Sensorless SynRG Based Variable Speed Wind Generator and Single-stage Solar PV Array Integrated Grid System with Maximum Power Extraction Capability

Deepu Vijay M, Member, IEEE, Bhim Singh, Fellow, IEEE, and G. Bhuvaneswari, Fellow, IEEE

Abstract—This work presents a grid-integrated hybrid renewable energy sources based system comprising a solar PV array and a wind energy conversion system (WECS). The WECS uses a position-sensorless synchronous reluctance generator (SynRG) for the electric power generation from the wind turbine (WT), wherein a sensorless field-oriented control (FOC) is made use of for the maximum power extraction (MPE). A second order flux estimation (SFE) method along with frequency-locked-loop (FLL) is utilised for the accurate flux estimation from the SynRG stator voltages and currents. A set of back-to-back connected three-phase two leg voltage source converter (VSC) topology is selected for the grid integration of WECS. This system has a common DC-link where the solar PV array and the machine side VSC (MSC) of the wind generator, are directly connected. The power output from the solar PV array and WECS, is shared between the grid and the local loads. The maximum power generation from SynRG in the WECS, is achieved by operating the SynRG at the speed estimated by the MPE algorithm. The maximum power is drawn from the solar PV array by adjusting the DC link voltage, which is decided by the algorithm. For the proper power control and power quality improvement, the grid side converter (GSC) is adequately controlled by implementing an observer-based control technique. The real time validation of the system, is carried out using a developed laboratory prototype.


I. INTRODUCTION

The desire to alleviate pollution and to reduce CO$_2$ (Carbon Dioxide) emissions compounded with limited availability of fossil fuels and constraints in the expansion of conventional electricity production have led to the increased demand for electricity production from renewable energy sources. From the renewable energy family, electricity generation from solar and wind, has become more popular [1]. The year 2017, has seen worldwide wind power installation of 52,492 MW, which has resulted in a global cumulative installation of 539,123 MW [2], [3]. In India, the total installed capacity of wind energy generation is 32848.46 MW and that of solar is 16070.07 MW [4]. With the increase in installations of solar and wind based renewable energy sources, the risks associated with increased penetrations of renewable energy sources into the existing grid have also increased [5], [6]. The integration of solar and wind energy conversion systems to the grid, improves the reliability of the system in terms of power availability.

A back-to-back connected converter topology is the best-suited for the grid integrated variable speed wind turbine (VSWT) system, due to its enhanced performance [7]. The prime motivation for the worldwide acceptance of this topology, is that the grid side converter (GSC) and wind generator are fully decoupled and it is possible to operate the generator in full speed range. Moreover, smooth grid integration and reactive power compensation, are also added advantages for this topology [7]. The prime objective of using VSWT with a full-scale converter, is that it can improve the energy conversion efficiency, by using an effective maximum power extraction (MPE) algorithm, which can harvest the peak power at any wind speed. Usually, this MPE algorithm is useful when the wind speed is within the prescribed limit.

Synchronous generators (SGs) and induction generators (IGs) are commonly used in wind energy conversion systems (WECS). For VSWT based on full-scale converter topology, squirrel cage IGs (SCIGs) from induction generator family and permanent magnet SG (PMSG) and wound rotor SG (WRSG) from SG family, have found applications up to several megawatts of power rating [8]–[12]. The major drawbacks of the PMSG are the use of costly permanent magnets in its rotor whose availability and heavy weight are major concerns. Applications of PMSG are limited, due to the demagnetisation issues associated with the permanent magnets when exposed to higher temperature and opposing magneto-motive forces (MMF). To eliminate the drawbacks of PMSG, mentioned above, an axially laminated anisotropic synchronous reluctance generator (SynRG) can be used in variable speed WECS. Advantages of SynRG as compared to PMSG and IGs are, the absence of permanent magnets, improved efficiency due to the absence of rotor currents and their associated losses, ease of control, and its rugged structure. The synchronous reluctance...
machine (SynRM) as a motor is already discussed in [13] and [14]. Improved rotor design of the SynRM has made it more suitable for its application as a generator (SynRG) [15].

Sensorless control of the cage-less axially laminated reluctance motor is initially reported in [16], where the estimated angle is not used for the inverter control. In [17], a sensorless torque vector based closed-loop speed control of the synchronous reluctance motor is proposed. However, in this interesting work, the presence of drift in the integrators affects the accurate flux estimation during low-speed operation. Two rotor position estimation methods, one for low speed (INFORM) and one for high speed (EMF method), are proposed in [18], wherein the signals are superimposed with disturbances. To eliminate these disturbances and improve the accuracy of position estimation in [18], employing a Kalman filter is a must. Jovanovic et al. [19], have proposed a sensorless control algorithm in which switching ripple on the current is utilised for the detection of variations in stator winding inductance (with rotor position). However, this method requires a start-up technique to find the initial rotor position. Hence, commencing the control process.

For low (or zero) speed operations, rotor position estimation using high-frequency (HF) injection methods are proposed in [20] and [21]. A modified HF injection method along with the concept of flux deviation is proposed in [22], which requires the knowledge of rotor position error (between the actual value and the estimated value) for the accurate rotor position estimation, as the relationship between flux deviation and rotor position depends on machine parameters and saturation. A test voltage injection-based encoder-less control of synchronous reluctance motor is proposed in [23], whose performance is compromised due to the presence of audible noise. A back EMF based reduced-order observer method is implemented in [24], which requires online stator resistance adaptation during the low-speed operation of the SynRM, even though the stator-resistance adaptation is not considered for experimental validation in this particular work. Among all the methods reported so far, stator voltage and current based method is found to be suitable for the VSWT applications because of its non-intrusive nature and ease of implementation. However, for accurate and efficient control of SynRG in VSWT applications, there is still scope for improvement. Applications of SynRG in variable speed wind power generation discussed in [25], [26], require a mechanical encoder for its operation. SynRG is more useful in variable speed wind generation when it is used without a mechanical sensor.

