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MONITORING AND CONTROL OF DOMESTIC DC LOADS CONNECTED TO SINGLE INPUT MULTIPLE OUTPUTS (SIMO) DC–DC CONVERTER USING IoT

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ABSTRACT

Photovoltaic (PV) power generation, utilization and home automation and domestic loads control are exciting fields that are exploding the recent technologies. Internet of Things (IoT) provides an attractive and technological platform to connect the two and make home automation and domestic energy utilization easier and attractive. This paper presents the use of IoT-based control topology to monitor and control power distribution and consumption by DC loads connected to single-input multiple outputs (SIMO) DC-DC converter, thereby reducing leakages, enhancing performance and reducing human efforts. A SIMO converter was first developed and integrated with the IoT/Raspberry Pi control topology, which enable the user to monitor and control power scheduling and load forecasting via an android app. The two systems were developed and tested with a reliable and convincing solution to home automation and loads management. Demands and supply were recorded by the user via mobile app created to monitor the management and control. The recorded data are plotted and shows how the two react to changes in solar energy supply and demands by the loads.

1. Introduction

In the last few decades, researchers are working on developments that utilize sustainable and clean energy resources to meet the global demand and overcome hazardous environmental and atmospheric threats due to human activities [1]. Energy generation and exploitation are increasingly getting interest worldwide [2]. Photovoltaic (PV) system is a promising and reliable source of renewable energy sequel to its ability to generate clean electricity [3, 4]. These days, PV systems have high significance due to their attractive specifications and simplicity in operation, installation and low cost of maintenance, and it produces no noise because it has no moving parts. But, one of its disadvantages is relative low efficiency [5]. The photovoltaic system's output voltage is unstable due to instability of the irradiances [6, 7]. DC-DC converters are employed to provide constant regulated output voltage [8].

There is consistent and significant market and consumer demands for portable, small-sized, reliable and efficient DC-DC converters for various DC applications [10]. It is envisioned that DC – DC converters

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would be used more often in future to reduce power losses and increase power density [11]. Single input multiple output (SIMO) converter enables various outputs, minimizes components number and production cost [12]. Various electronic devices have different voltage requirement, and a single output converter may not satisfy their requirements satisfactorily [13]. DC fan, television, or laptop may require higher amount of power than mobile phone, and the power required by phones may be too small for laptops, etc. Fig. 1 shows the interconnection of the PV array to the SIMO converter and to the four connected loads.

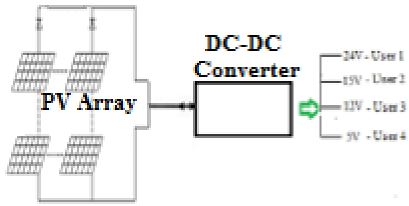

Fig. 1: Interconnection of the PV array to the SIMO converter and to the four connected loads.

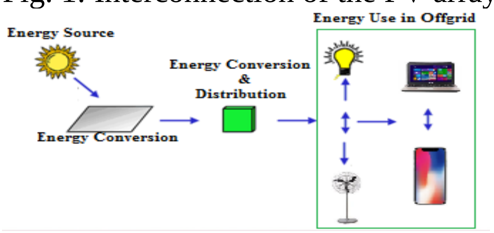

Fig. 2: Illustration of the energy source, energy conversion (based on the proposed SIMO converter) and energy use in off-grid application.

The conversion of solar energy into electrical energy has many application fields. Extensive research has been done on renewable energy conversion into electric energy [14-23] and residential energy management [20, 24]. Many families have a residential stand-alone solar powered system installed in their homes. The direct benefits of such systems at homes goes to the power consumer (user) by reducing the cost of getting electrical energy and also reducing the risk of contracting high-voltage electricity. The main function of a residential renewable energy system is to help the user manage consumption of electricity.

The aim of energy management system is to monitor and control utilization, access, optimize and manage the energy availability of the PV systems. This can be realized through real-time analyses and energy source and loads data control in a predictive way. There may be different categories of loads in the various homes, and the home owner may wish to control access to the solar generated energy to protect the storage from draining completely. In most cases, the energy is not properly utilized, it is being overused or randomly mismanaged. That leads to quick drain of the battery storage and/or disconnection of the most useful appliances in the house. Controlling the whole photovoltaic system operation by managing the converter output power and controlling how it feed the appliances will satisfy the residential load demand. And, efficient management, monitoring and control of homes and home appliances automatically is making the home to be a “Smart Home”. The major requirements for making are smart home are [25]: extensibility, heterogeneity, security and privacy protection, self-configurable, context awareness, usability and intelligence.

