Innovative: International Multi-disciplinary Journal of Applied Technology
(ISSN 2995-486X) VOLUME 02 ISSUE 03, 2024

Generator Synchronization utilizing Brushless based on Bang -Bang Control Method

Ansam.R.Raheem
Department Electronic and Communication Department, Al Muthanna University, Iraq
ansam296@gmail.com
Moneer Ali Lilo
Department Electronic and Communication Department, Al Muthanna University, Iraq
moneerlilo@mu.edu.iq

Abstract:

The significant shortcoming of the double-fed induction generator is the presence of brushes in the rotor windings slip rings that lead to increased machine maintenance costs. Recently, a doubly-fed induction generator brushless technology was utilized to investigate that problem. Its full-order model is presented in the reference of arbitrary coordinates to investigate the generator conduct. Based on this model, a bang-bang controller-based method has been presented for the smooth and fast synchronization of the generator with the grid. To evaluate the performance of the suggested synchronization method, the control method has been simulated in the Matlab/Simulink program, confirming the suggested controller's correctness

Keywords: synchronization, doubly fed, bang-bang control, brushless.

Introduction

Wind farms can be used off-grid, connected to the power grid or even combined with an energy storage system, such as flywheels, batteries or pumped hydro storage, etc. Several wind turbines are built close together to form a wind farm connected to the power transmission system or grid. In variable-speed wind turbines, permanent magnet synchronous generators, squirrel cage induction generators, and double-fed induction generators (DFIG) or their new arrangements are used. Although the presence of slip rings and poor low voltage transfer capability

(LVRT) are among the most important weaknesses of DFG, due to the reduction in the size and power of the electronic power converter in this type of generator, it is one of the most widely used technologies in wind turbines with power High (up to MW 6) has become [1]. In recent years, many efforts have been made to solve the problems of DFG, including removing the brush [2]. Direct Power Control (DPC) can directly control the active and reactive power of the brushless induction generator on both sides independently. Compared to the vector control method, the direct power control method does not need to measure the power stator flux range and requires fewer calculations, based on this method can resolve the problem related to indigent performance of the vector control, effect via the sensitivity to changes in the parameters of the brushless two-way induction generator. Fix Reference [3] proposed the direct power control method for the double-sided cascade generator as an alternative to the vector control method of the double-sided cascade generator. The features of this method are robustness, simple implementation, and fast dynamic response. The direct power control method delivers straight to adjust power machine by choosing suitable voltage vectors from a lookup table. This method has drawback which is the variable switching frequency, which causes current distortion and high power ripple. To improve to preserve the advantages of the direct power control method compared to vector control, reference [4] has proposed a second-order sliding mode direct power control method for the brushless two-way induction generator. The transient performance of direct power control in second-order sliding mode is similar to the common direct power control method, and its steady-state performance is similar to vector control and does not require a phase lock. The proposed controller is resistant to parameter changes and uncertainties, and the switching frequency is constant. Reference [5] presents a DPC technique constructed on 12 parts to realize the power pursuing of a brushless, open-coil, two-way fed induction generator system. The advantages of the proposed design compared to the method of direct control of the power of the induction generator on both sides of the brushless supply based on 6 and 12 parts are better functional behavior and fault tolerance, in the capacity and cost of the converter, a flexible and simpler control construction. Direct torque control (DTC) has the characteristics of fast dynamic response, simple structure, and resistance to machine parameters that resolve the problems of sensitivity to parameter change, large amounts of calculations, and the complex structure of vector control. For direct torque control, the hysteresis comparator is unable to detect the quantity of link flux and the torque error magnitude. During the control cycle, the voltage vector is applied by the controller. When the torque error is smaller in a cycle, the torque quickly reaches a given value due to the voltage, creating a large torque ripple. To eliminate torque ripple in direct torque control, many studies and methods have been presented, such as using a combination of predictive control and duty factor modulation, fuzzy control, discrete space voltage vector, predictive control, duty factor modulation, and voltage space vector modulation. The DTC algorithm of voltage space vector modulation can reduce the torque ripple, but it requires more parameters and a large number of calculations. In [7] proposed controller utilized discrete space based on a voltage vector that will increase the accuracy and at the same time the complexity rises. While [9] suggested utilizing the Fuzzy Logic (FL) to reduce the ripple of the torque, However, in machine-state equations, variable membership has uncertainty. If the membership selection is not appropriate, the performance of the system will deteriorate. Reference [10] used the improved fuzzy control method of discrete space vector modulation direct torque control to improve the control of speed and torque, while utilizing fuzzy rules, increase the complexity of the system with five inputs to FL. Reference [11] uses predictive control, which improves the stator current waveform and reduces the torque ripple, but it requires a lot of calculations. Another proposal provided a DTC method based on duty factor modulation, in two vectors the non-zero voltage and zero voltage, utilized with control vector time and residual time respectively, as mentioned in [12]. Reference [13] has proposed a method to combine predictive control and duty factor modulation to diminish ripple behaviors of torque. This technique maintains the fast torque response furthermore reducing torque ripple based on used the DTC method. Each generator needs a soft synchronization process to connect to the grid [14–16]. When an error occurs in the network, a brushless double-fed induction generator (BDFG) is isolated from the network by the protection relay. After the fault is cleared, it is necessary to use a fast and smooth method to connect the generator to the network. Also, since a fractional capacitance converter is used to control the BDFG, the synchronizing process of this generator is more difficult than that of other AC generators. In this article, to solve this problem, the soft and fast synchronization method based on the direct torque control method and the proposed simplified models are presented.

