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Voltage Equalization for Partially Shaded Photovoltaic Generators with Coordinated Control and Protection for Islanded Hybrid Microgrid System

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Abstract: This paper provides the control and protection of hybrid microgrid system at stand-alone mode, grid connected mode and islanding mode of operations. The hybrid microgrid consists of solar, fuel cell and battery. The requirements of hybrid microgrid system are to maintain the constant voltage and frequency and to have the soft transition between the modes of operation and it also needs the balanced real and reactive power flow. To satisfy these mentioned requirements the control and protection of the hybrid microgrid system has to be implemented. The power system needs V-F control for the stand-alone and islanding modes of operation and it also requires P-Q control for the grid connected mode of operation using ICOSΦ control algorithm. To improve the efficiency of partially shaded photo-voltaic generators the voltage equalization technique with LLC resonant inverter is provided. To obtain the stable, reliable, secured and the steady state operation of the microgrid, the protection scheme is proposed in this paper.

Key words: Voltage and frequency control · Active and reactive power control · Protection · Solar · Fuel cell · Hybrid microgrid · Stand-alone mode · Grid-connected mode · Islanded mode · Distributed generation(DG) · Photovoltaic(PV) · Microgrid

INTRODUCTION

The Distributed Energy Resources (DER) is of smaller scale production of power in order of 1KW to 50MW which can be used by the end users. These electric power generations makes the power system to get decentralized by the process restructuring power system. It has low maintenance cost, running cost, higher efficiency and with low pollution. In this paper the distributed generators proposed are PV-solar and fuel cell which are renewable energy producers. It produces clean and green energy which is eco-friendly to nature. The Distributed Generation (DG) has several advantages which provide energy at the emergency power supply, reduction in peak power requirements and provision of ancillary services like regulation, operating reserves, reactive power supply and blackstart. The solar is the renewable form of energy which can be used for bulk power production in the power system. Due to the introduction of net metering the PV plays an important role in the field of power system. A small scale PV is considered for the grid connected mode to control both real and reactive power in the system. For the easy mode of control abc to dq0 transformation and vice versa is required [1]. For the frequency control both battery and super capacitor is used as energy storage device and also different frequency scenarios are considered [2].

In a series connected solar photovoltaic module as shown in Fig. 1, performance is adversely affected if all its cells are not equally illuminated [3]. All the cells in a series array are forced to carry the same current even though a few cells under shade produce less photon current. The shaded cells may get reverse biased, acting as loads, draining power from fully illuminated cells. If the system is not appropriately protected, hot-spot problem can arise and in several cases, the system can be irreversibly damaged. In the new trend of integrated PV arrays, it is difficult to avoid partial shading of array due to neighbouring buildings throughout the day in all the seasons. This makes the study of partial shading of modules a key issue. The model is used to study the effect of shade on varying number of cells on the power output of the module and stresses on the shaded illuminated cells under various illumination levels. The current delivered by the PV generators which depends on solar radiation and temperature of the cell are found by the equation (1)

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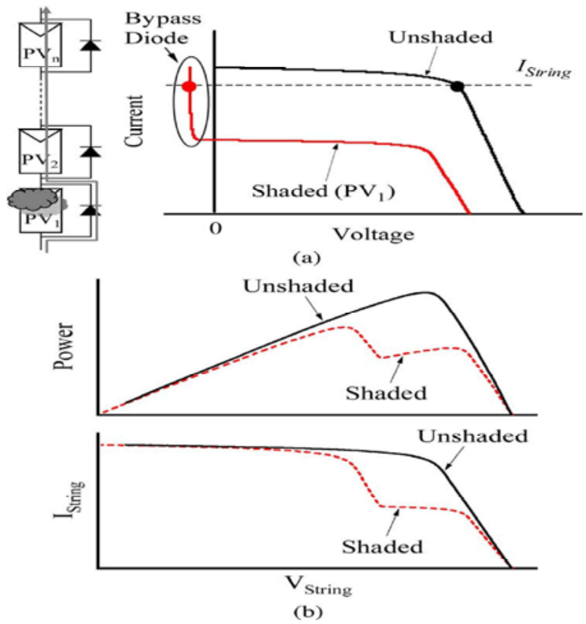

Fig. 1: PV under partially shaded condition. (a) Current path and module characteristics (b) String characteristics.

