Effective Load Management System for Sudden Shutdown Avoidance of Stand Alone Photovoltaic Operation

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Abstract. Stand-alone system is the system that operates independently of the electrical grid. Conventionally, the energies absorbed through photovoltaic modules are stored in batteries to reserve for night-time use. Moreover, the function of batteries in stand-alone system is to stabilize the output supplied for the load particularly during the fluctuating circumstance. Sudden shutdown of dedicated photovoltaic system during this period may occur when the storage of batteries approaches empty level which may significantly degrade the lifespan and performance of the batteries. In this study, a sequential load switching system is introduced in order to overcome the sudden shutdown of storage battery-based photovoltaic system. The developed system is mainly equipped with Arduino, MOSFETs and DC bulbs as microcontroller, high-speed switching and load, respectively. As a result, the proposed sequential load switching method is highly effective since it has successfully extended the standby time period up to approximately 27 times longer, before the system shutdowns at the cut-off voltage.

1. Introduction

Generally, photovoltaic system is categorized into two; Grid-Connected and Standalone. Standalone photovoltaic (SAPV), which also known as off-grid solar energy systems are covering approximately 80% of the photovoltaic applications utilized world widely [1]. There is high demand of standalone photovoltaic system in several countries specifically to the locations that have faced dramatical change in climate [2]. The SAPV system is designed to maintain a good performance of SAPV system components (PV, Battery and load) in order to increase the reliability and efficiency [3]. Besides, solar array is unable to store the energy by itself; a battery is required as energy storage system so that the load can be used during night-time. Typically, lead acid batteries are used due to its wide availability of sizes, low cost and well understand performance criteria [4]. Meanwhile, a charge controller functions to be capable of varying voltage and current in order to avoid the battery from being damage due to over-charging or over-discharging [5]. Due to this limitation of capacity, the system may experience sudden shutdown when the batteries drop to the cut-off voltage level [6]. Once this circumstance occurs, the PV components such as the load and battery itself are exposed to the risk of damage or malfunction.

Therefore, any initiatives in overcoming this issue are desirable since this SAPV application is greatly contributing to rapid development of secondary energy harvesting resources for human necessities, nowadays. In this paper, an effective load management system based on autonomous sequential load switching algorithm has been proposed. The main idea is to structure the switching algorithm that can feasibly extend the standby time period of the system’s operation before the battery totally shutdown by itself at the cut-off voltage. Detailed methodology and finding will be discussed in the next section.
2. Methodology

2.1 Circuit Design Using Proteus
Proteus software has been used in order to simulate the overall circuit connection of hardware for this project. Figure 1 shows the overall circuit designed for this study.

![Figure 1](image1.png)

Figure 1. The overall circuit design for the project

2.2 The Block Diagram of the system
Figure 2 represents the block diagram of the developed system. Solar module (100W), battery 12V 17Ah and the load are connected to the MPPT charge controller as the charge controller acts as the regulator and protection system. Seven IXFH44N50P MOSFET switches and seven 871C optocouplers are connected to the solar module, battery and each load to undergo the switching process whether it is HIGH or LOW. MOSFET switch, and the voltage divider will be connected to the Arduino for coding process. A voltage divider is simply constructed by directly connecting the 12 V battery, to two series-connected resistors. One resistor will take 7 V and another one resistor will take 5 V. This 5 V will then be connected to the Analog input of Arduino to read the voltage. All the data that are read by the Arduino will be displayed through the serial monitor in Arduino IDE.

![Figure 2](image2.png)

Figure 2. Block diagram of the developed system
2.3 Load Switching Algorithm

In this project, an algorithm of load switching will be executed in order to assist the consumer to perform a load management effectively. Figure 3 exhibits the overall flowchart of the algorithm for the system.

Figure 3. Flowchart of the Algorithm of Load Switching

In this study, MOSFET is trusted in protecting the switching medium and mechanism as it is successfully proven during the experiment. The ON and OFF’s switching of the MOSFET includes the protection for the battery to avoid from being over-discharged. The MOSFET is set to switch off and shutdown the system when the battery voltage reaches 10.8 V. This value is the typical recommended cut-off voltage for the lead acid battery. If the lead acid battery is discharging until cut-off less than 10.5 V, it will damage the battery severely.