Diverse combinations of wind-PV hybrid systems, are reported in the present literature [27]–[30]. In the hybrid topology presented in [27], maximum power from solar PV array is harvested either by controlling the DC-DC converter or the grid side inverter. However, the speed range over which maximum power can be extracted from WT of the system is compromised due to the uncontrolled rectifier connected to the PMSG, and DC-DC converter remain under utilised when there is no power generation from wind. Hybrid solar-wind standalone systems are proposed in [28] and [29], in which solar PV is connected to DC link through a DC-DC boost converter. In standalone systems, maximum power extraction depends on the state of charge (SOC) of the battery and load demand. Whereas in a grid-integrated system such constraints are eliminated, thus making the distributed-generation system more valuable under all the operating conditions. Further, a solar PV array connected to a three-phase grid through a DC link is more suitable in terms of reduced cost, size and efficiency [31], [32].

In this work, to overcome the issues associated with the hybrid solar-wind grid integrated system discussed so far, a back-to-back connected voltage source converter (VSC) topology, where the solar PV array is connected to the three-phase grid through a DC link, is selected. A microgrid comprising a new efficient position/speed sensorless SynRG based variable speed wind generator and a single-stage solar PV array, is proposed here. In the variable speed WECS, SynRG is controlled by a machine side VSC (MSC) for the extraction of maximum power from the wind turbine. A modified version of the stator voltage and current based position estimation algorithm is implemented, for the SynRG control. A new flux estimation method for SynRG using a second order flux estimator along with frequency-locked-loop (SFE-FLL) is realised in this work to overcome the issues associated with a conventional integrator and low pass filter. For every wind speed, there exists a SynRG speed for which the power generated by the SynRG is maximum. Having known the wind speed, the generator is driven at such a speed that optimum tip speed ratio (TSR) is achieved to harvest maximum power from the wind turbine [33]. The speed control scheme employed for the SynRG, is position/speed sensorless field oriented control (FOC) thus eliminating speed sensors and making the system cost-effective. The solar PV array is directly connected to the DC link of the system due to its merits over a two-stage system. The DC link voltage is adjusted so that the MPE from solar PV array is achieved. Since partial shading condition is neglected in this case, a well-known perturb and observe (P&O) technique is used for drawing apex power from the solar PV array. A reliable observer [34] based technique is implemented for the accurate extraction of the fundamental components of the nonlinear load currents, which results in fast dynamics of the grid side VSC (GSC) control. The GSC control shares active power with the grid and local loads and maintains the DC link voltage at the value corresponding to maximum power point of the solar PV array during the day time. As there are no energy storage devices in the system, the generated power is shared between the grid and the local loads connected at the point of common coupling (PCC). The major contributions of the paper, are as follows.

- Realisation of solar-wind hybrid grid-integrated microgrid using back-to-back connected VSCs without additional DC/DC conversion stages.
- Improved functioning of a wind-solar grid-integrated hybrid system using a new sensorless SynRG control and observer based grid control.
- An observer is used for extracting the peak of the fundamental load current, for the fast dynamic performance of the GSC, during variation in load demand.
- SFE-FLL technique is proposed for the mechanical sensor-less SynRG control for the accurate flux estima-
The proposed hybrid system, given in Fig.1, consists of SynRG based WECS, solar PV array and utility grid. A back-to-back connected converter topology is implemented here for the decoupled control of SynRG and the utility grid. A solar PV array is connected to the DC link, between the MSC and GSC, without any DC-DC converters. The DC link voltage \( V_{dc} \) is decided by the solar MPE algorithm (for the extraction of peak power for the given irradiation and temperature) and the \( V_{dc} \) is maintained at this value by the GSC control. Local loads, interfacing inductors and R-C filters are connected at the PCC. R-C filters and interfacing inductors \( (L_{m}) \) are included for reducing the ripples in PCC voltages and currents, respectively. GSC output voltages \( (v_{i1}, v_{i2}, v_{i3}) \) are generated from the \( V_{dc} \) by controlling GSC suitably. GSC currents are \( i_{usc1}, i_{usc2} \) and \( i_{usc3} \), per phase voltages of the grid are \( u_{g1}, u_{g2}, u_{g3} \), and currents flowing into the RC filters are \( i_{f1}, i_{f2} \) and \( i_{f3} \), and currents flowing into the grid are \( i_{g1}, i_{g2} \) and \( i_{g3} \). \( C_{F} \) and \( R_{F} \) are the capacitance and resistance of the RC filter. State variables selected are inductor currents and RC filter capacitor voltages. The state equations of the system include maximum power extraction from WT and solar PV array, power flow management and power quality improvement. MSC control provides maximum power extraction from the WT, and GSC control provides MPE from solar PV array besides providing power quality improvement. Both MSC and GSC controls are discussed in this section.

### II. System Description

The primary functions of the control used in the proposed system include maximum power extraction from WT and solar PV array, power flow management and power quality improvement. MSC control provides maximum power extraction from the WT, and GSC control provides MPE from solar PV array besides providing power quality improvement. Both MSC and GSC controls are discussed in this section.