BDFG dynamic modeling

The rotor loop has a dependent source voltage and resistance in the equivalent circuit of the brushless doubly-fed generator. Therefore, it is difficult to find the control equation between λp or vp and λc, which is necessary to implement the proposed synchronization method. The simplified model of the brushless two-way induction generator is shown in Figure (1).

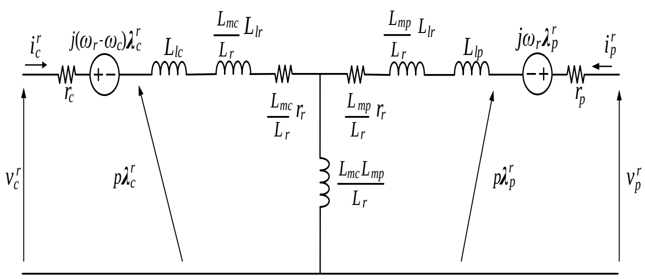

Figure (1) Proposed equivalent circuit for brushless two-way induction generator

The simplified dynamic equations are as follows :

$$\vec{v}_c^r = r_c \vec{i}_c^r + p\vec{\lambda}_c^r + j(\omega_r - \omega_c)\vec{\lambda}_c^r \tag{1}$$

$$\vec{v}_p^r = r_p \vec{i}_p^r + p\vec{\lambda}_p^r + j\omega_r \vec{\lambda}_p^r \tag{2}$$

,so that

$$\vec{\lambda}_c^r = (L_{lc} + \frac{L_{mc}}{L_r} L_{lr})\vec{i}_c^r + \frac{L_{mc}L_{mp}}{L_r}\vec{i}_p^r + \frac{L_{mc}r_r}{L_r}\int \vec{i}_c^r dt \tag{3}$$

$$\vec{\lambda}_p^r = (L_{lp} + \frac{L_{mp}}{L_r} L_{lr})\vec{i}_p^r + \frac{L_{mc}L_{mp}}{L_r}\vec{i}_c^r + \frac{L_{mp}r_r}{L_r}\int \vec{i}_p^r dt \tag{4}$$

The presence of the flow integral in the flux equations indicates the effect of the resistance of the rotor ring. Both the amplitude and the angle of the currents of these integrals are time-dependent, which complicates and complicates the calculation of the mathematical relationship for transferring the proposed model to other coordinate references, so the proposed model can be easily transferred to other references. It is not the coordinates.

BDFG synchronization using Bang-Bang controller

The proposed soft synchronization method consists of two functional modes. Operating mode one is when the generator is in the process of synchronizing with the grid. After synchronization, the generator is connected to the grid and injects power, which is called the second operating mode.

The first functional mode is also called the unloaded or independent functional mode. During the synchronization process, the terminals of the power stator will isolated from the main grid, which represents the operation of this mode. In this section, the bang-bang controller is modified to synchronize the generator with the network, but the switching table is the same as the switching table of the common direct torque control. Before presenting the synchronization method, the equation between network fluxes, control stator and power stator is stated.

The grid flux is obtained using the grid voltage $\vec{v}_g$ and the grid frequency ωg in the dqs grid coordinate reference:

$$\wp\vec{\lambda}_g^s = \vec{v}_g^s \tag{5}$$

$$\theta_g \triangleq \angle\vec{\lambda}_g^s = \angle\vec{v}_g^s - \frac{\pi}{2} \tag{6}$$

$$|\vec{\lambda}_g| = \frac{|\vec{v}_g|}{\omega_g} \tag{7}$$

Since the grid frequency ωg is constant value , also the grid flux takes a fix amplitude.

