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Power Smoothing Approach to Control Solar Photovoltaic Output Power Fluctuations Using a Supercapacitor Storage System

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Abstract: Non-linear power-voltage characteristics of Solar cell and frequently changing output power due to variation in solar irradiance caused by movement of clouds are the major issues need to be considered in photovoltaic penetration to maintain the power quality of the grid. In recent years several authors have developed the power smoothing approaches for solar photovoltaic system. This work proposes, a power smoothing control approach to smoothen out the power output variations of a Solar photovoltaic system using a supercapacitor energy storage device. Fuzzy logic - Proportional Integral (PI) charge controller are developed for Buck-Boost converter to deliver the constant current and suitable voltage for supercapacitor and to achieve better power smoothing. In this study, Boost converter is working as an MPPT converter to ensure the operation at available peak power point and the Fuzzy controller are developed for Boost converter switches to adjust the duty ratio of the Pulse-Width Modulation (PWM) generator. Three different case studies with variable irradiance and temperature are considered for this work and validated on mono-crystalline solar photovoltaic module. To confirm the accuracy of the proposed model comparison of results are studied by using three different case studies with and without the use of Energy Storage System (ESS). The proposed model is developed and examined on MATLAB/Simulink environment. Simulation outcomes shows that it can effectively smooth out the power output variations of the solar photovoltaic system.

Keywords: Power Smoothing Approach, Two-diode Photovoltaic Cell, Fuzzy Logic Controller, Supercapacitor Energy Storage device, Poly-crystalline solar cell, Electric double layer capacitor

1. Introduction

A. Motivation

Solar Photovoltaic (PV) power sources are gaining more popularity and are measured as one of the main resources of electrical power for distributed generation. In recent years the cost of photovoltaic cells is decreasing day by day, which helps to increase Photovoltaic penetration in electrical power generation. One of the major concerns is its dependence on solar irradiance and temperature which make these energy sources intermittent in nature. It is important for a solar PV system to always operates at its peak or maximum power point to increase efficiency and to maintain grid stability. Integration of intermittent power sources to the power grid causes the voltage flicker and reverse power flow, power quality issues, power conversion loss, and instability [1, 2]. Variations in ecological conditions and passage of cloud cover always affect the photovoltaic output power. The main factor which impacts the output power variations is the passage of cloud cover. These negative effects can be minimized by use of the supplementary sources like batteries, supercapacitors, fuel cells, and MPPT controllers. The most efficient and cost-effective storage devices are batteries and supercapacitors can increase global efficiency, be more reliable, reduces pollution, and improves system performance. Supercapacitor-based energy storage system are developed in [3, 4] to effectively smoothen out the power output variations of wind and solar PV system. Supercapacitors are measured as a supplementary device to conventional batteries for short-term duration energy storage purpose. Supercapacitors are mostly

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suitable in situations where quick charge and discharge cycles are essential for power levelling in Solar PV system. Energy storage technology is chosen according to current and future grid code necessities, supercapacitors are the best preferred storage devices for high power and low energy storage. The power smoothing control approach with a hybrid ESS is more beneficial in comparison to the single energy storage-based control approach by use of either battery or supercapacitor used for power output smoothing which improves the life span of storage devices [5]. A fuzzy-based approach with a Supercapacitor-ESS are developed for wind power leveling during the short-term grid instabilities, which shows better performance compared to conventional smoothing approaches [6]. ESS will help the distributed power generation networks to meet the peak demand for effective operation, to maintain the grid stability and reliability.

B. Literature Review

Many power smoothing strategies were developed for wind and solar photovoltaic systems are being of power smoothing approaches with the use of energy storage devices. Conventional and Converter control techniques are most frequently used smoothing technique for wind and solar power sources [7]. In recent years many authors have proposed various smoothing methods with and without the use of energy storage systems and also different optimization approaches to improve the consistency and effectiveness of the PV systems. The most recent intelligent optimization approaches, their key challenges, and main issues related to solar photovoltaic optimization are described in [8].

Ramp rate-based algorithms with a battery energy storage scheme are more advantageous to mitigate the power fluctuation problem with reduced size of energy storage capacity and increases its functioning life. However, this algorithm approach does not guarantee the ramp rate control within the acceptable limits [9]. Ramp rate control-exponential leveling approach with battery energy storage overcomes the limitations of moving average and conventional exponential smoothing approach it reduces the impact of memory effect, lesser the size of battery storage capacity and increases its life span and ensures the control within the desired limits [10].

Authors in [2] have presented a review on problems related to the intermittent energy sources, and techniques for smoothening of photovoltaic power output fluctuations using geographical dispersion, energy storage technologies: batter storage system, capacitor, EDLC, fuel cell, etc. Based on the comparative analysis the usage of efficient storage approaches like battery storage devices, capacitors and fuel cells are very effective in smoothing the photovoltaic output fluctuations [2].

So far, many MPPT algorithms have been proposed such as Perturb & Observe technique, Incremental conductance technique, Hill climbing technique, Fuzzy logic controller technique, Extremum seeking control technique, etc. [11, 12, 13]. These techniques vary in terms of operating efficiency, design complexity, cost, number of sensors used, and performance of tracking under various environmental conditions. The fuzzy logic controller-based MPPT method is a very efficient and popular technique that responds quickly under varying climatic conditions and does not depends on any system constraints. Under partial-shading conditions, the Fuzzy logic-MPPT controller works quite effectively in tracking the maximum operating point value in very less tracking time [12, 14]. Although Perturb and observe method is very simple to implement, and needs fewer computational constraints but it has the limitation of fluctuation around MPP even after the point has been tracked. Photovoltaic system with Fuzzy logic control – Firefly Algorithm with MPPT controller is proposed in [15] for tracking the maximum operating point with increased tracking speed and also improved accuracy in comparison to perturb and observe method.

Supercapacitors are having fast charge/discharge rates making them most attractive in those applications were to control the short-term variations in output power and not to store a high quantity of energy. Supercapacitors devices fill the gap among the batteries and conventional capacitors based on their specific power and energy rates [16]. Supercapacitors are best preferable for high charge and discharge rates in few seconds to minutes. Authors in [17] have developed a power leveling approach for solar and wind power systems with battery-supercapacitor-based energy storage to reduce the stresses on the battery and to increase its effective life span. Although these approaches have improved accuracy and its certain advantages the outcomes of the developed technique are not compared with the power smoothing approach without the use of ESS.

An optimal control approach [18] are proposed to maintain the system voltage with in the acceptable limits and to smooth out the power fluctuations of Solar photovoltaic system connected to distributed system. Fuzzy making decision predictive voltage-current controller are developed in [19] to regulate both the input current and Boost-inverter DC voltage in order to enhance the performance of Solar PV system.

Research on developing various power smoothing strategies especially soft computing-based approach for solar PV system is another scope need to be emphasized. In the literature some researchers had developed soft computing-based approach using Battery energy storage system for both wind energy and solar PV systems. So far, very few studies have been carried on soft computing-based approach using supercapacitor storage system for solar PV system [7]. In this study the power smoothing approach based on soft computing technique using supercapacitor energy storage system are developed to reduce the Solar PV power generation fluctuations. In the proposed work the accuracy of the power smoothing method is compared under different case studies with and without the use of a supercapacitor storage under the change in irradiance and temperature conditions.

C. Contribution

Energy storage systems and power smoothing methods plays an important role in mitigating the power output fluctuations of intermittent renewable energy resources. The main objective of this study is to propose a power smoothing control technique to smoothen out the output power fluctuations of the Solar photovoltaic system using an EDLC - supercapacitor energy storage device. The most crucial step is to control the maximum power operating point as it essential to attain the current, voltage and power curves of a photovoltaic module. A two-diode photovoltaic module was preferred in this study because of its accuracy and improved performance, especially at lower irradiance. In this work Fuzzy logic controller-Maximum power point tracking (FLC-MPPT) method are developed since it is a very efficient and popular technique that response quickly under varying ecological conditions, reduced computational complexity, and does not depends on any system constraints. For quick charging of supercapacitor with reducing losses, it requires the constant current and suitable voltage during charging. Fuzzy logic - Proportional Integral (PI) charge controller applied to Buck converter for providing constant current and controlled voltage to supercapacitor and to perform improved power smoothing. PI charge controller is preferred in this work as it offers better outcomes and is very simple to implement. The accuracy of the proposed system is confirmed by a comparison of the results for three different case studies with and without the use of a supercapacitor storage system under the change in irradiance and temperature conditions.

D. Orgination of Paper

This paper is systematized in the following manner: In the Section 2 the structure of proposed PV system and modeling of Two-diode model and EDLC supercapacitor are presented. Section 3 describes the design of DC-DC converter. Control strategies of proposed system are presented in Section 4. Proposed model simulation results with discussions are presented in Section 5 and Section 6 provides conclusions.

