A photovoltaic system using supercapacitor energy storage for power equilibrium and voltage stability

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ABSTRACT

In a photovoltaic system, a stable voltage and of tolerable power equilibrium is needed. Hence, a dedicated analog charge controller for a storage system which controls energy flow to impose power equilibrium, and therefore, voltage stability on the load is required. We demonstrate here our successful design considerations employing supercapacitors as main energy storage as well as a buffer in a standalone photovoltaic system, incorporating a dedicated supercapacitor charge controller for the first time. Firstly, we demonstrated a photovoltaic system employing supercapacitors as main energy storage as well as a buffer in a standalone photovoltaic system. Secondly, we design a constant voltage maximum power point tracker (MPPT) for peak power extraction from the photovoltaic generator. Thirdly, we incorporated a supercapacitor charge controller for power equilibrium and voltage stability through a dedicated analog charge controller in our design, the first of its kind. Fourthly, we analyzed the use of supercapacitor storage to mitigate disequilibrium between power supply and demands, which, in turn, causes overvoltage or under voltage across the load. Lastly, we then went ahead to demonstrate the control of the energy flow in the system so as to maintain rated voltage across a variant demand load.

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1. INTRODUCTION

Mitigating the effects of fossil fuel burning is of great interest worldwide. Renewable energy holds the key to sustainable generation. Solar energy is one such form of energy available wherever there is sunlight and is expected to be a major clean energy provider in the near future. Photovoltaic (PV) power systems are usually installed as standalone systems, where the PV generator supplies an isolated load, or as grid-connected systems, where the PV generator and load are linked to a larger grid to which excess power can be sold or from which extra power can be bought.

Power output from a PV panel or array of PV panels is dependent on temperature and irradiance conditions. High irradiances and low temperatures are beneficial for more power. Load conditions also affect power output of a PV array, resulting in the need for a maximum power point tracker (MPPT) to extract the highest possible power irrespective of load, thus increasing efficiency.

Furthermore, as with all electric power systems, power stability is a concern in PV systems. Disequilibrium between load demand and supply from the PV generator results in overvoltage or undervoltage across the load. A storage system is able to alleviate the problem by absorbing the imbalances between supply power and demand, thus providing voltage stability.

However, maximum power point (MPP) tracker is important factor to be considered in this research. The current-voltage and power-voltage characteristics of a typical PV panel are such that the rated maximum power can be obtained at only one bias point, called the maximum power point and the equation is given by (1). Figure 1 illustrates this, where V_{mpp}, I_{mpp}, and P_{mpp} are the voltage, current, and power, respectively, at the MPP

$$P_{mpp} = V_{mpp} I_{mpp} \tag{1}$$

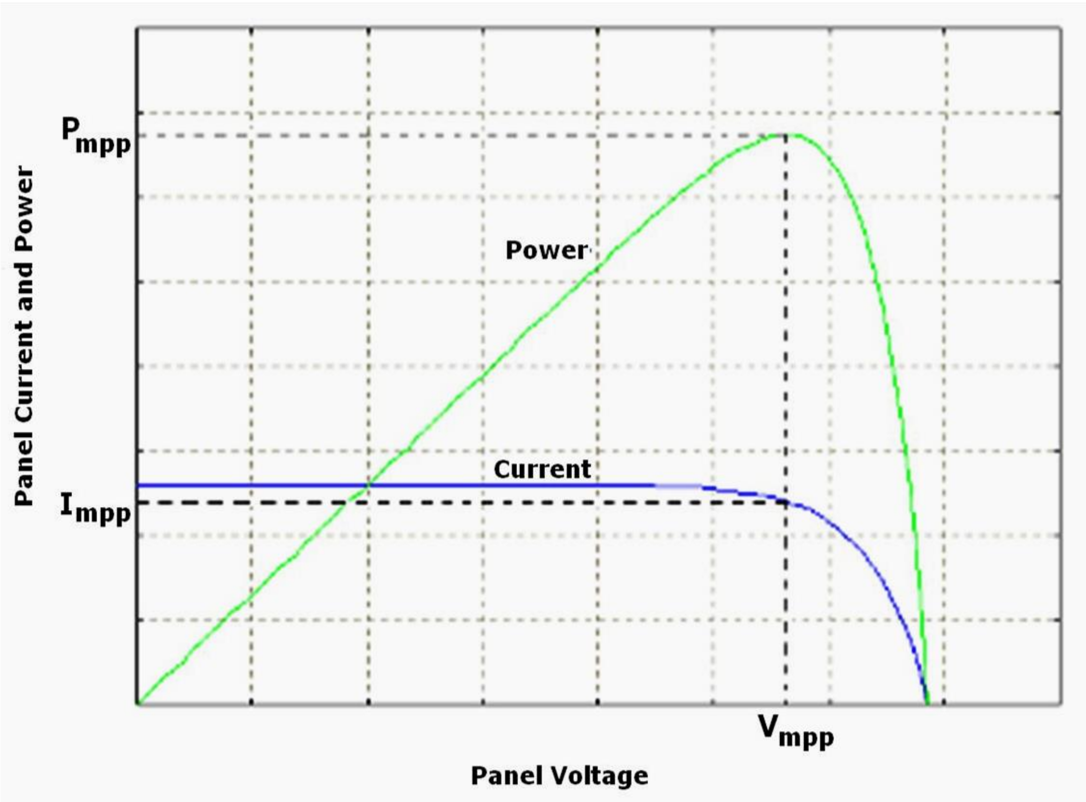


Figure 1. Magnetization current-voltage and power-voltage characteristics of a typical PV panel

The bias point, and therefore the power output, of the PV panel depend upon the load connected across it. Thus, an arbitrary load will not necessarily bias for maximum power. An MPPT is an interface connecting PV generator to load. Its task is to bias the input PV panel or array at the MPP, and supply this to any load connected to its output. The basic component of a MPPT is a power electronic converter. The type of converter and the control scheme employed varies with system requirements. At least 19 distinct control methods have been identified, varying in complexity, effectiveness, and cost [1]. Many algorithms use approximations to determine the maximum power point; for example, the fractional open-circuit voltage [2]–[4] and the fractional short-circuit current [5]–[7] methods, which are voltage and current-based methods, respectively. Other algorithms are more precise, such as hill-climbing [8]–[10], perturb-and-observe [11]–[14] and incremental conductance [15]–[17]; these are power-based algorithms. Various implementations of these algorithms exist, with novel methods being constantly developed. Most are digital microcontroller or fuzzy logic systems, while analog methods are less common [1].