### A. MSC Control

MSC controls the SynRG speed by using a speed/position sensorless FOC technique. MSC control operates SynRG at the speed determined by MPE algorithm, so that maximum power is generated from WECS.

1) **Reference Speed \( (\omega_{m}^{ref}) \) Generation:** Any wind turbine (WT) delivers maximum power, at a particular generator speed corresponding to a specific wind speed \( (V_{ws}) \), where the tip speed ratio \( (\lambda) \) is at an optimal value. The value of \( \lambda \), for a specific WT, remains constant, irrespective of the wind speed. For a wind turbine with radius \( r \), performance coefficient \( (C_p) \), internal resistances of interfacing inductance \( (L_{m}) \) and grid inductance \( (L_{g}) \), respectively. \( x \) is the particular phase (1,2,3) selected. State equations of the synchronous reluctance machine in dq reference frame, are given as follows.

\[
\begin{align*}
\frac{d\psi_d}{dt} &= v_d - R_i i_d + \omega w \psi_q \\
\frac{d\psi_q}{dt} &= v_q - R_i i_q - \omega w \psi_d \\
i_d &= L \frac{d\psi_d}{dt} \\
i_q &= L \frac{d\psi_q}{dt} \\
T_e &= \frac{3}{2} p (L_d^2 - L_q^2) i_d i_q
\end{align*}
\]

where, \( \psi_d \), \( \psi_q \), and \( L_d \), \( L_q \) are the stator flux linkages and stator inductances in dq reference frame. \( v_d, v_q, i_d \) and \( i_q \) are the stator voltages and currents in dq reference frame, respectively. \( p \), \( R_i \), \( \omega_w \), \( J \), \( T_L \) and \( T_e \) are number of pole pairs, stator winding resistance, rotor speed, moment of inertia, load torque and electromagnetic torque of the synchronous reluctance machine, respectively.
which is a function of λ and β (pitch angle), the mechanical power generated by the WT (P_{mech}) for wind speed, V_{sw}, is given as,

$$P_{mech} = 1.57 \rho C_p(\lambda, \beta) \rho^2 V_{sw}^3$$

(3)

Assuming pitch angle, β = 0° and air density, ρ = 1.2Kg/m³. λ is a function of the SynRG speed (ω_r^m), and is expressed as,

$$\lambda = \frac{r \omega_r^m}{V_{sw}}$$

(4)

For the WT under consideration, the maximum value of the power coefficient (C_{pro,max}) occurs only when then tip speed ratio is at a unique value (λ_{opt}) of 8.1. So, at any V_{sw}, the WT speed is adjusted so that λ is maintained constant at λ_{opt} and maximum power generation can be achieved. Hence, the SynRG speed at which maximum power is generated for any V_{sw}, is estimated as,

$$\omega_r^m = \frac{\lambda_{opt}}{r} V_{sw}$$

(5)

2) Pulse Generation for MSC: Fig.2 shows the MSC control for the SynRG. MPE algorithm yields the reference speed (ω_r^m) at which SynRG will be able to deliver maximum power. FOC technique, which controls the speed of SynRG, compares this reference speed with the estimated speed to determine the three phase currents (i_{w1}, i_{w2}, i_{w3}). These currents are tracked using hysteresis current controller, which delivers switching pulses (S_{w1}-S_{w5}) to the MSC devices. In this work, the speed and position are estimated accurately by making use of terminal voltages and currents of the machine, thereby eliminating the use of speed and position sensors. The FOC control is implemented using two current sensors (for i_{w1} and i_{w2}) and one voltage sensor (for V_{dc}). Sensed DC link voltage (V_{dc}), and the switching pulses S_{w1}, S_{w3}, and S_{w5} of the MSC are used for the reconstruction of SynRG stator voltages (v_{w1}, v_{w2}, and v_{w3}) as follows.

$$\left\{ \begin{array}{l}
v_{w1} = V_{dc}(2S_{w1} - S_{w3} - S_{w5})/3 \\
v_{w2} = V_{dc}(2S_{w3} - S_{w1} - S_{w5})/3 \\
v_{w3} = V_{dc}(2S_{w5} - S_{w1} - S_{w3})/3 \\
\end{array} \right. $$

(6)

$$\text{Fig. 2. MSC control.}$$

$$\text{Fig. 3. Block diagram of second order flux estimation with FLL.}$$

$$\text{Fig. 4. Space vectors of SynRM.}$$

The estimated stator voltages and sensed stator currents are converted to their corresponding values in stationary reference (αβ) frame as follows.

$$\left\{ \begin{array}{l}
v_\alpha^{w1} = v_{w1}; \quad v_\beta^{w1} = \frac{1}{\sqrt{3}} (v_{w2} - v_{w3}) \\
v_\alpha^{w2} = i_{w1}; \quad v_\beta^{w2} = \frac{1}{\sqrt{3}} (i_{w2} - i_{w3}) \\
\end{array} \right. $$

(7)

The stator flux components (ψ_α^{w}, ψ_β^{w}) in stationary (αβ) reference frame of SynRM are calculated as,

$$\psi_\alpha^{w} = \int (v_\alpha^{w} - i_\alpha^{w} R_s) dt; \quad \psi_\beta^{w} = \int (v_\beta^{w} - i_\beta^{w} R_s) dt$$

(8)

