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Research Article

Analysis of Supercapacitors in Renewable Energy Systems for Managing Power Fluctuations

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Environmental decarbonization drives the world to find better ways to generate and store energy. Sustainable energy in the form of solar and wind is explored with the use of conventional energy storage systems (batteries) to close the gap. Green energy generation is weather-dependent, leading to power output fluctuations, and the short-term variability in irradiance adversely affects the system's energy output and reliability. Standalone operation of a generating system necessitates a storage energy unit that manages transient loading and effectively shares power between the load and energy storage. This article presents an approach to managing energy fluctuations when renewable energy sources fluctuate, this occurs when short-term variability in irradiance, and transient loading occurs. The approach uses supercapacitors as a short-term energy storage solution. The proposed configuration has the following key advantages: effective power sharing, rapid charge, and discharge cycles in supercapacitors result in voltage restoration under transient conditions. The performance of the system is confirmed in MATLAB/Simulink. The proposed study confirms that integrating supercapacitors with PV systems does provide significant power oscillation management when sudden variations occur in renewable sources. A practical test was performed using smaller components following the same concept, and the results supported the hypothesis. The results show that the output voltage is managed when oscillation in irradiance occurs. This is seen in the simulation without supercapacitors when the output voltage fluctuates between 100 and 450 V within the first second of the simulation; however, with the introduction of SC, the voltage becomes stable and maintains an output of 620 V within 0.02 seconds. This is further supported by the experimental outcomes where almost 50% of the solar panel is covered and the output voltage is maintained.

1. Introduction

The economy has continued to grow globally in the last few years, and the energy demand and power requirements are also increasing. Currently, demands for energy supplies are mostly met with fossil fuels, including coal and natural gas. These fossil fuels have an environmental impact [1]; burning of these fossils releases harmful gases into the atmosphere [2], raising toxic gases which contribute to respiratory illness, acid precipitation, and global warming. Renewable energy is explored: with solar and wind generation as the most advanced sources. These technologies are improving; however, they have drawbacks which include but are not limited to weather dependency and initial high capital cost [3]. As a result, high oscillation occurs in the system which causes voltage instability and frequency control problems when weather changes [4]. The research and investigation of power management in renewable energy are still in their primary stages. This necessitates comprehensive research in design systems to manage power oscillations during weather fluctuations. The research objective is to analyze the effectiveness of using supercapacitors in energy systems for managing energy output centered around the hypothesis that supercapacitors used as short-term storage may lead to energy improvement in renewable energy. The method approach includes the collection of Meteodata, irradiation levels, PVsyst simulation, and MATLAB-Simulink to analyze the effectiveness of supercapacitors.

Hybrid energy systems have been proposed to achieve better battery performance [5–8]. The main storage technology is lead-acid and lithium-ion batteries [9]. Other methods have been researched and carried out for coping with oscillations in wind energy generation [10], namely, the doubly fed induction generators (DFIG) and variable speed generators (VSG), while in solar generation, energy storage systems are used. [11] presented a review of integrating solar and photovoltaic cells for sustainable energy devices. Although batteries are an excellent choice to meet the demand of sudden fluctuations, they have challenges, such as fast response. They cannot handle high ramp power because their lower energy density affects their life span [12]. Supercapacitors provide a possible solution. The investigation of supercapacitors is captivating as they can operate effectively when sudden weather changes occur. Supercapacitors have high power density and low energy density [13]. This is due to their low equivalent series resistance (ESR) [2, 14]; other applications presented include EV regenerative braking and wind generation smoothing when wind varies. [15] offered an energy conversion system using supercapacitors to manage fluctuations in battery energy storage while improving its operation. This was done by introducing supercapacitors to the charge controller stage before the direct current circuits. Further, [16] proposed a direct current connection of the supercapacitor to the DC bus, and the results exhibited the effectiveness of power management. [7, 17] presented PV connection with a supercapacitor for system fault ride-through for strategy control management to capture irradiance using maximum power point tracking and power transfer to a buck-boost converter to reduce oscillation.

Controlling techniques using linear and nonlinear have been proposed for grid-tied PV systems [17]. Energy management for solar using a fuzzy logic controller system for the management of conserved energy is explored by [3, 18]. Previous research looked at the direct connection of supercapacitors with DC bus points [16], while some used fuzzy logic controllers, phase-shifted full bridge converters [19], and multilevel converters to manage output fluctuations. This article proposes a bidirectional converter integration with energy generated from a PV array into the electricity grid; the approach is different compared to earlier research presented since it is a convenient two-way transmission energy with high efficiency. The converter works in two modes (on and off), and the difference is the buildup of a magnetic field. Further, interest is given to analyzing the power fluctuations when sudden weather changes. This is done by inputting different values into the stair generator in MATLAB-Simulink. The storage system is connected through a bidirectional boost converter, while the PV system is connected through a boost converter. The stair generator controls the input irradiance, and MATLAB-Simulink is used to examine the proposed configuration. The main contributions of this paper are as follows:

(i) Focused on energy management based on the voltage variation approach, using the PV's fluctuating power. The proposed method is first evaluated through PVsyst simulation using the Meteodata and irradiation levels. Second, an experimental test bench is carried out to complement the simulation results

(ii) Validation of the proposed method using the experimental results as compared with that of the simulation ones, whereby the practical results support the simulation ones

(iii) Determination of the variations in simulation results for voltage with and without the use of SC in the proposed method

(iv) The research identified an innovative method for improving and managing energy output on solar energy, and it builds on and strengthens existing knowledge with new supporting data to advance theoretical and simulation knowledge

(v) The use of a proposed configuration which has effective power sharing, rapid charge, and discharge cycles in supercapacitors resulting in voltage restoration under transient conditions

The proposed system structure of photovoltaics and supercapacitors is described in Section 2, system design and modeling are presented in Section 3, simulation results and discussion are presented in Section 4, and Section 5 concludes the paper.

2. System Modeling

2.1. System Structure. Figure 1 describes the configuration of the system structure of the photovoltaic system integrated with supercapacitors connected to the grid via a DC link. One solar panel is used in which solar radiation is projected and converted the radiation to direct current. A stair generator is used to vary the irradiance at different intervals of the day to simulate real-time system operation. PV is connected to a boost converter, and the supercapacitor is connected via a bidirectional boost which all connects to the DC link. A function to manage energy is connected to the DC link. Below is an overview of the system configurations.

2.2. PV Array. Photovoltaic cells are made of semiconducting material that converts the sun's radiation to electric current. Operation philosophy is that when a semiconducting material absorbs light, it increases the energy valence band electron, pushing it into the conduction band [20]. This happens when the energy of the incident is higher than the band energy gap; therefore, the conducting band produces a flowing current (Figures 2(a) and 2(b)) [21, 22].

