A solar PV augmented hybrid scheme for enhanced wind power generation through improved control strategy for grid connected doubly fed induction generator

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A solar PV augmented hybrid scheme for enhanced wind power generation through improved control strategy for grid connected doubly fed induction generator

Adikanda Parida* and Debasis Chatterjee

Abstract: In this paper, a wind power generation scheme using a grid connected doubly fed induction generator (DFIG) augmented with solar PV has been proposed. A reactive power-based rotor speed and position estimation technique with reduced machine parameter sensitivity is also proposed to improve the performance of the DFIG controller. The estimation algorithm is based on model reference adaptive system (MRAS), which uses the air gap reactive power as the adjustable variable. The overall generation reliability of the wind energy conversion system can be considerably improved as both solar and wind energy can supplement each other during lean periods of either of the sources. The rotor-side DC-link voltage and active power generation at the stator terminals of the DFIG are maintained constant with minimum storage battery capacity using single converter arrangement without grid-side converter (GSC). The proposed scheme has been simulated and experimentally validated with a practical 2.5 kW DFIG using dSPACE CP1104 module which produced satisfactory results.

Subjects: Power Engineering; Renewable Energy; Systems & Controls

Keywords: wind–solar PV hybrid generation; model reference adaptive system; doubly fed induction generator; DC micro-grid

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PUBLIC INTEREST STATEMENT

The solar PV augmented wind energy conversion system presented in this paper addresses power generation issues during low-wind speed situations. The scheme can also have enormous potential to generate low-cost power in the remote region where the grid is absent and the average rotor speed remains in the sub-synchronous region with availability of solar power. The continuity of power generation both in the grid connected and standalone mode of operation is the major advantage of the proposed scheme. Moreover, the quality of power delivered to the grid or load can be considerably improved with the proposed scheme.
1. Introduction

The wind power generation is gaining increasing global importance due to environmental safety and growing energy crisis. Harnessing the generally fluctuating power from wind and maintaining continuous exchange of power with the utility grid is found to be a challenging task for the researchers in the recent past. The proposed solar PV augmented wind energy conversion system addresses the DFIG control issues under such situations in a cost-effective manner.

The wind turbine produces power in accordance with the available wind speeds with the help of existing technology (Yang & Yang, 2010; Zhang, Chen, & Hu, 2014). As the penetration of DFIG-based wind firms to the existing grids is significantly increasing day by day, the fluctuating power fed to the grid would adversely affect the power quality of the interconnected or weak or isolated grids as reported in Chen and Spooner (2001), Diaz-González, Sumper, Gomis-Bellmunt, and Bianchi (2013), Kanellos and Hatzigiargyiou (2012). To overcome such problems, comprehensive measures have been suggested in Lu, Chang, Lee, and Wang (2009), Zhou and Francois (2011) with the augmentation of power storage devices. The continuity of generation from DFIG-based wind energy conversion system which can be achieved through maximum power tracking control mechanism with augmentation of multiple renewable energy sources is presented in Mendis, Mutaqi, et al. (2014), Mendis, Mutaqi, Perera, and Kamalasadan (2015) for remote area power supply. A similar type of technique is proposed in Kou, Liang, Gao, and Gao (2015) for grid connected operation. However, increased complexity in terms of coordinated control and cost of energy is a subject of concern for practical implementation of such topologies. An appropriate scheme for rated power generation at generator bus is proposed in Vijayakumar, Tennakoon, Kumaresan, and Ammasai Gounden (2013), Daniel and AmmasaiGounden (2004) and Shukla and Tripathi (2015). However, the presented scheme does not clarify the operation over wide speed range or proper sizing methodology of the storage batteries under such situations.

The precise control over generated power requires enhanced performance of the rotor-side converter (RSC) controller, which can be achieved through accurate information of rotor position angle. The rotor position and speed estimation techniques reported in Cardenas, Pena, Proboste, and Asher (2005), Cardenas and Pena (2004), Cardenas, Pena, et al. (2008), Cardenas, Pena, Clare, Asher, and Proboste (2008) are based on model reference adaptive system. The scheme presented in Cardenas et al. (2005) is implemented using stator flux as adjustable variable, while Cardenas and Pena (2004) considers rotor flux for the same. The estimation technique adapted in Cardenas, Pena, Proboste, Asher, and Clare, (2008) is different from Cardenas et al. (2005) and Cardenas and Pena (2004) which considers rotor current as adjustable variable. The performance of the techniques adapted in Cardenas et al. (2005), Cardenas and Pena (2004), Cardenas et al. (2008) is analyzed in Cardenas et al. (2008). The reported techniques (Karthikeyan, Nagamaní, & Ilango, 2012; Karthikeyan, Nagamaní, Ray Chaudhury, & Ilango, 2012) are implemented with the use of differentiators based on open-loop methods. This can introduce severe errors for estimation of rotor speed and position due to noise in the input signals. Moreover, all these existing techniques have almost the similar snag of having strong dependency on various machine parameter variations.