$$I_{PV} = (I_{PV,n} + K_1 \Delta T)\frac{G}{G_n} \quad (1)$$

where $I_{PV,n}$ is the photo current at standard test condition (STC, 25°C and 1000W/m^2). K_1 is the ratio of the short circuit current and temperature coefficient. ΔT is the difference between actual and the nominal temperature in Kelvin. G is the radiation on the given surface in W/m^2 and G_n is the nominal radiation in W/m^2. The fuel cell is also one of the renewable form of energy which need the continuous supply of oxygen and hydrogen from the environment. The best solution for the supply of hydrogen is bio-mass system. The PV cannot provide the continuous supply to load, but fuel cell has the ability to supply power uninterruptable manner. The control and protection for this hybrid system are required to get the stable, reliable and flexible operations of the microgrid system. The modes of operation of hybrid microgrid are standalone mode, grid connected mode and islanding mode. The control has to be provided for the all three modes of operation and its soft transition of its control modes. The operating modes are controlled by use of Icosφ control algorithm. The traditional droop controller provides the voltage sag and voltage swell compensation [4]. This paper provides the Voltage-Frequency (V-F) control for standalone, islanding modes of operation and also real - reactive power (P-Q) control for grid connected mode of operation [1-4]. It also provides the control for

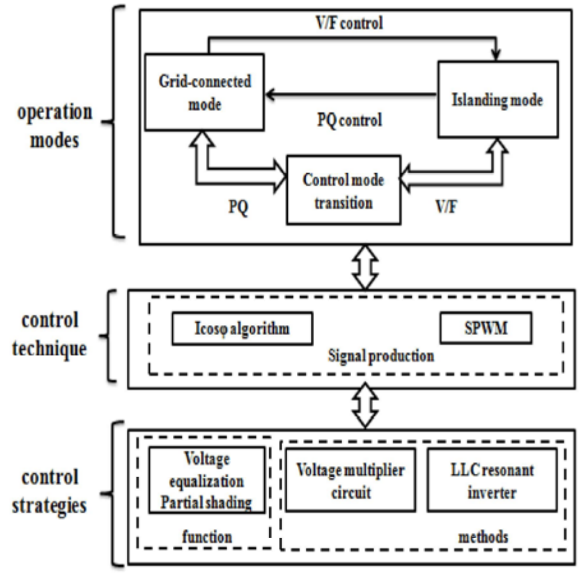

Fig. 2: Overall PV system control

battery i.e. charging and discharging of both batteries according to the DC microgrid voltage. The controls strategies proposed will provides the perfect solution for critical problems faced in the microgrid. In addition to this effective control, protection has to be provided to fulfill the requirements of the hybrid microgrid. The system has to be protected for purpose of safety and reliability. The maximum short circuit current rating is has to be limited or less than two times of the rated current of more DG connected to the microgrid. The protection at the islanded mode has to be provided to maintain reliable and secure operation of the hybrid microgrid [8-10]. Here no fault or islanding is detected, because the system is made islanded intentionally for the purpose of maintenance or other severe three phase faults.

Control Scheme for Hybrid System

Control of Hybrid System Topology: The operating modes of hybrid microgrid system are stand-alone mode, grid-connected mode and islanding mode of operation in the power system. To satisfy the main requirement of hybrid microgrid the hierarchical control structure has to be framed and it is given in architecture as shown in the Fig.2. The control architecture provides the V-F control to the stand-alone mode and islanding mode of operation and P-Q control to the grid connected mode in the power system [1-3]. Soft transition between the modes had to be provided for the system. i.e. from stand-alone or islanding mode to grid connected mode and vice versa by the control transition.

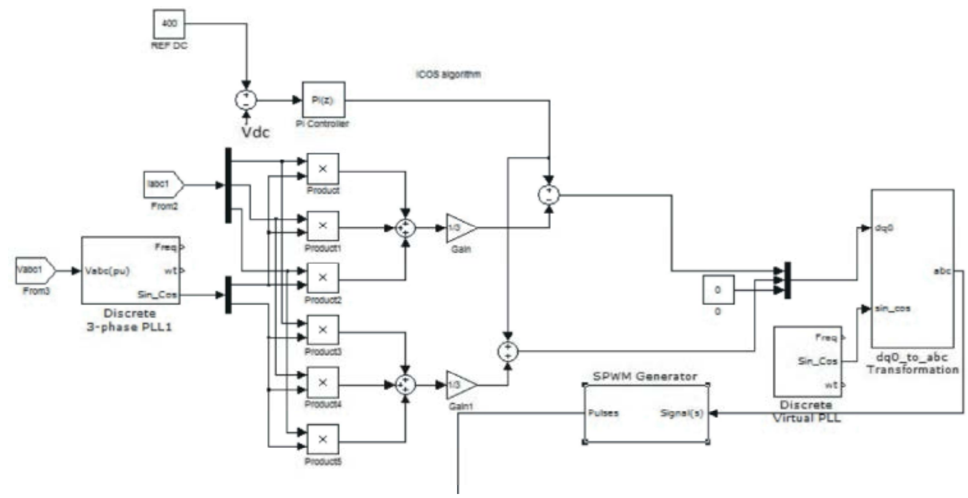

Fig. 3: Icosφ algorithm for control

Modes of Operation and its Control:

