototyping, and evaluation of the proposed sensor array system have been demonstrated. This technique provides a novel solution for the centralized power monitoring of residential system in a safe, non-intrusive and cost-effective way.

Index Terms—Residential system power monitoring, non-intrusive monitoring, sensor array.

I. INTRODUCTION

Over the years, electrical energy needs of distribution system have grown tremendously. With the increasing awareness of energy conservation and the extension of smart grid, it becomes more critical to understand how energy is spent in residential systems [1]. Such information is valuable and is of significant interests to both residential customers and utility companies. If the power usage of residential systems can be obtained and monitored conveniently in real-time, the residential customers are able to make informed decisions to optimize their electricity operation, supporting the demand response of the utility industry. The utility companies can also improve their control of electricity consumption, evaluate programs like load shifting/conservation and forecast the future power transmission capabilities more easily.

Thus, the attempts of load monitoring in residential system have emerged and become an active research area. The non-intrusive load monitoring (NILM) technique is one of the most suitable solutions because it is very cost-efficient and easy-to-implement [2]. NILM techniques are able to classify appliance usage by collecting the entire electrical power usage data at a centralized location. The total energy consumption can be decomposed into appliance level, which makes it possible to monitor the operating status of different appliances in real-time and obtain the power cost associated with each use of an appliance [3]. Traditionally, there are three major approaches to acquire the data; however, all of them have their own limitations:

1) The first approach is to directly mount a device in close proximity of the utility revenue meter. The device reads the meter indication to infer the total household power consumption [4]. Some products in the market such as the PowerCost Monitor by Blue Line Innovations Inc. are based on this approach. The disadvantages of this approach are obvious. Firstly, the device is not compatible with every meter type. In addition, since it is located at the exterior of the house, the adverse weather conditions (snow, freezing rain, dust) can possibly obstruct the device from giving accurate readings.

2) The second approach is to use the signals provided by utility smart meter [5, 6]. Unfortunately, most of the smart meter data has relatively low resolution due to the hardware or communication restrictions, and accesses to the meter data could probably be barricaded due to the privacy issue, making this approach difficult to practice.

3) The third approach involves the installation of traditional current probes and voltage sensors inside of the customer’s electrical panel. Most of the home energy monitoring companies, such as the Energy Detective (TED®), Brutech Research Inc., etc. have developed their products based on this approach [7, 8]. However, this approach is invasive since the monitoring device installation involves working around exposed hazardous wires, which typically requires the licensed professionals. Although the customers have shown some interests in these products, the added labor expense and the complicated installation can be severe drawbacks.

This paper presents a fundamentally different scheme from the existing approaches, which can be a perfect data source for NILM applications. As shown in Fig. 1, a magnetic sensor array device is clamped on the electric conduit feeding into residential power panel, it can figure out the currents in the power conductors that are enclosed in the conduit. A calibrator is connected to the home outlet and can calibrate the sensor array automatic. After the completion of calibration, the sensor array can start to process and send the computed currents to the calibrator. Power line is used as the communication medium. The calibrator utilizes the received currents and its...
sampled system voltages to infer the real-time power consumption, which can be transmitted to a remote cloud server via home internet router. Any internet accessible device, if authorized, will be able to see the results online.

The proposed sensor array system has been evaluated through extensive tests in many pilot residential houses and provided very promising results. The installation and configuration is safe and simple, the test results have shown excellent accuracy, prompt response and high stability.

II. DESCRIPTION OF THE PROPOSED SYSTEM

The proposed measurement scheme and its embodiments include two key components. The first component as shown in Fig. 2 is a sensor array that surrounds the conductors whose currents are to be measured. This deployment eliminates the risk with working near an open service panel and the installation work burden from the users has been decreased to a very low level.

According to electro-magnetic theory, an AC current carrying conductor will produce a magnetic field in its surroundings. The strength of the magnetic field at a point in space, i.e. the sensing point, is in proportion to the current and is inversely proportional to the distance between that point and the conductor. A magnetic sensor is able to detect the magnetic flux density near or through the sensor. Since many different sensors could be used, we define their sensed quantities as the vector \( \mathbf{S} \). As illustrated in Fig. 3, in this practical application involving three parallel conductors and three sensors, the following equation can be established for sensors whose outputs are linearly related to the conductor currents (assuming there are 3 sensors of 1, 2 and 3, 3 conductors of a, b and n):

\[
\begin{bmatrix}
S_1(t) \\
S_2(t) \\
S_3(t)
\end{bmatrix} = \begin{bmatrix}
k_{1a} & k_{1b} & k_{1n} \\
k_{2a} & k_{2b} & k_{2n} \\
k_{3a} & k_{3b} & k_{3n}
\end{bmatrix} \begin{bmatrix}
i_a(t) \\
i_b(t) \\
i_n(t)
\end{bmatrix}
\] (1)

\[
\begin{bmatrix}
S_1(\omega) \\
S_2(\omega) \\
S_3(\omega)
\end{bmatrix} = \begin{bmatrix}
k_{1a}(\omega) & k_{1b}(\omega) & k_{1n}(\omega) \\
k_{2a}(\omega) & k_{2b}(\omega) & k_{2n}(\omega) \\
k_{3a}(\omega) & k_{3b}(\omega) & k_{3n}(\omega)
\end{bmatrix} \begin{bmatrix}
i_a(\omega) \\
i_b(\omega) \\
i_n(\omega)
\end{bmatrix}
\] (2)

where \( S_1, S_2 \) and \( S_3 \) denote the output of sensor 1, 2 and 3; \( i_a, i_b \) and \( i_n \) represent the AC current flowing through three power conductors simultaneously.