The main advantageous features of the proposed scheme can be summarized as,

(1) The rotor position estimation technique for the proposed scheme is almost independent of machine parameter variations, hence accurate.
(2) Continuous and consistent active power generation over wider wind speed range in comparison to the existing schemes.
(3) The single converter topology for DFIG considerably reduces the operational and installation cost of the system.
(4) No circulation of generated power between stator and rotor circuits of DFIG. Thus, the proposed scheme facilitates a reduced associated continuous power loss in the system.

Proper experiments and simulations have been performed on a practical 2.5 kW DFIG to validate the proposed topology of wind energy conversion system (WECS).
2. Scheme for the proposed system

2.1. System description
The schematic of the proposed hybrid generation scheme is shown in Figure 1. Stator terminals are directly connected to the grid and rotor windings are connected to RSC through slip rings. The RSC controls the rotor power of DFIG independent of the utility grid, unlike the existing widely used schemes. The rotor power management is accomplished through the following four modes.

Mode-I: Low wind speed and sufficient solar power
In this sub-synchronous mode of operation, the rotor power is supplied directly from solar panel. If solar energy generated is more than rotor power requirement, the excess power will be delivered to the DC micro-grid as shown in Figure 1 after storing in the battery.

Mode-II Both wind and solar power is low
In this sub-synchronous mode of operation, the rotor power needed is supplied from the battery.

Mode-III: Large wind power and low solar power
In this mode of operation, DFIG will deliver power through both stator and rotor. The rotor power can be directly stored in battery. If rotor power is very large, then DC micro-grid will be switched to evacuate the excess power available in the DC-link as shown in Figure 1.

Mode-IV Both wind power and solar power is high
In this case the DFIG will operate in the super-synchronous region and the power from rotor is added with the energy from solar PV and delivered to the DC micro-grid after charging the storage battery.

2.2. Rotor-side converter control
In the proposed scheme, RSC control signals are generated as shown in Figure 1 using measured values of stator voltage, stator current, rotor voltage, and rotor current as the input. Orienting stator flux $\psi_s$ along synchronously rotating d-axis, $\psi_s^e = \psi_{ds}^e$, thus $\psi_{qs}^e = 0$. Where, $\psi_{ds}^e$, $\psi_{qs}^e$ are the components of the stator flux in synchronous reference frame. The rated active and reactive power at the stator terminals of DFIG can be expressed as (Marques, Pires, & Sousa, 2011),

$$P_s = -V_{qs}^e \frac{L_m}{L_s} i_{qr}^r$$
$$Q_s = \left(\frac{V_{qs}^e}{\alpha L_s} - \frac{L_m}{L_s} V_{qs}^e i_{dr}^r\right)$$

(1)

The d-axis rotor current reference $(i_{dr}^r)^*$ is generated by comparing estimated value of stator active power $P_s^e$ with its reference value $P_s^r$. Similarly, comparing estimated and reference values of reactive power of the grid, the q-axis rotor current reference $(i_{qr}^r)^*$ is generated. The d-q axis rotor voltage references, $(V_{dr}^e)^*$, $(V_{qr}^e)^*$, can be expressed as,

$$(V_{dr}^e)^* = (V_{dr}^e)^* - \left(\omega_{\text{slip}}\right)\sigma L_{rqr}^e$$
$$(V_{qr}^e)^* = (V_{qr}^e)^* + \left(\omega_{\text{slip}} + \left(L^2 m/L_s\right)\right)\sigma r ms + \sigma L_{rdr}^e$$

(2)

(3)

where, $(V_{dr}^e)^*$ and $(V_{qr}^e)^*$ are the control outputs of PI controllers PI_3 and PI_4 respectively. The PI controller outputs $(V_{dr}^e)^*$ and $(V_{qr}^e)^*$ are used to generate rotor d-q axes voltage references $(V_{dr}^e)^*$, $(V_{qr}^e)^*$ using (2) and (3).
2.3. Active power flow of the proposed wind–solar PV hybrid system

