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Arduino based Appliance Monitoring System using SCT-013 Current and ZMPT101B Voltage Sensors

***Abstract**. This paper presents the design and development of a device for use as an energy monitoring system of home electrical appliances. The device can measure and log the details of appliance consumption directly from a 13 amps power plug outlet where the appliance is connected. Construction of the system is based on Arduino as main controller, SCT-013-000 current sensor, ZMPT101B voltage sensor, real-time clock, SD card and other passive electronic components. Performance and efficiency of the proposed system have been evaluated through an experiment employing several commonly used appliances such as electric iron, electric kettle, refrigerator and washing machine. From the comparison of logged appliance data consumption with the reading of a commercial energy meter, the overall results show a good agreement of voltage, current and power values with accuracy of up to 95%. The proposed device can be used in home energy management system for monitoring closely the appliance activities.*

***Streszczenie.** W artykule przedstawiono projekt urządzenia do zastosowania jako system monitoringu energii domowych urządzeń elektrycznych. Urządzenie może mierzyć i rejestrować szczegóły zużycia przez urządzenie bezpośrednio z 13-amperowego gniazdka elektrycznego, do którego urządzenie jest podłączone. Konstrukcja systemu oparta jest na Arduino jako kontrolerze głównym, czujniku prądu SCT-013-000, czujniku napięcia ZMPT101B, zegarze czasu rzeczywistego, karcie SD oraz innych pasywnych elementach elektronicznych. Wydajność proponowanego systemu oceniono w eksperymencie z użyciem kilku powszechnie używanych urządzeń, takich jak żelazko elektryczne, czajnik elektryczny, lodówka i pralka. Z porównania zużycia danych zarejestrowanych przez urządzenie z odczytem komercyjnego licznika energii, ogólne wyniki wykazują dobrą zgodność wartości napięcia, prądu i mocy z dokładnością do 95%. Proponowane urządzenie może być wykorzystane w domowym systemie zarządzania energią do ścisłego monitorowania pracy urządzenia. (**System monitorowania poboru mocy oparty na Arduino za pomocą czujników prądu SCT-013 i napięcia ZMPT101B**)*

Keywords: sensor, energy data logger, appliance monitoring system.
Słowa kluczowe: monitotowanie ppoboru mocy, kontroler Arduino, czujnik prądu.

Introduction

Malaysian government through the Ministry of Energy and Natural Resources has recently announced an initiative of 8% savings from the energy efficiency (EE) in 2025 [1]. One of the systematic approaches of implementing the EE program is by installing the smart energy meters [2, 3]. The smart meter can connect and communicate with other devices so that a proper implementation of home energy management system can be achieved [4, 5]. By understanding the overall electricity consumption in the domestic area including appliance by appliance energy profile, the end user and utility company can carry out planning on energy saving strategies and improve the prediction of residential area energy demand [6-8]. Therefore, it is vital to closely monitor the appliances activities and consumptions so that the loads data can be processed and analysed in a more detailed manner [9].

The research on energy monitoring of electrical appliances has been introduced since several decades through the studies about intrusive or non-intrusive load monitoring (ILM/NILM) [10]. An ILM refers to the measurement and logging of appliances consumption data at the power plug level using the energy monitoring devices continuously. The continuous monitoring provides useful information about individual appliance consumption patterns and operation status updated timely in which the data can be further processed by any type of controllers for further actions. The NILM on the other hand works in a similar way except for its single point data measurement where the energy meter is normally installed at a building's electrical service entry [11]. Here, the aggregated loads data are measured and logged continuously at around 1 Hz to several kHz frequencies. Since only the aggregated loads data are measured, NILM system is more difficult as it requires further processing of data by means of intelligent techniques to disaggregate the loads data. The disaggregation of load data into an individual appliance consumption needs actions from the central controllers [12, 13]. For example, researchers in [14] developed a NILM house monitoring system based on Arduino and the data collected is trained by a feed forward Artificial Neural Network (ANN) for the load recognition.

