International Journal of Technical Innovation in Modern Engineering & Science (IJTIMES)
Impact Factor: 5.22 (SJIF-2017), e-ISSN: 2455-2585
Volume 4, Issue 6, June-2018

Review of different vector control schemes used for WECS for AC and DC grids employing DFIG's

Himanshu Bansal [1], Dr. T. S. Saggu[2], Dr. Jagdish Kumar [3]
[1]Electrical Engineering Department, Punjab Engineering College
[2]Electrical Engineering Department, Punjab Engineering College
[3]Electrical Engineering Department, Punjab Engineering College

Abstract—***Climate change concerns and rising global fuel prices, have increased the focus on renewable energy resources for energy requirements. Thus, Wind Energy Conversion Systems (WECS) are gaining popularity as they allow for large scale power generation. Over the years, advantages such as controllability, better-quality of output power, increased energy efficiency and low cost of power electronics have made Doubly fed Induction Generators (DFIG's) the first choice systems for WECS. This paper presents a critical review of various control schemes used in DFIG's connected to AC grids. Also, some latest schemes of DFIG's schemes in DC grid are also presented.***

Keywords— Doubly fed induction generator, Wind energy conversion system, Back-to-back converter, Stator-flux oriented vector control, Stator voltage oriented vector control

INTRODUCTION

In the beginning of the 20th century, power systems werebuilt to supply loads such as heating, lighting, and motor loads which work satisfactorily on AC. Since AC supply became the dominant supplying medium, henceAC power systems were boosted at a humungous speed to the present scale. With the development of power electronics and advanced control technologies, the efficiency of energy utilization and control flexibility has improved, which led to the rapid growth of DC loads. Purely AC loads in today's power systems have considerably reduced with time. In our homes as well as offices, several sensitive devices such as computers, printers, and TVs are employed, which mostly work internally onDC. Even the traditional AC motor driven loads (pumps, washing machines, air compressors, refrigerators, and other industrial equipment) are being replaced by inverter driven motor drives,which control the motor speed and save energy. Even the fluorescent lamps which work equally well on both AC and DC, are being replaced by more efficient LEDs. In steel industry, a DC electric arc furnace consumes lesser energy than its AC counterpart with the same capacity, but most of the electrochemical processes used in industry require DC supply. Addition of DGs for integration of renewable energy sources like photovoltaic (PV) modules, fuel cells, battery energy storage systems (BESSs), and electric vehicles (EVs) into local distribution systems has further increased the motivation to add DCnetworks [1].

Today, there are many applications where DC grids have advantages over traditional AC grids. Over the years, a lot of research work has been done on Distributed generation [2–6], microgrids [7–10] and offshore WECS [11, 12]. WECS, which employ the variable speed DFIG's are most widely used because the cost of power electronics involved is greatly reduced [13].

DFIG's connected to an AC mains or standalone configurations aimed at feeding AC loads have been the topics of many titles available in the literature. Vector control was the first technique proposed for DFIGs employed for wind applications [14] and is still most commonly preferred in literature [15]. Two of the most common vector control techniques used are the stator flux oriented vector control [16], and the stator voltage orientation based control [17]. The basic issues related to control of rotor side converters and grid side converters using vector control techniques have been reported in [13,18]. Strategies using sensorless control have been investigated in [19–21] and techniques to achieve encoder-less control with a stable behaviour at synchronism are studied in [21–23].

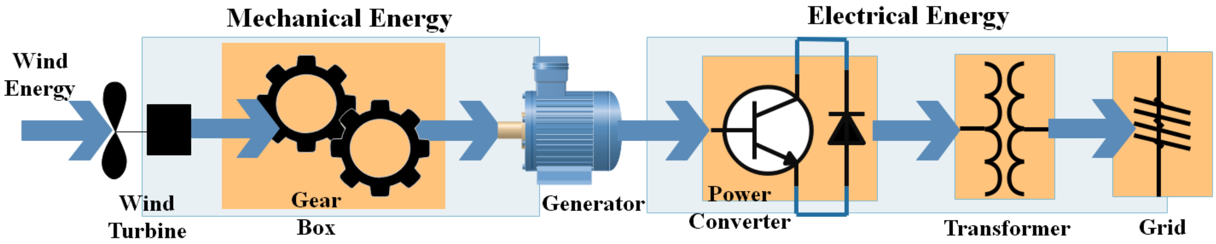

Fig 1: Components of a wind energy conversion system

This paper presents an overview of the various conversion topologies suitable for connection of WECS, using the variable speed DFIGs to AC as well as DC networks. Various control techniques proposed for DFIGs with respect to control of stator side converter and rotor side converters are discussed. Conversion topologies suitable for connection of DFIGs to DC networks along with their control schemes are also discussed.

OVERVIEW OF VARIOUS DFIG'S

All wind energy conversion systems are comprised of the components as shown in Figure 1.