In supercapacitors for storage, system instability occurs when supply power from the PV generators and load demand is not matched. Such conditions are dangerous to loads. Implementation of storage systems to absorb the imbalances is a solution, and is crucial in stand-alone PV systems, i.e., with no grid connection. Batteries are common storage devices but are susceptible to damage from fast charging and discharging and have short lifetimes. Supercapacitors, on the other hand have such high-power densities that they can tolerate fast charge and discharge with no detrimental effects. This high-power tolerance, their long lifetimes, and low series resistance promise to make them ideal energy storage solutions in a PV system suffering from frequent and significant power imbalances. Supercapacitor technology is relatively new, and its incorporation into many systems is still under evaluation. Many papers have presented supercapacitors as power devices in electric vehicles [18], and some work has been done on their use in uninterrupted power supplies [19]. Supercapacitors are also undergoing tests as storage devices in power grids for improvement of grid performance and financial gains [20], [21]. They have been successful as voltage compensation units in electric transportation networks in Cologne, Germany [22]. In renewable energy systems, supercapacitors are used to increase the lifetime of the primary battery storage, which is affected by fast power fluctuations [23]. Diarra *et al.* [24] presents a simple scheme to connect a supercapacitor module as energy storage in a PV system in order to maintain direct current (DC) bus voltage.

Furthermore, optimization of battery life for energy storage systems is key to the cost reduction of renewable energy sources. Various design systems employ supercapacitors as a potential solution to improving battery life [25]–[30]. MPPT techniques are implemented to detect and measure maximum power output parameters automatically; V_{mpp} and I_{mpp} under particular irradiance and temperature conditions. The report notes that for partial shading conditions, although it is possible to have multiple local maxima, there is only one true technique of MPP. Compared to batteries, supercapacitors have high power capability, making them applicable for energy storage in PV systems. In other literature, researchers proposed control and optimization mechanisms to achieve power stability. In [31], the bat-inspired algorithm (BAT) and gravitational search algorithm (GSA) are proposed to design model predictive controllers with superconducting magnetic energy storage and capacitive energy storage for load frequency control. The proposed mechanism is used to minimize frequency deviations in multi-area power system. A new design using a proportional integral derivative (PID) controller based on meta-heuristic algorithms for wind energy conversion using the whale optimization system to control generator speed deviations due to the penetration of wind speed and load demand fluctuations [32]. To regulate frequency and achieve power stability in electrical grids, [33] proposed a new variable structure gain scheduling (VSGS), taking advantage of the bacterial foraging optimization algorithm (BFOA) based proportional integral (PI) controller and the genetic algorithm (GA). Control strategies for optimum utilization of solar PV with energy storage systems are implemented in [34]. Power management is achieved through the development of a variable DC bus voltage-based algorithm with supercapacitor and battery. A modified noniterative incremental conductance MPPT method is developed to generate a fine-tuned duty cycle for sudden irradiance changes. In [35], power management and control of the PV system are achieved by implementing a hybrid battery-supercapacitor energy storage based on heuristics methods. Control of the power electronics converters. Optimizing a multi-source PV/wind with a hybrid energy storage system is proposed using a multi-objective-based genetic algorithm [36]. However, to the best of our knowledge, none of the stated approaches considered our proposed solutions, of design considerations employing supercapacitors as main energy storage as well as a buffer in a standalone photovoltaic system, incorporating a dedicated supercapacitor charge-controller, first of its kind. Over the years, many studies have investigated photovoltaic systems and their applications in standalone systems. We have compared some of the promising techniques and applications in Table 1.

This paper presents a stand-alone PV system supplying a resistive load that requires a rated DC voltage of 12 V. An analog constant-voltage MPPT is designed for the photovoltaic array, and is coupled with a supercapacitor energy buffer bank (SEBB), with a dedicated analog charge controller for the bank which controls energy flow to impose power equilibrium, and therefore, voltage stability, on the load. The circuits for these systems are given and explained, and the results of simulations carried out on Cadence OrCAD Capture are presented. The simulations involve varying the load demand and observing the performance of the system as it reverses the resulting rises and falls in load voltage. In summary, our contributions in this paper are as follows: i) we demonstrated a photovoltaic system employing supercapacitors as main energy storage as well as a buffer in a standalone photovoltaic system; ii) we design a constant voltage MPPT for peak power extraction from the photovoltaic generator; iii) we incorporated a supercapacitor charge controller for power equilibrium and voltage stability through a dedicated analog charge controller in our design, first of its kind; iv) we analyzed the use of supercapacitor storage for mitigation of disequilibrium between power supply and demands, which, in turn, causes overvoltage or under voltage across the load; and v) lastly, we then demonstrate the control of the energy flow in the system so as to maintain rated voltage across a variant demand load.

The rest of the paper is structured as follows. In section 2, we first described the methods adopted for the research. In section 3, we present the results and discussions of the results obtained from the proposed methods. Concluding remarks are presented in section 4.