In the previous years, applications of intelligent systems received significant attention in various fields of power systems, specifically in operations, planning, management and control [26]. Some research publications [27, 28] have shown how intelligent systems applications to power systems and control techniques for solar tracking with fuzzy logic [29] and other intelligent controllers have been realized.

Human reasonings and mathematical models were used in conventional designs, planning, operation, control and management of power systems [26] as solutions to power management and control problems. However, these models come with a lot of uncertainties in practical applications of power systems [26]. Those mathematical models mostly use assumptions to provide specific solutions to power systems.

In some occasions, the assumptions make the solutions untrivial. There are limitations with the mathematical-model-based methods of solving power systems issues. Intelligent techniques applications of like neural-based networks, genetic algorithms, fuzzy systems, knowledge-based expert systems and other intelligent control techniques have been widely investigated to provide efficient and reliable power systems operation, planning, control, management and energy utilization solutions. Many recent works have indicated interest in providing combination of simple intelligent technologies that will aid residential energy control and management [30-32].

With fast advancement of Internet Technologies and enormous increase of internet users and networking, control and management of many objects becomes easier and efficient [33]. The proliferation of internet in communications and controls creates the IoT, where sensors and actuators mingle around us, enabling sharing of information across a given platform to develop a common operating ground [34]. IoT are physical items communicating to each other (person – computer, computer – computer, etc.) [35, 36]. Human beings interact in their homes with things like air, light, electronics devices, etc. and regulate them accordingly. So, those home appliances are made to interact and respond to human behavior, and can be made to do that automatically with many advantages. Thus, intelligent home automation, monitoring and control consists of clusters of sensors with computing capabilities to analyze data regarding residents and proper utilization of the energy resources, thereby reducing cost and improving the standard of living at home with much convenience. Many researches focused on the use of IoT for automation and control [37, 38]. Some of the researches discussed management of resource constraints devices and mechanisms of interconnections [39-41]. However, energy management techniques and systems are deployed in homes to monitor, control, manage and schedule the electricity utilization to maximally reduce cost [42].

This paper therefore presents the use of IoT to monitor, control, manage and schedule DC home appliances connected to SIMO DC -DC photovoltaic converter. Raspberry Pi Zero W is used for wireless communications between the appliances connected to the converter, which are operated with a relay. A SIMO DC-DC converter was developed and connected to the solar supply. The multiple outputs are then subjected to connections on various DC loads. Raspberry Pi was implemented to transmit the input and output voltages via Wi-Fi to the IoT cloud, in which the android app of mobile phone has ability to monitor and control.

II INTERNET OF THINGS (IoT) AND RASPBERRY PI

The IoT is a new paradigm of envisioned as a global machines, systems and devices network capable mutual interaction. It is organized as an essential area of future technology that is getting significant industrial attention. The significance of IoT can be explored when devices, systems and machines are connected together via a platform with ability to communicate with each other [43]. It is an interconnection between objects and people with ability to exchange data over a network platform [44]. It offers connectivity from services, devices and systems working with machine-machine communication that cover protocols, domains and applications [45].

Raspberry Pi is a portable, low cost and miniaturized computer. It contains graphic chip, a processor random access memory (RAM) and several connectors and interfaces for external communication with other devices [46]. It is powerful and cheap with low power consumption [47]. It has a built-in software that enables users to design and program animation, videos, games, etc. [44]. Programmers uses Python programming language, which is its core language to develop programs or scripts. Fig. 3 shows the complete architecture.