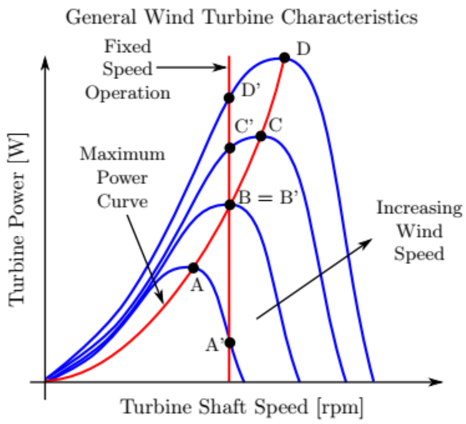

Fig 2: Wind Turbine Characteristics

A necessary condition to connect the wind turbine with the AC grid is that the frequency of turbine output power should match the grid frequency,

$$f_{grid}=\frac{N*P}{120} \tag{1}$$

where, fgrid is the grid frequency in Hertz, P is the no. of poles on the stator and N is shaft speed of DFIG in revolutions per minute. With the normal range of wind speeds available, the variation in slip is in the range of ±30% [24].

Typical configuration used to connect DFIG an AC grid is shown in Figure 3. DFIG is a good choice for wind energy applications since its stator can connect straightway to the AC grid while its speed at the shaft of the rotor can change with the changing wind velocity. Since the rotor carries slip frequency currents, hence a back-to-back AC-DC-AC converter, to change the slip frequency currents to the frequency of AC grid, along with an AC filter, and a transformer, to match the level of converter output voltage with that of AC grid, are required.

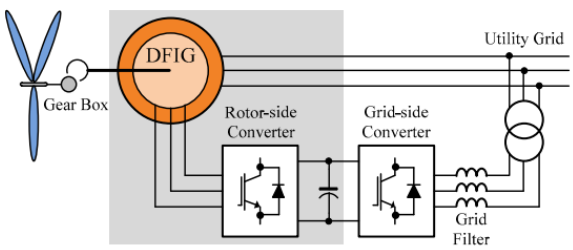

Fig 3: Configuration of a DFIG based WECS

A. Modelling and equivalent circuit

Equivalent circuit of DFIG under steady state conditions as reported in [25] is as presented in Figure 4.

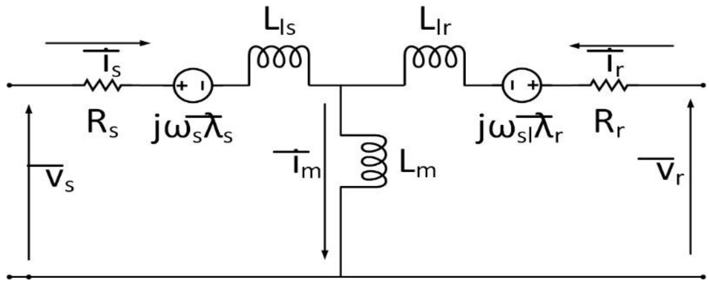

Fig 4: Equivalent circuit of a DFIG

Thus, the rotor and stator voltages and their flux linages are given by

$$\bar{v}_s=R_s\bar{i}_s+\frac{d\bar{\lambda}_s}{dt}+j\omega_s\bar{\lambda}_s \tag{2}$$

$$\bar{v}_r=R_r\bar{i}_r+\frac{d\bar{\lambda}_r}{dt}+j\omega_{sl}\bar{\lambda}_r \tag{3}$$

$$\lambda_s=L_s\bar{i}_s+L_m\bar{i}_r \tag{4}$$

$$\lambda_r=L_r\bar{i}_r+L_m\bar{i}_s \tag{5}$$

where,$\bar{v}_s$ and$\bar{v}_r$ are the space vectors for stator and rotor voltages respectively, $\bar{i}_s$ and$\bar{i}_r$ are the space vectorsfor stator and rotor current respectively, $\bar{\lambda}_s$ and$\bar{\lambda}_r$ arethe space vectors for stator and rotor flux linkagesrespectively, R_s,R_r are the resistances of stator and rotor respectively, L_m, L_s, and L_r are the magnetizing and stator and rotor leakage inductances respectively, ω_s, ω_r andω_{sl} aresynchronous, rotor and slip angular speeds respectively.

The expression for electromagnetic torque, Te produced by the DFIG is given as

$$T_e=\frac{3}{2}\frac{P}{2}Re(\bar{\lambda}_s\bar{i}_s^*)=\frac{3}{2}\frac{P}{2}\lambda_{ds}i_{qs}-\lambda_{qs}i_{ds} \quad \text{(Error! Bookmark not defined.)}$$

where, λ_{ds} and $\lambda_{qs}$are the d and q axis components of the stator flus linkage. Neglecting any losses in the stator resistances, the active and reactive powers in stator, P_s and Q_s respectively are given by

$$P_s=\frac{3}{2}Re\left(\bar{v}_s\bar{i}_s^*\right)=\frac{3}{2}(v_{ds}i_{ds}+v_{qs}i_{qs}) \tag{6}$$

$$Q_s=\frac{3}{2}Im\left(\bar{v}_s\bar{i}_s^*\right)=\frac{3}{2}(v_{qs}i_{ds}-v_{ds}i_{qs}) \tag{8}$$

Here, v_{ds}, v_{qs} and i_{ds}, i_{qs} are the d and q axis components of the stator voltages and currents respectively.