The dynamics of the active power exchange of the proposed hybrid generation scheme is shown in Figure 2(a). In case of existing schemes reported in Karthikeyan, Nagamani, and Ilango (2012) and Karthikeyan, Nagamani, Ray Chaudhury, et al. (2012), during sub-synchronous operation, the requirement of DFIG rotor power $P_r$ is supplemented from the grid. Thus, the net power supplied to the grid by the generation system will be reduced considerably as shown in Figure 2(b). For the proposed scheme, the net power output from the generation system has been enhanced. This is due to the solar PV system supplements the rotor power pool in isolation with the grid. For the analysis, $P_g$ signifies the air gap power, $P_{\text{Grid}}$ signifies the output power fed to the grid, and $P_m$ signifies the shaft mechanical power input. For the given machine specified in Appendix 1, Table 2, experiments were conducted with varying the rotor speed between 1,800 rpm and 1,050 rpm. Representing $V_{dc}$ and $i_{dc}$ as the measured DC-bus voltage and current, respectively, the rotor power $P_r$ is computed as $P_r = V_{dc} \times i_{dc}$.

The generated electrical power at stator terminals is measured as $P_s = V_{ac}^s \times i_{ac}^s + V_{bs}^s \times i_{bs}^s$. In this analysis, the losses incurred in the rotor-side converter, stator copper, and core losses are neglected for simplicity. The shaft mechanical power input can be calculated from the measured DC motor input power for known efficiency.

For each rotor slip, the corresponding values of $P_s$, $P_r$, and $P_m$ are computed and plotted as shown in Figure 2(b). From Figure 2(b), in the sub-synchronous speed region, it can be observed that the injected rotor power increases with increasing slip due to low shaft power. The net output power for the existing schemes is obtained by subtracting the rotor injected power $P_r$ from the power output $P_s$ at the stator side. It can be also observed that, for the proposed scheme, the net output power at the stator more than the existing conventional scheme due to the addition of solar PV source at the input of the rotor-side converter.
3. The proposed rotor speed and position estimator

3.1. Estimator modeling

In the proposed scheme, the rotor speed and position estimation is carried out with measured stator and rotor voltages and currents without using any differentiators and integration of low-frequency signals. The reference model variable is developed based on the measured values of rotor voltage and currents. The adjustable model variable requires the measured stator inputs and the rotor currents transformed to the synchronous reference frame as shown in Figure 3(b). With $v_{ds}^s$, $v_{qs}^s$, and $i_{ds}^s$, $i_{qs}^s$ being the measured values of stator voltages and currents in stationary reference frame, stator flux linkages $\psi_{ds}^s$, $\psi_{qs}^s$ can be expressed as (Leonhard, 2001),

$$
\begin{align*}
\psi_{ds}^s &= \int (v_{ds}^s - R_s i_{ds}^s) \, dt \\
\psi_{qs}^s &= \int (v_{qs}^s - R_s i_{qs}^s) \, dt
\end{align*}
$$

The synchronous frequency of the stator flux is computed using the relation,

$$
\omega_e = \left( \psi_{ds}^s \cdot \left( \frac{\dot{\psi}_{qs}^s}{\psi_{qs}^s} \right) - \psi_{qs}^s \cdot \left( \frac{\dot{\psi}_{ds}^s}{\psi_{ds}^s} \right) \right) / \left( \psi_{s}^s \right)^2
$$

