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Grid integrated photovoltaic system with active and reactive power control using fuzzy based controller

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Photovoltaic (PV) panels are costlier and have poor efficiency in energy conversion. Therefore, it is essential to utilize a PV based system effectively. The characteristics of PV cell are very much nonlinear that show only one point corresponding to maximum power on P-V curve when the insolation is uniform. But in partial shading situations, the P-V curve shows many peaks among which only one point corresponds to the maximum power. In this paper, grid interactive PV system is proposed with active as well as reactive power control capability even under partial shading conditions using a novel global peak power point tracking algorithm based on fuzzy logic. The proposed PV system delivers active as well as reactive power in presence of sunlight. In the absence of sunlight and under low insolation, the inverter of the PV system provides compensation of load reactive power otherwise inverter remains unutilized. This improves the utility of PV system and thus enhances the efficiency of the system. The proposed system is simulated for different partial shading and changing load conditions using MATLAB/SIMULINK™. The simulation outcomes authenticate the performance and effectiveness of the proposed system for active and reactive power flow control with the proposed control approach.

Keywords: *Photovoltaic system, Active and Reactive power control, Fuzzy logic controller, Global peak power point tracking, Partial shading.*

1.0 INTRODUCTION

Recently, the use of renewable energy sources is growing worldwide due to increasing energy demand, growing rate of use of fossil and nuclear fuels, growing consciousness about greenhouse gasses and global warming etc. Photovoltaic (PV) is gaining more attraction amongst the renewable sources as it is clean, environment friendly, zero fuel cost, insignificant maintenance and operational cost.

It is essential to utilize PV system very effectively due to very high cost of PV panels. The grid connected PV system eliminates the requirement of battery. In order to exploit the resources of PV system efficiently, during night when the insloation is zero, the system is controlled such that it caters to the load reactive power demand on the grid [1, 2].

Generally, the grid interactive PV system uses dual stages: DC-DC step up converter for maximum power point tracking (MPPT) followed by DC-AC inverter for grid integration [3, 4]. But due to more power processing stages, the power loss increases and hence the efficiency is reduced in addition to increase in cost. Therefore, recently many single-stage PV systems are proposed that reduces the number of components as well as cost and enhance the efficiency [1, 2, 5, 6]. But, the single-stage grid interactive PV system suffers from a drawback of regulating dc link voltage

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while tracking the global peak in partially shaded condition.

Many grid integrated PV systems with only one power processing stage along with active and reactive power control have been proposed [1, 5, 6] to increase the effectiveness of the system. The authors in [2, 3] have proposed grid integrated PVsystem that also provides compensation of reactive power along with injection of PV power in the grid Considering the power quality problems, the authors in [4, 7, 8] have projected grid-tied PV system with active filter functionality of harmonic elimination as well. The MPPT algorithms used in all these papers have not considered partially shaded condition that may arise because of dust, flying birds, utility poles, clouds, close by building shadow etc. Hence, it is not possible to extract the actual power produced by the PV array in various partial shading conditions.

Extracting maximum power is more challenging in PV system working in partial shading conditions that give several peaks on power-voltage (P-V) curve out of which single point is the global peak. The conventional MPPT algorithm presented in [9, 10] like incremental conductance method, estimation of MPP by measuring open circuit voltage and short circuit current, Perturb and Observe (P&O) method, fuzzy logic based method etc. fail in tracking global peak in partial shading as they may get stuck at a local peak. This may cause considerable power loss depending on the shading.

Several methods for tracking Maximum Power Point (MPP) in partial shading situations have been presented. In a two-stage MPPT presented in [11], the operating point is shifted to MPP with the assumption of uniform P-V curve in the first stage, and then in the second stage, it uses the increment resistor technique to track the actual MPP. This technique requires the measurement of short circuit current as well as open circuit voltage that limits its use for large PV system.

The MPP technique presented in [12] needs an additional switch in parallel with the PV array to determine the short circuit current frequently i.e., every few minutes to trace the global peak. The technique in [13] uses a controller to determine the open circuit voltage and the short circuit current by changing the duty cycle of the converter from 0 to 1 and hence calculate the optimum voltage and current. Using this information, the approximate location of peak point is obtained. Then using conventional hill climbing algorithm global MPP is tracked. Such method causes significant loss of power while computing the open circuit voltage and the short circuit current for large PV system.

In [14], a real MPPT technique is proposed for partially shaded PV array that first ensures the occurrence of partially shaded situation from a predefined range of current and voltage, shifts the operating point as per predefined linear function and then uses incremental conductance algorithm to track the MPP. This method suffers from the problem of selecting appropriate current and voltage range that may be different for different configuration of PV array.

An MPPT scheme for partially shaded PV system has been proposed by authors in [15] based on the study that the local peaks decrease consistently on both side of the global peak. However, the author in [16] has rejected the observation of [15] based on a simulation study of a PV system in partial shading. It is also noticed that in partial shading situations, the global peak is all the time positioned to the left of peak power point during uniform insolation condition. Hence, in order to detect the partial shading condition, a trajectory line of the PV system corresponding to different insolation levels is stored in a memory and hill climbing MPPT is used to find out the global peak. The technique eliminates needless global scan, but among PV systems the trajectory line is different and also there is variation in parameters of PV array with time.

The global peak operating point in a PV system during non uniform weather conditions is determined using an algorithm based on Particle Swarm Optimization (PSO) technique [17, 18]. The PSO based technique requires a large time delay to permit agents to calculate the global peak and it is computationally intensive.