DIFFERENT CONTROL STRATEGIES EMPLOYED FOR DFIG'S

As discussed earlier, for AC grid applications, the DFIG stator can connect straightway to the AC grid whereas, in the rotor circuit, two voltage source converters are required. The AC to DC converter at the grid side is joined to stator terminals using filters and a transformer at its AC side and its DC side is connected to a DC link. This DC link feeds the DC to AC converter connected to the rotor terminals [26].

For the converter at supply side, the control schemes reported in the literature aim to control, the active and reactive power flows between the AC grid and the DFIG stator, independently, while keeping constant the voltage at the DC link. The most commonly reported scheme in the literature is the stator voltage oriented vector control scheme.

For the converter on the rotor side, the control schemes reported in the literature aim at exciting the induction machine rotor, thus these control schemes should provide decoupled control between the electromagnetic torque and the rotor currents. The most reported scheme in the literature is stator flux oriented vector control scheme [16].

Stator side converter

The converter at the stator side should keep constant the DC link voltage, thus enabling control of active and reactive power flows between the AC grid and the stator of DFIG, independently. Stator voltage oriented vector control is the most commonly employed controlling strategy.

Stator voltages in dq reference frames can be written as

$$v_{ds}=R_s i_{ds}+\frac{d\lambda_{ds}}{dt}-\omega_s\lambda_{qs} \tag{9}$$

$$v_{qs}=R_s i_{qs}+\frac{d\lambda_{qs}}{dt}+\omega_s\lambda_{ds} \tag{10}$$

The expression for active and reactive powers is given in (7).

The angular position Θs of supply voltage is calculated using

$$\theta_s=\int \omega_s dt=\tan^{-1}\frac{v_\beta}{v_\alpha} \qquad \text{(Error! Bookmark not defined.}\,1)$$

where, vαs and vβs are the stationary components of stator voltage.

Aligning the d axis of the rotating dq reference frame with the stator voltage vector position given by (10), v_{qs} becomes zero and v_{ds} is equal to $|\overline{v}_s|$⎤. Therefore, from (7), the stator active and reactive powers become proportional to i_{ds} and i_{qs} respectively.

The control scheme as reported in [26] is as shown in Figure 5.

A. Rotor Side converter

The converter at rotor side provides excitation to the induction machine rotor. Thus the aim of control scheme is to provide decoupled control between the electromagnetic torque and the rotor excitation current. Stator flux oriented control technique where the control is done in a dq axis reference frame rotating at synchronous speed, with its d-axis aligned with stator flux position vector is the most commonly used technique. Implementation of this control scheme requires the measuring the stator voltage, rotor and stator currents and also the position of rotor.

The stator flux angle, Θ_e is calculated as

$$\lambda_{\alpha s}=\int (v_{\alpha s}-R_s i_{\alpha s})dt \tag{12}$$

$$\lambda_{\beta s}=\int (v_{\beta s}-R_s i_{\beta s})dt \tag{13}$$

$$\theta_e=\tan^{-1}\frac{\lambda_{\beta s}}{\lambda_{\alpha s}} \tag{14}$$

where, $i_{\alpha s,}$ $i_{\beta s}$are the αβ components of stator current vector and $\lambda_{\alpha s,}$ $\lambda_{\beta s}$are the αβ components of stator flux linkages respectively.

Aligning the d axis of the rotating dq reference frame with the stator flux vector position given by(8) and (9) v_{ds} becomes zero and v_{qs} is equal to $|\overline{v}_s|$.

