Maximum Power Extraction from PV System using fast and Robust Backstepping Controller

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Abstract

Maximum power point tracking (MPPT) plays a pivotal role in enhancing output power extracted from photovoltaic (PV) system. The major obstacle against MPPT is occurrence of undesired chattering and environmental variations, which may affect desire objective. Hence, in this paper, the objective of MPPT is fulfilled by using a non-linear Fast and Robust Backstepping based on sliding mode controller (FRBSMC), which has less rise time, fast convergence and robust enough against uncertainties and variations. For MPPT, a reference voltage is generated using neural network, which is tracked by proposed controller to confirm the accuracy and efficiency of aforementioned controller. To ensure the effectiveness of proposed control scheme, a comparison is carried with Backstepping sliding mode controller (BSMC), Backstepping controller (BSC) and Perturb and Observe (P&O) controllers. Simulation of the mentioned controller is done in Simulink/MATLAB.

Keywords: *Renewables, Photovoltaic, MPPT, Robust Backstepping, Converter.*

1. Introduction

About 80% of the world's energy demand is covered by coal, natural gas and oil, but the most accessible reserves are now being exhausted. These resources are also best in respect of cost, maintenance and environmental behavior [1]. The main preference of these resources over non-renewable energy resources is due to its clean and green nature. So, it is new era of research to utilize renewable energy resources which can give benefits to global environment [2].

Solar energy is the abundant, most prominent, inexhaustible, and clean as compared to the non-REs sources [3]. These sources rely on environmental conditions for power generation, such as temperature and irradiance [4]. The SE has become the prime area of active research due to the aforementioned features and characteristics. These PV systems can be installed in feasible sites for domestics as well as for commercial uses. Generally, PV systems are categorized in grid-connected (GC), stand-alone (SA) and hybrid systems. GC PV system synchronizes with conventional supply system, where hybrid PV system is composed of different sources of energies fed to one load or may be more [5]. The standalone PV (SAPV) system is the best to use for the areas which are far away from utility grids which are usually installed on the top of buildings and high places. These types of systems can generate power ranges from 1 to 100 kW.

The standalone PV system can be used both for AC as well as DC loads. For AC load, DC voltage is transformed into AC by using inverters. Usually, standalone PV system used at domestic scale is utilized for AC loads. While, in case of DC load, DC-DC conversion system is required to meet up the load beside this battery system is mandatory to store the excessive energy and also can be used as a backup source. The proposed SAPV system is composed of:

i. PV arrays, which generates electrical energy from sun by utilizing solar irradiance and temperature
ii. Buck-Boost converter to transform power
iii. Charge controller to generate pulse width modulation (PWM) signal
iv. A variable load connected across the system.

The major issue is the provision of power that is flawless in terms of harmonics and fluctuations [6]. Currently, most of the system depends upon the non-renewable energy resources. Though these resources fulfil the energy demands but they also add some harmful effects to environment, i.e., they generate harmful gases which deplete the ozone layer, beside this these resources depend upon the fossils fuels which are depleting rapidly [4]. Due to environmental concerns and the ending fossil fuels, researchers tend to create new energy resources that can overcome the environmental issues as well as has a long-lasting nature.

Non-renewable energy resources can't sustain for long time but nonconventional i.e., renewable energy sources like PV energy are non-vanishing and also environmental-friendly. Solar energy can be used with greater efficiency by using power electronic converters that transform power to consumers. With the aforementioned advantages of PV system, it also has a drawback of lower efficiency; usually it operates on 19% of efficiency, which is quite lower as compared to other resources of energy. It is very difficult to attain the maximum power point when the environmental variations are occurred. These variations may generate fluctuations and harmonics in output power. Hence, it is ever demanding to have such closed loop control mechanism that operates the system at optimal point, so that the environmental variations may not affect the output power. For this purpose, MPPT concept is merged, in which the PV panels operate at their best efficiency.

The purpose of MPPT controller is to bear the stresses of different climate conditions [7]. There are numbers of algorithms [8, 9, 10, 11], such as incremental inductance (IC), P&O, sliding mode, fuzzy logic etc. In this thesis our objective is focused on RB controller. This proposed technique is used to generate control pulses for switching of buck-boost converter to attain the MPPT by tracking the desire reference voltage, generated by neural network. The maximum power transfer is made possible by using buck-boost converter to the variable resistive load connected across it. Along environmental variations, fault conditions are also applied, because the main failure of PV system usually occurred due to fault in sensors and controller faults, hence the MPPT will also be performed under fault conditions. The proposed algorithm is robust in terms of fault case. The difficulty of nonlinear systems has been alleviated since the development of the Backstepping controller. These controllers are fast in terms of convergence and have improved rise and settling times, but they are not robust enough in the face of changing climate patterns such as irradiance and temperature. Hence, the sliding mode based controllers become the solution against the above-mentioned environmental uncertainties. Another unacceptable issue is the occurrence of chattering, so in this article, a fast and robust controller is proposed that is based on Backstepping controller, dealing with variations and uncertainties at a time. The main objective is to deal with MPPT under environmental as well as load variations and in the presence faults/uncertainties. Figure 1 is the general block diagram of proposed work.

