ARCHIVES OF ELECTRICAL ENGINEERING VOL. 69(2), pp. 389–401 (2020)

DOI 10.24425/aee.2020.133033

A control topology for frequency regulation capability in a grid integrated PV system

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(Received: 03.09.2019, revised: 13.01.2020)

Abstract: Photovoltaic (PV) cells are very costly because of the silicon element which is not cheaply available. Usually, PV cells are preferred to be used at maximum efficiency. Therefore, PV plants are emphasized to extract maximum power from PV cells. When inertia free PV plants are integrated into the grid in large numbers, the problem of maintaining system stability subjected to load perturbation is quite difficult. In response to this, a control topology is being an approach to make available the PV cells in maintaining system stability by utilizing the system frequency deviation as feedback to the controller. To implement this, the PVs are operated at Maximum Power Point Tracking (MPPT). This allows the PV to operate at Pseudo Maximum Power Point tracking (PMPPT) which makes it possible to run the PV with reserve power capacity without employing a battery for storage. The control strategy has been implemented over a two-stage power conversion model of the PV system. The simulation results showed that the proposed control PMPPT topology is effective in frequency regulation capability as compared to the MPPT technique.

Key words: frequency controller, maximum power point tracking (MPPT), photovoltaic (PV), power system, pseudo maximum power point tracking (PMPPT)

List of abbreviations

The following are the list of abbreviations used in this paper in addition to their citation at the appropriate place of use.

AGC	Automatic generation control
CMPPT	Current based maximum power point tracking
FLC	Fuzzy logic controller
INC	Incremental conductance
LFC	Load frequency control
MPPT	Maximum power point tracking
PMPPT	Pseudo maximum power point tracking
PV	Photovoltaic
VSC	Voltage source converter

1. Introduction

The growth of industries and domestic electrifications in the world require most of the energy from fossil fuel. To conserve primary energy assets, it is a promotional and needful drive to reduce the consumption of energy from conventional energy sources and suggested to use energy from renewable sources like solar, wind, biomass, tidal, geothermal, etc. However solar and wind have to gain more popularity among other renewable sources. India has been already in the path of becoming a global leader by the installation capacity of wind power of 21.1 GW. As solar power generation is completely pollution-free, easy for construction and the rate of development of photovoltaic (PV) generations have been increasing day by day. At present, India's total installed capacity of the grid integrated solar power plant as on 31.03.2014 is 2631.96 MW [1]. According to the National Solar Mission, India will be a global leader in installed solar generation capacity of 175 GW by the year 2022. Therefore, more immense research makes it possible to create the PV system more efficient. Though the silicon material is costly, it is a usual practice to run the PV unit at its maximum power generation by using maximum power point tracking (MPPT). In [2], authors have compared different types of MPPT algorithms for maximum power extraction from the PV panel.

By increasing the large numbers of the PV into the power grid, it is incapable of taking part in the inertial/frequency response when disturbances occur in the power system. This phenomenon is seen in the PV power plant because the MPPT does not allow the PV to operate according to the loading condition. Due to the incapability of the PV to take part in frequency regulation, the power system may lose its stability when there will be a fault like line outage, three-phase short circuit fault or a large change in load in the power system. To overcome these types of problems, many authors have developed control methodologies by employing battery storage [3]. However, battery storage facilities are very costly and also needs additional maintenance cost and further replacement cost. Therefore, a proper control methodology may be needed to avoid the use of the battery to achieve better frequency regulation of solar PV plants.