According to Figure (3), equation (2) is transferred to the stator coordinate reference. The voltage drop caused by the power stator resistance rp is insignificant compared to the power stator voltage, so the effect of the resistance rp is ignored to obtain the power stator flux:

$$\wp\vec{\lambda}_p^p = \vec{v}_p^p \tag{8}$$

$$\theta_p \triangleq \angle\vec{\lambda}_p^p = \angle\vec{v}_p^p - \frac{\pi}{2} \tag{9}$$

The stator voltage vector of the power machine, $\vec{v}_p$, should be equivalent to the Grid Voltage Vector(GVV), $\vec{v}_g$, to obtain synchronization conditions. Therefore, according to equations (8) to (12), the power stator flux vector $\vec{\lambda}_p$ should be equal to the Grid Flux Vector (GFV), $\vec{\lambda}_g$, that is:

$$\theta_p = \theta_g \tag{10}$$

$$|\vec{\lambda}_p| = |\vec{\lambda}_g| \tag{11}$$

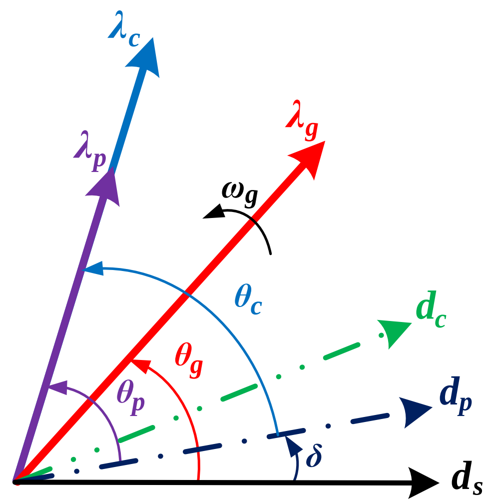

Figure (3) Network flux vectors, control stator flux and power stator flux during synchronization

In the operation mode independent from the generator grid, the power stator flux, $\vec{\lambda}_p$, is regulated by the control stator flux, $\vec{\lambda}_c$; Therefore, the equation between $\vec{\lambda}_p$, and $\vec{\lambda}_c$ should be extracted. As seen in figure (4), the power stator current is zero at the synchronization time. Based on real machine parameters:

(Lmc / Lr) rr ≪ ωre [Llc + (Lmc / Lr) Llr + (Lmc Lmp / Lr)]. Regardless of the component (Lmc / Lr) rr (Lmc / Lr) rr we can write:

$$\vec{\lambda}_c^r = (\frac{L_{mc}L_{mp}}{L_r} + L_{lc} + \frac{L_{mc}}{L_r} L_{lr})\, \vec{i}_c^r \quad (12)$$

$$\vec{\lambda}_p^r = \frac{L_{mc}L_{mp}}{L_r}\, \vec{i}_c^r \quad (13)$$

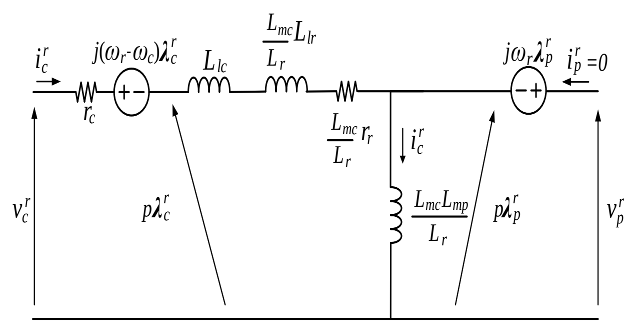

Figure (4) proposed an equivalent circuit for a brushless two-way induction generator at the time of synchronization

The equation between power and control stator flux vectors using equations (12) and (13) is attained as follows:

$$\vec{\lambda}_c^r = (1 + \frac{L_r}{L_{mc}L_{mp}} L_{lc} + \frac{L_r}{L_{mp}} L_{lr})\, \vec{\lambda}_p^r \quad (14)$$