2.3. Supercapacitors. Supercapacitors are high-energy versions of conventional capacitors, holding hundreds of energy per unit volume [23]; they have high power density but low energy density. They can be charged and discharged frequently and are therefore suitable for operations where high surge current occurs for a short period; this makes it suitable for selection to manage the sudden change in weather fluctuation, hence [24] supporting the theory that supercapacitors can be used as high-performance energy

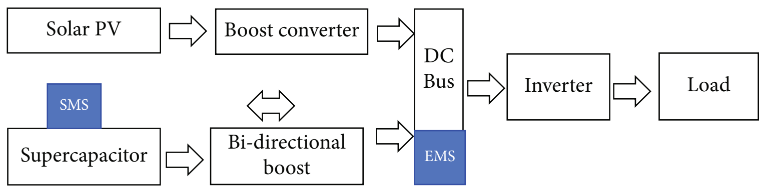
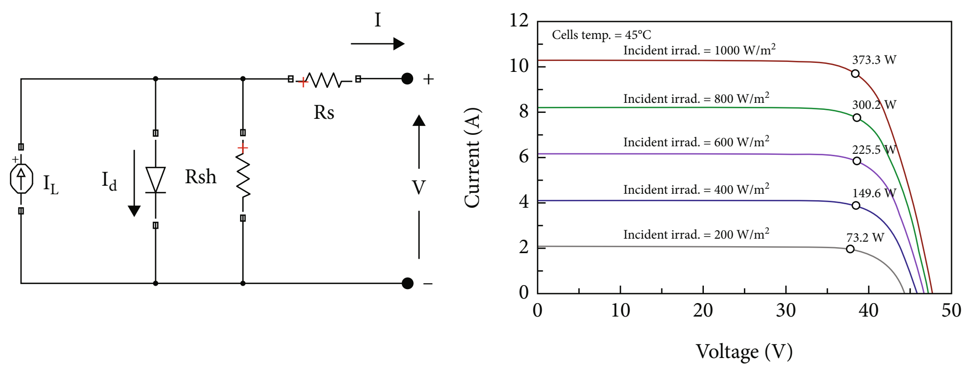


Figure 1: Photovoltaic and supercapacitor system integration (drawn by the authors).



(a) (b)

Figure 2: (a) Equivalent circuit of PV cell [17]. (b) I-V characteristic curve graph of selected solar panel extract from PVsyst.

Table 1: Comparison of supercapacitors with conventional batteries [25].

Parameters	Lead-acid	Lithium-ion	Supercapacitor
Energy density (Wh/kg)	10-100	150-200	1-10
Power density (W/kg)	<1000	<2000	<10000
Life cycles	1000 Data	5000 Data	>500 000 Data
Charge time	1-5 hours	0.5-3 hours	0.3-30 sec
Discharge time	0.3-3 hours	0.3-3 hours	0.3-30 sec
Charge-discharge efficiency	70-85%	99%	85-99%

Table 2: Key design supercapacitor parameters [25].

SC parameters	Values
Rated capacitance (F)	99.5
Equivalent DC series resistance (ohms)	$8.93e^{-3}$
Rated voltage (V)	90
Operating temperature (°C)	25

storage devices. [25] provided a comparison of electrochemical techniques for supercapacitors. A comparison with batteries is presented in Table 1.

The biggest challenge associated with supercapacitors is the energy density; as a result, this increases the initial cost of installation to have an equivalent density compared to batteries. Furthermore, the rated voltage is very low (less than 2.7 V), which necessitates a lot of series connections for practical use. Due to high current discharge and charge, long-term performance is still in question as the charging and discharging have an impact on the supercapacitor [26].

2.4. Experimental Setup. The supercapacitor is connected directly to the bidirectional boost converter which has a switch that is manually run for charging (1, 0) and for discharging. The output of the bidirectional converter is connected to a DC voltage source to power the supercapacitor when the charging state occurs. Voltage and current controllers with discrete time are used in line with the PWM generator with a frequency of $10e^{-6}$. Table 2 lists the supercapacitor's parameters.

To test the design operation philosophy, a simple test procedure is developed as follows.

(1) Connect the fixed input values to the input of the PV array

(2) Compute the input irradiance values and compare the PV array voltage

(3) Compute the output voltage of the boost converter and do a comparison with the input voltage

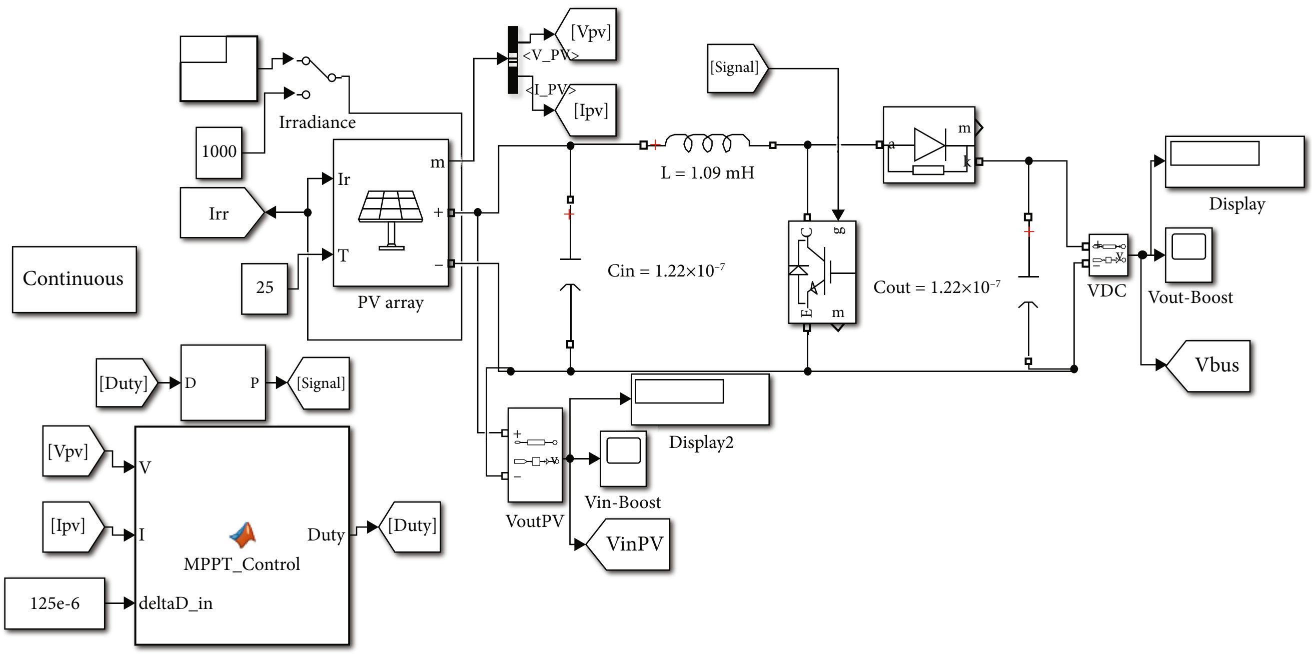


Figure 3: Boost converter with PV array (design using MATLAB).