Equation (2) states the relationship in time-domain while Equation (3) indicates the frequency-domain relationship. If the positions of the sensors and conductors are fixed, the above relationships are fixed; meaning the coefficient matrices are constant. Once the relationships are known, we can solve for the currents either in time domain or frequency domain according to

\[
[I]_{3\times1} = [K]_{3\times3}^{-1}[S]_{3\times1}
\] (3)

It can be seen that establishing the relationship between the sensor outputs and the conductor currents holds the key for measuring the conductor currents. Existing techniques rely on the precious knowledge of the relative positions and angular orientations between the sensors and the conductors to determine this relationship [9]. However, since the residential power conductors are always enclosed by the conduit, the geometry measurement is thus difficult to be implemented. The reference [10] utilizes redundant magnetic sensors to create an over-determined linear system, some numerical optimization algorithms can be therefore used to improve the measurement accuracy. Due to the unknown reference geometry information, such complicated computation may take very long time and their convergence is not easy to be achieved in practice. The reference [11] and [12] use pre-constructed enclosure to obtain partial accurate geometry to facilitate the sub-sequential computation. This method does not incorporate arbitrary conductor layouts. It is subject to inaccuracies if the sensors or conductors deviate from the assumed specific positions.

The proposed calibration scheme is different from the existing geometrical calculation based solutions. As shown in Fig. 4, the sensor calibrator is connected to the conductors at a home outlet downstream of the sensor array. The calibrator draws specific current patterns from the conductors for a short period in an automated manner. The characteristics of these patterns such as the magnitude and the frequency are known to the sensor array through communication. The sensor array uses
these known patterns to establish the relationship between the conductor currents and its sensed quantities, namely the calibration process. Once this relationship is established, i.e. the calibration process is completed; the sensor array can start to compute the currents using that relationship and its sensed quantities, which is the regular recording process. With this arrangement, the sensor array becomes capable of measuring currents in any unknown conductor and sensor configurations.

\[
[I]_{\text{calibrator}} = 0, \quad \text{resulting in } [I] = [I]_{\text{others}}. \quad (4)
\]

Normally, the calibrator is not functional meaning the calibrator current \([I]_{\text{calibrator}} = 0\), resulting in \([I] = [I]_{\text{others}}\). Once the calibration is performed on any one of or several of the conductor group, the calibrator is capable to create a sudden change on the conductor currents by temporarily drawing certain known currents through them. There is one assumption that the currents flowing to other devices remain the same during the calibration process if we can design a calibrator that works independently without interrupting other devices, i.e. \([I]_{\text{others}} = 0\) is guaranteed during the calibration. As a result, the change of the total circuit current is \([\Delta I] = [I]_{\text{calibrator}}\), where \([I]_{\text{calibrator}}\) is the generated calibration currents by calibrator.

Meanwhile, the sudden change of the conductor currents caused by the calibration currents will also reflect on the sensor outputs as \([\Delta S]_{\text{inst}}\). If the calibrator is able to inject three distinct current patterns by drawing different currents changes from various conductors, the sensing unit of the sensor array will then provide different outputs. This behavior can be represented as:

\[
[\Delta S]_{\text{inst}} = [K]_{\text{inst}}[\Delta I] = [K]_{\text{inst}}[\Delta I_{\text{calibrator}} + \Delta I_{\text{others}}] = [K]_{\text{inst}}[\Delta I_{\text{calibrator}}] + [K]_{\text{inst}}[\Delta I_{\text{others}}]\quad (5)
\]

The calibration current patterns are communicated to sensor array through a proposed power line signaling technology, the calibrator is also a power line communication (PLC) device. The sensor array then can utilize these known calibration current patterns to establish the relationship between the conductor currents and its sensed quantities by:

\[
[\Delta S]_{\text{inst}} = [K]_{\text{inst}}[\Delta I] = [K]_{\text{inst}}[\Delta I_{\text{calibrator}} + \Delta I_{\text{others}}] = [K]_{\text{inst}}[\Delta I_{\text{calibrator}}] + [K]_{\text{inst}}[\Delta I_{\text{others}}]\quad (6)
\]

The power signaling technology is a new class of information-orientated power electronics for transmitting signals over power conductors [13]. It has been successfully utilized in many areas of power systems, such as automated meter reading (AMR) [14], and DG islanding condition detection [15], etc.

III. CALIBRATION AND COMMUNICATION SCHEMES

The calibrator is expected to create three distinct momentary current patterns; appropriate calibration approach is required to suite the special nature of the residential system. Referring to Figure 5, the sensor calibrator is able to generate such current patterns by the activation of power electronic converters.

In this preferred embodiment, the calibrator involves the use of thyristors T1, T2 and T3, which are connected between phase A-N, B-N and A-B, respectively. When any of the thyristors is turned on, a momentary current pulse will flow through corresponding phases during the conduction period. Different current shapes can be easily realized by using power electronic switches such as IGBT or other converters. To limit the injected current pulse amplitude, small impedance is usually connected in series with the power converter.

The phase to phase voltage, say, phase A to neutral (denoted as A-N sequence), B-N and A-B are applicable to provide the reference carrier waveform in order to control the gating operation. The thyristor is fired several degrees prior to the carrier voltage reaching the zero-crossing point. It remains conducted until the thyristor current pass the zero-crossing point. After this instant, the thyristor is anti-biased and therefore can be turned off automatically.

The calibrator’s SCR current sensing and control unit can also measure the currents it draws from the conductors. The values of the currents can be communicated to the sensor array through the communication units of both devices via power line signaling means, which will be explain later.

A. Calibration current characteristic

The case where calibrator performs calibration between phase A and neutral as shown in Fig. 6(a) is used as an example to determine the calibration current characteristics.
The conduction period for the resistive connection situation is $\delta_1$. Similarly, the calibration current pulse as well as the thyristor voltage waveform is shown in Fig. 8.