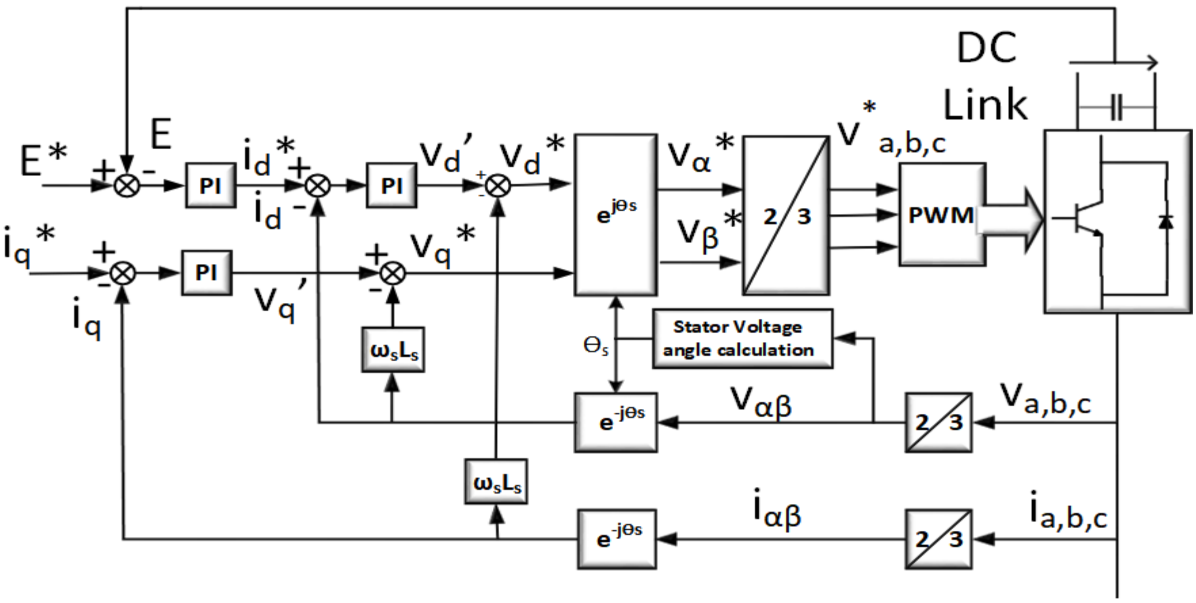

Fig 5: Control Scheme for stator side converter

$$Q_s=\frac{3}{2}v_{qs}i_{ds} \tag{15}$$

and hence by controlling i_{ds}, the reactive power flow can be controlled.

The rotor voltages can be written as

$$v_{dr}=R_r i_{dr}+\sigma L_r \frac{di_{dr}}{dt}-\omega_{sl}\sigma L_r i_{qr} \tag{16}$$

$$v_{qr}=R_r i_{qr}+\sigma L_r \frac{di_{qr}}{dt}+\omega_{sl}[\sigma L_r i_{dr}-\lambda_{ds}\frac{L_m}{L_s}] \tag{17}$$

where, σ is known as leakage factor. The electromagnetic torqueIn terms of rotor currents can be written as

$$T_e=-\frac{3}{2}\frac{P}{2}\frac{L_m}{L_s}\lambda_{ds}i_{qr} \tag{18}$$

Thus, from (18) we observe thatby controlling i_{qr}, the electromagnetic torque produced inside the DFIG can directly be controlled.

The control scheme as reported in [25] is as shown in Figure 6.

INTERCONNECTION OF A DFIG TO DC GRID

So far in this work, the AC grid connection of DFIG, where the stator can connect to an AC grid straightway, while two voltage source converters are required in the rotor circuit for connecting it to the same AC grid. If instead of connecting to an AC grid, the DFIG is connected to a DC grid, only a single voltage source converter is required on rotor circuit and the stator connection can be made to the same DC grid by the use of an uncontrolled diode rectifier. Various configurations of such systems are proposed in [11,27–40].

1. The main advantages of these systems are

2. No reactive power is required in DC systems. Also parallel operation of various machines is easier to achieve.

3. Minimization of conversion stages since only a single AC-DC converter is required instead of a back-to-back AC- DC-AC converter. This also reduces the cost and complexity of the system.

4. The DFIG's can also be integrated with other distributed generation sources and storage systems through a common DC bus.

5. On the stator windings, the diode bridge rectifier connected to a fixed voltage DC network applies highly distorted voltages, thus injecting current harmonics of order 5th, 7th, 11th etc. [37]. Since these harmonic orders can be predetermined based by the type of bridge rectifier used, appropriate DC filters can be designed for these which help in improving the overall quality of the output DC currents [27].

A. Conversion topology for a DC-DFIG System

The conversion topologyfora DC-DFIG system as reported in [27] is shown in Figure 7. The stator connection to theDC grid is made by the use of anuncontrolled diode bridge rectifier. To connect the rotor of the DFIG, to the same DC grid, a fully controlledAC-DC voltage source converter is used.