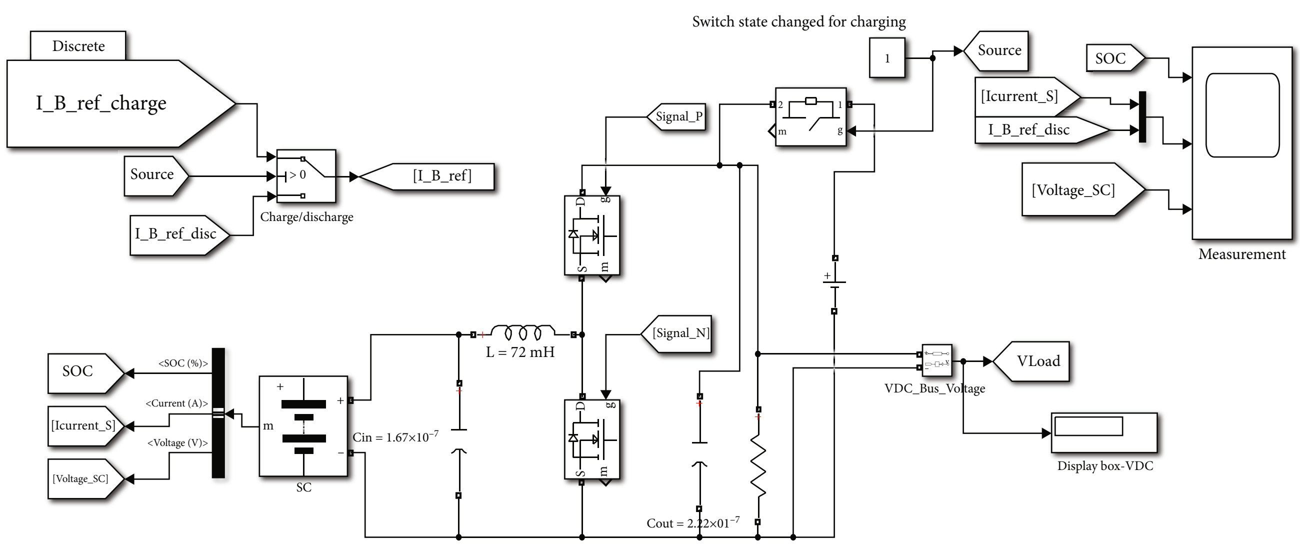


Figure 4: Supercapacitor integrated with a bidirectional converter (design using MATLAB).

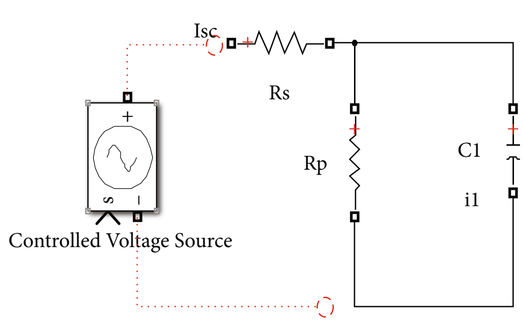


Figure 5: RC supercapacitor diagram [31].

(4) To confirm the output voltages, an analysis of the voltage graph will be done with a focus on voltage in (V_{in}) for the boost converter and voltage out (Vout)

(5) Repeat steps 2 to 4; however, this time, instead of using a fixed input value, a function stair generator was introduced to vary the inputs

(6) Introduce a SC design circuit to evaluate the effectiveness of supercapacitors in managing fluctuations

2.5. System Control Blocks. The system is integrated with converters and maximum power point tracking, all

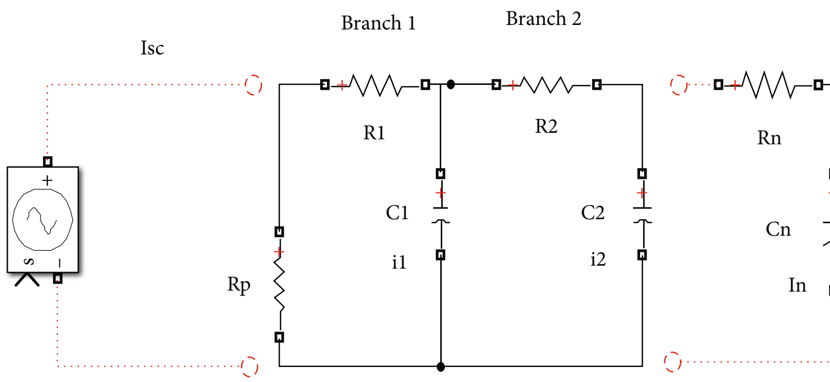


Figure 6: Multibranch RC model [33].

Table 3: Design parameters for boost and bidirectional converter [27].

Parameters and units	Boost converter	Bidirectional converter
Input voltage (V_{in}) (V)	50	18
Output voltage (V_{out}) (V)	478	47
Output current (I_{out}) (I)	8.17	2
Ripple current (ΔI_{out}) (I)	20% I_{out}	20% I_{out}
Inductor (L) (mH)	1.09	27.26
Duty cycle (DC) (sec)	0.89	0.6
Output capacitor (C_{out}) (C)	1.22×10^{-7}	1.02×10^{-7}
Resistance (R_{out}) (Ω)	58.5	26.3

connected to the DC bus. DC link voltage is controlled by a voltage control function managing the bus voltage. The boost converter is an electronic device that steps up the voltage in an electronic circuit. The energy process of stepping-up voltage is carried out using electronic elements such as an inductor, MOSFET switch, diode, and capacitors [27, 28]. Pulse width modulation is used through a signal input to the IGBT for switching purposes. The DC converter operates in mode 1-on and mode 2-off. The flow of inductor current is the main difference and the buildup of the magnetic field. When the circuit is in mode 1, the current flows from the source through the inductor via the switch. In charging mode, energy gets stored in the inductor. In mode 2, the current will flow directly via the inductor, diode, and resistive load. During off mode, the energy stored in the inductor during on mode gets discharged to the resistive load. Hence, the load voltage is higher than the supply voltage. Figure 3 represents a boost converter with a PV array connected. Refer to Figure 18 in the appendix for a precise figure.

Bidirectional DC-DC converter works in both buck and boost modes and can manage the energy flow from two energy sources, resulting in forward and backward directions [29]. Figure 4 represents the buck-boost converter. Refer to Figure 19 in the appendix for a clear diagram. The converter acts as a buck to recharge the supercapacitor in one direction and a boost to transfer energy to the link capacitor in the other direction. MOSFET switching devices are used to obtain the required boosting. Action pulse width modulation of 25 kHz is used to power the MOSFET [30]. The DC link voltage control operation is as follows: charge (Q_1) is conducting during this steps according to the duty cycle. In the discharging mode, Q_2 will conduct and vice versa.

3. Design and Modeling

The supercapacitor selection is chosen depending on the energy required to minimize the oscillation in the circuits of the PV array, as depicted in Figure 1. Excess energy is stored in the supercapacitor when the power demand from the load exceeds the power demand from the PV array. Whenever the power supply from the PV array is less, the supercapacitor will supplement and reduce the oscillations. The choice of a supercapacitor is given by the following formula:

$$P_g = P_{pv} \pm P_{sc}, \tag{1}$$

$$P_{sc} = \frac{1}{2} C_{sc} V^2, \tag{2}$$

where P_g is the grid power, P_{pv} is the power generated from the PV array at maximum, and P_{sc} is the supercapacitor power.

3.1. Supercapacitor Modelling. In this paper, a single- and two-branch supercapacitor model is explored. A supercapacitor can be schematized by a series resistance (R_s) and parallel resistance (R_p) with capacitance (C_d). Figures 5 and 6 represent the equivalent supercapacitor circuit and multi-RC branch circuits. R_s occurs during charging and discharging, and R_p represents the leakage charge of supercapacitor [31].

