A Potential Controller for Smart Electrical Energy Management System

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Abstract. Integrated energy utilization has been recognized as a productive way towards better energy management, besides increasing Renewable Energy (RE) penetration. Thus, the combination of RE integrated with the Battery Energy Storage System (BESS) has been recognized as the primary solution where it is necessary to have a controller to interface the system efficiently. Hence, a smart electrical energy management system controller is designed and developed based on load leveling and peak shaving applications for real-time AC power management in this work. The main function of the controller is to continuously monitor and maintain the load demand and to produce a leveled or shaved load profile that will be seen at the grid network by controlling the battery operation. The testing results concluded that the controller able to perform both the energy applications. Overall, a dual function controller based on energy applications to maintain consumer load demand usage more securely and reliably, so that the utility bill is reduced and the battery lifetime is prolonged simultaneously is achieved in this work.

Keywords. Smart Electrical Energy Management System Controller, BESS, Load Leveling, Peak Shaving, Solar PV.

1. Introduction
The demand and the utilization of electrical energy are rapidly increasing in the past few decades due to the mega-growth of the industrialization sector globally. The rate of energy consumption becomes one of the major defining factors to determine economic growth and the development of any country. Presently, the electrical energy generated by fossil fuels is declining due to their limited resources, hence an alternative way is highly needed to support the current consumption [1]. In this context, the utilization of Renewable Energy (RE) becomes a popular way to overcome the current demands of electrical energy. RE particularly the use of solar Photovoltaic (PV) is considered as the most sustainable resource due to its ubiquity, eco-friendly, large availability and sustainability [2]. However, the production of continuous and smooth energy conversion from solar is a real challenge. In meantime, the storage of the converted electrical energy is important to conserve maximum energy.

Research shows many commercial and industrial sectors find themselves struggling to manage their energy usage [3]. Moreover, it is common for commercial and industrial sectors to pay the maximum demand charge apart from the net consumption charges every month under the current electricity tariffs in Malaysia. The maximum demand can be charged up to 20% of the utility bill as the charges are based on the highest power demand rate and energy consumption although it is for short intervals in a day [4].
Hence, RE and Battery Energy Storage System (BESS) are recognized as the main integrated system to generate, store and use back electrical energy at the optimum level which also can improve on-grid utilization. Effective energy management incorporated with RE resources and battery storage is indeed necessary to allow end-user to control their electricity usage and to reduce their monthly utility bills.

There are various types of energy applications but the most emphasized applications in a grid network, besides being widely used among industries, commercials and residential consumers are the load leveling and peak shaving applications [5]. Large fluctuations that occur in electricity demand are balanced using load leveling method where the battery will act as load and start to charge from the grid during low load demand and vice-versa. Meanwhile, for peak shaving, the battery will start discharging to support the load peaks and reduce the maximum electricity demand drawn from the grid network [5]. Figure 1 illustrates the process of load leveling and peak shaving applications.

Figure 1. Load leveling and peak shaving applications [5]

These energy applications in the combination with BESS have become an immense attraction at all level of users due to BESS outstanding characteristic such as availability in a wide range of capacity from small to a big scale system, fast response, mobile and flexible enough to be fitted to either high power or high energy applications [6-7]. For grid owners, some of the benefits are increasing the utilization factor of facilities, saving facility renewal expenses and avoiding upgrading facilities. Meanwhile, reduction in utility bills and cost saving are notable benefits for end-user consumers [8].

Wide array of research works have been conducted in the aspect of BESS integration to RE resources, especially solar PV focusing on utilizing the output power effectively besides improving charge efficiency and prolong the battery lifetime. However, several works focus on battery integration to RE resources related to load leveling and peak shaving applications. Among them, Danish et al. presented a novel and fast algorithm for finding optimal BESS size and operation intervals to address peak load demand in a distribution network. Based on their simulation results, BESS integration and implementation together with PV can significantly improve the system performances by smoothing peak load and reducing power losses [9]. Meanwhile, a novel planning model for the BESS for both load leveling and voltage profile improvement applications in the distribution network is proposed by Mehrjerdi [10]. Furthermore, Uddin et al. introduced a novel decision-tree-based algorithm that effectively mitigates the peak load demand, facilitated by BESS but the optimum size of BESS has not been considered in their work [11]. Besides that, a home energy management that comprises solar PV, battery storage and grid network for a residential load to reduce the load demand is presented by Teki V K et al. [12].

