Low-Cost Self-Governing Energy Management System For Micro-Grids

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Abstract—**This paper presents development of an energy management system for micro-grid applications. The focus of the proposed system is affordability. The system is composed of a central station and several nodes. The nodes are energy consumers and the central station monitors and adjusts energy consumption in each node. The system uses a wireless sensor network to exchange energy consumption data.**

Keywords—Energy Management System, Fuzzy PI Controller, Micro-Grid,Wireless Sensor Network,.

I. Introduction

Micro-gridshave become increasingly popular with the introduction of ad hoc network enabled devices. They mainly rely on Wireless Sensor Networks (WSN) to operate efficiently and remotely. WSN is the outcome of multiple interconnected wireless devicesproviding flexibility and mobility in data collection. The most popular wireless device used for the development of WSN in small-scale micro gridsis the XBeemodule running on the Zigbee protocol based on the IEEE 802.15.4 mesh networking standard[1]. Zigbee allows for reliable and inexpensive data transfers inside WSN. This proves critical in small micro-grids whenmonitoringenergyconsumption is a key but the cost is a major concern. Energy consumption is the information passing through all nodes in the WSN. Since the consumption is changing in real time, maintaining accurate consumption valuesisessential in accurate operation of a micro-grid [2].One example of small-scale micro-grids is home energy managements systems (HEMS). Research shows energy efficient products significantly contribute in the overall home energy efficiency[3]. It is just logical to achieve more energy efficiency through HEMS. The implementation of HEMS is expected to growin near future and make these small-scale micro-grids popular.Research towards HEMS has included products that control all lights, door locks, garage door, and etc. from one platform[4]and[5].This is shown to be ineffective in the long-term as the user has to constantly make a decision for the system [6]. Therefore, a great deal of research is needed to tackle many detailed issues and to improve the overall system.

A great deal of research hasbeen done to control energy wasted in standby mode[7]-[10]. 10% of total household power is consumed during this standby mode when appliances and equipment are connected in the off position [11]. Additionally, the U.S. Department of Energy reports the demand and consumption for electricity in the U.S. have increased by 2.5% annually over the last couple of decades [12]. This calls for a more sophisticated system capable of not only monitoring energy consumption but capable ofmanaging consumption aswell.

Current research brings awareness to the problem of the ever-increasing electricity demand[13]. However, there is still a need for research towards making a self-governing system capable of managing energy consumption.The objective of this research study is to create an affordable system capable of monitoring and managing energy consumption within a small-scale micro-grid (e.g. HEMS) according to a set of pre-defined criteria.This will in turn encourage development of small-scale micro-grids that can significantly help the national electric grid as a whole[14].

It is well-known that the balance of energy generation and consumption has to be retained in any electric power system.In other words, enough energy must always be present to support the consumption.Micro-grids are able to respond within seconds to meet the energy needs through renewable energy resources or their reserve capacities[15]and [16].

As part of this research study, we developed the Smart Home Energy Regulator (SHER) system that is capable of managing the energy consumption in a small-scale micro-grid (HEMS).A priority is set by the user detailing the specifications of the energy consumption in the micro-grid.This priority is managed by a preset maximum energy consumption value, what type of appliance is connected to the outlet and other specifications. These presets inform the system of the order of hierarchy between the nodes and whether energy consumption at a node can be adjusted. The adjustment is implemented in two forms. Certain nodes have the ability to change their energy consumption if requested by the SHER system. For other nodes, the system can only stop energy consumption through relaying. The SHER system processes the information regarding energy consumption at each node and determines the changes in the system. Then it sends the commands to each node on how to adjust the node's energy consumption. Finally, the node will execute the command and report back the new energy consumption.

The paper is organized as follows. In Section II, we discuss elements of the developed system and explain its functionality. The control logic in adjusting the energy consumption is discussed in Section III. Section IV gives additional discussion on further applications of the developed system. Conclusions and future studies are given in Section V.

II. System Design

In this section, we will discuss the details of The SHER system. The SHER systemis implemented with low-cost open source hardware for affordability and simple integration of other elements. This led to utilizing anArduino MEGA as a prototyping platform. In our case, an Arduino microcontroller is on every node and is used to parse through the data collected from different sensors and determines the best course of action.