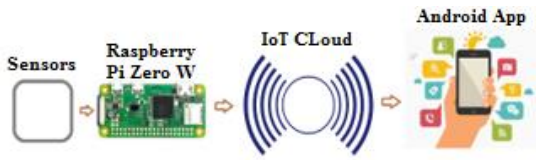

Fig. 3 IoT Architecture with Raspberry Pi W

III CONTROL, MONITORING AND MANAGEMENT METHOD USING IoT AND RASPBERRY PI ZERO W

In controlling and monitoring the converter functions, the following tasks were adopted; Monitoring, Control and Scheduling. The program is designed to monitor the DC power generation by determining the input voltage and current. The user will be able to see the input voltage and current, and can schedule or control the power dissipation based on priority. Also, the user will get alerts when the voltage and current supply is less than the load demand and vice versa. Fig. 4 illustrates the system from generation, distribution, monitoring and control via a Raspberry Pi and Android App. Upon reception of the signal to either activate or deactivate a device, the relays will act according to the commands.

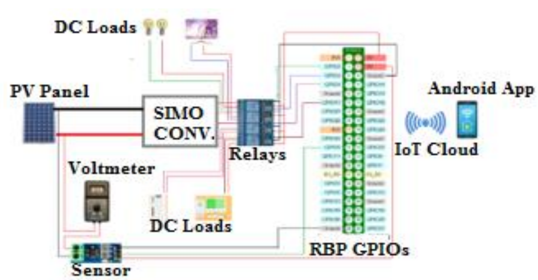

Fig. 4 Monitoring and Control Architecture Connected to the Converter

IV RELAY OPERATION AND CONNECTIONS TO LOADS (ACTUATION)

It is necessary to make the analyses of relay connections in complex electrical systems [48]. Upon reception of signal from the Raspberry Pi based on the instructions from the user, the relay acts. The relay is responsible for connecting or disconnecting supply to the device at any given instruction and time. Set of equations are used to describe any circuit and its operations. The equation terms represent the relay or switch terminals. The terminals of the relay used in this work are represented and denoted, in whatever circumstance, the operation is described as it may correspond to the instruction received from the Raspberry Pi, relay's task is only to execute. Fig. 5 shows the connection of a relay to one of the loads. DC voltage coming to activate the load has to wait the decision of the user from the mobile app via the Raspberry Pi, and through the relay to activate or deactivate a device. Each of the loads has its own relay; a total of four relays for the four outputs of the converter is used.

For the analyses of the operation of this relay, a simple notation and symbolic logic is adopted. The terminals of a relay need to satisfy some postulates when executing a certain command. Now, for every two terminals; which may either be X and Y, the following postulates holds:

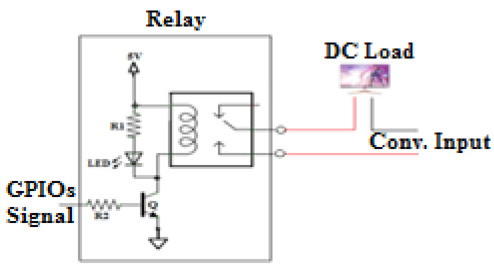

Fig. 5 Relay connection to the load

1. (a) When a closed circuit is connected in parallel with a closed circuit, the resultant circuit is closed;
   $0.0 = 0.$
   (b) When an open circuit is connected in series with an open circuit, the resultant circuit is open;
   $1 + 1 = 1.$
2. (a) In either order, when an open circuit is connected in series with a closed circuit, the resultant circuit is an open circuit;
   $0 + 1 = 1 + 0 = 1.$
   (b) In either order, when a closed circuit is connected in parallel with an open circuit, the resultant circuit is a closed circuit;
   $1.0 = 0.1 = 0.$
3. (a) When a closed circuit is connected in series with a closed circuit, the resultant circuit is a closed circuit;
   $0 + 0 = 0$
   (b) When an open circuit is connected in parallel with an open circuit, the resultant circuit is an open circuit;
   $1.1 = 1.$
4. At any given instance, is either;

(a) X = 1 or X = 0
(b) Y = 1 or Y = 0
(c) X = 1 or Y = 1
(d) X = 0 or Y = 0
(e) X = 0 or Y = 1
(f) X = 1 or Y = 0

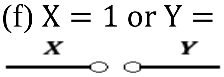

Fig. Two terminals of a relay

Limiting the circuit and logic treatment to relays and switches contacts, the circuit between any two terminals at any given instance must either give zero impedance (when closed) or infinite impedance (when open). Adopting the symbol X with terminals a and b, it is simply denoted as X_{ab}. The relay contact is represented by the symbol in Fig…..