At the same time, numerous types of research work have also been conducted involving energy management controller for BESS integrated with solar PV system over the years to enhance and optimize energy efficiency and consumption, reduce the utility bills and to prolong battery lifetime. Various methods and different algorithms have been introduced to achieve the above mention objectives as presented by Ramoul J et al., Hussain H M et al., Thounaojam, et al., Neupane, et al., Khalid R et al.
and Javaid N et al. Some of these authors introduced their charge controller as neural network energy management controller as by Ramoul J et al., home energy management controller by Hussain H M et al. and Javaid N et al., smart solar charge controller as by Thounaojam, et al. and Neupane, et al. and fuzzy energy management controller by Khalid R et al. [13-18].

In this work, we have designed and developed a potential controller for smart electrical energy management to make use of RE resources, manage the energy storage process and to deliver power to end users while maintaining the load demand. It will be a dual function controller, based on load leveling and peak shaving applications for real-time AC power management.

2. Design and development of smart electrical energy management system controller

In this work, a smart electrical energy management system controller integrated with BESS and Solar PV was designed and developed based on load leveling and peak shaving applications. Thus, this work goal is to produce a leveled or shaved load demand profile that will be seen at the grid network while maintaining the actual load usage. This is achieved by controlling the battery charge and discharge process, triggered by the developed controller in this work. Besides that, the battery constraints are also considered to increase battery reliability and lifetime.

In addition, the parameter involved in both energy applications are different. For load leveling, the main parameter is the average load demand value while for peak shaving, the parameters are the maximum and minimum limit of load demand. Hence, the load demand condition varies based on each application and is denoted on the controller specification. BESS used in this work is a lead acid battery that is widely used due to its best cost performance [19-20]. Figure 2 presents the smart electrical energy management system controller overall block diagram. In this work, the Arduino microcontroller board act as the brain to coordinate all the activities. The smart electrical energy controller is required to continuously measure consumer AC load demand and lead acid battery voltage, which are the main inputs for the overall system to function.

The consumer loads for testing in this work consist of resistive loads and are energized by single phase 230 V AC supply, 50 Hz. The load voltage and current are measured separately through the voltage and current sensing circuit before input to the microcontroller. Voltage measurement is done thru a step-down transformer that provides both electrical isolation required and lower voltage value for measurement. Current sensor IC, ACS712 is used to measure current in this work where the sensed load current is converted into a voltage directly before input to the microcontroller. ACS712 is a bi-directional hall effect-based linear current sensor which consists of a precise, low-offset, linear hall circuit with a copper conduction path located near the surface of the die. Moreover, the terminals of the conductive path are electrically isolated from the signal leads, which allow this ACS712 to be used directly in applications that require electrical isolation.
In this work, the charging and discharging function are performed using power MOSFET (IRF9540) due to its faster response and energy efficient. However, the gate driver is required because of MOSFET large stray capacitance between the gate and other terminals. Thus, a general purpose transistor (NPN 2N3904) is used as the gate driver in this design. Figure 3 presents the simplified diagram of the charging and discharging unit of the smart electrical energy management system controller. Besides that, as this is a dual function controller with two different applications, a selection switch is included for the consumers to choose the preferred application. In addition, the LCD module will display the selected application, current controller process and also the related measurement value. Meanwhile, the battery charge status is indicated by the LED in this work. Moreover, additional safety measures are also included in this controller such as electrical isolation, reverse current flow protection, low voltage disconnect and overload protection.

The smart electrical energy management system controller algorithm was developed based on the flow chart presented in Figure 4. The battery voltage is used as an initial checkpoint to avoid any over-charged or under-discharge. In this work, the battery voltage is limited between 11.7 V to 14.4 V for the
operation of the controller. Hence, if the battery voltage reaches 14.4 V, the program will trigger the controller to stop charging and turn on the green LED to prevent the battery from being over-charged. Conversely, if the battery voltage drops to 11.7 V while in discharging operation, the controller will automatically stop the ongoing operation and turn on the red LED, indicating the battery is under-discharged.

