GrabAmps: Grab a Wire to Sense the Current Flow

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ABSTRACT

In this paper, we present GrabAmps, an intuitive interface that allows users to simply grab a bundled cable and get feedback on the AC (Alternating Current) current flow through it. Single phase and three phase AC was estimated with a regression model developed using principles of applied electromagnetism. This regression model is embedded into a standalone glove with a display attached at the rear so that the users can intuitively read the current consumption information. The users may configure the glove to detect AC single phase or AC three phase current using the same sensor setup on the glove. End users such as electrical engineers and electricians who frequently wear gloves during their work can benefit from GrabAmp to identify a wire that is live, or even grab and move along a wire to trace any potential failures. We believe GrabAmps can potentially speed up maintenance processes and monitor equipment more efficiently without downtime, which is increasingly important for data centres and other critical infrastructure.

CCS Concepts

Human-centered computing—Ubiquitous and mobile computing systems and tools • Hardware—Sensors and actuators

Keywords

Intuitive Interfaces; Non-invasive Current Sensing; Augmented Glove

1. INTRODUCTION

An intuitive interface that provides an estimation of the electrical current flow is desirable in many instances, such as providing residential energy consumers with real-time electricity price feedback [3][19] and monitoring/troubleshooting an industrial machine without machine downtime. However, most of the current sensors are not intuitive for two reasons. Firstly, they require tedious invasive or semi-invasive installation, which requires users to either isolate a single wire or access crowded sockets and circuit breakers [15] [16]. Secondly, the feedback is presented through an indirect means where users have to login to a web portal or mobile application [19]. Non-invasive current sensing of an AC cable is a challenging problem, since most of the magnetic field generated by current flowing through negative and positive wires is cancelled. In addition, irregularities (such as kinks or twisting of individual wires) within bundled-wire makes the sensing process even more difficult. Multi-core cable current clamp sensors already exist and are available as commercial products\textsuperscript{1}, but they are bulky and cannot be used in a ubiquitous manner.

To overcome the limitations on existing invasive and non-invasive sensors, we present GrabAmps, a glove which contains a non-invasive sensor that estimates the current through a bundled-cable and provide immediate feedback. The main sensing principle of GrabAmps is based on the Biot-Savart law that describes the magnetic field generated by a current carrying wire. We obtain a large collection of measurements by systematically changing the sensor orientations and current loads for different diameters of AC cables. These measurements were used to fit a linear regression model to estimate the current. With adjustments to the coefficients in this regression model, GrabAmps can be adapted to sense both single phase and three phase current measurements.

The non-invasive sensing characteristic of GrabAmps allows users to simply grab a bundled AC cable to estimate the current flow. The GrabAmps provides appropriate feedback using a screen attached at the rear of the glove that displays the measured current when grabbing onto a cable.

\footnote{1 http://www.mouser.com/ds/2/263/MMC850_DS_en_V02-15853.pdf}
The main contributions of this paper includes the development of a regression model that can estimate the current flow for both single and three phase AC current; and development of a self-contained, non-invasive, compact wireless current sensor and demonstration of its design space through GrabAmps.

2. RELATED WORK

2.1 Invasive Current Sensing

MIT Plug [14] and [10] are some early works that introduced monitoring power consumption at the plug point level. In addition, Energine\(^2\), Kill-A-Watt\(^1\) and Efergy\(^4\) have become popular as commercial plug modules. Generally, such products feature embedded displays that display the energy usage data on the device itself. Works such as Acme[10], Greenbox\(^5\), EnergyHub\(^6\) and Plogg\(^7\) have gone a step further with introducing wireless sensor networks into these devices with information being available live on mobile and desktop computers. The transaction costs and time delays involved in these methods of influencing consumer behaviour have resulted in sub-optimal performance and limited effect of the significant investment in broad installation of these sensors in particular markets\(^8\).

2.2 Semi-invasive current sensing

In [7], the authors discuss an approach to identify individual appliances in operation within an electric grid by monitoring the power meter. Other researchers have used similar methods to improve such processes [7] with higher frequency [12], [13], better features [3], [5] and better disaggregation algorithms [1], [8]. Furthermore, distributed smart meters too have attempted to monitor individual appliances from a central location [9]. These systems have featured a wireless sensor network for metering devices [10], [4]. Other approaches for energy monitoring include acoustic, light, temperature and vibration sensing in combination with power meters to classify working appliances and calculate each of its power [18]. However, most of this work attempt to differentiate energy consumption characteristics of individual appliances using measurements made from a central location. In these works, the current sensing was done in a central position, generally in a circuit breaker, using sensors or current transformers around the live wire. As such, these sensors need to be installed by a technician since it involves exposing an individual pole for attaching the sensor.

2.3 Non-invasive current sensing

Works of [11] and [17], have been looking at using EMF (electromagnetic field) detection technologies to monitor energy. These works attach EMF sensors to detect the change in the EMF generated by the current pulses when devices are switched on and off to identify individual appliances on the grid. The current sensing however is still done as previous methods at central locations. Commercial products such as Watts Up\(^9\) require professional installation to provide an acceptable level of safety. Off-the-shelf current clamps offer a non-invasive way to measure current\(^10\). However, these handheld device form factors are designed for ad-hoc use; not as a ubiquitous current sensor.

The above works suggest that there is a strong interest in different ways of monitoring individual appliances. However, these techniques are limited by processes such as requiring the users to instrument the environment with smart plugs or requiring support of a technician to setup smart power monitors at the circuit breaker level. With GrabAmps, we attempt to overcome these limitations by providing an intuitive wearable solution to monitor current flow in a non-invasive manner and provide immediate feedback.

