E-ring: A Non-Invasive Electricity Consumption Monitoring System

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***Abstract*—Monitoring electricity consumption has a key role in reducing energy consumption. This monitoring can be frequent (several times per week) or continuous. Recent studies showed that such monitoring can reduce residential energy consumption by as much as 15%. The development of energy management systems in the monitoring systems and intelligent energy meters have been going for a while. In this paper, we will present a new electricity monitoring device called "E-ring". E-ring is a non-invasive tool mainly made from a current transformer clamp meter that clamps to the main electricity cables of the user's home and measures the electrical consumption and sends the measured data to an online server and then makes it accessible from the user's mobile phone using a specially-developed mobile application. It has many advantages such as low data rate, low price, and real-time access to the consumption data and simultaneously calculate the estimated price for the household/industrial electricity bill with a tolerance of around 2%.**

***Index Terms*—Current transformer; Electricity consumption; Monitoring system; Arduino IDE; Energy Efficiency.**

I. Introduction

Every year, mainly in the last 2 decades, thousands of technologies are being developed and turned into products and being integrated into household appliances. Most of these products are electrically powered, and this rapidly increases the electrical consumption in each and every house, and consequently the electricity bill too. As a result, as the number of electrically powered devices is increasing, the tendency to waste energy increases as well. In the United States of America, electricity consumption for residential and commercial sectors consumes around 40% of the total energy, with overall energy waste of around 50% in these two sectors [1]. As a result of this increment, a lot of new technologies and research, have been created and conducted to reduce the cost by reducing consumption.

Furthermore, multiple psychological studies and dedicated research found a strong correlation between the consumption of goods/ electricity/food/alcohol etc. and the ability to monitor the consumption on a regular basis [2]. Monitoring the consumption while it occurs, has a huge effect on the consumers' behavior, and that is why the budget trackers has been created, where users say that they were able to save up to 15% percent more after being aware of their outcome, and how much they have spent already [3], [4].

Recently, Wireless sensors and the internet of things (IoT) technologies are becoming rapidly more popular over the time and are being implemented in many applications such as energy management, home automation, and healthcare. Many research efforts have been put into further developing the functionality of wireless systems in every-day life such as the development of a wireless electricity consumption meter that can communicate directly with the end user [5].

Based on all the above, E-ring shows its significance. E-ring is a non-invasive electrical consumption monitoring device for the residential sector that connects to the user's electricity supply wire, measures the electrical consumption, and calculates the estimated cost of the electricity bill. Thus, giving the user the ability to keep track of his house consumption, wherever his whereabouts, and accordingly, his consumption will be significantly decreased.

The end user usually receives a monthly report for his electricity consumption and the estimated cost for it, while E-ring is created to provide accurate and continuous energy monitoring method without the need to expensive metering systems or specialized technicians. Taking into consideration that households are responsible for approximately 37% of the total electrical consumption in the USA [6], it is well worth pursuing.

II. Background

A. Quantifying the problem - global approach

The State of Indiana, USA was used as an example to show the effects and benefits of reducing electrical consumption. The households consume more than 30% of the electricity in Indiana. If we were able to decrease the consumption in such a sector by 10%, we will be getting rid of carbon dioxide emissions by approximately 3.6 million metric tons annually which are equivalent to eliminating the emissions of 700,000 passenger vehicles. Additionally, the estimated reduction is expected to save $265 million a year in electricity costs, which is estimated to be as much as $100 for each household in the state [7], [8].

B. Quantifying the problem - local approach

Jordan is considered one of the poorest countries in the primary energy sources not only in the region but also in the world. This makes the search for clean, sustainable, and

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cheap energy sources a serious need. Another objective for engineers and researchers is to find the optimum way of energy utilization in terms of production and efficiency. One of the measures that indicate the bad energy situation in Jordan is the huge amount of imported energy sources which represents 94% of the country's needs [9].

Electricity prices are getting higher continuously and this is a major problem in Jordan. Lately, a lot of residents and household owners are facing the problem of paying high bills which are considered a major economic burden.

