Research Article

An Advanced Control Performance of a Sophisticated Stand-Alone Wind-Driven DFIG System

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To supply resident loads far from the grid, a stand-alone wind system with a small-scale wind turbine and battery storage can be used. The traditional configuration of the system has a permanent-magnet synchronous generator (PMSG). Other alternative configurations use doubly fed induction generator (DFIG). The systems with DFIG have variable speed operation with a limited speed range which reduces the captured power from the wind turbine. Also, there is a rotor-side converter (RSC) which carries the reactive power of DFIG, in addition to the slip power. In this paper, an improved system configuration with DFIG is controlled by an advanced control scheme. By this advanced scheme, the speed range is increased such that maximum power operation of wind turbine is obtained for complete range of wind speed, and volt-ampere (VA) requirements of RSC are reduced by the operation at nearly zero-slip power.

1. Introduction

Generation of electricity from renewable sources (wind, solar, tidal, etc.) is motivated by the increase of power demand, environmental concerns, and scarcity of natural sources, such as petroleum. Wind energy is abundant, and the generation by wind gives lower cost per kW compared with other alternatives. Due to the varying nature of wind, variable speed operation of wind turbines is essential to maximize the captured power, where the turbine speed is changed in relation to wind speed.

For grid connection, there are two common configurations of wind system. In the first configuration, the wind turbine is connected to a permanent-magnet synchronous generator (PMSG) [1–5]. Gearless configuration can be obtained by using low-speed PMSG which is designed by large number of poles. The PMSG is connected to the grid through back-to-back converter (machine-side converter (MSC) and grid-side converter (GSC)). Advantages of this system are higher efficiency because the absence of rotor winding and gearless configuration, wide speed range, and decoupling between the generator and the grid is appropriate for grid code. Disadvantages of this system are higher initial cost due to manufacturing cost of the generator and due to full rating of the converter, higher converter losses, and changing of flux density of the permanent magnet by temperature. In the second configuration, the wind turbine is connected to doubly fed induction generator (DFIG) through a gearbox, the stator of DFIG is directly connected to the grid, and the rotor is connected to the grid through back-to-back converter (rotor-side converter (RSC) and grid-side converter (GSC)) [6–10]. An advantage of this system is the low rating of the converter (about 0.3 pu). A disadvantage of this system is the limited speed range of the generator (0.7 pu to 1.3 pu).

When the grid is not accessible, a stand-alone wind system with a small-scale wind turbine can be used to
supply local loads. The small-scale wind turbine has a passive yaw control. Also, when the wind speed goes to high values, beyond a stated value, passive control methods are used to regulate the power by decreasing rotor-blade area subjected to wind. Furling is a common passive control method. The common configuration of the stand-alone wind system has a small-scale wind turbine directly connected to the PMSG, and the PMSG is connected to the load through back-to-back converter (machine-side converter (MSC) and load-side converter (LSC)). A battery bank connected to the DC bus, and the battery bank is charged when the generated power is higher than the load demand, and it is discharged when the generated power is lower than the load demand [11–15]. The battery bank is protected against overcharging by using a dump (or diversion) load. This load is connected to the battery bank through a di- version (dump) load controller, and the excess energy is converted to heat. The LSC can be controlled to supply single phase loads or three phase loads. However, problems of this system are higher initial cost due to manufacturing cost of the generator and due to full rating of the converter, higher converter losses, and changing of flux density of the permanent magnet by temperature. An alternative configuration has a small-scale wind turbine connected to the DFIG through a gearbox, the stator of DFIG is directly connected to three-phase loads, and the rotor is connected to the three-phase load through back-to-back converter (rotor-side converter (RSC) and load-side converter (LSC)) [16–19]. There are three disadvantages of this configuration, in addition to the limited speed range of DFIG. The RSC carries the slip power and the reactive power of DFIG which increases the rating of this converter. Also, if the loads are single phase, an additional transformer, zigzag transformer, is required to provide the neutral line, which increases the cost. In addition, there is a problem of imbalance in case of single-phase loads. An alternative configuration with DFIG is proposed in [20]. The rotor connected to the load through back-to-back converter (rotor-side converter (RSC) and load-side converter (LSC)). The stator of DFIG is connected to the DC bus through diode rectifier. An advantage of this configuration is the LSC can be controlled to supply single phase loads or three phase loads. Therefore, in case of single-phase loads, there is no need for zigzag transformer, and there is no problem of unbalance. However, there are two problems, the limited speed range and the higher rating of RSC due to the slip power and the reactive power of DFIG.