2. STRUCTURE OF PROPOSED SYSTEM AND MODELING

A. Photovoltaic Output Power Smoothing using Supercapacitor

Non-linear power-voltage characteristics of Solar cell and frequently changing output due to variation in solar irradiance caused by movement of clouds are the major issues need to be considered in photovoltaic penetration to maintain the power quality of the grid. The possible solution to smoothen these generation fluctuations is made use of an Electric Double-Layer Capacitor (EDLC) or Supercapacitor, which is an effective storage device for power smoothing applications. Fig.1 represents the schematic view of the proposed Solar Photovoltaic system with a supercapacitor as an energy buffer. Supercapacitors are mostly appropriate in situations where quick charge and discharge cycles are essential for power smoothing in a Solar PV systems. Boost converter embedded with the capability of MPPT algorithm is crucial to confirm that possible peak power is obtained from the solar PV system. The FLC-based MPPT controller by Boost converter is used for operating the PV panels at MPP. The working point of maximum available power of photovoltaic (PV) power generation varies with changes in irradiance and temperature conditions. It is an important aspect while designing an effective photovoltaic system to extract the peak power point appropriately. The key purpose of MPPT is to acquire available peak power from a photovoltaic system. For quick charging of supercapacitor with reducing losses, it requires the constant current and appropriate voltage during charging. A bidirectional DC-DC Converter with a charge controller provides the constant current and suitable voltage for the supercapacitor. Bidirectional DC-DC converter interfaces between grid and storage system must be capable to allow the power transfer in either direction i.e. input to load side or from load to input side. Fuzzy logic - Proportional Integral (PI) charge controller is used for Buck-Boost converter to charge the supercapacitor with constant current and suitable voltage to decrease losses, fast charge, and to achieve better power smoothing. A fuzzy controller is used to adjusting the power output of the supercapacitor energy storage device to ensure improved power smoothing. PI charge controller provides the suitable PWM signals to the switches of Buck-Boost converter for regulating the load voltage and to charge/discharge the supercapacitor. A novel control approach is proposed to smoothen out the power output fluctuations of the Solar photovoltaic system using EDLC - supercapacitor energy storage device.

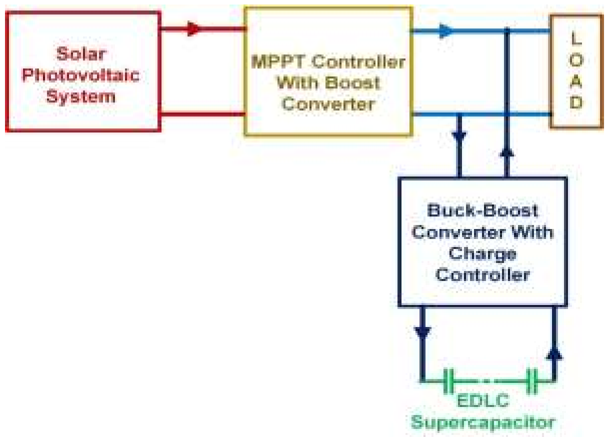


Figure 1 Schematic View of Proposed Solar PV System with ELDC Supercapacitor

B. Modeling of Two-Diode Photovoltaic Cell

The Two-Diode PV model is represented in Fig.2 [20]. The diode saturation current I_{DS2} and ideality factor C_2 are the added constraints essential to be measured. The effect of depletion region recombination loss compensates by diode current I_{DS2} [21].

By applying Kirchhoff's current law to Fig.3 as described in [22], expression for current I are expressed as:

$$I = I_{Ph} - I_{D1} - I_{D2} - \frac{V_0 + IR_{SE}}{R_{SH}} \quad (1)$$

Where

$$I_{D1} = I_{Ds1}[(e^{\frac{V_0 + IR_{SE}}{C_1 V_T N_{SE}}}) - 1]$$

$$I_{D2} = I_{Ds2}[(e^{\frac{V_0 + IR_{SE}}{C_2 V_T N_{SE}}}) - 1]$$

$$I_{SH} = \frac{V_0 + IR_{SE}}{R_{SH}}$$

$$I = I_{Ph} - I_{Ds1}[(e^{\frac{V_0 + IR_{SE}}{C_1 V_T N_{SE}}}) - 1] - I_{Ds2}[(e^{\frac{V_0 + IR_{SE}}{C_2 V_T N_{SE}}}) - 1] - \frac{V_0 + IR_{SE}}{R_{SH}} \quad (2)$$

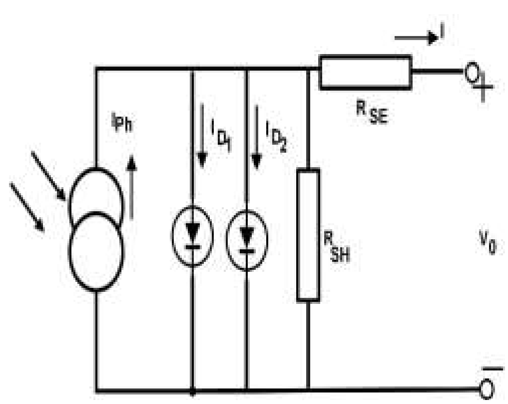


Figure 2 Equivalent Circuit of Two-Diode PV Cell

Also

Light or Photo current [23] is given by

$$I_{Ph} = (I_{SC} + \gamma_{SC}\Delta T_{Ac})\frac{G_{ir}}{G_{SC}} \quad (3)$$

$$I_{DS} = I_{DS1} = I_{DS2} = \frac{I_{SC}+\gamma_{SC}\Delta T_{Ac}}{(e^{\frac{V_0+\gamma_V\Delta T_{Ac}}{V_T}} -1)} \quad (4)$$

Where I_{Ph} is the Light or Photocurrent, I_{D1} and I_{D2} is diode current, I_{SH} is Current through R_{SH}, R_{SE} and R_{SH} are series and shunt connected resistances, V_0 is Applied voltage and I is module output current. I_{Ds1} and I_{Ds2} are diode reverse saturation current, C_1 and C_2 is Ideality factor of diode 1 and 2, N_{SE} is Series connected PV cells, V_T is called Thermal Voltage $= \frac{K\,T_{Ac}}{q}$, V_T is approximately 25.856 mV at 300 Kelvin, q is $(1.602\,X\,10^{-19})$ C is the electron charge, K – $(1.38\,X\,10^{-23})\,{}^{Joule}/_{Kelvin}$ is a Boltzmann constant, T_{Ac} is Cell's absolute temperature in Kelvin. G_{ir} – Irradiance in ${}^{W}/_{m^2}$, G_{SC} – Irradiance at Standard Test Condition (STC) = 1000 ${}^{W}/_{m^2}$, $\Delta T_{Ac} = T_{Ac} - T_{Ac,ref}$ (Kelvin), $T_{Ac,ref}$ – $(25 + 273 = 298\,Kelvin)$, I_{SC} is Cell's short circuit current at STC (25^0), γ_{SC} is current coefficient of temperature (A/K). γ_V –voltage coefficient of temperature (V/K). From equation (3) we can see that the current of the photovoltaic cells is constantly dependent upon the data of insolation and temperature.

The current-voltage curve of PV cell under the variation in irradiance and temperature conditions are shown in Fig. 3 and Fig. 4. The power-voltage curve of PV cell change in irradiance are illustrated in Fig. 5 and power-voltage curve of PV cell change in temperature are illustrated in Fig. 6.

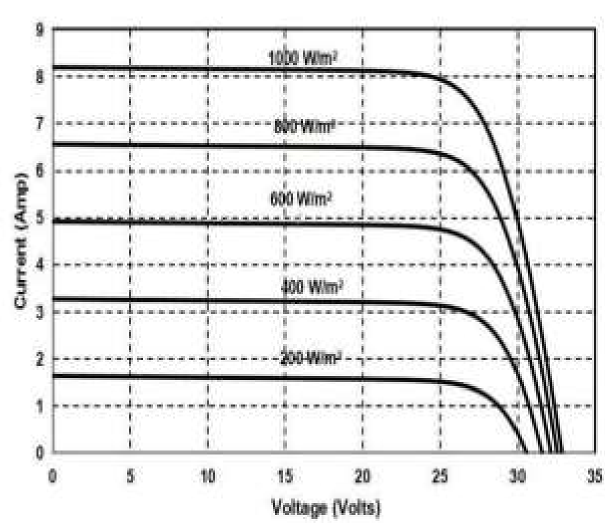


Figure 3 Current (A) Vs Voltage (V) Curve for Polycrystalline (Kyocera KC200GT) with different irradiance points at STC (25^0 C)

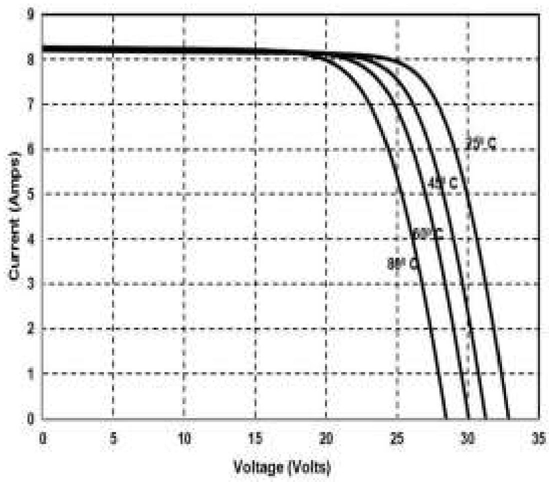


Figure 4 Current (A) Vs Voltage (V) Curve for Polycrystalline (Kyocera KC200GT) with different temperature points at STC (1000 W/m^2)

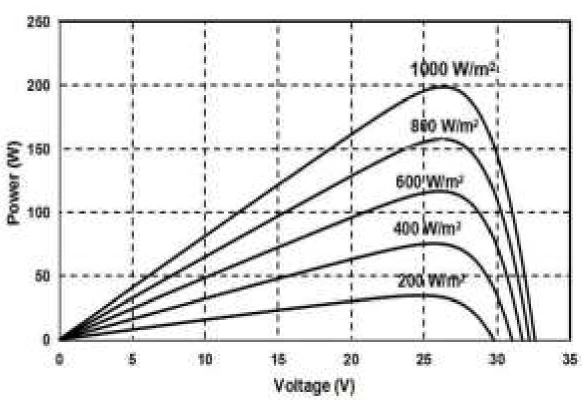


Figure 5 Power (W) Vs Voltage (V) Curve for Polycrystalline (Kyocera KC200GT) with different irradiance points at STC (25^0 C)