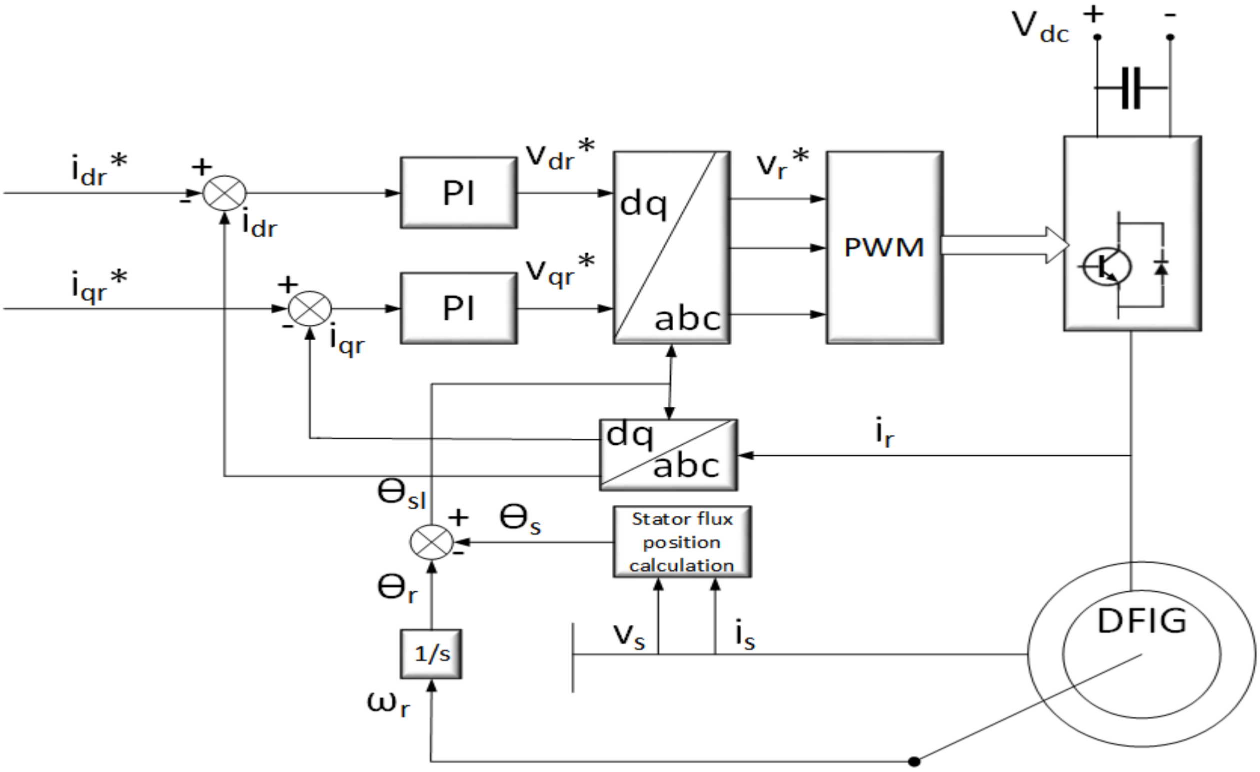

Fig 6: Control scheme for rotor side converter

B. Control requirements of DFIG connected to DC grid

When a DFIG is connected to an AC utility grid, the frequency of currents induced in the stator windings is controlled by the AC utility grid itself. However, when the DFIG is connected to a dc grid, the frequency of currents induced in the stator windings depends on the DFIG limits, since the stator windings are linked to an uncontrolled diode bridge rectifier. Hence, the frequency of stator currents should be regulated near the actual rating of the machine. This helps in utilizing the rated power of the DFIG and also limits the stator flux to proper values.

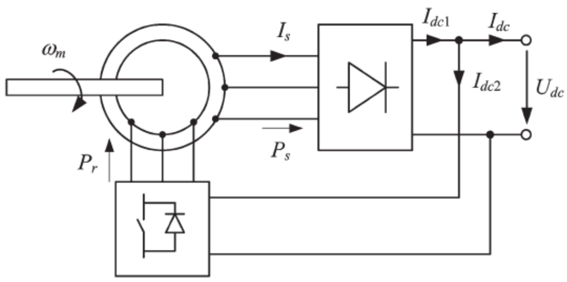

Fig 7: Layout of a WECS based on DFIG connected to a DC grid

The amplitude of voltages induced in the stator windings is set by the DC grid and the uncontrolled diode bridge rectifier. Thus the stator induced voltage is related to stator flux λs, and the frequency of induced currents as

$$|\overline{v}_s|=\omega_s\lambda_s \qquad (19)$$

Due to the ever changing nature of wind speeds, control of the DFIG shaft speed is necessary. Thus, a speed controller is required, which changes the shaft speed according to the reference torque. If torque and speed controllers are not used, then the speed of shaft is controlled by the wind turbine which is coupled to thyshaft of the DFIG, but this is generally not done.

C. Control Scheme

The control is based on aligning the d axis of a synchronously rotating dq axis reference frame, with the stator flux position vector.

From (18), similar to the case in the earlier topology, the electromagnetic torque produced inside the DFIG can directly be controlled by controlling the q-axis rotor current reference i^*_{qr}. The frequency of the induced stator currents is controlled with the use of an adaptation block, which works by adjusting the d-axis rotor current reference i^*_{dr}.