In this paper, an advanced control scheme and improved configuration of this alternative stand-alone wind system is proposed. By this control scheme, the DFIG is operated at negligible slip, and the RSC carries only the reactive power of DFIG, which reduces the rating of the converter. Also, the operation is for a wide speed range, which allows high power capturing efficiency for complete wind speed range.

2. Characteristics of Wind Turbine

The captured mechanical power (\(P_m\)) of the wind turbine at certain wind speed (\(V_w\)) can be given by

\[
P_m = \frac{1}{2} C_p \rho A V_w^3,
\]

where \(C_p\), \(\rho\), and \(A\) are the power coefficient, air density, and the area swept by the wind turbine respectively.

The coefficient \(C_p\) depends on the value of tip-speed ratio (\(\alpha\)), as shown by Figure 1 for a wind turbine. The value of the ratio \(\alpha\) depends on the values of \(V_w\), turbine speed (\(\omega\)), and radius of the turbine rotor (\(R\)), where

\[
\alpha = \frac{\text{tip speed of rotor blades}}{\text{wind speed}},
\]

\[
= \frac{\omega R}{V_w},
\]

Figure 1 shows there is a maximum coefficient value (\(C_{p_{\text{max}}}\)) occurred at optimum ratio value (\(\alpha_{\text{opt}}\)). These values correspond to the maximum power operation of the wind turbine.

3. Doubly Fed Induction Generator (DFIG)

The modeling of doubly fed induction generator (DFIG) is explained in text [21].

The torque equation is given by

\[
d\omega_m = \frac{T_m - T_e - B_m \omega_m}{J},
\]

where \(\omega_m\) is the mechanical angular speed of the DFIG, \(T_e\) is the electromagnetic torque of the DFIG, \(P\) is the number of pole pairs, \(T_m\) is the driving torque, \(B_m\) is the friction coefficient, \(J\) is the inertia. The developed torque (\(T_d\)) in the stator-flux frame can be given by

\[
T_e = \frac{3}{2} P \frac{L_m}{L_s} \lambda_s i_{qr(\lambda)},
\]

where \(i_{qr(\lambda)}\) is the \(q\)-axis component of rotor current, \(L_s\) is the self-inductance of the stator winding, \(L_m\) is the magnetizing inductance. The stator flux (\(\lambda_s\)) in the stator-flux frame, with the positive direction of stator currents is out of the stator terminals, can be given by

\[
\lambda_s = -L_s i_{dr(\lambda)} + L_m i_{dr(\lambda)},
\]

where \(i_{dr(\lambda)}\) is the \(d\)-axis component of stator current and \(i_{dr(\lambda)}\) is the \(d\)-axis component of rotor current.

4. Conventional Stand-Alone Wind-Driven DFIG Systems

General features of conventional wind-power generating systems with DFIG are explained in this section.

4.1. Wind-Speed Range. The slip of the generator is varied from about 0.3 to about –0.3, where the operation is at constant stator frequency, and the corresponding generator speed (\(\omega_m\)) is varied from about 0.7 pu to about 1.3 pu. At rated wind speed, the generator speed (\(\omega_m\)) is higher than the rated synchronous speed (\(\omega_{ms}\)) rated by 30% [16]. Thus,
The slip power is carried by RSC. The maximum value of this power can be obtained as follows:

For maximum power operation of wind turbine, \( \alpha \) is equal to \( \alpha_{\text{opt}} \), and the turbine speed (\( \omega \)) is proportional to the wind speed (\( V_w \)). Equation (2). Taken (8) in account, the wind speed range, corresponding to rated frequency operation, is given by

\[
0.7 \omega_{\text{ms}, \text{rated}} \leq \omega_m \leq 1.3 \omega_{\text{ms}, \text{rated}}.
\]

For the considered wind turbine, \( V_{w\text{r}}, \text{cut} \) is about 7.7 m/s. Thus, for a wind turbine of \( V_{w\text{r}}, \text{rated} \) equal to 10 m/s, the minimum useful wind speed is about 5.4 m/s, which is higher than cut-in wind speed of most wind turbines. Therefore, to increase the capturing power efficiency, the speed range of the wind system needs an increase to include the low wind speeds.

