

Doubly Fed Induction Generator: Grid Integration and Performance Analysis

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Abstract. Renewable energy sources are emerging to replace conventional energy sources in the energy mix as a result of the growing demand for power and the constraints of existing energy sources. With technological advancements, wind energy has become a promising secondary energy source, resulting in the proliferation of wind farms around the globe to bolster traditional energy systems. This has led to a rapid increase in the incorporation of wind power into the power grid, emphasizing the need to understand its effects on the system's parameters. A range of generators, including DFIG, SG, and SCIG, are used to generate wind power. Due to benefits of separate control over true and wattless power, variable speed operation and maximum power tracking, a DFIG based wind turbine became a favourite choice for power utilities.

1 Introduction

These days, research and development for more sustainable energy sources is moving quickly due to growing worries about the environment and the scarcity of conventional energy sources. A big focus on wind power development was made in 1995[1]. In today's worldwide energy sector, wind turbines using Doubly Fed Induction Generators (DFIGs) have become commonplace due to their capacity to optimize energy extraction in variable wind settings and control both average and wattless power for greater grid integration. At the moment, this technology is most commonly used in distributed generating applications and can produce electricity up to gigawatts.

The prevalent choice for the majority of wind turbines in today's market is the installation of doubly fed induction generators. Utility grid is directly tied to the stator of DFIG is where as the rotor is tied via a moderately rated variable frequency AC/DC/AC converter (VFC). Only a small portion (25–30%) of the entire power must be handled by the VFC—which is made up of a rotor side converter (RSC) and a grid-side converter (GSC) coupled back-to-back by a dc-link capacitor to manage the generator. SGs play a crucial role in a conventional power system's transient stability. The speed governor and AVR/exciter control the frequency (true power) and voltage (wattless power) of a stable system during a disturbance [2,3]. It takes a lot of effort and time to assess whether integrating wind energy into the grid is feasible, especially when it comes to power system security. The process of integrating wind power with current networks involves addressing several difficulties with caution [4-5]. Among the variables taken into consideration are the critical

clearing time, frequency, voltage, and the long- and short-term transient stability of rotor angles. Moreover, the assessment of the system's torsional, local, inter-area, and control modes is included in small-signal analysis. To guarantee system efficiency, dependability, and financial performance, these assessments are necessary for different wind energy penetration limitations [4-5]. In [6], During intense disruptions, SG controllers may face obstacles in bringing the SG back to its steady-state operating point. This causes the SG to lose synchronization or angular stability, necessitating a trip from the power system. More unforeseen events could arise in this situation and affect the stability of the system.

Wind turbine generators (WTGs), which rely a power electronics interface, are often cited as having a weaker resilience to grid failures than traditional synchronous generators (SGs). The voltage drops at the WTGs' connection point when they are connected to the grid and there is a grid fault resulting in a heavy current flowing in both the converters and rotor. This over-current has the potential to kill the converters because the VFC's power rating is just 25–30% of the DFIG's power rating. The WTGs might need to be unplugged from the power network to protect the system's DFIG converters, which must be tripped. Recently, there has been a noticeable enhancement in the dispersion of wind power in certain power networks, which is beginning to affect the general stability of the system [7,8].

Three distinct modes of operation are available for the DFIG: synchronous, super-synchronous, and sub-synchronous. The system's inertia and synchronization power are the primary factors influencing these electro-mechanical forms of oscillations [9,10]. Higher system inertia, however, indicates that the system is more stable

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in the face of large load fluctuations or disturbances. Nevertheless, wind power does not need more inertia because the power electronic converter has disconnected. On the other hand, from a system perspective, it can provide a sizable quantity of system wattless power. When DFIG is incorporated into the power system, it boosts system stability while concurrently reducing the network's total effective inertia.

2 Wind turbine system

The turbine begins to rotate when wind strikes its blades, converting the wind's energy into mechanical energy [11]. The air density and wind speed have an impact on generated electric power.

The turbine's wind power is calculated as follows

$$P = \frac{1}{2} C_p \rho A V^3 \quad (1)$$

where C_p represents the Co-efficient of power which represents the capability of wind turbine to produce electric power from the wind energy available at blades, ρ is the density of air in kg/m^3 , A is swept area of blade in m^2 and V is the wind strength in m/sec . The amount of wind energy that is transformed into rotational energy is indicated by the coefficient of power, or C_p . The power coefficient is influenced by the tip speed ratio λ , calculated as the turbine blade's linear speed divided by the wind speed

$$\lambda = R\omega/V \quad (2)$$

Generated power P is given by

$$P = \frac{1}{2} C_p(\lambda) \rho A \left(\frac{R}{\lambda}\right)^3 \omega^3 \quad (3)$$

Wind turbine rotor radius is represented by R and its units are meters. The highest coefficient of power is reached for a specific value of the tip speed ratio. The maximum amount of energy in the wind can be used by wind turbines with variable speed operations. Wind turbines are run at a speed that provides the best performance for this reason. To accomplish this, the turbine speed is adapted in response to changes in wind speed. There is an inverse correlation between peak power and the cube of wind speed, as evident from observation. An induction generator is preferred for generation with variable speed since its adaptability in reaching rotor speed, in contrast to synchronous generators (SG), which operate at a fixed speed.

