

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

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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.

Index Terms—Synchronous Reluctance Generator, Wind Energy Conversion System, PV-Wind Hybrid System, Sensor-less Position Estimation, Power Quality.

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

This work was supported in part by The Department of Science and Technology, Government of India, project under Grant RP03391 and in part by J. C. Bose Fellowship under Grant RP03128. (Corresponding author: Deepu Vijay M)

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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 affect 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 ahead of 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 micro-grid 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-

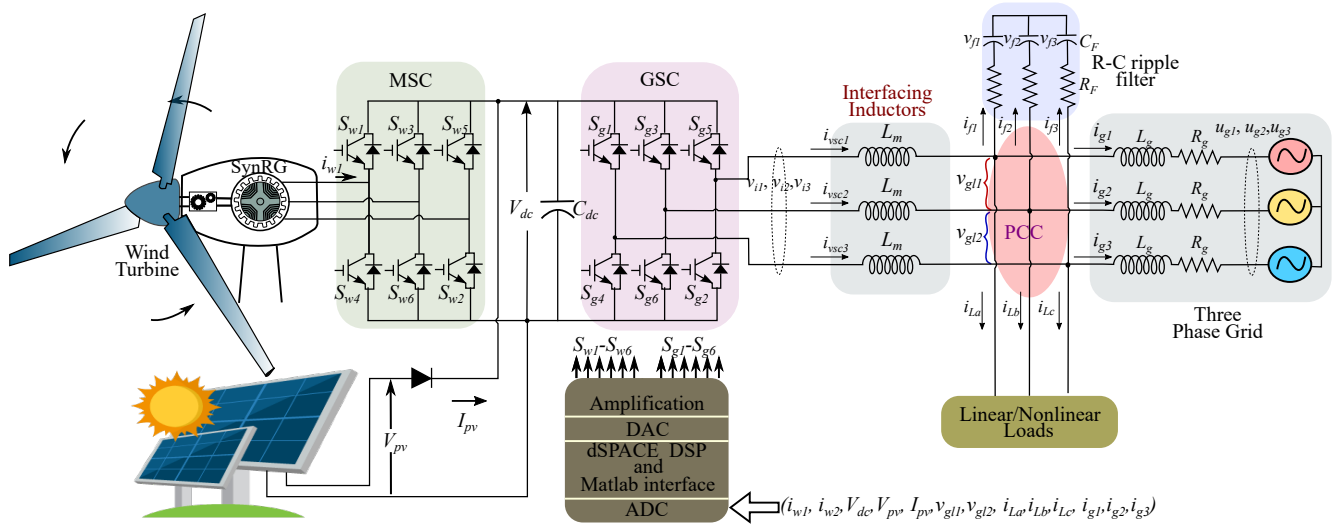


Fig. 1. Proposed configuration of the system.

- tion.
- Decoupled MPE from solar PV array and WECS, by controlling GSC and MSC independently.
- Extraction of maximum energy from the VSWT, by efficiently controlling the shaft speed of the SynRG without using any physical speed/position sensors.

II. SYSTEM DESCRIPTION

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} , and v_{i3}) are generated from the V_{dc} by controlling GSC suitably. GSC currents are i_{vsc1} , i_{vsc2} and i_{vsc3} , per phase voltages of the grid are u_{g1} , u_{g2} , and u_{g3} , 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 are as follows.

$$\left. \begin{aligned} \frac{di_{vscx}}{dt} &= -\frac{(R_m+R_F)}{L_m}i_{vscx} + \frac{R_F}{L_m}i_{gx} - \frac{1}{L_m}v_{fx} + \frac{1}{L_m}v_{ix} \\ \frac{di_{gx}}{dt} &= \frac{R_F}{L_g}i_{vscx} - \frac{(R_g+R_F)}{L_g}i_{gx} + \frac{1}{L_g}v_{fx} - \frac{1}{L_g}u_{gx} \\ \frac{dv_{fx}}{dt} &= \frac{1}{C_F}i_{vscx} - \frac{1}{C_F}i_{gx} \end{aligned} \right\} \quad (1)$$

where, R_m and R_g are 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.