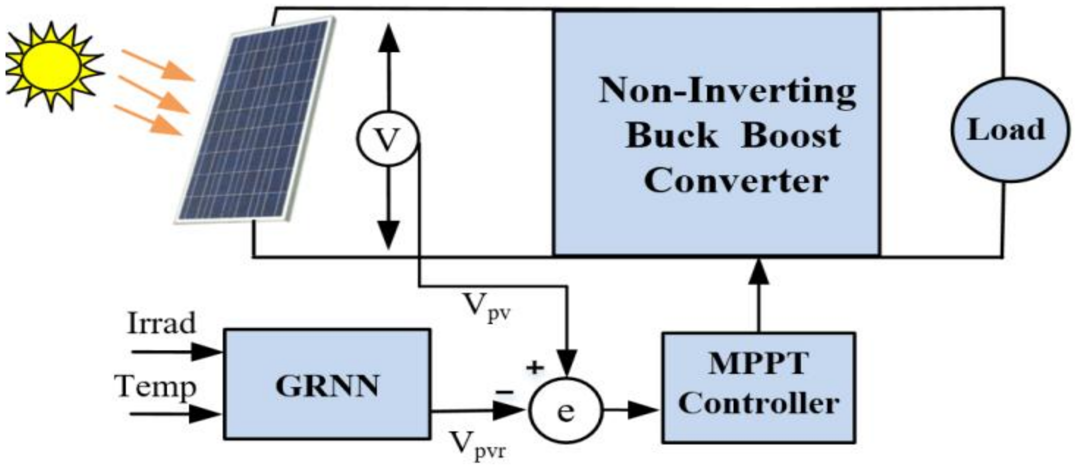

Figure 1: Block diagram of proposed work

The paper is assembled in the following way, Part II briefly explain the mathematical modelling of DC-DC non-inverted buck-boost converter. Reference voltage using GRNN is explained in Part III. Part IV shows making of proposed FRBSMC. Desired results with comparative study are explained in section V, while the paper is concluded with conclusion remarks in section VI.

1.1 Non inverted DC-DC buck-boost Converter (NBBC)

A NBBC is used to track the Vpv, to the desire reference voltage V_{ref} by continuously changing the duty switching, *u*, of the NBBC through a controller (MPP Tracker). A complete circuit diagram of PV panel along with NBBC and a variable load is shown in Figure 2.

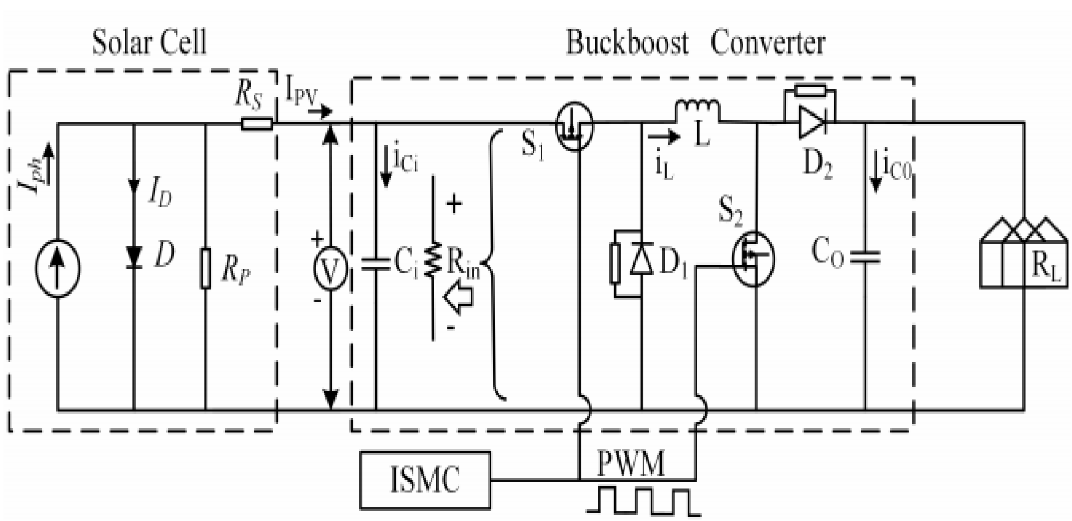

Figure 2: Complete PV system modeling

DC source voltage, V_{pv}, is obtained from PV panel, while two semiconductor switches S1 and S2 are used for controlling purpose, beside these, it consists of a two diodes, D_1 and D_2, an inductor, L, an input capacitor, C_i , output capacitor, C_0, and a variable load.