A PV generation system is becoming important as it offers many advantages including no fuel costs, almost no pollution, little maintenance and no noise emission [4]. Although, relatively, the high cost of the PV system makes it attractive for remote stand-alone loads and for small applications. However, it is expected that the designed technology will undergo cost reduction and its introduction into the electric power system will progress more rapidly in the future [5]. The power generated by a PV system is highly dependent on weather conditions. Also, it is too difficult to store the power generated by a PV system for future use [6]. To overcome this problem, the PV system may be integrated with alternate power sources and/or storage systems. The PV systems are one of the main parts of distributed power generation. The PV generators can be subjected to mismatching phenomena due to the different orientation of the modules concerning the sun rays or due to shadowing. In these cases, the MPPT technique must be designed carefully. In this work, an architecture including one DC/DC converter for each PV generator has been considered [7]. A solar PV system requires a regulation to extract the maximum of its energy taking account of the atmospheric fluctuations and external disturbances. Thereby, the MPPT technique using an Automatic Selection Algorithm to improve the efficiency of the PV system connected to a load via a DC–DC converter has been studied in [8]. In [9], a new current-based maximum power point tracking (CMPPT) method has been proposed for a single-phase PV power conditioning system and the current based MPPT modifies the incremental conductance method. The current based MPPT method makes the entire control structure of the power conditioning system simple and uses an inherent current source characteristic of the solar cell array. A new digital control scheme for a PV system using fuzzy logic and a dual MPPT controller has been studied in [10]. To obtain the maximum electricity from the solar cells, the PV modules have two MPPT controllers. The DC voltage and current are controlled to track the maximum power point, where the PV modules feed the maximum output power. An attempt to study and discuss the behavior of different MPPT techniques applied to PV systems has been concluded in [11]. In this work, techniques such as incremental conductance (INC) and fuzzy logic controller (FLC) are evaluated. Both the methods, the INC and FLC, are used with a boost DC/DC converter and a load. An application of the MPPT technique for a PV system using a grey wolf optimization technique has been studied in [12]. The problem of tracking the global peak of a PV array under partial shading conditions has been attempted by employing the grey wolf optimizer based MPPT technique. The proposed scheme is studied for a PV array under PSCs which exhibits multiple peaks and its tracking performance is compared with that of two MPPT algorithms, namely P&O-MPPT and improved particle swarm optimization based MPPT. An evaluation of the MPPT techniques with meaningful comparisons with respect to the amount of energy extracted from the PV panel, PV voltage ripple, dynamic response has been done in [13].

Subjected to automatic generation control (AGC) or load frequency control (LFC) issue, Asano *et al*. [5] have introduced the concept of integrating the PV into the hybrid power system. In this work, they have developed the mathematical model of the PV system to analyze its impact on the AGC. They have also considered a micro-grid having many generating sources. Multi-objective design optimization of a stand-alone hybrid power system accounting uncertainties in renewable power generation, load demand and modeling has been studied in [14]. The applications of optimization techniques may be shown in [15–18].

In this paper, a topology of the frequency control mechanism has been evolved and implemented in a grid integrated PV system. In this PV system, the PV plants are operated at the maximum power point or in other words, they are operated at pseudo maximum power point tracking (PMPPT). Therefore, the reserve power between the MPPT and PMPPT can be used to vary the operating point of the PV system in response to various loading conditions. This control methodology is achieved by formulating a controller using a system frequency deviation as feedback. The validation of this control mechanism is tested by switching a 2 MW load to a 4 MW load.

The remaining portion of this paper has been divided into four sections. In Section 2, the modeling of the PV system has been discussed. The controller for frequency control of the PV system has been elaborated in Section 3. The detailed schematic of the grid integration of the PV system has been explained in Section 4. Section 5 discusses the simulation results. Section 6 shows that observations of the research work were done.

2. Modelling of PV system

The PV cells develops energy based on the concept when light falls on the P-N junction. Subjected to this, the charge carriers are created in the form of carrying current. In order to increase the current rating, numbers of cells are connected in parallel whereas to increase voltage raring, the numbers of cells are connected in series [19]. The governing equation for the PV array design is given in (1).

$$I_{pv} = N_p I_{ph} - N_p I_{rh} \left(\exp\left(\frac{q}{kTA} \frac{v_{dc}}{N_s} \right) - 1 \right). \tag{1}$$

In (1), N_p and N_s are the total number of cells connected in parallel and series, respectively; I_{rs} is the reverse saturation current; q is the electron charge whose value is 1.6×10^{-19} C; k is Boltzmann's constant with a value of 1.38×10^{-23} J/K, A is the ideality factor, T is the temperature in Kelvin, v_{dc} is the output DC voltage of the PV panel and s is the irradiation in W/m^2. In (1), I_{ph} is the photon current which is given by (2).

$$I_{ph} = [I_{sc} + K_t (T - T_{\text{ref}})]. \tag{2}$$

where: I_{sc} is the short circuit current of the cell, T_{ref} is the reference temperature and K_1 is the temperature co-efficient. The date sheet for the expected PV performance is provided by the manufacturer under standard test condition. In this work, the 100 kW PV array consists of 66 strings of 5 series-connected 305.2 W modules connected in parallel ($66 \cdot 5 \cdot 305.2$ W = 100.7 kW). The PV array block has two inputs that allow you varying sun irradiance (input 1 in W/m^2) and temperature (input 2 in deg. C).

