Solar PV-BES Based Microgrid System with Seamless Transition Capability

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Abstract — This paper demonstrates a solar photovoltaic (PV)-battery energy storage (BES) based microgrid system with multifunctional voltage source converter (VSC). It deals with maximum power extraction from a PV array, reactive power compensation, harmonics elimination and seamless transition from the grid connected mode (GCM) to standalone mode (SAM) and vice versa. The maximum power extraction from a PV array, is achieved by using a DC-DC converter. A bidirectional DC-DC converter (BDDC) is used for regulating the DC link voltage. Whenever the BES is not connected then the VSC performs the regulation of the DC link voltage. The system behavior is studied on a prototype of the microgrid system under various operating conditions.

Keywords — Solar PV array, MPPT, DC-DC converter, BES, BDDC, VSC, SAM and GCM, power quality.

I. INTRODUCTION

The increasing population and industrialization, demands huge amount of energy. It is not possible to meet the energy demands by the conventional sources alone due to their depleting nature. So the renewable energy sources are becoming important. The energy production from the renewable sources is not causing any environmental pollutions hence it becomes popular for generating electrical energy [1-2]. Due to the ease of availability, environment friendly scheme and the absence of rotating parts in the energy conversion, makes the solar energy as prior choice among other renewable energy sources.

The main drawback of the solar energy, is its intermittent nature. So the battery energy storage (BES) is provided to meet the load demand without causing any interruption. Solar photovoltaic (PV)-BES based microgrid system is reported in the literature [3-4]. The extraction of maximum power from the solar PV array is achieved by using maximum power point tracking (MPPT) algorithm. Some of the MPPT control algorithms are reported in the literature [5-6]. In addition to the maximum power extraction, the improvement of power quality becomes an important consideration in the microgrid system due to the use of nonlinear loads at the point of common coupling (PCC). This task is achieved by controlling the voltage source converter (VSC). Various control algorithms are developed for improving the power quality. Some of the control algorithms are discussed in the literature [7-8].

The sudden failure of the grid is usually happened due to the occurrence of fault in the system. So it needs to operate the system in standalone mode (SAM), in order to ensure the continuity in supplying the load. Thus, the system needs to transfer its operation from grid connected mode (GCM) to SAM and vice versa without causing any oscillations or overshoots. The seamless transition can be achieved by using proper control techniques. Some control techniques are reported in the literature that presents seamless transition between GCM to SAM and from SAM to GCM [9-10].

This paper deals with a solar PV-BES based microgrid system. Here the DC-DC converter performs the extraction of maximum power from a PV array. The DC bus voltage regulation is performed by the bidirectional DC-DC converter (BDDC), by operating as in boost or buck mode depending upon the mode of operation. The VSC is controlled such that multifunctional feature is achieved, such as reactive power compensation, harmonics elimination, balancing of grid currents, operation in SAM and seamless transition from the GCM to SAM and vice versa. Whenever the BES is present in the system then the control of VSC is such that the constant power is fed to the grid. This avoids the power fluctuations in the grid that arises due to the continuous variations in the solar irradiance.

II. SYSTEM DESCRIPTION

Fig. 1 shows the PV-BES based microgrid configuration with multifunctional VSC. The DC-DC boost converter extracts the peak power from a PV array. The BDDC regulates the DC link voltage to the desired DC voltage. The VSC converts the DC power into AC power and it feeds to the PCC through interfacing inductors. The system operates in GCM when the grid is available and it operates in SAM when the grid fails. It also performs seamless transition from the GCM to SAM and vice versa. The ripples in grid and load voltages, are eliminated by using ripple filters in the grid and load sides.

III. CONTROL STRATEGY

The control of proposed microgrid configuration is composed of MPPT control and the VSC control.

A. MPPT Control

The MPPT control is used for extracting the maximum power from the solar PV array in all operating conditions. Here, the perturb & observe (P&O) algorithm is used for harvesting the peak power. It gives a reference voltage (\(V_{mp}\)), which corresponds to the maximum power point (MPP) voltage.

B. VSC Control

This proposed configuration works in both GCM and SAM. So, the control for the VSC, is different in these operating conditions. The control of the VSC in GCM and SAM, are discussed in the following sections.

1) Control of VSC in GCM of Operation

In the GCM of operation, different cases are considered, mainly a fixed power mode (FPM) and variable power mode (VPM). Whenever, the BES is present in the system, then the FPM of operation takes place that is a fixed power is fed to the utility grid irrespective of the solar PV generated power. When the BES is absent, then the VPM of operation takes place that is the power feeding to the grid is depending on the solar PV generating power. The control of VSC in GCM of operation, is
Where, $e_{ad}(j)$ is the error of adaptive component, $\mu$ and $\lambda$ are step size and mixing parameter, respectively.

$$e_{ad}(j) = i_{ad}(j) - u_{ad}(j)w_{ad}(j)$$  \hspace{1cm} (9)

Where, $w_{ad}(j)$, $i_{ad}(j)$ and $u_{ad}(j)$ are the active weight, load current and the in-phase unit template of ‘a’ phase respectively at the $j^{th}$ instant.