Table 1. Comparison of related work

Title	Citations	Year	Description	Pros	Cons	The uniqueness of this paper
Power management and control of a photovoltaic system with hybrid battery-supercapacitor energy storage based on heuristics methods	[35]	2021	Power management and control of the PV system which is achieved by implementing a hybrid battery-supercapacitor energy storage based on heuristics methods	Investigation of control and power management of hybrid energy storage system	The approached did not consider the use of supercapacitors for power equilibrium.	This paper considered the use of supercapacitors for power equilibrium.
New variable structure control based on different meta-heuristics algorithms for frequency regulation considering nonlinearities effects	[33]	2020	To regulate frequency and achieve power stability in electrical grids, the authors proposed a new variable structure gain scheduling (VSGS), taking advantage of the bacterial foraging optimization algorithm (BFOA) based PI controller and the genetic algorithm (GA).	Improvement on the gain selection of the proportional integral controller.	Voltage stability method was not properly considered	The design and implementation of voltage stability through a dedicated analog charge controller.
New design of robust PID controller based on meta-heuristic algorithms for wind energy conversion system	[32]	2020	A new design using a PID controller based on meta-heuristic algorithms for wind energy conversion using the whale optimization system to control generator speed deviations due to the penetration of wind speed and load demand fluctuations	Design of a robust PID controller for enhancing the damping characteristics of wind energy conversion system.	The design is specific for wind energy and not tested for other energy harvesting techniques.	Design of energy storage for power equilibrium and a dedicated analog charge controller for voltage stability.
Implementation of control strategies for optimum utilization of solar photovoltaic system with energy storage systems	[34]	2020	Control strategies for optimum utilization of solar PV with energy storage systems are implemented in the paper. A modified noniterative incremental conductance MPPT method is developed.	Power management is achieved through the development of a variable DC bus voltage-based algorithm with supercapacitor and battery.	The paper did not implement a novel voltage stability method.	This paper considers voltage stability through a dedicated analog charge controller.
Multi-objective genetic algorithm-based sizing optimization of a stand-alone wind/PV power supply system with enhanced battery/supercapacitor hybrid energy storage	[36]	2018	Optimizing a multi-source PV/Wind with a hybrid energy storage system is proposed using a multi-objective-based Genetic Algorithm.	Minimization of total cost and loss of power supply probability of the load using genetic algorithm.	Did not consider the voltage stability and power equilibrium in their design	Design of energy storage for power equilibrium and a dedicated analog charge controller for voltage stability

2. METHOD

This section described the procedures and methods adopted in carrying out this research. It is further subdivided into subsections. The system design elaborates on the modeling and steps followed to achieve the main design of the proposed method. MPPT and the MPPT simulation results were also presented in this section.

2.1. System design

The basic layout of the standalone PV system is given in Figure 2, with arrows indicating flow of power. The MPPT and charge controller are entirely analog in design. The load is resistive in nature, and is assumed to require 12 V DC. Thus, the load demand varies according to (2):

$$P_{demand} = \frac{(V_{rated})^2}{R_{load}} = \frac{(12V)^2}{R_{load}} \quad (2)$$

where P_{demand}: demand power (W), V_{rated}: rated load voltage (V), and R_{load}: load resistance (Ω).

The PV array modeled has MPP of 60 W at 24 V, and this is assumed to be invariable during operation. Hence, a constant-voltage MPPT is suitable for this array. The supercapacitor used in the SEBB is the CAP-XX GS206, 0.55 F, 5 V, 40 mΩ ESR; they are connected as parallel sets with two series-connected supercapacitors in each set. The charge controller adjusts the flow of energy in and out of the SEBB in order to regulate load voltage at 12 V.

System instabilities are created by setting R_{load} value such that P_{demand} is not equal to the supply power from the array, which is processed by the MPPT. When demand is less than supply, an overvoltage occurs across the load. An undervoltage occurs when demand exceeds supply. The role of the charge controller is to force excess supply power into the SEBB when overvoltage occurs and provide extra power from the SEBB to the load when undervoltage occurs. Either response should be controlled to re-achieve 12 V at the load.

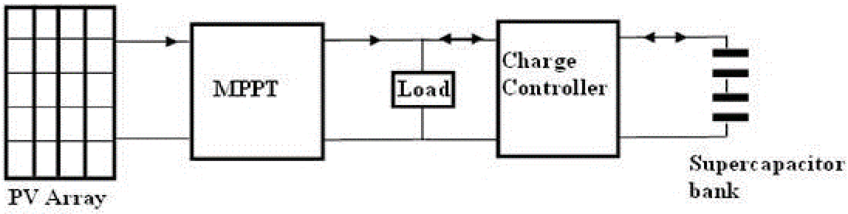


Figure 2. PV system layout

2.2. PV array

The array modeled has a rated maximum power of 60 W at 24 V. For simplicity, it is assumed that the array can provide 60 W at 24 V indefinitely, i.e. the environmental conditions are ideal always. Figure 3 shows the array model constructed on Capture. While the characteristics of the array are illustrated in Figure 4.

2.2.1. Solar radiation hours and photovoltaic array sizing

In this paper, the idea of peak solar hours is introduced, in accordance with [37], and preliminary work reported in [38], for the temperature of the cells at $25\ ^0C$, equal to the average temperature of the Palapye in the central district of Botswana. Let's now consider the actual irradiance profile for a particular day as X(t) at which the irradiance of the equivalent x9t) is 1 KW/m^2 during a time of peak solar radiation hours (PSRH). It then implies that, the total daily radiation for the day is:

$$\int_{day} X(t)dt = 1 \cdot PSRH \tag{3}$$

The solar cell in consideration has a maximum o current of 2.5 A and 24 V of voltage, similar to the report in [37]–[39] is as (4) and (5).

$$\int_{day} P_{max}(t)dt = 0.1982 \text{ KWh per day} \tag{4}$$

$$60W \times PSRH = 60\ W \times 3.25h = 195\ Wh/\text{day} \tag{5}$$

This work look into the worst-case scenario, for which the temperature is low to about 15 °C in addition to low irradiance values. In this work, the PSRH and energy balance relationship is (6).

$$P_{G-Nom} PSRH = \mathrm{L}_E \tag{6}$$

where P_{G-Nom} is the nominal output power of the photovoltaic system for a standard condition [37], L_E the consumed energy over the average day by the load in the worst case. We utilize the procedures as outlined in our previous research as contained in [37] for the reminder design procedures.