The mathematical modelling is simplified by neglecting leakage current [32]. The V_{sc} and I_{sc} are the supercapacitor module voltage and current. The main capacitance (C_1) is made with constant capacitance C_0 and constant parameter

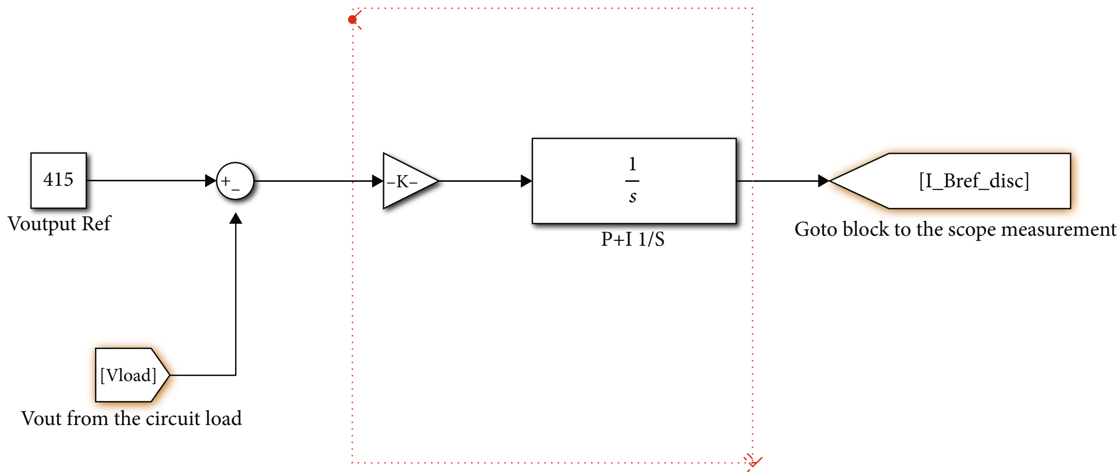


FIGURE 7: Voltage controller PI diagram (design using MATLAB).

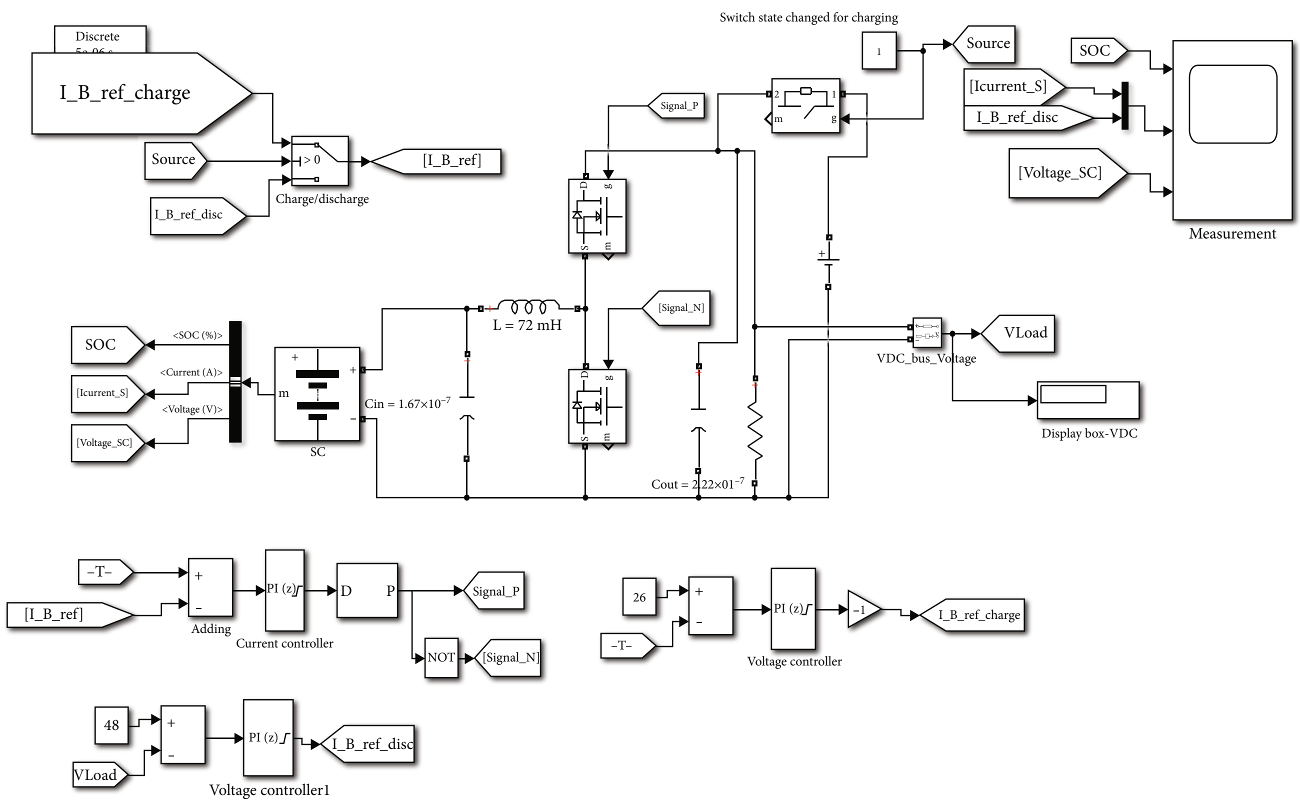


FIGURE 8: Supercapacitors integrated with bidirectional control functions (design using MATLAB).

C_v. The capacity is given by the following equation:

$$C_1 = C_0 + C_v V_1, \tag{3}$$

where V_1 is the voltage of C_1.

The second branch characterizes the redistribution phase of the charges during the rest phase. The rest phase is modeled by $R_2 - C_2$ branch with larger time constant. The R_p symbolizes the supercapacitor self-discharge which occurs after the redistribution phase. [33] proposed that by neglecting the leakage current, the voltage across supercapacitor can be described as follows:

$$U_{sc} = N_{s-sc} v_{sc} = N_{s-sc} \left(v_1 + R_1 * \frac{I_{sc}}{Np_{sc}} \right), \tag{4}$$

where U_{sc} and I_{sc} are the voltage and current of the supercapacitor and N_{s-sc} and Np_{sc} are the number of parallel and series connection of the SC. The voltage V_2 is given by