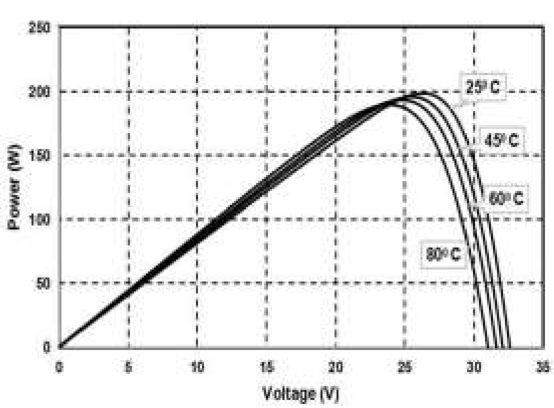


Figure 6 Power (W) Vs Voltage (V) Curve for Polycrystalline (Kyocera KC200GT) with different temperature points at STC (25^0 C)

Table 1 shows the Component Specifications of Poly-crystalline Kyocera KC200GT from manufacturer data sheet Table 2 shows the Estimated Values of Two-diode Photovoltaic Cell

Table 1 Component Specifications of Poly-crystalline Kyocera KC200GT from manufacturer datasheet

Constraints	**Poly-crystalline Kyocera KC200GT Solar Panel**
Maximum Power (P_{mpp})	200 W
Voltage at P_{mpp} (V_{mpp})	26.3 Volt
Current at P_{mpp} (I_{mpp})	7.61 Amp
Voltage at Open-circuit (V_o)	32.9 Volt
Current at Short-circuit (I_{SC})	8.21 Amp
Series Connected cell (N_{SE})	54
Irradiance at STC (G_{SC})	1000 W/m^2
Absolute Cell Temperature ($T_{Ac,ref}$)	298 Kelvin
Voltage Temperature coefficient (γ_v)	-123 mV/^{0}C
Current Temperature coefficient (γ_{SC})	0.65 mA/^{0}C

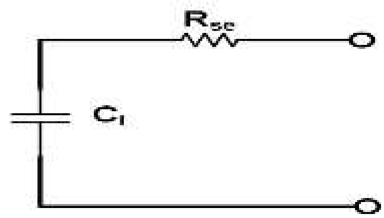
Table 2 Estimated Values of Two-diode Photovoltaic Cell

Constraints	**Poly-crystalline Kyocera KC200GT Solar Panel**
Maximum Power (P_{mpp})	200.11 W
Voltage at P_{mpp} (V_{mpp})	26.32 Volt
Current at P_{mpp} (I_{mpp})	7.603 Amp
Voltage at Open-circuit (V_o)	32.89 Volt
Current at Short-circuit (I_{SC})	8.211 Amp
Light Current (I_{Ph})	8.21 Amp
Saturation Currents ($I_{DS1} = I_{DS2}$)	4.073 x 10^{-10} Amp
Ideality Factor (C)	$C_2 = 1.3$
Series Resistance (R_{SE})	0.32 Ω
Shunt Resistance (R_{SH})	300 Ω

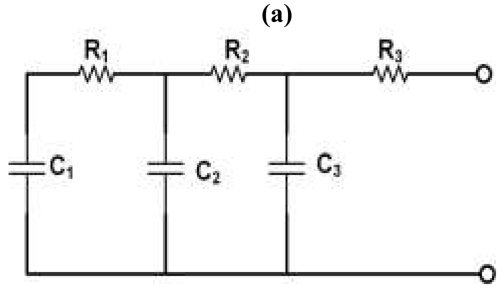
C. Electric double-layer Capacitor (or EDLC Supercapacitor) Modeling

In 1853 the electric double layer phenomena are first characterized by Helmholtz and patented by Howard I. Becker (GEC New York) in 1957. A low voltage large capacitance electrolyte capacitor made of carbon electrodes materials that can be able to withstand short circuits for infinite periods [24]. The physical structure of a supercapacitor consists of two electrodes and anionic membrane separator placed among them. Usually, electrodes are made up of activated carbon, Nanotubes, or graphene-based on their structural behavior. Electric double-layer capacitor is often called an EDLC supercapacitor (EDLC-SC). These are most extensively used and commercially existing in the market. Most of the EDLC-SC are formed by using a liquid electrolytic solution. When the supercapacitor is charged the electrons tend to move from positive to the negative electrodes with an applied field, thus oppositely-natured ions from electrolytic solution and electrodes form a structure of electric double-layer [16]. Supercapacitors are the most significant storage device to overcome the power gust in the wind energy systems and to smoothen out the power fluctuations in solar PV power.

Fig. 7 illustrates the Basic and Distributed circuit model of the EDLC supercapacitor [25]. In general, the distributed EDLC model is considered for use in power electronic simulations is shown in Fig. 7(b). The internal constraints of distributed model are estimated by the procedure as described in [25]. Table 3 shows Distributed model parameters of EDLC. For this study the EDLNF104A5R5C: 5.5 V, 10 F EDLC supercapacitor unit is preferred.



(a)



(b)

Figure 7 Electrical Equivalent Circuit of EDLC-Supercapacitor (a) Basic Equivalent Circuit Model (b) Distributed Equivalent Circuit Model

Table 3 Distributed EDLC Model Parameters

Capacitance (F)		Internal Resistance (Ω)	
C_1	0.02	R_1	1.2
C_2	0.5	R_2	30
C_3	0.48	R_3	28.8

3. Design of DC-DC Converters

DC-DC converter circuits varies the DC voltage from one level to another, which may be higher or lower and temporarily stores some input energy and then later releases this energy to load. It stores the energy in either magnetic field energy elements like inductor or electric field energy elements like a capacitor. These converters employ the pulse-width modulation (PWM) technique with fixed switching frequency for achieving the regulated output voltages and solid-state switching devices like power transistors, MOSFET or IGBT's. DC-DC converter gaining more attention in various applications like renewable energy systems, telecommunication, battery charging/discharging. MPPT controller with DC-DC converter is crucial to confirm that possible peak power is extracted from the photovoltaic system [26].

A. Boost Converter

The most common DC-DC converter used for the MPPT algorithm is the Boost converter owing to its maximum energy transfer capability. The design technique of the converter involves the estimation of parameters used for the MPPT converter. The extraction of these parameters is very important to operate the converter in continuous conduction mode and to reduce the voltage ripples. It is significant to select the value of parameters of the MPPT Boost converter as low as possible to maintain the operating point at maximum available power [27]. Boost converter is working as an MPPT converter to ensure the operation at available peak power point and FLC is used for Boost converter switches to regulate the duty ratio of the PWM generator [28].

Fig.8 demonstrates the Basic circuit of the Boost-converter [29]. It is a low-high voltage DC-DC converter and constantly provides the load voltage is higher than the source voltage. When switch S_2 is turned On, during $0 < t < DT_S$ inductor starts charging through input supply, diode D_1 is in reverse biased and capacitor maintains the output voltage as constant. When switch S_2 is turned Off, during $DT_S < t < T_S$ diode D_1 starts conducting both the energy stored in the inductor and supply voltage will deliver the energy to the load and also charges the output capacitor.

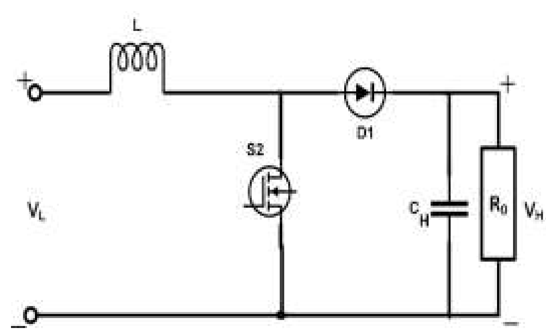


Figure 8. Basic Topology of Boost Converter

Assuming that converter is operating under continuous current-conduction. The average value of the load voltage equation is given by equation (5)

$$V_H = \frac{V_L}{(1-D)} \tag{5}$$

Inductor selection

The inductance is determined by the allowed current ripple at maximum voltage [29] and is given by equation (6)

$$L = \frac{R_0 D(1-D)^2}{2f_s} \quad (6)$$

Output Capacitor Selection

The output capacitance is estimated by the allowed ripple of load voltage [29] and is given by equation (7)

$$C_H = \frac{V_H D}{\Delta V_H R_0 f_s} \quad (7)$$

Where V_L is low (input) voltage, V_H is high (output) voltage, D – duty ratio, T_s – switching time, f_s – switching time-frequency, ΔV_H – allowed ripple in load voltage, C_H – capacitor (high voltage side).

The optimum value of output resistance R_0 of MPPT Boost converter can be determined by the procedure as described in [27]. For a lossless system, the load power and input power will be equal as shown in equation (8)

$$\frac{V_{mpp}^2}{R_{mpp}} = \frac{V_0^2}{R_0} = \frac{\left[\frac{V_{mpp}}{1-D}\right]^2}{R_0} \quad (8)$$

Where V_{mpp} is a voltage at MPP, R_{mpp} is resistance at MPP, V_0 is load voltage, R_0 is output resistance, D is duty ratio. By simplifying equation (8) we can obtain a relation for R_0 as shown in equation (9)

$$R_0 = \frac{R_{mpp}}{(1-D)^2} \quad (9)$$

From equation (9) we can write the modified equation for duty ratio as

$$D = 1 - \sqrt{\frac{R_{mpp}}{R_0}} \quad (10)$$

The specific range of R_0 are determined by using equation (9) for various values of D and R_{mpp} for ensuring a smooth operating point of maximum power. The parameters of the Boost converter are determined with equations (5), (6), and (7). Estimated values of Boost Converter are represented in Table 4.