**B. Calibration pattern extraction**

The current drawn by other loads also connected in the circuit can be time varying. To facilitate the detection of generated calibration patterns, the current pulse is designed to be injected in one cycle and not in the subsequent cycle.

The thyristors used to create the current pulses can be also connected in anti-parallel configuration and fired at the voltage in reference to the carrier voltage rising and falling edge respectively, which aimed at creating more patterns and eliminating DC and even-order harmonics so as to compensate power quality influenced by temporary distortions.

For example, one of the calibrations is performed starting at the rising edge of carrier voltage $V_{AN}$ as Segment 1. The first cycle of Segment 1 contains the calibration signal and the second cycle does not. It can be seen that during the calibration a current pulse is suddenly injected into phase A-N during the thyristor conduction period. Meanwhile, the phase B conductor is not involved and the current flowing through phase B remains unchanged, which is shown in Fig. 9.

Via subtraction of two consecutive cycles, the current waveform difference between two cycles, i.e. the calibration current pulse is extracted. This elegant method largely
suppresses background distortions and the currents from other loads is eliminated, i.e. the assumption $[\Delta I] = [I_{\text{calibrator}}]$ can be satisfied. It is proven by many experiment results; one representative is presented in Fig. 10.

![Fig. 10. Current waveform after subtraction for phase A-N calibration](image)

Based on the same signal extraction method, the changes on the sensed quantities of sensor array $[\Delta S]$ can also be determined by subtracting the signal containing cycle from next void cycle. One representative waveform for sensor circuit outputs and calibrator current pre-subtraction and after subtraction can be seen in Fig. 12.

![Fig. 12. Sensor circuit output voltage](image)

![Fig. 11. Sensor outputs and calibrator current waveform during calibration](image)

**C. Communication scheme**

This paper utilizes the power line signaling technology to complete the communication between sensor array and sensor calibrator. The use of power line communication is essential as the distance between the sensor and calibrator is uncertain, which will probably restrict the use of low-cost wireless communication methods.

As depicted in Fig. 3, by integrating an additional embedded thyristor into the sensor array, a two way power line communication scheme can be constructed. This thyristor, labeled as SCRV, can be triggered by the control unit of the sensor array to conduct in a sequence that presents digital information. Once the thyristor SCRV is conducting, the voltage of the SCRV collapses. (An impedance is also be connected in series of the thyristor to moderate the severity of the voltage dip). This voltage dip can be detected at any location downstream of the SCRV. So the sensor calibrator can detect the sequence of voltage dips and decode its meaning, as shown in Fig. 10. In this way, the sensory array can communicate to the sensor calibrator using power line. This forms a one way communication system for the adaptive sensor array.

![Fig. 10. Representing information using a sequence of voltage dips](image)

The sensor calibrator may also serve as a power line communication device. In this case, the patterns of calibration currents not only help to calibrate the sensors but also carry information about the characteristics of the currents produced by calibrator. For example, thyristor T1 can be fired in a specific sequence that represents digital information as Fig. 11.

![Fig. 11. Representing information using a sequence of SCR current pulses](image)

At the sensor array location, this sequence of current pulses will be sensed as a sequence of pulses of sensed quantifies such as pulses of magnitude fields or pulses of induced voltages. The sequence can be decoded to obtain information coded by the sensor calibrator. This completes a two way communication system.

**D. Thyristor control logic**

A complete calibration process consists of three calibration pattern generations, detections and extractions. The first mode is performed on phase A-N, the thyristor T1 is turned on to allow calibration current pattern 1 to flow through phase A conductor and neutral. The other two calibrations are thereafter implemented similarly by firing the thyristor T2, and T3 connected between phase B-N and phase A-B to create current pattern2 and pattern3. By adjusting the firing angle of the thyristors and utilizing power resistors, various calibration current patterns can be created. This calibration scheme greatly increases the flexibility of the proposed sensor array system. Generally, the calibration current flow path can be seen in Fig. 12 and the gating sequence is shown in Table 1.
A. It can be set followed by low cost. A prototype and also its low cost is difficult to access by users current and large current, the is the transpose matrix of $M$. 

$\Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta \Delta 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B. Design of the calibrator

As shown in Fig. 15, the calibrator is also a conductor current data receiver. During the regular recording state wherein the device has been calibrated successfully, the calibrator relays on the computed conductor current information and the sampled system voltages by itself to calculate the power consumption. Such real-time power data is transmitted through common internet connection to a remote cloud server for further analysis.

The calibrator is composed of a plurality of elements as shown in Fig. 16. Aside from the power supply, the anti-parallel thyristors serve to generate preset current pulses through each of the conductors of interest while the voltage and current sensors that embeded on the printed circuit board serve to measure the voltage between conductors and the characteristics of the calibration current patterns respectively. These elements are connected to all three conductors of interest. Initiated by pressing the activation button by the user, the calibration request is made. Gating signals to the thyristors from a MCU generates a sequence of signal pulses. A optical coupler acts as isolation interface between the control end and the high voltage side to achieve safe operation.

C. Communication between sensor array and calibrator

There are two operation modes of the proposed system, the regular recording and the calibration. The communication flow during regular recording process between sensor array and calibrator is shown by Fig. 17 and the calibration process is further illustrated in Fig. 18.