3 Variable and fixed speed turbine systems

Generators that are asynchronous, or squirrel cage induction generators (SCIG), are utilized in wind turbines that run at a persistent speed. Here, the generator's output is directly served into the grid,

maintaining a steady rotational speed. The wind turbine rotates at a constant pace since the generator's speed is constant. The rotor of a wind turbine produces mechanical power that varies according to changes in wind speed. When there is an extremely strong wind, the conditions become uncomfortable because the rotor torque increases significantly yet the generator rotor speed only little changes. Consequently, the rotor components are under stress during each severe wind moment. The generator's output changes abruptly as a result of the rotor torque suddenly increasing. The fluctuation in the generator's output power when linked to the grid causes instability issues for the grid [12]. With SCIG, SG, and DFIG, variable speed operation is possible.

Variations in torque are prevented with the DFIG system, which spares the turbine's rotor components stress. As a result, it is beneficial to have a steady supply of power from the generator. In a similar vein, the wattless power flow between the grid and DFIG can be adjusted [13]. Additionally, it assists in managing the system's power factor [14]. The installation of DFIG makes electricity generation possible even in the presence of low wind speeds. Variable speed wind turbines (VSWT) with three phase SG and power electronics can achieve comparable outcomes. The generator speed in this system is determined by wind speed. AC is produced by the generator, and AC is converted to DC by the converter. Another converter transforms DC into the necessary frequency and magnitude of AC that the power network requires. Larger sizes and higher ratings are essential for power converters to effectively manage the complete power output of the generator in this instance.

Conversely, only a tiny portion of the generator output power must be handled by the power converters utilized in DFIG [15]. As a result, the size of the power converter in DFIG is only roughly thirty percent that of the power converter in synchronous generators [16-18]. The power converter's smaller size lowers losses and makes it more affordable. Pitch control is used to produce the best outcomes from wind turbines operating with fixed speed. The pitch control system is expensive and sophisticated since it needs mechanical components. Shaft speed can be used to track wind speed during varying generating speeds to maximize energy output. The amount of power that may be produced, however, is limited in the case of constant speed generation since the coefficient of power falls with increasing wind speed. By employing appropriate algorithms, it becomes possible to achieve maximum power output regardless of speed. By doing this, there's a chance that power will eventually surpass the generator's rating and become more than its rating. At that point, giving up on the ideal tip speed-ratio to limit the power becomes imperative [19].

A linear relationship exists between the speeds of wind and rotor in a variable speed operation. On the other hand, the shaft's speed abruptly drops to maintain a constant power output as the wind speed drops. Wind turbine pitch control regulates wind speed changes in fixed speed fixed frequency (FSFF) systems because the function of synchronous generators is to transform

mechanical energy into electrical energy [20]. Converters with greater ratings and higher costs are required for squirrel cage induction devices. Due to their limited power handling capacity, smaller converters are sufficient for wound-rotor induction devices. They also cost less because of this feature. The increased cost of slip ring maintenance and upkeep is a drawback of these devices. Rather of managing the entire amount of power generated, the power converters in the doubly-fed system are only intended to handle the extra power that is not transferred to the power network.

4 DFIG Scheme and model

4.1 Working principle

An induction generator (IG) or regular induction motor (IM) are single fed, meaning that the rotor or stator receives mechanical or electrical energy, respectively. The DFIG rotor receives power from both electrical and mechanical sources.

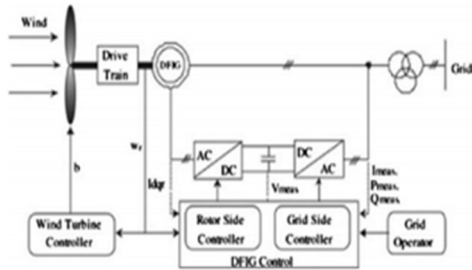


Fig 1. Schematic diagram of DFIG

An induction generator's capability to adjust to variable speeds aligns well with the fluctuating nature of wind speeds. Converters ensure that voltage and frequency remain constant in wind generators with changing speeds, regardless of wind speed. As illustrated in Fig. 1, the system consists of a generator with a wound rotor, stator windings connected with power network, and rotor windings tied with grid via a couple of converters. The converters are voltage source type and utilizes PWM method. Double-fed induction machines function as motors when they run below synchronous speed and as generators when they run above synchronous speed. Thus, a DFIG can function in four distinct ways. Concerns arise for wind energy conversion systems when their machinery operates in the generating mode and at speeds higher than or lower than synchronous. A DC link, as depicted in Fig. 1, bridges the two power converters.