Table 4 Estimated values of Boost Converter

Constraints	Values
Duty Ratio (D)	0.557
Boost Inductor (L)	66.13 µH
Capacitor (C_H)	1.841 mF
Load Current (I_0)	1.986 A
Resistance (R_{mpp})	4.75 Ω
Load Resistance (R_0)	24.2 Ω

B. Buck-Boost Converter

Most of the DC-DC converter permits power transfer only in a single direction, from the input to the load side. The elementary Buck and Boost DC-DC converter structure does not have the capability to allow power transfer in either direction due to the presence of a diode in its structure. However, all switching power regulators can be made bidirectional which allows power transfer in either direction i.e. input to load side or from load to input side by replacing all diodes with controllable switches. Bidirectional DC-DC converter interfaces between grid and storage system must be capable to allow the power transfer in either direction i.e. input to load side or from load to input side. Fig.9 illustrates the outline of a bidirectional buck-boost converter with a two-switch topology [4]. The converter represented in Fig.9 can be operated in two modes, Buck mode transfers energy to charge supercapacitor and in the Boost mode demanding energy from the supercapacitor. In Buck mode, it allows the power transfer from the low (source) side to the high (load) side. In Boost mode, it allows the power to flow from the load (low) side to the source (high) side.

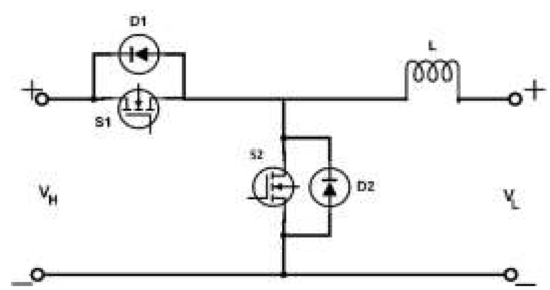


Figure 9 Outline of Bidirectional Buck-Boost Converter

C. Buck Converter

Fig.10 illustrates the basic topology of the Buck converter derived from Fig.9. Buck converter is a High to Low voltage DC-DC converter. It continuously offers the load voltage lesser than the source voltage. During $0 < t < DT_S$, switch S_1 is kept on, inductor stores the energy and diode D_2 remain in reverse biased, energy will be delivered to the load. During $DT_S < t < T_S$, switch S_1 is turned Off diode D_2 is in forwarding bias freewheels the stored energy from inductor to load and capacitor maintains output voltage as constant. Fuzzy-PI controller is applied to Buck converter as a charge controller for providing constant current and controlled voltage to the supercapacitor.

Assuming that Buck converter is operating under continuous current-conduction. The average value of the load voltage equation is given by equation (11)

$$V_L = DV_H \quad (11)$$

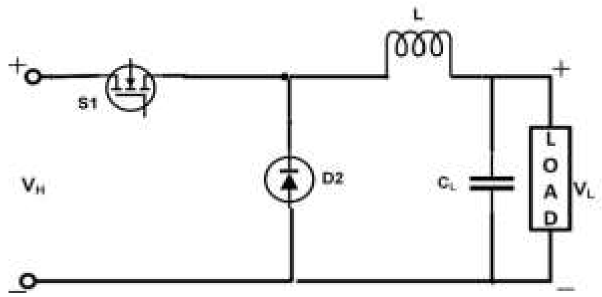


Figure 10 Basic Topology of Buck Converter

Inductor selection

The inductance of the Buck converter is determined by the allowed current ripple at maximum voltage [11] and is given by equation (12)

$$L = \frac{R_0(1-D)}{2f_s} \quad (12)$$

Output Capacitor Selection

The output capacitance of the Buck converter is estimated by the allowed ripple of load voltage and is given by equation (13)

$$C_L = \frac{V_L(1-D)}{8\Delta V_L L f_s} \quad (13)$$

Table 5 Estimated values of Buck Converter

Constraints	Values
Duty Ratio (D)	0.334
Buck Inductor (L)	66.13 µH
Capacitor (C_L)	3.734 mF
Load Current (I_0)	10 A
Output Resistance (R_C)	1.6 Ω

Where V_H is high (source) voltage, V_L is low (load) voltage, D is the duty cycle, T_s is the switching time period, f_s is switching time-frequency, ΔV_L is allowed ripple in load voltage, C_L is a capacitor (low voltage side). The constraints of the Buck-Boost converter are estimated by using equations (11), (12), and (13). Estimated values of Buck Converter are shown in Table 5.

4. Control Strategies for Proposed System

A. Fuzzy MPPT Controller

An MPPT is termed an electronic DC-DC converter which tracks the maximum available power output from the PV system. By regulating the duty ratio (D) of the converter we can achieve the maximum output power by matching the internal source resistance with the load resistance. Fuzzy MPPT controllers have been efficiently used in tracking the MPP of the photovoltaic systems because it is a very effective and popular technique that response quickly under varying ecological conditions, reduced computational complexity, and does not depends on any system constraints. FLC is the most crucial tool owing to its simplicity for linear and non-linear mechanisms. The operation of FLC includes three steps: Fuzzification, Rules inference, and Defuzzification. Mamdani approach is most popular for the fuzzification process. Two input functions to FLC is an Error (E) and Change in Error (CE) is given by Equation (14) and (15):

$$E(K) = \frac{\Delta P_{pv}}{\Delta V_{pv}} = \frac{P_{pv}(K) - P_{pv}(K-1)}{V_{pv}(K) - V_{pv}(K-1)} \quad (14)$$

$$CE(K) = E(K) - E(K-1) \quad (15)$$

Where $P_{pv}(K)$ and $V_{pv}(K)$ -power and voltage of photovoltaic cell and $P_{pv}(K-1)$ and $V_{pv}(K-1)$ - previous values of power and voltage of photovoltaic cell.

In this work variation in power (ΔP_{pv}) and variation in voltage (ΔV_{pv}) of PV modules are measured as inputs and duty ratio (D) are measured as the output of the fuzzy controller.

Table 6 Proposed Rules used for Fuzzy MPPT controller

E	CE						
	PH	**PM**	**PL**	**ZE**	**NL**	**NM**	**NH**
NH	ZE	NL	NM	NH	NH	NH	NH
NM	PL	ZE	NL	NM	NH	NH	NH
NL	PM	PL	ZE	NL	NM	NH	NH
ZE	PH	PM	PL	ZE	NL	NM	NH
PL	PH	PH	PM	PL	ZE	NL	NM
PM	PH	PH	PH	PM	PL	ZE	NL
PH	PH	PH	PH	PH	PM	PL	ZE

In general, there are different types of membership functions (MF) are used like Triangular, Trapezoidal, Symmetrical Gaussian, etc. In this study, Triangular and Trapezoidal MF are considered for fuzzy membership function. These fuzzy MF have preferred the linguistic variable by seven subsets as illustrated in Fig. 11, PH means positive high and NH means negative high. Moreover PM, NM, PL, NL, and ZE indicate positive and negative medium, low and zero. Consequently, a proposed set of 49 different fuzzy rules are given in Table 6. The centroid method is considered for the process of defuzzification. Fig. 12 illustrations the power-voltage characteristics of the photovoltaic cell. The operating area on this curve is divided into five different regions:

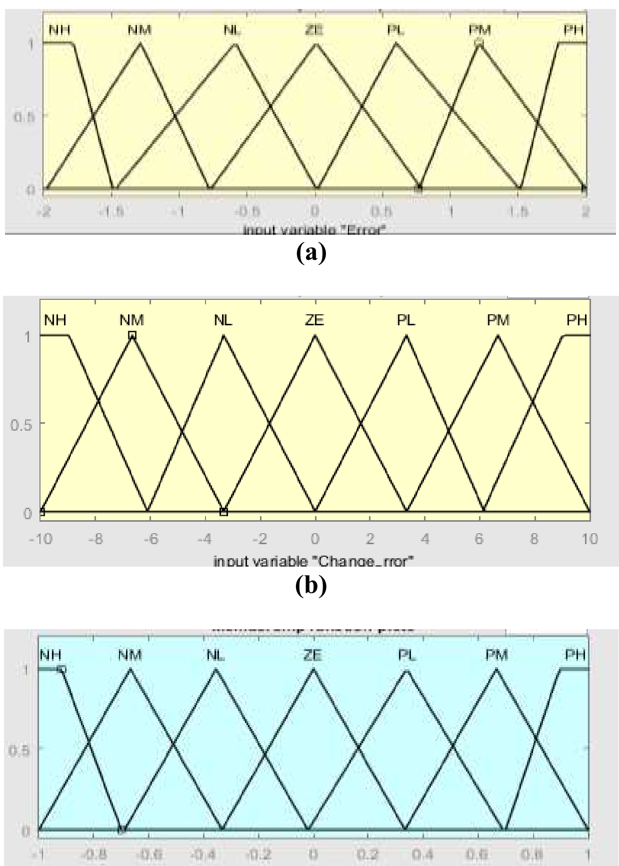
(1) When the change in power ($\Delta P_{pv} > 0$) is positive and ($\Delta V_{pv} > 0$) is positive, the voltage should be increased to reach maximum power point (MPP) (Red region-point A in Fig. 12).