A hill climbing technique based on fuzzy logic proposed in [19] tracks the global peak in PV system employed in microgrids. The method performs the scanning of the entire *P-I* curve to search the global peak. The difference among the searched global peak and the present operating point is estimated. If it is greater than the predefined limit, the duty ratio of the converter is increased or else the fuzzy based hill climbing MPPT algorithm continues to operate. It is not ensured that the duty ratio is to be increased or decreased under different partial shadowing conditions, which may miss global peak.

The authors in [20] have presented review of various MPPT techniques based on soft computing methods. The authors in [21] presented a brief description of different modified MPPT techniques, different array configurations and different converter topologies to mitigate the partial shading effects in photovoltaic arrays.

In this paper, a two-stage grid interactive PV system with active and reactive power flow control capability by considering partial shading conditions is proposed using a novel fuzzy logic based Global Peak Power Point (GPPP) tracking algorithm. The proposed algorithm is capable of detecting the global peak in uniform insolation as well as partially shaded condition with any number of peaks located anywhere on P-V curve. The algorithm performs scanning of the complete P-V curve at regular interval in larger steps using boost converter to discover the approximate position of global peak. Then the proposed fuzzy logic controller locates the real GPPP. The proposed algorithm is easy to implement, converges quickly, and alleviates the tracking performance with least oscillation. The grid interactive PV system proposed in this paper supplies active power extracted from PV array using the proposed GPPP tracking algorithm and can also be used for reactive power compensation if desired. Especially during night, the PV inverter is employed for the compensation of reactive power, thus increasing the utility of the system. The simulation results obtained using proposed algorithm show the effectiveness of the grid interactive PV system under varying load and different partial shading conditions.

The characteristics of partially shaded PV array are represented in section-2. The proposed GPPP tracking algorithm is explained in section-3. The configuration of two-stage grid interactive PV system along with the control strategy is described in section-4. The simulation results are discussed in section-5. Conclusions drawn from the simulation results are given at the end of this paper.

2.0 PV MODELING AND CHARACTERISTICS IN PARTIAL SHADING CONDITIONS

In order to attain necessary voltage and current levels, the PV array is configured by connecting many PV modules in series known as string and many such strings are linked in parallel. In order to carry out simulation study, a 10.8 kW PV system is developed by connecting 15 strings in parallel with each string made up of 12 series connected Solarex MSX60 PV panels. A parallel connected bypass diode with each module protects it from the problem of hot spot whereas the series connected blocking diode with each string protects the PV module from the effect of potential dissimilarity among the PV strings [22- 24].

2.1 PV Cell Model

The electrical model of a PV cell contains a diode in parallel with current source [24, 25]. The PV cell (I_{cell}) output current is given by (1).

$$I_{cell} = I_{ph} - I_D - I_{sh} \quad ....(1)$$

where,

$$I_D = I_0(e^{\frac{q(V_{cell}+I_{cell}R_S}{\eta kT}} -1) \quad ....(2)$$

$$I_{sh} = \frac{V_{cell} + I_{cell}R_S}{R_{sh}} \quad ....(3)$$

where, Boltzmann constant $k=1.38 X 10^{-23} J/^oK$, charge $q=1.6 X 10^{-19} C$ and diode ideality factor $\eta=1.2$ *to* 1.4. T is temperature in Kelvin, I_{ph} is photocurrent, I_0 is reverse saturation current of diode, V_{cell} and I_{cell} are the PV cell output voltage and current respectively.

Due to very large value of R_{sh}, its effect on the *I-V* characteristic of PV cell is negligible and hence (1) can be modified to

$$I_{cell} = I_{ph} - I_0(e^{\frac{q(V_{cell}+I_{cell}R_S)}{\eta kT}} - 1) \quad \text{....(4)}$$

For a PV array made up of N_s modules connected in series and N_p modules connected in parallel, (4) can be written as,

$$I_{PV} = N_p\left\{I_{ph} - I_0\left(e^{\frac{q\left(\frac{V_{PV}}{N_s}+\frac{I_{PV}}{N_p}R_S\right)}{\eta kT}} - 1\right)\right\} \quad \text{....(5)}$$

where in Eq. (5), V_{PV} and I_{PV} represents PV array output voltage and current respectively.

2.2 Characteristics of PV Array in Partial Shading Conditions

The simulation of PV array is carried out in MATLAB using the model developed in [23] based on (1) to (5) with Solarex MSX60 PV panels. The resulting *I-V* characteristics is presented in Figure 1(b) and *P-V* characteristics is presented in Figure 1(c) for three shading patterns SP_1, SP_2 and SP_3 as shown in Figure 1(a). The selection of shading patterns is done in such a way that the location of global peak point is in different voltage regions to show the effectiveness of the proposed algorithm for tracking the GPPP in any shading condition. It is observed that during partial shading, the *I-V* characteristic has several steps and the *P-V* characteristic has several peaks out of which only one point is a global peak.

Moreover, the global peak is randomly located on the *P-V* curve depending on the shading condition. However, it can be noticed that the peak points whether local or global, lie close to the voltage that is in multiple of 75-80% of open circuit voltage of one module V_{ocm} (i.e. nearly 17 V for Solarex MSX60 PV modules).