4.3. Rating of a Rotor-Side Converter. The rating of this converter depends on the maximum value of the slip power. This value is occurred at rated wind speed as explained in the previous section. In addition, RSC carries the reactive power of DFIG (\( Q_g \)) supplied through the DC-bus [16–19]. Therefore, the rating of this converter is much higher than the corresponding converter in grid connected systems.

5. Structure Considerations of a Sophisticated Stand-Alone Wind System

The basic configuration of considered system is proposed in [20], and the improved configuration is shown in Figure 3, where a buck-boost converter is added to the basic configuration. As aforementioned, advantages of this system, compared with other systems with DFIG, are that single phase loads can be supplied without a zigzag transformer and without problem of imbalance. Disadvantages of this system are, as the other systems, that the RSC is carrying the slip power and the reactive power of DFIG, and the speed range is limited, which reduces the captured power from the wind turbine.

5.1. Stator Voltage and DC-Bus Voltage. The stator voltage is related to the DC-bus voltage because the stator is supplying the DC bus through the diode rectifier. For continuous stator current, the minimum value of the rectified voltage is equal to DC-bus voltage, Figure 4.
Thus,
\[ U_s = \frac{\sqrt{2}}{\sqrt{3}} u_{dc} \]
\[ U_s,\text{max} = \frac{2}{\sqrt{3}} u_{dc} \]
(16)
(17)

where \( U_s \) is the rms value of line value of the stator voltage.

5.2. Control of RSC. The rotor currents are controlled, through RSC, to obtain maximum power-point tracking and to control the stator flux. The reference rotor currents are obtained as follows [20]:

The reference torque of the DFIG is given by
\[ T_{\text{ref}} = \frac{T_{\text{opt}}}{\text{gear ratio}} - B_m \omega_m \]
(18)

where \( T_{\text{opt}} \) is the optimal torque of the wind turbine.

The torque \( T_{\text{opt}} \) is obtained as follows:
\[ T_{\text{opt}} = \frac{1}{2} C_{p,\text{max}} \rho A \left( \frac{R^3}{\alpha_{\text{opt}}} \right) \omega^2 \]
(19)

The reference rotor current \( i_{qr,\text{ref}} \) can be obtained by substituting the values of \( T_{\text{ref}} \) and \( \lambda_{s,\text{ref}} \) in equation (4). Thus,
\[ i_{qp}(\lambda) - \text{ref} = T_{\text{ref}} \frac{2}{3} \frac{L_s}{L_m} \lambda_{s, \text{ref}}. \]  

(20)

The reference rotor current \( i_{dr}(\lambda) - \text{ref} \) can be obtained by substituting with the values of \( \lambda_{s, \text{ref}} \) and \( i_{ds}(\lambda) \) in equation (5). Thus,

\[ i_{dr}(\lambda) - \text{ref} = \frac{\lambda_{s, \text{ref}} + L_m i_{ds}(\lambda)}{L_m}. \]  

(21)

The output of current (PI) controllers is used to determine the switching states of the RSC converter.

6. Advanced Control Scheme of the Presented Wind-Power Generating System

By the advanced control scheme, the rating of RSC is reduced by reducing the slip power to about zero. Thus, the RSC carries only reactive power of DFIG. Also, the speed range is extended to include wind speeds of lower values. Thus, the efficiency of capturing power is improved at low wind speed values. In the proposed control scheme, the synchronous speed \( (\omega_s) \), elec. rad, is controlled to follow the rotor speed \( (\omega_e) \), elec. rad, by controlling the DC-bus voltage \( (U_{dc}) \) and the stator flux linkage \( (\lambda_s) \). The dependence of \( \omega_s \) on \( U_{dc} \) and \( \lambda_s \) can be explained as follows: In the steady state, \( \omega_s \) is related to \( U_s \) and \( \lambda_s \) by

\[ \lambda_s = K_a \frac{U_s}{\omega_s}, \]  

(22)

and using (17) yields

\[ \lambda_s = K_b \frac{U_{dc}}{\omega_s}, \]  

(23)

where \( K_a \) and \( K_b \) are constants.

