IOT POWER CONSUMPTION MONITORING SYSTEM FOR OFF-GRID HOUSEHOLDS

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Abstract: *This paper represents a practical solution for a dynamic, affordable and flexible, power consumption monitoring system that is based on electrical sensors which are connected to the building's own power grid. By using embedded technology and the Internet Of Things concept we have prototyped a real-time power monitoring system that is to be implemented in an autonomous smart home or building which uses renewable energy. Our automated system is able to read data from the sensors convert it to digital values, store it and then feedback it to the prosumer online and offline. The goal of the paper is to highlight the real possibility of further extending the system's features from monitoring to automation, in order for the prosumer to benefit from smarter and faster decisions over its own energy efficiency and power management..*

1. INTRODUCTION

The race for sustainable energy [1] implementation into the actual power generation and distribution systems has been proved to be the safest and best way to provide, on a long term, with enough clean energy for the ever raising demand and securing the future for the next generations.

The effect of this development is the smartification process of the electrical power system from developed countries which is mainly focused to the on-grid one, leaving the off-grid standalone prosumers [2] develop their own behavioral practices towards power generation and consumption.

For the grid tied consumers, the first step was the implementation of smart meters followed by energy management devices such as smart chargers and smart inverters and finally smart appliances with automated capabilities for scheduled usage. In the on-grid scenario, although being necessary, smart meters raised alot of concerns regarding privacy, cyber security, health safety, fire hazards and even bill cost related problems.

Worldwide, most of the traditional IT&C and electronics companies embraced and developed new mobile products and services regarding home automation [3] and monitoring, to increase energy efficiency by using embedded electronics with sensors and the Internet of Things concept as an evolutionary development of machine-to-machine communication, since the early '90s. To name a few, consecrated companies like: Google, Amazon, Microsoft, Samsung, IBM, Intel, Cisco, Siemens, Bosch, Texas Instruments, Nokia, AT&T, Hitachi, Huawei, Sillicon Labs are already offering IoT [4] solutions in industry, business and society for collecting and transmitting data via the internet. In conclusion, it is not a question of "if" anymore, but more of "when" all the electronic devices will communicate with each other on a massive global scale by forming a gigantic WAN.

It is forecasted by the industries, business and trade experts that by the year 2020, about 50 billion devices will be connected in the Internet of Things communication network. Cisco also predicted the exponential trend as follows in Fig. 1[5].

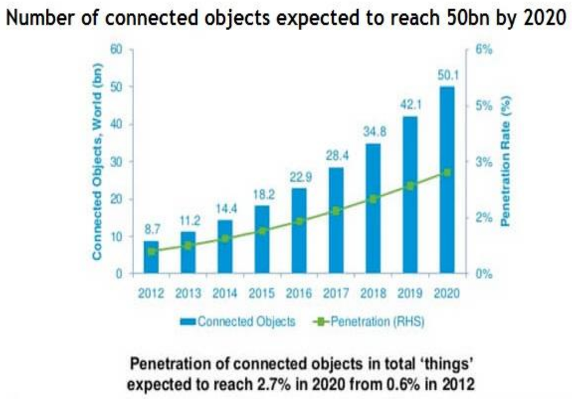

Fig. 1 Cisco forecasting regarding the IoT evolution till 2020.

People choose to live off the grid for various reasons, many of them because of poverty [6], energy independence, easy to install and affordable PV systems, information abundance on “how to”, no billing to utilities companies, “environmentally friendly” movements, survivalism, privacy and remote locations.

Fig. 2. depicts a typical off-grid [7] electrical power system implemented into a household, which is mainly composed of photovoltaic panels, charging controller, battery bank, inverter and an optional fossil fuel generator; some cheaper off-grid power systems rarely having monitoring software support for energy consumption.

Fig. 2 Diagram representation of an off-grid photovoltaic system installed in a home or building.

Regarding the IoT devices cloud solutions for household monitoring offered by big companies like Google, Microsoft and Amazon, there is limited free traffic, for a trial period, based on the number of total information messages and packages sent, thus there is the issue of costs involved over time for subscribing to such services. Another issue with the external IoT cloud platforms is that they are solely dependent on the internet network in order to synchronize the data in real-time.