Stand-alone Mode: The sources of DC microgrid such as solar, fuel cell and battery are the main source of supply for the load at the stand-alone mode of operation. The DC microgrid should have the equal capacity to run the load. The proposed V/F control is provided for this mode by using of IcosΦ control algorithm as shown in the Fig. 2. In Fig. 2, v_{dc} denotes the voltage across the dc micro grid and v_{abc1} denotes 3-phase voltage across ac grid. The reference voltage across dc microgrid is taken as constant 400V. I_{abc1} gives the current in the ac grid. The sinusoidal and cosine waves are generated corresponding the given grid voltage values. Then cosine and sinusoidal components are separated and multiplied and it is averaged and dq0 components are generated. The generated dq0 components are converted into abc component for the control for 3-phase given to the inverter. It is then given to sinusoidal pulse width modulation (SPWM) pulse generator for V/F control in the proposed system. The proposed V/F controller has good dynamic response.

Grid-connected Mode: The system shifts from stand-alone mode to grid connected mode when the load gets increased. In this mode only DC microgrid can't satisfy the full load, so both DC microgrid and AC grid supplies to the load. The proposed Icosφ algorithm provides the real and reactive power control for this mode of operation[5] as shown in the Fig 3.

Islanded Mode: In this mode of operation, the grid intentionally disconnected for the purpose of maintenance. This mode has more difference from the stand-alone mode of operation. At this mode also DC microgrid is the main source of supply but it can't satisfy the load fully, so the protection system requires for the grid connected mode of operation. The V-F control is proposed for this mode as shown in the fig.3 using IcosΦ control algorithm.

Transition from Stand Alone or Islanded Mode to Grid-connected Mode: The self-synchronization is adopted for the seamless control at the transition from stand alone or islanded mode to grid connected mode. This is a step by step process and it is given as.

Step1: Preparation of voltage regulation:

Voltage regulation is a regulation to set the voltage in the specified limits. The voltage at the microgrid is maintained by using the V-F control with the calculated and the reference voltage. It is given in the equation as

$$\left.\begin{array}{c} |f_{mic} - f_{grid}| \leq f_{limit} \\ \left(\left(|V_{grid}| - |V_{mic}|\right)/|V_{grid}|\right) \times 100\% \leq V_{limit} \\ |\theta_{mic} - \theta_{grid}| \leq \theta_{limit} \end{array}\right\} \quad (2)$$

where f, v and Δ are the frequency, voltage magnitude and phase angle respectively. The 'mic' and 'grid' denotes the microgrid and power distribution grid respectively. The 'limit is the threshold value.

Step 2: Contactor states transition:

The voltage and frequency is synchronized with the main grid, the grid-connected contactor should be turned on by the BESS in the point of common coupling (PCC) is used. The power oscillations may occur at the time of contactor switching. To reduce this oscillations real and reactive power (PQ) control is required.

Step 3: Control modes transition:

Hence by tuning on the contactor at PCC, V/F control gets shifted to PQ control at the transition of stand-alone mode to the grid-connected mode.

Transition from Grid-connected Mode to Stand-alone or Islanded Mode: The self-isolation is adopted for the seamless control at the transition from grid-connected mode to stand alone or islanded mode of operations.

By controlling the voltage and frequency of the system PQ control in 3-phase can obtained and it explained by equation (3) and (4)

$$P_{abc} = V_{abc} I_{abc} cos\emptyset \quad (3)$$

$$Q_{abc} = V_{abc} I_{abc} sin\emptyset \quad (4)$$

The equation in the dq coordinates is given as (5) and (6)

$$P = V_d I_d + V_q I_q \quad (5)$$

$$Q = V_d I_Q - V_q I_d \quad (6)$$

Step1: preparing for power regulation:

The hybrid energy storage system (HESS) can achieve real and reactive power flow control by adjusting the power reference. It is given in the equation as

$$\left. \begin{array}{l} P_{pcc} \leq P_{limit} \\ Q_{pcc} \leq Q_{limit} \end{array} \right\} \quad (7)$$

P_{pcc} and Q_{pcc} are the real and the reactive power at PCC respectively. The P_{limit} and Q_{limit} denote the real and reactive power limit respectively or it can be stated as threshold values.