Firstly, the solar module absorbs the sunlight and converts it to the electrical energy which makes the battery starts to be charged. All load will be turned ON. In this system, the load that will be used are all DC lamps which are denoted as, L1, L2, L3, L4 and L5, respectively. Once all load is turned ON, automatically the battery is undergoing a discharging state. During the discharging state, all parameters such as the voltage, withdrawn current and capacity will be measured and recorded by the Arduino and then displayed on the monitoring PC. The voltage of the battery will start to decrease time by time. Once the voltage of the battery ($V_B$) is lesser than 11.0 V, the first load, L1 will be turned OFF by the MOSFET switch as it is set to be “LOW”. Consequently, as the $V_B$ is greater than 11.0 V again, the battery will continue to discharge. After certain period of time, $V_B$ is expected to drop below than 11.0 V again. At this point, the second load, L2 will be turned OFF and hence, the $V_B$ will increase slightly and then, it will undergo the same discharging process again for other cases of L3, L4 and L5. Nevertheless, if the $V_B$ remains not to be more than 11.0 V again, all load will be turned OFF. The battery will stop undergo the discharging process as there are no more load or device that is consumed by the battery. Eventually, if the $V_B$ increases more than 12.5 V, the battery will revert automatically to the charging mode back again.
3. Results and Discussion

3.1 Conventional Battery Discharging Method

![Figure 4](image)

**Figure 4.** Battery voltage’s movement during discharging using conventional method.

The condition of the system while the battery at discharging state is shown in Figure 4. In this project, the battery system will stop operate and totally shutdown when it reaches its cut off voltage that has been set to 10.80 V. Meanwhile, the standby time is set as 11.0 V. The duration taken by the battery to discharge from the standby time (11.0 V) until the cut off voltage (10.80 V) will be recorded and analyze.

The system is operating in discharging state by turning on all the loads. Figure 4 and Table 1 exhibit the result of battery voltage’s movement and related data for the battery during discharging using a conventional method, respectively. The current drawn from the positive terminal of the battery was measured by using Kyoritsu clamp meter and the value displayed was 12.9 A. Eight 36W-rated DC bulbs was used here. From Figure 4 and Table 1, it can be clearly understood that the voltage is decreasing with time, starting from the initial voltage which value is 11.83 V. The overall system operated for about 42 minutes and 22 seconds. The duration taken by the battery to discharge from the standby time (11.0 V) until the cut off voltage (10.80 V) was 4 minutes and 47 seconds. This is the usual phenomenon of using load, all load will be used at one time but when it is applied on the storage battery based on standalone PV system, this method can drain the storage battery very fast and the operation of the system will shut down quickly as the user does not manage the load usage wisely. Typically, user will use and solely depend on the storage battery during night, rainy or cloudy conditions. Therefore, when the battery is empty, user will face problem or uncomfortable condition when there is no supply of electricity. If the users are doing their work or online business at home or factory, the sudden shutdown may affect their income and work. The user has to wait until the next morning when there are source of sunlight to charge the battery.

From Figure 4, state A is the initial voltage as soon as the system is integrated to the Arduino Mega. State B is when the battery reaches the standby time where the voltage level of the battery is 11.0 V and state C is when the battery reaches the decided cut off voltage of 10.80 V. Once the battery voltage reaches the cut off voltage, the systems will totally shutdown as the battery becomes empty. The duration taken between the state A and state B is approximately 37 minutes and 35 seconds. The duration taken is relatively shorter if the current drawn from the battery is higher as it drains the battery faster and pulls a greater voltage. The duration taken between state B and state C is about 4 minutes and 47 seconds. This situation occurs when the voltage and capacity of the battery have been already lesser from time to time, so the discharged current and voltage will drop quickly at the end.

Initially, the recorded voltage of the battery before connected to Arduino Mega was 12.36 V. As soon as the system integrated with the Arduino Mega, the voltage decreased abruptly from 12.36 V to 11.83 V. There was a 0.53 V of voltage drop that was being pulled suddenly and significantly by the load from the battery. Additionally, the analysis of voltage drop from the obtained curve in Figure 4 is detailed in Table 2. From Table 2, as the load draws high amount of current which is 12.9A from the
battery, it affects to the decreasing of 4.29 % of voltage from the battery initial voltage. The voltage decreases to 11.63 V after 500 seconds at about 5.91 % of voltage drop. After 1000 seconds, the voltage decreases to 11.54 V with 6.63 % of voltage drop. 500 seconds, the voltage decreases to 11.39 V with 7.85 % of voltage drop. The voltage continues to decrease after 2000 seconds from the initial stage to 11.19 V with 9.47 % of voltage drop. At the end of the system, the voltage decreases to 10.78 V with 12.78% of voltage drop, eventually. Therefore, the voltage drop increases by time and it takes 12.78 % of voltage drop from the initial level of battery voltage to reach the cut off voltage of 10.80 V.