According to equation (14), the control stator flux, $\vec{\lambda}_c$, and the power stator, $\vec{\lambda}_p$, are the same phase. Because the power stator is an open circuit and does not inject power into the grid. So, the angle and amplitude of the control stator flux can be computed as follows:

$$\theta_p = \theta_c \quad (15)$$

$$\left|\vec{\lambda}_{\mathrm{c}}\right| = \left(1 + \frac{\mathrm{L_r}}{\mathrm{L_{mc}L_{mp}}}\mathrm{L_{lc}} + \frac{\mathrm{L_r}}{\mathrm{L_{mp}}}\mathrm{L_{lr}}\right)\left|\vec{\lambda}_{\mathrm{p}}\right| \tag{16}$$

The differential equation between power and fluxes of control stator was converted as algebraic equations: therefore, synchronization with the network can be achieved using the following two steps:

Based on equations (15) and (16), the control stator flux angle θc must be equal to the network flux angle θ_g; Therefore, the control stator flux must be in phase with the grid flux. to establish this condition, the electromagnetic torque T_e is replaced by the virtual torque T_v in the DTC method, as follows:, as follows:

$$T_v = K\left|\vec{\lambda}_g\right|\left|\vec{\lambda}_c\right| sin\gamma \tag{17}$$

$$\gamma = \theta_c - \theta_g \tag{18}$$

The Virtual Torque (VT) T_v is represented that torque between the grid and the control stator. Anywhere the control stator flux and the grid values should be not zero, the VT equals to zero, if the voltages of grid stator fluxes and control are in phase. Consequently, the reference of virtual torque T_v^* should be considered zero value, as shown below:

$$T_v^* \triangleq K\left|\vec{\lambda}_g\right|\left|\vec{\lambda}_c\right| sin\gamma = 0 \tag{19}$$

According to equations (16), (11), and (7), the control stator flux range is evaluated as follows:

$$\left|\vec{\lambda}_c^*\right| = (1 + \frac{L_r}{L_{mc}L_{mp}}L_{lc} + \frac{L_r}{L_{mp}}L_{lr})\ \frac{|\vec{v}_g|}{\omega_g} \tag{20}$$

The above equation (20) shows that the control stator flux is dependent on the changes in the control and power machines' mutual inductances, however , the summation of the second and third components inside the parentheses of this equation is smaller than 1 pu, the inductance changes can be ignored due to having a small effect.

In this case, the power stator terminals are linked to the grid, and the torque of machine is regulated by the usual DTC method. In the suggested method, the change from the first mode (synchronization) to the second mode (connected to the grid) is achieved by varying the Torque Reference (TR) from the VT, T_v^*, to the outside torque, T_e^*, to inject the required power into the grid.

Simulation results

To verify the proposed synchronization method, the MW 2 brushless induction generator is simulated in a Matlab/Simulink environment. Table (1) shown below given the generator parameters. The power stator is connected to the voltage source Vrms 690, Hz 50, and the rated speed of the generator is 600 rpm equal to pu 1. DC link voltage is 1200V.

Table (1) specifications of induction generator with two sides feeding without brush MW 2

p_p	**3**	**p_c**	**2**	**L_{lp} (mH)**	**014/0**
f_p (Hz)	50	**f_c (Hz)**	50	**L_{lrp} (mH)**	014/0
V_{pn} (V_{rms})	690	**V_{cn} (V_{rms})**	690	**L_{mp} (mH)**	626/0

V_{rp} (V_{rms})	690	V_{rp} (V_{rms})	690	L_{lc} (mH)	012/0
r_p (Ω)	408/0	r_c (Ω)	186/1	L_{lrc} (mH)	012/0
r_{rp} (Ω)	445/0	r_{rc} (Ω)	186/1	L_{mc} (mH)	373/0

The proposed method simulated based on carrying out a 2 MW generator with a fixed rotor speed of 0.85 pu. The results of the simulation in terms of torque/real/virtual power, phase voltage of the network/power stator, three-phase current of the power stator and three-phase current of the control stator are shown in figures (5) to (8). At the moment s 0 = t, the power switch CB1 is closed. Then the CB2 power switch is closed; Therefore, the power converter is directly connected to the grid and the DC link capacitor voltage is charged to its nominal value. The synchronization process (first mode) starts at the moment s = 0.02 t and the power switch CB3 is closed. Then, the proposed direct torque control method is applied to the power converter on the control stator side. At the moment s = 0.2 t, CB4 is closed and the power stator is connected to the grid while no current jump occurs.

It is very important to change the control strategy from the first functional mode (synchronization) to the second functional mode (normal) and no current jump should occur. After four time constants, the transients are damped. The current range of the power stator is insignificant because the two-way induction generator without a brush does not inject any power and it is responsible for providing a part of the magnetizing current.

