SyRG-PV-Battery Based Standalone Microgrid with D-EPLL Based VSC Control Algorithm

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Abstract—This paper proposes a solar photovoltaic (PV)-battery-pico-hydro turbine driven synchronous reluctance generator (SyRG) based microgrid. The SyRG driven by pico-hydro turbine is the only AC generator, so a VSC (Voltage Source Converter) with damped E-PLL (Enhanced Phase Locked Loop) based control algorithm provides voltage regulation, harmonics mitigation and load balancing while feeding the nonlinear loads. To provide power balancing, a storage battery is connected across the DC link of VSC through a DC-DC bidirectional converter (BDC). The BDC with a storage battery, provides the optimal power flow to maintain the power equilibrium between load and sources through DC bus voltage regulation. Moreover, BDC mitigates the second harmonic current from the battery charging and discharging current. A solar PV array is connected to the DC bus of VSC. For extracting the maximum power from the solar PV array, the MPPT (Maximum Power Point Tracking) is achieved by BDC. In the laboratory, a prototype of the system is developed and tested under different situations to confirm the effectiveness and viability of control strategy.

Index terms—Bidirectional Converter, Damped EPLL, Power Quality, Pico-Hydro Generation, PV (Photovoltaic), SyRG (Synchronous Reluctance Generator).

I. INTRODUCTION

Foremost, concern of current environment situation, is the alarming rise in the rate of the greenhouse effect and global warming. Hydro, solar and wind energies, are some of the renewable energy sources (RES), which offer solution for depletion of fossil fuel and environmental pollution [1]. These renewable energy sources, are used in remote areas due to lack of road infrastructure and the grid non-availability. Since the grid is not available, one of the major problems, is generation away from the load, which increases the distribution losses. Thus the solution is the installation of rooftop PV (Photovoltaic) array in an isolated microgrid. The solar PV array provides the benefit of low maintenance, grid parity and fast installation [2]-[3]. Due to nonlinear characteristics of PV array across the terminals, maximum power of PV array, is tracked using MPPT (Maximum Power Point Tracking). A MPPT technique namely INC (Incremental Conductance) is used for extracting the maximum power from a given PV array and active power is fed to DC link [4]. There is intermittency of PV array power due to continually varying weather conditions and nonlinear characteristics thus it is imperative that other sources like BES (Battery Energy Storage), DG (Diesel Generator), and fuel cells, are to be integrated. A storage battery is a promising alternative, which is widely used to balance the source fluctuations. Therefore, during load dispatch, the extra energy is stored and the battery discharges during peak load hours. BES can also deliver significant crucial services such as load shifting, dynamic local load support, short-term frequency smoothing, and also reduces support from fossil fuel based generation [5]-[7]. When the battery is directly connected across the DC link without any proper control of discharging and charging of the battery current then the battery is exposed to dominant second order harmonic component, which leads to degradation of the battery life. The bidirectional DC-DC converter (BDC) in proposed system, not only controls the mode of operation of the battery but it also extracts maximum power from the PV array. This converter controls the amount of active power and the direction of active power flow to regulate the DC link voltage. In addition, the bidirectional converter also removes the second order harmonic from the battery current. A bidirectional converter and a PV array with a well-organized configuration, are used in the proposed system. However in the two-stage system, the first converter implements MPPT and the VSC is used for AC conversion, which increases the system losses.