In 2013, the electrical consumption in the residential sector was 5,666 GWh which represents 40% of the total electrical consumption for all sectors (industrial, street lighting, water pumping, commercial buildings). In 2014, this ratio increased to 43%. Residential sector energy consumption share represents 21% of the final energy consumption in Jordan [10], [11]. There has been many studies and projects in Jordan that address energy efficiency and different possibilities of generating energy from sustainable and renewable resources in Jordan [12]–[14]. However, very few of these studies targeted the residential sector.

Using E-ring, we aim to reduce the electrical consumption in residential sector by 8-10% of total consumption saving (45.33-56.66) GWh and thus reducing carbon oxide emissions from different application, it saves CO2 emissions equivalent to 4.5 Million gallons of gasoline consumed or 43 Million Pounds of coal burned, or 7000 homes' electricity use for one year or 5 Billion smart phones charged.

In Jordan, people keep consuming electricity without paying much attention to the amount consumed. People of Jordan cannot monitor their consumption regularly and thus, end up consuming too much and paying huge bills at the end of each month.

C. Electricity audit alternatives

Thanks to the high returns on investment (ROE) achievable by the high understanding of the energy use of huge items using electrical metrology. Electricity metering systems for business and industrial buildings are offered for many years and several small-scale residential merchandises have emerged. Residential electricity sensors are sometimes promoted to save lots of energy, for financial and sometimes environmental reasons. It is either whole-house or plug-load meters, with some exceptions. Neither possibility accurately measures individual appliances or track the changes in consumption over time. We are going to explore a number of the overall options of those meters. Samples of commercially offered meters in these three classes are shown in Table I. This section provides details regarding how E-ring will prove its market practicability and scale back the economic risk of commercializing it.

This first kind of meters is **whole-house meters**. Before the power is distributed to separate circuits, they are usually put in on or close to the utility meter or within the home's breaker panel. Some meters are capable of merely relaying the utility meter's reading once capturing it either using optical sensors (Blue Line Innovations 2009) or decoding the radio signal by that the meter is communicating with the utility. Additionally, one or additional current transducers are placed around the main electrical feed lines to measure the electrical current. In some meters, the voltage is measured in addition, to calculate power more accurately. Metrics like the home instant power in watts or the estimated monthly energy use in watt-hours are usually showed on a dedicated display unit, and in some cases, data port permits a connected PC to log data. However, it's going to be difficult to work out the power draw and so to provide acceptable feedback because they do not provide real-time whole-house electric power values.

TABLE I: Battery Types and Technologies Considered

Meter type	Meter brand/mode	Meter price
Whole house	The Energy Detective (TED) (Energy Inc. 2009)	$200
	Power Cost MonitorTM (Blue Line Innovations 2009)	$109
Plug-load meters	WattsUp? PRO (Electronic Educational Devices 2009)	$236
	Kill-a-watt (P3 International 2009)	$20
Packaged solutions	AlertMe (AlertMe.com 2009)	$600+ $160/yr/12device

The second type of meters is **smart meters (AMR/AMI)**. With all of these new technologies being spread out in the market, and all of the new standards being published, it is still under questioning and discussions on consumers understanding and managing their consumption. These meters have been called smart meters as an indication of their ability to acquire data and information about the building's energy demand and transfer these data to the electric utilities through establishing communication with them, getting the latest prices from them and take it back to the building owners. To some extent, it means making the grid, rather than the consumer, smart. The term does not generally imply providing feedback to the users or any other direct interaction with users, despite consumer expectations for the technology. There are plenty of upcoming investments towards the smart grid, and most of them are in the area of improving the infrastructure of energy transmission and distribution, where the advanced metering infrastructure (AMI) equipment will be installed on many homes and secure two-way communication between the meter and the facility. However, while AMI systems will allow utilities to send real-time pricing signals and demand-response requests to homes, they will not necessarily provide real-time power level readings to consumers or otherwise help people to understand and reduce their consumption.

The third type is **plug-load meters**; those meters monitor each outlet individually, where the meter is plugged into the power wall outlet and other devices are plugged into it. It then measures the instantaneous power, accumulating the energy, and calculating other quantities. All of these values will be displayed on an LCD mounted on the device itself. Some versions transmit those values through Ethernet or wireless connections. It should be noted that this type of meters self-consume a substantial amount of energy when you use multiple meters for multiple household appliances. Additionally, as those meters are not smart themselves, they will not be able to calculate the cost of electricity consumed by the appliances and thus require the user to manually calculate according to the ever-changing tariffs. This makes the plug-load meters unreliable for putting the user in the context of real-time monitoring and changing behaviors as they do not provide real-time data or cost estimates.