For the accurate estimation of ψ_α^{w} and ψ_β^{w}, a generalised integrator based second order flux estimator (SFE) is implemented. The block diagram of the SFE along with FLL for the frequency adaptation, is shown in Fig.3. SFE extracts ψ_α^{w} and ψ_β^{w} accurately, only when the center frequency (ω) of SFE is equal to the frequency (ω_c) of the input air-gap voltage (ε_w = [ε_α^{w} ε_β^{w}]). As ω_c is unknown, and it varies with the shaft speed of the SynRG, an FLL is used for estimation of ω_c. For frequency adaptation, FLL makes use of the frequency error which is the product of the error of input signal from its filtered value (ε_w(t) - ̇ε_w(t)) and the quadrature component of the filtered input signal. This error is minimised (so that ̇ω = ω_c) using an integral controller with a linearised gain. In Fig.3, M and ζ are the coefficients of the SFE and FLL, respectively. Here, the selected values of M and ζ are 1.4142 and 50, respectively. The SFE takes the airgap voltage (ε_w = [ε_α^{w} ε_β^{w}]) and after integration it outputs ψ_α^{w} and ψ_β^{w}.

The angle (θ_α^{w}) of the stator flux-linkage space vector (ψ_w) and its speed (ω_α^{w}) are estimated as,

$$\theta_\alpha^{w} = \arctan(\psi_\beta^{w}/\psi_\alpha^{w})$$

(9)

$$\omega_\alpha^{w} = \frac{d\theta_\alpha^{w}}{dt} = \frac{\psi_\alpha^{w} (d\psi_\beta^{w}/dt) - \psi_\beta^{w} (d\psi_\alpha^{w}/dt)}{\psi_\alpha^{w}^2}$$

(10)

From Fig.4, the angle θ_β^{w} is estimated as,

$$\theta_\beta^{w} = \sin^{-1} \left( \frac{(L_d^\alpha)^2 \hat{v}_w^2 / |\psi_\alpha^{w}|^2 - (L_d^\beta)^2 / (L_d^\alpha)^2}{1 - (L_d^\alpha)^2 / (L_d^\beta)^2} \right)$$

(11)
where, \( |\tilde{i}_{wu}|^2 = (i_{wu}^2 + \tilde{i}_{wu}^2) \) and \( |\tilde{\psi}_{wu}|^2 = (\psi_{wu}^2 + \tilde{\psi}_{wu}^2) \).

For the selected axially laminated anisotropic (ALA) type SynRG, the ratio \( (L_q^a)^2/(L_d^a)^2 \) is very small and is neglected. Moreover, for an ALA type SynRG, due to the large air-gap, \( L_w^a \) is considered as constant. So (11) is written as,

\[
\theta_r^a \approx \sin^{-1} \left( \frac{|\tilde{i}_{wu}|^2}{\sqrt{|\tilde{i}_{wu}|^2 + |\tilde{\psi}_{wu}|^2}} \right) \tag{12}
\]

From (9) and (12), the rotor position \( \theta_r^a \) and speed \( \omega_r^a \) of the SynRG are estimated as,

\[
\theta_r^a = \theta_r^a - \theta_d^a; \quad \omega_r^a = \frac{d\theta_r^a}{dt} \tag{13}
\]

The stator reference currents are generated from their reference components \((i_{wu}^* \) and \(i_{wu}^0)\) in \(dq\) reference frame using the rotor position angle in (13). The difference in the sensed stator currents from its reference value is passed through a hysteresis pulse generator, which generates MSC gating pulses.

**B. GSC Control**

A detailed description of the control algorithm, used for generating the gating pulses for GSC is discussed in this section.

1) **MPE from Solar PV Array**: To utilise the solar PV array effectively, the maximum power needs to be harvested from it. From the reported MPE techniques it is found that the perturb and observe method is the best if the partial shading is not considered. The prime function of MPE logic, is to adjust the DC link voltage to \(V_{mpp}\) (MPE voltage of the solar PV array) at which the power generation from solar PV array is maximum. If the system in Fig.1, is operated with \(V_{dc} = V_{mpp}\) then, the largest power \(P_{mpp}\) is produced from the solar PV array for that given irradiation. The logic of the P&O technique is as follows.

\[
\begin{cases}
  \text{if } & \Delta P_{pv} = 0 \quad \text{then } \quad V_{mp_{pp-\text{new}}} = V_{mp_{pp-old}} \\
  \text{else if } & \Delta P_{pv} > 0 \quad \text{then } \quad V_{mp_{pp-\text{new}}} = V_{mp_{pp-old}} + \Delta V_{mp_{pp}} \\
  \text{else } & \Delta V_{mp_{pp}} = V_{mp_{pp-old}} - \Delta V_{mp_{pp}} \\
\end{cases} \tag{14}
\]

where, \(\Delta P_{pv} = P_{pv-old} - P_{pv-old}, \Delta V_{mp_{pp}} = V_{mp_{pp-new}} - V_{mp_{pp-old}}\) and \(\Delta V_{mp_{pp}}\) is the step change in solar PV array voltage \(V_{pv}\).