Power can move both ways in the configuration displayed. When a machine operates above synchronous speed, electricity goes from the rotor to the power network, and when it operates below synchronous speed, rotor receives average power from grid [21]. The converter at the grid side maintains a steady connection DC voltage. Additionally, it manages the real and reactive power transfers from the power network and rotor. The converter, located on the rotor side, regulates flux to manage the stator actual and reactive power. Additionally, a converter feeds the DFIG reactive

power. Figure 2 displays the DFIG power flow schematic. The generator can operate either below or above the synchronous speed. The power obtained from the converters, or the slip power, is determined by

$$P_{Rotor} = s P_{Stator} \text{ indicating zero stator and rotor losses}$$

Stator true power of DFIG, Network power and mechanical power developed related by the following equation

$$P_{Stator} = \frac{P_{Network}}{(1-s)} = \frac{\eta_g P_m}{(1-s)} \quad (5)$$

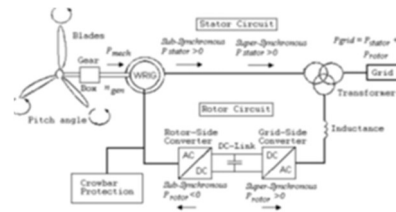


Fig 2. Flow of true power in DFIG

Where P_m represents the mechanical power and η_g is generator efficiency. The direction in which power flows between the rotor and the power network is determined by both positive and negative slip values. Whether the slip value is positive or negative, power moves from the stator to the power network [22].

4.2 Equivalent Circuit of DFIG

From the basic equivalent circuit of a transformer, we can establish the equivalent circuit for an induction machine. As seen in Fig. 3, X_r and R_r denotes rotor reactance and resistance of rotor when referred on stator side. Converters are tied between the rotor winding of an induction machine that is doubly fed and the grid. This fact is considered when designing DFIG equivalent circuit which is doubly fed, as seen in Fig. 4. True and wattless powers of the DFIG are determined considering corresponding circuit of a DFIG. This can be used in addition to other methods to extract different DFIG properties for analysis and study. Both the voltage that the converter supplies to the rotor and the stator voltage are taken into account during computations.

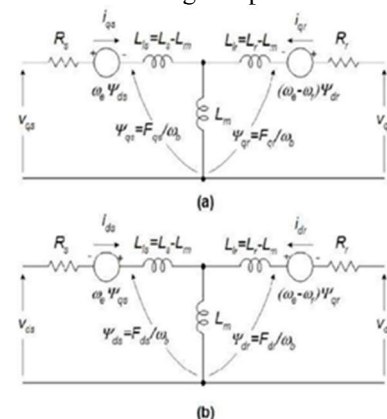


Fig 3. DFIG d-q equivalent circuit

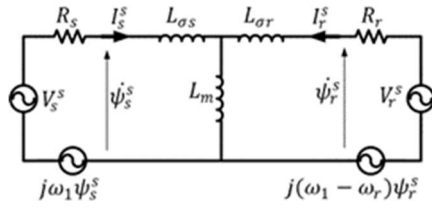


Fig 4 Equivalent circuit of DFIG

As the signals that the converter at the rotor side receives vary, so do the rotor voltage's magnitude and angle. When the speed is higher than synchronous, a typical constant speed induction machine operates as a generator; when the speed is lower than synchronous, it operates as a motor. The operating range of a constant speed induction machine is approximately $\pm 2\%$, that is, the generator operates between slightly above 100% and 102% while the motor runs between 98% and slightly below 100% of synchronous speed. The capability of a standard induction machine to generate electricity is contingent upon operating speeds exceeding synchronous speed; in contrast, the doubly fed induction machine (DFIM) has the unique ability to produce electricity both below and above synchronous speed.

5 Control of DFIG

Vector control procedure decouples the regulation of wattless and average power through the use of the Park transformation. After aligning the stator flux vector with the d-axis and making reference frame speed ω equal to stator flux speed ω_e , we obtain

$$\Phi_{sq} = 0 \quad (6)$$

$$\Phi_{sd} = \text{Constant} \quad (7)$$

True power and wattless powers of DFIG are given by

$$P_S = \frac{3}{2} \frac{L_m}{L_s} \omega_e \Phi_{sd} i_{rq} \quad (8)$$

$$Q_S = -\frac{3}{2} \frac{L_m}{L_s} \omega_e \Phi_{sd} \left(\frac{\Phi_{sd}}{L_m} - i_{rd} \right) \quad (9)$$

Where

- Φ_{sd} is d axis stator flux,
- L_m is mutual inductance
- i_{rd} is d axis rotor current
- i_{rq} is q axis rotor current
- P_S is true power of the DFIG
- Q_S is wattless power of DFIG

The true power is controlled by rotor current in d axis, and wattless power controlled by rotor current in q axis.. When medium power machines are employed in wind energy conversion systems, the phase stator resistance R_s is ignored.