$$V_2 = \frac{1}{C_2} \int i_2 \quad dt = . \tag{5}$$

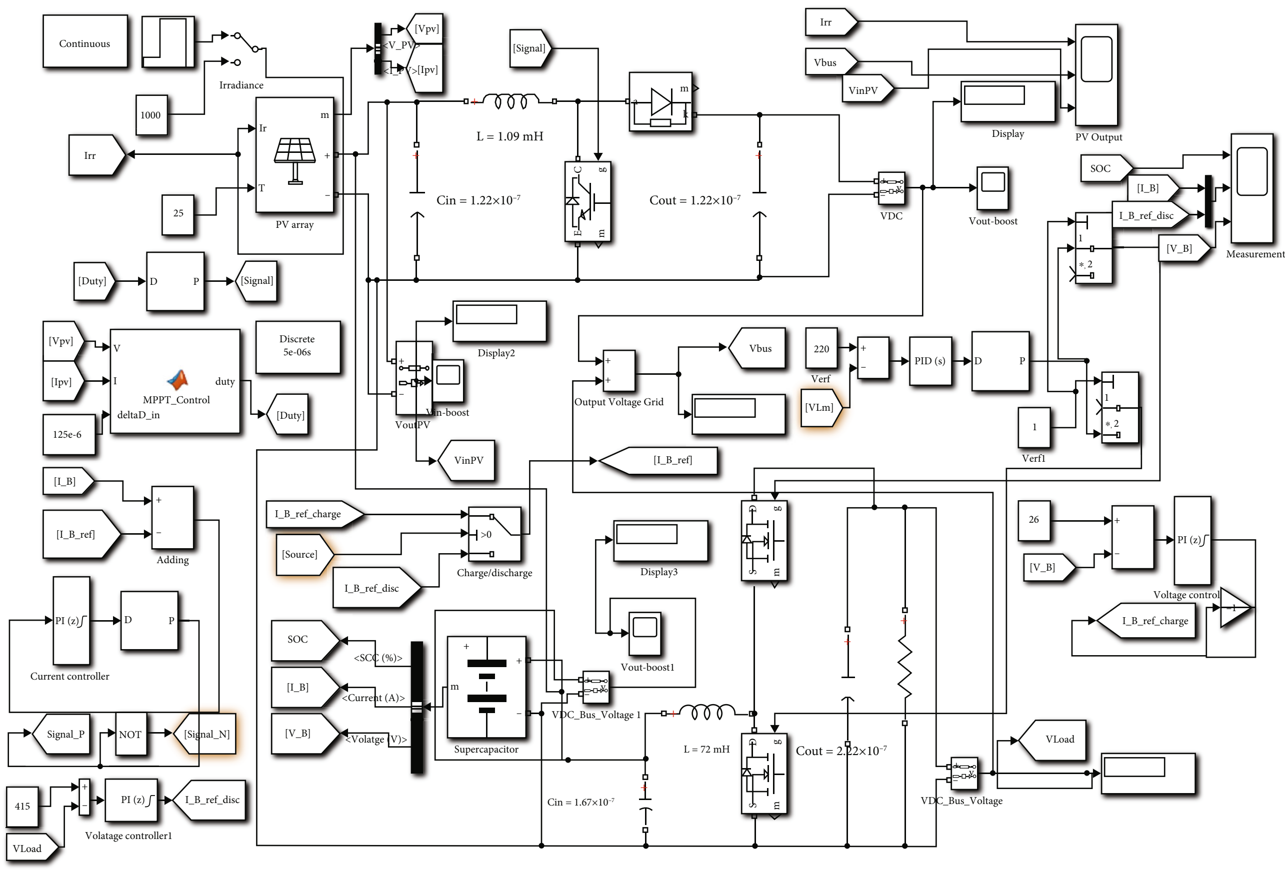


Figure 9: Hybrid solar and supercapacitor (design using MATLAB).

Current i_1 is expressed in relation to instantaneous charge Q_1 and C_1 as follows:

$$i_1 = C_1 \frac{dv_1}{\mathrm{dt}} = \frac{\mathrm{d}Q_1}{\mathrm{dt}} = (C_0 + C_v v_1)\frac{dv_1}{\mathrm{dt}}, \quad (6)$$

where the charge Q_1 is given by

$$Q_1 = C_0 v_1 + \frac{1}{2} C_v {v_1}^2. \quad (7)$$

And the voltage v_1 is defined as

$$v_1 = \frac{-C_0 + \sqrt{{C_0}^2 - 2C_v Q_1}}{C_v}. \quad (8)$$

The parameters needed to calculate the power stages for the boost and bidirectional converter circuit are listed in Table 3 [27]. A pulse width modulation of 25 kHz is used to power the MOSFET to obtain the boosting action.

The mathematical modeling for the selection of boost converter components is as follows:

Boost converter calculations:

$$\text{Duty cycle } (D) = \frac{V_{\text{out}} - V_{\text{in}}}{V_{\text{out}}}, \quad D = \frac{478 - 50}{478}, \quad D = 0.89, \quad (9)$$

$$\text{Change } I_{\text{o}} (\Delta I_{\text{out}}) = \frac{V_{\text{in}}}{(1 - D)^2 \times R}, \quad \text{Change } I_{\text{o}} = 20\% \times 8.17, \quad \text{Change } I_{\text{o}} = 1.634\ \text{A}, \quad (10)$$

$$L = \frac{V_{\text{in}} \times D}{F_s \times \Delta I_{\text{out}}}, \quad L = \frac{50 \times 0.89}{25000 \times 1.634}, \quad L = 1.09\ \text{mH}, \quad (11)$$