The mathematical modeling is done for the whole system shown in Figure 2. For this system the mathematical form is presented by following state space modeling equations. .

Figure 2 shows the entire PV system, which employs a buck-boost converter to get the desired maximum power from the PV panel. NBBC is working in two modes of operation, for which the desire equations are derived as follows:

$$\frac{dv_{pv}}{dt} = \frac{i_{pv}}{c_{in}} - \frac{i_L}{c_{in}}\mu \tag{1}$$

$$\frac{di_L}{dt} = \frac{v_{pv}}{L}\mu - \frac{v_o}{L}(1-\mu) \tag{2}$$

$$\frac{dv_{c_{out}}}{dt} = \frac{i_L}{c_{out}}(1-\mu) - \frac{v_o}{Rc_{out}} \tag{3}$$

Where V_{pv}, i_L, $V_{c_{out}}$ are the output voltages of PV array, inductor current and output capacitor (c_{out}) voltage. μ is the signal that controls the input. Averaging the model over one switching period for control design. Assuming that x_1 , x_2 , x_3 and u are average value of V_{pv} , i_L , $V_{c_{out}}$ and μ, respectively. The state space model is given by:

$$\dot{x_1} = \frac{I_{pv}}{c_{in}} - \frac{x_2}{c_{in}}u \tag{4}$$

$$\dot{x_2} = \frac{-x_3}{L} + \left(\frac{x_1+x_3}{L}\right)u \tag{5}$$

$$\dot{x_3} = \frac{x_2}{c_{out}} - \frac{x_3}{Rc_{out}} - \frac{x_2}{c_{out}}u \tag{6}$$

1.2 Reference Generation using Neural Network

Neural network (NN) is considered as fast and efficient method in artificial intelligence. NN are of different types, in which; Generalized regression neural network (GRNN) is used to train the obtained data from PV panel, this train data gives a specific reference termed as reference voltage. In this article, GRNN is used for its two benefits, i.e., better ability to predict and the ability to learn quickly. GRNN is modelled at many levels, such as with different sun irradiation (1000 W/m^2 - 650 W/m^2). Non-linear properties of PV panels provide training data for GRNN, which provide a reference level that is subsequently tracked by the controllers stated.

An input layer, a pattern layer, a summation layer, and an output layer make up the four layers of GRNN. Figure 3 depicts the general architecture of the GRNN and its layers. The generated reference voltage, on the other hand, is depicted in 3-D dimension in Figure 4. Proposed controller's design is summed up in next section which will explain its design to track the generated voltage reference through GRNN.

