Abstract— In this paper, a solar Photo Voltaic (PV)-battery energy storage based micro-grid with a multifunctional Voltage Source Converter (VSC) is presented. The maximum power extraction from a PV array, reactive power compensation, harmonics mitigation, balancing of grid currents and seamless transition from Grid Connected (GC) mode to Stand-Alone (SA) mode and vice versa, are performed in this system. Whenever the grid fails, this system operates in SA mode automatically, thereby without causing any interruption in supplying the load. Similarly, it automatically shifts to the GC mode, when the grid is restored. The VSC functions in current control for GC mode, and it operates in voltage control for SA mode of operation. This system is capable of extracting the maximum power from the solar PV array irrespective it is operating in the GC mode or SA mode. The charging and discharging of the battery are controlled by using a bidirectional dc–dc converter. It regulates the dc-link voltage to the maximum power point voltage of the PV array. If the absence of the battery is detected, then the control is automatically shifted to VSC for performing the extraction of the maximum power of the PV array.

Keywords: Battery energy storage (BES), bidirectional dc–dc converter (BDDC), grid connected (GC) mode, power quality, solar photovoltaic (PV) array, standalone (SA) mode.

1. INTRODUCTION

DUE to the depletion of conventional energy sources and environmental impacts, the role of renewable sources for energy generation has become a prior choice nowadays. Due to the ease of availability, environment friendly nature, and the reducing trends in the cost of solar photovoltaic (PV) panels, solar-based energy generation has become popular as compared to other energy sources [1]. The main drawback of solar energy is its intermittent nature. So the PV array alone is not possible to meet the load demand at every time. This causes poor reliability of the system. This problem is overcome by using battery energy storage (BES) along with PV array [2].

There are several configurations, which are available for integrating the PV array and BES into the utility grid. A single stage grid interfaced solar PV-BES system is reported in the literature with maximum power extracting capability [3]. A grid integrated PV-BES system involving two stage conversion is also reported in the literature [4], where the extraction of maximum power from the PV array is achieved by using maximum power point tracking (MPPT) control, which generates duty cycle for the dc–dc converter.

The power quality aspects are met by controlling the voltage source converter (VSC) with proper control algorithms. Most of the loads connected at the point of common coupling are highly inductive and nonlinear loads. Due to the highly inductive loads, the power factor of the grid side is poor and the nonlinear loads cause high distortion in the grid currents and that further distorts the grid voltages. So the power quality improvement plays a vital role in the grid connected PV system. The solution to the power quality issues like harmonics, reactive power burden, and load unbalance, etc., is achieved by the use of a distribution static compensator (DSTATCOM) [5]–[7]. Due to its simplicity, fast and stable operation makes it an attractive solution to load compensation over passive compensation. The DSTATCOM is a shunt connected compensating device hence its operation is based on current control mode. So the switching of DSTATCOM is decided by the generated reference currents through an appropriate control technique. There are several controls, which are implemented by the researchers for improving the power quality and are reported in the literature such as instantaneous reactive power theory [8], synchronous reference frame theory [9], instantaneous symmetrical component theory [10], least mean square (LMS) [11], self-tuning filter [12], hyperbolic tangent function [13], digital disturbance estimator [14], etc. The effectiveness of the control algorithm is decided by how fast it responds to the dynamic condition with lower oscillation in weight. Here, a leaky least mean mixed norm (LLMMN) [15] adaptive control is used for controlling the VSC in the grid connected (GC) mode of operation. This control algorithm provides fast operation during the dynamic change with minimum oscillations in the estimated weight.

This article presents PV-BES-based microgrid system with the main features of maximum power extraction from the PV array, balancing of grid currents, unity power factor (UPF) operation at grid.
side, harmonics elimination, SA mode of operation and seamless transition from the GC mode to SA mode and vice versa.