In order to have reserve capacity of a PV panel, the PV panel has operated at an operating point away from its maximum power point. This can be achieved by a modified fractional V_{oc} method. To know the details on this, it may be studied in [20]. In this approach of tracking the PV panel operates at pseudo-MPPT (PMPPT), more control over the active power may be possible that can be injected into the grid (check the statement). In this work, a novel control methodology has been proposed to maintain system frequency by keeping some portion of the PV system output as reserve. This reserve power is used whenever there is a need for injection of extra power to gain system stability followed by a large disturbance. The flowchart of the PMPPT algorithm is shown in Fig. 1.

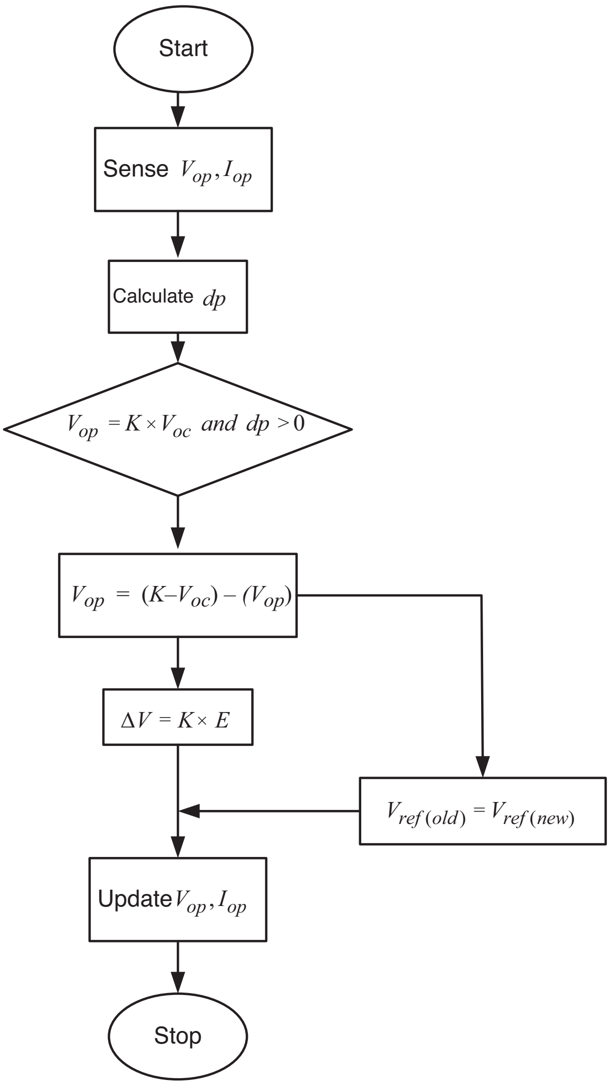

Fig. 1. Flow chart of PMPPT algorithm

3. Frequency control methodology by PV

The controller makes the PV available for change in active power generation in proportion to the deviation in grid frequency. The expression for frequency deviation (Δf) may be shown in (3).

$$\Delta f = f_{\text{actual}} - f_{pmpp} . \tag{3}$$

This controller processes the signal from pseudo MPPT and the feedback signal (i.e. Δf) from the grid. If any disturbance occurs in the grid, the corresponding change in grid frequency is processed by a PI controller in order to produce a corresponding change in duty ratio (refer Fig. 2). As shown in Fig. 3, the controller uses the reserve power (P_{reserve}) to do the required change in active power at PV output. The expression for reserve power may be expressed in [21].