Step 2: Contactor states transition:

After regulating the real and reactive power flow regulation, the BESS is used to turn off the contactor at the point of common coupling (PCC). The voltage oscillations may occur at the time of contactor switching. To reduce this oscillations the V/F control is required for the system.

Step 3: Control modes transition:

Hence by tuning off the contactor at PCC, PQ control gets shifted to V/F control at the transition of grid-connected mode to the stand-alone mode of operation. From the above over all controllers the voltage, frequency, real and reactive power is within the specified limits are provided for the system.

Effects of PV Partial Shading: Shading of solar cells is a critical issue in their performance because [4]-[6]:

- As the shaded cells can get reverse biased they consume power instead of generating power resulting in loss of total output power.
- The power losses in the individual shaded cells would result in local heating and increase the temperature affecting surrounding cells. The increase in temperature creates thermal stress on the entire module and cause hot spots and local defects which potentially result in the failure of the entire array.
- Under extreme cases of shading the reverse bias on the solar cell might exceed its breakdown voltage. The cell gets fully damaged, develops cracks and an open circuit can occur at the serial branch where the cell is connected.

Voltage Equalizer: The voltage equalizer is accomplished by including of the diode and the inductor as in basic converter. The voltage multiplier technique is used to increase the static gain of voltage equalizer [6]. Many operational characteristics of the basic converter are changed with the proposed modification. The inductor is charged with the output voltage of the PV panel. The Fig. 4 provides the voltage equalizer circuit for each PV array connected.

The bridgeless configuration will reduce the conduction losses and the multiplier cell will increase the gain and reduce the switch voltage stress. A single-ended primary-inductor converter stage is utilized. By actively controlling the dc link voltage with respect to the variation of voltage, the conversion efficiency of the voltage equalizer is always regulated to be the optimal value through keeping the switching frequency close to its primary resonant frequency and thereby minimizing the circulating current in the resonant tank. With the proposed maximum efficiency point tracking technique, the efficiency performance of voltage equalizer is improved across the wide battery voltage range. The input voltage is given through the input terminal of the equalizer from the PV panel. The energy stored in the input inductor L is transferred to the output through the

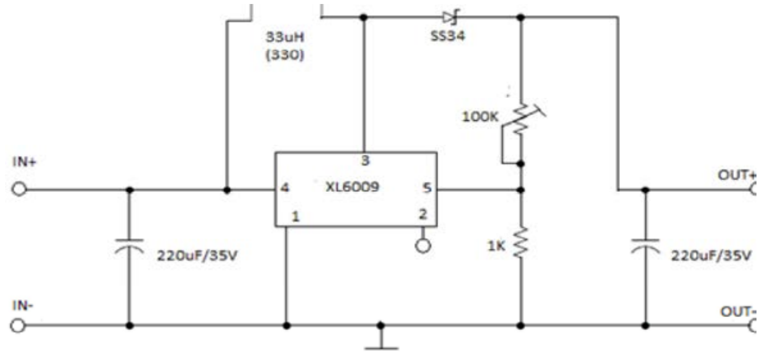

Fig. 4: Voltage equalizer circuit

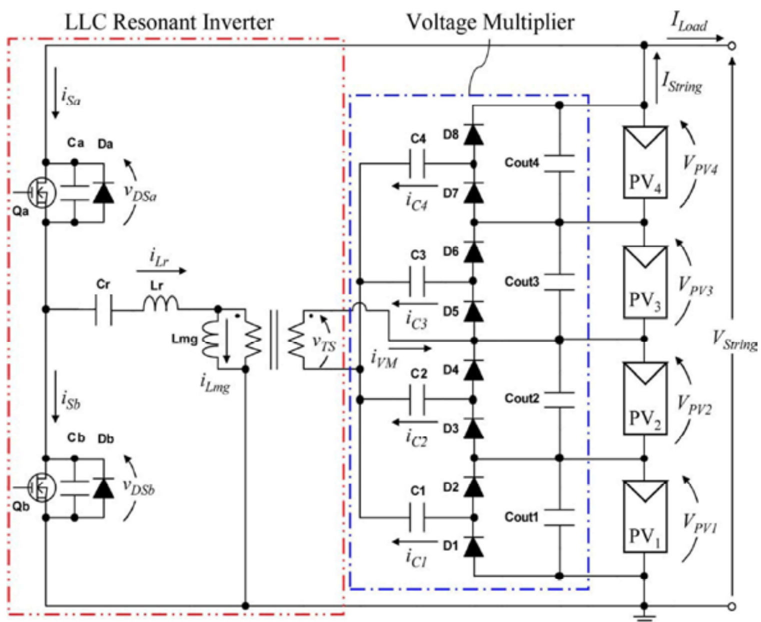

Fig. 5: Voltage multiplier with LLC resonant inverter

capacitor and output diode and also to the capacitor through the diode. Therefore, the voltage is equal to the capacitor voltage. A converter is proposed for actively control the dc link voltage and track over the wide voltage range. The Performance analysis of dc-dc converter with variac has keep wide output voltage in low input voltage conditions.