2) **GSC Gating Pulse Generation**: The hysteresis current control used for controlling the GSC, requires an accurate reference grid currents \((i_{g1}, i_{g2}, i_{g3})\) estimation. The GSC control shown in Fig.5, makes sure that the grid currents follow the reference currents. The grid current amplitude is decided from the amount of power generated from the renewable sources (solar PV array and WECS), the amplitude of the fundamental component of the load current \(I_{la}\) and the loss component \(I_{de}\). The main purpose of the loss component is to maintain \(V_{dc}\) and its magnitude is decided by the deviation of \(V_{dc}\) from its reference value \(V_{dc-ref}\). The value of \(V_{dc}\) is set based on:

\[
V_{dc-ref} = \begin{cases} 
V_{mp_{pp}} \quad \text{if } P_{pv} > 0 \\
V_{dc-ref} \quad \text{otherwise}
\end{cases} \tag{15}
\]

where, \(V_{dc-ref}\) is the DC link voltage reference, when output power from solar PV array becomes zero.

The DC link voltage PI (Proportional and Integral) controller takes the DC link voltage error \((V_{dc-ref} - V_{dc})\) and generates the loss component \(I_{de}\).

The phase voltages at PCC \((v_{g1}, v_{g2}, \text{and } v_{g3})\) are estimated from the sensed line voltages at PCC \((v_{g11} \text{ and } v_{g22})\), as follows [35].

\[
\begin{bmatrix}
  v_{g1} \\
  v_{g2} \\
  v_{g3}
\end{bmatrix} = \frac{1}{3} \begin{bmatrix}
  2 & 1 & 0 \\
  1 & -1 & -2 \\
  0 & -2 & 1
\end{bmatrix} \begin{bmatrix}
  v_{g11} \\
  v_{g12}
\end{bmatrix} \tag{16}
\]

The peak of the PCC phase voltage, \(V_{gp}\), is estimated as,

\[
V_{gp} = \left\{ \frac{2}{3} \left(v_{g1}^2 + v_{g2}^2 + v_{g3}^2 \right) \right\}^{1/2} \tag{17}
\]

The in-phase \((u_{p1}, u_{p2} \text{ and } u_{p3})\) and quadrature-phase \((u_{q1}, u_{q2} \text{ and } u_{q3})\) unit templates of the PCC phase voltages are estimated as follows.

\[
\begin{bmatrix}
  u_{p1} \\
  u_{p2} \\
  u_{p3}
\end{bmatrix} = \frac{V_{gpp}}{V_{gp}} \begin{bmatrix}
  v_{g1} \\
  v_{g2} \\
  v_{g3}
\end{bmatrix} \tag{18}
\]

\[
\begin{bmatrix}
  u_{q1} \\
  u_{q2} \\
  u_{q3}
\end{bmatrix} = \frac{1}{\sqrt{3}} \begin{bmatrix}
  0 & -1 & 1 \\
  1 & -1 & 0 \\
  0 & 0 & -2
\end{bmatrix} \begin{bmatrix}
  u_{p1} \\
  u_{p2} \\
  u_{p3}
\end{bmatrix} \tag{19}
\]

The feed-forward components of the grid current reference \((I_{cpv} \text{ and } I_{cw})\) are estimated using \(P_{pv}\), SynRG output power \(P_w\) and the amplitude of the PCC phase voltage \(V_{gp}\) as follows.

\[
I_{cpv} = \frac{2P_{pv}}{3V_{gp}}; \quad I_{cw} = \frac{2P_{pv}}{3V_{gp}} \tag{20}
\]

An observer is proposed for accurately extracting the fundamental component of the load current, which is shown in Fig.5. The observer can reconstruct the required fundamental component and other harmonic components from the sensed load current effectively. The periodic phase \("a" \) load current \(i_{la}\) can be expressed as,

\[
I_{La}(t) = \sum_{k \in N} i_{La_k}(t) \tag{21}
\]

where \(i_{La_k}(t)\) is the magnitude of \(k^{th}\) harmonic component of the load current, \(\omega\) is the angular frequency, and \(\phi_k\) is the phase angle of \(k^{th}\) harmonic component of the load current. Number of harmonics (N) present in \(i_{La}\) are finite for the considered application.

\[
I_{La_k} = 0 \quad \forall k \notin \{1, 2, \ldots, N\} \tag{22}
\]

This is represented by the model,

\[
\begin{bmatrix}
  x(t) \\
  i_{la}(t)
\end{bmatrix} = \begin{bmatrix}
  A & B \\
  C & D
\end{bmatrix} \begin{bmatrix}
  x(t) \\
  i_{la}(t)
\end{bmatrix} + \begin{bmatrix}
  R_0 & R_1 & \cdots & R_{N} \\
  0 & R_0 & \cdots & R_{N}
\end{bmatrix} \begin{bmatrix}
  u_{v1} \\
  u_{v2} \\
  \cdots \\
  u_{vN}
\end{bmatrix} \tag{23}
\]

where,

\[
R_k = \begin{bmatrix}
  0 & \cos(\omega_k(t-t_i)) & \sin(\omega_k(t-t_i)) \\
  -\omega_k & -\omega_k & -\omega_k
\end{bmatrix} \tag{24}
\]
The solution of (23) is expressed as,

\[ X(t) = \left[ i_{La1}(t), i_{Lb1}(t) + \frac{\omega}{3}, \ldots, i_{LaN}(t), i_{LbN}(t) + \frac{\omega}{3} \right]^T \Gamma (t - t_i) \tag{25} \]

The linear estimate of load current (\( \hat{i}_{La} \)) is,

\[
\begin{align*}
\dot{\hat{i}}_{La}(t) &= A \hat{X}(t) + L(\hat{i}_{La}(t) - \hat{i}_{La}(t)) \\
\hat{i}_{La}(t) &= C \hat{X}(t)
\end{align*}
\]

where, \( L \) is the gain of the observer. The \( \hat{X}(t) \) in (26) is finally represented as,

\[ \hat{X}(t) = (A - LC) \hat{X}(t) + L \hat{i}_{La}(t) \tag{27} \]