$$P_{\text{reserve}} = P_{mpp} - P_{pmpp} \,. \tag{4}$$

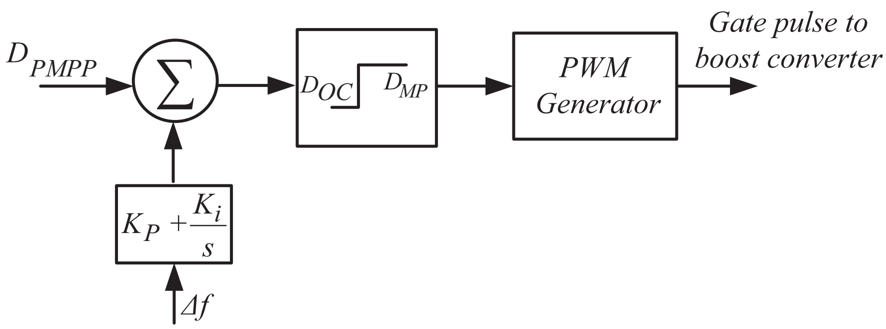

Fig. 2. Schematic for frequency control

To have reserved in the PV panel, the PV is loaded by a voltage above to the operating voltage corresponding to the power reserve. Since the PV power needs to change in accordance with frequency deviation, a signal proportional to the frequency deviation is subtracted from the duty ratio corresponding to, i.e. after being processed by a PI controller. For example, when there is an increase in load, the PV decreases in order to increase in active power generation as shown in Fig. 3.

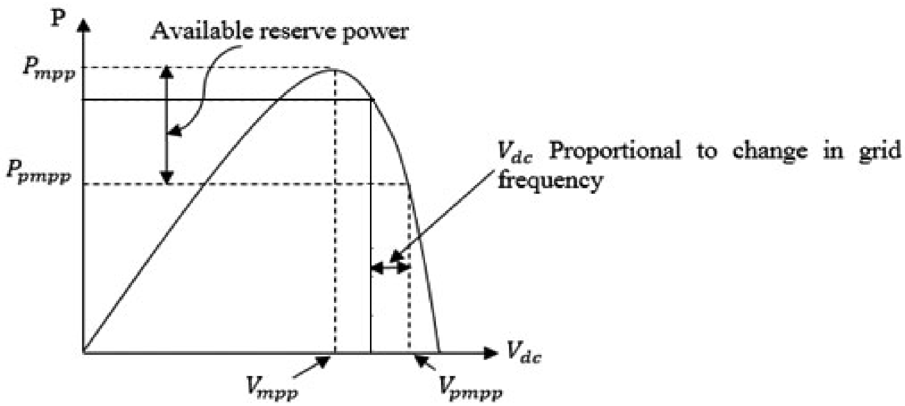

Fig. 3. PV with reserve power capacity

4. Studied test system

A 100 kW PV array is connected to a 25 kV grid via a DC–DC boost converter through a 3-phase 3-level voltage source converter (VSC) [22]. The average model contains PV array delivering a maximum of 100 kW at 1000 W/m^2 sun irradiance, a DC–DC boost converter, 3-level 3-phase VSC, 100 kVA, 260 V/25 kV three-phase coupling transformer and the utility grid. The detail data of the PV system are shown in Table 1. This table refers that the total number of series connected cells is 96, the open-circuited voltage is 64.2 V, the short-circuit current is 5.96 A, the voltage at maximum power is 54.7 V and the current at maximum power is 5.58 A.

Table 1. Data of PV system

Number of series-connected cells:	96
Open-circuit voltage: V_{oc}	64.2 V
Short-circuit current: I_{sc}	5.96 A
Voltage at maximum power: V_{mp}	54.7 V
Current at maximum power: I_{mp}	5.58 A

The schematic of the proposed model is shown in Fig. 4. The complete model has been developed in the Matlab/Simulink environment. In this model, the PV runs in the PMPPT technique. Initially, a 2 MW load is applied to run the simulation in a normal operating mode. In order to impose a disturbance into the system, a large amount of a load of another 2 MW load is switched into the grid.