Making an analogy to our household IoT system solution, we identified some of the characteristics that make this system feasible for off-grid homes or buildings that require monitoring:

- there are no necessary costs for subscriptions to external IoT services
- if remote monitoring is needed, the system only requires a free account for the online power monitoring ThingSpeak API server
- the system has an offline power monitoring HTML server, developed by us, when an internet service is not available for online monitoring
- all the data is stored and available on the local offline HTML server in a CSV data log file on micro-SD card to be accessible for the prosumer
- we conceived our system to plot the real time data on the serial port when neither the online or the offline power monitoring server works due to a software fail or lack of Ethernet equipment like a router
- our system offers mobile solution compatibility for monitoring, through HTML 4.0 browser support and JavaScript based jQuery
- the overall power consumption of our embedded system is less than 2.5W
- the system is flexible enough to be equipped with other additional digital or analog sensors for different purposes such as weather monitoring, household gas leakages or household fires
- the entire system can work independently of any external communication network.

2. SYSTEM HARDWARE COMPONENTS AND DATA ACQUISITION

Our power monitoring system is represented by a modular, low cost, embedded [8], programmable electronic platform (Fig. 3.), equipped with two sensors, that is easy to install on the actual off-grid power system that is described in Fig. 2. It can provide power consumption information online by using a WAN [9] network and a typical wireless router, but it can also operate offline into a LAN network configuration designated to the respective building.

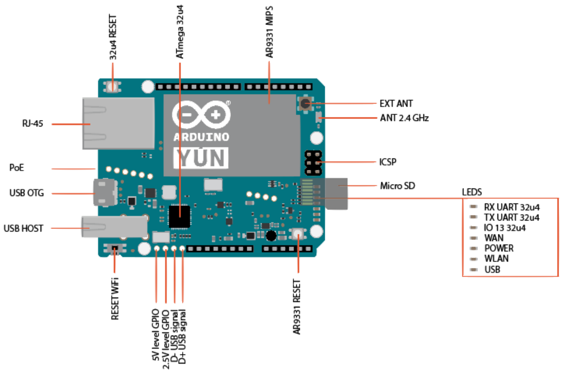

Fig. 3 Arduino YUN features diagram, ports and connectors.

The core of our monitoring system is based on the Arduino YUN [10] open-source board which has a 10 bit ADC for converting input signals, 5V DC operation voltage and input pin reference voltage, SD card slot and USB for data storage, wireless and Ethernet LAN communication modules, standard protocols for data communication (SPI, UART and I2C), digital I/O pins, USB programming port, Linux based operating system and open source capability for customized programming and configuration. The YUN developing board can be configured as a microserver, a router and also have acquisition board capabilities at the same time.

In order for the system to make measurements of the power consumption, we have acquired two types of aftermarket sensors, one to read the voltage (Fig. 4.) and one to read the current (Fig. 5.) that passes through a load represented by home appliances or typical consumers.

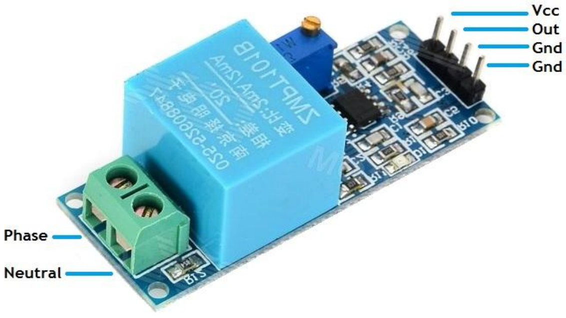

Fig. 4 Pinout description of the ZMPT101B voltage sensor.

Fig. 5 Representation of the SCT-013 open-loop current transformer.

Both sensors have the advantage that are cheap, they are low power consumers of 2 to 10 milliamperes, they are accessible and can work in the 5V DC range which makes them compatible with any DAQ (data acquisition) board.

The electrical characteristics of the voltage sensor are extracted from the producer’s datasheet in Table 1.1.

Table 1.1 Electrical specifications of ZMPT101B voltage sensor

Primary current	3 mA
Secondary current	2 mA
Turn ratio	1000:1000
Linearity	0.2%
Current range	0~3 mA
Voltage range	0~1000 V
Sampling resistor	200 Ω
Accuracy class	0.2
Phase angle error	<3°(50 Ω)

The voltage sensor is dedicated to single phase AC line applications and outputs a proportional analog signal that already has a 2.5V DC offset.

As with the voltage sensor, the current transformer’s electrical characteristics are described in Table 1.2.