The stationary reference frame parameters can be converted into synchronous reference frame ($d^q - q^o$) with $d^o$-axis aligned to stator flux axis. Therefore, the unit vectors can be computed as,
\[
\cos \theta_e = \psi_e^s / \psi_e^q, \quad \sin \theta_e = \psi_e^q / \psi_e^s, \quad \text{with the help of unit vectors, the stator voltages can be transformed from stationary to synchronous reference frame as,}
\]
\[
\begin{bmatrix}
V_{ds}^e \\
V_{qe}^e
\end{bmatrix} =
\begin{bmatrix}
\cos \theta_e & -\sin \theta_e \\
\sin \theta_e & \cos \theta_e
\end{bmatrix}
\begin{bmatrix}
V_{ds}^e \\
V_{qs}^e
\end{bmatrix}
\]
\[
(6)
\]
The no load \((i_r^* \approx 0)\) reactive power drawn by the DFIG at steady state neglecting stator resistive voltage drop can be obtained from Figure 3(a), as,
\[
Q_m = \left(1 / \omega_e L_s \right) \left(V_s^e \right)^2
\]
\[
(7)
\]
Therefore, with,
\[
(8)
\]
Stator reactive power of DFIG at any load can be expressed as,
\[
Q_s = \left[ V_s^e i_s^d - v_s^e i_s^q \right]
\]
\[
(9)
\]
Thus the air gap reactive power \(Q_{ag}\) can computed from (8) and (9) as,
\[
Q_{ag} = \left[ V_s^e i_s^d - v_s^e i_s^q \right] - \left(1 / \omega_e L_s \right) \left(V_s^e \right)^2
\]
\[
(10)
\]
The d-q axis stator currents \(i_s^d, i_s^q\) in synchronous reference frame can be expressed as,
\[
\begin{bmatrix}
I_{ds}^s \\
I_{qs}^s
\end{bmatrix} = \frac{1}{L_s} \begin{bmatrix}
\psi_e^d \\
\psi_e^q
\end{bmatrix} - \frac{L_m}{L_s} \begin{bmatrix}
i_{dr}^r \\
i_{qr}^r
\end{bmatrix}
\]
\[
(11)
\]
where, \(i_{dr}^r\) and \(i_{qr}^r\) of (11) can be expressed as,
\[
\begin{bmatrix}
i_{dr}^r \\
i_{qr}^r
\end{bmatrix} = \begin{bmatrix}
\cos \theta_{slip} & \sin \theta_{slip} \\
-\sin \theta_{slip} & \cos \theta_{slip}
\end{bmatrix}
\begin{bmatrix}
i_{dr}^* \\
i_{qr}^*
\end{bmatrix}
\]
\[
(12)
\]
where, \(i_{dr}^*, i_{qr}^*\) are the measured rotor currents in rotor reference frame.

Substituting \(i_{ds}^r\) and \(i_{qs}^r\) from (11) in (10) gives,
\[
Q_{ag} = \left( L_m / L_s \right) \left( V_{ds}^e i_{ds}^r - v_{ds}^e i_{dr}^r \right) + \left[ \left( V_{qs}^e \psi_e^d / L_s \right) - \left( v_{qs}^e \psi_e^q / L_s \right) \right] - \left(1 / \omega_e L_s \right) \left(V_s^e \right)^2
\]
\[
(13)
\]
Neglecting stator resistance drop, \( \psi_{qs}^e, \psi_{qs}^e \) of (13) can be expressed as,

\[
\begin{bmatrix}
\psi_{qs}^e \\
\psi_{ds}^e
\end{bmatrix} = \left( \frac{1}{\sigma_e} \right) \begin{bmatrix}
V_{qs}^e \\
V_{ds}^e
\end{bmatrix}
\]

(14)

Considering (13) and (14),

\[
Q_{ag} = \frac{(L_m/L_s)}{\left(1 - \sigma_s\right)} \left[ V_{qs}^{e* - V_{qs}^e} \right] = \left(1 - \sigma_s\right) \left[ V_{qs}^{e* - V_{qs}^e} \right]
\]

(15)

The inverse T-model equivalent circuit of DFIG is shown in Figure 3(a), where,

\[
L_s \approx L_{Ir} + L_{ls}; \quad \frac{1}{\sigma_s} = \frac{(L_m/L_s)}{\left(1 + \sigma_s\right)} V_{Ve}^e; \quad \frac{1}{\sigma_s} = \frac{(L_s/L_m)}{\left(1 - \sigma_s\right)} V_{Ve}^e
\]

(16)

The adjustable model reactive power \( \hat{Q}_s \) as shown in Figure 4(a) can be expressed as,

\[
\hat{Q}_s = \left(1 - \sigma_s\right) \left[ V_{qs}^{e* - V_{qs}^e} \right] - \left(\hat{\omega}_s\right)^2 \omega_{slip} L_s
\]

(17)

The reference model stator reactive power (\( Q_s^* \)) is calculated in the proposed algorithm with a concept that the rotor-side reactive power is same as the stator reactive power crossing the air gap. Considering inverse T-model equivalent circuit of DFIG at steady state, \( Q_s^* \) can be obtained in the rotor reference frame as,

\[
Q_s^* = \left[ V_{qs}^{e* - V_{qs}^e} \right]
\]