(2) power ($\Delta P_{pv} > 0$) is positive and ($\Delta V_{pv} < 0$) is negative, the voltage should be decreased to reach MPP (Yellow region-point B in Fig. 12).

(3) power ($\Delta P_{pv} < 0$) is negative and ($\Delta V_{pv} > 0$) is positive, the voltage should be decreased to reach MPP (Green region-point C in Fig. 12).

(4) power ($\Delta P_{pv} < 0$) is negative and ($\Delta V_{pv} < 0$) is negative, the voltage should be increased to reach MPP (Blue region-point D in Fig. 12).

(5) power ($\Delta P_{pv} = 0$) is zero and ($\Delta V_{pv} = 0$) is zero, the voltage should be remained constant (Orange portion-point E in Fig.12).



(a)

(b)

(c)

Figure 11 Fuzzy Membership Function (a) Error (E) input variable of fuzzy (b) Change in Error (CE) input variable of fuzzy and (c) Duty Ratio (D) output variable of fuzzy

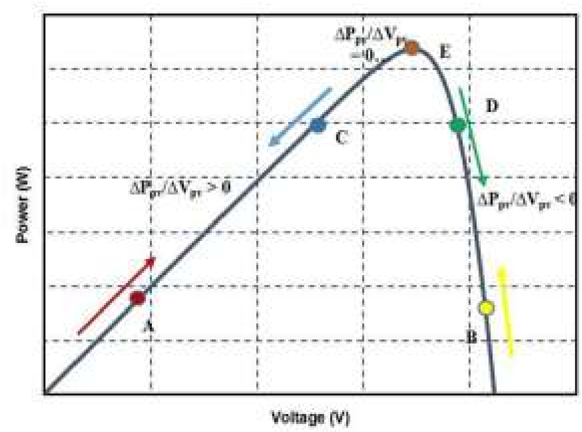


Figure 12 Power (W) Vs Voltage (V) Curve for MPPT Algorithm

From Fig.12 we can observe that when the operating point moves far away from peak point at portions A and B, a higher variation of voltage is essential to reach MPP and when the working point is nearer to MPP, a smaller variation of voltage is essential to reach MPP. Consequently, the proposed set of 49 fuzzy MPPT rules are presented in Table 6. Fig. 13 represents the Schematic view of the Fuzzy-MPPT controller and Fig. 14 represents the Simulink diagram of Fuzzy-MPPT controller. A fuzzy logic controller with a converter circuit will regulate the duty ratio to attain the peak output power by matching the internal source resistance with the load resistance.

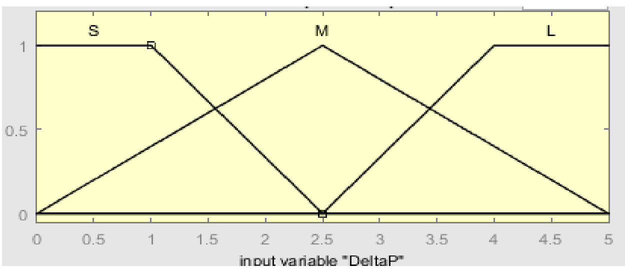
B. Charge Controller for EDLC Supercapacitor

A fuzzy controller is used to regulating the power output of the supercapacitor ($\boldsymbol{P_{sc}^{*}}$) to ensure improved power smoothing. The two inputs to the fuzzy controller are variation in power (ΔP) (i.e. the difference of Load power (P_{out}) and power output of PV panel (P_{pv})) and state of charge (SOC) and the output signal is the power output of supercapacitor energy storage device (P_{sc}^{*}). The state of charge of supercapacitors specifies the quantity of charge presently existing in supercapacitors. The fuzzy MF variables are represented in Fig. 15. The input ΔP has three fuzzy MF, i.e. Small (S), Medium (M), Large (L) as shown in Fig. 15 (a) and SOC is divided into five fuzzy MF as shown in Fig. 15 (b), i.e. Small Reserve (SR), Normal Small (NS), Normal Intermediate (NI), Normal Large (NL), Larger Reserve (LR). These variables are the combination of Triangular and Trapezoidal MF. NS, NI, and NL are considered as Triangular MF (between 0.05 to 0.95). SR and LR are considered as Trapezoidal MF (i.e. 0.05 to 0 and 0.95 to 1) to improve the performance of power smoothing. The output variable P_{sc}^{*} is divided into five fuzzy MF as shown in Fig. 15 (c), i.e. Very Small (VS), Small (S), Medium (M), Large (L), and Very

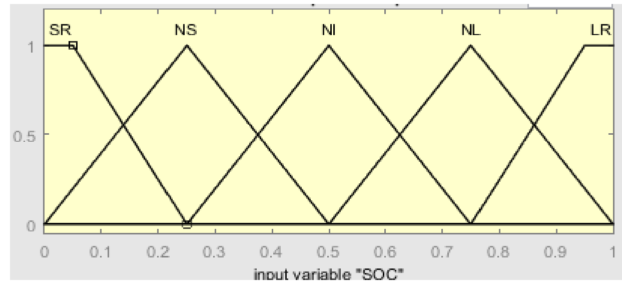
Large (VL). Consequently, a proposed set of 15 rules are shown in Table 7. The centroid method is used for the process of defuzzification

Table 7 Set of Proposed Fuzzy Rules used for a Charge controller

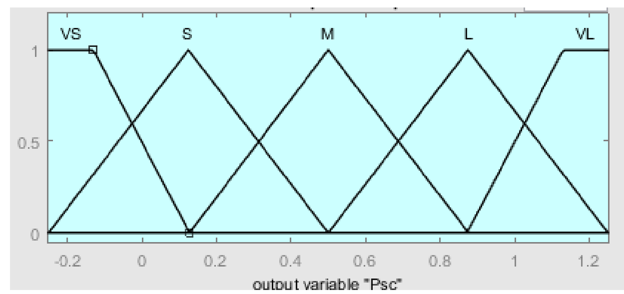
	SOC				
ΔP	**SR**	**NS**	**NI**	**NL**	**LR**
S	VS	S	M	L	L
M	VS	S	M	L	VL
L	S	S	M	L	VL



(a)



(b)



(c)

Figure 15 Membership functions (a) Power (ΔP) input variable of fuzzy (b) Supercapacitor State of charge (SOC) input variable of fuzzy and (c) Power (P_{sc}^{*}) output variable of fuzzy