2. EXISTING SYSTEM

In existing method instantaneous reactive power theory, synchronous reference frame theory, instantaneous symmetrical component theory, Least Mean Square (LMS), self-tuning filter, hyperbolic tangent function, digital disturbance estimator are used for power quality improvement.

2.1 Disadvantages
- Complexity is high.
- Size of the system is high.
- Oscillations are high.

3. PROPOSED SYSTEM

In proposed system Leaky Least Mean Mixed Norm (LLMMN) adaptive control is used for controlling the VSC in the Grid Connected (GC) mode of operation.

3.1 System Configuration

The PV-BES based microgrid [20] is depicted in Fig. 1. It includes a PV array, a BES, a BDDC, a three-leg VSC, three-phase grid, and nonlinear loads. The grid outage and grid restoration, are realized by using a solid-state switch at the grid side. Ripple filters are used at the grid side and the load side, to remove the ripples in voltages. A BDDC is used for controlling the charging and discharging of the BES. A DSP (dSPACE 1006 real-time controller) is used for generating the switching signals to the VSC.

3.2 Control Strategy

The control strategy of the microgrid is broadly classified into four parts: MPPT control, VSC control, synchronization control and BDDC control. These control strategies are described in the following sections.

a) MPPT Control

Whenever the solar PV array is producing power, it needs to extract the peak power from it whether the system is operating in the GC mode or in the SA mode of operation. Here, perturb & observe (P&O) control technique is used for performing this task.

b) VSC Control

This system is operating in two modes. One is in GC mode when the grid is present and the other is in SA mode when the grid is absent. The structure of VSC control is depicted in Fig. 2. 1) Control of VSC in GC Mode of Operation: In GC mode, if BES is present, then VSC is operated to feed a constant power to the grid. Here, BDDC maintains the dc-link voltage to the desired voltage. If BES is absent in the system, then the VSC performs the regulation of the dc-link voltage to the desired voltage and this mode leads to variable power feeding to or drawing from the grid depending upon the PV generation and the load demand. The control of VSC in GC mode is shown in Figure. The main steps of VSC control in GC mode are discussed as follows.

Calculation of unit templates: The grid phase voltages are estimated as follows:

\[ v_{ga} = \frac{2v_{gb} + v_{gbc}}{3}, \quad v_{gb} = \frac{-v_{gb} + v_{gbc}}{3}, \]

\[ v_{gc} = \frac{-v_{gb} - 2v_{gbc}}{3} \quad (1) \]

where \( v_{gb} \) and \( v_{gbc} \) are the sensed grid line voltages.

The amplitude (Vt) of the grid voltages is given as follows:

\[ V_t = \sqrt{\frac{2}{3}(v_{ga}^2 + v_{gb}^2 + v_{gc}^2)}. \quad (2) \]

The in-phase unit templates are generated as follows:

\[ u_{ia} = \frac{v_{ga}}{V_t}, \quad u_{ib} = \frac{v_{gb}}{V_t}, \quad u_{ic} = \frac{v_{gc}}{V_t}. \quad (3) \]

d) Calculation of active loss components

In the GC mode of operation, when the BES is absent, then the VSC performs the regulation of the dc-link voltage to the desired voltage; otherwise, the BDDC performs the regulation of the dc-link voltage to the desired voltage. The MPPT control gives the reference dc voltage \( V_{dc}^* \) corresponding to the MPP voltage. The comparison of reference dc-link voltage \( V_{dc}^* \) with the sensed dc-link voltage \( V_{dc} \) at the jth instant, is given as follows:

\[ V_{dc}(j) = V_{dc}^*(j) - V_{dc}(j). \quad (4) \]

Whenever the PV array is not able to generate power, then suddenly the reference dc voltage \( V_{dc}^* \) shifts...
from Vpvp∗ to a constant dc voltage (Vdcmin = 365 V). Thereby, the disturbance is not affected by the dc-link voltage. The regulation of the dc-link voltage is achieved by a proportional-integral (PI) controller by utilizing the error voltage (Vde). The output of the PI controller is given as follows

\[ w_{ci}(j + 1) = w_{ci}(j) + K_{pd}(V_{d}(j + 1) - V_{d}(j)) + K_{id}V_{d}(j + 1) \]  