(18)

Here in (18), \( V_{qs}^e, V_{qs}^{e*} \) are the measured rotor voltages in rotor reference frame. Expression (17) generates the adjustable model variable as a function of measured stator voltage, rotor current, and adjustable parameters of rotor position angle \( \theta_r \). Slip speed \( \omega_{slip} = \omega_e - \hat{\omega}_s \) and \( \omega_e \) is computed using (5). An error signal \( \xi \) is generated based on difference of \( Q_s^* \) calculation from (17) and (18) which is given by,

\[
\xi = Q_s^* - \hat{Q}_s
\]

(19)

An adjustable mechanism designed by a hysteresis controller to drive the error \( \xi \) computed using (19) to zero. The output of adjustable mechanism is the estimated rotor speed and is integrated for rotor position \( \theta_r \) estimation.

### 3.2. Parameter Sensitivity

For most of the existing rotor speed and position estimation techniques, the adjustable variables are rotor current, stator flux, or rotor flux. These adjustable variables can be expressed as,

i. Rotor current, \( \hat{i}_r = \frac{v_{qs} - i_{qs}}{L_{m} \omega_e} e^{-j\theta_r} \)

ii. Stator flux, \( \hat{\psi}_s = L_{s} \left( i_{qs} + \frac{v_{qs}}{L_{m}} \right) i_{qs} \) and

iii. Rotor flux \( \hat{\psi}_r = L_{r} \left( i_{qs} + \frac{v_{qs}}{L_{m}} \right) i_{qs} \)

From the above equations, the adjustable variables are directly sensitive \( L_m \) variations.

The direct sensitivity of the adjustable variables with \( L_m \) will considerably affect the performance of the DFIG controller as the same usually varied during DFIG operation. In proposed control scheme, the adjustable variable \( Q_s^* \) seen from (17) is very weakly coupled to \( L_m \). From (17), the term directly related with \( L_m \) is \( (1 - \sigma_s) \). For any variation \( \Delta L_m \), the new magnetizing inductance is given by \( (L_m + \Delta L_m) \). Therefore, \((1 - \sigma_s)\) can be modified to,
The variation of the adjustable variable $\hat{Q}_s$ is plotted and shown in Figure 4(a) for $L_m$ deviation between $-50\%$ and $+50\%$. It is observed from Figure 4(a) that the maximum variations of $(1 - \sigma_s)$ are $+1.23\%$ and $-1.2\%$ for $L_m$ deviations of $+50\%$ and $-50\%$. This error is acceptable. The rotor position estimation for $L_m$ variation of $-50\%$ and $+50\%$ is shown in Figures 4(b) and 4(c), respectively, using widely used techniques including the proposed one. The rotor position estimation error in radian for the same is shown in Figure 4(d). Observation of Figures 4(b)–4(d) shows the superiority of the proposed technique over the existing schemes.

3.3. Stability analysis

The block diagram for the stability analysis is shown in Figure 5(a). The distribution of stator and rotor space vectors are shown in Figure 5(b) when rotor is at sub-synchronous speed and in Figure 5(c) for super-synchronous speed with $\mu$ as the angle between $V_s$ and $I_r$ vectors (Wu, Lang, & Zargari, 2011). Assuming, $\sigma_s \approx 0$, (17) can be written as,

$$ (1 - (\sigma_s + \Delta \sigma_s)) = \frac{(L_m + \Delta L_m)}{(L_m + \Delta L_m + Ls)} = \frac{\left(1 + \frac{\Delta L_m}{L_m}\right)}{\left(1 + \frac{\Delta L_m + Ls}{L_m}\right)} \quad (20) $$

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$$ \hat{Q}_s = (1 - \sigma_s) [V_s \times I_r \sin(\gamma)] - K_{f2} \quad (21) $$

where $\times$ is the symbol of cross product. From the vector diagram in Figures 5(b) and 6(c), (21) can be rewritten to obtain the estimated reactive power magnitude as,

$$ \hat{Q}_s = K_{f1} [V_s I_r \sin(\gamma)] - K_{f2} \quad (22) $$

Assuming a disturbance of $\Delta \theta_r$ in estimation of rotor position $\theta_r$, the new space position angle between $V_s$ and $I_r$ will be $\gamma + \Delta \theta_r$. This will modify the estimated torque $\hat{Q}_s$ to $\hat{Q}_s + \Delta \hat{Q}_s$.