$$\left. \begin{aligned} \frac{d\psi_w^d}{dt} &= v_w^d - R_s i_w^d + \omega_r \psi_w^q \\ \frac{d\psi_w^q}{dt} &= v_w^q - R_s i_w^q - \omega_r \psi_w^d \\ \psi_w^d &= L_w^d i_w^d; \quad \psi_w^q = L_w^q i_w^q \\ \frac{d\omega_r}{dt} &= \frac{p}{J} (T_e - T_L) \\ T_e &= \frac{3}{2} p (L_w^d - L_w^q) i_w^d i_w^q \end{aligned} \right\} \quad (2)$$

where, ψ_w^d , ψ_w^q and L_w^d , L_w^q are the stator flux linkages and stator inductances in dq reference frame. v_w^d , v_w^q , i_w^d and i_w^q are the stator voltages and currents in dq reference frame, respectively. p , R_s , ω_r , 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.

III. CONTROL ALGORITHM

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 (ω_r^{m*}) Generation:* Any wind turbine (WT) delivers maximum power, at a particular generator speed corresponding to a specific wind speed (V_{sw}), where the tip speed ratio (λ) is at an optimal value. The value of λ , for a specific WT, remains constant, irrespective of the wind speed. For a wind turbine with radius r , performance coefficient (C_p)

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,

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

Assuming pitch angle, $\beta = 0^\circ$ and air density, $\rho = 1.2Kg/m^3$. λ is a function of the SynRG speed (ω_r^m), and is expressed as,

$$\lambda = \frac{r\omega_r^m}{V_{sw}} \quad (4)$$

For the WT under consideration, the maximum value of the power coefficient (C_{pmax}) 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,

$$\omega_r^{m*} = \frac{\lambda_{opt}}{r} V_{sw} \quad (5)$$

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_{w6}) 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.

$$\begin{cases} v_{w1} = V_{dc}(2S_{w1} - S_{w3} - S_{w5})/3 \\ v_{w2} = V_{dc}(2S_{w3} - S_{w1} - S_{w5})/3 \\ v_{w3} = V_{dc}(2S_{w5} - S_{w1} - S_{w3})/3 \end{cases} \quad (6)$$

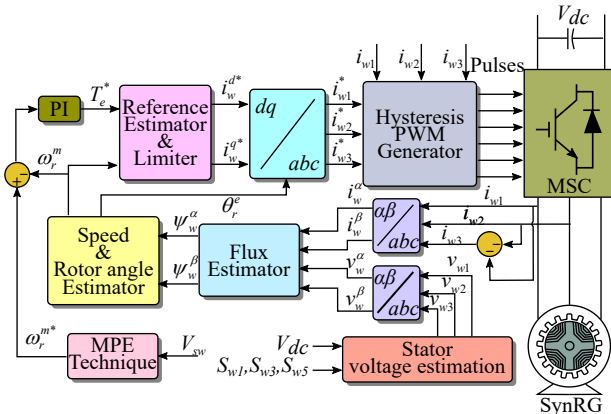


Fig. 2. MSC control.

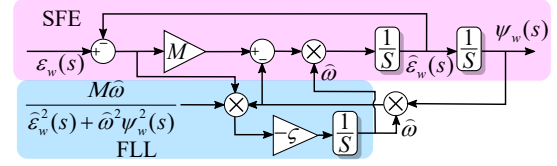


Fig. 3. Block diagram of second order flux estimation with FLL.

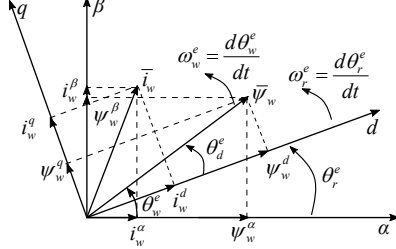


Fig. 4. Space vectors of SynRM.