In this work, we consider the whole building of load consumption of 7,500 Wh per day at 24 V. Each of the solar panels has the following ratings:

$$P_{SP} = 60\ W; \quad V_{OC} = 44.60\ V, \quad I_{SC} = 1.2\ A, \quad I_{MP} = I_{GM} = 0.82\ A, \quad V_{MP} = V_{GM} = 36.5\ V$$

We then compute the required current drawn by the load over the entire day as (7).

$$I_{eq} = \frac{L_E}{24V_{cc}} = \frac{7500}{24*24} = 13.02\ A \quad (7)$$

where $L_E = \frac{7500\ Wh}{day}$

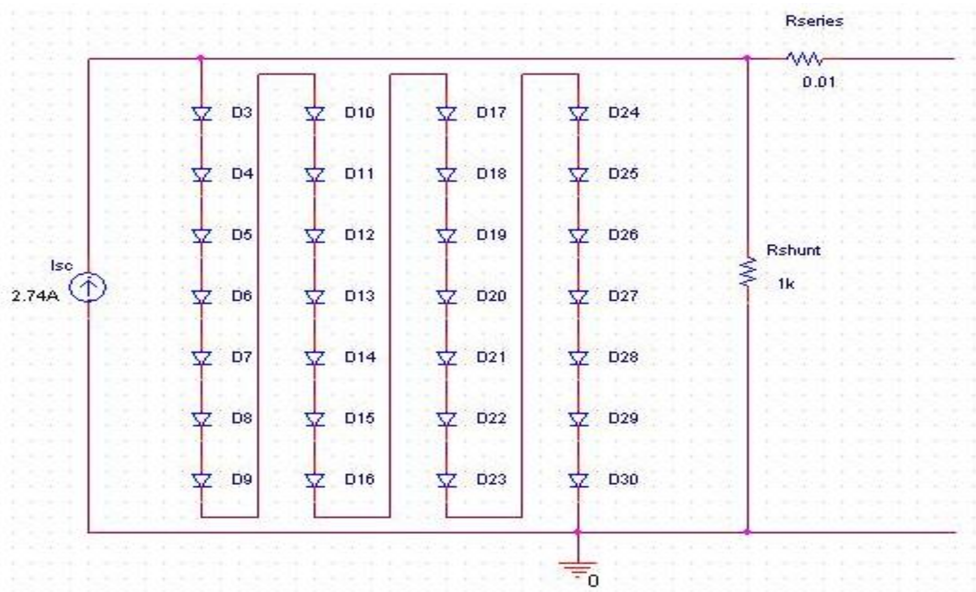


Figure 3. PV array model

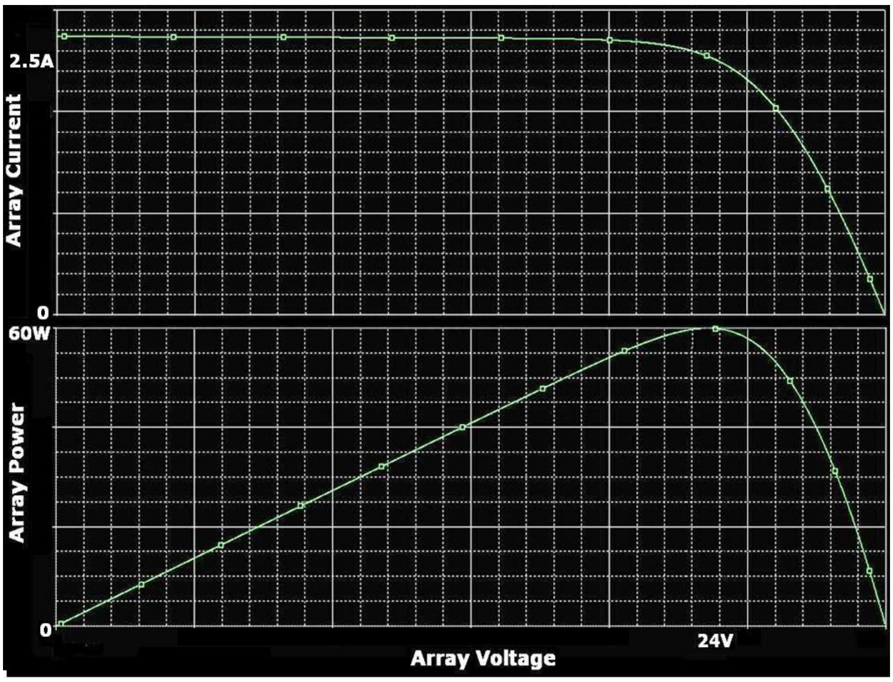


Figure 4. PV array current-voltage and power-voltage curves. The values correspond to MPP

2.3. MPPT

As explained above, the PV array modeled allows the use of a simple constant-voltage. This MPPT, therefore, seeks to permanently bias the array at V_{mpp}=24 V. This section further explained the topology adopted for the MPPT. The section also detailed the simulation results for the proposed MPPT.

2.3.1. MPPT topology

The MPPT is essentially a power electronics converter employing a buck converter topology. The circuit is given in Figure 5. The fundamental of MPPT operation is the variation of duty cycle to adjust bias point. For example, an increase in duty cycle of the converter's switch will result in an increased current-draw from the PV array, thus moving its bias point to the left of the characteristic curve. The MPPT design works likewise; feedback control compares the actual PV array voltage to a reference corresponding to V_{mpp} and uses the difference to make the required changes to the duty cycle via a simple amplifier-integrator-comparator chain.