From (22),

$$ \hat{Q}_s + \Delta \hat{Q}_s = K_{f1} [V_s I_r \sin(\gamma + \Delta \theta_r)] - K_{f2} = K_{f1} [V_s I_r \sin(\gamma \cdot \cos(\Delta \theta_r) + \cos \gamma \cdot \sin(\Delta \theta_r))] - K_{f2} \quad (23) $$

For $\Delta \theta_r$ to be small, (23) can be written as,

$$ \hat{Q}_s + \Delta \hat{Q}_s = K_{f1} [V_s I_r \sin(\gamma + \Delta \theta_r \cdot \cos \gamma)] - K_{f2} \quad (24) $$

The difference between (24) and (22) can be expressed as,

$$ \Delta \hat{Q}_s = K_{f1} [V_s I_r \cos \gamma \Delta \theta_r] \quad (25) $$
Therefore from Figure 5(a), $\xi = K_f V_s I_s [\cos \gamma] \Delta \theta_r$  \hspace{1cm} (26)

\[
\frac{d\Delta \theta_r}{dt} = \omega_o (q - \omega_m)
\]  \hspace{1cm} (27)

From (26),
When the hysteresis controller output slides between (0 to 2) per unit, condition for stability is analyzed as (Marques et al., 2011; Silva & Pinto, 2011),

\[ \dot{\xi} = \frac{K_{f_1} V_s I_r \cos \gamma}{\omega_o} (0 - \omega_m) \]  (28)

Substituting from (27) in (28),

\[ \dot{\xi} = \frac{K_{f_1} V_s I_r \cos \gamma}{\omega_o} (q - \omega_m) \]  (29)

For \( \xi < 0; q = 0; \)

\[ \dot{\xi} = \frac{K_{f_1} V_s I_r \cos \gamma}{\omega_o} (0 - \omega_m) \]  (30)

\[ \xi > 0; q = 2; \]

\[ \dot{\xi} = \frac{K_{f_1} V_s I_r \cos \gamma}{\omega_o} (2 - \omega_m) \]  (31)

To satisfy condition for system stability, from (30), (31), \( \cos \gamma < 0, V_s \neq 0, I_r \neq 0 \). From Figures 5(b) and 5(c), \( \xi < \gamma < \frac{3\pi}{2} \) for rotor speed from sub-synchronous to super-synchronous including synchronous speed at all loads. Therefore, irrespective of the load at the machine terminal, the estimation model is stable at all operating points.

4. Power generation economics

To justify the economical feasibility of the proposed scheme over the existing systems reported in Vijayakumar et al. (2013) and Cardenas et al. (2005), an economic analysis is performed for all the systems. The average availability of solar power is assumed to be between 9 am and 4 pm (http://www.nrel.gov/rredc). The capacity of solar panel is so considered that it can supply power to both DFIG rotor and to the battery during day time and low wind speed situations. Considering an average slip magnitude of 0.2 for the 2.5 kW DFIG in sub-synchronous and -0.15 in super-synchronous operating region, a 1 kW capacity of solar unit is taken so that both the charging of the battery and supplementing power to DFIG rotor can take place during sub-synchronous operation. The rated rotor voltage of 150 V for the DFIG will require a DC-bus and the battery voltage of 192 V. Considering charging–discharging cycle shown in Figure 6, a battery capacity of 50Ah is selected for the system. However, the capacity of both the solar unit and battery can be selected for different locations based on operation cycles. A comparison of the proposed and existing schemes has been made using HOMER Pro-3.2 (Hybrid Optimization Model for Electric Renewables) software. For the proposed system, an extra investment is required due to the PV modules along with the charging unit and the storage battery.
On the other hand, the conventional scheme with dual converter will require additional grid-side converter and transformer for grid inter connection. The other scheme with only one converter and battery backup will need a large storage battery capacity to cope up the situation of the system to be in the sub-synchronous region for the given cycle. Inclusion of both PV module and storage battery in the proposed scheme will result in additional generation of power compared to the existing schemes and results in lesser size of storage battery. On this basis, the three schemes are simulated and the results for the important parameters are tabulated in Table 1.