With regards to the state-of-the-art and implementation of ILM and NILM technologies, both methods require large numbers of home electrical appliances consumption data. Some NILM algorithms have been developed by past researchers based on the publicly available datasets [15]. The public datasets are easily accessible and downloaded from some well-known databases such as UK-DALE, REDD, AMPds, I-BLEND and many others [16]. However, these datasets are limited to the appliances that are mostly used in countries where the data were measured. Furthermore, some of these data were measured based on non-varying supply voltage that caused the inconsistency of the reported NILM techniques [17]. Another approach of obtaining the loads data is by using commercial measuring instruments like the portable energy meters or power analyzers [18]. The commercial power analyzers have advantages in terms of measurement accuracy, reliability and some devices are portable which can be easily transferred from one house or appliance to another. However, those instruments are costly, limited data storage, unsupported high frequency data measurement and lack of data management flexibility. Recently, NILM and ILM technologies are moving toward a real-time load monitoring solution which processes the aggregated loads into individual appliance consumption patterns that can be visualized in real-time. The system is built based on a microcontroller-based energy monitoring device for appliance data measurement. The real time NILM solution or RT-NILM in [17] for example utilized the universal smart meter (i.e an EKM Omnimeter v3) to measure and record the appliances consumption. However, the EKM metering devices are mostly sold in packages inclusive of its cloud data system and communication devices that still can be considered costly. Despite the advantages in terms of accuracy of existing smart meter technologies in producing real power, reactive power, power factor, voltage and currents usage of home appliances, however this meter also has disadvantages as the online data leads to internet security issues. Another innovative solution for home energy management systems was introduced by [19] which is a hardware prototype of smart plug. Zigbee technology was used to demonstrate the home energy management system through an optimized scheduler to reduce energy consumption and the total electricity bill. The use of the ZigBee module in the developed device claimed to be cost effective, however the use of a transformer installed in each socket is quite expensive [20]. Furthermore, the proposed device is not a type of detachable one, in which it is designed specifically for measuring a certain device's energy.

Another research in the field of ILM was carried out by [21] that invented a smart socket and mobile application to monitor and control the power usage at socket. However, the device requires an initialization process every time it is connected to a new socket. Therefore, consumers with no background in electronics may find some difficulties in doing such a process every time they need to connect the device to another socket. An Arduino-based microcontroller non-intrusive load management system has been introduced in [22] to monitor the power consumption of a building. The developed measurement prototype has an accurate power and error measurement at less than 5%. Despite the less cost system that has been introduced, however the measurement system does not work as a detachable plug system that can be transferred seamlessly from one plug socket to another. In this regard, the idea of making detachable plug is more cost effective as one plug with one set of sensors can be connected to any 13 Ampere power sockets. In this work, a portable appliance monitoring system based on an Arduino microcontroller board with SCT-013 current and ZMPT101B voltage sensors is introduced to contribute to ongoing research on real-time ILM systems. The device was developed for accurate measurement of appliances power consumption pattern and operation status.

Research method

The construction of the proposed prototype started with the design of circuits in Fritzing software. Then, Arduino Integrated Development Environment (IDE) is used to sketch the code, setting up DS3232 real time clock (RTC) board and Arduino SD card module so as calibrating SCT-013 current transformers (CT) and ZMPT101B voltage sensors by means of the commercial clamp meter and energy meter, respectively. Later, the source code is developed according to the requirement of the prototype and finally the experiment is conducted to log and analyse the data, thus evaluating the proposed system performance.

A. Design of circuit

The system is developed based on the concept of the ILM to measure the appliance consumption at plug level so that the appliance's consumption pattern and operation status can be monitored. The device comprises the extension plug which is modified to sense the voltage and current by ZMPT101B voltage, and SCT 013 current sensor, respectively as shown in Fig. 1.