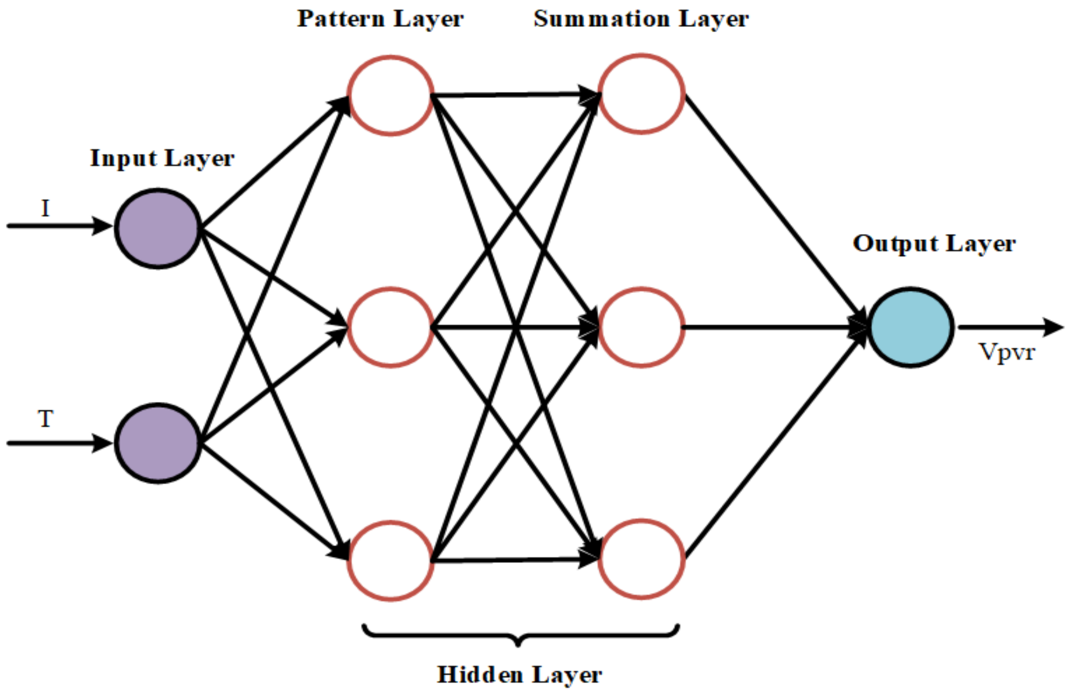

Figure 3 : GRNN

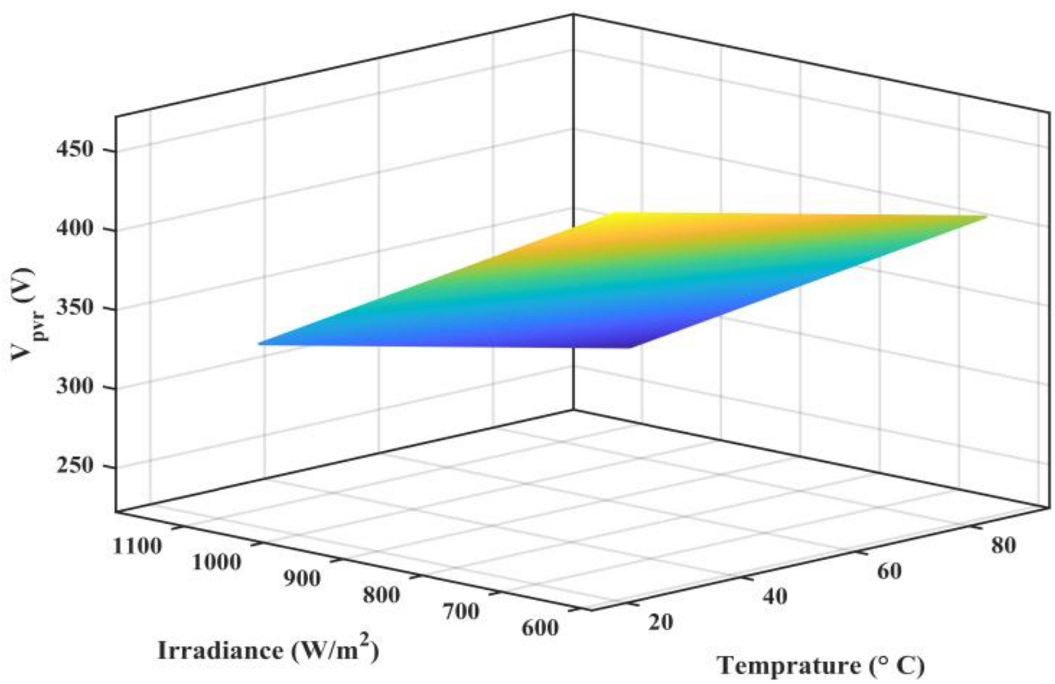

Figure 4: 3d plane of GRNN

2. FRBSC MPPT Controller Design

To get Maximum Power (MP) from a Photovoltaic system, a nonlinear FRBSMC controller is presented that controls the cycle of duty (D) of converter switches to monitor output voltage (V_{pv}) to reference voltages (V_{pvr}). The main purpose of FRBSMC is to change a PV system's state trajectory toward a sliding manifold or switching surface specified by a surface. To begin, identify the tracking error.

$$e_1 = x_1 - x_{1r} \tag{1}$$

Taking the derivative of (1),

$$\dot{e_1} = \frac{I_{pv}}{c_{in}} - \frac{x_2}{c_{in}} u - \dot{x_{1r}} \tag{2}$$

Now define the second error,

$$e_2 = x_2 - \beta \tag{3}$$

After that, rearrange the (2).

$$\dot{e_1} = \frac{I_{pv}}{c_{in}} - \frac{x_2+\beta}{c_{in}} u - \dot{x_{1r}} \tag{4}$$

Derivative of (3) along the replacement of 'β',

$$\dot{e_2} = -\frac{x_3}{\mathrm{L}} + u\left(\frac{x_1+x_3}{\mathrm{L}}\right) - \frac{1}{u}\left(-c_{in}\mathrm{k}_1^2 e_1 + \dot{I_{pv}} - c_{in}\ddot{x_{1r}}\right) + k_1 e_2 + \dot{u}\frac{\beta}{u} \qquad 5)$$

Sliding manifold is defined as follows while designing FRBSMC controller:

$$s = y_1 e_1 + e_2 \tag{6}$$

$$\dot{s} = y_1 \dot{e_1} + \dot{e_2} \tag{7}$$

Utilizing (2) and (5) in (7), we get

$$\dot{s} = y_1\left(\frac{I_{pv}}{c_{in}} - \frac{x_2}{c_{in}} u - \dot{x_{1r}}\right) - \frac{x_3}{\mathrm{L}} + u\left(\frac{x_1+x_3}{\mathrm{L}}\right) - \frac{1}{u}\left(-c_{in}\mathrm{k}_1^2 e_1 + \dot{I_{pv}} - c_{in}\ddot{x_{1r}}\right) + k_1 e_2 + \dot{u}\frac{\beta}{u} \tag{8}$$