Therefore, PV array is used in the proposed system without boost converter. Moreover, the PV array has the inability to supply energy at nights and to optimize the use of the battery in the system, the hydro generation is used in collaboration. This is done, so that the hydro system provides a stable and continuous generation, which is especially important in the islanded microgrid. Pico-hydro turbine is proposed in this system because unlike large hydro plants, the pico-hydro plant does not need a building of a dam thus reducing the investment cost [8]-[10]. Normally for a pico-hydro application, a SEIG (Self-Excited Induction Generator) is used. A SyRG (Synchronous reluctance generator) has all the benefits of SEIG with an added benefit; in spite of excitation capacitance and loading condition the frequency remains constant [11]. Whereas PMSG (Permanent Magnet Synchronous Generator) is based on material such as neodymium iron boron (NdFeB) and offers higher efficiency, torque and low rotor bearing temperature. However, the main drawback is rare earth magnets, which are costly and are subjected to price variation. As compared to conventional IM (Induction Machine) and PMSG [12], SyRG provides REE (Rare Earth Elements) free, less maintenance, low operating temperature, and reduced inertia and high power density for a small foot print. Without cage and PM, the construction of the rotor, is much simpler in SyRG than IM or PMSG. The operation of pico-hydro generating system is considered as almost constant power source. When the suitable capacitor is connected to the stator terminals, it initiates the self-excitation. SyRG has high excitation current, the solution to which is the voltage source converter (VSC), which is capable of supplying the reactive power. Moreover, VSC also reduces the size of excitation capacitor [13]-[14]. The PCC voltage regulation and active power balance in
standalone microgrid, need a fast and accurate control algorithm for VSC. It is evident from the literature that many controls like SRF (Synchronous Reference Frame), SOGI (Second Order Generalized Integrator) and E-PLL (Enhanced Phase Locked Loop) have been implemented for VSC in the microgrid. Where SOGI has a good tracking capability but it has constant ripple even when the reference is stable. Moreover, in SOGI as compared to PLL based controller, there is an advantage of avoiding calculations of sine and cosine. However, it is essential to perform square root and inverse tangent computation for phase and amplitude calculation. Whereas E-PLL has wide acceptance as it provides noise rejection characteristic, simple structure, robust performance and signal parameter can be calculated directly. In the proposed system, damped E-PLL is proposed. The fundamental component from the nonlinear load current, is extracted using proposed damped E-PLL control algorithm, which shows the capability of DC offset filtering. Moreover, the implemented control has the additional advantage of noise rejection, high accuracy, robustness and fast frequency tracking characteristics [15]-[16].

II. STRUCTURE OF PROPOSED SYSTEM

A solar PV–BES-hydro based microgrid consisting of a 3.7 kW pico-hydro turbine driven SyRG is shown in Fig. 1. The pico-hydro based SyRG proposed in the system, is considered to be almost constant power source. A solar PV array is connected to the DC link, which is designed to generate a power of 1.40 kW. Moreover, the storage battery is also connected across the DC link through a BDC to maintain power balance during the dynamics in the system. Therefore, the BES stores the surplus power as well as supplies power during deficit. The VSC is connected in shunt through interfacing inductors, which provides voltage regulation, harmonics elimination and load balancing while feeding a nonlinear load. Moreover by using the interfacing inductors, high-frequency ripples are eliminated from the source currents whereas the RC filter is used to remove high-frequency ripple from the PCC voltages.

III. CONTROL ALGORITHM

The control of PV-battery pico-hydro based microgrid is categorized into two main parts: (1) DC-DC bidirectional converter control and, (2) VSC control, which is based on damped E-PLL control algorithm. The control of DC-DC bidirectional converter maintains the optimum active power balance by DC link voltage regulation. Whereas, VSC control provides voltages and frequency regulation, load balancing and harmonics elimination while feeding a nonlinear load.

A. VSC Control

The VSC control maintains the voltage and frequency of the system and also provides load balancing. In Fig. 2, the damped E-PLL control algorithm, is developed for evaluation of the fundamental component of load current. The proposed damped E-PLL control algorithm is stable, robust, it reduces the steady state error, provides immunity to noise and in addition damping, which removes the DC component during the transients. The AC side voltagte regulation and system frequency regulation, are obtained through PID (Proportional-Integral-Derivative) controller and PI (Proportional-Integral) controller, respectively. The amplitude of the terminal voltage, \( V_{\text{in}} \) is calculated as,

\[
V_{\text{in}} = \left( \frac{2}{3} \right)^{\frac{1}{3}} \left( v_{a}^2 + v_{b}^2 + v_{c}^2 \right)^{\frac{1}{3}}
\]

As \( V_{\text{in}} = V_{\text{abc}} \times V_{\text{dcm}} \), thus by sensing the two line voltages, phase voltages can be estimated as,

\[
v_{sa} = \frac{1}{3} \left( 2v_{sab} + v_{sbc} \right), \quad v_{sb} = \frac{1}{3} \left( -v_{sab} + v_{sbc} \right)
\]

\[
v_{sc} = \frac{1}{3} \left( -v_{sab} - 2v_{sbc} \right)
\]