From the Fig. 1, the analog signals from the sensors are processed by Arduino where the data of the appliance consumption in terms of current, voltage and power are saved in the SD card. To cater for the actual progress of time and adequate frequency setup of the logging process, the real time clock (RTC) is used. Arduino Uno has an advantage in terms of easy operation, customizable for wide range of applications, and it comes with the built-in Analog to Digital Converter (ADC), which makes it cost effective and easy to use when integrating with analog CT sensors and voltage sensor. As the Fig. 1 shows, signal wires of from the ZMPT101B and SCT-013 are connected to A0 and A1 analog pins, respectively. Whereas, A4 and A5 pins are used for the RTC. These analog pins are part of the Arduino's on-board ADC channels that can accept the voltage range from 0-5V. Other components connected to the circuit are 470 kΩ resistor, 33 Ω resistor and 10 μF capacitor, respectively where the ratings of these components were chosen based on calibration of sensors.

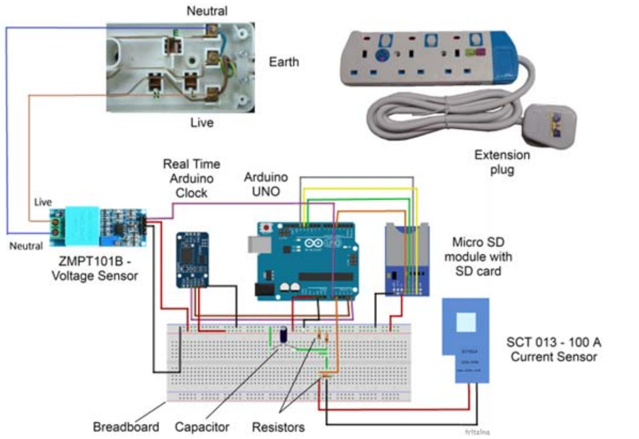


Fig. 1. Complete system design circuit

B. Calibration of sensor

The SCT-013 CT sensor is a type of current output signal sensor which needs the burden resistor to convert the current signal output into voltage signal which can be read and processed by an Arduino microcontroller. From the CT sensor specification, the measurement ratio is 2000 times, meaning that when maximum current of 100 A is flowing in the live wire, the secondary output current of CT sensor becomes 0.05 A. However, since the current flow of the live wire is measured based on RMS value, the secondary coil current value of the sensor is measured as 0.0707 A. To maximize the voltage measurement resolution, the peak current should be equal to one-half of the Arduino analog reference voltage [23]. Thus, from the calculation, a 35.4 Ω burden resistor is recommended as an ideal burden resistor. In this case, a closer value to the suggested burden resistor, i.e. 33 Ω resistor was selected. In theory, the calibration value which is to be used in program code is specified by taking the ratio of the CT sensor measurement ratio with the burden resistor (i.e. 2000/33=60.606). As for the voltage sensor, calibration is straight forward by simply adjusting the potentiometer on the module until the value shown in the serial monitor of Arduino IDE is the same as the multimeter [24]. In this regard, calibration of both voltage and current sensors were based on comparison with a reliable commercial standard instrument that is the multimeter used was from TECPEL DCM-2606 Digital AC DC Current Clamp Meter True RMS.

C. Development of source code

The Arduino UNO uses C++ to communicate the Arduino with the Arduino IDE software. Since both input sensors and addition modules were successfully calibrated and set up individually by Arduino UNO, the source code has been improved and combined according to the requirement of the system in the present study. A file is created and opened in the SD card making room for the

RTC to record the actual time and write them to the file. Later, the CT and voltage sensors collect the data from the input source and write them in the same file. Besides, the current and voltage values, the program code is also included with calculation of the corresponding power and directly written to the file. The data array in the file comprises date, time and days of the data being collected, current and voltage values measured by the sensors, so as the calculated power during the instantaneous measurement. The program code will only stop, save and close the file when the system is interrupted.