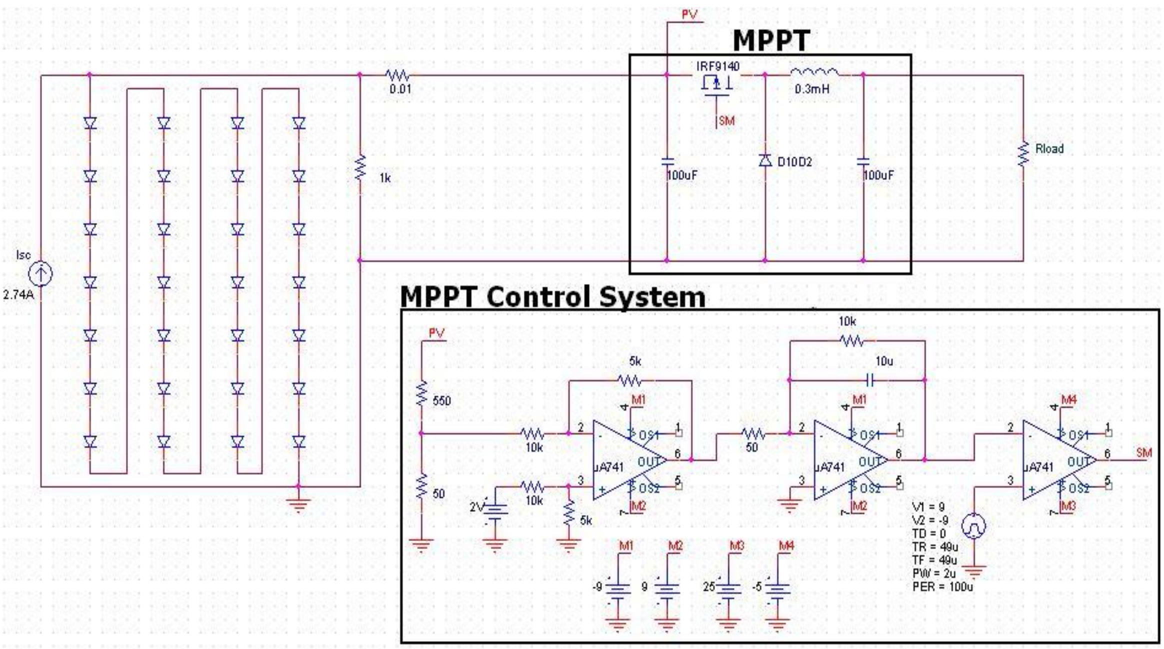


Figure 5. MPPT circuit and control system

2.3.2. MPPT simulation results

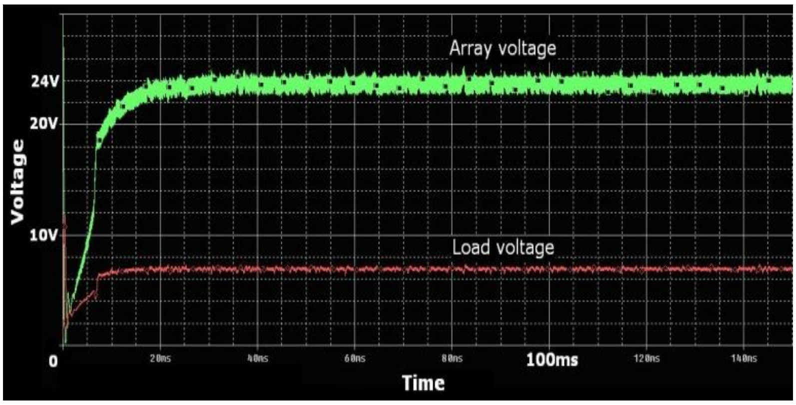
The MPPT was run for various load resistance values. The results are presented in Figure 6. MPPT simulation results for R_load values 1 Ω is presented in Figure 6(a). In Figure 6(b) is for 3 Ω, Figure 6(c) for 5 Ω, and Figure 6(d) is of 6 Ω. They demonstrate that the MPPT is effective in biasing the PV array at MPP.

2.4. The SEBB and charge controller

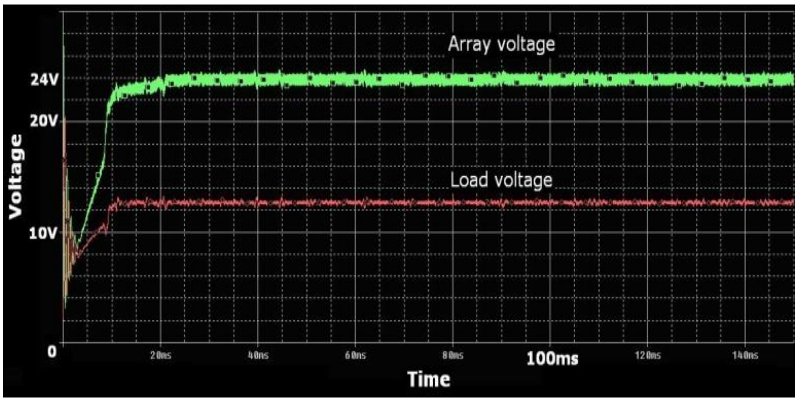
The SEBB consists of parallel sets, with two series-connected supercapacitors in each set. The maximum allowed voltage of the SEBB is 10 V and the minimum allowed voltage is 5 V. The charge controller functions as a charge/discharge regulator for the SEBB.

Figures 7 (a) to 7(d) shows the entire PV system with the SEBB and charge controller incorporated. However, Figure 7(a) demonstrates OrCAD construction of final PV system, Figure 7(b) SEBB, and Figure 7(c) control scheme for the SEBB charge controller The charge controller utilizes a bidirectional buck-boost topology to facilitate two-way power flow. Two switches, S2 and S1, correspond to buck and boost mode respectively. Each switch, operated by pulse-width modulation (PWM) signal, has its own independent control scheme. S1 permits the SEBB to discharge stored energy into the load in boost mode and is operated by a PWM signal generated by the discharge control system. S2 permits the SEBB to absorb energy from load side in buck mode and is operated by a PWM signal generated by the charge control system. Both control systems work similarly, using a simple amplifier-integrator-comparator chain to compare the actual load voltage to a reference corresponding to *V_rated* =12 V, and using the error to adjust the duty cycle of the PWM signal.

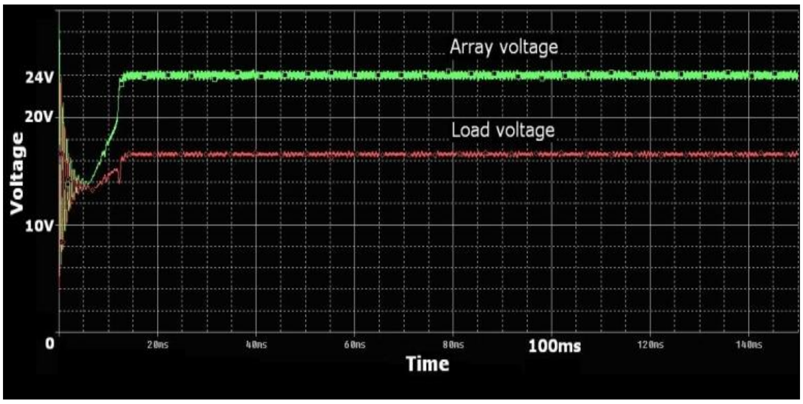
The control systems are in turn driven by a simple TTL-based decision system. This decision system monitors load voltage and decides which mode, buck (charge) or boost (discharge), the charge controller should operate in. It then activates the correct control system for this mode of operation, while keeping the other one off. For example, if an overvoltage is detected by the decision system, it will activate the charge control system, which in turn will drive switch S2 (buck mode) at the correct duty cycle so that the excess power is diverted to the SEBB and load voltage is brought down to 12 V.