III. Design of E-ring

A. Overview

The proposed system consists of two main components: The sensor device, and the mobile application that is connected to the cloud. As shown in Fig. 1, our sensor connects to the main electrical wire, then sends the information through WIFI to our cloud. The cloud will forward the information and be visualized in the mobile application for the end user.

Fig. 1: E-ring overview

B. Hardware

E-ring hardware consists mainly of a current transformer, that is connected to a signal conditioning circuit that is used to generate and regulate the voltage so that the Arduino could read it. The current transformer is a 2000 : 1 non-laminated split core made of iron. It clamps to the home's main electricity cable and the cable acts as a single turn on primary and the 2000 turns are considered the secondary. The relationship between the primary and secondary current is shown in (1). The secondary current is then transmitted to a signal conditioning circuit which is simply a bridge so that a voltage within the range acceptable by the Arduino is generated. After that, the Arduino calculates the needed data to determine electrical consumption. A hardware overview of the E-ring is shown in Fig. 2.

$$\frac{N_p}{N_s} = \frac{1}{2000} \tag{1}$$

$$\frac{I_s}{I_p} = \frac{1}{2000} \Longrightarrow I_s = 0.005 \times I_p$$

The signal-conditioning circuit (bridge) is a simple circuit that consists of three resistors; one burden resistor to generate a voltage from the transformed current, and two others to create a bias from the Arduino voltages. The regulation circuit diagram is depicted in Fig. 3.

$$I_p = [0, 10]A$$

$$I_s = [0, 0.005]A$$

With the calculations taken into consideration, and according to Ohm's law, the resultant voltage on the Arduino will range between 0-5 volts, refer to (2).

$$V = I_s \times R \tag{2}$$

$$V = [0, 5]V$$

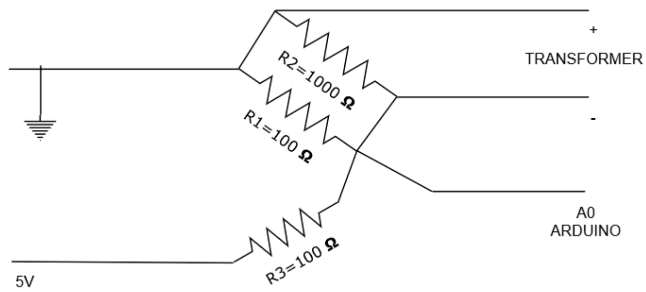

Fig. 3: E-ring regulation circuit

It is to be noted that Eddy current losses are the result of Faraday's law. When the core is being subjected to a rotating magnetic field, a voltage, or EMF will be induced in the coils. This induced EMF causes circulating currents to flow, referred to as eddy currents. The power loss caused by these currents is known as eddy current loss. The equation for eddy current loss is given as in (3).

$$P_e = K_e \times B^2 \times f^2 \times t^2 \times V \tag{3}$$

Where P_e is eddy current loss (W), K_e is eddy current constant, B is flux density (Wb/m^2), f is frequency (Hz), t is material thickness (m), and V is volume (m^3).

It is known that laminations are used to decrease eddy current losses that happen in the transformer. But in this application, using the nonlaminated transformer is more economically efficient. Keeping in mind that the system operates at low frequencies and having a substantially small core that limits the losses due to eddy currents. Additionally, iron cores that are subject to small magnetic fields are used, thus not reaching magnetic saturation; since the cores are not reaching the saturation. As a result, hysteresis losses will be negligible. According to the aforementioned reasons, backed by equations, the effect of eddy currents and hysteresis are neglected and the system's accuracy can be quantified by testing.