![Flow chart for the smart electrical energy management system controller](image)

**Figure 4.** Flow chart for the smart electrical energy management system controller

3. Results and discussion

In this section, the developed smart electrical energy management system controller as shown in Figure 5 has been tested accordingly for load leveling and peak shaving applications. Figure 5 also presents the testing setup that consists of a 12 V 7.2 Ah valve-regulated lead acid battery, developed load panel and power supply replacing solar PV for indoor testing. Bulbs with the rating between 25 W to 100 W, controlled by the switches and a 12 V, 18 W DC light in place of a grid-tie inverter are developed in the load panel. This DC light is used because a normal inverter cannot be used in this work as it needs to accurately match the voltage and phase of the grid sine wave AC waveform. In addition, a multimeter was used to measure and verify the battery voltage directly in reference to the smart electrical energy management system controller reading through the microcontroller. A simplified version has opted for testing purposes as this work focuses on the controller operation.
Figure 5. Smart electrical energy management system controller

Table 1 presents the testing results for the smart electrical energy management system controller. The battery charging is indicated by the power supply current value and the DC lights confirm the battery discharging process. For load leveling, whenever the load demand is below the average load value of 150 W, the battery will start to charge and vice-versa. Meanwhile, the battery will only start charging when the load demand is below 100 W for peak shaving application. And when the load demand is above 200 W, the controller will trigger the battery to discharge to support the load peaks. At the same time, whenever the load demand is between 100 W to 200 W, the battery will be in no operation and standby mode. This is because battery needs to support sudden spikes that can occur in load demand for peak shaving application. Besides that, Table 1 also includes the LED status where the red LED will turn on to indicate the battery is at a low voltage limit once the controller stops the operation automatically.

Table 1. Smart electrical energy management system controller testing results

| Application Type | Input Load (W) | Battery Voltage (V) | Battery Condition | Power Supply Current (A) | DC Light | LED Status |
|------------------|----------------|---------------------|-------------------|--------------------------|----------|------------|
| Load Leveling    | 25             | 12.91               | Charging          | 0.45                     | Off      | Off        |
|                  | 85             | 12.92               | Charging          | 0.49                     | Off      | Off        |
|                  | 160            | 12.32               | Discharging       | 0                        | On       | Off        |
|                  | 260            | 12.03               | Discharging       | 0                        | On       | Off        |
|                  | 300            | 11.58               | No operation      | 0                        | Off      | Red on     |
| Peak Shaving     | 60             | 12.67               | Charging          | 0.38                     | Off      | Off        |
|                  | 100            | 12.6                | Charging          | 0.28                     | Off      | Off        |
|                  | 200            | 12.15               | Idle              | 0                        | Off      | Off        |
|                  | 285            | 11.89               | Discharging       | 0                        | On       | Off        |
|                  | 300            | 10.62               | Idle              | 0                        | Off      | Red on     |
The varying load demand and the developed smart electrical energy management system controller outcome for load leveling and peak shaving are presented in Figure 6. As the same load demand profile is used for both applications, the results are combined in one graph. The load demand data is taken at 5 minutes interval for the testing purpose. The battery charging and discharging is measured through the battery voltage value where an increase in voltage profile indicates battery in charging mode and vice-versa.

Based on Figure 6, during the first 5 minutes interval, the load demand is 60 W and the battery initial voltage is 12.96 V. Hence, the developed controller triggers the battery to charge where an increase in the battery voltage can be seen for both the load leveling and peak shaving applications. Whereby, in the following interval, when the load demand increased to 160 W, the battery starts to discharge to support the load for load leveling application. In contrast, for peak shaving application, the battery voltage is maintained indicating the battery is in idle condition. However, the battery starts to discharge to support the load peak in the next interval as the load demand increased to 285 W. This process of charging and discharging continues for a given time frame as triggered by the controller based on the load demand profile and the application that has been selected. Thus, the overall results conclude that the developed smart electrical energy management system controller is working well for smart energy utilization, besides prolong battery lifetime.

Figure 6. Load demand and battery voltage against time for load leveling and peak shaving applications
4. Conclusion
In this work, a dual function controller for smart electrical energy management system for BESS integrated with solar PV for real-time AC power management was designed and developed successfully. This initial work focuses on small-scale energy usage, mainly residential consumers but it can be used for big-scale consumers with modifications to its specifications while maintaining similar design concepts and control algorithm methods. From the testing results, it is concluded that the controller is performing well to either produce a leveled or shaved load demand profile that will be seen at the grid network for smart energy utilization while maintaining the actual load usage. Besides that, the importance of BESS integration with solar PV system for energy applications are realized through the developed smart electrical energy management system controller in this work. Furthermore, using this controller, consumers can gain control over their power consumption patterns and utility bills, besides adopting this overall system as a source for income generation. With reference to future work, Maximum Power Point Tracking (MPPT) will be studied as the charging method to be included in this dual function smart electrical energy management system controller.

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