Since the frequency of induced stator currents is related to the speed of the stator flux vector, control is achieved by fixing the position of the stator flux vector using a reference position which rotates at rated speed of the machine. By integrating the reference speed, ω^*_s of the machine, the reference position, Θ^*_s is obtained. This is corrected using a PI controller, which is shown in Figure 8 as the frequency error detector. The output of the frequency error detector is the phase difference δ which can be taken as the frequency error.

$$\delta=\Theta_s^*-\Theta_s \qquad (20)$$

The adaptation block uses another PI controller to force the frequency error δ to zero.The control scheme as reported in[29] and shown in Figure 8fulfils all the control requirements.

V. Conclusion

This paper presents a summary of the latest research on DFIG's employed for WECS. DFIGs are suitable for WECS since they allow to generate power on a large scale. Also, power converters required in DFIG's need to handle only the slip power, which is in the range of ± 30%. Hence, the ratings of power converters used in the DFIG's are only 30% of the total machine rating.

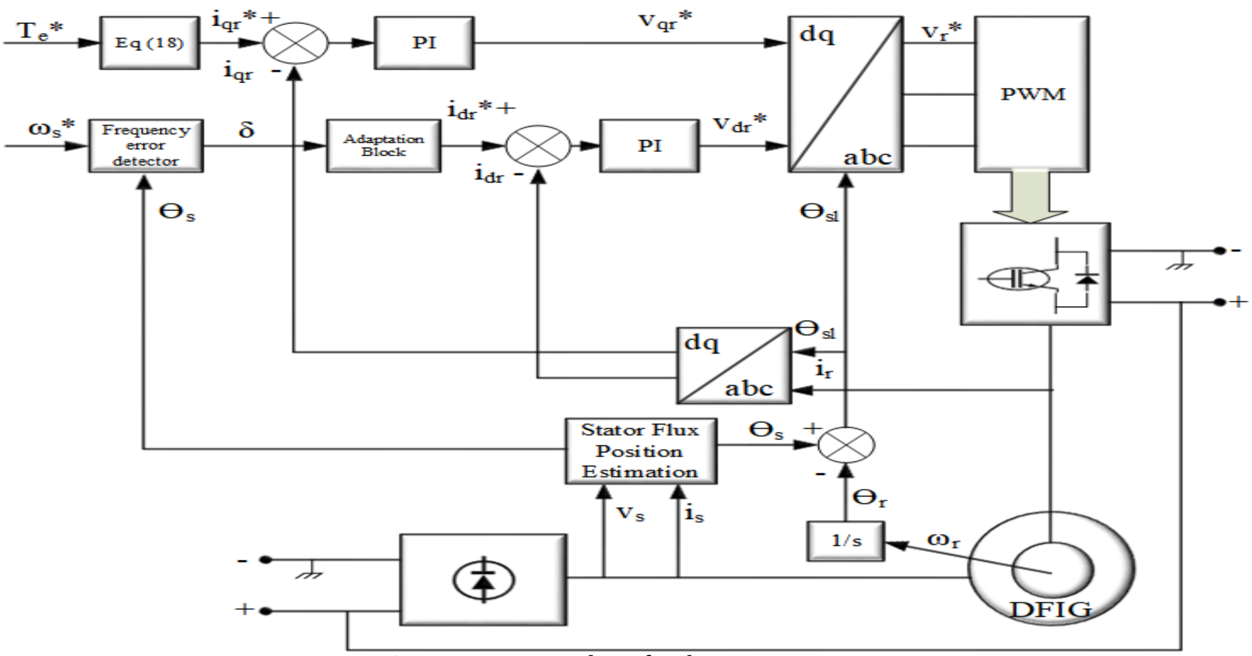

Fig 8:Conversion topology for the DC-DFIG system

Connections of the DFIG to an AC grid as well as a DC grid are also reviewed in this paper. The control requirements for each type of connection are established and the control strategies for each one of them is presented.

DFIG's connection to an AC grid requires a back-to-back AC-DC-AC converter. The converter on the stator side acts as an AC to DC converter and the control strategy aims to control, the active and reactive power flows between the AC grid and the DFIG stator, independently, while keeping the voltage at the DC link constant. Stator voltage oriented vector control scheme is found to be most suitable for this purpose and is most widely presented in the literature.

Also, the connection of a DFIG to a DC grid is presented in this paper. The stator connection of the DFIG, to the DC grid is made by the use of an uncontrolled diode bridge rectifier. To connect the rotor of the DFIG, to the same DC grid, a fully controlled AC-DC voltage source converter is used. Hence, a control scheme based on this topology has also been reviewed.

REFERENCES

[1] Peng Wang, L. Goel, Xiong Liu, and Fook Hoong Choo, “Harmonizing AC and DC: A Hybrid AC/DC Future Grid Solution,” *IEEE Power Energy Mag.*, vol. 11, no. 3, pp. 76–83, May 2013.

[2] F. Blaabjerg, Z. Chen, and S. B. Kjaer, “Power Electronics as Efficient Interface in Dispersed Power Generation Systems,” *IEEE Trans. Power Electron.*, vol. 19, no. 5, pp. 1184–1194, Sep. 2004.