Table 1.2 Electrical specifications of SCT-013 current transformer

Primary max current	70 A
Turn ratio	1800:1
Secondary max Output current/voltage	50 mA/1 V
Non-linearity	±3%
Sampling resistor	62 Ω
Dielectric strength	1000 V AC/1min

The current sensor [11] outputs an AC sinewave signal as well, but without a DC offset. It has a built-in sampling resistor of 62 Ω in order to convert the sensed current into rms voltage values [12].

As the Arduino ADC can't read negative values from the current transformer analog signal, we have used a common solution for offsetting the output signal form 0 V to 2.5V DC by using a voltage divider. The voltage divider is connected to the Arduino 5V DC and GND, and uses two 10 KΩ resistors. The 10 bit ADC of the Arduino uses 1024 positive values resolution in strict dependency with the default reference or input voltage of 5V DC (Fig. 6.).

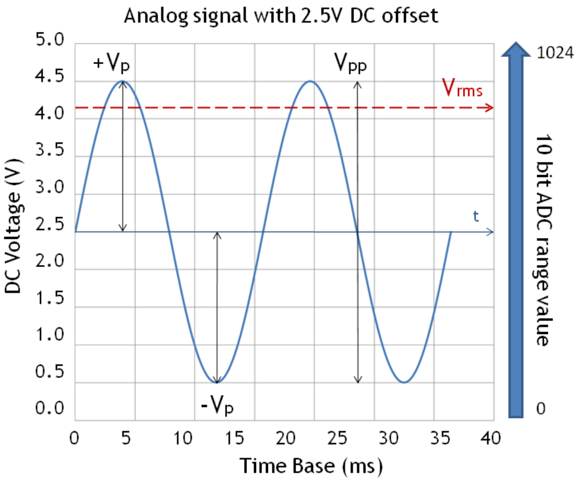

Fig. 6 Representation of the sensor's analog signal offsetted to 2.5V DC with the voltage divider and Arduino ADC range values from 0 to 1024 in direct correspondence with the internal reference voltage of 5 V DC.

Thus all the positive and negative values of an analog signal [13] will be translated by the ADC into positive values over and under 512 offset value in correspondence with the 2.5 V DC offset voltage. In order to conduct laboratory experiments and retrieve comprehensive results from our system, we have used a modified AC socket adapter (Fig. 7.) that has the phase wire exposed as a loop for the clamp-on current transformer.

The voltage sensor has an AC connector attached to neutral and phase wires for fast connection, so basically there is no invasive connection or wires exposed to the rig. The rig has the advantage that allows multiple measurement instruments like clampmeter and voltmeter to be connected on the phase loop in respect to the current flow direction. The AC socket serves as the power source for consumers as well, so we can simulate power consumption of a home appliance.

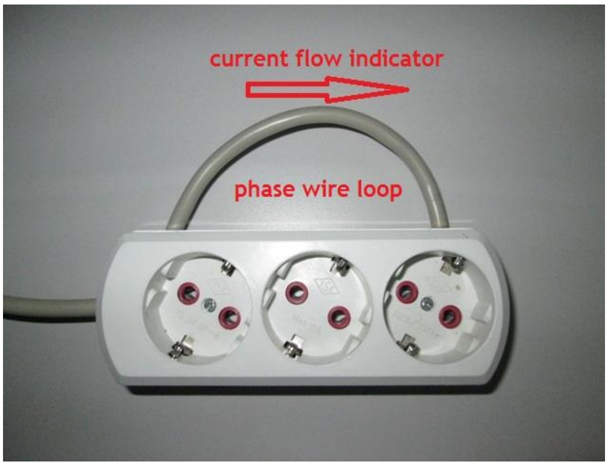

Fig. 7 Representation of the AC socket rig with current flow indicator for the current transformer and clampmeter.

As a home appliance, we have used an aftermarket air heater rated at ~2000W/220V AC at 50Hz, with multiple heating levels (Fig. 8.).

Fig. 8 Representation of a resistive load such as an aftermarket air heater of 2000W, 220V AC/50Hz and heating adjuster chose for testing on the socket rig.

3. EXPERIMENTAL LABORATORY RESULTS

After the global setup of the system, we have acquired data from a professional clampmeter on separate electrical measurements [14] consisting in average power, rms voltage, rms current and also power factor, with the resistive air heater turned to maximum consumption dial (Table 1.3.).

Table 1.3 Clampmeter independent measurements: W, V, A and pf.