The voltage multiplier with LLC resonant inverter provides the concept of voltage equalization as shown in the Fig. 5. Resonance is the critical problem in the power system. Instead of considering resonance as a problem, the system used it as a voltage equalization technique with some parameters limited.

Droop Control: The droop control has to be performed for battery energy storage system (BESS) for the charging and the discharging of battery which increases the life cycle of the battery and provide safety for the battery from the overcharging. The droop control is provided by the droop graph which provides threshold limits for the charging and discharging of batteries.

The droop curve Fig. 6 provides the clear overview of the battery control technique. It takes the microgrid voltage as a reference voltage. The constant voltage for the microgrid provided should be of 400V.

Any fault occurs or if load gets increased the microgrid voltage get reduced. If the microgrid voltage crosses below the 380V the battery should operate at the discharge mode to compensate the grid voltage and to maintain the microgrid voltage as 400V. By balancing the load and the generation the voltage and frequency control can be maintained constant at the ac grid in all modes of operation. If load gets decreased the system voltage gets increased. If the microgrid voltage crosses beyond

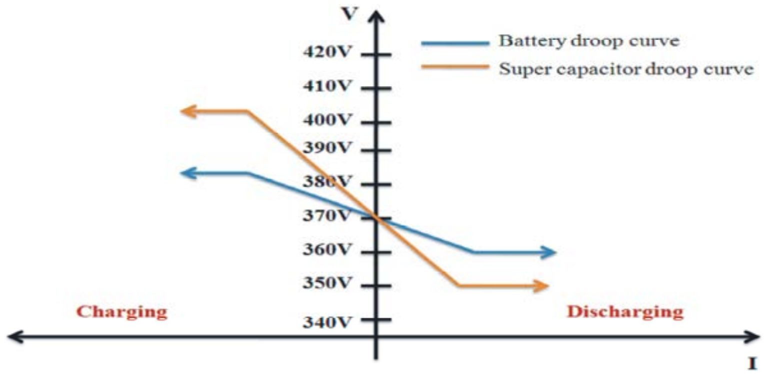

Fig. 6: Proposed droop control

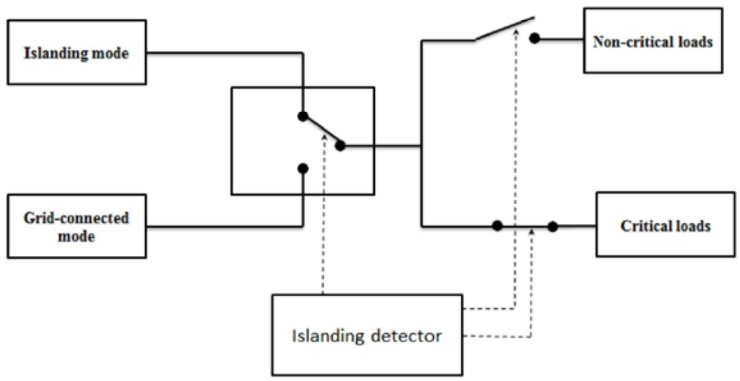

Fig. 7: Block diagram for protection scheme

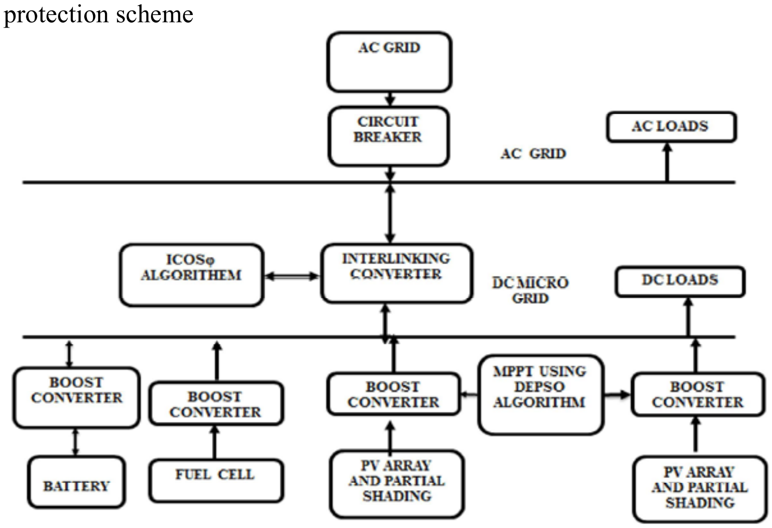

Fig. 8: Topology of hybrid microgrid

the limit of 380V the battery can be operated at the charging mode. Hence charging and discharging of the batteries can be performed by using the droop curve.