3.0 PROPOSED ALGORITHM

The GPPP tracking technique proposed by the authors of this paper in [22] is used for tracking a real MPP. The algorithm is briefly described as follows:

3.1 Proposed Technique For Tracking Global Peak Power Point

The PV array characteristics given in section-II depict that the location of any peak, may be local or global, is close to the voltage in multiple of 75-80% of one modular voltage (i.e. nearly 17 V for Solarex MSX60 PV modules) on the entire *P-V* curve. Therefore, the proposed algorithm performs scanning of the complete *P-V* curve at predefined voltage step equal to open circuit voltage of a single module, to search the approximate location of GPPP. Then the operating voltage of PV array is set close to the searched approximate global peak point and the FLC tracks the actual MPP. The scanning is carried out at regular time interval (each 20-25 s). By performing the scanning at larger steps and using the FLC which provide faster convergence at the GPPP, the tracking time is appreciably reduced. The flowchart in Figure 2 demonstrates the sequence of operation in the proposed algorithm.

The step-size of duty ratio D_{step} is selected so as to vary the PV voltage in steps of 75% of V_{ocm} during scanning to make sure that no peak is missed. D_{min} is selected as per 75% of open circuit voltage of PV array (75% of 252V) and D_{max} is selected as per 75% of open circuit voltage of one module (75% of 21V). The location of all peaks is within the range of PV array output voltage corresponding to duty ratio interval (D_{min},D_{max}) of the boost converter. Initially, $P_{max}$is set to zero. During scanning of the *P-V* curve, at each step, the PV power is computed by sensing PV array voltage and current. Then the computed PV power is compared with maximum power (P_{max}) stored in the memory and if computed power is found greater, P_{max} is replaced by the computed power and V_{max} and D_{set} are updated. These steps are repeated and the approximate location of global peak is estimated. Then the duty ratio of step up converter is set to D_{set} as per the estimated peak and the FLC shown in Figure 3 tracks the actual GPPP and thus maintains the operation of PV array at the GPPP. The scanning and subsequent fuzzy logic based tracking is repetitive at predefined time interval so as to keep the PV array working at GPPP in partial shading and rapidly varying environmental conditions.

3.2 Proposed Tracking Technique based on Fuzzy Logic

The proposed FLC block diagram is shown in Figure 3. There are three stages of the FLC, viz., (i) fuzzification, (ii) fuzzy rule base formation and (iii) defuzzification described as follows:

In the first stage of FLC, fuzzification is done to divide the input and output into linguistic fuzzy sets with the help of the prior information of the range of input and output.By accepting only one input, the slope of the *P-V* curve $\Delta P(k)/\Delta V(k)$, the proposed FLC outputs the duty cycle *D* which is used to control the boost converter to make the PV array operating at GPPP and extracts the maximum available PV power which is to be injected into the grid. Based on the magnitude of the slope of *P-V* curve, the input and output are divided in seven fuzzy sets as shown in Figure 3.