D. Experimental procedure

The experiment is conducted to evaluate performance of the proposed prototype. Several electronic products that are widely used in a household were selected as targeted loads. Among the appliances are devices that use heating elements such as electric iron and electric kettle, also some common consumer appliances such as refrigerator and washing machine. The washing machine is used to represent the variable state load device. Four types of loads used with the corresponding power ratings of each appliance. Firstly, the power consumption of Panasonic electric iron is rated at 1000 Watts 240V 50Hz, whereas the Faber electric kettle power rating is within the range of 1850 and 2200 Watts 220V-240V 50/60Hz. As for the refrigerator, it is a traditional type refrigerator that uses R-134a refrigerant from Toshiba that consumes a rated power about 66 Watts 220V-240V 50Hz. Finally, the washing machine is a medium size one by Samsung with a maximum capacity of 6.5 kg and consumes about 330 Watts 230V-240V 50Hz. The selection of old appliances that operate using electric motors is intentionally to evaluate the effect of motor efficiency used in those old appliances.

The final complete prototype for experiment purpose is as shown in Fig. 2. More detailed about the separation of the power system voltage seciton and the digital logic voltage section (microcontroller) can be referred to the circuit in Fig. 1. The experiment is started by plugging in the extension plug to the power supply socket. Later, each electric appliance (load) is connected to the extension plug one by one. Before beginning the measurement of each load, the power is switched on allowing the system to standby for about 2 minutes. After that, the load is switched on to operate as normal operating condition. The current and voltage measurement data is then logged in the file that is automatically saved in the SD card. The collected data also displayed simultaneously in Arduino IDE software if the serial monitor window is opened. Every time after completing the experiment and switching off each load, the system is left to operate for another 2 minutes to make sure all the data is successfully recorded. This is to enable some safety margin of data that turned to steady-state after switching ON/OFF. The logged data in the SD card are then analysed and compared with the electric appliance specification so as comparing the measurement values with the commercial energy meter.

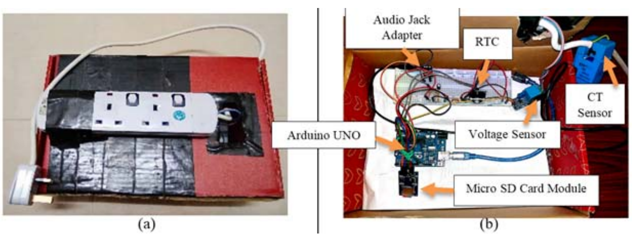


Fig. 2. The final completed device: (a) whole system prototype, (b) the circuit of the system inside the box

Results and discussion

The results are arranged into two categories for all four types of selected appliances, that is resistive loads and inductive loads, respectively. The electric iron and kettle belong to resistive type loads, while the refrigerator and washing machine represents the inductive loads. The results are explained based on the voltage, current and power consumptions of each load used in the experiment. In general, the observation of results is in terms of accuracy of voltage and current measurements as well as the power consumption pattern over time.

A. Voltage consumption pattern

Fig. 3 presents the variations of voltages supplied to each load. The voltage fluctuates between 235 V and 252 V for all loads tested. Clearly these voltages are within the specified range regulated by the power utility, i.e. Tenaga Nasional Berhad (TNB) which specifies the steady state voltage fluctuation limit for 230 V supply can vary within -6% and +10% [25]. As Fig. 3(a) shows, the electric iron's voltage increases and decreases due to the turning on and off its heater to maintain the required setting temperature. However, for the electric kettle, the overall voltage measured over 220 seconds shows less variation and steady to keep boiling the water until it reaches the boiling point. The inductive loads of refrigerator (Fig. 3(a)) and washing machine (Fig. 3(b)) that use electric motors cause continuously varying voltages depending on the state of operation. However, both average voltages of each appliance were measured within acceptable range of 242 V (refrigerator) and 240 V (washing machine), respectively. The graph of the washing machine in Fig. 3(b) even it is old, however it still functions properly with consistent voltage despite the different processes occurring such as soak, wash, rinse and spin.