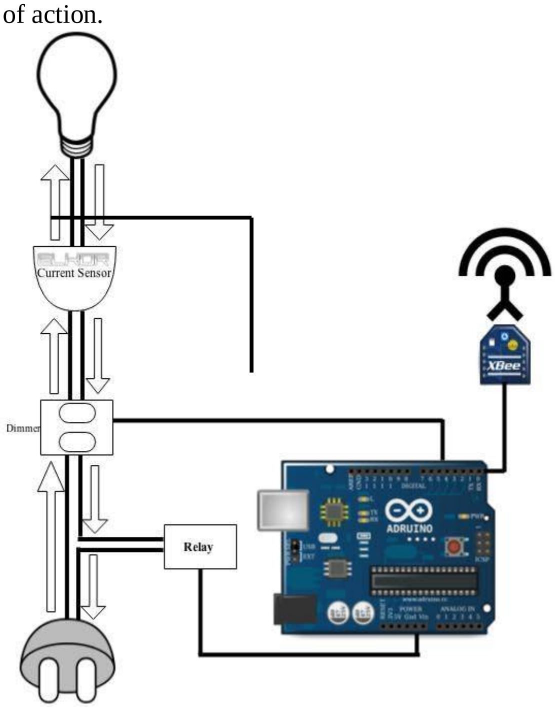

Fig. 1 Example of an Endpoint.

We used XBee radio modules running on the Zigbee protocol as ourcommunication to create a WSNas a necessary component for the SHERsystem. XBee is a low-cost, low-power consuming, and reliable standard [17] with the capability of robust mesh networking. A mesh network is a local area network where nodes can be connected wirelessly to each other directly or indirectly in the network. We took advantage of this by creating a mesh network for sharing the value of power consumption of each node. This value is transferred from a sensing node (endpoint) to the central station (coordinator). There is only one coordinator in the network in charge of all the endpoints. The coordinator is in essence the master of the network. Its task is to ensure proper operation of the network.Once the coordinator receives all the values, the Arduino microcontroller will decide whether a course of action is needed.

One course of action will be shutting off the energy transfer at a node.If the coordinator decides for a node to shut off its energy, then a command is sent to that specific node. This node will process the command and will complete the command. This is realized by flippinga relay at the node. The system has a relay at each node and therefore, each node can be disconnected from the energy system. In such case, the flow of electric energy is interrupted but the node is still part of the WSN. Likewise, ifthenodeitself determines its localenergy consumption is too high then the relay flips to cause an open circuit for protection reasons.The coordinator detects the incident and may issue a command to re-close the relay suspecting that the energy consumption is returned to its normal range. However, the node is not allowed to change the relay status after a protective action. In other words, the node can stop electric power for protective reasons, but starting the flow of electric power has to be restored by the coordinator. If the relay is triggered off by the coordinator to manage total energy consumption, itmaybe triggered onto allow energy to flow in the node when the coordinator determines that enough energy is available to support the node's energy consumption.

Another course of action, instead of turning the node off through relaying, is adjusting the energy consumptionat each node. This will only be possible with appliances or equipment capable of adjusting. An incandescent light bulb, for example, will be able to dim down to still give off light while keeping the total energy consumption stable. Another example is electric fans. The system adjusts their energy consumption by slowing down the fan.We incorporate this into our system using anenergy adjustment module (e.g. AC dimmer module). The energy adjustment moduleuses a zero-crossing reference to determine its placement on the sinusoidal wave. Using this reference, a Triac is triggered to allow a portion of the sinusoidal wave through depending on a time interval of operation. This time interval is set by considering the dimming value received by the node from the coordinator. The Arduino microcontroller then uses the dimming value to calculate when the Triac is opened thus how much of the sinusoidal wave is allowed to flow through, as seen in Fig. 2.