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

$$\begin{cases} v_w^\alpha = v_{w1}; & v_w^\beta = \frac{1}{\sqrt{3}}(v_{w2} - v_{w3}) \\ i_w^\alpha = i_{w1}; & i_w^\beta = \frac{1}{\sqrt{3}}(i_{w2} - i_{w3}) \end{cases} \quad (7)$$

The stator flux components (ψ_w^α , ψ_w^β) in stationary ($\alpha\beta$) reference frame of SynRM are calculated as,

$$\psi_w^\alpha = \int \underbrace{(v_w^\alpha - i_w^\alpha R_s)}_{\varepsilon_w^\alpha} dt; \quad \psi_w^\beta = \int \underbrace{(v_w^\beta - i_w^\beta R_s)}_{\varepsilon_w^\beta} dt \quad (8)$$

For the accurate estimation of ψ_w^α and ψ_w^β , 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_w^α and ψ_w^β accurately, only when the center frequency ($\hat{\omega}$) of SFE is equal to the frequency (ω_w^e) of the input air-gap voltage ($\varepsilon_w = [\varepsilon_w^\alpha \ \varepsilon_w^\beta]^T$). As ω_w^e is unknown, and it varies with the shaft speed of the SynRG, an FLL is used for estimation of ω_w^e . For frequency adaptation, FLL makes use of the frequency error which is the product of the error of input signal from its filtered value ($\varepsilon_w(s) - \hat{\varepsilon}_w(s)$) and the quadrature component of the filtered input signal. This error is minimised (so that $\hat{\omega} = \omega_w^e$) using an integral controller with a linearised gain. In Fig.3, M and ς are the coefficients of the SFE and FLL, respectively. Here, the selected values of M and ς are 1.4142 and 50, respectively. The SFE takes the airgap voltage ($\varepsilon_w = [\varepsilon_w^\alpha \ \varepsilon_w^\beta]^T$) and after integration it outputs ψ_w^α and ψ_w^β .

The angle (θ_w^e) of the stator flux-linkage space vector ($\bar{\psi}_w$) and its speed (ω_w^e) are estimated as,

$$\theta_w^e = \arctan(\psi_w^\beta / \psi_w^\alpha) \quad (9)$$

$$\omega_w^e = \frac{d\theta_w^e}{dt} = \frac{\psi_w^\alpha (d\psi_w^\beta / dt) - \psi_w^\beta (d\psi_w^\alpha / dt)}{|\bar{\psi}_w|^2} \quad (10)$$

From Fig.4, the angle θ_d^e is estimated as,

$$\theta_d^e = \sin^{-1} \left(\sqrt{\frac{(L_w^q)^2 |\bar{i}_w|^2 / |\bar{\psi}_w|^2 - (L_w^q)^2 / (L_w^d)^2}{1 - (L_w^q)^2 / (L_w^d)^2}} \right) \quad (11)$$

where, $|\bar{i}_w|^2 = (i_w^\alpha)^2 + (i_w^\beta)^2$ and $|\bar{\psi}_w|^2 = (\psi_w^\alpha)^2 + (\psi_w^\beta)^2$.

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

$$\theta_d^e \approx \sin^{-1} \left(\sqrt{(L_w^q)^2 |\bar{i}_w|^2 / |\bar{\psi}_w|^2} \right) \quad (12)$$

From (9) and (12), the rotor position (θ_r^e) and speed (ω_r^e) of the SynRG are estimated as,

$$\theta_r^e = \theta_w^e - \theta_d^e; \quad \omega_r^e = \frac{d\theta_r^e}{dt} \quad (13)$$

The stator reference currents are generated from their reference components (i_w^{d*} and i_w^{q*}) 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_{MPE}) is produced from the solar PV array for that given irradiation. The logic of the P&O technique is as follows.