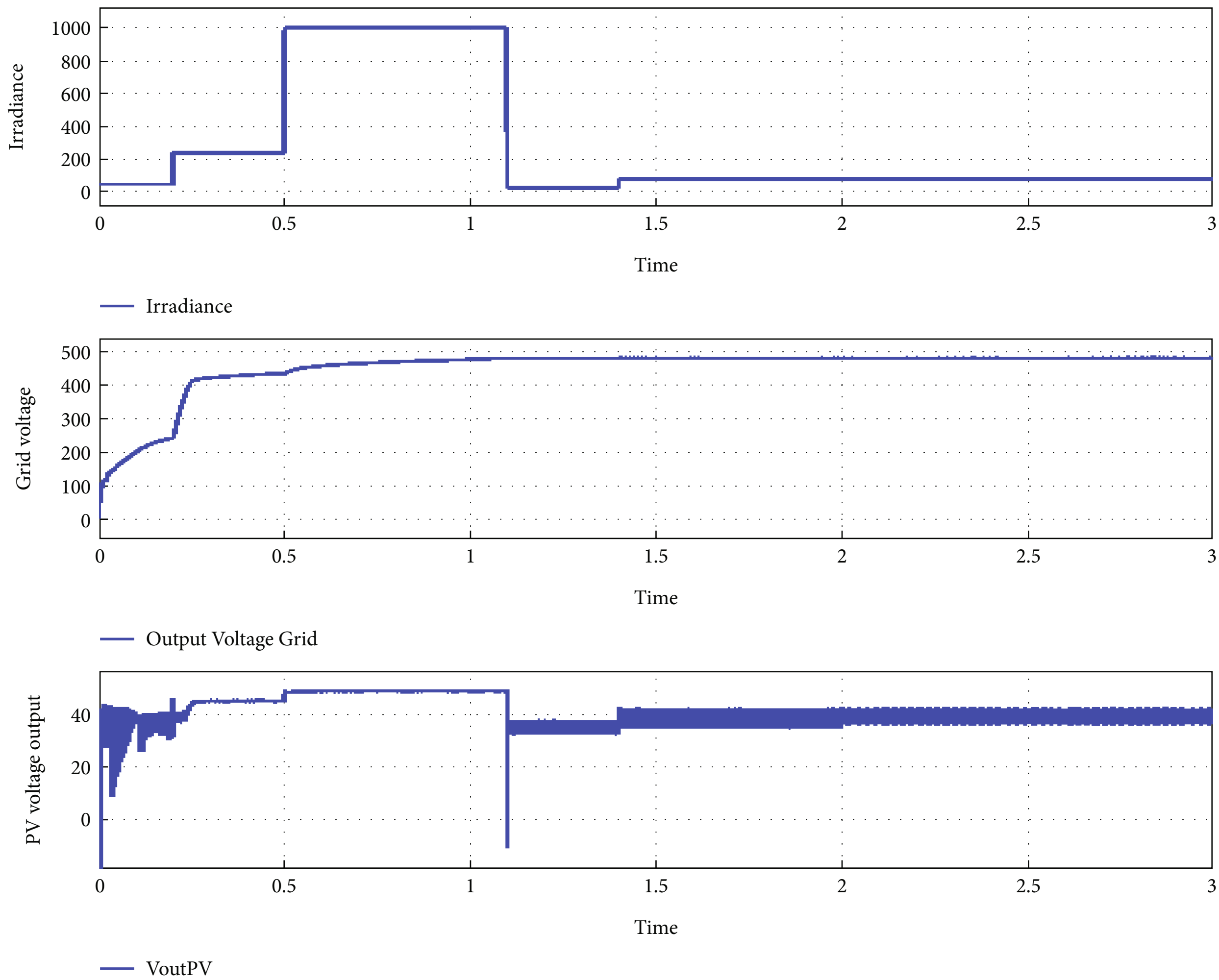


Figure 10: Simulation response of a PV standalone system (MATLAB output graph).

$$C_{out} = \frac{I_o \times D}{F_s \times V_{out}},$$
$$C_{out} = \frac{1.634 \times 0.89}{25000 \times 478}, \quad (12)$$
$$C_{out} = 1.22 \times 10^{-7}\ \text{C},$$

$$V = IR,$$
$$R_{out} = \frac{478}{8.17}, \quad (13)$$
$$R_{out} = 58.5\ \text{ohm}.$$

3.2. MATLAB Design and Simulation. Figure 7 indicates the voltage controller PI with the gain and sum up block, with Figure 8 representing the integration of supercapacitors with bidirectional control functions. Figure 9 represents the overall configuration system with solar input, bidirectional converter, and supercapacitor.

4. Simulation Results and Discussion

One PV panel was used and connected along with a supercapacitor energy storage system connected to a common DC link. Solar intensity varies in the simulation with a stair generator at 25°C. The expected result when the input irradiance is at maximum operating power from the PV source will be 373.3 W (37.3 V and 10 A), as depicted in Figure 2(b).

The supercapacitor was designed to have a capacity of 70 W with a voltage of 18 V to minimize fluctuations using equation (1). A stair generator with different parameters, time, and irradiance at different intervals is controlled to create fluctuations in the real system world. A comparative analysis comparing voltage output sent to the grid without supercapacitors when irradiance is varied with comparison of voltage output when supercapacitors are introduced with respect to irradiance changed. Analysis output is represented with the two system simulation outputs in Figures 10 and 11.

The simulation results show that during the initial period where the irradiance is low, fluctuations occur in the PV output between 40 and 18 V, and the voltage sent to the grid is not stable. However, with the introduction of

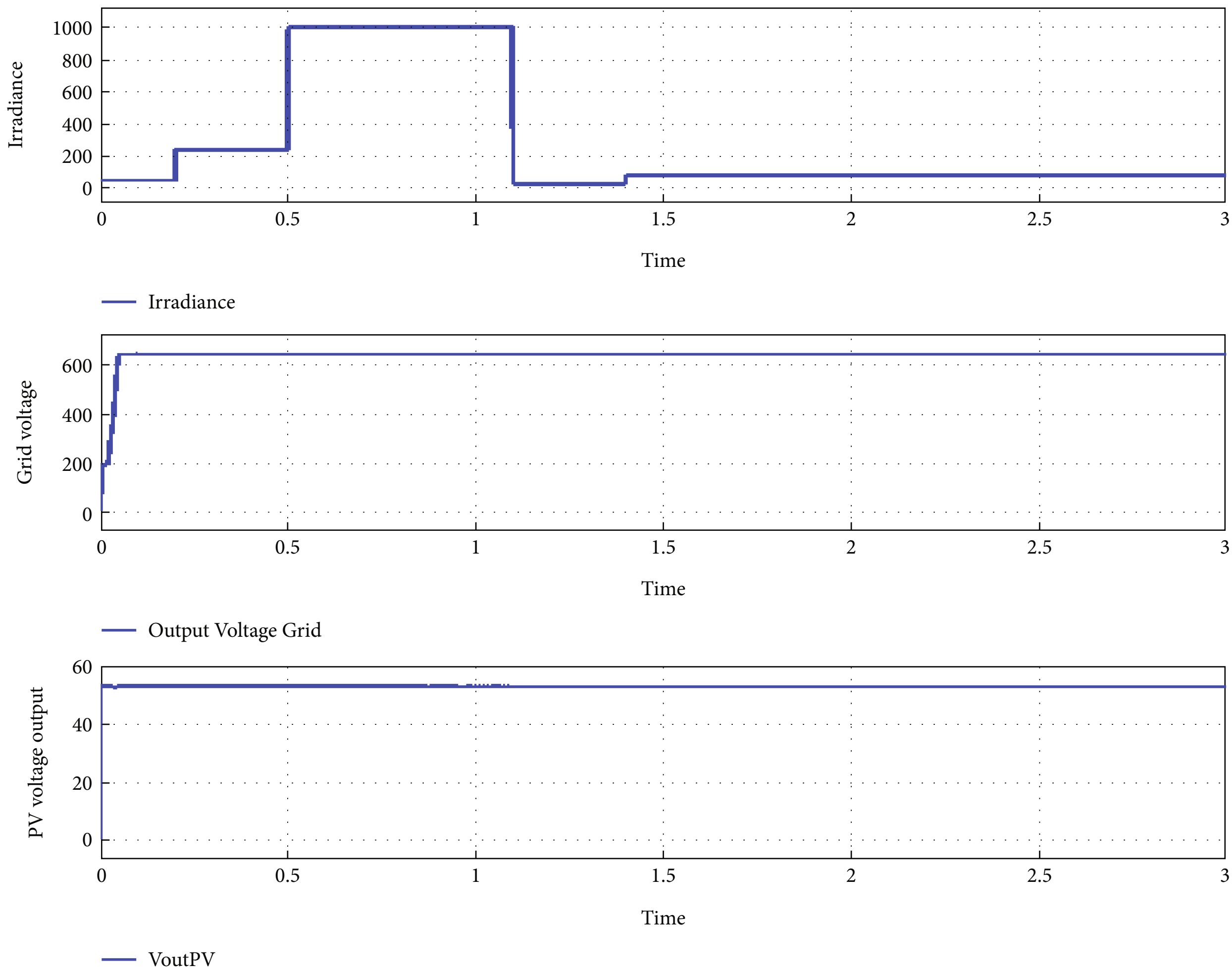


Figure 11: Response of PV integrated with supercapacitors (MATLAB output graph).

Table 4: Voltage response output with and without supercapacitors.

Time (sec)	Irradiance	V_{out} without SC	V_{out} with SC
0	50	100	200
0.2	240	120	300
0.5	1000	410	620
1.1	30	450	620
1.4	80	450	620

supercapacitors, it was seen that the fluctuations are being managed, and the output stays the same regardless of the irradiance input. Below are the response figures, respectively. This highlights the importance of using supercapacitors in photovoltaic generation as a short-term storage. One limitation of note in a practical environment when SC is integrated with renewables would be the initial cost of investment; this would be mainly due to the large number of series connections that would be required, as well as the space required to mount which can have an environmental impact and damage vegetation.