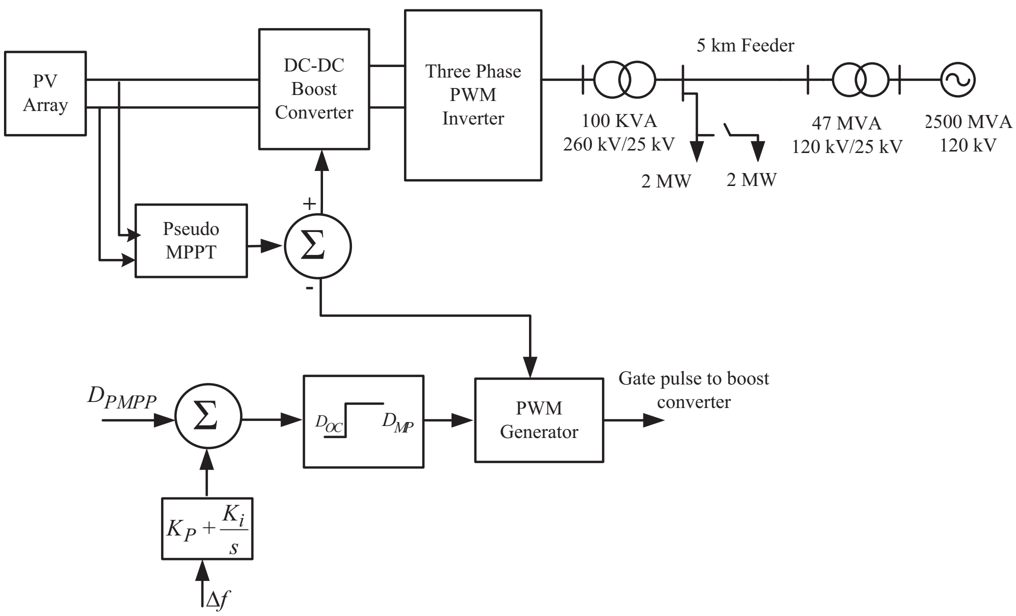

Fig. 4. Schematic of grid integrated PV plant

5. Results and discussions

To distinguish between the performance of the PV panel due to the MPPT and PMPPT algorithm, the schematic model is first run by the MPPT and then by the PMPPT algorithm. In this paper, the MPPT of the incremental conductance method is adopted for maximum power point operation [23]. Figs. 5 and 6 showed the P–V and I–V characteristics of the designed PV panel under various irradiance levels. From these plots, it may be observed that maximum power output from the PV panel is 100 kW and the corresponding output voltage from the PV panel is 275 V.

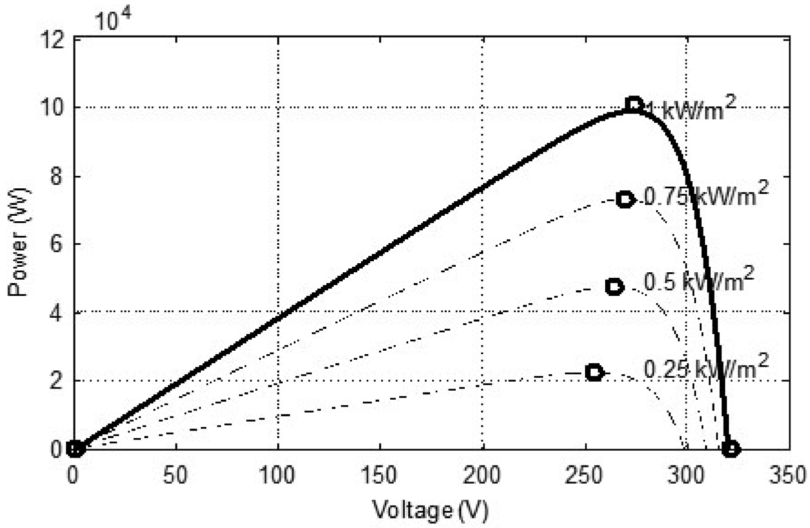

Fig. 5. P–V curve of the PV plant under various irradiance level

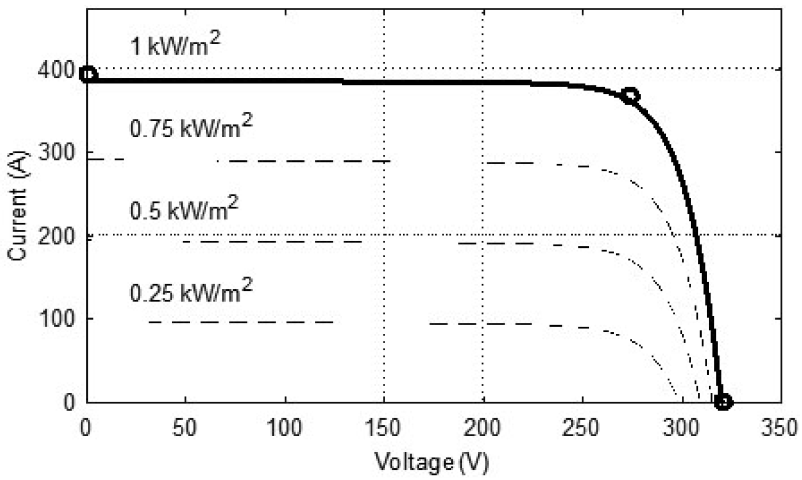

Fig. 6. I–V curve of PV plant under various irradiance level

For the LFC study, the plot of change in grid frequency subjected to load perturbation has been shown in Fig. 7. In this figure, the load demand is 2 MW up to 1 s. As it is an increase in load demand, a decrease in frequency deviation is observed in terms of undershooting. However, the system regains its stable mode of operation after 0.25 s. Again, at $t = 1$ s, load demand has been increasing up to 4 MW. In response to this, frequency deviation is observed in the same Fig. 7. As expected, an increase in load demand may be observed with decrease in frequency. However, the proposed PMPPT method is quite effective to regulate the frequency deviation with fewer oscillations.