To obtain equivalent control law, put '$\dot{s}$' equal to zero,

$$\dot{u_1} = -\frac{u}{\beta}\left[y_1\left(\frac{I_{pv}}{c_{in}} - \frac{x_2}{c_{in}} u - \dot{x_{1r}}\right) - \frac{x_3}{\mathrm{L}} + u\left(\frac{x_1+x_3}{\mathrm{L}}\right) - \frac{1}{u}\left(-c_{in}\mathrm{k}_1^2 e_1 + \dot{I_{pv}} - c_{in}\ddot{x_{1r}}\right) + k_1 e_2\right] \tag{9}$$

Eq. (9) is based on Backstepping controller, which is used in FRBSMC.

Define the discontinuous control law, which is based on sliding mode controller, as

$$\dot{u_2} = -k_2(s) - k sign(s) \tag{10}$$

Where constants, k and k_2 are greater than zero.

The total control law of FRBSMC is as follows:

$$\dot{u_t} = \dot{u_1} + \dot{u_2} \tag{11}$$

(11) is the sum of continuous control law, i.e., the Backstepping controller (9), and discontinuous control law (10), obtain from sliding mode controller.

After computing we get, FRBSMC as follows

$$\dot{u_t} = -\frac{u}{\beta}\left[y_1\left(\frac{I_{pv}}{c_{in}} - \frac{x_2}{c_{in}} u - \dot{x_{1r}}\right) - \frac{x_3}{\mathrm{L}} + u\left(\frac{x_1+x_3}{\mathrm{L}}\right) - \frac{1}{u}\left(-c_{in}\mathrm{k}_1^2 e_1 + \dot{I_{pv}} - c_{in}\ddot{x_{1r}}\right) + k_1 e_2\right] - k_2(s) - k sign(s) \tag{12}$$

3. Simulations Results

The performance of the designed control method, FRBSMC, on a PV array is tested using MATLAB/Simulink. The pulses are created using the proposed controller for controlling BBC switching. Tables 1 and 2 list all of the parameters used in this study. A desired reference is generated using GRNN to achieve the MPPT goal. Under non-variable and continuously changing environment conditions, the performance of the proposed controller is compared to that of regular methods such as BSMC, BSC and P&O. These controllers are presented recently in [18]. Figures 5, 6, and 7 show variable resistive loads and quickly changing climatic patterns. The simulations are divided into two groups i.e., Robustness against Environmental variation and robustness against fault and varying environmental as well as load variations.

Table 1: PV Array Parameters

S. No.	***Parameters Value***		
	Parameters	Symbol	Value
1	Numbers of PV modules	N_m	16
2	Numbers of series connected modules	N_s	4
3	Numbers of parallel connected modules	N_p	4
4	Cells per modules	N_c	72
5	Open circuit Voltage	V_{oc}	3.8 V
6	Short circuit Current	I_{sc}	3.56
7	Voltage at maximum power (MP)	V_{mpp}	3.6V
8	Current at MP	I_{mpp}	15.16 A
9	MP	$P_{max.}$	1555.4 W

Table 2: Parameters used in Simulation

S. No.	***Parameters Value***		
	Parameters	Symbol	Value
1	Gain	k	0.02
2	Gain	k_1	10
3	Gain	k_2	1000
4	Gain	y_1	400
5	Capacitor across input	c_{in}	1e-3 F
6	Inductor	L	0.5e-3 H
7	Capacitor across output	c_{out}	48e-6 F
8	Resistor across Load	R_1	50 *Ω*
9	Resistor across Load	R_2	100 *Ω*
10	Resistor across Load	R_3	150 *Ω*
13	Switching frequency	f_s	5000 Hz