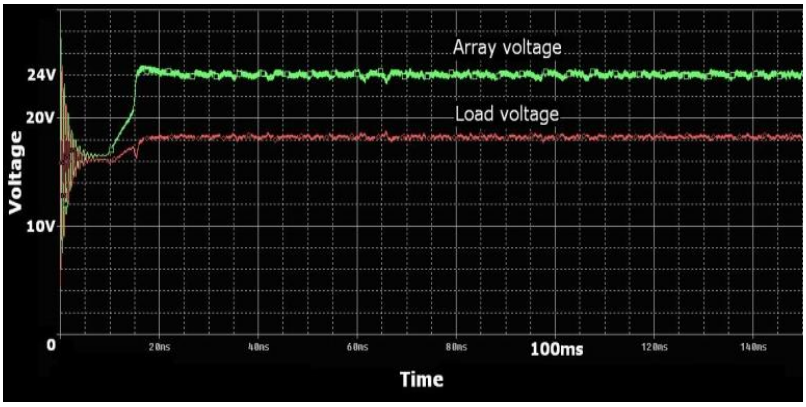
(a)



(b)



(c)



(d)

Figure 6. MPPT simulation results for *R_load* values of (a) 1 Ω, (b) 3 Ω, (c) 5 Ω, and (d) of 6 Ω

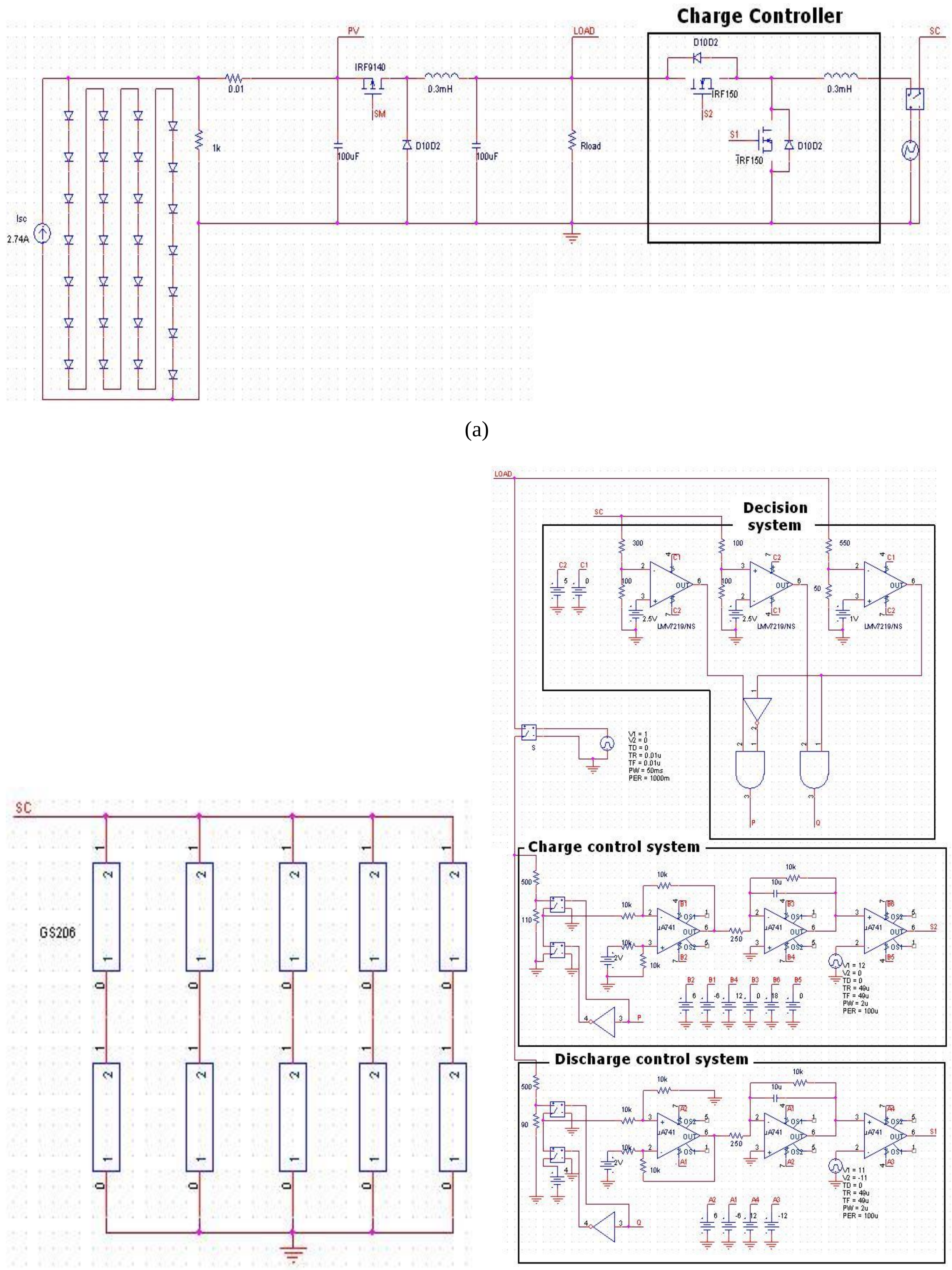


Figure 7. OrCAD construction of (a) final PV system, (b) SEBB, and (c) control scheme for the SEBB charge controller

In the meantime, the discharge control system is kept off so as not to interfere with the corrective action. The reverse occurs in the case of undervoltage. A second but important role of the decision system is to protect the SEBB from overcharging and undercharging. It can allow discharge to occur if, and only if, the SEBB voltage is greater than the 5 V minimum. Likewise, charging can only be allowed if, and only if, the SEBB voltage is less than the 10 V maximum. The algorithm of the charge controller is illustrated in Figure 8. *V_load* refers to the load voltage, while VSEBB is the SEBB voltage.