W(meas)	*Vrms(meas)*	*Arms(meas)*	*pf(meas)*
1851.00	221.60	8.26	0.99
1848.00	221.66	8.26	0.99
1849.00	222.50	8.27	0.99
1850.00	222.45	8.27	0.99
1854.00	221.80	8.26	0.99
1852.00	220.76	8.25	0.99
1849.00	220.63	8.25	0.99
1851.00	220.57	8.25	0.99
1849.00	221.84	8.26	0.99
1849.00	222.03	8.27	0.99

In parallel, we have conducted measurements with our system comprised of the Arduino YUN microserver and the two sensors attached to the AC socket rig. The output results are best described in Table 1.4.

Table 1.4 Our system simultaneous measurements: W, V, A and no pf.

W(meas)	*Vrms(meas)*	*Arms(meas)*
1822.47	221.42	8.23
1816.52	220.70	8.23
1816.52	220.70	8.23
1822.47	221.42	8.23
1822.47	221.42	8.23
1816.52	220.70	8.23
1816.52	220.70	8.23
1828.43	222.14	8.23
1810.56	219.97	8.23
1828.43	222.14	8.23

All the measurements with our system were obviously made together so there is a direct correlation between them.

The purpose of the measurements was to prove the functionality and accuracy of the data acquired by our system.

We can clearly acknowledge that the measurements difference between our system and the laboratory instruments are very small and have an insignificant deviation error.

Software calibrations of our system can easily solve the voltage reading error. To calculate the standard deviation error [15] of the variance of our readings, we use (1):

$$SD = \sqrt{\frac{(S_1 - \mu)^2 + (S_2 - \mu)^2 + \ldots + (S_n - \mu)^2}{n - 1}} \tag{1}$$

,where S_1,S_2...S_n are the read samples, μ is the population mean of the sample, n is the total sample number.

4. SYSTEM SOFTWARE INTERFACING, DATA PROCESSING AND DATA ROUTING

In Fig. 9, we have represented the complete system architecture and interfaces in order to make measurements, record and plot them on a local and remote server simultaneously [16].

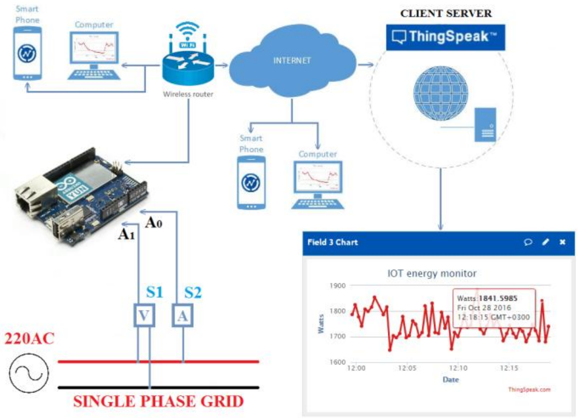

Fig. 9 Hardware and software components diagram of our off-grid power monitoring system.

The Arduino [17] platform has the two sensors connected to the A0 and A1 ADC analog inputs. The platform is configured as a local microserver to plot the data on an offline HTML page, while at the same time it sends the gathered data to an online client server using API calls (Fig. 10.). The remote client server is called ThingSpeak [18] and allows us to monitor our power consumption from our home, anywhere from the internet.

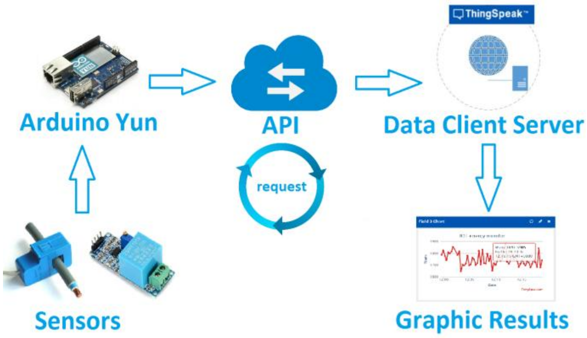

Fig. 10 Diagram of data routing using API requests for plotting power consumption values on the ThingSpeak remote client.

The ThingSpeak client requires an account, which has associated with it an API client key, used by Arduino to know where to send the data. It needs a user name and a password and also some data fields that we created for each measurement (watts, amperes and volts) [19].

Fig. 11, Fig. 12 and Fig. 13 represent the plot fields for our measured values acquired by our system.