From the observer output, the fundamental components (\( i_{La1}, i_{Lb1}, i_{Lc1} \)) of the load currents, are selected. The quadrature components (\( u_{g1}, u_{g2}, u_{g3} \)) along with zero crossing detector and sample and hold blocks are used for extracting the fundamental peaks of load currents (\( I_{La1}, I_{Lb1}, I_{Lc1} \)) from their fundamental signals. Average of estimated individual fundamental peaks of load currents (\( I_{cl} \)), is calculated and is used for the generation of the reference grid currents. The amplitude (\( I_{gp} \)) of reference grid currents, is estimated as,

\[ I_{gp} = I_{cl} + I_{cdc} - (I_{cpv} + I_{cw}) \tag{28} \]

The reference currents, for GSC gate pulses generation, are estimated as,

\[ i_{g1} = I_{gp} \times u_{p1}; \quad i_{g2} = I_{gp} \times u_{p2}; \quad i_{g3} = I_{gp} \times u_{p3} \tag{29} \]

The deviations of grid currents (\( i_{g1}, i_{g2} \) and \( i_{g3} \)) from their references obtained from (29), are processed through hysteresis PWM generator as shown in Fig.5, which produces the gating pulses for the GSC devices.

In this work, the location of SynRG and solar PV array cannot be too far as the DC link is common. Hence, there could be shadow flickering effect of the rotating wind turbine blades on the solar PV arrays, which may affect the solar PV output power. By correctly placing the SynRG and solar PV array and modifying the MPE algorithm suitably, shadow flickering effect can be minimised.

### IV. EXPERIMENTAL PERFORMANCE

The proposed wind-solar based hybrid grid-connected system and its control, have been tested on a developed prototype in the laboratory as shown in Fig.6. The variable speed WECS used in the prototype comprises a 3.7 kW SynRG, a variable frequency drive (VFD075E43A) controlled induction motor (IM) and a three-leg VSC as MSC. Shafts of SynRG and IM, are directly coupled to each other. Variable speed command to the drive is provided from the MATLAB/Simulink for emulation of WT. A 2.5 kW solar PV array is emulated using a solar PV emulator (AMETEK ETS600x17DPV) whose parameters (irradiation and temperature) can be changed online with the help of a host PC. A digital signal processor (dSPACE-1103) is interfaced to MATLAB/Simulink platform using another host PC, for the real-time execution of the control techniques. For the real-time realisation of the system parameter variation, the control desk platform of the dSPACE-1103 is used. The ADC channels of dSPACE-1103 controller receive sensed voltage and current signals from the respective Hall-Effect voltage and current sensors (LV-25P, LA-25A). The gating signals to the IGBT (Insulated-Gate Bipolar Transistor) switches, used in MSC and GSC, are generated by the dSPACE-1103. These signals are given to the respective gate driver circuits of the IGBT switches after providing necessary isolation and amplification using optocoupler circuits. A 220 V, 50Hz utility grid is realised through a three-phase autotransformer connected to 415V, 50Hz supply. A three-phase full-bridge diode rectifier fed R-L load is used for the validation of GSC control algorithm. Steady-state waveforms of microgrid are monitored using a power quality analyser, and dynamic responses are observed on a digital storage oscilloscope.

### A. Steady State Performance

Steady state behaviour of the hybrid grid-connected system at a steady wind speed and solar irradiation of 10 m/s and 700
This section explains the variable wind speed operation of the proposed solar-wind hybrid grid-connected system. Figs. 8(e)-(f) show the behaviour of the system during wind speed variation. The system is exposed to a wind speed of $V_{sw} = 10$ m/s, and a solar irradiation of 500 W/m$^2$. The powers generated from solar PV array and WECS are sufficient to support depicted in Fig. 8(d), which confirms the decoupled operation of the WECS and solar PV generating system.

C. Effect of Wind Speed on System Behaviour

This section explains the variable wind speed operation of the proposed solar-wind hybrid grid-connected system. Figs. 8(e)-(f) show the behaviour of the system during wind speed variation. The system is exposed to a wind speed of $V_{sw} = 10$ m/s, and a solar irradiation of 500 W/m$^2$. The powers generated from solar PV array and WECS are sufficient to support
the local nonlinear load demand, so that excess power is fed to the grid. Once $V_{sv}$ is increased to 12 m/s, MPE control of WECS generates a new reference speed (corresponding to maximum $P_w$). SynRG is run at that speed by the position sensorless MSC control so that MPE is achieved from WECS which is depicted in Fig.8(e). From Fig.8(e), it is clear that the estimated speed ($\omega_m$) and torque ($T_s$) are increased with the increment in wind speed, so that maximum power is generated by SynRG, while the DC link voltage remains unaffected. Hence, $P_g$ increases and the excess power is absorbed by the grid as shown in Fig.8(f). In this case, only the wind feed-forward component ($I_{sv}$) increases due to the increase in power generation from SynRG. The performance of the system, is also tested against a wide variation in wind speed. Fig.8(g) shows the corresponding variations in $\omega_m$, $P_w$ and $V_{dc}$. From the variations in $\omega_m$ and $P_w$ shown in Fig.8(g), it is obvious that, with the variations in $V_{sv}$, MSC control operates the SynRG at the reference speed generated by the MPE algorithm so that maximum power extraction is achieved; however, $V_{dc}$ remains unaffected.