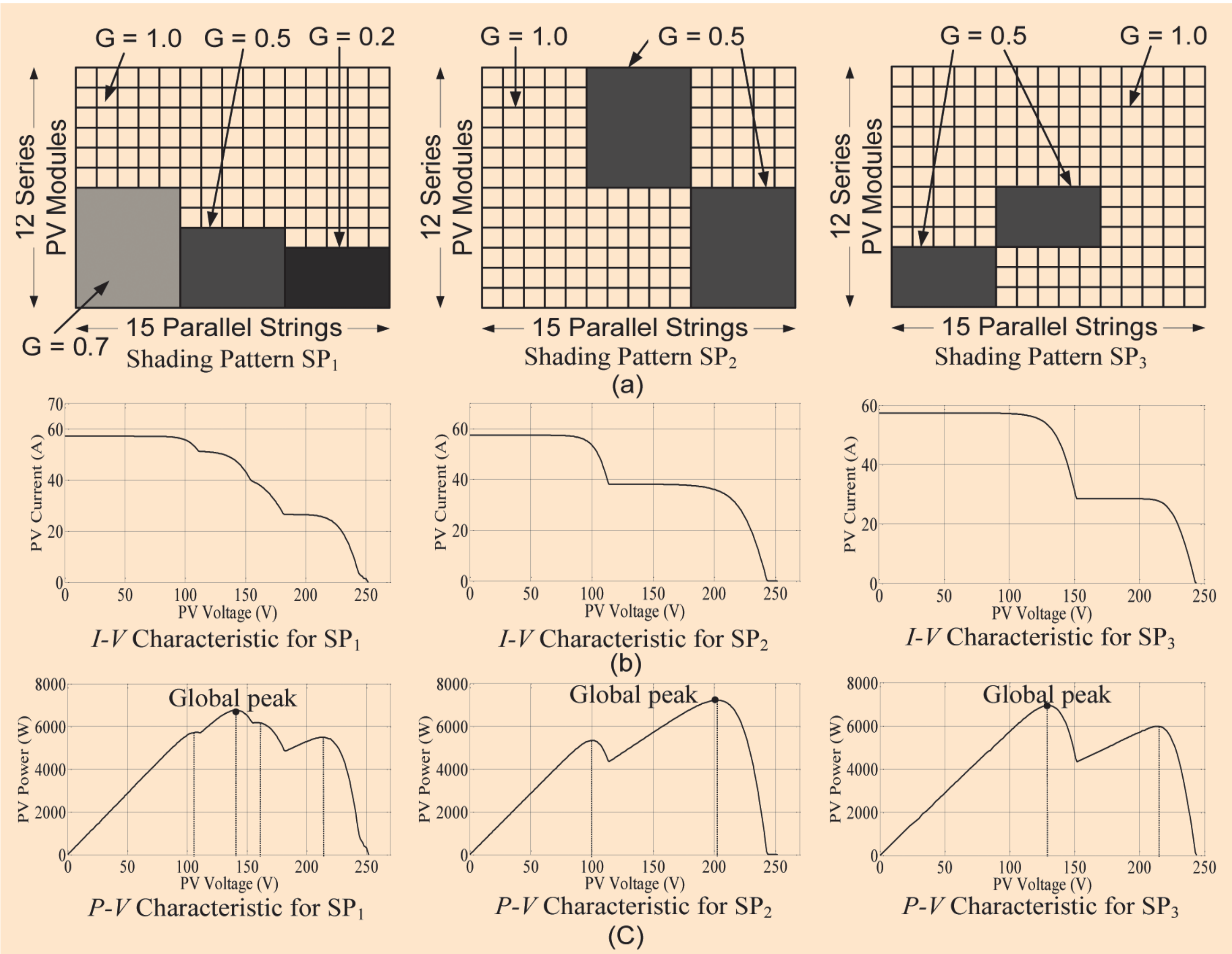

FIG.1 (A) SHADING PATTERNS (SP_1, SP_2, SP_3) (B) CURRENT-VOLTAGECHARACTERISTIC AND (C) POWER-VOLTAGE CHARACTERISTIC OF PV ARRAY

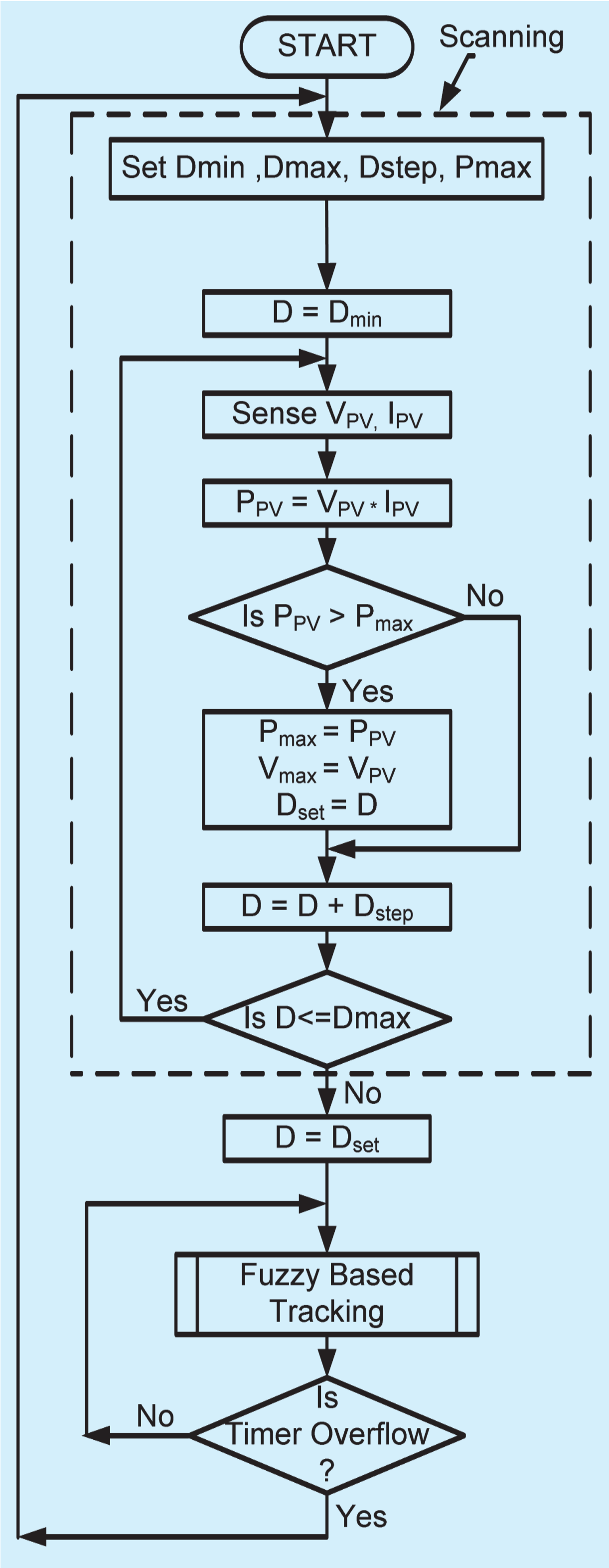

FIG. 2 FLOWCHART OF PROPOSED GPPP TRACKING TECHNIQUE

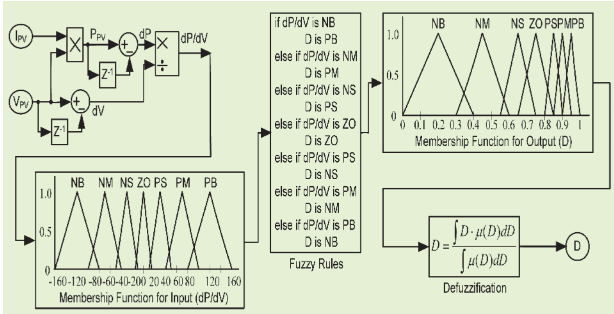

FIG. 3 PROPOSED FUZZY LOGIC CONTROLLER FOR TRACKING GPPP

The second stage of FLC precisely defines fuzzy rules to generate duty ratio *D* as the output based on the magnitude of the slope of P-V curve to move the operating point towards GPPP. The following logic is used to achieve the same.

if ($\Delta P(k)/\Delta V(k) > 0$)

D is decreased to increase the voltage of PV array

if ($\Delta P(k)/\Delta V(k) < 0$)

D is increased to decrease the voltage of PV array

The proposed technique uses seven rules for GPPP tracking as shown in Figure 3.