3. OVERVIEW OF THE TECHNOLOGY

3.1 Development of regression model

In a typical cable, the wires that carry current to and from a device (eg. live, neutral and the earth) are combined together resulting in the magnetic field generated to be close to zero. This is due to the magnetic flux generated by the live wire being cancelled out by the inverse flux generated by the neutral wire that carries the returning current. However, since the individual wires are spatially separated within a bundled wired, there is a minute amount of flux that is generated in the magnitudes of micro Teslas as per the Biot-Savart law. A magnetic flux sensor that is within this range can sense this generated flux when placed closer to the wire.

To analyse this phenomenon, we placed the sensors in different radial positions from a wire arrangement as seen in Figure 1. Sensors were placed in five different orientations in a test bed (single phase AC current source connected to a controllable resistive load) which was rotated 60° with respect to the placement of the live, neutral and earth wires as seen in Figure 2. The maximum flux readings were averaged over N=1000 samples for each angular position and for each of the 5 positions on the wire. At each position, maximum flux readings along the x, y, and z axes of each sensor were lumped together using vector summation. This makes the measurements insensitive to the orientation of the magnetometer.

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\(^2\) [https://energie4u.co.uk/]
\(^3\) [http://www.p3international.com/products/p4400.html]
\(^4\) [http://www.efergy.eu/]
\(^5\) [http://getgreenbox.com/]
\(^6\) [http://www.energyhub.com/]
\(^7\) [http://www.plogg.co.uk/]
\(^8\) [http://spectrum.ieee.org/energywise/energy/the-smarter-grid/the-smart-grid-needs-an-app-store]
\(^9\) [https://www.wattsupmeters.com/secure/index.php]
\(^10\) [http://en-us.fluke.com/products/clamp-meters/]

Figure 2: Sensor configurations on an AC wire for initial analysis
3.2 Linear regression model

AC single phase current: Our analysis showed that the maximum difference between the sensor readings occurred when two sensors are 180° apart. The trend shown by the flux measurements summed between the sensors in these relative orientations found to be decidedly linear with increasing current. A linear regression model Equation 1 was fit to the data where, 'I' represents measured current, 'X' represents sensor readings and ‘Θ₀’, ‘Θ₁’ are the coefficients.

\[ I = \theta_0 + \theta_1X \]  \hspace{1cm} (1)

The ground truth (reference current) was measured using a CT sensor attached to an isolating a single wire. From the measured data, the following were calculated:

\[ \theta_0 = 0.0995 \quad \text{and} \quad \theta_1 = 0.0251 \]

\[ I = 0.0995 + 0.0251X \]  \hspace{1cm} (2)

Since the magnetic sensors are arranged in a 180 degree separation, it ensures that at least one of the sensors is closest to the current carrying conductor than the other. This may also explain why a single regression model works for the same type of bundled cable (8mm three core AC cable) irrespective of wire arrangement (live, neutral and the earth) inside the cable.

AC three phase current: Similar process was used to develop a linear regression model for AC three phase current. The resulting model parameters are as follows:

\[ \theta_0 = 0.0803 \quad \text{and} \quad \theta_1 = 0.0375 \]

3.3 Results

The Figure 3 shows the results of the linear regression models for both single phase and three phase AC. The results indicate that placing the sensors 180° apart at any positions senses the current through the wire with a maximum error of 0.2A. For the scope of this paper, this level of accuracy is acceptable to investigate potential usage scenarios and interactions.

4. GRABAMPS

Before developing GrabAmps, we encapsulate the above sensing technique as a compact device which can clamp onto a bundled wire. The overall setup of the initial GrabAmps clamp prototype is shown in Figure 4. In this version, we use the Freescale MAG3110 as the magnetic field sensors and an Arduino Pro Mini as the main processor to implement the regression model. An RGB LED and a OLED display has been used to provide simple immediate feedback on various states related to current monitoring.

The non-invasive currents sensing capability of the first prototype motivated us to explore the design space of this novel sensing methodology. Many industrial settings, such as a wafer fabrication plant, demand instantaneous current monitoring without having to shut-down important processes. To address such situations, we developed GrabAmps by integrating the sensors to the palm and tip of the middle finger (Figure 5 (A), (B)). When the user grabs onto a wire, the sensors would form the required relative orientation of the sensors. With the display attached at the rear of the glove, the users can intuitively read the current consumption information. In addition, users may configure the glove to detect AC single phase or AC three phase current levels using the same sensor setup on the glove. GrabAmps can potentially speed up the maintenance processes and monitor equipment more efficiently without downtime (Figure 1 (B)). Generally, electrical engineers and electricians who frequently wear gloves during their work, can benefit from GrabAmps. For example, they can identify a wire that is live, or even grab and move along a wire to trace any potential failures, etc.
Also, this design is beneficial for the EM (electromagnetic) hobbyists who design and implement applications and systems with AC power supplies. For example, GrabAmps can be used to sense the EM signal of an AC power supply to observe and optimise other sources of EM. In addition, this can be used as an oscilloscope in digital applications to observe signal traces, digital communication signals, etc.

5. LIMITATIONS AND FUTURE WORK
There are few limitations of the existing system. As mentioned in the sensor specifications, the current version of the regression model works only with 8mm wires. In future we aim to develop regression models for various thicknesses and load the correct model automatically with thickness estimation (from two magnetic sensor data). In addition, the sensors, upon activation, requires a few seconds to warm-up for calibration. Moreover, the regression model’s error could be up to 0.2A which could be significant for high precision current monitoring applications. This error is partly because of the sensing limitations of the sensor. In future versions, we wish to address these limitations and enhance the robustness of GrabAmps.

6. ACKNOWLEDGMENTS
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7. REFERENCES