Fig. 14. Circuit diagram of the sensor array

Fig. 15. The prototype of sensor array device

Fig. 16. Circuit diagram of the calibrator

Fig. 17. The communication flow chart during regular recording
D. Internet based real-time monitoring

The latest and historical real-time power consumption data is stored in the database installed on a lab server. The data can be retrieved from a website designed for the display purpose by any internet accessible devices, such as the computer or cellular phones. The updating rate is one snapshot per second under current hardware and communication capacity, which is quite high and will be very helpful for further analysis such as appliance signature extraction. It is very attractive and friendly to the user since all the power usage parameters are formatted to charts and tables. As shown in Fig. 19, one can easily understand the load behavior by observing the real-time power usage, aware of the electricity cost, and finally establish proper energy management strategies.

V. LAB AND FIELD TEST RESULTS

The proposed sensor array system was at first tested in lab. An experiment bench as seen in Fig. 19 mimics the typical electric panel setup in residential home has been established. The reference values of the two-phase currents are measured by the current clamps. A data acquisition system composed of an NI-DAQ instrument and a laptop continuously restores the reference currents, which is compared with the computed currents by sensor array system.

![Lab experiment setup](image)

![Lab experiment setup](image)

Different types of loads are used to permit not only 60 Hz sinusoidal currents, but also high order harmonic contents to appear on the conductor current waveforms. By changing the load level, it provides many kinds of conductor current combinations with different amplitude of fundamental and harmonic indices. Fig. 20 shows the performance of the computed current at two frequencies, 60 Hz and 180 Hz, flowing through the two phase conductors. The 180 Hz current is actually the third harmonic current content. After the calibration on phase A-N and phase B-N, the sensor array system well follows the conductor current patterns timely with high accuracy.
In addition, some trial tests have been implemented in over 10 pilot residential houses, allowing at least one week data at each house. Two representatives are shown in Fig. 23. The installation of sensor array is completed by the house owners without special attention in order to evaluate the work load and time needed statistically. According to the user feedback, the installation is simple and can easily be completed by one single non-professional person without training, the average time for the installation, calibration and internet configuration.

The representative field test results in the above two houses are presented in Fig. 25 and Fig. 26, the fundamental current magnitude on two phases and the hourly electricity usage are illustrated. The current clamps are deployed in comparison with the sensor array results. It can be seen that the prototype sensor array system has successfully detected currents as small as 100 mili-Ampere in amplitude, which is already capable for many applications requiring centralized electrical data. The proposed system should be able to detect substantially smaller currents with optimized signal processing hardware to filter the noises and interferences.

This paper has presented a new technique to monitor the real-time power usage for the residential system. It does not require installing traditional contact current sensors such as current transformers or clamp-on current transducers to each conductor in home electric panel. A magnetic sensor array is deployed in close proximity of the interested conductor group, and an active current pattern injection method is proposed to calibration the sensor array. The proposed system is capable to compute the real-time power with high resolution (1 snapshot per second) and will provide essential and accurate data for many power monitoring applications.

This proposed scheme has the potential to fill the gap where traditional direct measurement is difficult or even not feasible to implement due to the topology, space, cost or safety limitations. The sensors could lead to a new tool for the monitoring and measurement of power systems and their loads, enabling the implementation of smart grid concepts such as demand response and energy conservation.

VI. CONCLUSION
REFERENCES


A Novel Current Sensor for Home Energy Use Monitoring
(Final Version)

Pengfei Gao, Student Member, IEEE, Shunfu Lin, Member, IEEE, Wilsun Xu, Fellow, IEEE

Abstract—This paper presents a novel magnetic sensor array based technique for measuring currents in a group of enclosed conductors. It is designed specifically for monitoring the real-time power consumptions of North American homes. The technique consists of three key components: magnetic field sensors deployed in close proximity of the power conductors to be measured; algorithms to compute the conductor currents based on the magnetic fields measured; a simple, integrated sensor calibration and communication scheme. Prototype devices have been developed based on the technique. Extensive lab and field tests have demonstrated that the technique can provide adequate current measurements for residential homes. Combining with the non-intrusive load monitoring methods, the proposed measurement technique represents an attractive platform to create a complete home energy use tracking system.

Index Terms—Current measurement, power monitoring, magnetic field sensor array

I. INTRODUCTION

In recent years, the increasing awareness on energy conservation and the development of smart grid have created a great need to monitor the energy use of homes, especially that consumed by individual appliances [1], [2]. Such information will enable residential customers to make informed decisions on the energy conversation and to participate in the demand response programs. The utility companies will also be able to gain in-depth understanding on the characteristics of the residential loads and improve their demand response programs.

The research and development of innovative techniques for the home energy use monitoring have, therefore, attracted a lot of interests. One proposed direction is to monitor major household appliances using a sensor network [3], [4]. A competing direction is to measure only the total power consumption of a home and then decompose the power data into individual appliance level through intelligent algorithms [5]–[7]. This direction is called NILM (Non-intrusive Load Monitoring). Regardless which direction is followed, there is a need to monitor the total power entering a home.

Literature survey showed that three types of techniques have been proposed or developed to accomplish the task of tracking the total power consumption of a home, as follows:

1) The first type is to use an optical reader to read the power indicator of a utility revenue meter, thereby infer the power consumption of a home. The reader is typically mounted on the cover of the meter [8]. This technique has several disadvantages. One of them is that the data collected do not have sufficient resolution and contain inadequate information for the NILM algorithms. For example, reactive power and harmonic information cannot be collected using this technique.

2) The second type is to access the data collected by the smart meters (if they are available) [1], [9]. Unfortunately, the majority of smart meters installed so far have low data refreshing rate, such as one sample per 15 minutes, due to the communication constraints. More importantly, there are ownership and legal challenges for a home owner to access the data in real-time, at least for the foreseeable future. The future smart meters could stream the power data wirelessly to homes. However, this will not happen soon since the installed smart meters cannot be replaced just in a few years.

3) The third type involves installing traditional current and voltage probes inside a customer’s electrical panel [2], [10]. This approach is able to collect high quality data for NILM analysis. However, it is not practical for many home owners since the installation of the measuring probes requires licensed professionals.