Finally, the third stage of FLC performs defuzzification to generate the output duty ratio *D* as a single crisp value from the aggregated set of fuzzified output values using the well known centroid technique [26].

Thus, the proposed FLC applies variable steps of duty cycle in order to control the boost converter according to present operating point and consequently provides fast convergence with least oscillations at GPPP. The effectiveness of the proposed algorithm under any partial shading condition is demonstrated through simulation outcomes presented in section-IV.

4.0 CONFIGURATION OF GRID INTERACTIVE PV SYSTEM AND ITS CONTROL STRATEGY

The configuration of the proposed grid interactive PV system is demonstrated in Figure 4. The boost converter is used as GPPP tracker in addition to the boosting of output voltage of PV array for grid integration. The duty ratio of the converter is controlled by the proposed algorithm explained in section-III to extract the maximum power which can be pumped into the grid.

The voltage source inverter is used to inject PV generated power into the grid in addition to providethe compensation of load reactive power within the capacity of the inverter. The voltage of DC bus is regulated at 700 V by using PI controller for grid integration.The additional functionality of reactive power compensation by the PV inverter enhances the overall utilization of the system.

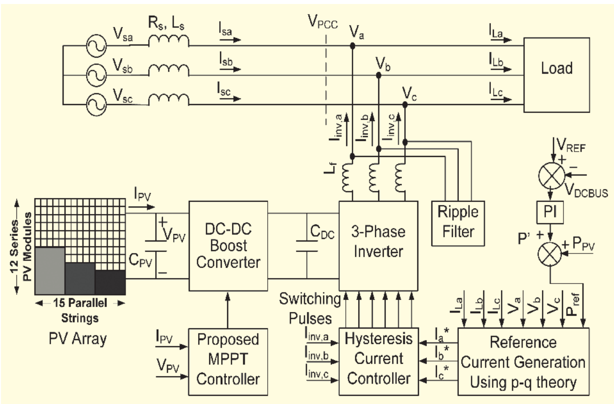

FIG. 4 GRID INTERACTIVE PV SYSTEM CONFIGURATION

In order to pump the power produced by the PV array (P_{PV}) in the grid and also to provide compensation of load reactive power demand, the references required for the control circuit are generated based on well established instantaneous power (*p-q*) theory [27] which are given by (6) and (7) respectively.

$$p^* = P_{PV} + P' \quad ....(6)$$

$$q^* = \bar{q} - Q_c \quad ....(7)$$

where, P_{pv} is the peak power extracted using the proposed algorithm, Q_c is the reactive power compensation provided by ripple filter and $\bar{q}$ is the reactive power demand from the load. The power loss in ripple filter (P_c) is negligibly small. P' is the small component of power (corresponds to the losses in the inverter) that is required to retain the voltage at dc link.

Using the reference power p^* and q^* calculated using (6) and (7), the current references are computed using appropriate coordinate transformation [27]. The command signals for the inverter switches are generated by comparing the reference currents with the actual inverter currents using hysteresis current controller.

The ripple filter demonstrated in Figure 4 is a series R-C filter used to eliminate the switching ripples and also provides fixed amount (Q_c) of reactive power compensation.

5.0 SIMULATION RESULTS

The two-stage grid interactive PV system presented in Figure 4 is simulated in MATLAB/ SIMULINK™ environment using the proposed GPPP tracking algorithm. The parameters of the grid interactive PV system used in simulation study are specified in Table 1.

The simulation model of 10.8 kW PV system is developed by connecting 15 strings in parallel, with each string made up of 12 Solarex MSX60 PV panels connected in series. Each Solarex MSX60, 60W PV panel contains 36 polycrystalline cells connected in series.The value of electrical circuit parameters are calculated using the design equations given in [8] and [28].

During simulation study, first the effectiveness of the proposed algorithm is analyzed for tracking GPPP in different partially shaded and uniform insolation as well as varying load conditions. Then the capability of the proposed system to control active and reactive power under different partial shading and varying load conditions is demonstrated. It is also verified through the simulation results that under any situation of partial shading, uniform insolation and load variations, the voltage and current of the grid are in phase/anti-phase that justifies almost complete compensation of reactive power by the inverter and ripple filter.

TABLE 1 PARAMETERS OF GRID INTERACTIVE PV SYSTEM	
Parameter	**Value**
Parameter of PV system	
Open circuit voltage (V_{OC}) of a PV module	21.0 V
Short circuit current (I_{SC}) of a PV module	3.74 A
Voltage of a PV module at MPP (V_m)	17.1 V
Current of a PV module at MPP (I_m)	3.5
Maximum Power of a PV module (P_m)	60 W
Reference temperature	25º C
Reference solar radiation (1 sun)	1000 W/m^2
No. of PV modules connected in series in a string	12
No. of PV strings connected in parallel	15
Parameters of electrical power system	
L_s, R_s	0.5 mH, 0.01 Ω
L_f, L_{boost}	3.5 mH, 0.3 mH
C_{pv}, C_{DC}	1000 μF , 2000 μF
V_p(peak grid voltage)	360 V
Ripple filter (R,C)	10 Ω, 20 μF

5.1 Performance of Proposed Algorithm in Tracking Global Peak

The GPPP tracking performance of the proposed PV system operating under different partial shadowing and rapidly varying uniform insolation conditions is shown in Figure 5. Curve-1, curve-2 and curve-3 show the tracking of global peak corresponding to shading patterns SP_1, SP_2, and SP_3 respectively and they match with the *P-V* characteristic under partially shaded conditions as shown in Figure 1(c). Curve-4 and curve-5 demonstrate the tracking of GPPP when PV array is receiving uniform insolation of 1000 W/m^2 and 300 W/m^2 respectively.