Protection Scheme of Hybrid System

Structure of Protection System: At the intentional islanding scheme the protection is required for the secure, reliable and stability of the system. The Fig. 7 provides the protection block diagram for the islanded mode of operation. At this mode the DC microgrid will not have the ability to provide the loads while shifting from grid connected mode of operation. So load has to be divided into two categories and they are critical loads and non-critical loads. While the intentional islanding mode takes place the DC microgrid only supplies to the critical loads by tripping of non-critical loads using of islanding detecting system. Hence the power system obtains the stable, reliable and secured operation.

Hybrid Grid Topology: The topology shown in Fig. 7 helps to design the test system in MATLAB Simulink. This provides the basic structure, over-all control and protection associated in the power system.

RESULTS AND DICUSSIONS

Stand-alone Mode: At the stand-alone mode all the DC sources such as solar, fuel cell and battery produces of constant 400V DC in which all are connected in parallel. This provides the constant 400 DC microgrid voltage to the power system which is shown in the Fig. 8.

The V-F control is provided at this mode of operation. The Fig. 9 shows the three phase RMS voltage and current across the AC grid in the power system. The controller provides the constant voltage and frequency from the time duration of 0.5 to 1.0 seconds and it is clear from the Fig. 9.

Grid Connected Mode: In this mode of operation both AC grid and DC microgrid supplies to both AC and DC loads in the system. The real and reactive power control is provided using the suitable controller for this mode of operation. The P-Q control is shown in the Fig.9 and 10 at the AC grid and loads.

Islanded Mode and its Protection: The intentional islanding takes place at the time of AC grid maintenance or during the occurrence of fault. At this time the AC grid