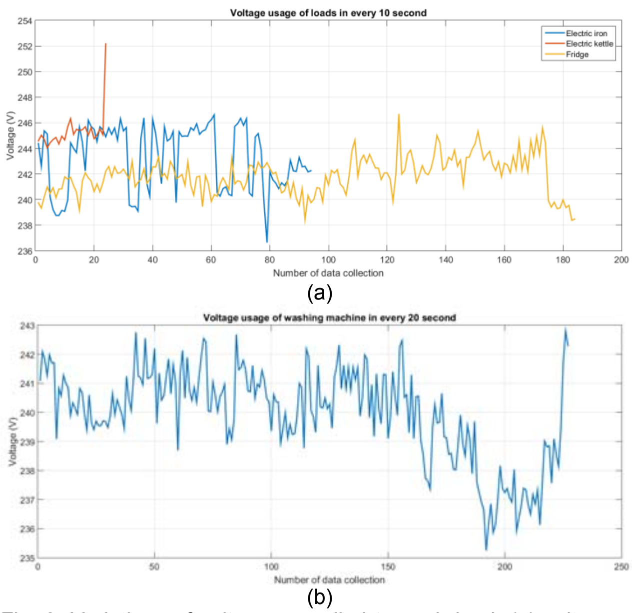
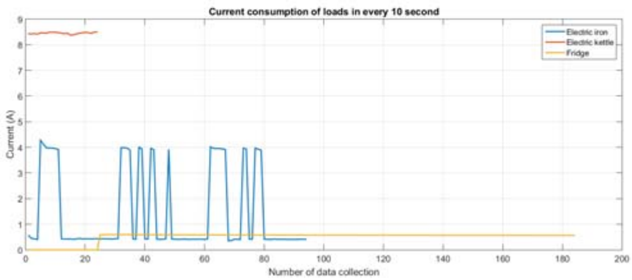


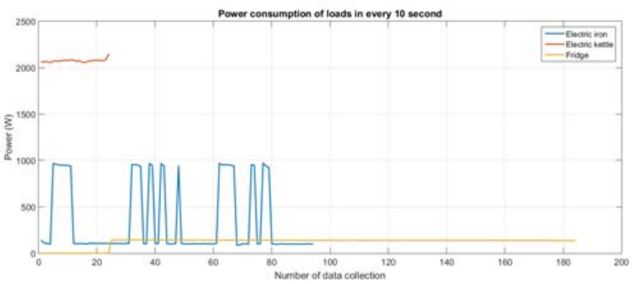
Fig. 3. Variations of voltages supplied to each load: (a) voltage of an electric iron (blue), kettle (red) and refrigerator (yellow) in every 10 second when active, (b) voltage of washing machine during operation time in every 20 second

B. Current and power consumption pattern

The result of the voltage measurement of each load shows that voltage values have small differences compared to the current usage of each appliance. Consequently, the current influences the pattern of power consumption of each load because power is the product of current and voltage. Fig. 4 presents current and power consumption of electric iron (blue), electric kettle (red) and refrigerator (yellow) during the experiment. In Fig. 4 (a), the electric iron graph shows the current use in the range of 0.5 A to 4.0 A. The current increase and decrease frequently due to the temperature setting for heating up and maintaining the iron temperature. Besides, the current value of electric kettle shows the consistent value between 8.35 A and 8.50 A over the 220 seconds of measurement. When the electric kettle power is on, the current immediately rises to a steady state and varies slightly throughout the heating process in order to heat up the coil in the kettle. Similarly for the refrigerator, the current increases once at around 230 second and turns steady state after that indicating the operation of the compressor to keep the temperature at its constant state during interruption by the user for example in the event of opening the door. Here, the compressor starts to consume current to convert refrigerant gas back to liquid for the cooling purpose. After the fridge is cooling back, the current consumption value decreases. For the power consumption graph in Fig. 4(b), the patterns are almost similar to the current. It is normal as no significant voltage drop or rise during experimental operation of all loads. The highest power consumption of the electric iron recorded is at average of 969 W which is around 3.1% lower than the rated value. In addition, the recorded power consumed by an electric kettle is between 2040 W and 2143 W which matched its specification limit.