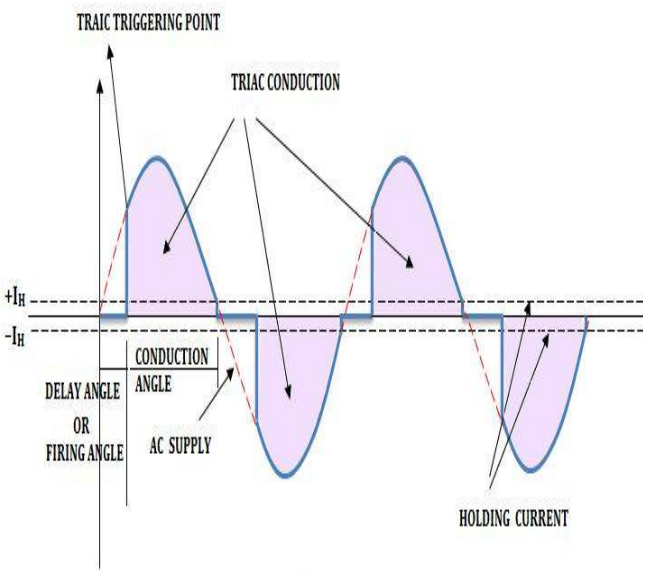

Fig. 2 Triac conduction waveform

Nodeshave arelay, energy adjustment module and a current sensor, as shown in Fig. 1. The current sensor is a closed loop current transducer that non-invasively measures electric current. Closed loop current sensorshave a magnetic core with an opening in the center for the primary current to be positioned through. The magnetic flux generated from a primary current is then compensated by a current from a secondary wiring.

The secondary current is generated by a Hall-Effect sensor, which is proportional to the primary current being measured. This produces an instantaneous response, high linearity, and low temperature drift. This measured value will then be sent to the Arduino microcontroller for further processing.We use this valueto determine the variable current (I) combined with the US standard outlet fixed voltage of 110VAC (V) and our defined time interval to calculate the total energy of the outlet (Δt), as in (1).

$$Energy = V \bullet I \bullet \Delta t \qquad (1)$$

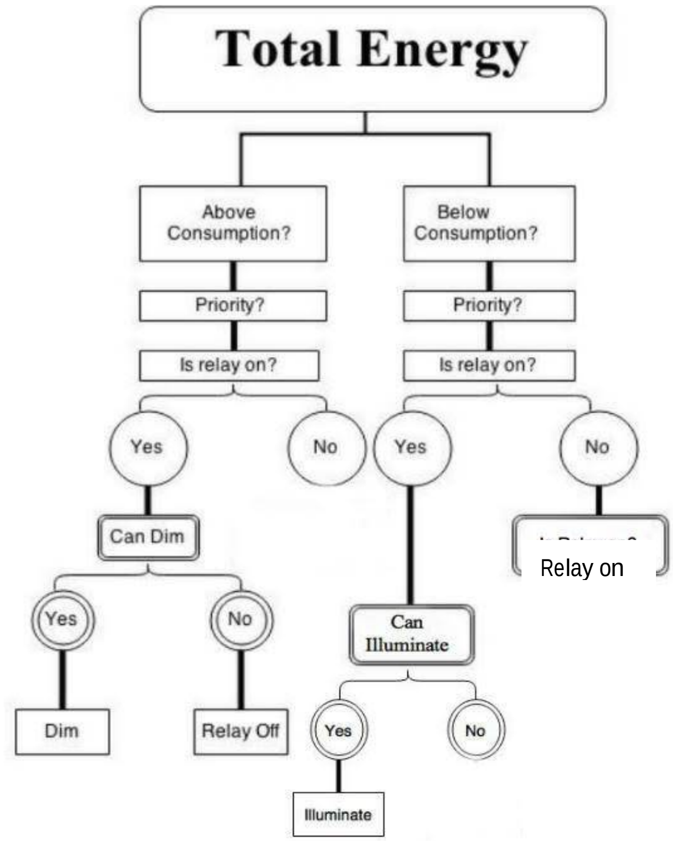

Fig. 3 Example of a Coordinator.SHER System flowchart.

This energy value will be sent to the coordinator to calculate the total energy consumption of all the nodes. The SHER system uses relays based on the pre-defined priorities and energy adjustment modules on certain adjustable stations to fine-tune the total energy consumption.The coordinator calculates total energy consumption and uses it to determine if any action is needed. If so, the coordinator will determine which node has the lowest priority and then will send a command to the chosen node. If the chosen node is adjustable, the command will carry an adjustment value or a change of state for the Relay. Once the command is sent, the coordinator will wait to receive the new energy value from the chosen node and recalculate the total energy consumption. If the new total consumption is not satisfactory further actions will be taken by the coordinator. This process will repeat until the total consumption is stabilized at the desired value, as seen in Fig. 3. This is not limited to a single node being dimmed or shutoff at a time. Multiple actions to various nodes may take place if necessary.