Similarly, the phase ‘b’ and ‘c’ reference active current components are estimated as,

$$w_{bd}(j + 1) = w_{bd}(j) + \mu u_{bd}(j)[2\lambda e_{bd}(j) + (1 - \lambda)\text{sign}(e_{bd}(j))]$$  \hspace{1cm} (10)

$$w_{cd}(j + 1) = w_{cd}(j) + \mu u_{cd}(j)[2\lambda e_{cd}(j) + (1 - \lambda)\text{sign}(e_{cd}(j))]$$  \hspace{1cm} (11)

**c) Generation of Reference Grid Currents**

The performance is carried out at unity power factor (UPF) operation at the grid side. In FPM operation, the grid active weight $w_{gf}$ is given as,

$$w_{gf} = w_{gf}$$  \hspace{1cm} (12)

Where, $w_{gf}$ is the fixed weight that is fed to the utility grid. In VPM operation, the total active weight ($w_{gf}$) of grid currents is given as,

$$w_{gf} = w_{gf} + w_{ci} - w_{pv}$$  \hspace{1cm} (13)

Where, $w_{avg}$ is the average active weight of load currents and is given as,

$$w_{avg} = \frac{w_{avg} + w_{bf} + w_{cf}}{3}$$  \hspace{1cm} (14)

The weight $w_{bf}$ is the active loss component, which is utilised for regulating the DC link voltage and $w_{pv}$ is the weight of PV power.

The reference grid currents are obtained as,

$$i_{ga} = w_{gf}u_{ga}, i_{gb} = w_{gf}u_{gb}, i_{gc} = w_{gf}u_{gc}$$  \hspace{1cm} (15)

The switching pulses for the VSC, are generated by using the hysteresis controller. The error signals obtained by comparing the reference grid currents and the sensed grid currents, are fed to the hysteresis controller, which gives the switching pulses.

2) **Control of VSC in SAM of Operation**

The reference load voltages are given as,

$$v_{ja}^* = V_{ja}^* \sin(w_{ja}t), v_{jb}^* = V_{jb}^* \sin(w_{jb}t - \frac{2\pi}{3}), v_{jc}^* = V_{jc}^* \sin(w_{jc}t + \frac{2\pi}{3})$$  \hspace{1cm} (16)

Where, $V_{ja}^*$ and $w_{ja}$ are the amplitude and frequency (314 rad/sec) of the voltages.

These reference load voltages are compared with the sensed load voltages. The error signals are fed to PI controller, which gives the reference load currents. These reference load currents are compared with the sensed load currents and the hysteresis controller gives the switching signals for the VSC in SAM. The control of VSC in SAM is depicted in Fig. 3.

**C. Synchronization Control**

The synchronization control is depicted in Fig. 4. When the grid voltage magnitude ($V_{p}$), grid frequency ($f_{p}$) and the difference between the grid phase angle ($\theta_{p}$) and load phase angle ($\theta_{l}$) become in the specified range then the main grid is connected to the system by controlling the solid state switch. Otherwise, the system operates in the SAM.

**D. DC-DC Boost Converter Control**

It tracks the PV array at its MPP. The duty cycle for the boost converter switch is generated as,

$$D = 1 - \frac{P_{pv}}{V_{p}}$$  \hspace{1cm} (17)
Where, error signal, which is given to a PI controller. The PI controller compared with the sensed DC link voltage yields output signal is given to another PI controller, which gives the controllers are used for generating the duty signals for the switches. The PI voltage when the BES is present in the system. The PI controllers are used for generating the duty signals for the switches. The PI controller output expression is given as, 
\[ i_{dc} = w_{rd} + w_{rb} + w_{rc} \]
(18)
Where, \( K_{rd}, K_{rb}, K_{rc} \) are gains of the PI controller.

The reference battery current \( (I_b) \) from the PI controller is compared with the sensed battery current \( (I_s) \). The compared output signal is given to another PI controller, which gives the duty signals for the switches. The PI controller output expression is given as,
\[ D(j+1) = D(j) + K_{pd}(I_{pb}(j+1) - I_{ps}(j)) + K_{pd}I_{pd}(j+1) \]
(20)
Where, \( I_{pb}(j) = I_{pb}(j) - I_{ps}(j) \)
\( K_{pd} \) and \( K_{pd} \) are the gains of the PI controller.