The outcomes of the simulation and research show the practical possibility of being implemented in a small-scale embedded generation; this is due to their high-peak-power delivery capability; however, because of their smaller size and the energy density, this poses a challenge to support large energy generation. For large generations, they can be integrated with other sources of energy storage such as conventional batteries. This is supported by [34] in their survey of hybrid devices based on supercapacitors. The response summary of the output voltage with the variable irradiance input is listed in Table 4.

4.1. Field Experimental Setup. A practical presentation with associated tests is conducted to confirm the simulation results. The practical setup is made up of a boost converter, a 5 W solar panel with a supercapacitor bank which has 4X 2.7V 100F supercapacitor, and a bidirectional converter. The practical components used are not the same size as the simulated ones; however, the concept behind the system is the same; hence, the practical result supports the simulation. The following is the testing output of the practical's supercapacitor charging: the supercapacitor bank voltage connected in series gives an output of 0.7 V before charging as seen in Figure 12, with the introduction of 5 W solar as shown in Figure 13, and the charge voltage output measured is 7.5 V as shown in Figure 14.

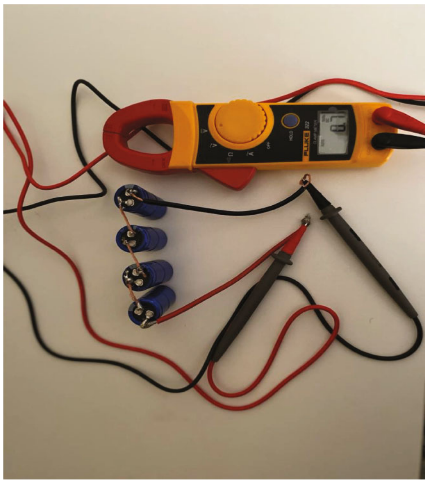


Figure 12: SC voltage before charging (photo taken during experimental setup by the authors).

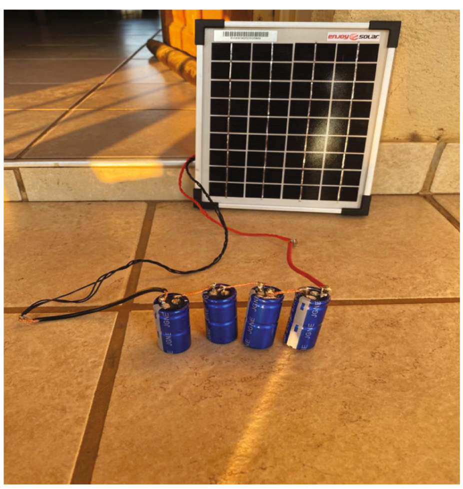


Figure 13: Charging of supercapacitors using a 5 W solar panel (photo taken during experimental setup by the authors).

Figure 14: Output of SC after charging (photo taken during experimental setup by the authors).

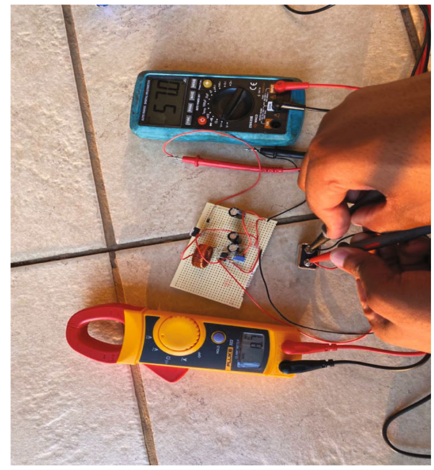


Figure 15: Boost converter test: input 8.7 V with an output of 57 V (photo taken during experimental setup by the authors).

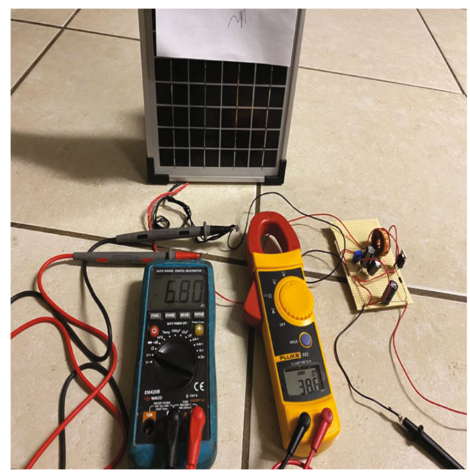


Figure 16: 50% solar output connection (photo taken during experimental setup by the authors).

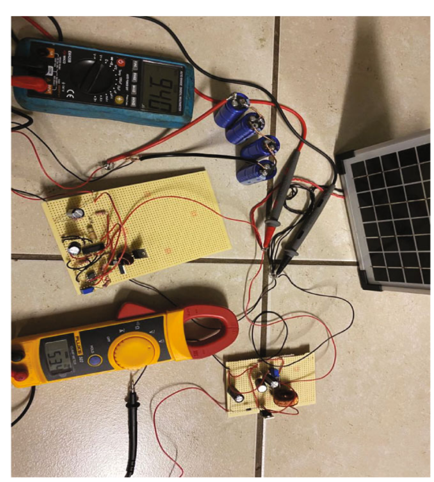


Figure 17: Integration of supercapacitors with boost and bidirectional converter (photo taken during experimental setup by the authors).

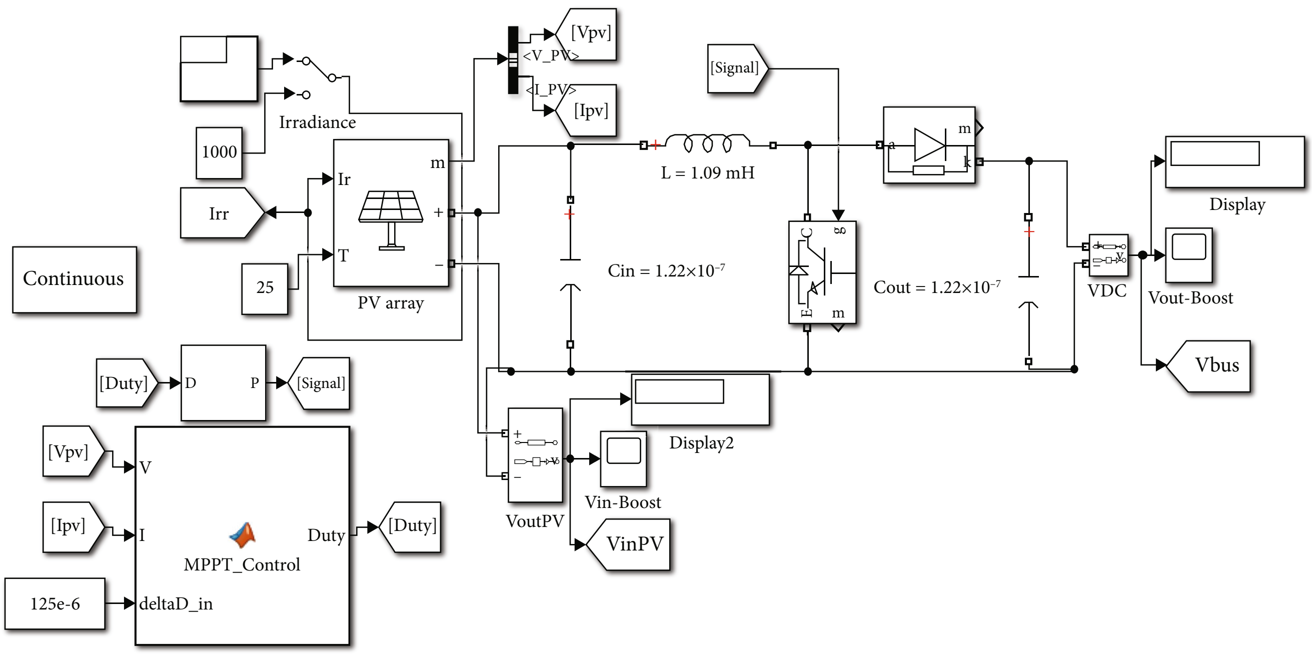


Figure 18: Clear representation of Figure 3 (design using MATLAB).