The coordinator will only have the radio communication, XBee, an Arduino microcontroller and finally a SD module with a SD card, as seen in Fig. 4. The SD card will sustain all energy values received by the coordinator from the nodes, the commands sent from the coordinator to the nodes and other necessary data variables considered. This allows the user to have a backup for possible information for analysis.

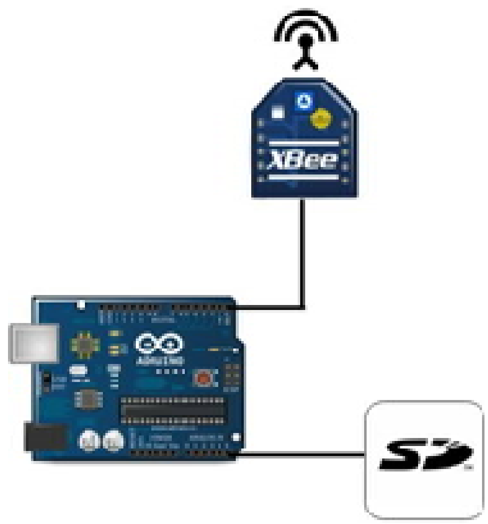

Fig. 4Example of a Coordinator.

III. CONSUMPTION CONTROL

As explained in Section II, the general operation of the SHER system is intuitive. But the command sent from the coordinator to energy adjustment module on each node merits further discussion. Not all nodes have this module. But for those nodes that have this module, the coordinator will issue a command to adjust their energy consumption if needed. The coordinator determines the command based on the current energy consumption. It can follow different schemes where each scheme changes dynamics of energy consumption in the system. To further illustrate this process, we discuss an experimental setup and implement different controllers and explain their impact on dynamics of the system.

In the following experiments, three nodes with different distances and independent energy consumptionsare used. The coordinatoris places a meter above ground level on a stable platform for minimal attenuation[18]. The first node (e1) was at ground leveldirectly below the coordinator with a fan as the load. The second node (e2)was coplanar to the coordinator at a meter away with an incandescent light as the load. Finally, the third node(e3) wasalso coplanar to the coordinator and e2 at three meters away with a heat gun as the load. Node e2 is the only node with energy adjustment module. Therefore, the coordinator has to adjust the overall energy consumption using this module. The coordinator is intentionally programmed to adjust the total energy consumption at a certain threshold only with commands to the module (no control over relays). This scheme helps in understanding the dynamics of the system when controlling the module independently.

A threshold of 27.5 joules is set. A Proportional-Integral (PI) controller is used to generate the command for the energy adjustment module. The input to the controller is generated using the threshold (desired) and total energy consumption (feedback). The controller is given below:

$$u(k+1) = u(k) + \left(K_p + \frac{\Delta t K_i}{2}\right) e(k+1) + \left(\frac{\Delta t K_i}{2} - K_p\right) e(k) \qquad (2)$$

where$u$ is the command to the energy adjustment module, e is the error signal, K_p and K_i are the controller constants, and $\Delta t = 0.1$ is the sampling time of the system.

The experimental results of the control scheme with low and high controller gains are shown in Fig. 5 and Fig. 6, respectively. It can be seen that the controller with lower gains act slower than the controller with higher gains. In this sense higher gains are desirable. However, the oscillations in the energy adjustment command in the controller with high gains are problematic. Firstly, they results in improper operation of the node. For instance, in our experiments, we observed flickers as a result of these oscillations. Secondly, these oscillations will cause the energy entering to the device connected at the node and may damage the device over time.

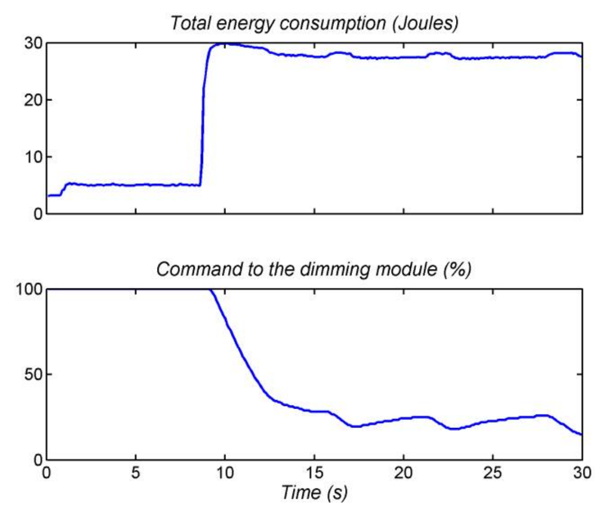

Fig. 5 Experimental results with low PI controller gains.

