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Power Quality Analysis of DFIG Based Wind Energy System

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A B S T R A C T

With the escalating demands for electricity driven by rapid industrialization and population growth, traditional energy resources are being exploited at an unsustainable pace. Wind energy generation has emerged as a promising solution. Doubly Fed Induction Generator (DFIG) technology has produced remarkable energy efficiency compared to the conventional squirrel cage induction generator. In this research, the coupling of wind turbines with DFIG technology has been done. A series of comprehensive case studies has been presented wherein we analyze the variations in the harmonics spectrum and their corresponding effects on the torque produced. To conduct our analyses, advanced simulation techniques are employed. The primary contribution of this research lies in the novel technique developed by the author for the accurate computation of power quality parameters.

Keywords **DFIG (Doubly fed induction generator, Wind energy generation, harmonics, Wind turbine, Renewable energy resources, Power quality**.

1. Introduction

The conventional sources of energy production have been exploited rapidly. The prices of fuels for the production of electricity from the conventional plants are very high for the country like Pakistan. Further; the conventional sources of energy are polluting the environment adversely which can cause global warming. The demand of electricity is increasing due to industrialization and population growth in Pakistan [1]. The energy resources in the country are not utilized efficiently. Due to which the country has been facing the problem of energy shortfall. The electricity generation system in Pakistan is majorly inclined towards thermal source of energy. The high prices of furnace oil are not affordable. Further; the generation from fossil fuel is continuously polluting the natural environment and is producing greenhouse gases in the atmosphere which deplete the ozone layer in the atmosphere [2].

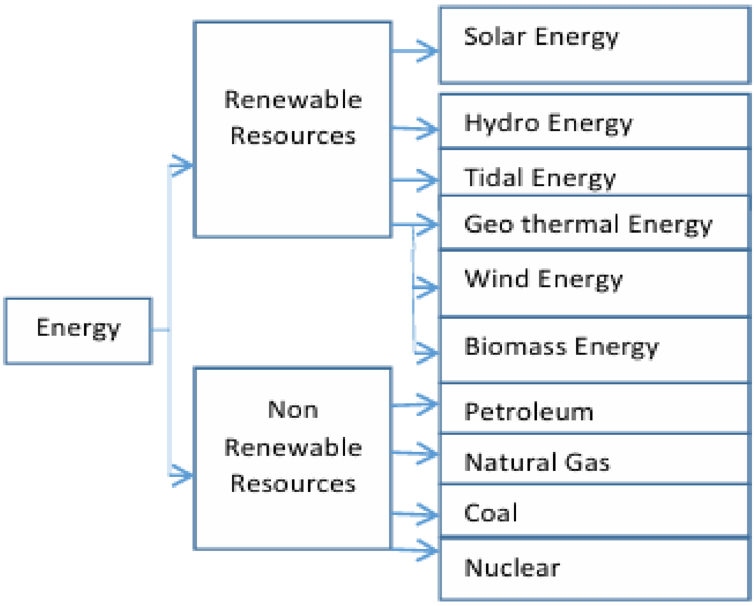

Fig.1: Block diagram of Energy System

Wind energy has gain attraction in the field of power industry [2]. The speed of wind is not uniform all the time. The wind turbines start production at wind speed above 2 m/s and reach maximum power production around 12-15 m/s. When the wind speed is above 12-15 m/s, the rotor has to waste the excess power by letting it pass by the pass by the rotor in order not to damage the turbine [3]. The DFIG is coupled with the wind energy system as depicted in the following figure[3]:

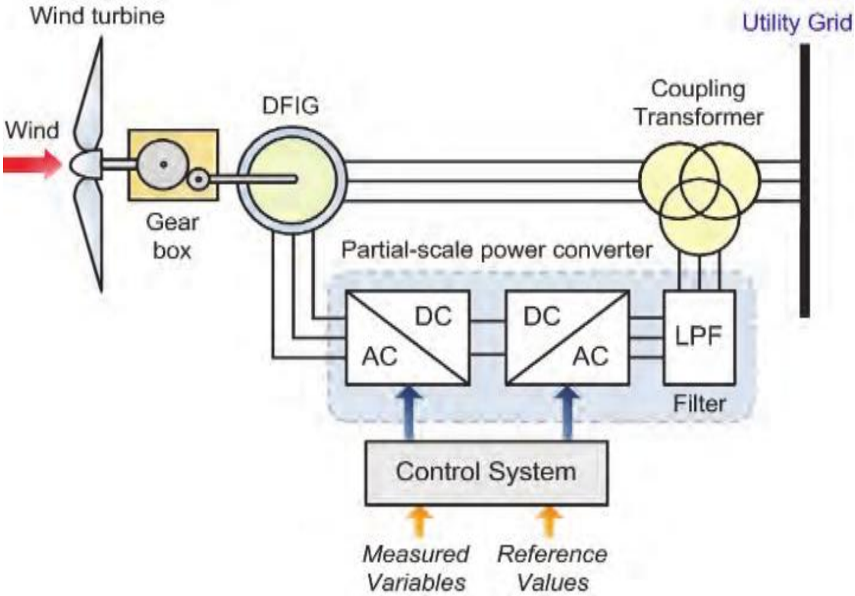

Fig. 2: DFIG based Wind Energy System

DFIG enables wind turbines to operate with variable range of speeds. Back to back converter is connected to the rotor of DFIG and its purpose is to feed rotor with current of varying frequency [3]. Power contained in form of K.E. in the wind P_v is shown as:

$$P = \frac{1}{2}\rho R^2 V_v^3 \qquad (1)$$

V_v is the average wind speed in the swept area, P is the power in the wind, R is the diameter of the rotor blade, ρ is the air density. The following curve shows Power in the wind as function of the average wind speed:

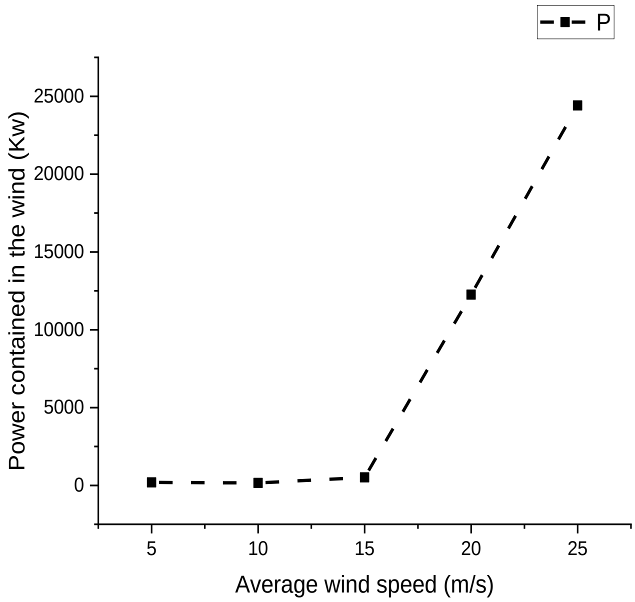

Fig. 3: Power Variations in Wind Energy System

It can be observed from above trend the large power contained in the wind can be utilized at high average wind speed.

II. METHODOLOGY

DFIG is an induction generator where both rotor and stator terminals are available for power flow. When the machine works as a generator, the input is mechanical power. The active power transmitted to the grid is the sum of stator power and rotor power assuming power inverter is lossless (P_r=P_{grid}) [3]:

$P_r = P_s + P_{grid}$ (2)

The active power from the rotor is proportional to the slip s of the generator:

$P_r = - s . P_s$ (3)

Where the slip is defined as [3]:

$$S = ws - wr/ws \quad (4)$$

2. DFIG Based Wind Energy System

DFIG is an induction machine with wound rotor where both rotor and stator are connected to electrical sources. The rotor has three phase windings which are energized with three phase currents. The rotor currents establish rotor magnetic field. The rotor magnetic field interacts with stator magnetic field to produce torque. The magnitude of the torque depends on strength of two fields and the angular displacement between two fields [3]. Torque is developed by the magnetic interaction between magnetic poles of opposite polarity. The stator side has two parasitic elements R_s and L_s, where R_s is the resistance of stator phase winding and L_s is the leakage inductance of phase winding respectively. The rotor circuit also has two parasitic elements: the rotor leakage reactance L_r and rotor resistance R_r. The rotor and stator are connected through transformer. The turn ratio of the transformer depends on the actual turn ratio between stator and rotor and slip of the machine.

$S = n_s - n_r/n_s$ (5)

Where n_s and n_r are the synchronous and rotor speeds respectively. The synchronous speed can be determined as [3]:

$$ns = \frac{60\,fe}{P}\,rpm \quad (6)$$

Where P is the number of pole pairs and f_e is the electrical frequency of the applied stator voltage. When the rotor accelerates beyond the synchronous speed, the frequency of the rotor voltage begins to increase again. But it has opposite phase sequence to the sub synchronous mode. Therefore; the frequency of the rotor voltage is [3]:

$f_r = s\, f_e$ (7)

The mechanical torque generated by the machine can be calculated by computing the power absorbed by the rotor resistance component. It is shown as [3]:

$$Pm = 3\, i_r^2 \left(\frac{1-s}{s}\right) R_r \quad (8)$$

Rotor resistance is R_r and leakage inductance is L_r.