The in phase unit templates and quadrature unit templates, are estimated as follows,

\[
u_{aq} = \frac{v_{ab} - v_{ac}}{3V_{\text{in}}}, \quad u_{ap} = \frac{v_{ab} - v_{bc}}{3V_{\text{in}}}, \quad u_{cp} = \frac{v_{ac} - v_{bc}}{3V_{\text{in}}}
\]

\[
u_{aq} = \frac{u_{ap}}{\sqrt{3}} + \frac{u_{cq}}{\sqrt{3}}, \quad u_{ap} = \frac{3u_{aq}}{2\sqrt{3}}, \quad u_{cq} = \frac{3u_{aq}}{2\sqrt{3}}
\]

For regulating the frequency, the reference frequency is compared with sensed frequency to generate a frequency error. The frequency error is given as,

\[
f_{e}(r) = f_{s}(r) - f_{c}(r)
\]

Where \( f_{s} \) is the system reference frequency, which is considered as 50 Hz and \( f_{c} \) is the frequency estimated by PLL. The frequency controller output is given as,

\[
I_{lp}(r) = I_{lp}(r-1) + K_{pf} \left[ f_{s}(r) - f_{c}(r) \right] + K_{qf} f_{c}(r)
\]

The average output of active fundamental load current \( I_{lp}^{\text{avg}} \) is then subtracted from the output of frequency controller \( I_{lp} \) then estimating the net fundamental current is given as,

\[
I_{lp}^{\text{avg}} = I_{lp} - I_{lp}^{\text{avg}}
\]

Where, \( I_{lp}^{\text{avg}} \) is the per phase active load current component. The load current fundamental component is harmonic free.
and sinusoidal, which is achieved by damped EPLL based algorithm. However, the shape of load current is quasi-square as it contains all the harmonics component. The fundamental current component of load current is achieved through D-EPLL as shown in Fig. 2. The fundamental current component of load current is estimated as [16],

\[
i_{L1} = \mu_4 e \sin \phi + \sigma_{L1} \tag{8}
\]

Where, \( e = i_{L1} - i_{L2} \) and \( \sigma = \mu_4 e \sin \phi \)

\[
i_{L2} = i_{L2} \sin \phi + d \tag{10}
\]

Where, \( d \) is used for DC offset compensation component and \( i_{L1} \) is fundamental component of load current, which is given as,

\[
i_{L1} = i_{L1} \sin \phi \tag{11}
\]

In (8) and (10), the value of \( \phi \) is estimated as,

\[
\phi = \mu_4 e \cos \phi + \omega \tag{12}
\]

Where, \( \omega \) is the system estimated frequency and it is expressed as,

\[
\omega = \mu_5 e \cos \phi \tag{13}
\]

Here, \( \mu_1, \mu_2, \mu_3 \) and \( \mu_4 \) are the constants of the DEPLL. The selection of these constant values are given here as,

\[
\mu_2 = \frac{\mu_1}{2f_0} = \mu_1, \mu_3 = \mu_4 = 2f_0 \text{ where } f_0 \text{ is the nominal frequency of oscillation, which is 50 Hz. The gain of the DC integrator } \mu_0 \text{ is given as,}
\]

\[
\mu_0 = \frac{\mu_3}{2} \tag{14}
\]

Thus the parameters calculated from these equations and these constants values are given as,

\[
\mu_0 = 25, \mu_1 = 100, \mu_2 = 50 \text{ and } \mu_3 = 62500
\]

After the extraction of load fundamental component, it is fed to sample and hold (S&H) logic. To find active power component \( (I_{pq}) \) of phase a, a constant value is fed to input of ZCD (Zero Crossing Detector). ZCD includes voltage compensator logic (S&H logic), which is used for triggering. Similarly, the phase’s b and c active components \( (I_{pqb} \& I_{pqc}) \) of load currents are assessed. The average active component per phase of the load currents, is estimated by using all three phase active components. For each phase, the average power load current component is calculated independently and it is given as,

\[
I_{lavg} = \frac{I_{lpa} + I_{lpb} + I_{lpc}}{3} \tag{16}
\]