$$\left. \begin{array}{l} \text{if } \Delta P_{pv} = 0 \text{ then } V_{mpp-new} = V_{mpp-old} \\ \text{elseif } \Delta P_{pv} > 0 \\ \quad \left\{ \begin{array}{l} \text{if } \Delta V_{pv} > 0 \text{ then } V_{mpp-new} = V_{mpp-old} + \Delta V_{mpp} \\ \text{else } V_{mpp-new} = V_{mpp-old} - \Delta V_{mpp} \end{array} \right. \\ \text{else} \\ \quad \left\{ \begin{array}{l} \text{if } \Delta V_{pv} > 0 \text{ then } V_{mpp-new} = V_{mpp-old} - \Delta V_{mpp} \\ \text{else } V_{mpp-new} = V_{mpp-old} + \Delta V_{mpp} \end{array} \right. \\ \text{end} \end{array} \right\} \quad (14)$$

where, $\Delta P_{pv} = P_{pv-new} - P_{pv-old}$, $\Delta V_{pv} = V_{mpp-new} - V_{mpp-old}$ and ΔV_{mpp} 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_{cl}) and the loss component (I_{cdc}). 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}^*). The value of V_{dc}^* is set based on:

$$V_{dc}^* = \begin{cases} V_{mpp} & \text{if } P_{pv} > 0 \\ V_{dc-ref} & \text{otherwise} \end{cases} \quad (15)$$

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 ($V_{dc}^* - V_{dc}$) and generates the loss component (I_{cdc}).

The phase voltages at PCC (v_{g1} , v_{g2} , and v_{g3}) are estimated from the sensed line voltages at PCC (v_{gl1} and v_{gl2}), as follows [35].

$$\begin{bmatrix} v_{g1} & v_{g2} & v_{g3} \end{bmatrix}^T = \frac{1}{3} \begin{bmatrix} 2 & 1 \\ -1 & 1 \\ -1 & -2 \end{bmatrix} \begin{bmatrix} v_{gl1} & v_{gl2} \end{bmatrix}^T \quad (16)$$

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

$$V_{gp} = \{(2/3)(v_{g1}^2 + v_{g2}^2 + v_{g3}^2)\}^{1/2} \quad (17)$$

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

$$u_{p1} = \frac{v_{g1}}{V_{gp}}; \quad u_{p2} = \frac{v_{g2}}{V_{gp}}; \quad u_{p3} = \frac{v_{g3}}{V_{gp}} \quad (18)$$

$$\begin{bmatrix} u_{q1} & u_{q2} & u_{q3} \end{bmatrix}^T = \frac{1}{\sqrt{3}} \begin{bmatrix} 0 & -1 & 1 \\ \frac{3}{2} & \frac{1}{2} & -\frac{1}{2} \\ -\frac{3}{2} & \frac{1}{2} & -\frac{1}{2} \end{bmatrix} \begin{bmatrix} u_{p1} & u_{p2} & u_{p3} \end{bmatrix}^T \quad (19)$$

The feed-forward components of the grid current reference (I_{cpv} 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.

$$I_{cpv} = \frac{2P_{pv}}{3V_{gp}}; \quad I_{cw} = \frac{2P_w}{3V_{gp}} \quad (20)$$

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,

$$i_{La}(t) = \sum_{k \in N^*} I_{Lak} \sin(k\omega t - \phi_k) \quad (21)$$

where $I_{Lak}(t)$ is the magnitude of k^{th} harmonic component of the load current, ω is the angular frequency, and ϕ_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.