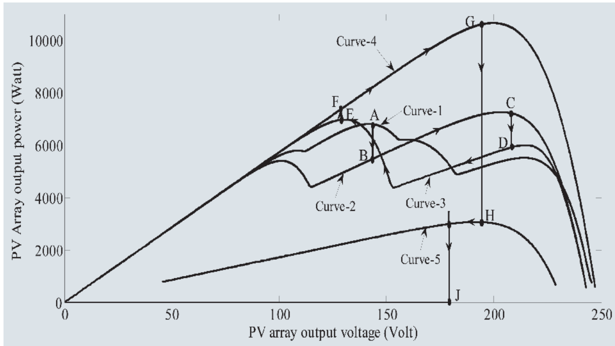

FIG. 5 GLOBAL PEAK POWER POINT TACKING PERFORMANCE

At t = 0, PV array is shaded by applying shading pattern SP_1. The proposed GPPP tracking controller scans the curve-1 and detects the peak point A. When pattern SP_2 is applied at t = 1.5 s, the controller detect peak point C by scanning curve-2. At, t = 3 s, the array is shaded by pattern SP_3 and the controller track peak point E on curve-3. At, t=4.25 s, when the array is subjected to uniform radiation of 1000 W/m^2, the controller makes the operating point to converge to G by tracing the curve-4.Then at t = 5 s, the uniform insolation is reduced to 300 W/m^2. The controller detects peak point I by tracking curve-5. Finally at t = 5.5 s, when the insolation is made zero, the operating point is moved from I to J. Thus it is demonstrated that the proposed GPPP tracking algorithm determine the GPPP accurately and reliably in partial shadowing and also rapidly changing uniformly insolation conditions.

The variations in the current, voltage and power of PV array along with dc link voltage while tracking GPPP is demonstrated in Figure 6. The algorithm performs scanning of the entire *P-V* curve regularly, every 0.75 s during simulation (in real situation every 20-25 s). It is observed that the proposed algorithm is capable of tracking the GPPP accurately in different partial shading as well as rapidly changing uniform insolation situations.

From Figure 6(d), it is seen that the voltage of dc link is maintained at 700 V and is not affected considerably by the scanning process carried out at regular time intervals. This feature allows the PV inverter to inject reactive power along with PV power in the grid. Since the voltage of dc link is regulated at the desired value, even at zero insolation, the PV inverter is capable of injecting reactive power. This situation invariably occurs during the night time and the PV system can be utilized effectively.

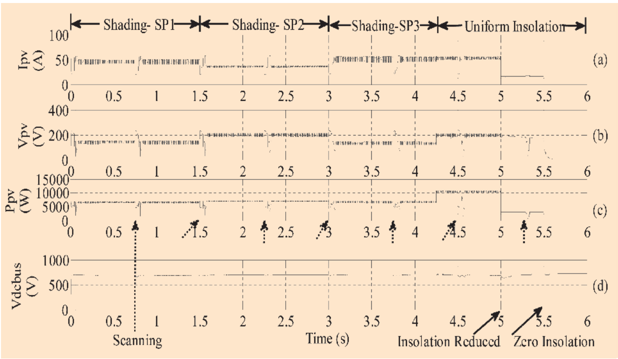

FIG. 6 PV SIDE WAVEFORMS DURING GPPP TRACKING: (A) OUTPUT CURRENT (IPV) (B) OUTPUT VOLTAGE (VPV) (C) OUTPUT POWER (PPV) AND (D) DC LINK VOLTAGE

The waveforms of the active and reactive power with changing partial shadowing condition at a constant load (P_{Load}=13 kW and Q_{Load}=7 kVAR) is shown in Figure 7. At t = 0.75 s, suddenly the shading pattern SP_1 is removed and shading pattern SP_2 is applied. It can be noticed from Figure 7(a) that as PV array gives more active power under shading pattern SP_2 compared to shading pattern SP_1 and hence, the PV inverter supplies more active power whereas the active power supplied by the grid decreases to meet the constant load demand. At t =1.5 s, the shading pattern SP_2 is removed and uniform insolation of 900W/m^2 is applied. It can be noticed in Figure 7(a) that as PV array is capable of supplying more active power under uniform insolation of 900 W/m^2 compared to shading pattern SP_2, the active power drawn from the grid is further reduced to deliver the constant load power demand.

Finally, the performance of grid interactive PV system is analyzed in zero insolation condition. At t = 1.75 s, the uniform insolation is decreased from 900 W/m^2 to zero. It is visible from Figure 7(a) that as PV array supplies zero power, the inverter draws minimal active power from the grid in order to supply the losses. The complete load demand of 13 kW is drawn from the grid. Thus, under varying partial shadowing conditions, the balance of active power is given by, $P_{Load} + P_c = P_{grid} + P_{inv}$ where P_c is the power loss in ripple filter which is negligibly small.