The value of \( \omega_s \) can be estimated by

\[ \omega_s = \frac{d\theta_s}{dt}, \]  

(24)

where \( \theta_s \) is the angle of the stator flux linkage,

\[ \theta_s = \tan^{-1} \left( \frac{\lambda_{qs}}{\lambda_{ds}} \right), \]

\[ \lambda_{qs} = \int \left( u_{qs} + R_s i_{qs} \right) dt, \]  

(25)

\[ \lambda_{ds} = \int \left( u_{ds} + R_s i_{ds} \right) dt, \]

where \( \lambda_{qs} \) and \( \lambda_{ds} \) are components of stator flux linkage, \( u_{qs} \) and \( u_{ds} \) are components of stator voltages, and \( i_{qs} \) and \( i_{ds} \) are components of stator currents (with the positive direction is out of the stator terminals).

The advanced control scheme is shown in Figure 5. There are two regions of control, voltage-controlled region and field-weakening region. A flowchart, explaining control operation, is shown in Figure 6.

6.1. Voltage-Controlled Region. During this region, the value of the stator flux linkage \( (\lambda_s) \) is equal to its rated value \( (\lambda_{s, \text{rated}}) \), and the value of the DC-bus voltage \( (U_{dc}) \) is controlled. Starting and low speed operation of the system is in this region. During low-speed values, the rotor terminal power was positive (input power to the rotor winding), Figure 2, because the slip was positive, i.e., the synchronous speed \( (\omega_s) \) was higher than the generator speed \( (\omega_e) \). By the proposed control scheme, \( \omega_s \) is controlled such that the slip is nearly equal to zero. The difference between the speeds \( \omega_s \) and \( \omega_e \) is controlled. This control region is ended when \( U_{dc} \) reached its rated value \( (U_{dc, \text{rated}}) \). It should be noted that the wind speed range includes the low values of wind speed.

6.2. Field-Weakening Region. During this region, the value of \( u_{dr} \) is equal to the rated value \( U_{dc, \text{rated}} \) and the value of \( \lambda_s \) is controlled. This control region is started when \( u_{qr} \) reached to \( U_{dc, \text{rated}} \). The rotor terminal power was negative (output power from the rotor winding), Figure 2, because the slip was negative, i.e., the synchronous speed \( (\omega_s) \) was lower than the generator speed \( (\omega_e) \).

By the proposed control scheme, \( \omega_s \) is controlled such that the slip is nearly equal to zero. The difference between the speeds \( \omega_s \) and \( \omega_e \) is used to obtain the reference stator flux \( (\lambda_{s, \text{ref}}) \) depending on PI controller. The increasing of the wind speed leads to increase of \( \omega_s \) and a corresponding decrease of \( \lambda_{s, \text{ref}} \) to increase \( \omega_e \).

When wind speed is decreased, \( \lambda_s \) is increased, and the region is ended when \( \lambda_s \) reached its rated value \( (\lambda_{s, \text{rated}}) \). Further decrease of the wind speed transfers the control to first region (voltage-controlled region).

7. Results and Discussion

MATLAB/SIMULINK is used to obtain the results. Data of the system are found in the Appendix. The single-phase load is of 110 V, 60 Hz, 2.5 kVA and 0.8 power factor lagging. The performance of the system is studied for the two regions of control, i.e., voltage-controlled region (1st region) and field-weakening region (2nd region). Figures 7–11 show the operation in the two regions and the transferring between them. Figure 7 shows the wind speed and Figure 8 shows the corresponding captured power from the wind turbine. A good maximum power-point tracking is obtained with deviation less than 0.1% for all wind speeds. Therefore, the wind speed range is increased to include lower wind values, started with cut-in wind speed (4 m/s). The operation during \( V_w \) of 4 m/s is in the 1st region when the voltage \( U_{dc} \) is less than its rated value, the stator flux linkage \( (\lambda_s) \) is at its rated value, Figures 9 and 10 respectively. Also, the operation is close to zero slip, where there is a tiny difference between the synchronous speed \( (\omega_s) \) and the rotor speed \( (\omega_e) \), Figure 11.