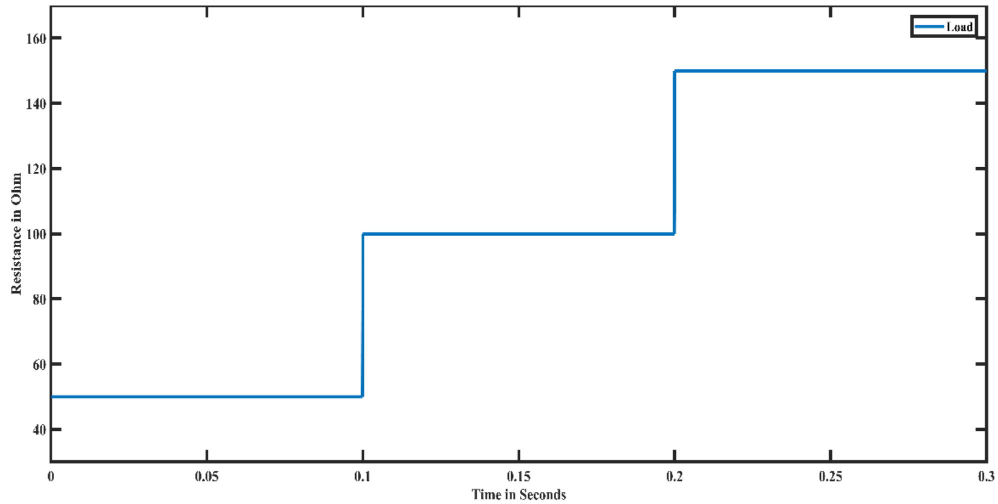

Figure 5: Load profiles

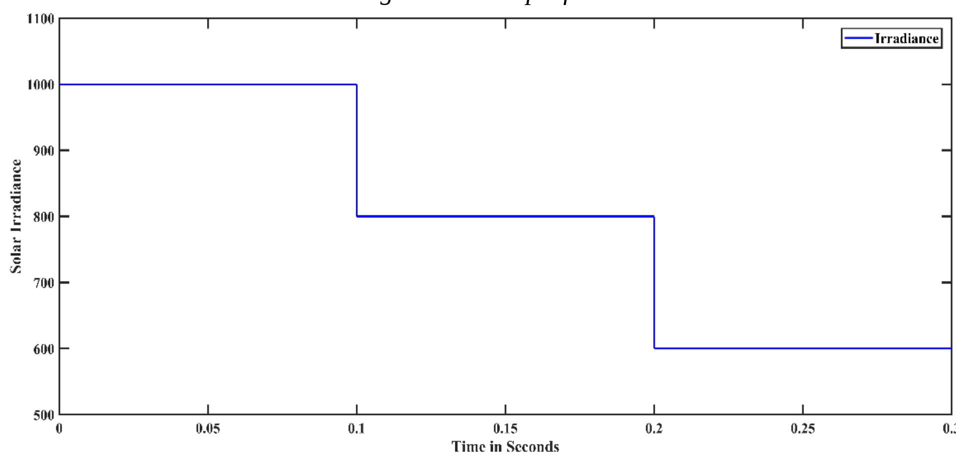

Figure 6: Varying irradiance levels

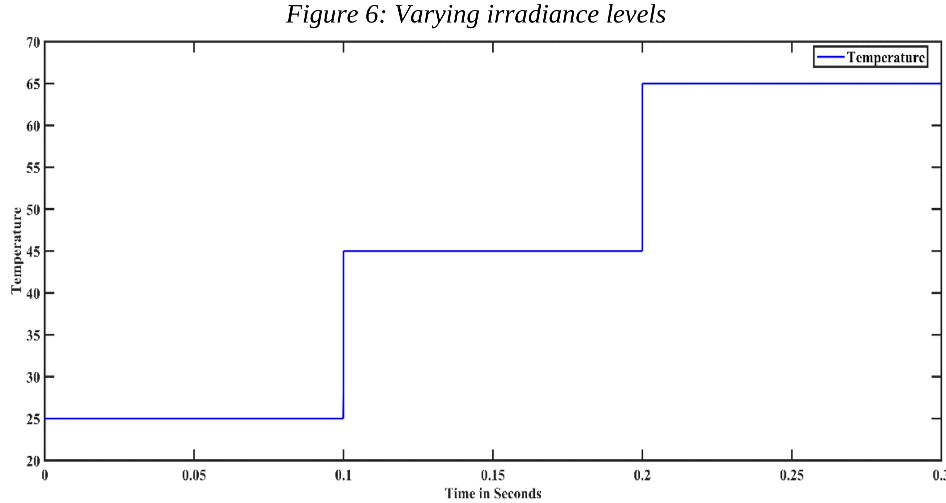

Figure 7: Varying temperature levels

3.1 Robustness against Environmental Variations

Temperature, irradiance, and load are all changed in this scenario to test the resilience of the suggested MPPT approach. The highest PV output power is 25.1 kW for the: temperature kept at 25 ^{0}C, the solar irradiation is kept at 1000 W/m^2, and the electrical load on the system is kept at

50 *Ω* during the first time interval t = [0, 0.1] (s). In the second time period t = [0.1, 0.2] (s), the temperature is increased to 65 ^{0}C, solar irradiation to 850 W/ m^2, and electrical load to 100, and maximum power is 17.02 kW. Finally, the temperature is set to 25 ^{0}C, the solar irradiation is set to 650 W/m^2, the electrical load is set to 150, and the maximum PV power is 18.4 kW during the time interval t = [0.2, 0.3] (s).