**IV. TEST RESULTS**

The system response under different operating modes, is analysed by conducting experiments on the system prototype.

**A. Performance of System in GCM of Operation**

The GCM of operation of proposed system in different operating scenarios, is discussed in the following sections.

1) **Steady State Response of Solar PV-BES**

Fig. 6 shows the steady state behavior of the system at 1000W/m² solar irradiation. Fig. 6 (a) shows the grid voltages and grid currents waveforms. Figs. 6 (b)-(c) show the total harmonic distortions (THDs) of grid voltages and grid currents, it shows the THDs of grid voltages and grid currents are within the recommended values. The performance is studied while feeding a fixed power of 1.7kW to the utility grid as shown in Fig. 6 (d). Figs. 6 (e)-(f) show the load current waveforms and load power. Fig. 6 (g) shows the load current THD. It is 24.3%, since the load is nonlinear consisting of diode bridge rectifier with RL load. Figs. 6 (h)-(i) show the VSC current and the VSC power. Fig. 6 (j) shows the battery voltage and battery current. Here, the BES is operated in charging mode since the solar PV array generating power is higher than the load demand and the fixed grid power. The solar PV array voltage, current and power at 1000W/m² irradiance, are depicted in Fig. 9 (a). From this, it is clear that the maximum power is well extracted from the PV array at 1000W/m² irradiance. Fig. 6 (k) shows the DC link voltage and DC link current. It gives, the BDDC regulates the DC link voltage to the desired value.

2) **Dynamic Response under Solar PV Array Disconnection**

Fig. 7 shows the dynamic response of the system under the disconnection of the PV array. Fig. 7 (a) shows the grid current, load current, battery current and the PV array current. Fig. 7 (b) shows the grid power, load power, battery power and the PV array power. Here, the performance is studied in FPM operation. Initially, the irradiance is 1000W/m², so the excess power is available after meeting the fixed grid power (1.7kW) and the load demand, which is used for charging the BES.
When the solar PV array is disconnected then the BES changes from the charging mode to discharging mode in order to keep the power that is fed to the grid as constant and for supplying the load demand as shown in Fig. 7 (b). Fig. 7 (c) shows the grid voltage, DC link voltage, PV array voltage and PV array current. It shows that the DC link voltage is maintained to the desired voltage even though during the disturbance in the solar irradiance.

3) Dynamic Response under Varying Irradiance

Fig. 8 shows the VPM operation of the microgrid configuration under varying irradiance. In this mode of operation, the BES is not present. Here the performance is analysed by changing the solar irradiance from 1000W/m² to 500W/m² and after some time the PV array is disconnected. Fig. 8 (a) shows the grid power, load power, PV array power and the PV array current. The performance is studied at constant load power.

When the irradiance is reduced from 1000W/m² to 500W/m², the PV array power is reduced, thereby the power that is fed to the grid, is also reduced and it is depicted in Fig. 8 (a). After the solar PV array disconnection, the grid power becomes positive. That is now the grid is supplying the load demand. Fig. 8 (b) shows the grid voltage, grid current, VSC current and the PV array current during the irradiation change from 1000W/m² to 500W/m² and during the solar PV array disconnection. Fig. 8 (c) shows the grid voltage, load current, DC link voltage and the PV array current. Even though during the disturbances in the solar irradiation, the DC link voltage is maintained to the desired voltage by the VSC. The variations of internal signals such as total grid active weight, average active weight of load currents and PV feed forward weight with respect to the PV array current, are depicted in Fig. 8 (d). After the PV array disconnection, the system is working as distribution static compensator (DSTATCOM).

![Fig. 6 Steady state response of PV-BES microgrid system in GCM (a) grid voltages and grid currents, (b)-(c) harmonic spectrum of grid voltages and grid currents, (d) grid power, (e) load current, (f) load power, (g) harmonic spectrum of load current, (h) VSC current, (i) VSC power, (j) battery voltage and battery current, (k) DC link voltage and DC link current](image1)

![Fig. 7 (a)-(c) Dynamic response under solar PV array disconnection](image2)
Figs. 9 (a)-(b) show the performance of the PV array at 1000W/m² and 500W/m² solar irradiations. It depicts that the maximum power is effectively extracted from the PV array.