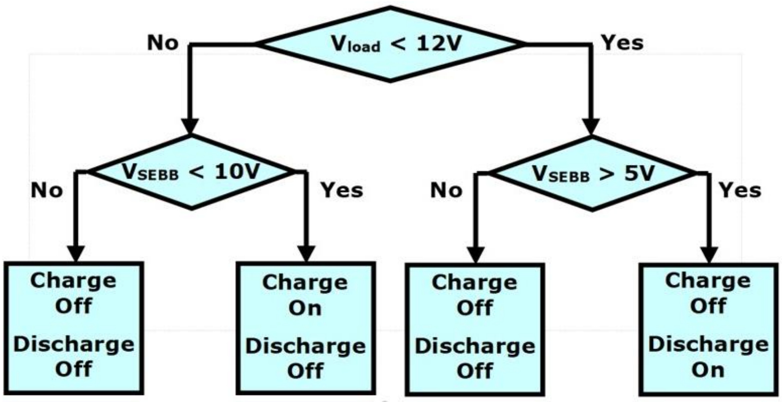


Figure 8. SEBB charge controller algorithm

3. RESULTS AND DISCUSSION

Explaining the MPPT simulation results (given previously) show that the MPPT has an efficiency of around 90%, providing 54 W to the load. Thus, effectively, supply is P_{supply} = 54 W. The (2) can be used to find the demanded power, P_{demand}. Thus, if R_{load}>2.67 Ω, then $P_{demand} < P_{supply}$, and overvoltage occurs. Similarly, if $R_{load} < 2.67$ Ω, then $P_{demand} > P_{supply}$, and undervoltage occurs. The system is simulated under a variety of load demand conditions achieved by varying R_{load}.

3.1. Overvoltage response

A test of the system's ability to handle overvoltage is carried out. In the simulation, a low demand (R_{load} = 8 Ω) is introduced at time 50 ms to trigger an overvoltage (prior to this, a load of R_{load} = 2.67 Ω ensured that demand matched supply). The SEBB consists of 8 supercapacitors and has an initial voltage of 9 V. The response is illustrated in Figure 9. The sudden increase in load voltage at 50 ms is clearly visible, as is its quick reduction to 12 V as the supercapacitors absorbed the excess power.

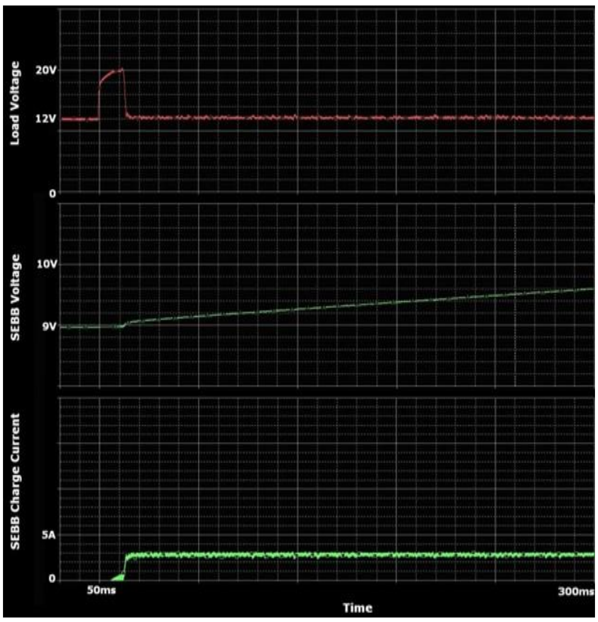


Figure 9. System handling of overvoltage

3.2. Undervoltage response

In this simulation, excessive demand (R_{load} = 1.75 Ω) is introduced at time 50 ms to trigger an undervoltage (prior to this, a load of R_{load} = 2.67 Ω ensures that demand matches supply). The SEBB consists of 8 supercapacitors and is initially fully charged at 10 V. The response is illustrated in Figure 10. The sudden drop in load voltage as soon as demand is increased is apparent. The system is seen to respond promptly, discharging the supercapacitors into the load to meet the demand and re-achieve 12 V.

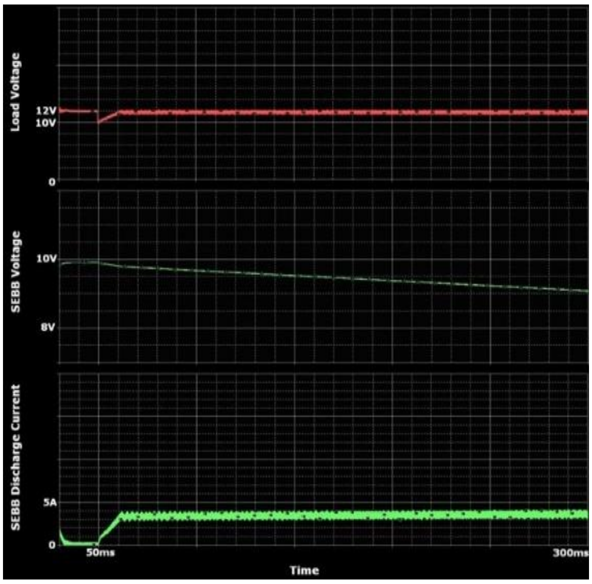


Figure 10. System handling of undervoltage

3.3. Test run

A period of low demand (R_{load} = 5.6 Ω) is simulated for 200 ms, followed by a period of excessive demand (R_{load} = 1.75 Ω) for another 200 ms. The SEBB consists of 8 supercapacitors and has voltage 9 V initially. The results are shown in Figure 11. The test run demonstrates the efficacy of the SEBB and charge controller system in absorbing power disequilibria to stabilize load voltage, as well as the ability of the MPPT to continually bias the PV array at MPP.