$$I_{Lak} = 0 \quad \forall k \notin \{1, 2, \dots, N\} \quad (22)$$

This is represented by the model,

$$\left\{ \begin{array}{l} \dot{X}(t) = \underbrace{\begin{pmatrix} J_1 & 0 & \dots & 0 \\ 0 & J_2 & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & J_N \end{pmatrix}}_A X(t) + \underbrace{\sum_i \begin{pmatrix} R_1 & 0 & \dots & 0 \\ 0 & R_2 & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & R_N \end{pmatrix} \begin{pmatrix} a_{1i} \\ b_{1i} \\ \vdots \\ a_{Ni} \\ b_{Ni} \end{pmatrix}}_{\nu(t)} \delta(t - t_i) \\ i_{La}(t) = \underbrace{\begin{pmatrix} 1 & 0 & 1 & 0 & \dots & 1 & 0 \end{pmatrix}}_C X(t) \end{array} \right. \quad (23)$$

where,

$$J_k = \begin{pmatrix} 0 & k\omega \\ -k\omega & 0 \end{pmatrix}; R_k = \begin{pmatrix} \sin(k\omega(t - t_i)) & -\cos(k\omega(t - t_i)) \\ \cos(k\omega(t - t_i)) & \sin(k\omega(t - t_i)) \end{pmatrix} \quad (24)$$

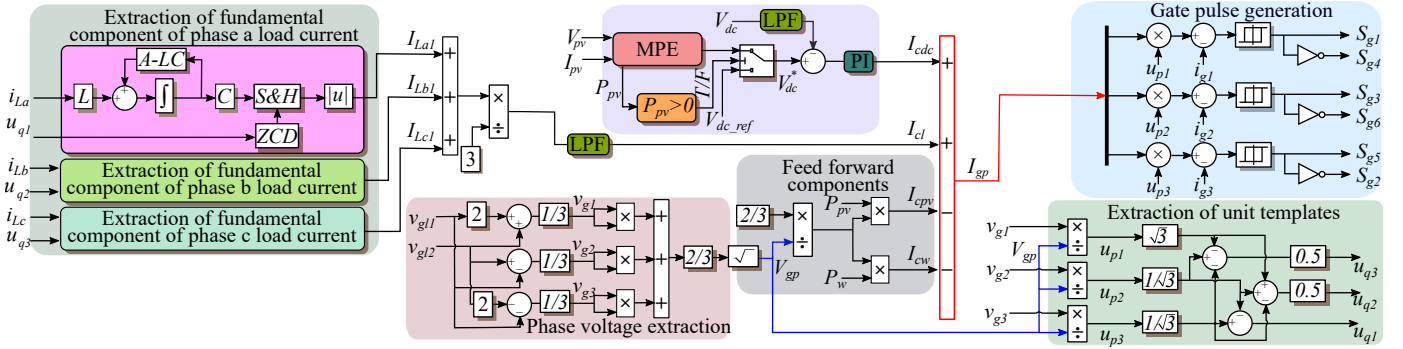


Fig. 5. GSC control.

The solution of (23) is expressed as,

$$X(t) = \begin{bmatrix} i_{La1}(t) & i_{La1}(t + \frac{\pi/2}{\omega}) & \dots & i_{LaN}(t) & i_{LaN}(t + \frac{\pi/2}{N\omega}) \end{bmatrix}^T \Gamma(t - t_i) \quad (25)$$

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

$$\begin{cases} \dot{\hat{X}}(t) = A\hat{X}(t) + L(i_{La}(t) - \hat{i}_{La}(t)) \\ \hat{i}_{La}(t) = C\hat{X}(t) \end{cases} \quad (26)$$

where, L is the gain of the observer.