This paper presents an innovative measurement method and hardware, named the magnetic sensor array technique, for monitoring home energy use. As shown in Fig. 1, the measuring device, composed by an array of magnetic field sensors, is clamped on the conduit feeding into the electric panel. Based on the surrounding magnetic fields sensed by the magnetic sensors, conductor currents inside the conduit are determined computationally.
The most obvious advantage of the proposed technique is its easiness for installation. There is no electrical contact to the conductors so a home owner can install it by himself/herself. Additionally, the sensor can deliver data with a resolution of 1 sample per second or higher. Currents in both hot conductors are available and the 3rd harmonic currents are also available. Therefore, it is an ideal fit for NILM-based home monitoring strategy. The proposed technique has been evaluated through extensive tests in multiple residential houses. Satisfactory measurement performances have been achieved.

II. DESCRIPTION OF PROPOSED TECHNOLOGY

The proposed measurement technique includes two key components. The first component, shown in Fig. 2, is a set of magnetic field sensors that surround the conductors whose currents are to be measured. In the figure shown, there are three conductors A, B and N, which is the typical situation in North America. Conductor A is energized with +120V and B with -120V, N is the neutral. Three sensors, 1, 2 and 3 are deployed outside the conduit.

According to the electromagnetic theory, an AC current carrying conductor will produce a magnetic field in its surroundings. The strength of the magnetic field at a point in space, i.e. the sensing point, is proportional to the current and is inversely proportional to the distance between that point and the conductor. Since many different types of sensors can be used to measure the magnetic field strength, we define the sensor output as the vector $[S]$. For this linear system, the following relationship will hold:

$$
[S](t) = [k_a k_b k_n][i_a(t)] \\
[S](t) = [k_a k_b k_n][i_b(t)] \\
[S](t) = [k_a k_b k_n][i_n(t)] \tag{1}
$$

where $S_1$, $S_2$ and $S_3$ denote the output of sensors 1, 2 and 3; $i_a$, $i_b$ and $i_n$ represent the AC current flowing through the conductors. Eqn. (1) states the relationship in time-domain while Eqn. (2) indicates the frequency-domain relationship.

Since the positions of the sensors and conductors are fixed, the coefficient matrices are constant. If the matrices are known, we can solve for the currents either in time domain or frequency domain according to

$$
[I]_{3x1} = [K]_{3x3}^{-1}[S]_{3x3} \tag{3}
$$

It can be seen that establishing the relationship between the sensor outputs and the conductor currents holds the key for measuring the conductor currents. A commonly known method to determine $[K]$ is to obtain the geometric information of the conductors and sensors [11]–[14]. However, this approach is not applicable for home monitoring since such required information is not attainable. References [15] and [16] utilize redundant magnetic sensors to create an over-determined linear system, optimization algorithms are used to determine the currents by minimizing the differences between the calculated and measured $[S]$. Extensive case studies revealed that this approach is not applicable to home monitoring either, as the optimization algorithms rarely converge to the correct results, in addition to requiring very long computing time.

This paper proposes a calibration scheme to determine $[K]$. A calibrator, which is the second key component of the proposed technology, is connected to the conductors at a home outlet downstream of the sensor array (Fig. 3). Using the power electronic switching, the calibrator draws specific currents and current patterns for a short period in an automated manner. The characteristics of the currents drawn are made known to the sensor array through a power line communication (PLC) scheme that is also realized by the calibrator (explained later). The sensor array uses these known patterns and current information to establish the matrix $[K]$. Once this relationship is established, the sensor array can start to “measure” the conductor currents by calculating them using that relationship and the sensed magnetic fields.

One of the main innovations of the proposed calibration scheme is that the calibration current contains a special pattern: it is created every other cycle. The difference of the
currents between two consecutive cycles is the calibration current. As a result, this scheme is immune from background waveform distortions and the impact of currents from other loads can be eliminated.

The second advantage of drawing current every other cycle is that the peak instant of the calibration current can be detected at the sensor side. This instant is used to synchronize the phasor \([S]\) with the phasor \([I]\). Note that to solve for \([K]\), both phasors must be synchronized to the same time instant.

The calibration current \([I_{calibrator}]\) is determined and transmitted to the sensor location by the calibrator. In other words, the calibrator is also a power line communication device, which is the third innovation of the proposed technique. As a result, the sensor system does not require other communication means.

### III. CALIBRATION AND COMMUNICATION SCHEMES

The calibrator is expected to create three distinct momentary current patterns. The scheme to achieve this goal is shown in Fig. 4. In this scheme, simple thyristor switches are used to create the calibration current every other cycle.

![Fig. 4. The system configuration of the sensor array with the calibrator.](image)

#### A. Calibration Scheme

The principle of the calibration scheme is demonstrated as follows. During a single calibration event that lasts for 12 cycles, the conductor currents consist of the currents drawn by the calibrator and the currents from other electrical loads also connected in the circuit, as follows:

\[
[I]_{3×1} = [I_{calibrator}]_{3×1} + [I_{other}]_{3×1}
\]  

(4)

The corresponding sensor output is represented as \([S]_{3×1}\). After the waveforms of \([S]_{3×1}\) are acquired, their \((n+1)\)th cycle data is subtracted by the \(n\)th cycle data \((n=1,3,5,…11)\), creating a new set of data denoted as \([ΔS]_{3×1}\). If the cycle-by-cycle subtraction is performed on the current \([I]_{3×1}\), one will get \([ΔI]_{3×1}\) similarly. Since the loads draw the same current every cycle during this short calibration period, the equation \([ΔI]_{3×1} = [I_{calibrator}]_{3×1}\) holds, which leads to:

\[
[ΔS]_{3×1} = [K]_{3×3}[ΔI]_{3×1}
\]  