To improve the system's performance, we replaced the PI controller with a fuzzy PI controller. The advantage of fuzzy PI controller is a fast response with minimal oscillations. When the error is large, the fuzzy controller will adjust the proportional and integral gains to obtain a fast response. As the error is getting smaller, the fuzzy controller slows down the system by tuning the proportional and integral gains to avoid oscillations in steady state operation. The experimental results using the proposed fuzzy PI controller are shown in Fig 7. It can be seen from these results that the control input to the energy adjustment module is faster than Fig. 5 and with less oscillations than Fig. 6.

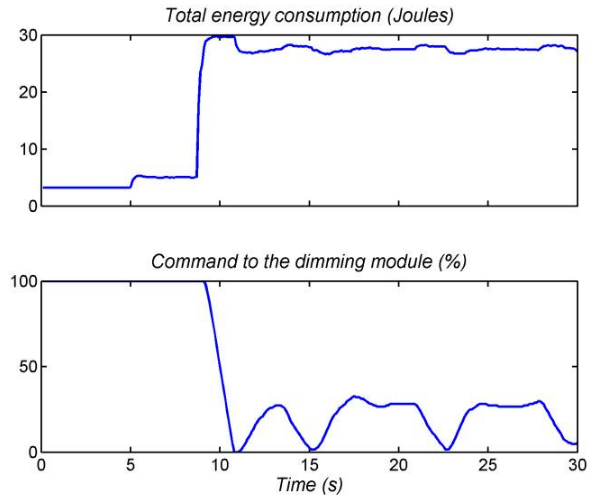

Fig. 6 Experimental results with high PI controller gains.

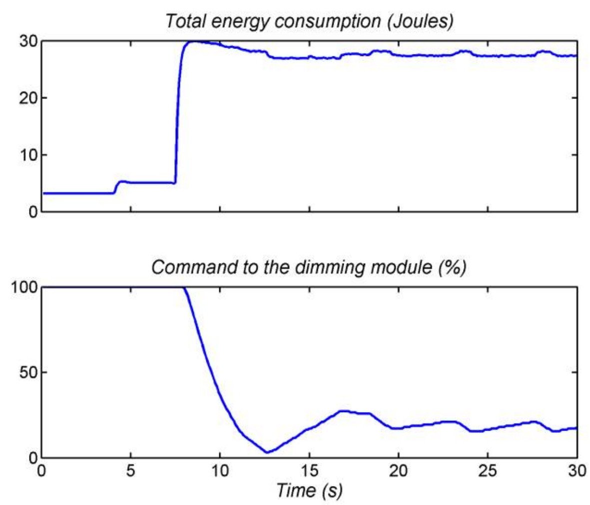

Fig. 7 Experimental results with fuzzy PI controller.

IV. Discussion

The proposed system is mainly developed for HEMS applications. However, it can be used for other micro-grid applications. In particular, the role of energy management system is significant when the micro-grid is powered by renewable resources and therefore total available energy is limited. In such cases, the intermittency in renewable energies will endanger the sustainability of the micro-grid. The variations in energy generation will result in voltage oscillations that must be avoided. In such cases, storage capacities can help to alleviate this problem which is due to the unexpected changes in renewable generation. However, enough storage to sustain the micro-grid is usually not available. The developed system can help in those cases where the micro-grid depends on energy harvested from renewable resources and storage capacities are limited.

The programmability of the SHER system offers a variety of options to the user. For instance, protective schemes can be added to avoid damages to expensive or sensitive assets. A set of priorities can also be defined for the system for the cases where load shedding is inevitable. Other schemes can be defined based on storage capacities. For instance, certain applications may require a minimum amount of reserve energy to be available for emergency cases. For applications with batteries or capacitor banks as storage capacity, the number of switching may be kept at its minimum to extend storage lifetime. Finally, economical aspect of the micro-grid can be integrated into the SHER system to minimize the cost to the user.

V. Conclusions

An energy management system is developed for HEMS. The developed system is suitable for small micro-grid applications. The main property of the system is its affordability. The system is programmed for pre-defined tasks and its superior performance is verified through experimental results. Fuzzy proportional-integral controller is used for energy consumption control. The future work will be on incorporating new schemes into the developed system.

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