The $\dot{\hat{X}}(t)$ in (26) is finally represented as,

$$\dot{\hat{X}}(t) = (A - LC)\hat{X}(t) + Li_{La}(t) \quad (27)$$

From the observer output, the fundamental components (i_{La1} , i_{Lb1} , i_{Lc1}) of the load currents, are selected. The quadrature components (u_{q1} , u_{q2} , u_{q3}) 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,

$$I_{gp} = I_{cl} + I_{cdc} - (I_{cpv} + I_{cw}) \quad (28)$$

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

$$i_{g1}^* = I_{gp} \times u_{p1}; \quad i_{g2}^* = I_{gp} \times u_{p2}; \quad i_{g3}^* = I_{gp} \times u_{p3} \quad (29)$$

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

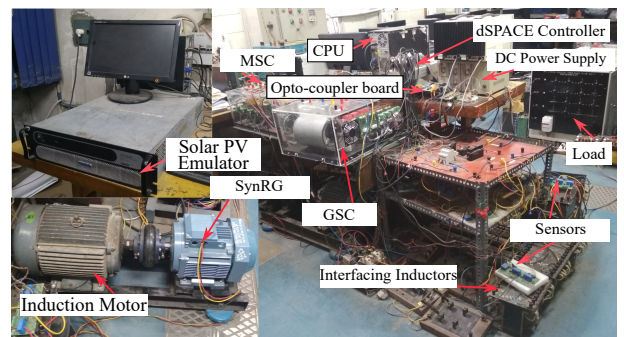


Fig. 6. Photograph of laboratory prototype.

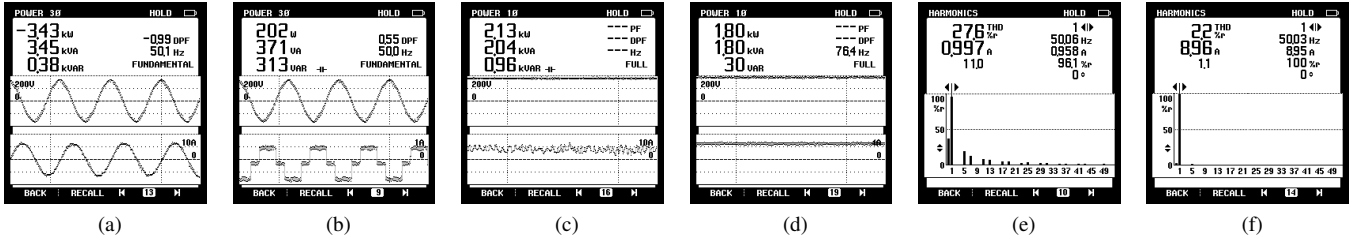


Fig. 7. Steady-state performance at a wind speed of 10 m/s and solar irradiation of 700 W/m² (a) Grid power (P_g) along with v_{g11} and i_{g1} (b) Load power (P_L) along with v_{La} and i_{La} (c) Power from SynRG (P_w) (d) Power from solar PV array (P_{pv}) along with V_{dc} and I_{pv} (e)-(f) Harmonic spectra of load current and grid current.

W/m², respectively, is discussed in this section. Figs. 7(a)-(b) show the power levels along with corresponding line voltages and currents at grid and load terminals, respectively. Figs. 7(c)-(d) show the power generated from the SynRG and solar PV array, respectively. Out of the total power generated by solar PV array and WECS, load takes 202W (Fig.7(b)) and the rest is flowing into the grid (Fig.7(a)). The power flowing into the grid is taken as negative. In Fig.7(d), V_{dc} is held at V_{mpp} (for a single-stage configuration, $V_{dc} = V_{pv}$) for the given solar irradiation of 700W/m², so that maximum power is harvested from it. Load current waveform in Fig.7(b) is non-sinusoidal, however, the GSC control maintains the grid current waveform sinusoidal which is depicted in Fig.7(a). An uncontrolled rectifier fed R-L load connected at PCC takes a nonlinear current with a THD of 27.6% which is shown in Fig.7(e). GSC control provides optimum switching pulses to IGBT switches of the GSC so that the grid current THD is maintained at 2.2% (shown in Fig.7(f)), which is within the limit as per the IEEE 519 standard [36].