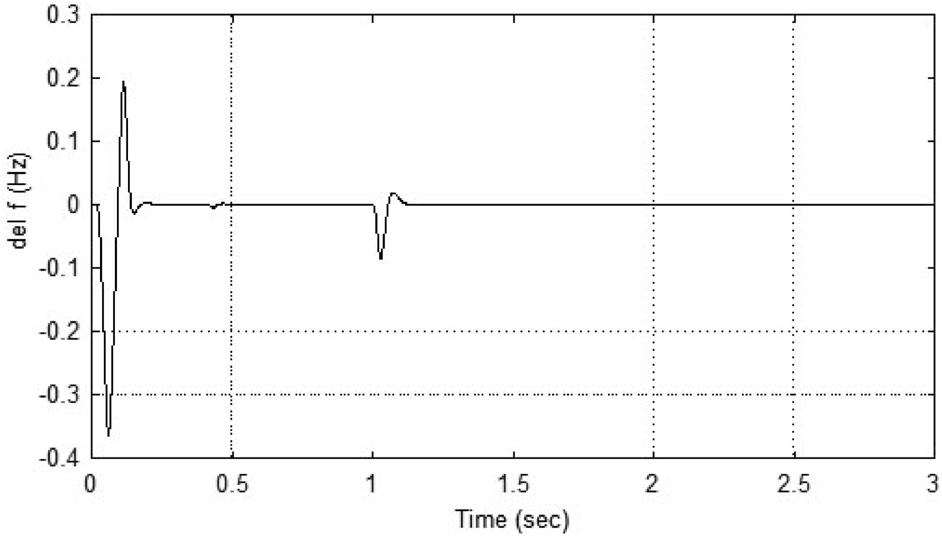

Fig. 7. Plot of the change in grid frequency of the proposed method

Figs. 8 and 9 represent the core idea of the paper. To take those plots, the simulation is first made to run with the MPPT algorithm under the conditions that for the first one second, the simulation runs with 2 MW load and then it is run with an additional 2 MW resulting in a total load demand of 4 MW. After this, the same should be maintained to run the simulation with the PMPPT algorithm.

In Figs. 8 and 9, the power and voltage output from the PV panel are plotted based on MPPT and PMPPT algorithms, in order. As observed from the simulation results, the PV panel output power is 100 kW whereas the PV panel operating voltage is approximately 275 V in both the conditions, whether the load demand is 2 MW or 4 MW using the MPPT technique (refer Table 2).

This shows that the MPPT technique operates at its maximum power point operation with constant voltage both at steady-state and dynamic conditions and does not follow the load demand. In effect of this, the frequency regulation cannot be controlled to the satisfactory value. This shows that some modified techniques are needed for the frequency regulation action. As concerned with the PMPPT algorithm, the power generation by the PV panel follows the load demand and its operating point changes subjected to load demand for the better frequency regulation. As shown in Fig. 8, when load demand is 2 MW, the PV panel output power is 68.02 kW and PV panel