6 Grid integration of DFIG

Integration of bulk amount of renewable energy sources to the utility grid was started nearly two decades ago. It is required to sense the grid frequency and voltage in

order to connect a DFIG to the grid. This is achieved by connecting Phase Locked Loop (PLL) [22]. PLL continuously track the frequency and voltage of the grid and these signals were sent to control mechanism of DFIG. DFIGs when integrated to grid, influences the system stability, transmitted power, and power quality.

6.1 System stability

Since the DFIG is coupled to variable speed turbines, they have capability to adjust wattless power and ability to control both average and wattless powers independently. This can be accomplished by power electronic converters. Since wattless power can controlled, it is possible to enhance the voltage stability of the grid [23-24]. In case of grid disturbances, DFIG act like ancillary source of wattless power and hence enhances the grid voltage stability. The DFIGs has the ability to enhance frequency stability along with voltage stability. A properly designed controller can regulate the frequency in transient conditions such as loss of network generation.

6.2 Wind power transmission

Power transmission from large size DFIGs into power system always a challenging job since wind is uncontrollable in nature [25-28]. In case of large offshore plants, the power transmission is accomplished by incorporating common collection bus exclusively controlled by STATCOM. To onshore grid, the power is transmitted using HVDC cables.

6.3 Power quality

When bulk wind power is injected into the grid, it may cause voltage flicker and deviations in frequency. Frequent switching of power switches in Power converters of DFIG is the major cause for voltage flicker [29-34]. Voltage flicker also depends on average wind velocity, impedance angle of the grid and short circuit capacity of the grid. Frequency deviations are inevitable as the wind is intermittent in nature. Deterministic method using transfer function is one of the methods to estimate the frequency deviation.

7 Simulation results

The intended system is simulated utilizing MATLAB simulink. A 9 MW rating DFIG is considered for simulation. The DFIG is simulated under the conditions of steady state and fault conditions.

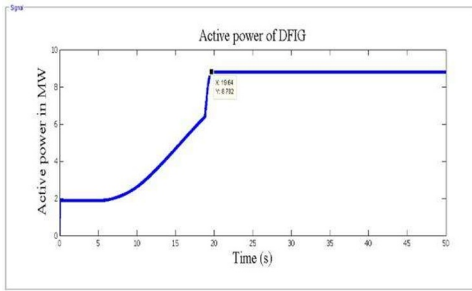


Fig. 5 Active power of DFIG in steady state

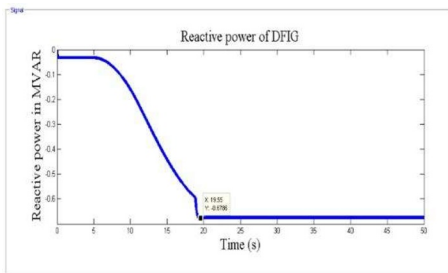


Fig. 6 Reactive power of DFIG in steady state

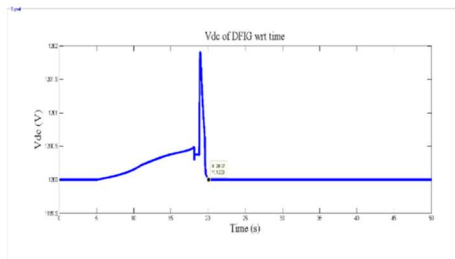


Fig. 7 Vdc of DFIG in steady state

Different types of shunt faults are simulated and the behaviour of DFIG is analysed. It has been found that DFIG tripping time is inversely proportional to the severity of the fault. For L-G fault, tripping is more compared to the LLL or symmetrical fault. The results are shown in Table 1.

Table 1. Trip time of DFIG under different fault conditions.

S.No.	Faults	Trip time in secs
1	LG	5.221
2	LL	5.111
3	LLG	5.108
4	LLL	5.01
5	LLLG	5.01

8 Conclusion

This article has explored various wind turbine setups, highlighting different generators and power electronic converters. It outlines the electrical topologies necessary for optimizing technical advantages in wind farms. The DFIG connection enhances system stability and load voltage. In scenarios of sudden load connection, DFIG-based wind power generation demonstrates superior

terminal voltage recovery. The paper also proposes a vector control strategy for the decoupled control of active and reactive power in a DFIG wind energy conversion system, offering valuable insights into the generator's dynamic response to various faults.

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