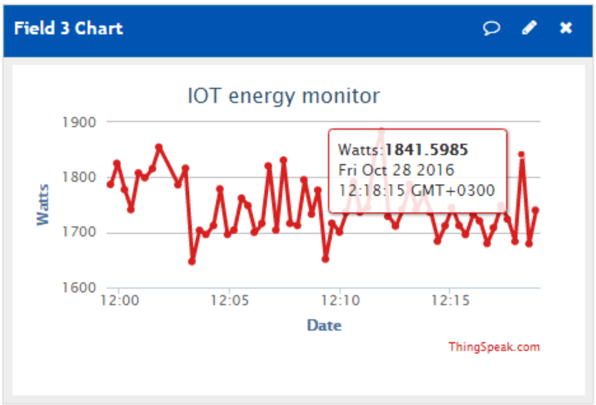

Fig. 11 Client server recorded watts values from the system.

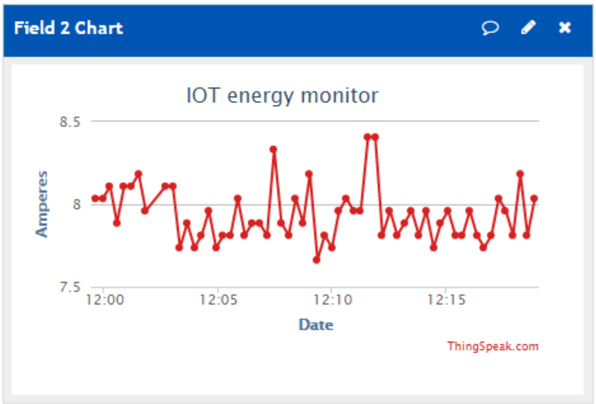

Fig. 12 Client server recorded amperes values from the system.

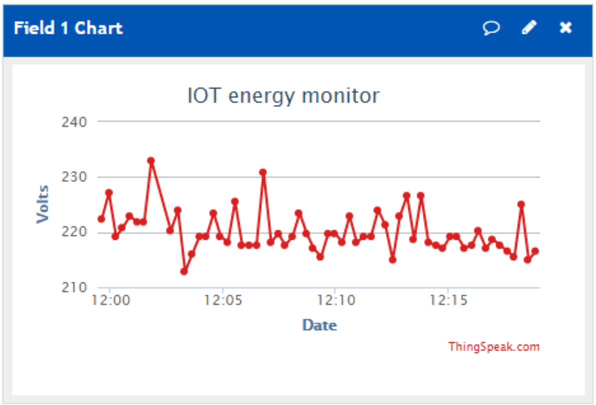

Fig. 13 Client server recorded volts values from the system.

In Fig. 14 it is represented the local HTML plotting page with the same recorded measurements.

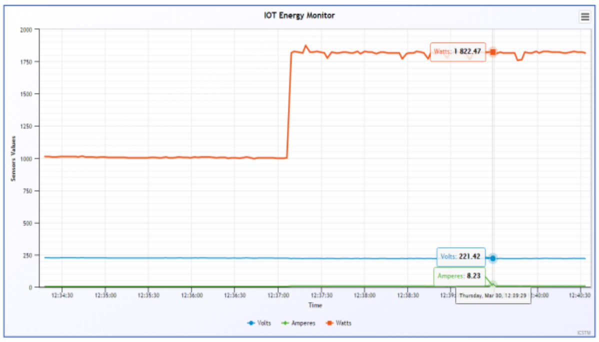

Fig. 14 HTML plot of the system measurements on the Arduino YUN local server (watts are represented by the orange plot, volts are represented by the blue plot and amperes are represented by the green plot).

In Fig. 15 we have described a brief version of the system processing algorithm for data acquisition and plotting [20].