B. Effect of Solar Irradiation on System Behaviour

This section explains the effect of variation in solar irradiation on the system behaviour and test results are depicted in Figs.8(a)-(d). The system considered here, is operating at solar irradiation of 500 W/m² and a wind speed of 10 m/s. The maximum power is extracted from both the renewable energy sources (Solar PV array and WECS), and is distributed between the local loads and grid which is depicted in Fig.8(a). The power produced by SynRG (P_w), power output of solar PV array (P_{pv}), grid power (P_g) and the load power (P_L) are shown in Fig.8(a). In this case, $P_L < P_{pv} + P_w$, therefore, excess power generated is flowing into the grid, which is taken as negative power. Once the solar irradiation is increased from 500 W/m² to 700 W/m², MPE algorithm generates a new reference voltage (V_{mpp}) and the GSC control adjusts the DC link voltage to V_{mpp} , so that maximum power is harvested from the solar PV array. As P_w and P_L are fixed, excess power produced from solar PV array due to increase in irradiation, is fed to the grid (P_g increases in the negative direction), which is shown in Fig.8(a). Among the intermediate current signals (components of reference grid currents), which are depicted in Fig.8(b), only the solar power feed-forward term (I_{cpv}) is affected by the increase in solar irradiation. The rise in I_{cpv} , increases the magnitude of the reference grid currents (as per (28)) so that i_{g1} increases (shown in Fig.8(c)). Corresponding signals (i_{w1} , T_e and θ_r) of the SynRG, along with I_{pv} , are

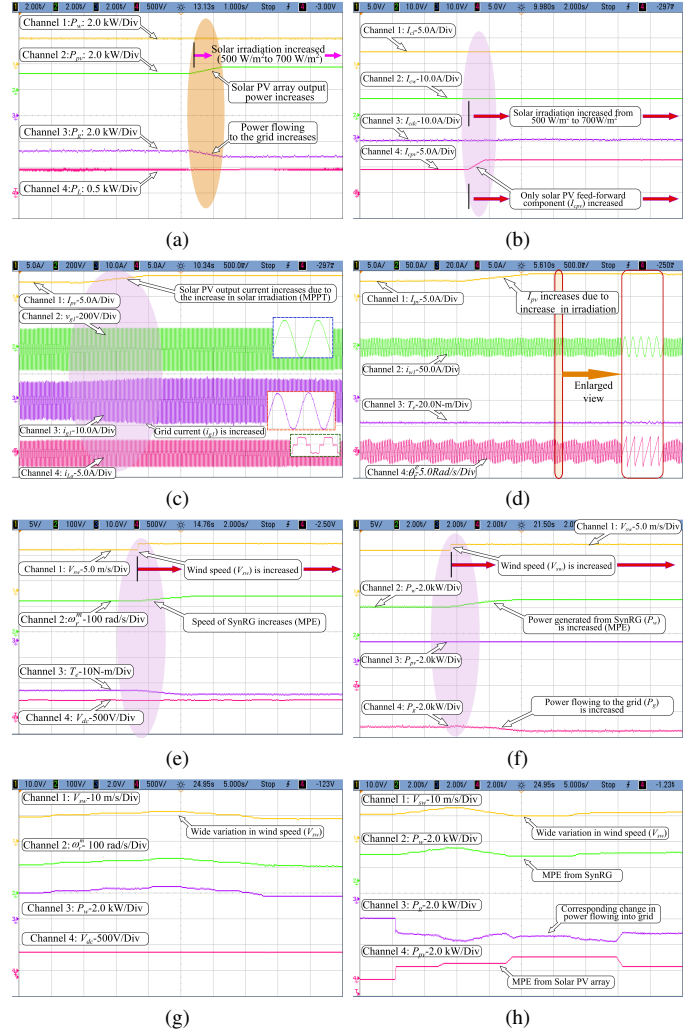


Fig. 8. Dynamic behaviour (a)-(d) under variation in solar irradiation (e)-(f) under wind speed variation (g) under wide variation in V_{sw} (h) under variations in both V_{sw} and solar irradiation.