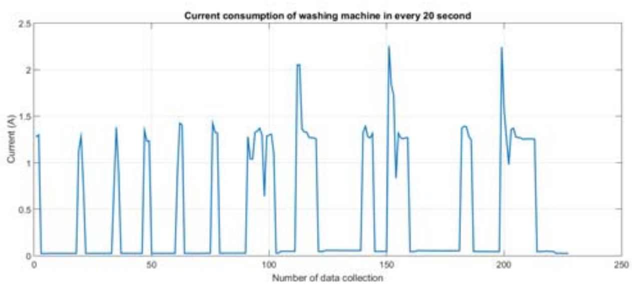
(a)



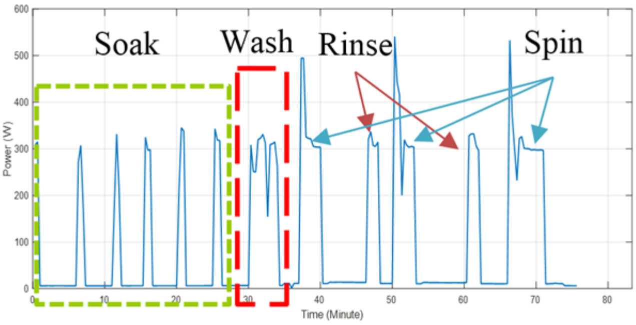
(b)

Fig. 4. Consumption patterns of electric iron (blue), kettle (red) and refrigerator (yellow), respectively: (a) current and (b) power

The washing machine represents the variable state device. Fig. 5 demonstrates the current and power consumptions of washing machines where the data have been collected every 20 seconds over the 75 minutes of operation to clearly observe the pattern.



(a)



(b)

Fig. 5. Consumptions of the washing machine: (a) current, (b) power

From the figure, the current and power consumption of washing machines consistently rise and fall following the washing cycle. When the washing machine starts with a soak cycle, the motor is rotating repeatedly at a constant period that causes the current and power value to increase regularly. After that, it starts to wash, rinse and spin cycle repeated for 3 times. Current and power values increase when the motor starts to rotate for the washing process at around the 30th minute. The washing process continues for about 5 minutes. Then, at around 37th minute, the motor starts to spin to discharge the water. Later, the water is filled again to start the rinse process at 46th minute. The consequent processes of rinse and spin were repeated until the final rinse and spin process cycle at around 1 hour and 15 minutes. As can be observed from the figure, the final spin process takes longer time to dry out the clothes completely.

The inductive loads, particularly the old type appliances influence the overall power consumption. It is due to the motor getting old and causes increase in power factor, thus decreasing efficiency. The actual measurement shows higher value of apparent power compared to the real power as indicated in Fig. 6. For example, the power consumption of the refrigerator is measured at 144.6 W and the true power recorded is 138.8 W despite its specification limit of only 66 W. Meaning that more than double increase of power consumption. Similarly, for the washing machine, the maximum apparent power and true power consumed were recorded around 540.57 W and 529.76 W, respectively despite its specification limit of only 330 W. These old inductive load appliances consume more power than expected due to decreasing efficiency of electric motors.