All the three controllers properly track the reference, V_{pvr}, of the peak power voltage generated by the neural network. However, as shown in Figure 8, the proposed controller converges on steady state at all settings in 0.006 s, which is significantly faster than the other MPPT approaches, this proves the efficiency of proposed controller against the performance of controllers used for comparison. Greater the convergence error lower will be the efficiency.

Figure 8 also depicts PV array output power. Comparison with other MPPT approaches shows that, the proposed controller successfully achieves MPP in 0.006 s with practically minute chattering. It is also cleared from sub-Figures that chattering in proposed controller in case of fault is slightly acceptable in comparison to rest of controller's performance. Hence, once again it is proved that the proposed controller is far better than the rest of controllers in term of rise time, settling error and fast convergence.

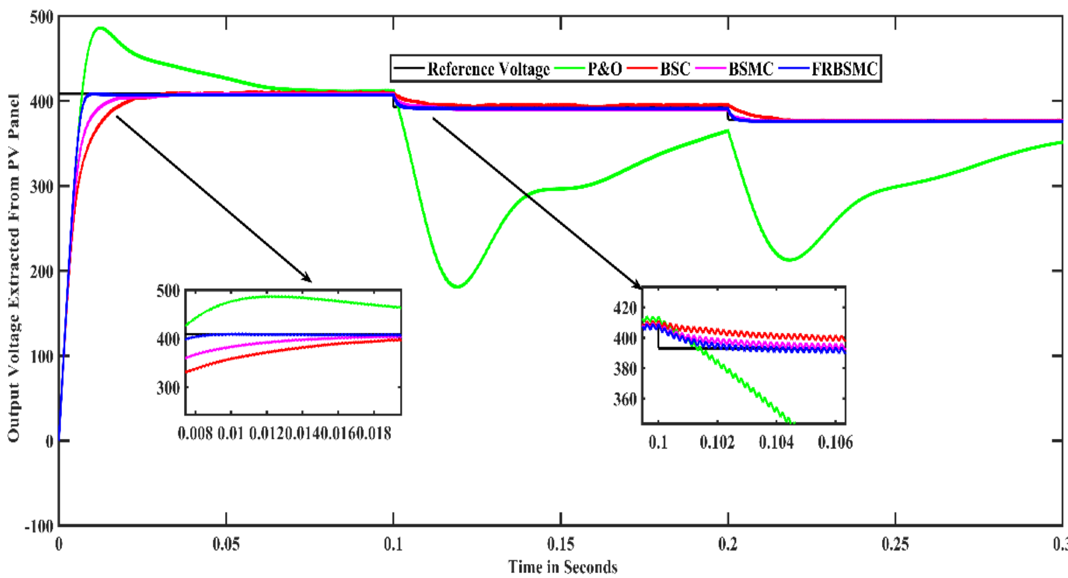

Figure 8: Output voltage of PV array under varying temperature and irradiance.

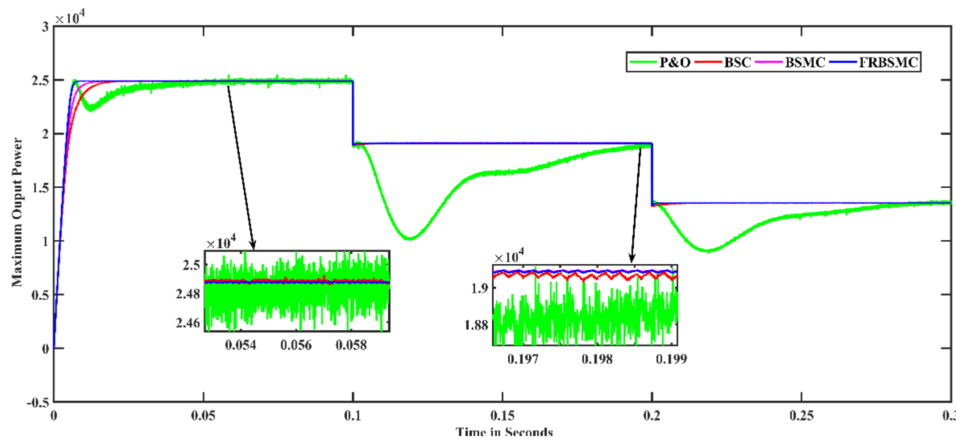

Figure 9: Output power of PV array under varying temperature and irradiance.

3.2 Robustness against Fault and Varying Environmental as well as Load Variations

To validate the performance of any controller, it is necessary to check its working against some faults and uncertainties. If the controller performed nearly to its normal performance, then it is the condition of its working as robust. Hence, in this section, multiple sensor faults are introduced in this case under changing solar irradiance, temperature, and load conditions. A fault, x_3f = 30usin (t)/$C_{i,}$ is added to the output voltage capacitor x_3 in the time interval t = [0.13, 0.15] (s), as Dx3 = x_3 + x_3f. In the time interval t = [0.23, 0.25] (s), a second fault x_2 f = 0.5usin (t)/Ci is added to inductor current x_2 as $Dx_2 = x_2 + x_2$ f.