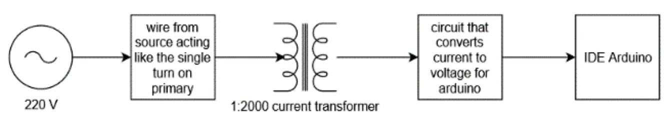

Fig. 2: E-ring hardware overview

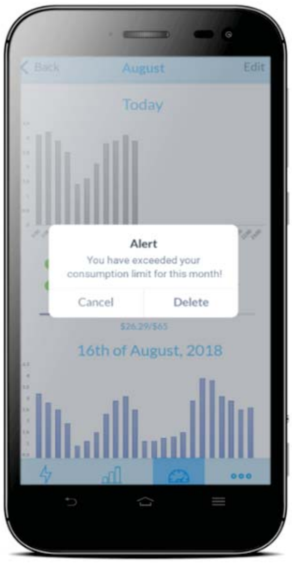

Fig. 4: E-ring application screenshot

C. Software

The Arduino code is responsible for taking samples from the analog input that is connected to the output of the signal-conditioning circuit that varies from 0V to 5V. And using Arduino coding, the microcontroller is detecting the peak voltage from the AC voltage input. After that, the peak value of the voltage is being converted to the RMS value of the voltage, as given in (4).

$$V_{rms} = \frac{V_{peak}}{\sqrt{2}} \tag{4}$$

Then, using MATLAB curve fitting toolbox, Arduino transforms the final readings and maps them to corresponding original current values. In the end, after the original current values have been calculated, we use the current to calculate the instantaneous real power consumed as shown in (5).

$$P = I_{rms} \times V_{rms} \tag{5}$$

where I_{rms} is the RMS current, V_{rms} is the RMS voltage which is considered a constant equals to 220 V, and P is the instantaneous power at any given moment.

After having the instantaneous power values calculated, the Arduino sends it to the cloud via WIFI connection. Then, after the cloud gets the final reading of the power, it will start accumulating the readings, integrating it with respect to time, thus calculating the energy consumed by the user. With the amount of energy determined, the system will be able to calculate the cost according to the official tariffs, considering the consumption segment prices that are predefined within the Arduino. These numbers will be shown in the application on the user's smart phone. A screenshot of this application is shown in Fig. 4.

The data will be visualized, and the application will be equipped with tools to help users reduce their consumption by notification after the consumption reaches a preset electricity bill limit for the month.

IV. Building E-ring Prototype

The prototype, see Fig. 5, was made using a non-laminated split-core, a microcontroller (Arduino mega), and a Bluetooth module to communicate the data. The Bluetooth module was used instead of the wireless because it was simpler and cheaper to test the data. We used a prototype application made by MIT app inventor 2 which received the data from the Arduino and stored it in a database in the smartphone made in the app. Photos of the secondary-coil prototype and the final visualization for the product are shown in Fig. 6 and Fig. 7, respectively. The list of materials for the prototype with the prices is itemized in Table II, which shows that the cost of the entire system does not exceed \$22.

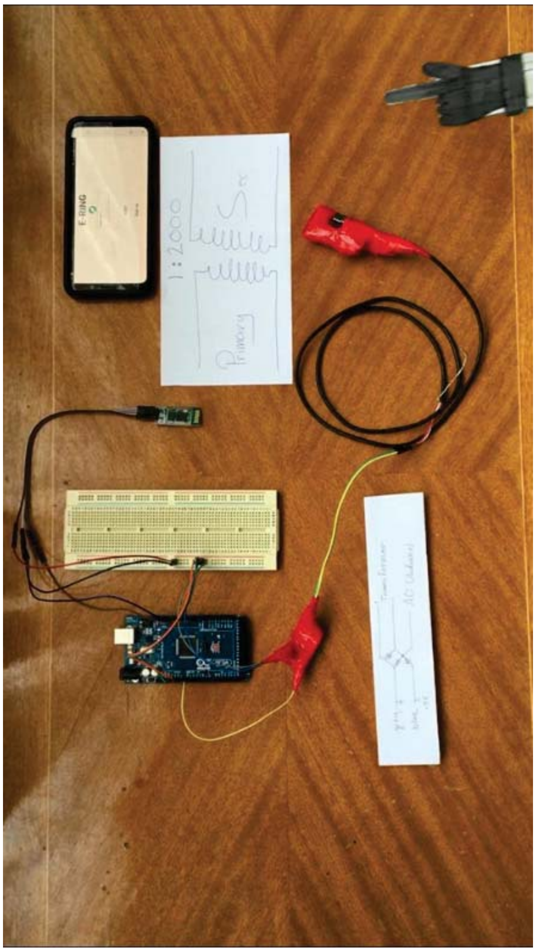

Fig. 5: E-ring prototype components

V. Testing

A. Calibration

For the calibration of the proposed device, a voltage source was used to apply specific voltages covering the 0 to 10A