(5)

The calibrator is designed to draw three distinct current patterns from various conductor combinations (A-N, B-N and A-B). Three calibration events will result in:

\[
[ΔS]_{p_1}, ΔS_{p_2}, ΔS_{p_3}] = [K]_{3×3}[ΔI]_{3×1}
\]  

(6)

where \(p_1, p_2\) and \(p_3\) represent three different current patterns. For the above equation, both \([ΔS]_{3×3}\) and \([ΔI]_{3×3}\) are known. So the matrix \([K]_{3×3}\) can be solved as follows:

\[
[K]_{3×3} = [ΔS]_{p_1}, ΔS_{p_2}, ΔS_{p_3}][ΔI]_{p_1}, ΔI_{p_2}, ΔI_{p_3}]^{-1}
\]  

(7)

#### B. Characteristics of Calibration Current

The case of using phase A and the neutral for calibration is shown in Fig. 5(a). In this circuit, \(Z_{sys}\) represents the system impedance upstream of the calibrator. There is an impedance \(Z_{SCR}\) in series with the thyristor. Its purpose is to limit the calibration current. Extensive studies conclude that a resistor is the best option from a number of perspectives, such as the size and the cost. The simplified equivalent circuit is shown in Fig. 5(b). The load is neglected in the equivalent circuit as its impact on the calibration current is small, which is similar to the short-circuit analysis where the loads can be neglected.

![Fig. 5. Circuit analysis when calibration is performed on phase A-N.](image)

The steady-state phase A-N voltage is expressed as

\[
V_{ph0}(t) = \sqrt{2}U_{ph} \sin \omega t
\]  

(8)

If the thyristor firing angle is selected as \(δ_1\), the corresponding waveforms of the thyristor current, i.e. the calibration current is:

\[
i_{SCR}(t) = \frac{\sqrt{2}U_{ph}}{R_{sys} + \omega L_{sys} + R_{SCR}} \sin \omega t, \omega t \in [\pi - δ_1, \pi]
\]  

(9)

Fig. 6 shows the calibration current as well as the thyristor voltage waveform before and after the thyristor conduction.

![Fig. 6. Thyristor voltage and current waveform for resistive connection.](image)

In the actual implementation, the calibration current is processed by the Fast Fourier Transform (FFT). The FFT window starts at the current peak as shown in Fig. 6. This window position must be detected and used at the sensor
location so that $[\Delta S]_{3 \times 1}$ and $[\Delta I]_{3 \times 1}$ are synchronized.

Fig. 7 illustrates one set of waveforms during the calibration process. The firing angle is set to 90° after the rising edge of carrier voltage $V_{\text{ac}}$. Each calibration pattern in one segment consists of two cycles, the first cycle of Segment 1 contains the calibration signal and the second cycle does not. It can be seen that during the calibration, a current pulse is suddenly injected into phase A-N. Meanwhile, phase B current is not involved and the current flowing through phase B remains almost unchanged.

The current waveforms shown in Fig. 7 are the currents entering a home, i.e. those measured at the electric panel. The calibration current that the sensor array used to generate the matrix $[K]$ is actually sampled at the calibrator location. To verify the consistency of the calibration current at the different locations, two consecutive cycles of the conductor current $I_p$ are subtracted by each other. The results should be equal to the current drawn by the calibrator. Fig. 8 shows the comparison of $I_{\text{calibrator}}$ and the actual calibration current $\Delta I_p$ seen at the sensor. It can be seen that the agreement is quite good. The small difference of the waveform is caused by the existence of the system impedance $Z_{\text{sys}}$. Although very small, $Z_{\text{sys}}$ could cause the voltage drop between the sensor location and the calibrator location during the calibration, which has a minor impact on the current from other background loads connected in parallel with the calibrator.

![Fig. 7. Carrier voltage and conductor current pre and during A-N calibration.](image)

![Fig. 8. Current waveform after the subtraction for phase A-N calibration.](image)

**C. Actual Implementation**

For the actual implementation, the calibrator is a portable device that draws the current from two outlets only (A-N and B-N). This is shown in Fig. 9. This simplification has two advantages. Firstly, it simplifies the calibrator and reduces its cost. Secondly, it avoids the use of four-prong outlets which are difficult to access in some homes. (Such outlets are available only at locations such as the washing machine and the electric range). Note that the currents flowing through A and B conductors will return through the neutral N.

![Fig. 9. Two-phase calibration scheme for the actual implementation.](image)

At the time that the calibration is applied on one single phase A-N or B-N, the calibration currents occurring on the neutral is described as:

$$\Delta I_p = K_a \Delta I_p + K_b \Delta I_p$$

where $\Delta I_p = 0$ for A-N calibration and $\Delta I_p = 0$ for B-N calibration. The values of $K_a$ and $K_b$ are dependent on the target residential system circuit topology and will remain constant. Combining (5) and (10) yields:

$$[\Delta S_{p1}, \Delta S_{p2}] = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \\ M_{31} & M_{32} \end{bmatrix} \begin{bmatrix} \Delta I_p \\ 0 \end{bmatrix} = [M]_{3 \times 2} [\Delta I_p, \Delta I_p]$$

(11)

where $[M]_{3 \times 2}$ is the modified coefficient matrix from the matrix $[K]_{3 \times 2}$ and can be derived as:

$$[M]_{3 \times 2} = [\Delta S_{p1}, \Delta S_{p2}][\Delta I_p, \Delta I_p]^{-1}$$

(12)

Once the two-phase calibration is completed, i.e. the matrix $[M]_{3 \times 2}$ is determined, the phase A and phase B currents can be computed as follows:

$$[I]_{3 \times 1} = ([M]_{3 \times 2}^T[M]_{3 \times 2})^{-1} [M]_{3 \times 2}^T[S]_{3 \times 1}$$

(13)

where $[M]_{3 \times 2}^T$ is the transpose matrix of $[M]_{3 \times 2}$. 
With this design, a home owner conducts the calibration through the following steps:

1) The first calibration: After installing the sensor array, the home owner can plug the calibrator into any outlet to activate the first calibration on one of the phases (either A-N or B-N).