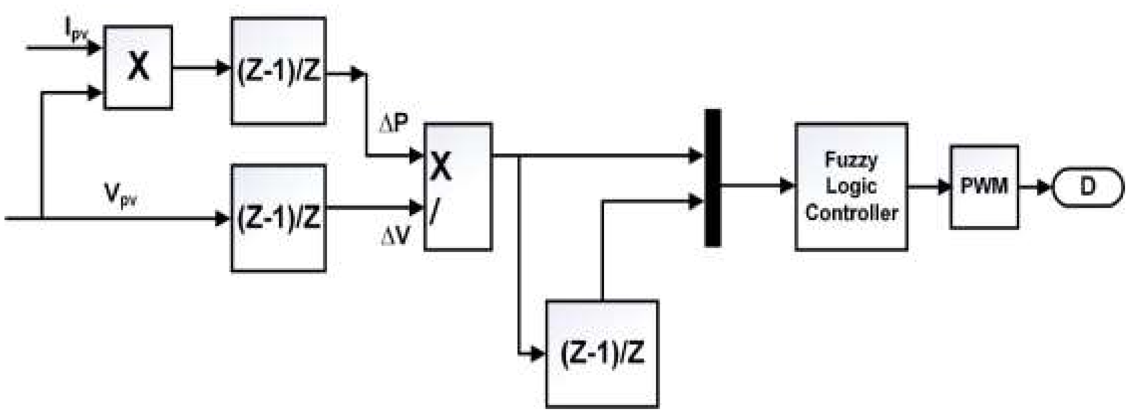


Figure 13 Schematic view of Fuzzy-MPPT Controller

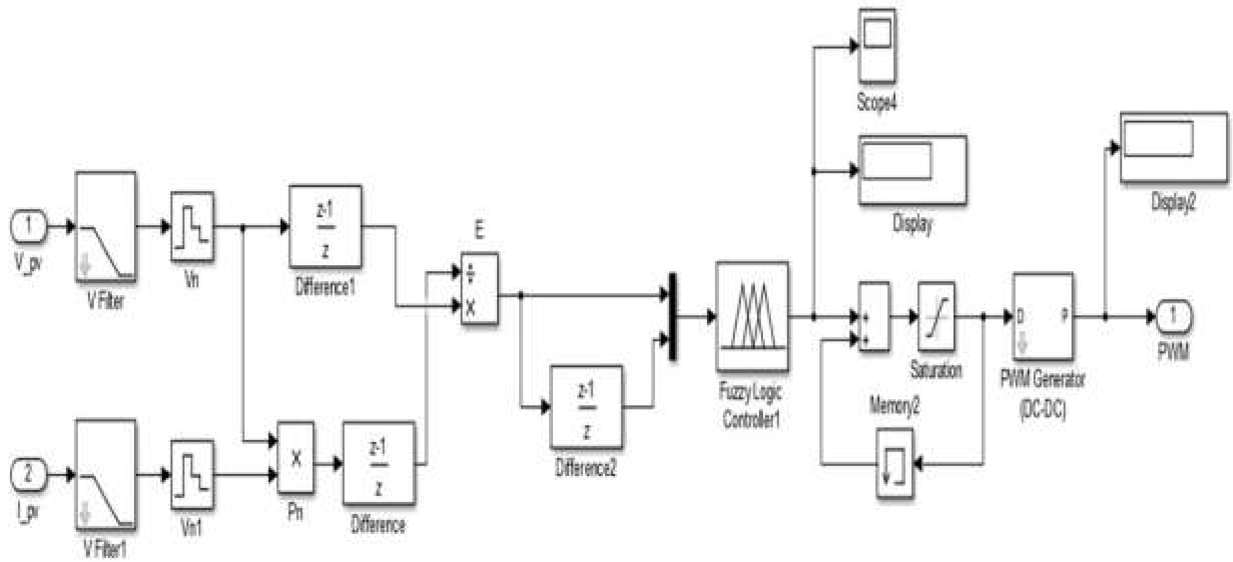


Figure 14 Fuzzy-MPPT Controller is Implemented in MATLAB/Simulink

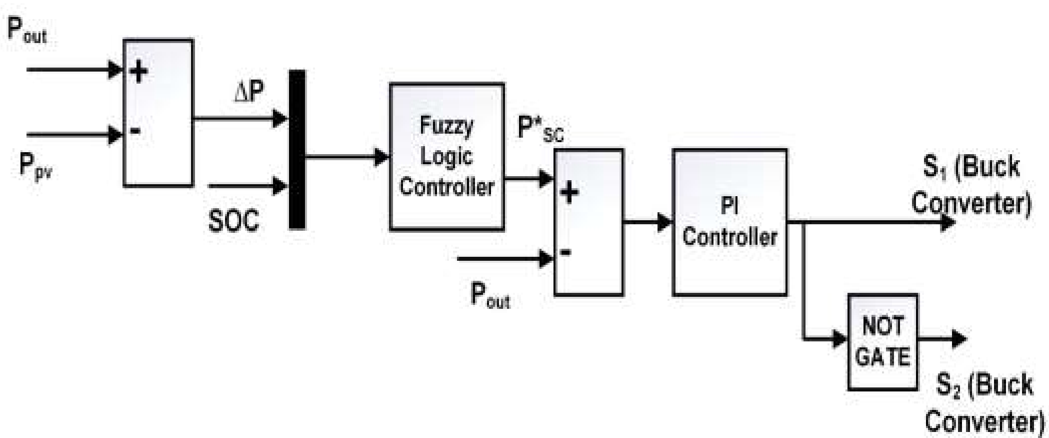


Figure 16 Proposed Power Smoothing Method based on Fuzzy-PI Controller

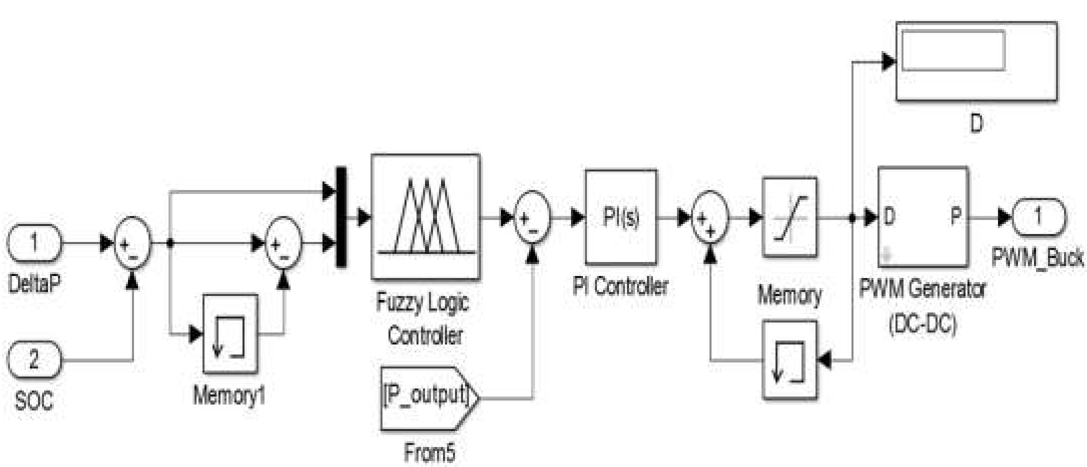


Figure 17 Fuzzy-PI Charge Controller is Implemented in MATLAB/Simulink

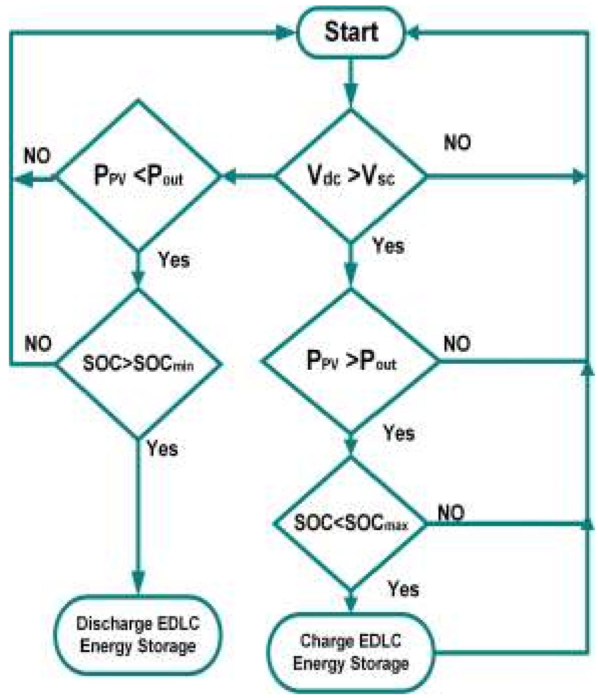


Figure 18 Flow Chart of Proposed Control Strategy for EDLC Energy Storage Device

PI controller is preferred in this work as it provides better results and is very easy to implement. PI controller consists of three constraints, namely proportional gain (K_P), Integral gain (K_I) and derivative time (T_U). Ziegler-Nichols approach is analyzed in MATLAB/Simulink environment to tune the values of K_P and K_I. By using the trail and error method the values of K_P and K_I is adjusted to produce the required output signals given for the Buck-Boost converter. The best values are chosen for K_P and K_I are 0.8 and 1. The input signal to the controller is a difference of power (power output of supercapacitor $(\boldsymbol{P}^*_{sc})$ and load power (P_{out})) and the output signal is providing suitable PWM signals to the switches of Buck-Boost converter for adjusting the load voltage and to charge/discharge the supercapacitor.

The main objective of power smoothing is to produce a power profile (P_{SC}) to mitigate the fluctuating power output of the panel (P_{pv}) and to generate the controlled changing power output $(P_{out} = P_{pv} + P_{SC})$. The State of Charge (SOC) is very crucial term for battery and supercapacitor storage devices which indicates the amount of charge stored in device. It is very significant to maintain the 50% SOC to maximize the effective power smoothing and for extensive operation of storage device [4].

The power smoothing method based on the Fuzzy-PI charge controller is shown in Fig. 16. Implementation of Fuzzy-PI charge controller in MATLAB/Simulink is represented in Fig. 17. The key purpose of Buck-Boost converter is to allow the power transfer between EDLC-supercapacitor and Solar PV system. Flow chart of proposed control strategy for EDLC energy storage device is demonstrated in Fig 18 [18]. When the PV output power of the panel (P_{pv}) is more than load power (P_{out}), the EDLC storage device gets charge by switching on the switch S_1, and switch S_2 is kept off (i.e. power flows from PV panel to energy storage side). When the P_{pv} is less than the P_{out}, the EDLC storage device gets discharged by switching on S_2, and switch S_1 is kept off (i.e. power flows from energy storage side to PV panel).