(5)

where wci is the active loss component, and Kid and Kpd are the gains of the PI controller.

e) Calculation of feed-forward components

The feed forward component for constant power feeding mode, is given as follows:

\[ w_{fg} = \frac{2P_{fixed}}{3V_{t}} \]  

(6)

where Pfixed is the fixed power supplied to the grid. The feed-forward weight of the PV power is given as follows:

\[ w_{pv}(j) = \frac{2P_{pv}(j)}{3V_{t}} \]  

(7)

where Ppv is the power output from the PV array.

f) Calculation of fundamental active weights of load currents

The fundamental active weight of load current of phase ‘a’ using LLMN adaptive control is given as follows

\[ w_{ia}(j + 1) = (1 - \mu)e_{ia}(j) + \mu e_{ia}(j) \times \{\delta + (1 - \delta)e_{ia}^{2}(j)\} u_{ia}(j) \]  

(8)

where eia(j) is the error of adaptive component, \( \mu \) is the step size, \( \alpha \) is the leakage factor, and \( \delta \) is the mixing parameter

\[ e_{ia}(j) = i_{La}(j) - u_{ia}(j)w_{ia}(j) \]  

(9)

where wia(j), iLa(j), and uia(j) are the active weight, load current, and the in-phase unit template of “a” phase at the jth instant. Similarly, phase “b” and “c” reference active current components are estimated as follows:

\[ w_{ib}(j + 1) = (1 - \mu)e_{ib}(j) + \mu e_{ib}(j) \times \{\delta + (1 - \delta)e_{ib}^{2}(j)\} u_{ib}(j) \]  

(10)

\[ w_{ic}(j + 1) = (1 - \mu)e_{ic}(j) + \mu e_{ic}(j) \times \{\delta + (1 - \delta)e_{ic}^{2}(j)\} u_{ic}(j) \]  

(11)

g) Estimation of reference grid currents

The performance is studied at the UPF operation at the grid side. In UPF operation, the reference grid currents are generated by utilizing the total active weight wgi.

Table 1

<table>
<thead>
<tr>
<th>Mode of operation</th>
<th>Condition</th>
<th>Components present in wgi</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode I- Fixed power</td>
<td>Both solar PV array and RES are present</td>
<td>wgi</td>
</tr>
<tr>
<td>Mode II- Fixed power</td>
<td>Only RES are present</td>
<td>wgi</td>
</tr>
<tr>
<td>Mode III- Variable power</td>
<td>Only solar PV array is present</td>
<td>wgi + wpv</td>
</tr>
<tr>
<td>Mode IV- Variable power (DISTATCOM operation)</td>
<td>Both solar PV array and RES are absent</td>
<td>wgi + wpv</td>
</tr>
</tbody>
</table>

Different modes of operation. The active weight terms present in weight wgi are shown in Table I. Where wfg is the fixed weight that is fed to the utility grid. wLi is the average active weight of load currents and is given as,

\[ w_{Li} = \left(\frac{w_{ia} + w_{ib} + w_{ic}}{3}\right) \]  

(12)

wci is responsible for dc-link voltage regulation, and wpv is the weight of solar PV array power. The reference in-phase grid currents are obtained as multiplying the weight wgi with the unit templates and are given as follows:

\[ i_{ga}^* = w_{gi}u_{ia}, \quad i_{gb}^* = w_{gi}u_{ib}, \quad i_{gc}^* = w_{gi}u_{ic}. \]  

(13)

h) Generation of switching pulses

The switching signals for the VSC in GC mode are generated by feeding the error signals obtained by comparing the reference grid currents (i∗ga, i∗gb, and i∗gc) and the sensed grid currents (iga, igb, and igc) to the hysteresis controller.