The voltage PID controller gives the reactive power component for PCC voltage regulation and the mathematical expression of voltage PID controller is as follows,

\[
I_{r}(r) = K_p \left( V^* - V_r \right) + K_i \int \left( V^* - V_r \right) dt + K_d \frac{d}{dt} \left( V^* - V_r \right)
\]

\[
= K_p \left( V^* - V_r \right) + K_i \int \left( V^* - V_r \right) dt + K_d \frac{d}{dt} \left( V^* - V_r \right)
\]

\[
+ K_q \left( Q^* - Q_r \right) + K_d \frac{d}{dt} \left( Q^* - Q_r \right)
\]

\[
+ K_q \left( Q^* - Q_r \right) + K_d \frac{d}{dt} \left( Q^* - Q_r \right)
\]

Where

\[
V_r = V_m \cos \left( 2\pi f_0 t \right)
\]

\[
V_m = \text{the magnitude of AC supply voltages at the PCC}
\]

\[
V_{m} \text{ is reference three-phase magnitude of voltage at PCC. The average output of reactive fundamental load current } (I_{qavg}) \text{ is subtracted from the output of terminal voltage controller } (I_{qv}) \text{ and then the net fundamental current is estimated as,}
\]

\[
I_{q}(r) = \frac{I_{q} - I_{qav}}{3} \tag{17}
\]

Where the \( I_{qav} \) is the per phase reactive load current component and it is estimated as,

\[
I_{qav} = \frac{I_{qpa} + I_{qpb} + I_{qpc}}{3} \tag{18}
\]

Therefore, the reference in-phase and quadrature currents, are calculated as,

\[
i_{qpa} = I_{qpa} \times u_{ip}, i_{qpb} = I_{qpb} \times u_{ip}, i_{qpc} = I_{qpc} \times u_{ip} \tag{19}
\]

\[
i_{qpa} = I_{qpa} \times u_{ip}, i_{qpb} = I_{qpb} \times u_{ip}, i_{qpc} = I_{qpc} \times u_{ip} \tag{20}
\]

Thus the total reference currents \( (i_{qa}, i_{qb}, i_{qc}) \) are estimated as,
\[ i_{sa} = i_{qpu} + i_{qp}^* \]
\[ i_{sb} = i_{qgh}^* + i_{gh}^* \]
\[ i_{sc} = i_{qpu} + i_{qp}^* \]
\[ i_{ne} = i_{sa} - i_{sc}, i_{nh} = i_{sb} - i_{sc}, i_{ne} = i_{sa} - i_{sc} \]

Therefore for generating the gating signals of IGBT’s of VSC, these current error signals \((i_{ne}, i_{nh}, i_{ne})\) are given to the hysteresis current controller.

**B. Control Strategy of Bidirectional Control**

The control of BDC (Bidirectional DC-DC Converter) is shown in Fig. 3. The DC bus voltage of VSC is regulated by the BDC. The BDC performs buck and boost operations during charging and discharging of the battery current. The generation and the load, are synchronized by storage of surplus energy and supplying in case of deficiency. The DC bus voltage is maintained by the PI controller as,

\[ V_{dc}^* = V_{dc} - k_{mp} \left( V_{pv} - V_{dc} \right) \]

Where \( k_{mp} \) is the reference battery current EPC and \( V_{dc} \) is the sensed voltage of the DC link of VSC.

The battery current PI controller governs the duty cycle of converter and its value is estimated as,

\[ D_{dc} = D_{dc} \left( r-t \right) - k_{mp} \left( I_{desired} - I_{dc} \right) - k_{mp} I_{desired} \]

Where \( I_{desired} \) is the reference battery current, which is achieved from the DC-link PI controller and \( I_{dc} \) is the sensed battery current. By comparison of output of PI controller (duty cycle) with the saw-tooth signal, it generates the PWM pulse for the converter.

**IV. RESULTS AND DISCUSSION**

To authenticate the control algorithm and operational approach, a prototype of three-phase PV-battery-pico-hydro based microgrid is developed using IGBTs (Insulated Gate Bipolar Transistors) based VSC. The system dynamics and steady state condition, are demonstrated in the section. To emulate a rooftop solar PV array, a photovoltaic array simulator (AMETEK Make ETS600 17DPVF) is used. To sense various quantities, Hall-Effect current sensors (LAS5P) and voltage sensors (LV25), are used. The DSP (dSPACE 1103), a real-time controller is used to implement the control. For recording the steady state and the dynamic responses of the system, a digital storage oscilloscope of four channel (Agilent DSO model: DSO6010A) and a power analyzer (Fluke-43B), are used. In the following sections, the experimental performance under various operating conditions, is presented.