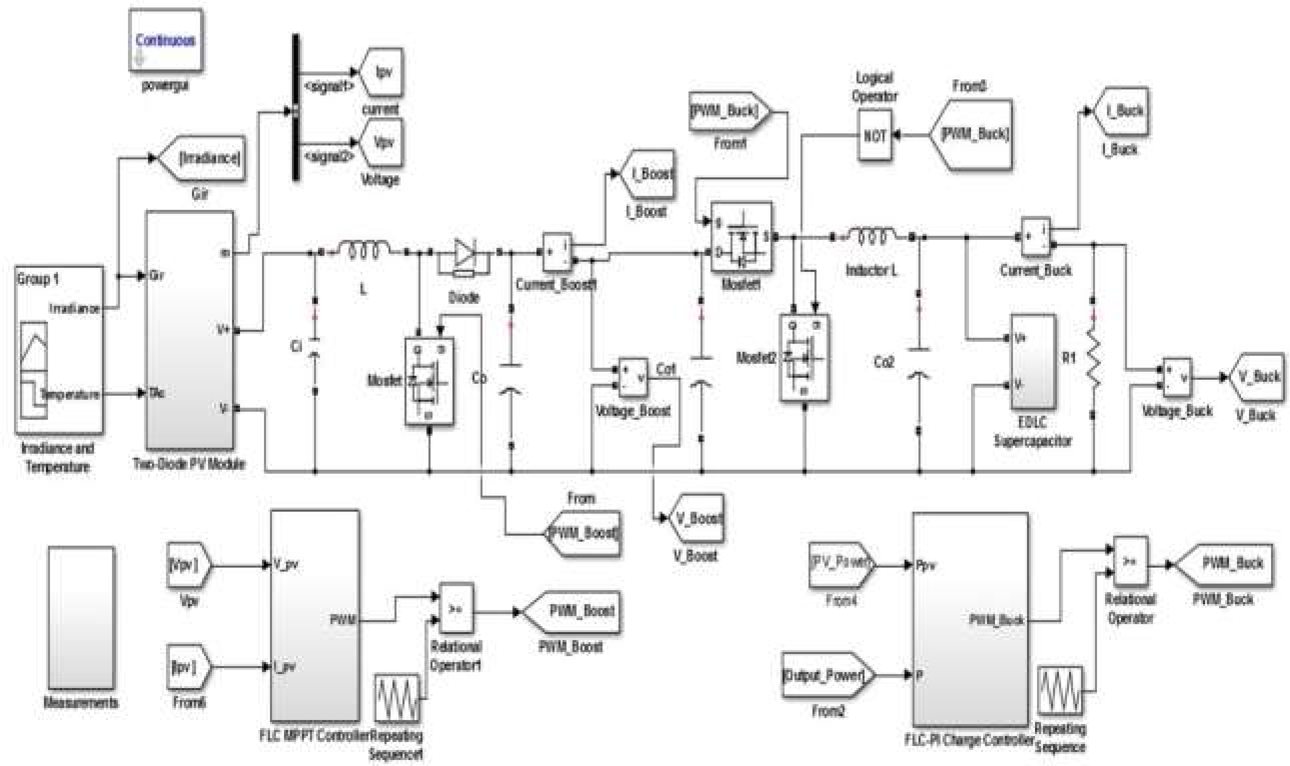
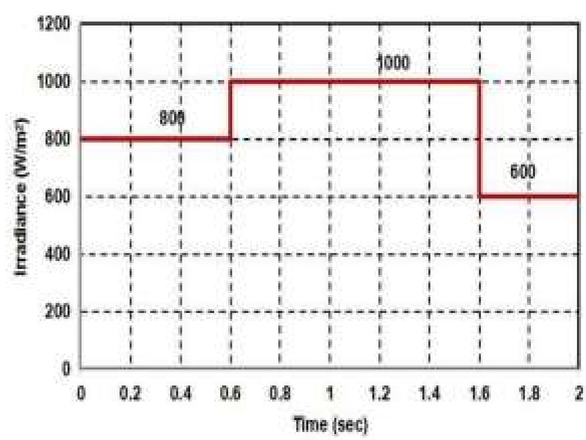


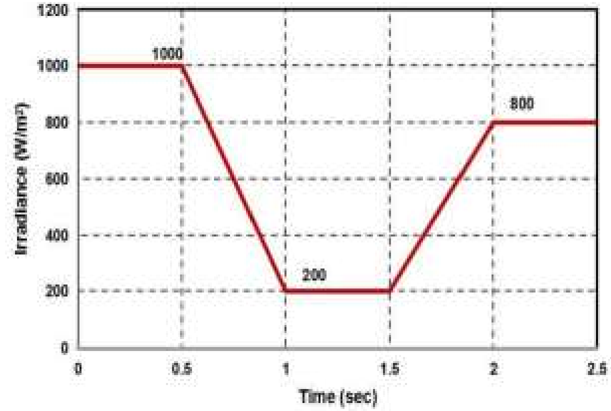
Figure 19 Proposed Solar Photovoltaic System with Supercapacitor Energy Storage is Implemented in MATLAB/Simulink

5. Results and DisCussion

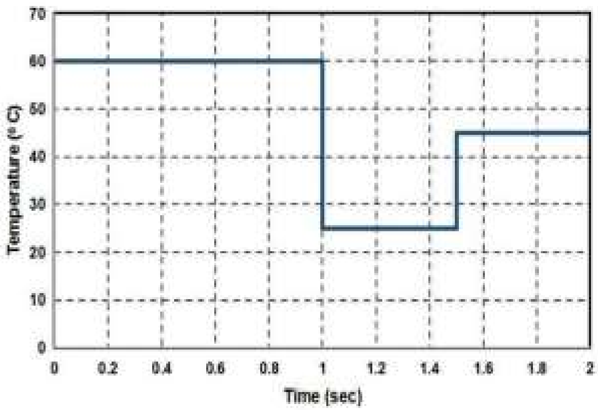
The proposed Solar Photovoltaic System with Supercapacitor Energy Storage under three different case studies have been developed in MATLAB/Simulink as demonstrated in Fig.19. For case study 1 the variable irradiance and temperature profile have been considered as shown in Fig. 20 (a) and (b). Output voltage and smoothed output power results are illustrated in Fig.21 and Fig. 22. Performance comparison between the PV output power with and without the use of supercapacitor under case study 1 profile are presented in Fig. 22. Similarly, for case profile 2 the different variable irradiance and temperature profile have been considered as shown in Fig. 23 (a) and (b). Output voltage and smoothed output power outcomes are demonstrated in Fig.24 and Fig. 25. Performance comparison between the PV output power with and without supercapacitor under case study 2 profile are shown in Fig. 25



(a)



(a)



(b)

Figure 20 Case Study 1 Profile: (a) Variable Irradiance (W/m^2) and (b) Variable Temperature (^{0}C)

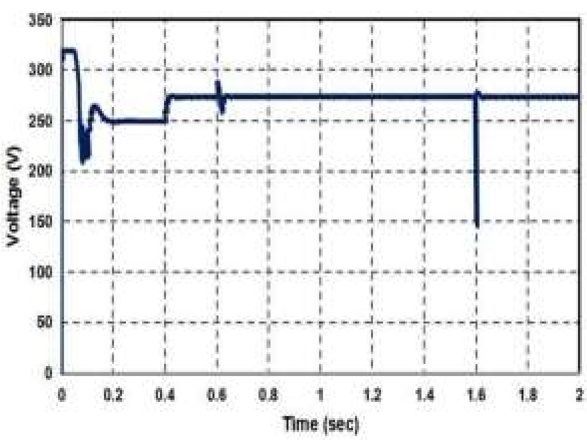


Figure 21 Voltage of Boost Converter under Case Study: 1

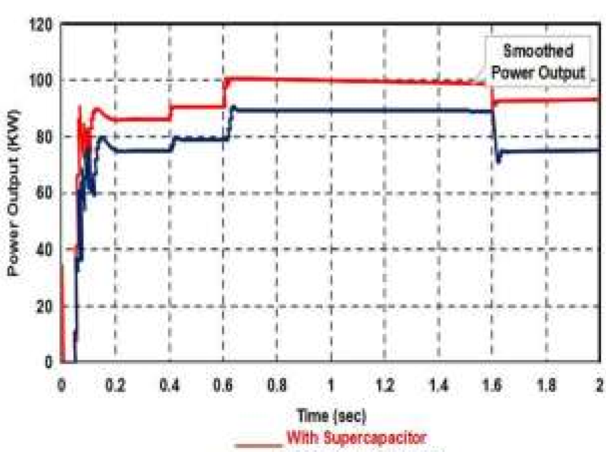
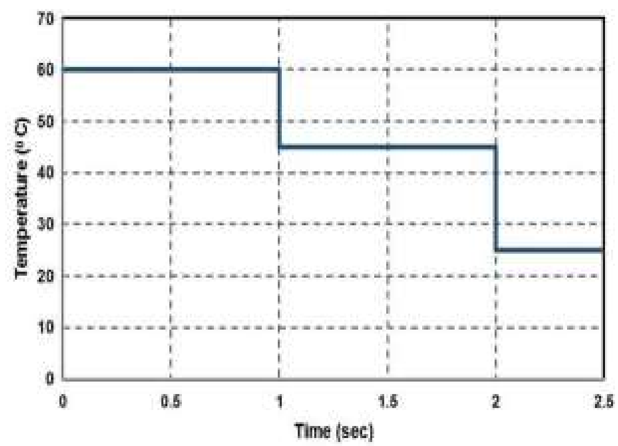


Figure 22 Case Study 1: Performance Comparison between PV power output and Smoothed Power Output



(b)

Figure 23 Case Study 2 Profile: (a) Variable Irradiance (W/m^2) and (b) Variable Temperature (^{0}C)

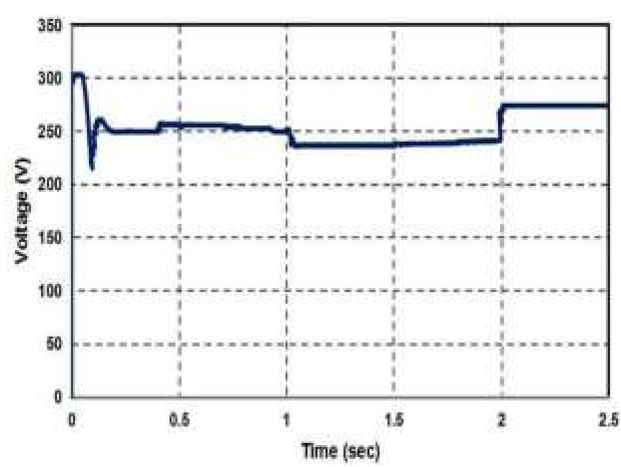


Figure 24 Voltage of Boost Converter under Case Study: 2

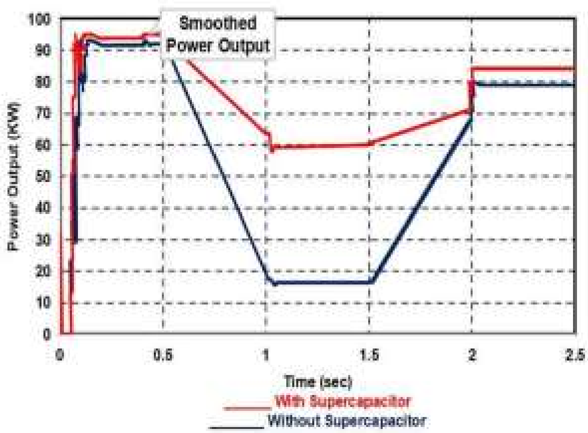


Figure 25 Case Study 2: Performance Comparison between PV power output and Smoothed Power Output