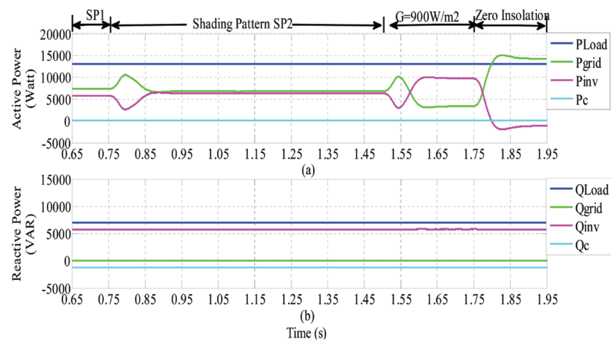

FIG. 7 EFFECT OF VARIATION IN PARTIAL SHADOWING CONDITION WITH CONSTANT LOAD: (A) ACTIVE POWER OF LOAD, INVERTER, GRID AND RIPPLE FILTER (W) (B) REACTIVE POWER OF LOAD, INVERTER, GRID AND RIPPLE FILTER (VAR)

From Figure 7(b), it is observed that the reactive power requirement of the load is almost entirely fulfilled by the PV inverter and ripple filter in changing partial shadowing as well as zero insolation situations. The reactive power drawn from the grid is zero. The reactive power balance follows, $Q_{Load} = Q_{inv} + Q_c$ with $Q_{grid} = 0$.

Figure 8 shows the variations in currents when insolation is decreased from 300 W/m^2 to zero at t = 5.5 s. The current delivered by the PV inverter is in quadrature with the grid voltage indicating that the reactive current is injected. The current supplied by the grid is in phase with the grid voltage as observed in Figure 8(a) and Figure 8(b).This justifies almost complete compensation of reactive power demand of the load by the PV inverter along with ripple filter.

Thus, it is demonstrated that the proposed PV system can be utilized for reactive power compensation in addition to supplying PV power into the grid irrespective of the availability of solar power. This feature enhances the utilization of PV system.

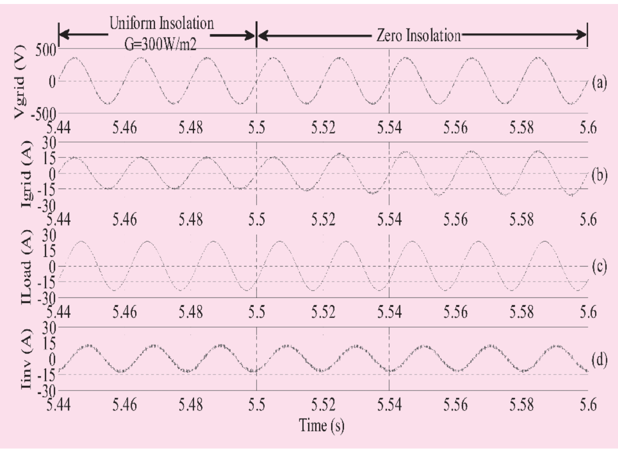

FIG. 8 EFFECT OF VARIATION IN INSOLATION FROM UNIFORM TO ZERO ON PARAMETERS OF PHASE-A: (A) GRID VOLTAGE (B) GRID CURRENT (C) LOAD CURRENT AND (D) INVERTER CURRENT

5.2 Performance of Active and Reactive Power Control with Variation in Load

In this section, the PV system performance is studied through simulation by step variation in the load demand and the results are presented in Figure 9. The PV array is shaded by shading pattern SP_2 for this study. Due to this partial shading, the PV array can supply only 7.2 kW. At t = 1.8 s, the load active power is increased from 13 to 18 kW and the load reactive power is also increased from 7 to 12 kVAR as shown in Figure 9(a).

In order to deliver the increased load demand, the active power supplied by the grid increases which is observed in Figure 9(b). Figure 9(c) shows that the increased demand of the load reactive power is completely fulfilled by the inverter along with ripple filter and the reactive power drawn from the grid is zero. Then at t = 2 s, the active power requirement of the load is reduced from 18 kW to 13kW and the reactive power requirement of the load is also reduced from 12 kVAR to 7 kVAR as shown in Figure 9(a). The active power supplied by the grid reduces as the load demand reduces which is seen in Figure 9(b). Also, due to reduction in load reactive power demand, the amount of reactive power delivered by the inverter reduces as seen in Figure 9(c).

Thus even in the situation of step change in load, active power balance is given by, $P_{Load} + P_c = P_{grid} + P_{inv}$ and reactive power balance given by, $Q_{Load} = Q_{inv} + Q_c$ are achieved under steady state with zero reactive power drawn from grid.

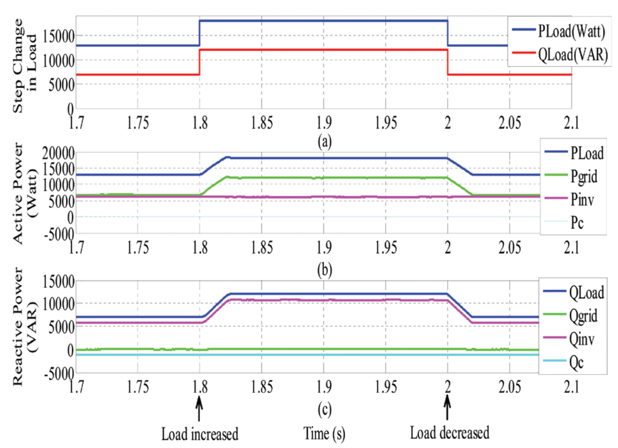

FIG. 9 EFFECT OF VARIATION IN LOAD DEMAND DURING SHADING PATTERN SP2: (A) STEP CHANGE IN LOAD (B) ACTIVE POWER OF THE LOAD, INVERTER, GRID AND RIPPLE FILTER (C) REACTIVE POWER OF THE LOAD, PV INVERTER, GRID AND RIPPLE FILTER

5.3 Performance of power flow control when both load and insolation are changing simultaneously

In this section, the worst case situation of simultaneous variation in insolation along with load is analyzed. Figure 10 shows the result of power balance amongst load, grid, inverter and filter. At t = 4.25 s, the partial shading pattern SP_3 is removed and uniform insolation of G=1000 W/m^2 is applied, simultaneously the load is reduced from 13 kW to 5 kW and 7 kVAR to 2.5 kVAR . As the shadow is removed and insolation is increased to full sun, the PV array generates more power which is higher than the reduced load active power demand. Hence, the PV inverter supplies the excess active power into the grid as seen from Figure 10 (b).