At time equal to 5 s, \( V_w \) is changed from 4 m/s to 10 m/s, Figure 7. This leads to increase of the \( \omega_s \), Figure 11, and
corresponding increase of \( u_{dc} \), Figure 9, to make \( \omega_s \) follows the ascending \( \omega_e \), Figure 11, to obtain zero slip. When \( u_{dc} \) is reached to its rated value, the transition to the 2nd region is occurred. \( \lambda_s \) is decreased, Figure 10, to make \( \omega_s \) follows the ascending \( \omega_e \). Finally, the operation is settled in the 2nd region.

At time equal to 20 s, \( V_w \) is changed from 10 m/s to 6 m/s. Figure 7. This leads to decrease of the rotor speed, Figure 11, and corresponding increase of \( \lambda_s \), Figure 10, to make \( \omega_s \) follows the descending \( \omega_e \). When \( \lambda_s \) is reached to its rated value, the transition to the 1st region is occurred. The voltage \( u_{dc} \) is decreased, Figure 9, to make \( \omega_s \) follows the descending \( \omega_e \). Finally, the operation is settled in the 1st region.

The stator-phase current is shown in Figures 12–15. Figure 14 shows the stator-phase current when \( V_w \) is equal to 10 m/s. The frequency of this current is about 78 Hz. To show the rotor current, a longer time period is required because of the very small rotor frequency, where the slip is trivial. Figure 16 shows \( V_w \) of 10 m/s is sustained for a longer time period, and Figure 17 shows the rotor current when \( V_w \) is equal to 10 m/s. The rotor frequency is about 0.0035 Hz, which means insignificant slip value.

To show the effect of load variation on the system performance, the results of step changes of the load when \( V_w \) is equal to 10 m/s are shown in Figures 18–20. The obtained results illustrate the good dynamic behavior of the control system while maintaining the DC-bus voltage to be kept constant at the reference value.

To show the robustness of the control system, the previous results with varying of wind speed are obtained again under parameters uncertainty including a reduction of the magnetizing inductance \( (L_m) \) with 20% which is considered as the most effective parameter in the proposed control system, Figures 21–24. The results show a trivial change of the behavior of the system. This is owed to the given analysis in Section 5 which assures that the value of \( i_{dr} (\lambda) - \text{ref} \) (21), depends on the nearly constant ratio \( (L_s/L_m) \), where \( \lambda_s \) is nearly proportional to \( L_m \), equation (5), which also leads to the current component \( i_{qr} (\lambda) - \text{ref} \) equation (20), depending on the nearly constant ratio \( (L_s/L_m) \). Similar performance is obtained when the stator resistance is changed.

Stator active and reactive powers with and without enhancing of control scheme are shown in Figures 25 and 26. Without the enhancing of control scheme, there is a slip power output from the rotor, through RSC, during super-synchronous speeds. With the enhancing of control scheme, this slip power is negligible, and all output power is from the stator. This is explained by Figure 25, where the stator power is increased by the enhancing of control scheme during wind speed higher than about 7.6 m/s. Also, without the enhancing of control scheme, there is a slip power input to the rotor, through RSC, during sub-synchronous speeds, and this power is a part of the output power from the stator. With
\[ \lambda_{\text{ref}} = \lambda_{\text{rated}} \]

**Start**

**MPPT Control**

**Read \( \omega_s \) & \( \omega_e \)**

- **Voltage-controlled Region**
  - Yes: \( \omega_s > \omega_e \) & \( u_{d\text{c,ref}} \leq U_{d\text{c,ref}} \) → decrease \( u_{d\text{c,ref}} \) to make \( \omega_s = \omega_e \)
  - No: \( \omega_s < \omega_e \) & \( u_{d\text{c,ref}} < U_{d\text{c,ref}} \) → increase \( u_{d\text{c,ref}} \) to make \( \omega_s = \omega_e \)

- **Field-weakening Region**
  - Yes: \( \omega_s < \omega_e \) & \( \lambda_{\text{ref}} \leq \lambda_{\text{rated}} \) → decrease \( \lambda_{\text{ref}} \) to make \( \omega_s = \omega_e \)
  - No: \( \omega_s > \omega_e \) & \( \lambda_{\text{ref}} < \lambda_{\text{rated}} \) → increase \( \lambda_{\text{ref}} \) to make \( \omega_s = \omega_e \)

**Figure 6**: Flowchart of control operation.

**Figure 7**: Wind speed.
the enhancing of control scheme, the slip power is negligible, and the stator power is reduced. This is explained by Figure 25 during wind speeds lower than about 7.6 m/s. The decrease of the handled active power by RSC is shown in Figure 25. This power is about 707 W at $V_w$ of 10 m/s.