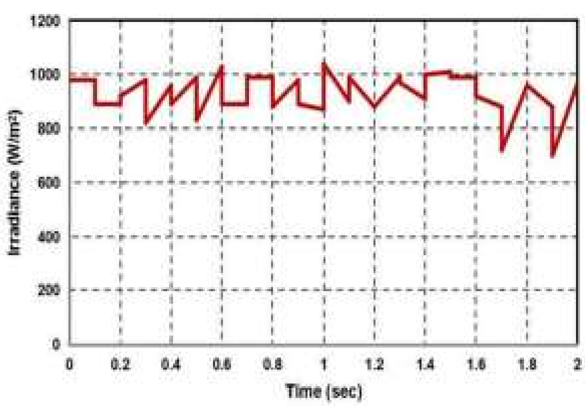


Figure 26 Case Study 3 Profile: Variable Irradiance (W/m^2) and Constant Temperature (25 ^{0}C)

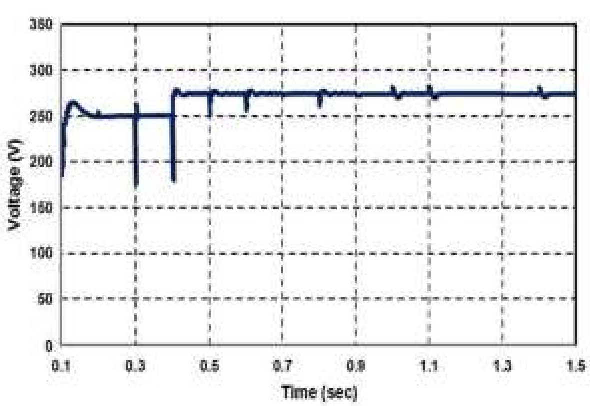


Figure 27 Voltage of Boost Converter under Case Study: 3

Table 8 illustrates the performance comparison between PV power output with and without the use of Supercapacitor energy storage device for different Case Studies. From Table 8 we can observe that with use of supercapacitor it shows the improved performance in smoothing of power output. From simulation results, we can observe that the proposed power smoothing control approach can efficiently smooth out the power variations under variable irradiance and temperature situations.

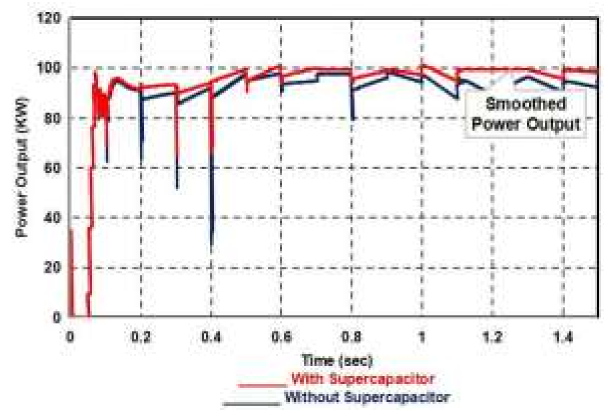


Figure 28 Case Study 3: Performance Comparison between PV power output and Smoothed Power Output

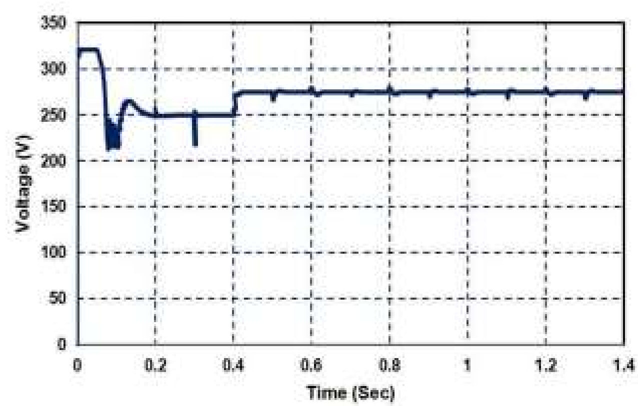


Figure 29 Case Study 3: Voltage Profile of Solar PV system with MPPT Controller

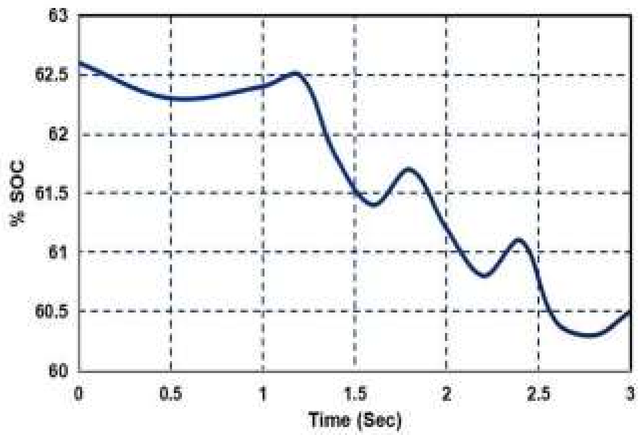


Figure 30: Case Study 3- Percentage SOC variation of Supercapacitor

Table 8 Performance Comparison between Power Output with and without Supercapacitor for different Case Studies

Case Study Profile	Variable Irradiance and Temperature	Power Output (KW) with Supercapacitor (P^*_{out})	Power Output (KW) without Supercapacitor (P_{out})
Case Study 1	800 W/m^2, 60 ^{0}C	87.6	74.3
	1000 W/m^2, 25 ^{0}C	100.07	91.2
	600 W/m^2, 45 ^{0}C	83.1	60.2
Case Study 2	1000 W/m^2, 60 ^{0}C	94.08	91.4
	200 W/m^2, 45 ^{0}C	59.6	16.3
	800 W/m^2, 25 ^{0}C	86.2	79.02
Case Study 3	Variable Irradiance and Constant Temperature (25 ^{0}C)	98.8 (Mean Value)	92.7 (Mean Value)

For case study 3 the variable irradiance and constant temperature of 25 ^{0}C profile have been considered as shown in Fig. 26. Output voltage and smoothed output power results are illustrated in Fig.27 and Fig.28. Performance comparison between the PV output power with and without the use of supercapacitor under case study 3 profile are represented in Fig. 28. Voltage profile of Solar PV module with varying irradiance under case study 3 are illustrated in Fig. 29. The variation of State of Charge (SOC) with time for supercapacitor storage device are illustrated in Fig. 30. In real time applications, percentage SOC should not reach less than 50% and consequently device will get charged when it goes beyond 50%.

Table 9: Performance Comparison based on SPVP for Smoothing Methods

Term	Smoothing Method	
	Conventional Converter Control	Proposed Method (Fuzzy based approach)
SPVP	9.02 %	2.81 %

The comparison of the smoothing methods is carried out through a term known as Smooth power varying percentage (SPVP) [7].

Smooth power varying percentage = $\frac{P_{Max} - P_{Min}}{P_{Rated}}$

P_{Max} and P_{Min} – maximum and minimum values of smooth power for a particular interval of time and P_{Rated} – rated power of PV system.

Performance comparison based on SPVP for conventional control method without energy storage and proposed method for case study 3 are given in Table 7.3. From Table 7.3 we can observe that the conventional converter control approach results in higher power variations compared to proposed method. The fuzzy-based control method provides relatively improved results with reduced power variations. From simulation results we can observe that the proposed smoothing control approach can effectively smooth out the power variations under variable irradiance and temperature situations.

CONCLUSION

In solar photovoltaic system the output power fluctuations are mainly caused due to change in irradiance and cloud passages. Integrating intermittent power sources to the grid impart challenges in several practical features like consistency, variation of power in the grid, voltage fluctuation, and frequency deviation. This study proposes, a power smoothing control approach to smoothen out the output variations of a Solar PV system using an EDLC-supercapacitor energy storage device. Fuzzy logic-based MPPT controller with Boost DC-DC converter is developed for operating the PV panels at MPP. Fuzzy logic - Proportional Integral (PI) charge controller is implemented with Buck-Boost converter to charge the supercapacitor with constant current and suitable voltage for fast charge and to achieve better power smoothing. The accuracy of the proposed method is confirmed by comparison of results for different case studies with and without the use of supercapacitor storage device under the change in irradiance and validated for a poly-crystalline photovoltaic module. To confirm the accuracy of the proposed approach the outcomes are compared with the conventional converter control approach based on SPVP. The proposed Solar Photovoltaic system with the use of supercapacitor storage can effectively work under partial shading conditions and efficiently smooth the output power variations of the PV system.

Nomenclature

PV	Photovoltaic
EDLC	Electric Double Layer Capacitor
MPPT	Maximum Power Point Tracking
STC	Standard Test Condition
PWM	Pulse Width Modulation
FLC	Fuzzy Logic Controller
MPP	Maximum Power Point
ESS	Energy Storage Systems
KCL	Kirchhoff's Current Law
PI	Proportional Integral
SOC	State of Charge
SPVP	Smooth Power Varying Percentage
P_{mpp}	Power at Maximum Power Point
V_{mpp}	Voltage at Maximum Power Point
I_{mpp}	Current at Maximum Power Point
P_{SC}	Power Output of ESS
P_{pv}	Power Output of PV Panel
P_{out}	Controlled Changing Power Output
V_o	Voltage at open circuit
I_{SC}	Current at short circuit
I_L	Light current
I_{DS}	Saturation currents

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