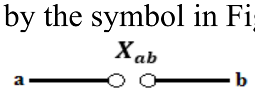

Fig. Symbol of a function between two terminals of a relay

This variable X_{ab} is used to represent a function of time between two terminals $a - b$. The symbol 0 (zero) represents the function of a closed circuit while the symbol 1 (one) represents the function of an open circuit. When the circuit $a - b$ is open, X_{ab} = 1 and when $a - b$ is closed, $X_{ab} = 0$.

Ordinary algebra is used for these analyses of relay operation. However, other theorems are used for further analyses of the relay operation as in this work:

$X + Y = Y + X$

$XY = YX$

$1. X = X$

$0 + X = X$; duality principle

$1 + X = 1$

$0. X = 0$

Note that, X here is either 1 or 0. If it is 1, postulate $3b$ stands and if it is 0, it follows postulates $2b$.

A new operation called *negation* is can be used by the relays during execution of the commands and instructions. A negative of the function X can be X'. It is a variable that is equal to 0 when X is equals to 1 and/or 1 when X is equal to 0. If X is the function assigned to make the relay contact, then X' is the function that will break the contact of the same relay. The following theorems arises from the definition of the negatives of a relay terminal X contact:

$$X + X' = 1$$

$$XX' = 0$$

$0' = 1$

$1' = 0$

$$(X')' = X$$

With these analogies, any calculus theorem interpreted in terms of relay and switch circuits is true. In negating the operation of the terminal of the relay in this work, $De\ Morgan's\ Theorem$ gives the negative of the sum of product:

$(X + Y)' = X'.Y'$

$(X.Y)' = X' + Y'$

Fig. …..illustrates the relay connection to the loads, though a single relay is used here. But total of four relays are used each for each of the converter outputs and each of the loads.

V CONTROL AND MANAGEMENT PROCEDURE

Starting from the main control topology as in Figures 1 and 2, the system starts by receiving instructions from the user via a mobile app which transmits the signal to the cloud, and subsequently to the Raspberry Pi, which then instruct the relays to execute. The flow chart of Fig. 6 illustrates the monitoring and control procedure.

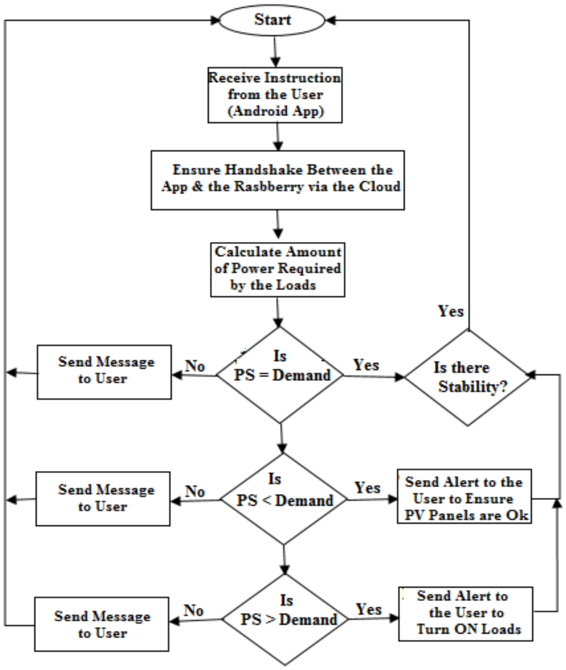

Figure. 6: Flowchart of the main Intelligent Control algorithm.

In essence, this IoT/Raspberry based control performs the following functions:

- Load detection and access control.
- Overvoltage detection and alert.
- Under-voltage detection and alert.
- Distribution Control.

A. Load Forecasting

The consumptions of energy by humans in a particular period can be estimated by considering the hourly solar flux incident on the surface of the earth [49]. The load forecasting ability of this intelligent inverter will be able to predict and decide the load configurations according to power demand as follows:

i. Maximum power demand of the house is estimated and predicted 24 hours before utilization based on weather conditions and forecast. Then the intelligent controller will decide the number of loads to be applied on the inverter.
ii. The hourly or daily power demand of the house is predicted based on the result of (i).
iii. The network will then be able to predict the weekly power demand of the house based on the loads applied such as lamps, fridges, televisions, etc.
iv. Based on the applications and discrimination of the heavy and light appliances, and the time variations, the system will predict the savings and loss.
v. The system will be able to then to estimate the power loss and savings in a week.