Table 1. Related data for the battery during discharging using conventional method

| Voltage (V) | State | Transition | Duration     | Current (A) |
|------------|-------|------------|--------------|-------------|
| 11.83      | A     | A – B      | 37min 35sec  | 12.9        |
| 10.98      | B     | B – C      | 4min 47sec   | 12.9        |
| 10.78      | C     | -          | -            | -           |

| Voltage (V) | State | Transition | Duration | Current (A) |
|-------------|-------|------------|----------|-------------|
| A - C       | 42min 22sec |            |          |             |

Table 2. The analysis of voltage drop from Figure 4

| Time (seconds) | Voltage (V) | Voltage Drop (V) | Voltage Drop (%) |
|----------------|-------------|------------------|------------------|
| 0              | 12.36       | -                | -                |
| 1              | 11.83       | 0.53             | 4.29             |
| 500            | 11.63       | 0.73             | 5.91             |
| 1000           | 11.54       | 0.82             | 6.63             |
| 1500           | 11.39       | 0.97             | 7.85             |
| 2000           | 11.19       | 1.17             | 9.47             |
| 2540           | 10.78       | 1.58             | 12.78            |

3.2 Proposed Method: Automatic Sequential Load Switching

Similar to distribution of power generation, it is monitored by the usage of the load, when one line is overloaded, then the circuit breaker that acts as the protection will cut off the supply. In this project, the proposed method is implemented by switching off the load one by one by monitoring directly the voltage state of the battery or supply. Figure 5 depicts the curve of voltage’s movement in the battery during discharging when the proposed automatic sequential load switching has been applied in the developed system. From here, it can be obviously suggested that the proposed method successfully manages to prolong the duration of standby time before the system shutdowns for about 2 hours, 14 minutes and 28 seconds.

Figure 5. Battery voltage’s movement during discharging using proposed method

Initially, the recorded voltage of the battery before it was connected to the Arduino Mega was 12.53 V. As soon as the system integrated with the Arduino Mega, the voltage decreased abruptly from 12.53 V to 11.81 V. There was 0.72 V of voltage drop that was being pulled suddenly and significantly
by the load from the battery. Table 3 and Table 4 demonstrate the data recorded of the battery discharging using the proposed method and analysis of voltage drop from Figure 5, respectively. From Table 4, as the load draws high amount of current which is 12.9 A from the battery, it affects to the decreasing of 5.75 % of voltage from the battery initial voltage. The voltage decreases to 11.71 V after 500 seconds at about 6.54 % of voltage drop. After 1000 seconds, the voltage decreases to 11.66 V with 6.94 % of voltage drop. 500 seconds after that, the voltage decreases to 11.57 V with 7.66 % of voltage drop. The voltage continues to decrease after 2000 seconds from the initial stage to 11.47 V with 8.46 % of voltage drop. Until at the end of the system, the voltage decreases to 10.79 V with 13.89 % of voltage drop, eventually. Therefore, the voltage drop increases by time and it takes 13.89 % of voltage drop from the initial voltage battery to reach the cut off voltage of 10.80 V. From Figure 5, state A is the initial voltage as soon as the system is integrated to the Arduino Mega. State B, C, D, E are when the battery reaches the standby time where the battery voltage is 11.0 V. State F is when the battery reaches the cut off voltage of 10.80 V. Once the battery voltage reaches the cut off voltage, the systems will totally shutdown as the battery becomes empty. From Table 3, it can be clearly understood that the duration taken between the state A and state B is 56 minutes and 15 seconds. Next, the duration taken between the state B and state C is 5 minutes and 18 seconds. Here, the duration taken is relatively shorter as the current drawn is still high with 8.5 A. The duration taken from the state C to D is 16 minutes and 37 seconds. This duration is a bit longer since the drawn current is less than before with of 5.5 A as the second load is off. The duration taken from the state D to E is 37 minutes and 4 seconds. This duration is a bit longer since the drawn current is much less than that of the state C to D with of 2.8 A as the third load is off. Surprisingly, the duration taken from the state E to F is 1 hour, 15 minutes and 29 seconds. This duration is relatively longer since the drawn current is lower than that of other states with the value of 1.6 A as the fifth load is turned off. Thus, the total duration for the battery to discharge starting from the state A to F is by far longer than that of conventional discharging method with 3 hours, 10 minutes and 43 seconds. From Table 3 also, the voltage increment is recorded and analysed. It is apparent that the voltage increment is approximately 0.24 V when the first load is automatically switched off. When all load is on, the discharged current and battery capacity are still higher. Thus, when the first load is disconnected from the battery, it reduces the burden from the battery and causes the voltage increases as much as 0.24 V. When the second load has been off, the voltage increment is 0.19 V. Next, when the third load is turned off, the voltage increment maintains at around 0.2 V. Since more load is disconnected from the battery, it significantly reduces the burden of the battery to carry the load. Eventually, when the fourth load is turned off, the voltage increases slightly at a rate of 0.07 V since the battery has lesser capacity already. In this experiment, a 100 W solar module becomes the source to charge up the battery. The solar module, battery and load are connected to the charge controller. The charge controller functions as a safety precaution medium to avoid over-charge and also over-discharge of the battery.