[3] F. Blaabjerg, R. Teodorescu, M. Liserre, and A. V. Timbus, “Overview of Control and Grid Synchronization for Distributed Power Generation Systems,” *IEEE Trans. Ind. Electron.*, vol. 53, no. 5, pp. 1398–1409, Oct. 2006.

[4] D. Salomonsson and A. Sannino, “Low-Voltage DC Distribution System for Commercial Power Systems With Sensitive Electronic Loads,” *IEEE Trans. Power Deliv.*, vol. 22, no. 3, pp. 1620–1627, Jul. 2007.

[5] K. Kurohane, T. Senjyu, Y. Yonaha, A. Yona, T. Funabashi, and C. H. Kim, “A distributed DC power system in an isolated island,” *IEEE Int. Symp. Ind. Electron.*, no. ISlE, pp. 1–6, 2009.

[6] P. Karlsson and J. Svensson, “DC Bus Voltage Control for a Distributed Power System,” *IEEE Trans. Power Electron.*, vol. 18, no. 6, pp. 1405–1412, 2003.

[7] J. A. P. Lopes, C. L. Moreira, and A. G. Madureira, “Defining control strategies for microgrids islanded operation,” *IEEE Trans. Power Syst.*, vol. 21, no. 2, pp. 916–924, 2006.

[8] H. Kakigano, Y. Miura, and T. Ise, “Distribution voltage control for DC microgrids using fuzzy control and gain-scheduling technique,” *IEEE Trans. Power Electron.*, vol. 28, no. 5, pp. 2246–2258, 2013.

[9] A. A. A. Radwan and Y. A. R. I. Mohamed, “Linear active stabilization of converter-dominated DC microgrids,” *IEEE Trans. Smart Grid*, vol. 3, no. 1, pp. 203–216, 2012.

[10] H. Kakigano, Y. Miura, T. Ise, and R. Uchida, “DC micro-grid for super high quality distribution - system configuration and control of distributed generations and energy storage devices,” *PESC Rec. - IEEE Annu. Power Electron. Spec. Conf.*, pp. 1–7, 2006.

[11] N. Holtsmark, H. J. Bahirat, M. Molinas, B. A. Mork, and H. K. Høidalen, “An All-DC offshore wind farm with series-connected turbines: An alternative to the classical parallel AC model?,” *IEEE Trans. Ind. Electron.*, vol. 60, no. 6, pp. 2420–2428, 2013.

[12] R. Teixeira Pinto, P. Bauer, S. F. Rodrigues, E. J. Wiggelinkhuizen, J. Pierik, and B. Ferreira, “A novel distributed direct-voltage control strategy for grid integration of offshore wind energy systems through MTDC network,” *IEEE Trans. Ind. Electron.*, vol. 60, no. 6, pp. 2429–2441, 2013.

[13] K. Vijayakumar, N. Kumaresan, and N. Ammasai Gounden, “Operation and closed-loop control of wind-driven stand-alone doubly fed induction generators using a single inverter-battery system,” *IET Electr. Power Appl.*, vol. 6, no. 3, p. 162, 2012.

[14] Dr. Fatih Birol, “Key World Energy Statistics,” 2017.

[15] G. Abad, L. Jesus, M. A. Rodriguez, L. Marroyo, and G. Iwanski, “Doubly Fed Induction Machine Modeling and Control for Wind Energy Generation,” in *Wiley-IEEE Press*, 2011, pp. 1–14.

[16] R. Pena, J. C. Clare, and G. M. Asher, “Doubly fed induction generator using back-to-back PWM converters and its application to variable-speed wind-energy generation,” *IEE Proc. - Electr. Power Appl.*, vol. 143, no. 3, p. 231, 1996.

[17] H. Akagi and H. Sato, “Control and performance of a doubly-fed induction machine intended\nfor a flywheel energy storage system,” *IEEE Trans. Power Electron.*, vol. 17, no. 1, pp. 109–116, 2002.

[18] R. Pena, J. C. Clare, and G. M. Asher, “A doubly fed induction generator using back-to-back PWM converters supplying an isolated load from a variable speed wind turbine,” *IEE Proc. - Electr. Power Appl.*, vol. 143, no. 5, p. 380, 1996.

[19] Roberto Cardenas, Ruben Petial, Jose Proboste, Greg Asher, Jon Clare2, and Pat Wheeler, “MRAS Observers for sensorless control of doubly-fed induction generators,” 2008, p. 788.

[20] B. Shen, B. Mwinyiwiwa, Y. Zhang, and B. T. Ooi, “Sensorless maximum power point tracking of wind by DFIG using rotor position phase lock loop (PLL),” *IEEE Trans. Power Electron.*, vol. 24, no. 4, pp. 942–951, 2009.