2) The second trial calibration: the sensor array stores the information from the first calibration and waits for the calibration signal on the other phase. Like the first step, the user can perform the second trial calibration on another arbitrary outlet. However, it is possible that the 2\textsuperscript{nd} outlet is in the same phase as the 1\textsuperscript{st} outlet. The sensor can detect this case by comparing the \([M]\) matrices. If the two calibrations are on the same phase, one column of \([M]\) will be linearly correlated. A threshold based on the distance of the two matrices is used to determine if the 2\textsuperscript{nd} outlet is in the same phase as the first outlet. If yes, a sound will be activated, informing the owner to find another outlet. If no sound occurs, the calibration is completed.

Typical home panels have labels indicating the locations of the outlets associated with each phase. Using this information, a user does not need to try multiple times to complete the calibration process.

D. Communication Scheme

The magnitude and phase of the calibration current are communicated from the calibrator to the sensor utilizing the PLC technology [17]. The patterns of calibration current are used to represent a sequence of digital information. At the upstream sensor array location, this sequence of pulses will be sensed and decoded based on the pre-defined PLC protocol. For example, the thyristor \(T_{\text{SCR}}\) can be fired in a specific sequence that represents digital bits, as shown in Fig. 10. Two cycles are needed to represent one digital bit, i.e., if the subtraction of the two cycles includes the injected pulse, it represents a bit ‘1’. The idle status, otherwise, represents ‘0’.

A typical calibration and communication transaction can be described as the following steps: Normally, the sensor considers the power line as the idle status, i.e., the calibration is not enabled. It computes the two phase conductor current by Eqn (13) with the sensor outputs and the previously stored matrix \([M]\), if applicable. Once the user activates the calibration, the calibrator injects one pulsed current sequence as a frame of command to inform the sensor the beginning of the calibration. The frame structure is defined in the proposed PLC protocol and is demonstrated in Fig. 11(a).

The one phase calibration lasts for the time of \(t_c\) (typically 200ms when the calibration patterns consists of 6 signal containing cycles and 6 void cycles to facilitate the detection on the sensor array unit). After a short delay of time \(t_{\text{pc}}\), which the sensor used to accomplish the data storage for \([\Delta S]\), the calibrator sends another frame of command to inform the sensor the beginning of the data transmission. Four data frames are required for one single phase calibration: the real part and the imaginary part of the fundamental component of the calibration current, and then the 3\textsuperscript{rd} harmonic of the calibration current. One completed calibration and communication period defined by the PLC protocol in a completed calibration process is further illustrated in Fig. 11(b).

In the actual calibration scheme, it requires at least two calibrations on phase A-N and B-N, respectively. The PLC transaction is repeated in each calibration. After receiving all the data for \([\Delta I]\) and \([\Delta S]\), the sensor will be able to update the matrix \([M]\) and then starts to refresh the phase current computation results.

E. Hardware Structure

The hardware implementation of the calibrator is shown in Fig. 12. The size is slightly larger than a smart phone. The anti-parallel thyristors serve to generate current pulses through the conductors of interest. The 10Ω/25W 1% tolerance power resistors are intergrated in series connection with the thyristor pair. The current sensors are embeded on the printed circuit board to measure the calibration current accurately. Initiated by pressing the activation button by the user, the calibration request is made. Gating signals to the thyristors from a MCU creates a sequence of signal pulses. A optical coupler acts as the isolation interface between the control end and the high voltage side to achieve safe operation.

IV. SENSOR ARRAY

A prototype of sensor array system has been developed to evaluate the performance of the proposed calibration scheme,
which is explained in this section.

A. Extraction of Sensor Output

There are two power monitoring states of the system. The first one is the calibration state. Fig. 13 shows the sensor output during this state. The first cycle of segment 1 contains the calibration current. It shows up in the voltage output of the sensor circuits. Due to the existence of the background current drawn by other loads, three sensor outputs on the cycle 2 are not zero. To obtain the sensor output related to the calibration current only, a signal extraction algorithm subtracts the void cycle (cycle 2) from the signal containing cycle (cycle 1) on each of the sensor output waveform respectively.

The post-subtraction waveforms for the three sensors, i.e. ΔS₁, ΔS₂ and ΔS₃ are depicted in Fig. 14. The FFT window is selected starting from the top peak of the [ΔS]₃×₁ waveforms. This window is similarly used in Section III.A for the calibration current so the synchronization for [I_calibrate]₃×₁ and [ΔS]₃×₁ is guaranteed. Based on the FFT results of [I_calibrate]₃×₁ and [ΔS]₃×₁, the coefficient matrices [M]₃×₂ at both the fundamental (60 Hz) and 3rd harmonic (180 Hz) frequencies are computed and stored in the sensor circuit memory unit.

B. Hardware Structure

The sensor array consists of a front-end analog chain to process the sensor signals, a MCU for control and post-computation, and some peripherals: a 6-channel 16-bit simultaneous analog-to-digital converter (ADC) and a power supply circuit connected to high voltage side. The block diagram of the sensor array device can be seen in Fig. 15.

Fig. 15. Circuit diagram of the magnetic sensor array.