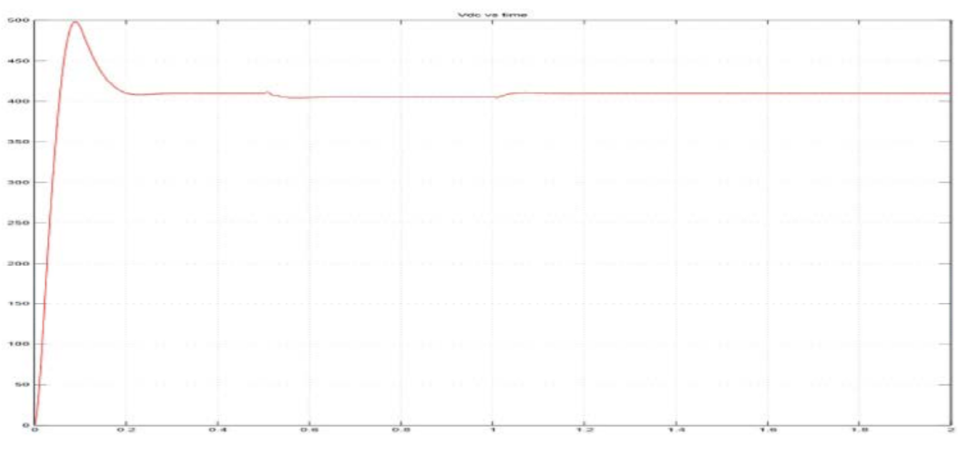

Fig. 8: DC microgrid voltage

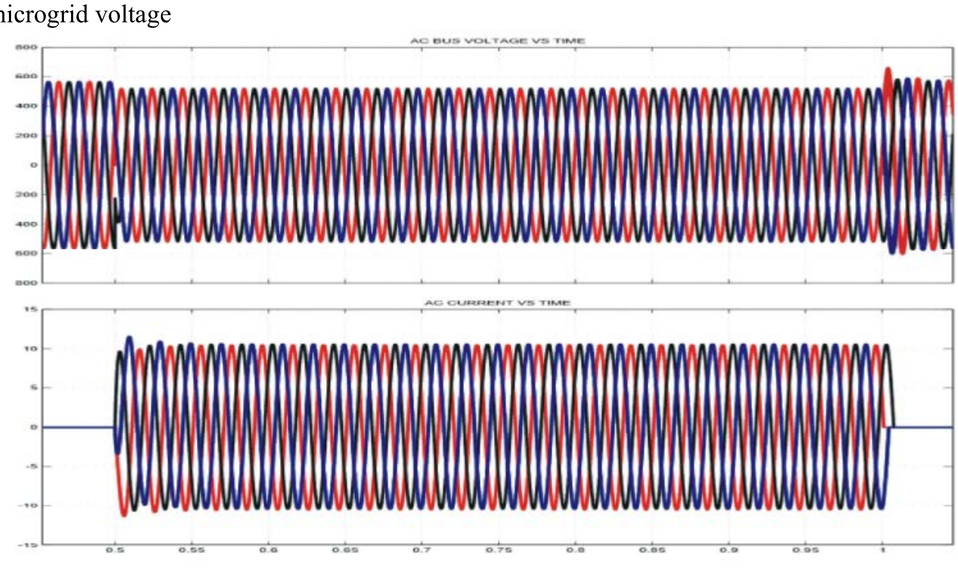

Fig. 9: Voltage and current at AC grid

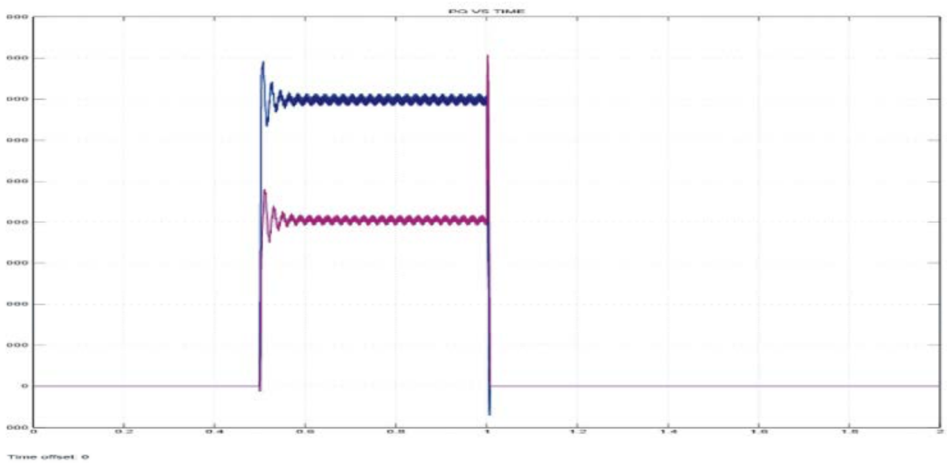

Fig. 9: Real and reactive power at AC grid

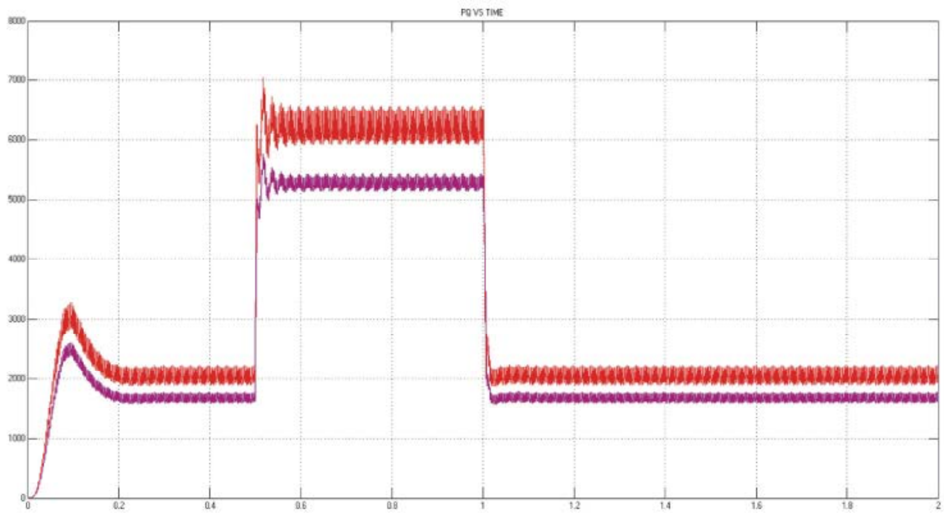

Fig. 10: Real and reactive power at AC load

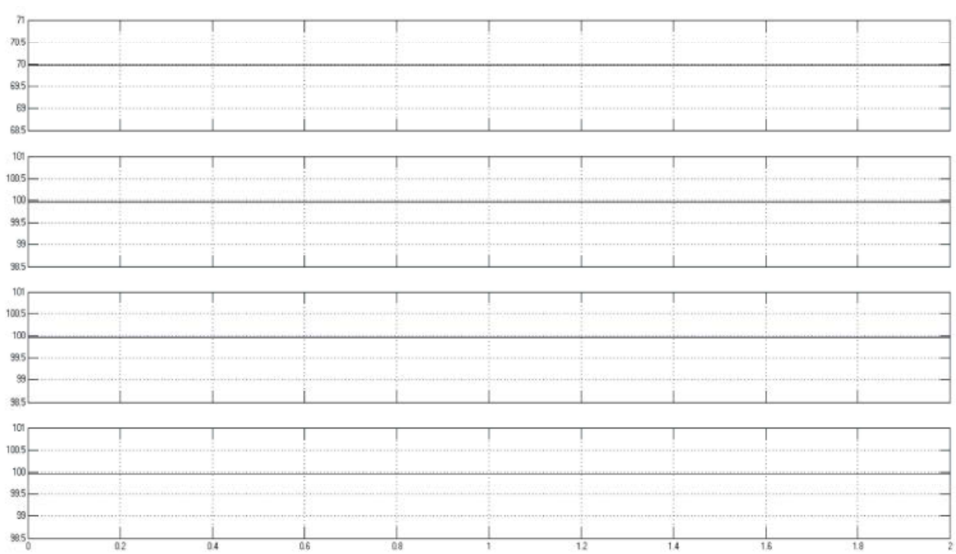

Fig. 11: Voltage supplied by each PV array

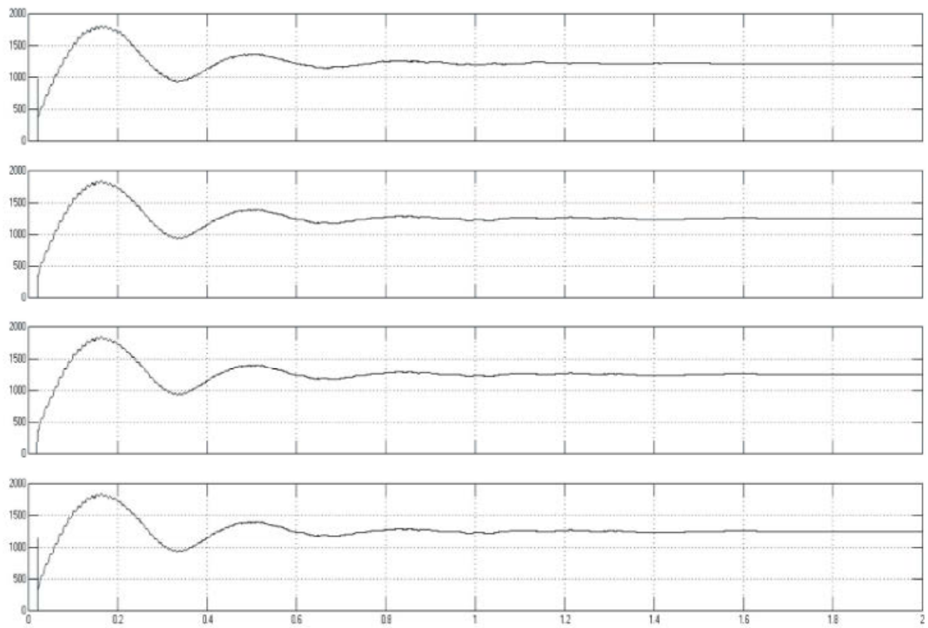

Fig. 12: Constant power supplied by each PV array

is tripped off, only the microgrid has to supply the power at that time for the loads in the system. At the Fig.9 and 10 at the time duration of 1.0 to 2.0 second the operation of islanding takes place. At that time no real and reactive power will be supplied by the load. During this mode of operation the DC microgrid can't satisfy the load fully. So protection has to be provided to maintain the load generation balancing. For this only critical loads are supplied by the DC microgrid system, while the non-critical loads are tripped intentionally.

PV Shading Condition: Consider the PV panel has four arrays, in which one of the PV array is affected by partial shading condition which provides 70V DC as other PV arrays gives of 100V DC as shown in the Fig.11 in which all are connected in series.

Though one of the panel is partially shaded, by the technique of voltage equalization constant 1200W DC Power is supplied by each PV array as shown in the Fig. 12.

CONCLUSION

The proposed simulation results provides the following conclusion are

- Thus the effective microgrid and grid synchronization is obtained using the ICOSΦ controller algorithm at post intentional islanding operation.
- Soft transition of grid connected to the islanded mode and vice versa with its control mode transitions is obtained successfully and it is clear from the results.
- Voltage equalization at partially shaded PV with MPPT is obtained by using LLC resonant inverter. Hence efficiency of the PV gets increased.
- Hence this hybrid system provides the stable, reliable and flexible operations in power system with higher efficiency.

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