D. Effect of Wind Speed and Solar Irradiation on System Behaviour

This section validates the behaviour of proposed solar-wind hybrid grid integrated system for simultaneous variations in $V_{sv}$ and solar irradiation. Fig.8(h) shows the behaviour of the system for stochastic changes in both wind speed and solar irradiation. Due to the combined actions of MPE algorithm and GSC control, maximum $P_g$ is exported for every wind speed and solar irradiation as shown in Fig.8(h). As the load consumes a constant power, variations in $P_w$ and $P_{pv}$ are reflected in the grid power (as shown in Fig.8(h)).

E. Variation in Load Demand

In this section, the system behaviour has been tested against a sudden increase in load power demand, while power generation from wind and solar remain unchanged. Fig.9(a) shows that, as the load power is increased, since $P_w$ and $P_{pv}$ are constants, $P_g$ is reduced. With the increase in $P_L$, load current increases and as per the control, only the grid current is reduced while the grid voltage and $V_{dc}$ remain constant. Variations in the components constituting the reference grid current are depicted in Fig.9(b). The reduction in grid current (shown in Fig.9(c)), as per (28), is due to the increase in load current component, $I_{cl}$. Furthermore, the effect of variation in load power, on SynRG control, is given in Fig.9(d). Due to the decoupling provided by back-to-back connected converters, variation in load current has no effect on the SynRG parameters ($i_{w1}$, $T_c$ and $\theta_r$), which is clear from Fig.9(d).

F. Performance of System at Extreme Conditions

Extreme conditions considered here, are i) $P_L > (P_w + P_{pv})$, ii) $P_w$ and $P_{pv}$ are unavailable, and iii) under unbalance at load terminals.

1) $P_L > (P_w + P_{pv})$: Fig.9(e) shows the dynamic behaviour of the system, when $P_L > P_w + P_{pv}$. The system considered is operating at an irradiation of 300 W/m² and $V_{sv}$ is less than the cut-in speed ($P_w = 0$). Power generated from solar PV array ($P_{pv} = 615.84$ W), is greater than the load power demand ($P_{pv} > P_L$), hence the surplus power is fed to the grid. As the excess power available is very small, $i_{g1}$ is also very small and is $180^\circ$ out of phase with $v_{g1}$ waveform as shown in Fig.9(e). Once $P_L$ is increased so that, $P_L > P_{pv}$, the grid started supporting the load by supplying power. Therefore, $i_{g1}$ reverses its direction, becoming in phase with $v_{g1}$, as shown in Fig.9(e). Under both conditions unity power factor operation is maintained, which is obvious from the phase relationship between $v_{g1}$ and $i_{g1}$. This confirms the expandability of the GSC control under extreme case of $P_L > P_w + P_{pv}$.

2) $P_w$ and $P_{pv}$ are Unavailable: In Fig.9(f), transition of DC link voltage ($V_{dc}$) from $V_{mpp}$ to $V_{dc-ref}$ is shown. In this case $V_{sv}$ is less than the cut-in speed ($P_w = 0$) and solar PV array is exposed to a solar irradiation of 500 W/m². As $P_{pv} > P_L$, the excess power available is fed to the grid. Once power
generated from solar PV array is reduced to zero, due to lack of solar irradiation, the DC link voltage reference is changed from $V_{mpp}$ to $V_{dc-ref} = 360 \text{ V}$, as shown in Fig.9(f). From this moment onwards, the grid feeds the load as can be seen from the grid current direction. GSC acts as a DSTATCOM (Distribution Static Compensator) and corresponding converter current ($i_{vsc1}$) waveform is shown in Fig.9(f). Throughout, UPF operation at PCC is maintained.

3) Unbalance at Load Terminals: Fig.9(g) shows the performance of the system under extreme condition of unbalance (phase ‘a’ terminal of load is disconnected) at load terminals. During this condition, $P_L$ decreases, and as $P_{pv}$ and $P_w$ are fixed, the extra power available flows into the grid ($P_g$ increases). It is depicted in Fig.9(g), where, once $i_{La}$ becomes zero, $i_{g1}$ increases due to the increased power flowing in to the grid. From Fig.9(g), it is confirmed that the load unbalance has no effect on the PCC voltage ($v_{g1}$) and current ($i_{g1}$). Both remain sinusoidal.

G. Accuracy of Sensorless Control

In this section, the reference speed of SynRG is increased, and the accuracy of the SynRG control is validated using the test results shown in Fig.9(h). The upper part of Fig.9(h), shows the actual waveforms of reference speed, actual speed, estimated position and the actual position of the SynRG, and its enlarged view during the transition (speed change) is shown in the bottom part. Initially, the estimated speed and position are coinciding with their actual values. Once the reference speed is increased, estimated speed and position are adjusted so that they again coincide with their reference values as depicted in Fig.9(h). From Fig.9(h), it can be concluded that the estimations are accurate enough to confirm the effectiveness of the system’s control.