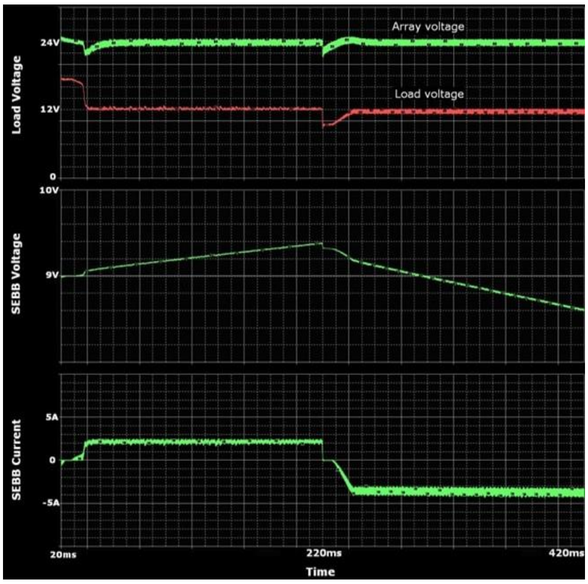
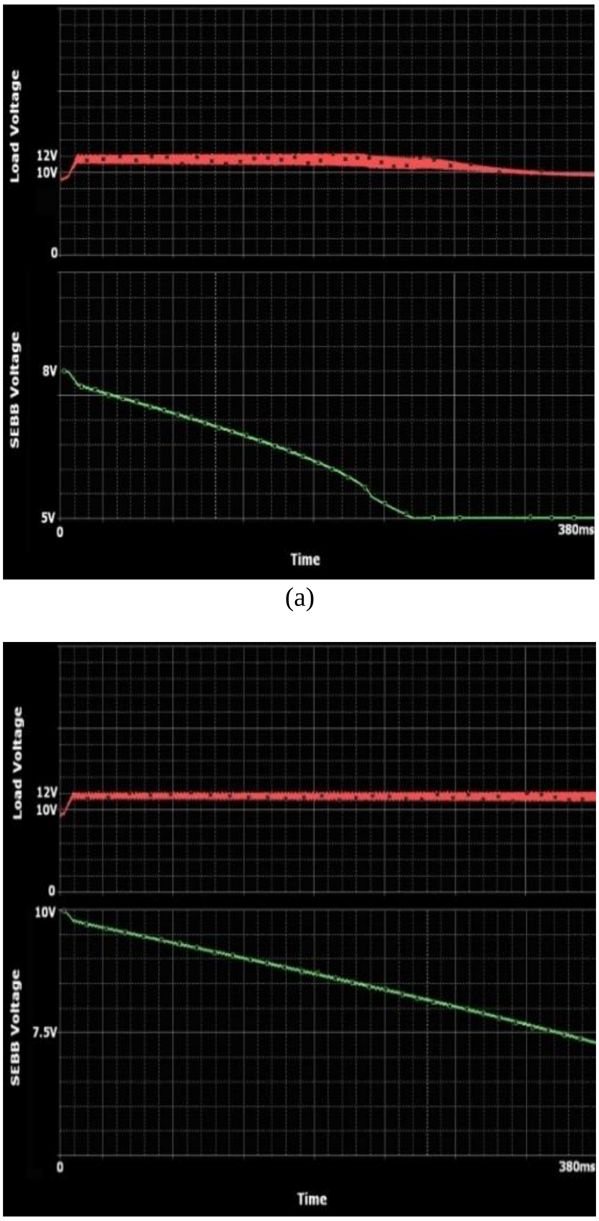


Figure 11. System response in test run

3.4. Effect of SEBB voltage on undervoltage response

The effect of the SEBB's level of charge on the response during a period of excessive load demand is investigated. A high-demand load of Rload = 1.75 Ω creates an undervoltage situation. This scenario is simulated, first with a 4-supercapacitor SEBB of 8 V initial voltage, and then with 10 V initial voltage. Comparison of the undervoltage responses with initial SEBB voltages of 8 and 10 V are presented in Figures 12(a) and 12(b) respectively.

The results show that the higher level of charge corrects the load voltage for longer and in a smoother manner. Therefore, a higher SEBB voltage is desirable for good undervoltage management. The reasons for this are twofold; firstly, the significantly larger storage in 10 V compared to 8 V (energy is proportional square of voltage), and secondly, the improved performance of the boost converter when there is a higher input voltage; the former explains the longer duration of voltage stability in the case of 10 V initial voltage, and the latter explains the relative smoothness of the load voltage. Another performance aspect demonstrated by these results is the protection provided to the SEBB: in the 8 V initial voltage situation, the system stops SEBB discharge once its minimum allowed voltage of 5 V is reached.



(b)

Figure 12. Comparison of the undervoltage responses with initial SEBB voltages of (a) 8 V and (b) 10 V

3.5. Possible improvements

Figure 13 illustrates a scenario where the SEBB cannot absorb excess supply power because it is fully charged, thus forcing the load to bear the overvoltage. In practice, an overvoltage could seriously damage a load, and such a situation should be avoided at all costs. To prevent this situation in the PV system, the MPPT control scheme can be upgraded to monitor the load voltage and SEBB state of charge and bias the PV array at a sufficiently lower power output if the SEBB is full and an overvoltage presents itself across the load. A simpler, but less dependable, solution would be to use a large number of supercapacitors in the SEBB such that a fully charged situation is unlikely to occur.

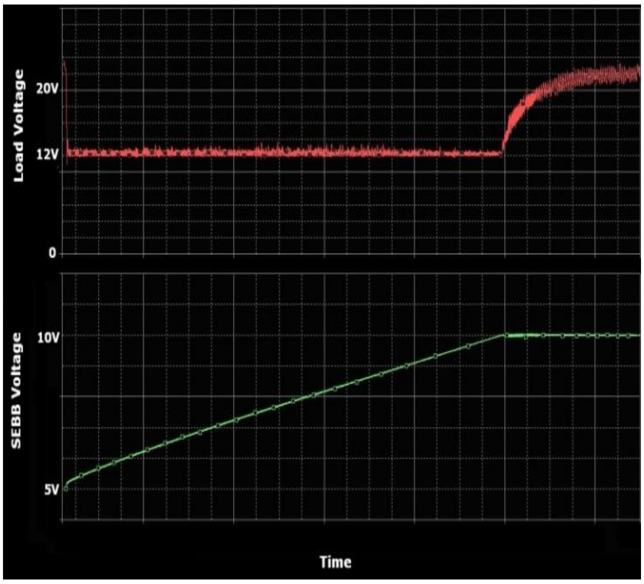


Figure 13. Scenario where SEBB is unable to absorb excess supply power due to fully charged state

4. CONCLUSION

Provide The results demonstrate that the MPPT is able to effectively bias the PV array at MPP. More importantly, the dedicated analog charge controller effectively controls the energy flow in and out of the SEBB to regulate the load voltage at 12 V. This analog system, therefore, shows positive results in improving the efficiency of PV systems. It also demonstrates that incorporation of supercapacitor storage in a PV system provides equilibrium of supply and demand power, thus stabilizing load voltage. This small-scale system can be used as the basis for large-scale PV systems, both grid-connected and standalone. For example, it could be used to power a home or a community of homes during daytime with the grid supplying the night-time demand.

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