Table 3. Data recorded of the battery discharging when using the proposed method.

| State | Duration  | Current (A) | Voltage Increment (V) |
|-------|-----------|-------------|----------------------|
| All Load ON | A – B | 56min 15sec | 12.9 | - |
| 4     | B – C    | 5min 18sec  | 8.5   | 0.24 |
| 3     | C – D    | 16min 37sec | 5.5   | 0.19 |
| 2     | D – E    | 37min 4sec  | 2.8   | 0.2  |
| 1     | E – F    | 1hr 15min 29sec | 1.6  | 0.07 |
|       | A – F    | 3hr 10min 43sec |    |   |
|       | B – F    | 2hr 14min 28sec |    |   |

From Table 3 also, the voltage increment is recorded and analysed. It is apparent that the voltage increment is approximately 0.24 V when the first load is automatically switched off. When all load is on, the discharged current and battery capacity are still higher. Thus, when the first load is disconnected from the battery, it reduces the burden from the battery and causes the voltage increases as much as 0.24 V. When the second load has been off, the voltage increment is 0.19 V. Next, when the third load is turned off, the voltage increment maintains at around 0.2 V. Since more load is disconnected from the battery, it significantly reduces the burden of the battery to carry the load. Eventually, when the fourth load is turned off, the voltage increases slightly at a rate of 0.07 V since the battery has lesser capacity already. In this experiment, a 100 W solar module becomes the source to charge up the battery. The solar module, battery and load are connected to the charge controller. The charge controller functions as a safety precaution medium to avoid over-charge and also over-discharge of the battery.
Table 4. The analysis of voltage drop from Figure 5

| Time (seconds) | Voltage (V) | Voltage Drop (V) | Voltage Drop (%) |
|----------------|-------------|------------------|------------------|
| 0              | 12.53       | -                | -                |
| 1              | 11.81       | 0.72             | 5.75             |
| 500            | 11.71       | 0.82             | 6.54             |
| 1000           | 11.66       | 0.87             | 6.94             |
| 1500           | 11.57       | 0.96             | 7.66             |
| 2000           | 11.47       | 1.06             | 8.46             |
| 2500           | 11.37       | 1.16             | 9.26             |
| 3000           | 11.22       | 1.31             | 10.45            |
| 3500           | 11.22       | 1.31             | 10.45            |
| 4000           | 11.21       | 1.32             | 10.53            |
| 4500           | 11.06       | 1.47             | 11.73            |
| 5000           | 11.31       | 1.22             | 9.74             |
| 5500           | 11.31       | 1.22             | 9.74             |
| 6000           | 11.21       | 1.32             | 10.53            |
| 6500           | 11.19       | 1.34             | 10.69            |
| 7000           | 11.23       | 1.30             | 10.38            |
| 7500           | 11.23       | 1.30             | 10.38            |
| 8000           | 11.19       | 1.34             | 10.69            |
| 8500           | 11.19       | 1.34             | 10.69            |
| 9000           | 11.14       | 1.39             | 11.09            |
| 9500           | 11.09       | 1.44             | 11.49            |
| 10000          | 11.04       | 1.49             | 11.89            |
| 10500          | 10.94       | 1.59             | 12.69            |
| 10994          | 10.79       | 1.74             | 13.89            |

4. Conclusion
Based on the result, the proposed method has successfully and effectively applied in a standalone photovoltaic-based load management system by pushing the limit of the storage battery at its maximum capability. User can use any load that they want to be connected with this method. The switching mechanism by using MOSFETs are considered trustable as the safety precaution for the storage battery from over discharge is executed. By using the sequential load switching through the specific monitoring of the voltage battery’s states, it is proven by the experiment that the proposed method is clearly effective since it is by far extending the standby time period before the system totally shutdowns.

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