V. CONCLUSION

A wind-solar hybrid renewable energy sources based microgrid system, integrated with the main grid has been presented in this work, wherein the hybrid renewable sources are capable of delivering maximum power under varying wind velocities and solar irradiation. SynRG is used for the generation of electrical power from the WECS. Maximum power extraction from WT for different wind speeds, using position sensorless FOC on SynRG, has been tested on a developed laboratory prototype. A back-to-back power converter topology, used in the proposed system has provided a decoupled control of the MSC from the GSC. Test results have confirmed that disturbances in the grid side does not affect the operation of the WECS. Experimental results for varying solar irradiation support that solar PV array, directly integrated into the DC link, is operated at its full efficiency by adequately controlling the DC link voltage, which is decided by the MPE algorithm. Fast and accurate estimation of the fundamental peak of the nonlinear load current is achieved by the proposed observer-based algorithm. The proposed solar-wind hybrid grid integrated system provides a reliable and efficient power flow control along with power quality improvements.

APPENDIX

The system parameters used in the proposed topology is given in Table I.

<table>
<thead>
<tr>
<th>TABLE I</th>
<th>SYSTEM PARAMETERS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar PV Array</td>
<td></td>
</tr>
<tr>
<td>Open circuit voltage, $V_{oc}$</td>
<td>430 V</td>
</tr>
<tr>
<td>Short circuit current, $I_{sc}$</td>
<td>7A</td>
</tr>
<tr>
<td>Peak power, $P_{MPE}$</td>
<td>2.5 kW</td>
</tr>
<tr>
<td>SynRG parameters</td>
<td></td>
</tr>
<tr>
<td>Power rating</td>
<td>3.7 kW</td>
</tr>
<tr>
<td>Voltage rating and frequency</td>
<td>220V, 50Hz</td>
</tr>
<tr>
<td>Speed and number of pole pairs</td>
<td>1500rpm and 2</td>
</tr>
<tr>
<td>Rated current</td>
<td>16.3A</td>
</tr>
<tr>
<td>Resistance of stator winding, $R_s$</td>
<td>2.5 Ω</td>
</tr>
<tr>
<td>Direct and quadrature axes inductances</td>
<td>99.47 &amp; 10.15 mH</td>
</tr>
<tr>
<td>Grid side</td>
<td></td>
</tr>
<tr>
<td>Rated grid voltage and frequency</td>
<td>220 V, 50 Hz</td>
</tr>
<tr>
<td>RC filter values $C_p$ and $R_p$</td>
<td>10 μF and 5 Ω</td>
</tr>
<tr>
<td>Interfacing inductor and DC-link capacitance</td>
<td>4mH, 2200 μF</td>
</tr>
</tbody>
</table>

REFERENCES


Deepu Vijay M (M’17) was born in Kerala, India, in 1984. He received the B.Tech. degree in Electrical and Electronics Engineering from the Cochin University of Science and Technology, Cochin, India, in 2007 and the M.Tech. degree in Power Electronics, Electrical Drives and Machines from the Indian Institute of Technology Delhi (IIT Delhi), India, in 2010. He is currently working toward his Ph.D. in Electrical Engineering from the Indian Institute of Technology Delhi (IIT Delhi), India. He was a Software Engineer with IBS software services, Cochin, India, from 2007 to 2009. From 2014 to 2015, he was with the Bitra Institute of Technology & Science (BITS), Pilani-Hyderabad Campus as a Lecturer. His research interests include power electronics, electrical machines, drives, synchronous reluctance generator (SynRG) based wind energy conversion systems, solar energy conversion systems, power quality improvement in the distribution systems and microgrids.

Bhimg Singh (SM’99, F’10) was born in Rhamapur, Bihar (UP), India, in 1956. He has received his B.E. (Electrical) from the University of Roorkee (Now IIT Roorkee), India, in 1977 and his M.Tech. (Power Apparatus & Systems) and Ph.D. from the Indian Institute of Technology Delhi (IIT Delhi), India, in 1979 and 1983, respectively. In 1983, he joined the Department of Electrical Engineering, University of Roorkee (now IIT Roorkee), India as a Lecturer, where he became a Reader in 1988. In December 1990, he joined the Department of Electrical Engineering, IIT Delhi, India, as an Assistant Professor, where he has become an Associate Professor in 1994 and a Professor in 1997. He has been ABB Chair Professor from September 2007 to September 2012. He has also been CEA Chair Professor from October 2012 to September 2017. He has been Head of the Department of Electrical Engineering at IIT Delhi from July 2014 to August 2016. He has been the Dean, Academics at IIT Delhi from August 2016 to August 2019. He is also Dean, DST, Government of India from December 2015. He has guided 79 Ph.D. dissertations, and 167 M.E./M.Tech. M.S.(R) theses. He has filed 46 patents. He has executed more than eighty sponsored and consultancy projects. He has co-authored a text book on power quality: Power Quality Problems and Mitigation Techniques published by John Wiley & Sons Ltd. 2015. His areas of interest include solar PV grid interface systems, microgrids, power quality monitoring and mitigation, solar PV water pumping systems, improved power quality AC-DC converters, power electronics, electrical machines, drives, flexible alternating transmission systems, and high voltage direct current systems. Prof. Singh is a Fellow of the Indian National Academy of Engineering (NAE), The Indian National Science Academy (FNA), The National Academy of Sciences, India (FNAsc), The Indian Academy of Sciences, India (FASc), The World Academy of Sciences (FTWAS), Institute of Electrical and Electronics Engineers (IEEE), The Institution of Engineers and Technology (IET), the Institution of Engineers(India) (FIE), and Institution of Electronics and Telecommunication Engineers(FIETE) and a Life Member of the Indian Society for Technical Education(ISTE), System Society of India (SSI), and National Institution of Quality and Reliability (NIQR).