The extra investment for the proposed scheme compared to the existing schemes with back-to-back converter can be paid back within 3.5 years and generate profit beyond this period up to the first replacement schedule of storage battery. On the other hand, the larger battery required for the existing scheme with single converter and battery will result in larger unit cost of energy as shown in Table 1. Where, the life of the PV modules and battery is considered to be 20 years and 5 years, respectively, for the present calculations. Therefore, the proposed scheme is more reliable in terms of power generation and economically profitable than the existing schemes.

5. Simulation and Experimental Results
The proposed generation scheme is implemented with a 2.5 kW doubly fed induction generator with machine parameters as shown in Appendix 1, Table 2. The experimental arrangement is shown in Figure 7, where the measured values of stator voltage, stator currents, rotor voltage, and rotor currents are fed as inputs to the controller. The stator and rotor currents are sensed through Hall Effect sensors LTS25NP (LEM make), while the voltage sensing process has been accomplished through CV3-1000(LEM make) sensor. A 5Hp, 1,500 rpm, separately excited DC motor with necessary torque control arrangement is coupled to the DFIG can emulate the wind turbine.

![Figure 7. Experimental setup for the proposed scheme.](image)

| Table 1. Comparative economic analysis of existing conventional system with the proposed system |
|---------------------------------------------|------------------------------------------------|------------------------------------------------|------------------------------------------------|
| Decisive factors type of the system         | Proposed DFIG system with storage battery and PV modules | Existing DFIG system with single converter and storage battery (Vijayakumar et al., 2013) | Existing DFIG system with back to back converter (Cardenas et al., 2005) |
| Initial capital required ($)                | 1500                                           | 1500                                           | 1800                                           |
| Cost of energy ($/kWh)                      | 0.008                                          | 0.009                                          | 0.01                                           |
| Net present cost ($)                        | 2047                                           | 2549                                           | 1532                                           |
| Operating cost ($/year)                     | 45                                              | 72                                             | 36                                             |
A closed-loop torque controller is used for the separately excited dc machine incorporating the wind turbine model. The shaft encoder gives the information regarding the speed and position of the shaft for the control of the prime mover. The proposed MRAS computes rotor speed and position and is compared with measured value for validation. The rotor speed and position information from
The speed estimator are fed to the RSC controller. A dSPACE CP1104 module with a PC interface is used for implementation of the experimental system.

Initially, the machine was running at 1,150 rpm with the help of the DC motor drive system. Then the speed was slowly increased to 1,860 rpm in 4.5 s. The estimated speed through the proposed controller and the corresponding measured speed is shown in Figure 8(a), while the measured and estimated rotor position at near synchronous speed are shown in Figure 8(b). It can be observed
from Figure 8(a) and Figure 8(b) that the proposed controller accurately estimates both the rotor position and speed during the speed transient. Figure 8(c) shows the computation of sin and cosine terms of slip angle which is used for demodulating the rotor voltage and current signals. The d-q rotor current $i_{r \_dq}$ in synchronous reference frame is shown in Figure 8(d) corresponding to the speed variation as shown in Figure 8(a).

The response of the DC-link voltage and current can be observed from Figure 9(a) and Figure 9(b), respectively, during speed transition corresponding to Figure 8(a). The stator voltage and current are shown in Figure 9(c) and Figure 9(d), respectively, which remain unbiased during the transition of rotor speed. Then the proposed scheme of position estimation was compared with the conventional rotor position estimation schemes realized through open-loop methods. The results are shown in Figure 10(a) and Figure 10(b) in which it can be observed that the proposed technique is superior to the existing technique. The proposed scheme have integration of three type of source e.g. battery, PV, and wind was tested for power sharing to the DC-bus. The wind speed varied from 0.8 to 1.2 p.u when the battery was fully charged and the solar insolation was at constant value. The power was measured at various points e.g. battery, PV module, DFIG rotor and DC micro-grid, and variations of each of them are recorded during the speed transition. The results are shown in Figure 11. The battery, PV, DFIG rotor, and DC micro-grid powers are denoted by $P_b$, $P_p$, $P_{aux}$, and $P_r$, respectively, in Figure 11. The DC micro-grid power can be given by, $P_{dcg} = P_p + P_b - P_r$ as per the chosen convention of rotor power. It is observed from Figure 11 that when the DFIG is in sub-synchronous region and speed is increasing, the rotor power absorbed by the machine is reducing, and the DC micro-grid power is increasing. At the rotor speed of 1.0 p.u, the power delivered to rotor is low and the DC micro-grid power is almost equal to the sum of the battery power and the PV power which can be observed from Figure 11. After the speed crosses 1.0 p.u value i.e. in the super-synchronous region, the rotor delivers increasing power and as a result the DC micro-grid power is further increased.