Control of VSC in SA Mode of Operation: In SA mode, reference three-phase load voltages are generated as follows:

\[ v_{La}^* = V_{*}^{*}\sin(\omega_{o}t), \quad v_{Lb}^* = V_{*}^{*}\sin(\omega_{o}t - \frac{2\pi}{3}), \quad v_{Lc}^* = V_{*}^{*}\sin(\omega_{o}t + \frac{2\pi}{3}) \]  

(14)

where V∗ is a magnitude of the reference voltages, and \( \omega_{o} \) is the nominal frequency of 314 rad/s. The reference voltages (v∗La, v∗Lb, and v∗Lc) are compared with the sensed load voltages (vLa, vLb, and vLc) and the resulting error signals are fed to PI controllers. The PI controller output is reference load currents (i∗La, i∗Lb, and i∗Lc), which are compared with the sensed load currents (iLa, iLb, and iLc) and the outputs are fed to a hysteresis controller for generating the VSC control pulses in SAmode. The block diagram of SAmode control of the VSC is shown in Fig. 2. When the grid phase voltage magnitude Vt goes higher than Vtmn, then the reference voltage phase angle is replaced by θnew for grid synchronization.

i) Hysteresis controller
Basic self-oscillating controllers based on hysteresis are well described in the literature [1,2]. The hysteresis controller can be made with either a current- or a voltage loop. The benefits of hysteresis controllers are primarily the linear modulation caused by the sawtooth-shaped carrier with ideally straight slopes, and by the infinite power supply rejection ratio, PSRR, if the supply variation can be considered very slow compared to the switching frequency. Power supply variations at higher frequencies are not suppressed totally, and will result in sum and difference products of the reference signal and the power supply variation, but these still meets high suppression. For use in audio amplifier applications, the hysteresis controller is very desirable due to the high linearity and simple design. However, hysteresis controllers suffers from a switching frequency dependent on the modulation index, M, of the amplifier. All other basic types of self-oscillating modulators suffer from this phenomenon too.

The above figure shows current mode and voltage mode implementations of the basic hysteresis controller. The basic operation of the current mode hysteresis controller is: The output inductor integrates the differential voltage between the output voltage of the power stage and the output voltage of the amplifier. If the output voltage of the amplifier can be considered constant within one switching period, the integration results in a sawtooth shaped inductor current, which is subtracted from the reference current programming voltage, and fed into a hysteresis window to control the switching frequency by controlling the time-delay trough the controller loop. The voltage mode hysteresis controller differs from the current mode controller by integrating the difference between the output voltage of the power stage and the input reference voltage with an active integrator, which again results in a sawtooth shaped carrier that is fed to a hysteresis window. The major functional difference between the two is that the current mode controller is a voltage controlled current source with an integrated output filter. The voltage mode controller is a voltage controlled voltage source without output filter. Both controllers have a first order closed loop function. In switch mode audio amplifier applications some additional control feedback loops are often desired to reduce distortion caused by non-linearities in the circuit. Furthermore if a current mode controller is used, a voltage feedback control loop is required since an audio amplifier as often is a voltage amplifier. To reduce distortion as much as possible, it is desired to apply the voltage feedback after the output filter, so errors from both power stage and output filter will be reduced.

In the ideal model for a hysteresis controller, the switching frequency is dependent on the modulation index, M, by:

\[ f_s(M) = f_s(0) \cdot (1 - M^2) \]

In this paper a second integrator block inserted before the hysteresis window in either a current or a voltage mode controller is proposed to obtain a close to constant switching frequency, regardless of M.