It can be verified in Figure 10 (c) that the load reactive power requirement is completely delivered by the inverter and ripple filter, $Q_{Load} = Q_{inv} + Q_c$ without drawing any reactive power from grid ($Q_{grid} = 0$).

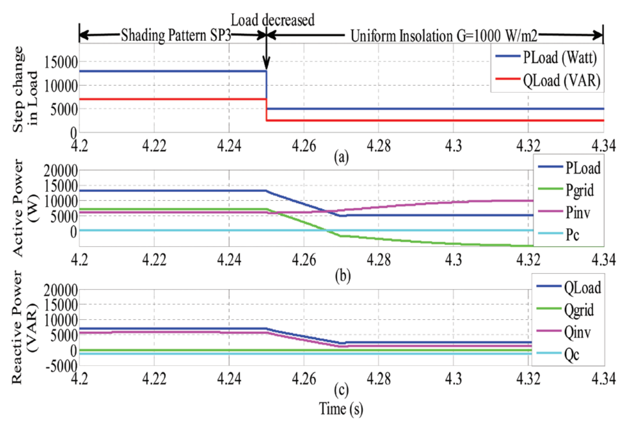

FIG. 10 EFFECT OF SIMULTANEOUS VARIATION IN INSOLATION AND LOAD: (A) ACTIVE POWER OF THE LOAD, GRID, INVERTER AND RIPPLE FILTER (B) REACTIVE POWER OF THE LOAD, GRID, INVERTER AND RIPPLE FILTER

The variations in currents is shown in Figure 11 under the situation of simultaneous variation in shading along with load which is applied at t = 4.25 s. It can be noticed in Figure 11(d) that the current delivered by the PV inverter increases under full insolation whereas the current drawn from the grid decreases as in Figure 11(b) as the load current is decreased.

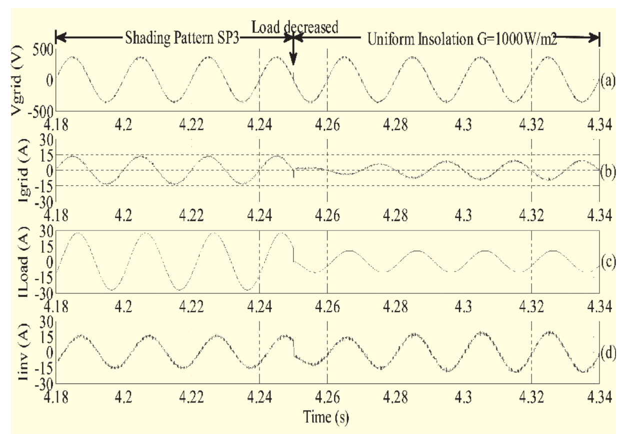

FIG. 11 EFFECT OF SIMULTANEOUS CHANGE IN SHADING AND LOAD ON PARAMETERS OF PHASE-A: (A) GRID VOLTAGE (B) GRID CURRENT (C) LOAD CURRENT AND (D) PV INVERTER CURRENT

Figure 11(a) and Figure 11(b) show that the current and voltage of the grid are in anti-phase as the power produced by PV inverter is higher than the load requirement indicating that the additional current and hence power is fed into the grid.

The current balance under simultaneous change in insolation and load conditions is given by,

$$I_{Load,\ a} = I_{grid,\ a} + I_{inv,\ a} \qquad ....(8)$$

Figure 10 and Figure 11 demonstrate the capability and the robustness of the proposed algorithm for controlling the grid interactive PV system under worst situation of simultaneous change in both insolation and load.

6.0 CONCLUSIONS

In this paper, a two-stage grid interactive photovoltaic system by considering partial shading conditions using a fuzzy logic based GPPP tracking algorithm is proposed. The controller tracks the actual peak power point accurately and reliably in rapidly changing uniform insolation as well as different partial shadowing situations. The fuzzy based control is made simple by accepting the slope of the P-V curve as input and generating single output as duty ratio of boost converter for GPPP tracking. The GPPP tracking algorithm provides faster convergence with minimum oscillations at final GPPP. Also, the scanning interval is reduced considerably by performing large step scanning of complete P-V curve. It is demonstrated through simulation outcome that the algorithm is capable of tracking the GPPP under any partial shadowing condition appreciably faster compared to existing algorithms.

The proposed PV system also provides compensation of the reactive power requirement of the load during day time along with active power injection into the grid. In the absence of sun during night, the inverter is utilized for reactive power compensation when it is not supplying any active power. This feature enhances the overall utilization of the proposed system. The voltage and current of the grid are in phase/anti-phase that justifies almost complete compensation of reactive power during varying load, different partial shading patterns, uniform and zero insolation.

The simulation results demonstrated by considering all possible situations of varying insolation, shading and load justify the robustness of the grid integrated PV system for active and reactive power flow control by means of fuzzy logic based GPPP tracking algorithm.

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