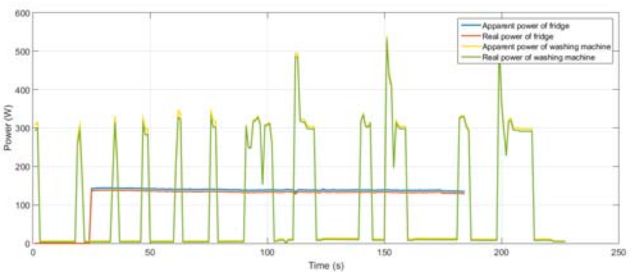


Fig. 6. The real power and apparent power of refrigerator and washing machine during operation time

C. Overall accuracy of measurement

A commercial energy meter is used to evaluate the measurement accuracy of data collected by the prototype device. The accuracy of current data for electric iron and kettle is 99.74% and 95.77%, respectively. On the other hand, for measurement of power, the percentage error of consumption for the electric iron is slightly higher which is 4.55% compared to the kettle which is around 2.49%. This slight difference can be attributed to the choice of burden resistor value used in the circuit. Consequently, since refrigerators and washing machines are inductive type appliances, therefore all the apparent power value obtained from the prototype device must be multiplied with the power factor to get the true power used by these appliances. The energy meter provides a power factor for each measurement and the average power factor for the refrigerator was found to be 0.96. Considering this power factor, it does not affect much on the accuracy of current and power measurement of the device for the refrigerator which is 97.14% and 98.98%, respectively. Further studies have been conducted to monitor the operation of the washing machine by observing the measurement accuracy for every cycle during the machine's operation. Fig. 7 shows an example of current, power factor and power consumption value of washing machines in different washing cycles from the energy meter. From the results of the reading of the energy meter (Fig. 7) and the experimental results shown in Fig. 6, power consumption accuracy of the washing machine during soak, wash and rinse cycle is 99.83%, 99.70% and 99.43% respectively. However, the accuracy of power consumption in the spin cycle is less than other cycles which is 95.21%. Clearly, the non-linear characteristic of an electric motor influences the calibration value of the sensors when the motor works for a longer time and its temperature increases. However, overall accuracy of measurement of the proposed system still can be considered only less than 5% error.

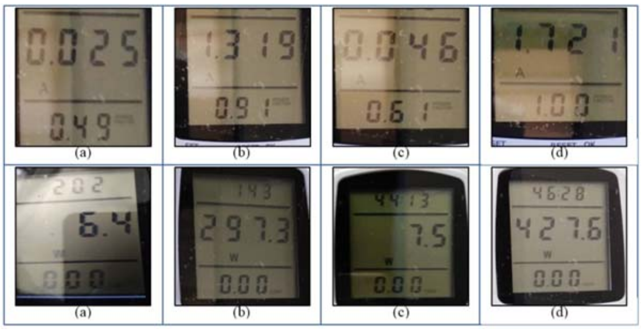


Fig. 7. Energy meter displays of current and power factor (top) and power consumption value (bottom) of washing machine in different washing cycles: (a) soak process without motor rotate (b) wash process (c) rinse process before motor start to rotate (d) spin process

Conclusion

A real time energy monitoring and data logger system based on Arduino microcontroller has been developed and experimentally tested. The device has advantage of measuring the appliances power consumptions at plug level. Meaning that it can be transferred from one plug to another to collect the data from where the appliances are connected. The device can be used as plug-and-play as no initialisation process is needed. Furthermore, most of the components used for the prototype are low cost and have great flexibility in terms of data storage. Thus, making it easier for the user to monitor and collect appliance data consumptions of different type appliances. The experiment results provide acceptable accuracy of the data measurement from both the resistive type and inductive type loads at 95% accuracy. Furthermore, it can accurately measure multi-state appliances such as the washing machine so that it is easier for the user to monitor its operation. The acquired data can be further processed employing the algorithms developed for NILM/ILM concepts and this system will upgrade into an online monitoring and data logger system in future work.

Future work

The prototype is intended to be used to measure long-term data of appliances' usage of a house hold. In the future, the prototype will be further improved so that it fits real-world environment by using industrial standard components with a comprehensive calibration and verification processes. Some circuit improvement considered including constructing a more stable circuit based on PCB board with proper wirings and so that it is close to industrial standard. Also protecting it with a proper enclosure. In addition, it can be included with harmonic analyser to study the power quality in more detail.

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