**A. Steady State Performance of Proposed Microgrid**

The performance of proposed PV-battery-pico-hydro based microgrid in steady state conditions, is shown in Fig. 4. Fig. 4(a) shows the generated voltage \((V_{pv})\), which is 192.3 V and current \((I_{pv})\) is 8.55A and these are sinusoidal in nature. Figs. 4(b) and 4(k) show the total generated power \((P_{pv})\), which is 4.03 kW from all renewable sources, SyRG power \((P_{sy})\) is 2.63 kW and solar PV array power \((P_{pv})\) is 1.40 kW. The performance of MPPT is shown in Fig.5.
B. Microgrid Dynamic Performance

To verify the proposed control dynamic performance, the change in level of insolation and load unbalancing, are presented here.

1) Microgrid Dynamic Performance under Change in Level of Solar Insolation

It is demonstrated in Fig. 6(a), as the solar insolation increases, it increases the produced power. The load is constant, the excess produced power is diverted towards the battery and the battery goes into charging mode. Thus it is seen that, the battery goes from discharging state to charging with an increase in level of insolation. In Fig. 6(a), it also shows the increase of level of insolation and there is no change in SyRG current and voltage of the system and the DC link voltage is also maintained constant. Similarly, when there is step decrease in insolation, the battery charging current decreases. Thus with same slope, there is decrease in PV array current. The battery goes from charging mode to discharging mode in the system to sustain the power equilibrium. For all the RES (pico-hydro, PV array), the load is less than the power generated. Thus under the dynamic condition of change in solar insolation, the controller sustains the power balance. Figs. 6(b)-6(c) show another RES solar PV energy, as its nature is uncertain. So with the change in insolation level, the output power of the solar PV array changes. When the power from pico-hydro is maintained constant with solar insolation increase, the battery goes in charging mode by using the additional power. Similarly, with a decrease in solar insolation, the battery discharges to feed the required load.

2) Microgrid Dynamic Performance under Change in Load

The dynamic response of the SyRG currents \((i_{sa}, i_{sb}, i_{sc})\) for sudden load changes, is verified by one phase load removal and inclusion as demonstrated in Fig. 7(a).

All the source currents \((i_{sa}, i_{sb}, i_{sc})\) remain balanced and sinusoidal as the decrease and increase in load currents are balanced by the BES to maintain the system frequency and voltage. When load of one phase, is removed then the load current decreases, thus the additional produced power is supplied to the battery because hydro runs at constant power. Now when the same phase of the load is injected into the system, the load current increases. Thus the extra power needed by the load, is provided from the battery to maintain the system power balance. SyRG is a constant power source thus there is no change in the source currents. Therefore, SyRG provides a constant power under the dynamic condition of load removal and inclusion. The performance of the system is checked from the capability of load injection and rejection. Fig. 7(b) shows the dynamic system response under a variation in nonlinear load. It shows that when there is one phase sudden load removal, it is witnessed that current of VSC \((i_{vsca})\) turns out to be sinusoidal for maintaining the voltage of PCC. Under sudden load removal, the battery starts charging. Whereas when one phase of load is injected, the VSC becomes nonsinusoidal injecting harmonics to the load for improving the quality of source current.

![Fig. 5 Solar emulator’s user interface showing P_{pv} and I_{pv} versus V_{pv}, performance of MPPT algorithm.](image)

![Fig. 6 Under dynamic performance (a) V_{dc}, I_{b}, v_{abc} & I_{pv} (b)-(c) I_{sa}, I_{sb}, I_{sc} & I_{pv} under solar insolation change.](image)
The dynamic and steady state balancing of the loads. To prove the feasibility of the system, a variety of results have been validated under unbalancing of the load. The dynamic and steady state performances of the system are found acceptable, and the THD of PCC voltages and source currents, is found within the tolerable IEEE 519 standard limits.

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