4) Dynamic Response under Unbalanced Nonlinear Load

Fig. 10 shows the response of the system under unbalanced load condition. Here the performance is studied at 1000W/m² irradiance and without BES. This mode of operation is dealt with VPM. Fig. 10 (a) shows grid voltage, grid current, VSC current variations with respect to the load current. The unbalance is created by removing the ‘a’ phase load for a particular duration of time. During the load removal, the current fed to the grid is increased. Fig. 10 (b) shows the grid power, PV array power, load power and the load current. It shows that during the removal of load current in ‘a’ phase the power fed to the grid is increased. Here the PV array power is unaltered. Fig. 10 (c) shows the DC link voltage, PV array voltage, PV array current and the load current. It shows that the DC link voltage is regulated to desired voltage by VSC even during the load disturbances. Figs. 10 (d)-(e) show the variations in the internal signals during the load unbalance. Fig. 10 (d) shows the total grid active weight, ‘a’ phase unit template and ‘a’ phase reference grid current with respect to the load current. Fig. 10 (e) shows the average active weight of load currents, error signal, and active weight of ‘a’ phase load current with respect to the load current. During the load removal, the active weight of ‘a’ phase becomes zero and hence the average active weight of load currents, is reduced. Figs. 10 (f)-(g) show the waveforms of grid currents with grid voltages and the grid current THDs, respectively before the load unbalancing. Figs. 10 (h)-(i) show the grid current waveforms with grid voltages and the grid current THDs at load unbalancing. It is clear that the current THDs are within the recommended value.

B. Performance of System in SAM of Operation

The performance of the microgrid configuration in SAM of operation is depicted in Fig. 11. Fig. 11 (a) shows the load voltages and the load currents. Fig. 11 (b) shows the THDs of the load voltages. It is clear that the THD of load voltages are within the level recommended by the IEEE 519 standard. Here, the performance is studied for a decrease in solar irradiance from 1000W/m² to 500W/m². Fig. 11 (c) shows DC link voltage, battery voltage, battery current and the PV array current. The DC link voltage is regulated to desired voltage by the BDDC. During the reduction in the irradiance, the battery changes its mode from charging to discharging in order to meet the load demand.

C. Seamless Transition of Microgrid from GCM to SAM and Vice Versa

Figs. 12 (a)-(b) show the seamless transition capability of the proposed system from GCM to SAM and from SAM to GCM.
Fig. 12 (a) shows grid voltage \( v_g \), load voltage \( v_L \), grid phase angle \( \theta_g \) and load phase angle \( \theta_L \). When the grid fails, the grid voltage and the grid phase angle, become zero. When the grid is restored, \( \theta_L \) tracks \( \theta_g \) with synchronization control. Fig. 12 (b) shows grid voltage \( v_g \), load voltage \( v_L \), grid current \( i_g \) and the load current \( i_L \). Here the performance is studied at 500W/m² irradiance and FPM operation. When the grid fails, the grid voltage becomes zero then the VSC control is shifted to the SAM control hence the load voltages are maintained to the desired voltages. The main grid is connected to the system when the grid voltage magnitude \( V_t \), sine of the phase angle difference \( \theta_g - \theta_L \) and the grid frequency \( f_g \) are become within the specified limits.

D. Comparison of Proposed Control with Conventional Controls

The proposed control is compared with the conventional least mean fourth (LMF) and least mean square (LMS) controls under the unbalanced load condition. Figs. 13 (a)-(b) show the variations of the active weight of the load current of phase ‘a’ \( w_{ia} \) and the average active weight of the load currents \( w_{Lavg} \). It shows that the oscillation associated in the weight with the proposed RMN control, is lesser as compared to those with the conventional LMF and LMS controls.

Fig. 10 (a)-(i) Dynamic response under unbalanced nonlinear load

Fig. 11 (a)-(c) Performance of the system in SAM of operation
V. CONCLUSION

The seamless transition of PV-BES microgrid from GCM to SAM and vice versa with compensation of reactive power and harmonics, balancing of grid currents and maximum power extraction from the PV array are demonstrated in this work. The PV array maximum power is harvested by controlling the DC-DC converter. The BDDC functions the regulation of the DC link voltage to the reference voltage. Whenever the BES is absent, then the control for regulating the DC link voltage, is automatically shift to VSC. The comparative analysis depicts that the proposed RMN control gives performance better than the conventional LMF and LMS controls.

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APPENDICES

<table>
<thead>
<tr>
<th>Test parameters</th>
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<tr>
<td>PV array $V_{mp}=360$ V, $I_{mp}=10.3$ A, $P_{mp}=3.7$ kW</td>
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<tr>
<td>DC-link voltage $V_{dc}=380$ V</td>
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<td>DC link capacitor $C_{a}=3$mF</td>
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<td>Battery $240$ V, $49$ Ah</td>
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<tr>
<td>Grid voltage $V_{LL}=230$ V (rms)</td>
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<tr>
<td>Interfacing inductor $L_{f}=4$mH</td>
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<tr>
<td>Step size $\mu=0.0156$</td>
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<tr>
<td>Mixing parameter $\delta=0.5$</td>
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REFERENCES