The input of the analog front-end is the sensor output voltage. It followed by a low-pass filter that attenuates the high frequency noises. Considering the wide range of current usage of normal residential homes, two-stage amplifiers are selected to improve the sensitivity under both small current and large current situations. Unless saturated, the second stage output is used to take the input range of ADC sufficiently. A final low-pass filter reduces the aliasing before sampling the two-stage signals. The sampling rate of the ADC is 128 points/cycle (7.68 kHz), which is enough to provide the fundamental and harmonic information. A picture of the prototype magnetic sensor array device has already been shown in Fig. 1.

V. LAB AND FIELD TEST RESULTS

The proposed sensor array system was tested in lab first. An experiment bench as seen in Fig. 16 mimicked the typical electric panel setup in a residential home. The reference values of the two-phase currents were measured by the current probes Fluke i1000s. A data acquisition system consisting of an NI-DAQ instrument and a laptop continuously recorded the reference currents, which were compared with the computed currents by the proposed technique.

The variation of the load currents are accomplished by varying different loads supplied by the panel. Fig. 17 shows the comparison of the calculated currents by the technique (“sensor”) and those measured directly by the current probes (“CT”). The results show that the sensor array technology can “measure” the conductor currents well, especially the fundamental frequency components. The 3rd harmonic currents are generally acceptable when they have higher magnitudes. Note that the system is not intended to measure the 3rd harmonic accurately. The results are intended for the NILM algorithms. The algorithms do not need precise 3rd harmonic currents, but requires the knowledge on the instants and the ranges of the magnitude changes [6].
Field tests of the technology have been implemented in over 10 residential homes. Each test has been run typically for a few days to weeks. Two representative installations (one indoor and one outdoor) are shown in Fig. 18. The installations were completed by the house owners without the help from the researchers. According to the users’ feedback, the average time for the installation, calibration and internet connection is approximately 15 minutes.

Sample test results of the above two houses are presented in Fig. 19 and Fig. 20. They are compared with the CT results. Long-time monitoring reveals that the power error is around 30W~120W, depending on the real-time load level. The energy estimation error is less than 3%.

To quantify the measurement error of the proposed system, the ‘error band’ characterized by the bias (μ) and standard deviation (σ) are determined (see Fig. 21) [18]. The results for the 60Hz current are reported in Table I. It is observed that the major error of bias (μ) is contributed by the light load situations, i.e. the current level less than 1A. This error is mainly due to the weak magnetic field. Fortunately, the standard deviation (σ) for both phases is independent of the current level and remained at around 50mA for both phase A and phase B. Overall, it is very promising that the fundamental current error is within 5% for the loading above 1A.
It can be seen that the prototype sensor array technology has a satisfactory performance when measuring currents above 1A, which is sufficient for home energy use tracking (not for billing). The main problem encountered in the field is the magnetic field interference. Research is ongoing to address this issue. Solutions under investigation include shielding and adding more sensors.

VI. AN INTERNET BASED ENERGY MONITORING SYSTEM

One of the direct applications of the proposed technology is to monitor the energy use of homes. In this research work, an internet based home energy use tracking system named the EnerTracker has been developed. The EnerTracker system is shown in Fig. 22. In the figure, the sensor unit (item 1) collects the current data using the proposed measurement technique. It then transmits the data to a receiver (item 2) using power RF communication with the baud rate of 1.2 Kbps. The receiver is connected to the homeowner’s internet router through an ethernet cable. So the data is shipped to a remote internet server (item 3). Data analytics such as the execution of NILM algorithms are performed at the server location. The results are displayed in an internet website (item 4). It is designed specifically for monitoring the power consumption of homes. The results are suitable for NILM algorithms so that the energy use of major home appliances can be tracked using the proposed technique.

VII. CONCLUSION

This paper has presented a novel magnetic sensor array technique for measuring currents in a group of enclosed conductors. It is designed specifically for monitoring the power consumption of homes. The results are suitable for NILM algorithms so that the energy use of major home appliances can be tracked using the proposed technique.

The main contributions of this research work include 1) the proposition of an easy-to-use, reliable calibration scheme to overcome the major challenge of the array-sensor based measurement techniques, 2) the integration with a PLC scheme into the calibrator to create an self-contained system, 3) the adoption of the technique to the special situation of the residential homes such as two-phase calibration, 4) the development of prototype devices, 5) the extensive tests to verify the performance of the proposed technology, and 6) the illustration of its application through the EnerTracker system.

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**Pengfei Gao** (S’10) received his B.S. and M.Eng. degrees in Electrical Engineering from Harbin Institute of Technology, Harbin, China, in 2008 and 2010, respectively. He is currently pursuing his Ph.D. degree in Electrical and Computer Engineering at the University of Alberta, Edmonton, AB, Canada. His main research interests include smart grid, adaptive sensor array technique and power signaling technology.

**Shunfu Lin** (M’12) received his B.S. in Applied Physics in 2002, and Ph.D. in Nuclear Technology and Application in 2007 from the University of Science and Technology of China. He worked for the Corporate Technology of Siemens Limited China as a research scientist in power monitoring and control of low-voltage distribution system from Jul. 2007 to Sep. 2009. He was a post-doctoral fellow at University of Alberta, Canada from Oct. 2009 to Oct. 2010. Dr. Lin is currently a distinguished professor at the Shanghai University of Electric Power. His research interests include power quality and smart grid technology of LV distribution system.

**Wilsun Xu** (F’05) received his Ph.D. degree from the University of British Columbia, Vancouver, Canada, in 1989. From 1989 to 1996, he was an Electrical Engineer with BC Hydro, Vancouver, Canada. Currently, he is with the University of Alberta, Edmonton, Canada as a research chair professor. His current research interests are power quality, information extraction from power disturbances and power system measurements.