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/m². The powers generated from solar PV array and WECS are sufficient to support

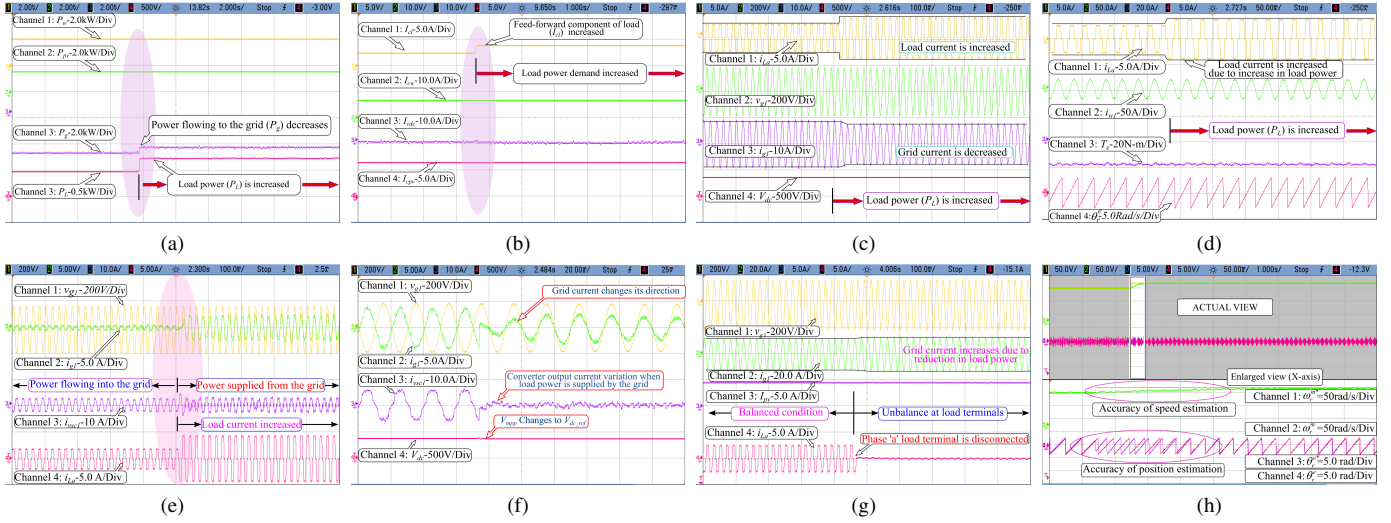


Fig. 9. Dynamic behaviour (a)-(d) at variation in load current (e) when $P_L > P_w + P_{pv}$ (f) when P_w and P_{pv} are unavailable (g) under unbalance at load terminals. (h) Accuracy of speed and position estimation.

the local nonlinear load demand, so that excess power is fed to the grid. Once V_{sw} 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 (ω_r^m) and torque (T_e) 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_{cw}) 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 ω_r^m , P_w and V_{dc} . From the variations in ω_r^m and P_w shown in Fig.8(g), it is obvious that, with the variations in V_{sw} , 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_{sw} 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_e and θ_r^e), 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_{sw} 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° 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_{sw} 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 $V_{dc_ref} = 360$ 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 micro-grid 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 I
SYSTEM PARAMETERS

Solar PV Array	
Open circuit voltage, V_{oc}	430 V
Short circuit current, I_{sc}	7A
Peak power, P_{MPE}	2.5 kW
SynRG parameters	
Power rating	3.7kW
Voltage rating and frequency	220V, 50Hz
Speed and number of pole pairs	1500rpm and 2
Rated current	16.3A
Resistance of stator winding, R_s	2.5 Ω
Direct and quadrature axes inductances	99.47 & 10.15 mH
Grid side	
Rated grid voltage and frequency	220 V, 50 Hz
RC filter values C_F and R_F	10 μF and 5 Ω
Interfacing inductor and DC-link capacitance	4mH, 2200 μF

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