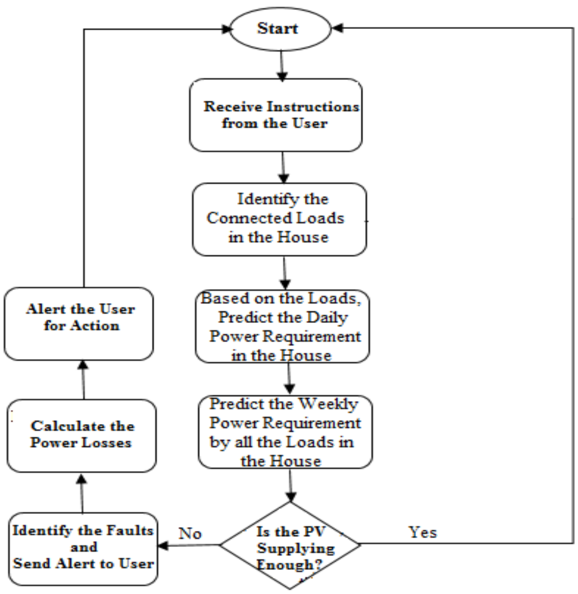

Figure. 7 Load forecast, scheduling and prediction flowchart.

VI RESULTS AND DISCUSSION

Using the algorithm of Fig. 6 and 7 flowcharts for main control, forecast, and prediction and scheduling respectively, the SIMO flyback converter was connected to loads to monitor supply from the PV, demand by the loads and stability and efficiency of the power system. The sensors connected to the supply and those connected at the relay and load terminals sent signals to the mobile app which are recorded for a whole day. Various records of the signals are plotted using R-Package software and the response is shown in Fig. 8.

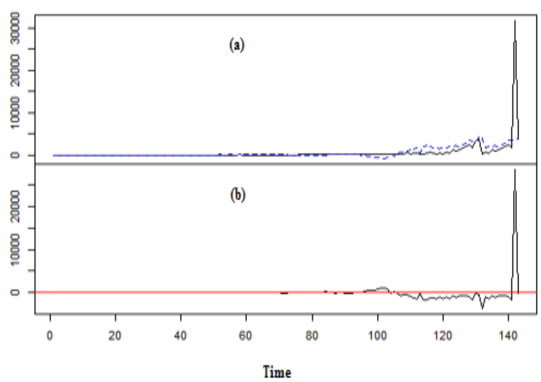

Figure 8: Loads Demand and PV Supply Plots of Recorded Controller Signals I

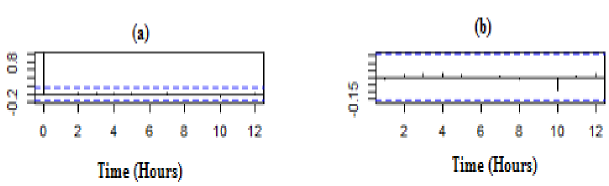

Figure 9: Stability and Risk periods

After careful study of the controller’s response to load demands and generation, the loads were set to match the generation to further study the response. The results are plotted as can be seen in Fig. 10 and 11.