In the aforementioned intervals of faults, all the three controllers used for comparison, deviates from reference voltage, while proposed controller is working in a robustness, which again proves the robustness of proposed controller. The controller, proposed in the paper, achieves steady-state faster than its conventional counterparts, as can be seen in the Figure 9. Furthermore, after the occurrence of faults, the maximum steady-state error is seen in the controllers used for comparison.

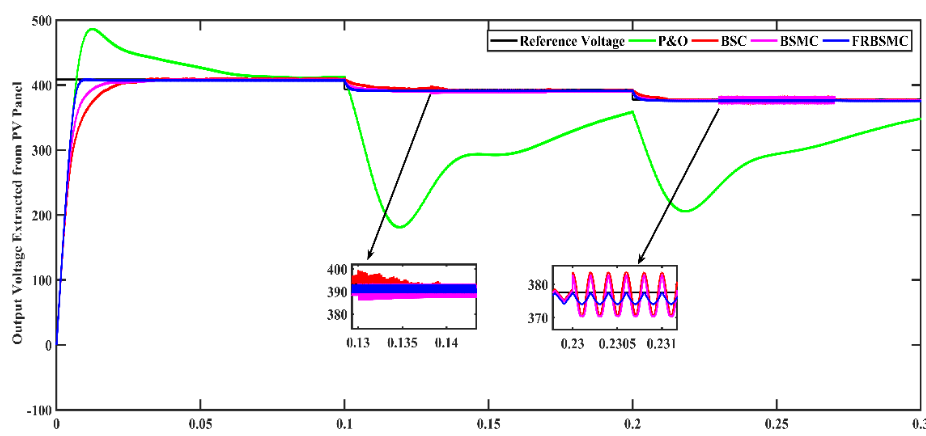

Figure 10: Output voltage of PV array under changing irradiance and temperature in the presence of sensor faults

The PV array output power is shown in Figure 10. The proposed controller clearly outperforms the others, reaching steady state in 0.006 seconds after faults and with nearly minute chattering. It is also cleared from subfigures that chattering in proposed controller in case of fault is slightly acceptable in comparison to rest of controller's performance.

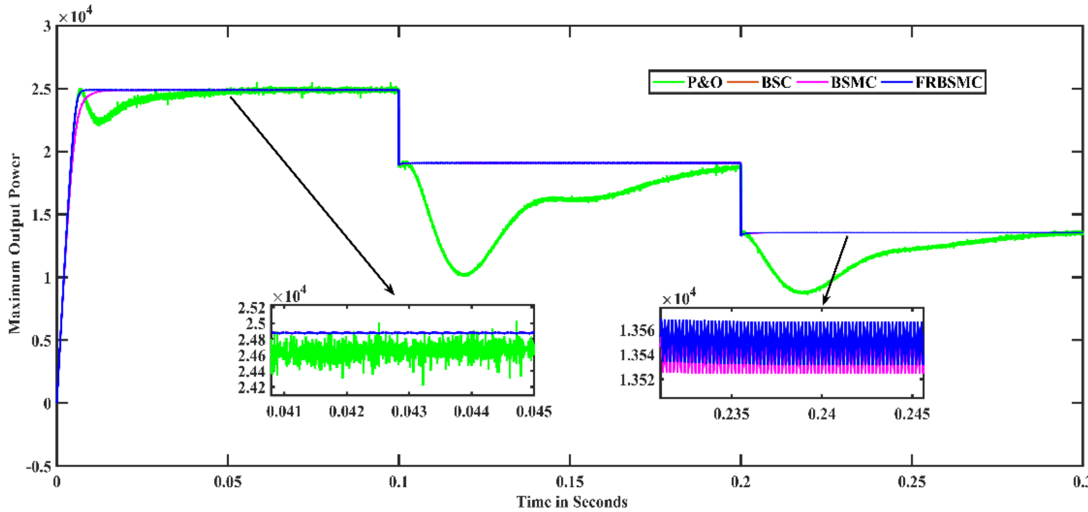

Figure 11: Output power of PV array under changing temperature and irradiance in the presence of sensor faults.

4. Concluding Remarks

In this article, FRBSMC is proposed to produce maximum power from PV panel under different conditions. Simulation is used to test the robustness of the studied method in the presence of climate changes and faults. In comparison to P&O, BSC, and BSMC, the proposed FRBSMC controller tracked the MPP fast and precisely. When it comes to steady-state error, tracking accuracy, overreach, rising time, and settle time, the results of simulation verify the proposed controller's good performance. The results verified that the above mentioned controller is preferable.

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