The stator is power. After the transients are damped (at t = 0.5 s), the control method switches from operating mode 1 to 2, while the TR is zero. Since both virtual and real torque references are of the same nature, the state change occurs without any current jump. At the moment s = 0.5 t, the step TR pu-1 is applied to the torque control loop; Thus, the power stator current amplitude is grown to fed power into the grid. At the moment s = 0.5 t, the TR decreases to pu -0.5; Therefore, the power stator current amplitude is reduced and less power is injected into the grid.

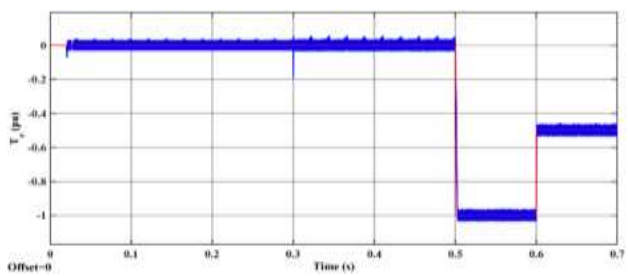

Figure (5) torque of the proposed synchronization method

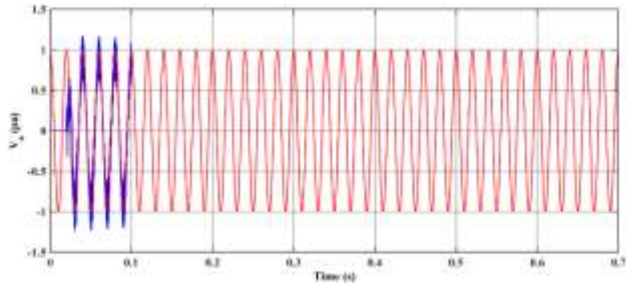

Figure (6) voltage waveform (mains voltage: red color and power stator voltage: blue color)

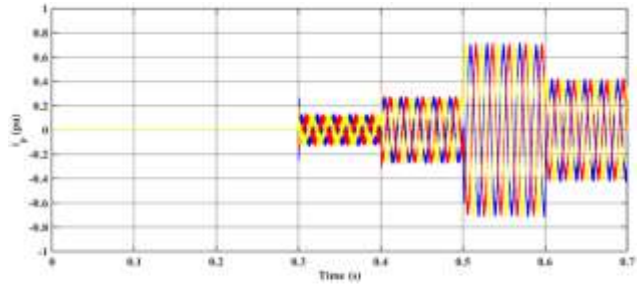

Figure (7) three-phase power stator current waveform

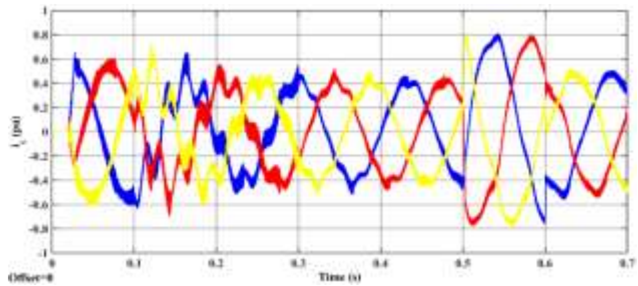

Figure (8) Three-phase waveform of the control stator current

Conclusion

Considering that it is important to connect the generator quickly and smoothly to the network, a method based on the bang-bang controller was presented to synchronize the induction generator on both sides without a brush. for this reason, the torque reference was applied to match the power stator voltage frequency and the control and the angle stator flux reference together with the power stator voltage range**.** The full-order model depends on the differential equation between the power stator voltage and the control stator flux. In order to make this equation simpler. The reference rotor coordinates were derived from the simplified model of a brushless two-side induction generator. Using this model, the impact of voltage sources within the basic rotor ring and the rotor ring impedance have been compared. The equation for the relationship between the power stator voltage and the control stator flux during synchronization was calculated using the simplified model. Additionally, it was simple to determine the control stator flux reference. The simulation results on a 2mw two-way induction generator without brushes (BDFG) proved the method of control.

References

1. G. Abad, J. Lopez, M. A. Rodriguez, L. Marroyo and G. Iwanski, Doubly Fed Induction Machine: Modeling and Control for Wind Energy Generation. New York: Wiley, Sep. 2011.
2. P. C. Roberts, A Study of Brushless Doubly-Fed (Induction) Machines, PhD dissertation, University of Cambridge, 2005.