[21] A. K. Jain and V. T. Ranganathan, "Wound rotor induction generator with sensorless control and integrated active filter for feeding nonlinear loads in a stand-alone grid," *IEEE Trans. Ind. Electron.*, vol. 55, no. 1, pp. 218–228, 2008.

[22] M. S. Carmeli, F. Castelli-Dezza, M. Iacchetti, and R. Perini, "A MRAS observer applied to sensorless doubly fed induction machine drives," *IEEE Int. Symp. Ind. Electron.*, no. 1, pp. 3077–3082, 2010.

[23] D. G. Forchetti, G. O. GarcIa, and M. I. Valla, "Adaptive observer for sensorless control of stand-alone doubly fed induction generator," *IEEE Trans. Ind. Electron.*, vol. 56, no. 10, pp. 4174–4180, 2009.

[24] G. Abad, J. López, Miguel Rodríguez, Luis Marroyo, and Grzegorz Iwanski, *Introduction to A Wind Energy Generation System*. 2011.

[25] W. Srirattanawichaikul, S. Premrudeepreechacharn, and Y. Kumsuwan, "A Comparative Study of Vector Control Strategies for Rotor-side Converter of DFIG Wind Energy Systems," 2016.

[26] I. John and B. Jayanand, "Voltage control and maximum power tracking of DFIG based wind power generator," in *2015 International Conference on Power, Instrumentation, Control and Computing (PICC)*, 2015, pp. 1–6.

[27] G. D. Marques and M. F. Iacchetti, "Stator frequency regulation in a field-oriented controlled DFIG connected to a DC link," *IEEE Trans. Ind. Electron.*, vol. 61, no. 11, pp. 5930–5939, 2014.

[28] M. F. Iacchetti, G. D. Marques, and R. Perini, "A Scheme for the Power Control in a DFIG Connected to a DC Bus via a Diode Rectifier," *IEEE Trans. Power Electron.*, vol. 30, no. 3, pp. 1286–1296, Mar. 2015.

[29] G. D. Marques, R. Perini, and M. F. Iacchetti, "Operation and design issues of a doubly fed induction generator stator connected to a dc net by a diode rectifier," *IET Electr. Power Appl.*, vol. 8, no. 8, pp. 310–319, 2014.

[30] M. F. Iacchetti, G. D. Marques, and R. Perini, "Torque Ripple Reduction in a DFIG-DC System by Resonant Current Controllers," *IEEE Trans. Power Electron.*, vol. 30, no. 8, pp. 4244–4254, 2015.

[31] G. D. Marques and M. F. Iacchetti, "Field-Weakening Control for Efficiency Optimization in a DFIG Connected to a DC-Link," *IEEE Trans. Ind. Electron.*, 2016.

[32] M. F. Iacchetti and G. D. Marques, "Voltage Control in a DFIG-DC system connected to a stand-alone DC Load," in *2015 9th International Conference on Compatibility and Power Electronics (CPE)*, 2015, pp. 323–328.

[33] G. D. Marques, D. M. Sousa, and M. F. Iacchetti, "Air-gap power-based sensorless control in a DFIG connected to a DC link," *IEEE Trans. Energy Convers.*, vol. 30, no. 1, pp. 367–375, 2015.

[34] G. D. Marques and M. F. Iacchetti, "A Self-Sensing Stator-Current-Based Control System of a DFIG Connected to a DC-Link," *IEEE Trans. Ind. Electron.*, vol. 62, no. 10, pp. 6140–6150, 2015.

[35] H. Misra and A. K. Jain, "Analysis of Stand-Alone DFIG-DC System and DC Voltage Regulation With Reduced Sensors," *IEEE Trans. Ind. Electron.*, vol. 64, no. 6, pp. 4402–4412, 2017.

[36] G. D. Marques and M. F. Iacchetti, "Control Method of the DFIG Connected to a DC Link through a Diode Bridge," *Energy Power Eng.*, vol. 05, no. 04, pp. 102–108, 2013.

[37] H. Misra, A. Gundavarapu, and A. K. Jain, "Control Scheme for DC Voltage Regulation of Stand-Alone DFIG-DC System," vol. 64, no. 4, pp. 2700–2708, 2017.

[38] M. F. Iacchetti and G. D. Marques, "Enhanced torque control in a DFIG connected to a DC grid by a diode rectifier," *2014 16th Eur. Conf. Power Electron. Appl. EPE-ECCE Eur. 2014*, pp. 1–9, 2014.

[39] G. D. Marques and M. F. Iacchetti, "Inner control method and frequency regulation of a DFIG connected to a DC link," *IEEE Trans. Energy Convers.*, vol. 29, no. 2, pp. 435–444, 2014.

[40] G. D. Marques and M. F. Iacchetti, "Sensorless Frequency and Voltage Control in the Stand-Alone DFIG-DC System," *IEEE Trans. Ind. Electron.*, vol. 64, no. 3, pp. 1949–1957, 2017.