The proposed modulator is shown Figures for both current and voltage mode operation. The extra integrator integrates the sign of the first saw tooth shaped carrier signal that results in a pure triangular shaped second carrier overlapped by the reference signal. The PWM signal to the power stage is made from the second carrier signal fed into a hysteresis window. The modulator loop has maintained a 1st order behavior at high frequencies, since the first comparator effectively differentiates the high frequencies, and followed by the second integrator, the -90º phase shift at high frequencies is maintained. The variable modulator forward gain is made by the second carrier signal, which will be a triangular shaped signal overlapped by the reference signal. For a DC reference signal, the second integrator will simply increase the forward gain by shift the second carrier signal with respect to ground, and ideally obtaining exactly the same forward gain and thereby the same switching frequency at all modulation indexes, M. The ability of keeping the switching frequency constant depends on the slopes of the
reference signal, since the correction of the falling switching frequency corresponds to the gain of the second integrator, which means that the switching frequency will have larger deviations from a constant value with high frequency reference signals at high levels, but if the time constant of the second integrator is high compared to the corresponding time constant for the reference signal, only small variations will occur at the switching frequency.

j) Synchronization Control

The synchronization control is depicted in Figure. The grid voltage magnitude, sine of the difference between the grid phase angle (θg) and load phase angle (θL), and the grid frequency (fg) are checked, whether those are within the prescribed limits. If the conditions are satisfied, then the output of the AND gate becomes “1” and that makes the solid-state switch shown in Fig., closed, then the grid is connected to the system and the VSC operates into the GC mode of operation. If any of the conditions, is not satisfied, then the output of AND gate becomes “0” hence the solid-state switch remains in open and the SA control is applied to VSC.

![Figure: (a) and (b) Synchronization control](image)

k) BDDC Control

The control for the BDDC is shown in figure. The comparison of the reference dc-link voltage (Vdc*) with the sensed dc-link voltage (Vdc) gives an error signal and that is fed to a PI controller. This PI controller regulates the dc-link voltage to the desired value. The output of this PI controller is reference battery current (Ib*) and it is compared to the sensed battery current (Ib) and the resulting signal is given to another PI controller. This gives the duty cycle for the BDDC. The comparison of this duty signal with the saw-tooth wave gives the pulsewidth modulation signal for the BDDC.

![Figure: BDDC control.](image)

l) Neural network

A neural network is a network or circuit of neurons, or in a modern sense, an artificial neural network, composed of artificial neurons or nodes. Thus a neural network is either a biological neural network, made up of real biological neurons, or an artificial neural network, for solving artificial intelligence (AI) problems. The connections of the biological neuron are modeled as weights. A positive weight reflects an excitatory connection, while negative values mean inhibitory connections. All inputs are modified by a weight and summed. This activity is referred to as a linear combination. Finally, an activation function controls the amplitude of the output.

4. RESULTS

The simulated performance of the microgrid is studied using MATLAB/Simulink toolbox. The performance is studied under various operating conditions at a line voltage of 230 V, 50 Hz.

4.1 Solar PV-BES Based Microgrid System With Multifunctional VSC

![Figure: Steady-state operation of the microgrid in GC mode.](image)
Figure: Steady-state operation of the microgrid in SA mode.

Figure: Performance of microgrid under a change in the level of solar irradiation.

Figure: Seamless transition of microgrid from GC mode to SA mode.

Figure: Seamless transition of microgrid from SA mode to GC mode.
4.2 By using Neural Networks

Figure: Steady-state operation of the microgrid in GC mode.

Figure: Performance of microgrid under a change in the level of solar irradiation.
CONCLUSION

The operation of the microgrid in different modes is investigated in this work, which proves the multifunctional capability of the system. This system operates in both GC mode and SA mode without causing any interruptions in load supply and also performed the seamless transition capability from GC mode to SA mode and vice versa. A BDDC performs the extraction of maximum power from the solar PV array when the BES is active in system performance. Whenever the BES becomes inactive, then the MPPT control is automatically shifted to VSC control, thereby the PV array is operated at its MPP in all operating conditions. The comparative analysis depicts that the proposed LLMMN control gives better performance than the conventional LMMN and LMS controls.

REFERENCES