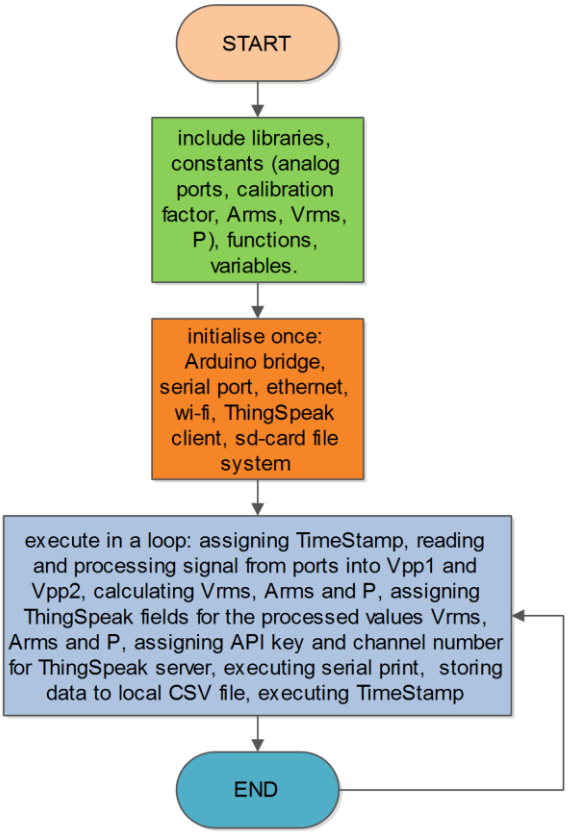

Fig. 15 Synthesized algorithm flowchart of the system for signal conversion, processing, storage and transmission.

Our algorithm reads the raw signal from each sensor and extracts the peak-to-peak values by using (2):

$$A_x V_{pp} = \frac{\left(max_{val} - min_{val}\right) * V_{ref}}{ADC_{val}} \qquad (2)$$

, where A_x is the analog port of the input signal, V_{pp} is the peak to peak amplitude of the input signal, max_{val} is the maximum peak value of the signal, min_{val} is the minumum peak value of the signal, V_{ref} is the 5V DC reference voltage of Arduino and ADC_{val} is the 210 range of the ADC [21] or 1024.

Then the system calculates the instantaneous values for voltage and current and converts them to *rms* values for the calculation of average power.

The instantaneous power is calculated using relation (3):

$$p(t) = V_{pk} \sin \omega t \times I_{pk} \sin \omega t \qquad (3)$$

, where where V_{pk} and I_{pk} are the peak values of the instantaneous voltage and current while ωt is the angular frequency of the sinewave in time *t*.

Thus, the average power calculation for our AC circuit is done by using (4):

$$P_{avg} = V_{rms} \times I_{rms} \times cos\varphi \qquad (4)$$

, where P_{avg} is the average power, V_{rms} is the *rms* quantity of voltage, I_{rms} is the *rms* quantity of current and $cos\varphi$ is the cosine of the phase angle between the voltage and the current or power factor *pf*.

Practically, our tested appliance has a resistive load, thus the *pf=1* and also according to the laboratory clampmeter, the measured *pf* was of *0.99* which is very close to the unity value provided by the inverter.

The system plots the readings on the remote server in a 15 seconds time, while on the local server it plots values in a CSV file on the SD-card and on the HTML page every 2 seconds.

As an example (Fig. 16), the Arduino YUN platform can further be configured and programmed to use its digital pins in order to control a relay array for scheduling the usage of home appliances or prioritise and manage power consumption of consumers during the day and night.

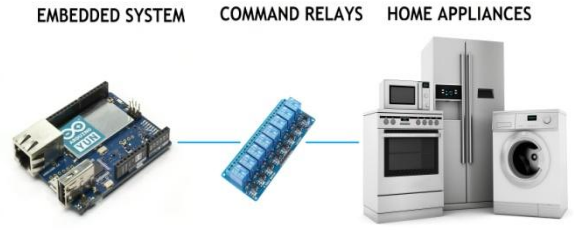

Fig. 16 Representation of home appliances scheduled for power management by relays module and a Arduino YUN smart platform.

5. CONCLUSIONS

By using a low cost and highly configurable electronic, embedded platform, we have demonstrated by experimental means, the real possibility of implementing of such systems in the off-grid homes and building of prosumers. Our system has been proven to be accurate enough to render real values about power consumption and can be further developed into a smart energy system by using additional sensors and relay modules for controlling any household consumer.

We have also demonstrated that by using the powerfull IoT feature, which the board supports, we can remotely monitor and control any electronic device to improve energy efficiency of the off-grid prosumers [22]. Based on the internal clock of the platform, a schedule can be developed through an additional algorithm that will control, using relays, some household appliances that can work unsupervised during the day, when solar energy production is at peak.

6. ACKNOWLEDGMENT

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7. REFERENCES

[1]. Hickson K., "*Race for Sustainability: Energy, Economy, Environment and Ethics*", World Scientific Publishing Company; 1st ed., pp. 328, 4 December 2013.