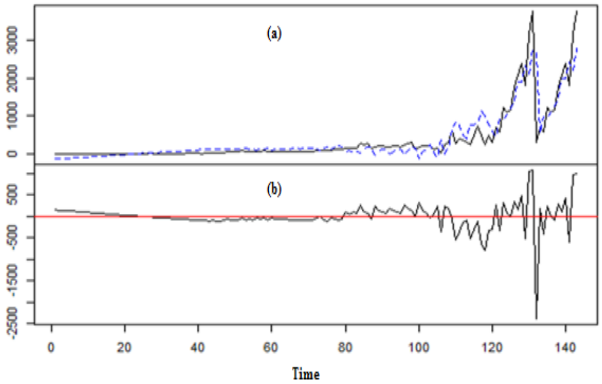

Figure 10: Loads Demand and PV Supply Plots of Recorded Controller Signals II

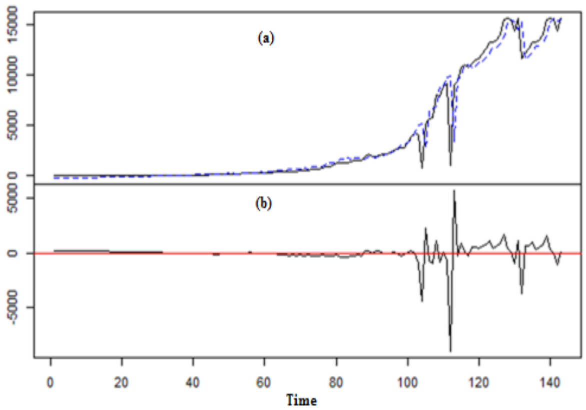

Figure 11: Loads Demand and PV Supply Plots of Recorded Controller Signals III

Fig. 8 is plotted using generated data from the controller via the mobile app. The data were recorded for a whole day while both the SIMO flyback converter and DC-AC inverter were fully connected with loads. The app was able to generate huge data every second, which is used on R-Package software. The response is seen on Fig. 8.

From Fig. 9 (a), there are two plots; blue and black. The blue plot represents generation (supply) while the black represents loads demand (usage). From the onset, there is stationary and stable demand and supply up to some points towards the night (dark) when the generation start dropping at constant demand. It can be seen that while the generation drops, the demand continues to shoot up beyond control. At that point, alert was sent to the user to disconnect or disable some appliances.

On Fig. 9 (b), there are also two plots; red and black. The red plot is a danger (risk) plot while the black plot is a load demand plot. In comparison with the plots of Fig. 9 (a), where the generation drops and the demand plunged to danger. It is reflected on Fig. 9 (b), the danger is seen below the red line (risk) as the generation drops. From there, the demand continues to shoot up after it must have sent alert to the user to act.

Fig. 10 illustrates the areas of stability and danger. Fig. 10 (a) specifically shows the captured stability plots between the demand and generation of Fig. 8 (a) which happened for over twelve hours. Whereas, Fig. 10 (b) shows the periods in which danger (risk) was recorded.

After careful study of the controller’s response to load demands and generation, the loads were set to match the generation to further study the response. The results are plotted as can be seen in Fig. 11.

In Fig. 11, the loads were varied to study the response and efficiency of the controller perform the tasks assigned to it. Fig. 11 (a) specifically shows the stability of both the loads demands and generation maintained at same level after careful study of what the PV could supply for 24 hours, the loads were then maintained to fit the generation. As such, both the blue and black lines for generation and demands respectively are maintained on same path. The demands were set by the controller to at all times match the generation by disabling some appliances. As soon as the generation drops, the demands follows it to drop together and vice versa.

Figure 12: Images of Testing of the Developed System

VII CONCLUSION

As discussed in this paper, control and management of photovoltaic power in residents is imminent to prevent unnecessary leakages and losses due to random access of unknown devices to the supply. IoT provides a better platform to connect, monitor and control loads and power distribution without much human efforts. The controller which is based on Raspberry Pi with the ability to send or receive signal and instructions from the cloud can at the same time estimate and predict the required power to be used by the loads in the house in a day or week based on the connected loads data. This can be sought by the user through the use of android application which connects to the cloud, and subsequently to the Raspberry Pi if the need arises to instruct the controller to perform estimation and prediction.

The control topology via Raspberry Pi and IoT has the ability to registers, allow or disallow a particular DC appliance in the house be it; fridge, washing machine, pressing iron, television, computers, kettles, handphones, etc. The user can instruct the system to automatically perform scheduling to either turn ON or OFF any appliances at the specified time. Android App was developed based on the requirement of the control system to enable automated control.

Both the SIMO DC-DC converter and the controller unit were developed and tested. Python programming was used to write commands to be used by the Raspberry Pi in sending or receiving instructions via the cloud. There was efficient handshake between the android app (user) and the Raspberry Pi Zero W used in this work via a cloud enabled by wireless communication. This work simplifies the domestic power management, monitoring and control by smartly adopting automated control method. It also leads to leakage and loss identification, which will significantly enhance performance of the power system and making homes smart. It has been developed with a very low cost and enhanced performance.

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