The reactive power of stator is supplied through RSC. This reactive power is increased/decreased by increasing/decreasing of the stator active power. This is shown in Figure 26. By enhancing of control scheme, this reactive power is increased during wind speeds higher than about 7.6 m/s, and is decreased during wind speeds lower than about 7.6 m/s. However, the increase of the stator reactive power is much lower than the decrease of the handled active power by RSC. E.g., at $V_w$ of 10 m/s, the increase of the stator reactive power is about 244 VAR, and the decrease of the handled active power by RSC is about 707 W. Therefore, the
Figure 15: Stator-phase current when \( V_w \) is equal to 6 m/s.

Figure 16: Wind speed with 10 m/s sustained for a longer time period.

Figure 17: Rotor currents when wind speed is equal to 10 m/s.

Figure 18: Wind speed with 10 m/s continued for a longer time period.

Figure 19: Load with step change.

Figure 20: DC-bus voltage.

Figure 21: Wind speed.

Figure 22: DC-bus voltage when the magnetizing inductance \( (L_m) \) is decreased by 20%.
VA requirements of RSC are decreased by the enhancing of control scheme. In addition, both the stator reactive power and the handled active power by RSC are decreased at low wind speeds, below 7.6 m/s, by the enhancing of control scheme. Therefore, the wider wind speed range includes lower wind speed values with higher system efficiency.

8. Conclusion

The existing stand-alone wind systems with a small-scale wind turbine, DFIG, and battery storage have common problems which are the limited speed range and the VA requirement of rotor-side converter (RSC). The limited speed range leads to exclude the low wind speed values from the maximum power operation. The problem of VA requirement of RSC is due to carrying both the slip power and the reactive power of DFIG. Other problems related to supplying single-phase loads are not associated with the system configuration considered in this paper. This paper has proposed an advanced control scheme for the stand-alone wind system. By this scheme, the operation of DFIG is at a negligible slip, where the synchronous speed of DFIG is controlled to track the rotor speed, while the rotor speed is controlled for maximum-power extraction. This will cause the speed range to be increased including the low values of wind speed, because the operation at these wind speeds is now far from the maximum slip limit. Also, this will lead to a reduction in the slip power to negligible values, which decreases the VA requirement of RSC, where the slip power is carried by RSC, and now the RSC will only carry the reactive power of DFIG. All the obtained results and analysis have confirmed the controllability of the suggested control system.

Appendix

A. DFIG and Wind Turbine Data

**DFIG Data**: Y-connected, 3.5 kVA, 4 poles, 60 Hz machine with the following parameters: $R_s = 0.45 \Omega$, $R_r = 0.7 \Omega$, $L_{ls} = 3.0 \text{ mH}$, $L_{lr} = 3.0 \text{ mH}$, $L_m = 110.0 \text{ mH}$ and turns ratio = 1.0.

**Wind Turbine Data**: 3.593 kW, $R = 2.25 \text{ m}, V_{cut-in} = 4 \text{ m/s}, V_{rated} = 11.5 \text{ m/s}$, and $C_{p-a}$ characteristics shown in Figure 1.

**Other Data**: System inertia = 0.15 kg · m², System friction coefficient = 0.001 N · m · s/rad, and gear ratio = 10.94.
B. Converters’ Data
Switching frequency of RSC = 5 kHz.
Switching frequency of Buck-boost converter = 10 kHz.
Switching frequency of LSC = 1.6 kHz.

C. PI Controllers’ Data
Stator-flux controller: \( K_p = 1.0 \) and \( K_i = 150 \).
DC-bus voltage controller: \( K_p = 1.0 \) and \( K_i = 10 \).
Current controllers: \( K_p = 150 \) and \( K_i = 40 \).

Data Availability
The data used to support the findings of this study have not been made available.

Conflicts of Interest
The authors declare that they have no conflicts of interest.

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