[2]. Hansen M., Hauge B., "*Prosumers and smart grid technologies in Denmark: developing user competences in smart grid households*", Energy Efficiency, pp. 1-20, 13 March 2017.

[3]. Campos L.B., Cugnasca C.E., Toschi G.M., "*Home automation networks: A survey*", Elsevier Science BV, vol. 50, pp. 42-54, February 2017,

[4]. Badra M., "*Internet of Things and Smart Cities: security, privacy and new technologies Preface*", Ad Hoc Networks, Elsevier Science BV, vol. 57, pp. 1-2, 15 Mach 2017.

[5]. McLellan Charles, "*The internet of things and big data: Unlocking the power*", 2015. [Online]. Available: http://www.zdnet.com/article/the-internet-of-things-and-big-data-unlocking-the-power/.

[6]. Bloomberg New Energy Finance report, "*Off-grid solar market trends report 2016*".

[7]. Bridgewater A., Bridgewater G., "*The Off-grid Energy Handbook*", New Holland Publishers Ltd , pp. 192, 30 May 2008.

[8]. Marwedel P., "*Embedded System Design: Embedded Systems Foundations of Cyber-Physical Systems*", Springer Netherlands , 2nd ed., pp. 400, 2011.

[9]. Teresa C. P., Terplan K., "*Network Design: Management and Technical Perspectives*", CRC Press, pp. 416, 19 August 1998.

[10]. Kuhnel C., "*Arduino for the Cloud: Arduino Yun and Dragino Yun Shield*", Universal Publishers, pp. 198, 2015.

[11]. Briggs Silsbee F., "*A method for testing current transformers*", Govt. Print. Off. 1918, pp. 13, 12 May 2011.

[12]. Laughton M.A., Warne D.F., "*Electrical Engineer's Reference Book*", Butterworth-Heinemann, 14th ed., pp. 992, 1 January 1985.

[13]. Jean Jiang, Li Tan, "*Fundamentals of Analog and Digital Signal Processing*", AuthorHouse , pp. 408, 1 May 2007.

[14]. Hoornaert W., Iwansson K., Middelhoek S., Sinapius G., "*Measuring Current, Voltage and Power*", Elsevier Science , vol. 7, 1st ed., pp 215, 1 June 1999.

[15]. Frederick J. Gravetter, Larry B. Wallnau, "*Statistics for the Behavioral Sciences*", Cengage Learning, 9th ed., pp. 792, 2012.

[16]. Alvin T. S. Chan, Hong-Va Leong, Jiannong Cao, Keith C. C. Chan, Ming Xu, Yingwen Chen, "*In-Network Data Processing for Wireless Sensor Networks*", IEEE Xplore, MDM '06 Proceedings of the 7th International Conference on Mobile Data Management, 30 May 2006.

[17]. Bhabani P. Sinha, "*Distributed Streaming Data Processing in Sensor Networks*", IEEE Xplore, The 3rd International Conference on Industrial and Information Systems (ICIIS) 2008, 06 March 2009.

[18]. Ahmed I. Abdul-Rahman, Corey A. Graves, "*Internet of Things Application Using Tethered MSP430 to Thingspeak Cloud*", IEEE Xplore, Symposium on Service-Oriented System Engineering (SOSE) 2016, 19 May 2016.

[19]. Intakot P., Tamkittikhun N., Tantidham T., "*AC Power Meter Design Based on Arduino: Multichannel Single-Phase Approach*", IEEE Xplore, International Computer Science and Engineering Conference (ICSEC) 2015, 11 February 2016.

[20]. Akshay D. Deshmukh, Ulhas B. Shinde, "*A low cost environment monitoring system using raspberry Pi and arduino with Zigbee*", IEEE Xplore, International Conference on Inventive Computation Technologies (ICICT) 2016, 26 January 2017.

[21]. Pallás Areny R., Reverter F., "*Direct Sensor-to-microcontroller Interface Circuits: Design and Characterisation*", Marcombo S.A., 1st ed. pp. 150, 2005.

[22]. Akshay Shriyan, Keerthi Unni, Prakash Yasarp, Vikas Thale, Sanket Thakare, "*Implementation of an energy monitoring and control device based on IoT*", IEEE Xplore, IEEE Annual India Conference (INDICON) 2016, 02 February 2017.