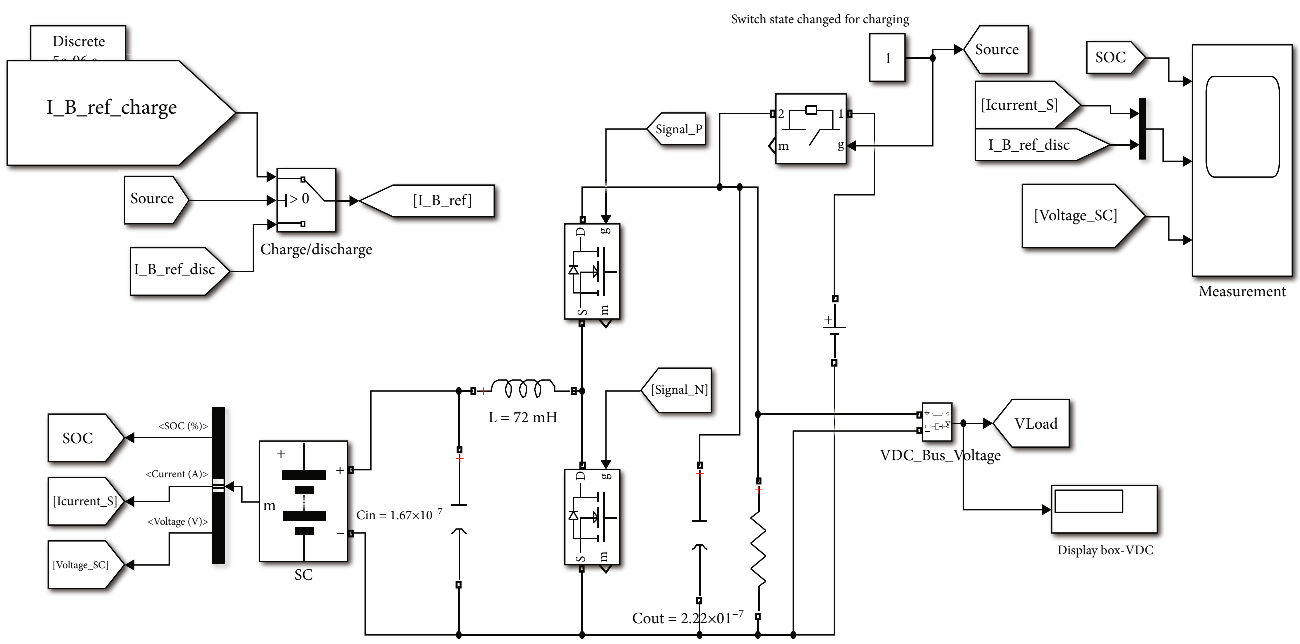


Figure 19: Clear representation of Figure 4 (design using MATLAB).

8.7 V input is induced from an external source (9 V battery), and the voltage is boosted by a factor of 5 to a total of 57.0 V as seen in Figure 15. Energy from the solar panel is sent to the boost converter which is connected to the output clamp meter. A scenario was created to validate the impact of fluctuation, and almost half of the panel was covered with a piece of paper which reduced the output of the solar panel to 6.8 V which resulted in the boosted voltage dropping by 15 V. A charged bank of the supercapacitor is connected to the buck-boost converter which supplements the required energy when the output from the solar fluctuates as seen in Figure 16. The simulation theory that supercapacitors integrated with renewable energy can manage output fluctuations and improve energy output is seen when the integrated system was connected while the paper covered half of the solar panel, and the results support the simulation modeling.

5. Conclusions

The paper analyzed supercapacitors in renewable energy systems to manage power fluctuations. The system makes up a

PV array connected to an energy storage system (supercapacitor). A stair generator is used to vary the input irradiance. Maximum power point tracking is used to track the maximum light from the solar. For the initial response of PV, a standalone system is being investigated, and the initial input irradiance is low, which causes the output voltage of the PV to be low. As a result, oscillations occur in the PV output, in turn, affecting the grid voltage. As time passes, the irradiance increases directly with the voltage sent to the grid.

However, when a sudden change occurs, a vast dip in fluctuation is noted. The integration of the supercapacitor is introduced to manage the dip and oscillation, as shown in Figure 10. The supercapacitor acts as a buffer when the irradiance is low, keeping the energy output when the voltage connected to the grid is low as shown in Figure 17. It supplies the required demand to stabilize the output of the voltage from PV. The generated DC is connected to the DC link via the boost and bidirectional converter. During normal operation, PV supplies the DC link. Under abnormal conditions, the supercapacitor is used to maintain and minimize fluctuations when there are sudden weather changes.

The advantages of the presented methodology are effective power sharing, rapid charge, and ripple limitations. MATLAB-Simulink-based simulation results have shown the validity of the proposed system. For future work, an analysis will be conducted in wind turbine generation to validate if a similar result is obtained, and further integration of different green energy systems will be investigated such as hydrogen.

Appendix

Figure 18 represents a clear version of Figure 3 (the boost converter integrated with PV array).

Figure 19 represents a clear version of Figure 4 (supercapacitor integrated with bidirectional converter).

Data Availability

The data presented in the study are available on request from the corresponding author.

Conflicts of Interest

The authors declare no conflict of interest.

Authors' Contributions

BM, BA, and CR provided the concept and designed the study. BM executed the design and testing with the guidance of BA and CR. BM, BA, and CR analyzed the results. BM, BA, and CR drafted the manuscript. Banele Mbendane, Bolanle Abe, and Coneth Richards conceptualized the study. Banele Mbendane and Coneth Richards contributed to the data curation. Banele Mbendane, Bolanle Abe, and Coneth Richards participated in formal analysis. Banele Mbendane and Bolanle Abe assisted in the investigation. Banele Mbendane, Bolanle Abe, and Coneth Richards contributed to the methodology. Bolanle Abe and Coneth Richards supervised the study. Banele Mbendane, Bolanle Abe, and Coneth Richards assisted in the validation. Banele Mbendane, Bolanle Abe, and Coneth Richards wrote the original draft. Banele Mbendane, Bolanle Abe, and Coneth Richards wrote, reviewed, and edited the manuscript. All authors have read and agreed to the published version of the manuscript.

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