3. J. Hu, J. Zhu, and D. G. Dorrell, ‘‘A new control method of cascaded brushless doubly fed induction generators using direct power control,’’ IEEE Trans. Energy Conv., vol. 29, no. 3, pp. 771–779, Sep. 2014.
4. R. Sadeghi, S. M. Madani, M. R. A. Kashkooli, and S. Ademi, ‘‘Supertwisting sliding mode direct power control of a brushless doubly fed induction generator,’’ IEEE Trans. Ind. Electron., vol. 65, no. 11, pp. 9147–9156, Nov. 2018.
5. S. Jin, L. Shi, L. Zhu, T. Dong, F. Zhang, and W. Cao, ‘‘Performance comparison of direct power control for brushless doubly-fed wind power generator with different control winding structure,’’ in Proc. IEEE Transp. Electrific. Conf. Expo, Asia–Pacific (ITEC Asia–Pacific), Busan, South Korea, Jun. 2016, pp. 261–266.
6. W. R. Brassfield, R. Spee, and T. G. Habetler, ‘‘Direct torque control for brushless doubly-fed machines,’’ IEEE Trans. Ind. Appl., vol. 32, no. 5, pp. 1098–1104, Sep. 1996.
7. Y. Ge and N. Wu, ‘‘Direct torque control for brushless doubly-fed machine based on SVPWM,’’ Small Spec. Electr. Mach., vol. 39, no. 8, pp. 58–60, 2011.
8. D. Casadei, G. Serra, and A. Tani, ‘‘Improvement of direct torque control performance by using a discrete SVM technique,’’ in Proc. Rec. 29th Annu. IEEE Power Electron. Spec. Conf. (PESC), Fukuoka, Japan, May 1998, pp. 997–1003.
9. S. J. Fattahi and A. A. Khayyat, ‘‘Direct torque control of brushless doubly-fed induction machines using fuzzy logic,’’ in Proc. IEEE 9th Int. Conf. Power Electron. Drive Syst., Dec. 2011, pp. 619–624.
10. X. Yao, L. Shi, and Q. Guo, ‘‘Brushless doubly-fed machine direct torque control based on fuzzy strategy,’’ J. Power Supply., vol. 11, no. 6, pp. 54–58, 2011.
    A. Zhang and Y. Zhang, ‘‘Direct torque control for brushless doubly-fed machine based on torque predict control strategy,’’ Electr. Mach. Control, vol. 11, no. 4, pp. 326–330, 2007.
11. J.-K. Kang and S.-K. Sul, ‘‘New direct torque control of induction motor for minimum torque ripple and constant switching frequency,’’ IEEE Trans. Ind. Appl., vol. 35, no. 5, pp. 1076–1082, Sep. 1999.
12. L. Bing, L. Shi, L. Teng, and Z. Jia, ‘‘Duty ratio modulation direct torque control of brushless doubly-fed machines,’’ Automatika, vol. 58, no. 4, pp. 479–486, Oct. 2017.
13. Z. Ai-Ling, J. Wen-Xia, Z. Zan-Qiang, and W. Xin, ‘‘A study on indirect stator-quantities control strategy for brushless doubly-fed induction machine,’’ in Proc. Int. Conf. Electr. Mach. Syst., Aug. 2011, pp. 1–6.
    A. Zhang, X. Wang, W. Jia, and Y. Ma, ‘‘Indirect stator-quantities control for the brushless doubly fed induction machine,’’ IEEE Trans. Power Electron., vol. 29, no. 3, pp. 1392–1401, Mar. 2014.
14. R. Zhao, A. Zhang, Y. Ma, X. Wang, J. Yan, and Z. Ma, ‘‘The dynamic control of reactive power for the brushless doubly fed induction machine with indirect stator-quantities control scheme,’’ IEEE Trans. Power Electron., vol. 30, no. 9, pp. 5046–5057, Sep. 2015.
15. H. Voltolini and R. Carlson, “Grid synchronization and maximum power point tracking for wind energy generation system with Brushless Doubly Fed Induction Generator,” in *34th Annu. Conf.* IEEE Ind. Electron., Orlando, FL, 2008, pp. 2173-2177.
16. Y. Liu, M. G. Hussien, W. Xu, S. Shao and E. M. Rashad, "Recent Advances of Control Technologies for Brushless Doubly-Fed Generators," in IEEE Access, vol. 9, pp. 123324-123347, 2021.