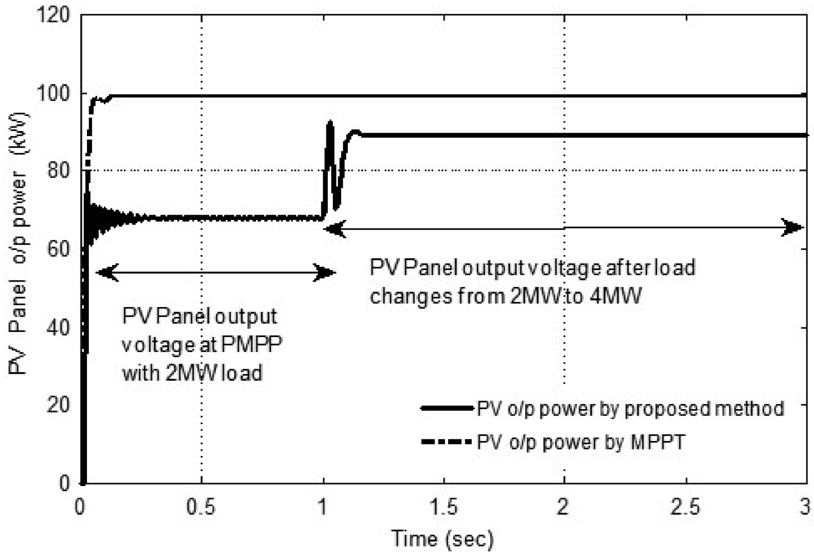

Fig. 8. Output power of PV panel under MPPT and PMPPT

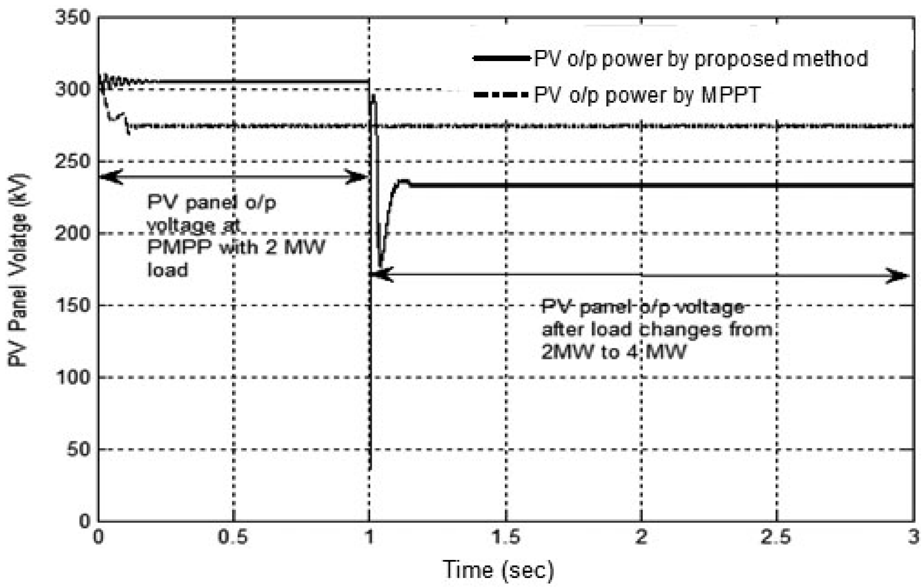

Fig. 9. Output voltage of PV panel under MPPT and PMPPT

output voltage is 310 V as per the PMPPT algorithm. Further, when load demand is increased from 2 MW to 4 MW, the power generated by the PV panel is approximately 89.01 kW whereas the operating PV voltage is reduces to approximately 235 V, which is quite sufficient to reduce

Table 2. Comparative analysis of MPPT and PMPPT algorithm

MPPT algorithm (Studied)	**PMPPT algorithm (Proposed)**
Load demand: 2 MW	
PV panel output power: 100 kW	PV panel output power: 68.02 kW
PV panel output voltage: 275 V	PV panel output voltage: 310 V
Load demand: 4 MW	
PV panel output power: 100 kW	PV panel output power: 89.01 kW
PV panel output voltage: 275 V	PV panel output voltage: 235 V

the frequency error to zero (refer Table 2). This increases the performance of the PV panel using the PMPPT algorithm. Moreover, this increases the reliability of the system. By doing this, we not only achieving good frequency regulation but also extend the PV pane life cycle.

6. Conclusions

A method of frequency regulation issue has been implemented in this paper for the studied grid integrated PV plant model. The proposed control theory has been implemented in the MATLAB/Simulink platform. A two-stage PV plant with a grid consisting of 2 MW load has been developed to implement the control topology. The reserve power has been made available at the PV plant by the PMPPT algorithm. The following observations may be concluded from the simulation results. These may be pointed as follows.

1. The simulation results showed that the implemented control strategy is effective to control the frequency regulation of the designed test system.
2. The advantage of the proposed method is that it allows the PV to operate at PMPPT which makes possible to run the PV with reserve power capacity without employing a battery for storage.
3. The proposed PMPPT algorithm effectively tracks the load following the performance of the PV panel.

Further work is going on to implement the proposed idea to design a damping controller in order to achieve power system stability.

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