Then, similar experiments were performed to validate the simulation results. The experimental results are shown in Figure 12 for the speed transition between 1,150 rpm and 1,860 rpm with the help of the prime mover. The rotor currents in rotor reference frame as shown in Figure 12(a), the rotor frequency is almost zero when the rotor speed is near synchronous speed region, thus the rotor current exhibits dc behavior. The DC-link voltage and currents during the speed transition is shown in Figure 12(b). The DC-link voltage remains constant while the DC-link current reduces near synchronous speed and again rises beyond synchronous speed. This is because, the rotor current at synchronous speed is dc and attains the minimum value. The stator voltage and current wave forms are given in Figure 12(c) and (d), respectively.

6. Conclusion
The proposed wind–solar hybrid generation scheme is successfully implemented for wide wind speed range. The continuity in the active power at stator terminals of DFIG can be maintained at minimum cost of energy. The single converter topology for the DFIG greatly reduces the operational and installation cost of the system. The overall generation reliability has been considerably increased through proper augmentation of solar PV system which supplements WECS during lean periods of available wind power. The performance of the system is considerably improved through accurate estimation of rotor speed and position of DFIG. Moreover, the proposed rotor speed and position estimation technique has negligible sensitivity to the machine parameter variations, which makes it more accurate. The proposed method is simple and can be implemented for grid-connected or grid-isolated modes through any already available drive compatible processors.

List of symbols

- $\psi_{ds}$, $\psi_{qs}$: Components of stator flux along d and q axes, respectively
- $v_{ds}$, $v_{qs}$: Components of stator voltages along d and q axes, respectively
- $v_{dr}$, $v_{qr}$: Components of rotor voltages along d and q axes, respectively
$i_d$, $i_q$ Components of stator currents along d and q axes, respectively  
$i_{d r}$, $i_{q r}$ Components of rotor currents along d and q axes, respectively  
$L_m$, $L_s$ Magnetizing, Stator self inductances of DFIG, respectively  
$L_{ls}$, $L_{lr}$ Stator and rotor leakage inductances of DFIG, respectively  
$\gamma$ Space angle between stator voltage and rotor current  
$R_s$ Resistance of stator  
$P_s$, $Q_s$ Active and reactive powers available at stator terminals of DFIG  
$\omega_m$, $\omega_r$ Angular velocity of stator magnetizing flux, Rotational speed of rotor  
$\theta_r$ Rotor position angle  
$\sigma_s$ Stator leakage factor  
$K_p$, $T_i$ PI controller constants  
$\mu_s$ Time constant of the delay introduced by sampling  
$\omega_0$ Electrical frequency of the machine  
$\omega_{slip}$ Slip speed of the machine  
$\sigma$ Leakage factor $= \left(1 - \frac{L_m}{L_s + L_r}\right)$  
$\text{ims}$ Magnetizing current of the machine

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Appendix 1.

Table 2. Design parameters

| Element | Parameter | Element | Parameter | Element | Parameter |
|---------|-----------|---------|-----------|---------|-----------|
| DFIG    | Magnetizing inductance | 0.44H | Ratings | 1000 PW |
| Stator  | Y-connected, 415 V (L-L) | RSC | Output voltage | 12 V |
| Rotor   | Y-connected, 150 V (L-L) | Type | 3 phase, Y-connected | Output current | 7.5A |
| Rated power | 2.5 kW | Rated power | 1 kW | Operating temperature | 25–35°C |
| No. of poles | 4 | DC-link voltage, \( V_{dc} \) | 200 V | STORAGE BATTERY | Rechargeable |
| Rated speed | 1440 rpm | DC-link current, \( I_{dc} \) | 7.5A | Type | Pb-acid |
| Stator resistance | 0.4ohm | AC voltage, \( V_{ac} \) | 150 V (L-L) | Total capacity | 50Ah |
| Rotor resistance | 0.45ohm | SOLAR PV MODULE | Output voltage/unit | 12 V |
| Stator self inductance | 0.015H | Type Polycrystalline |
| Rotor self inductance | 0.015H | |

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