Fig. 6: Secondary coil prototype

Fig. 7: E-ring device visualization

operational range and the voltages were measured by the Arduino. The results of the calibration are shown in Table III.

After getting these results, MATLAB was used to curve-fit the voltage data points. The 3rd-degree polynomial fitting was picked to generate the fitting equation shown in (6). The coefficients (with 95% confidence bounds) are $p_1 = 0.01751$; $p_2 = -0.1638$; $p_3 = 1.2672$; $p_4 = 0.1828$.

$$f(x) = p_1 \cdot x^3 + p_2 \cdot x^2 + p_3 \cdot \ + p4 \tag{6}$$

With that done, a sufficient fitting for the data was achieved and it is considered accurate enough in estimating energy consumption for the end user. The curve fitting got an R-square equals to 0.9971. The polynomial regression for the voltages is shown in Fig. 8.

VI. Conclusion

Wireless sensor network for single phase electricity monitoring system has been successfully designed in this paper and it proved a high accuracy after testing. This product was compared to the available similar products on the market and it is expected to over-perform them in terms of accuracy, cost, and most importantly, in terms of user experience.

TABLE II: Battery Types and Technologies Considered

Prototype components list		**Price (USD)**
Current transformer	DIY	7
Controller	Arduino Mega	10
Bluetooth module	HC06	5

TABLE III: Calibration Values

Voltage (voltage source)	**Voltage (read by Arduino)**	**Absolute error**
0	0.23	0.23
0.25	0.47	0.22
0.5	0.73	0.23
0.75	1.03	0.28
1	1.37	0.37
1.25	1.63	0.38
1.5	1.8	0.3
1.75	2.1	0.35
2	2.31	0.31
2.25	2.43	0.18
2.5	2.56	0.06
2.75	2.73	0.02
3	2.94	0.06
3.25	3.12	0.13
3.5	3.34	0.16
3.75	3.57	0.18
4	3.72	0.28
4.25	4.02	0.23
4.5	4.24	0.26
4.75	4.36	0.39
5	4.57	0.43

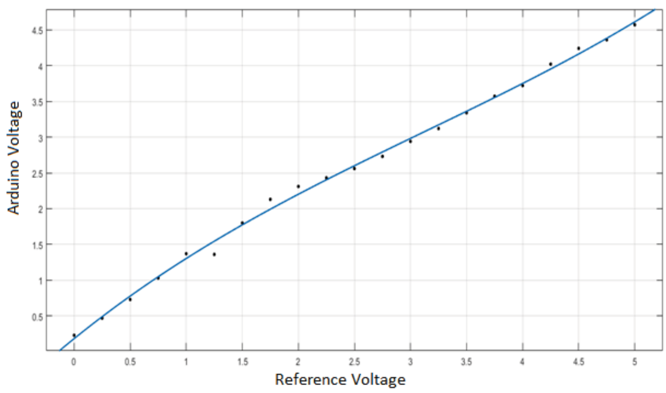

Fig. 8: Polynomial regression for voltages

The plan is to further expand the features of the system in real-world conditions. We are planning to implement a neural network in the software to detect the consumption behavior and track it over days, months, and even years to make each E-ring user-specific. That said, the device will be able to provide consumption recommendations for the user to help reduce consumption. Additionally, as another aspect to support the commercialization of the product, there is a consideration of gamifying the system by calculating and comparing the electricity savings for each household and neighborhood and then create an electricity-saving leaderboard where people who save the most, get rewarded.

E-ring is a very versatile device, giving the space to innovate in terms of software and hardware to make it more efficient and useful for users in the real world. This system aims at setting a basis for electricity monitoring in Jordan and the region and create a platform for people interested in such ideas to build on each others success.

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