The mechanical torque can be calculated as [3]:

$$Tm = 3\, i_r^2 \left(\frac{1-s}{s}\right) \frac{R_r'}{w_m} \quad (9)$$

2.1 Harmonic analysis

The electrical equipment with power electronics coupled to grid produce non sinusoidal grid currents due to non-linear characteristics of the power electronics. As the grid voltage is sinusoidal and the voltage produced by power electronics are non-sinusoidal, the current from power electronics will contain harmonics. According to the Fourier analysis, any periodic waveform consists of a sum of sinusoidal waveforms with different frequency and phase, w_1= fundamental frequency and h_w being the multiples of the fundamental frequency [3]. When a symmetrical three phase induction machine is connected to the system of three phase voltage, the air gap flux will contain harmonics [4]. This is due to non-perfect distribution windings both in stator and rotor. The doubly feed induction machine is fed by a cyclo-converter [5] has a certain amount of harmonic content in its current, if the stator is connected to the fundamental frequency voltage source. With DFIG, the rotor circuit is connected to the voltage source produce a current from rotor and its higher harmonics. There are two kinds of harmonics called stator harmonics and Rotor harmonics [4] are produced in the induction machine. The left side of the following table shows harmonics in the stator and the right side shows harmonics in the rotor. The first two lines in the table are harmonics due to the stator harmonics. The last two lines are the harmonics slip, these are called slip harmonics; n=1;2;3 and m=1;2;3 [3,4].

Table 1 – Stator Harmonics & Rotor Harmonics

Sr. No.	Stator Harmonics	Rotor Harmonics
1.	(6m-1)fgrid-6(n-1)fslip	(6m)fgrid-(6n-5)fslip
2.	(6m+1)fgrid-6(n-1)fslip	(6m)fgrid+(6n-5)fslip
3.	(6m-1)fgrid-6(n)fslip	(6m)fgrid-(6n-1)fslip
4.	(6m+1)fgrid-6(n)fslip	(6m)fgrid-6(n+1)fslip

3. SIMULATIONS

Let us consider the case study in which the electrical frequency, f_e is equal to 50 Hz, rotor current is 2030.8 A and R_r the rotor resistance is 1.497 x 10^{-3} ohm. The other electrical parameters are shown in the following table:

Table 2 – Electrical Parameters of Wind Turbine

No. of Poles	Synchronous speed (n_s) rpm	Rotor Speed (n_r) rpm	Slip	Rotor frequency (f_r)
2	1500	1200	0.2	10
4	750	500	0.3	15
6	500	300	0.4	20
8	375	200	0.4	23
12	250	100	0.6	30

The synchronous speed is usually higher than the rotor speed [6]. It shows that the value of the slip is positive. Normally, the value of slip is less than 1. But, if the value of synchronous speed is less than the rotor speed then it means that slip will be negative. When various values of slip [7] at different points, the gap between synchronous and rotor speed can be observed. The following curves show the comparison of synchronous speed and rotor speed [6] with fixed values of the slip at different points:

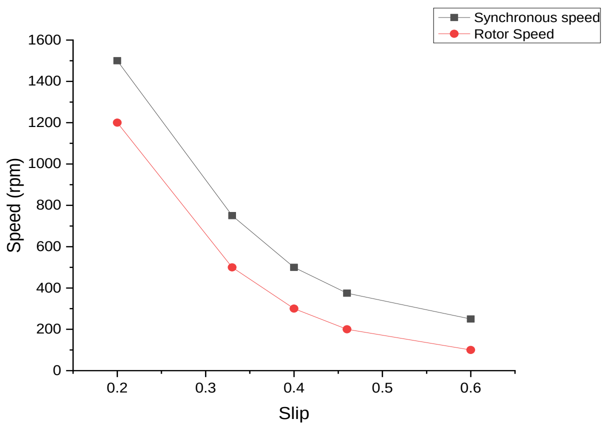

Fig. 4: Variations of Speed w.r.t Slip Values

The above curve shows that the synchronous speed is more than the rotor speed and slip is less than 1. The frequency of the rotor will change with the varying values of the slip at the grid frequency i.e. f= 50 Hz

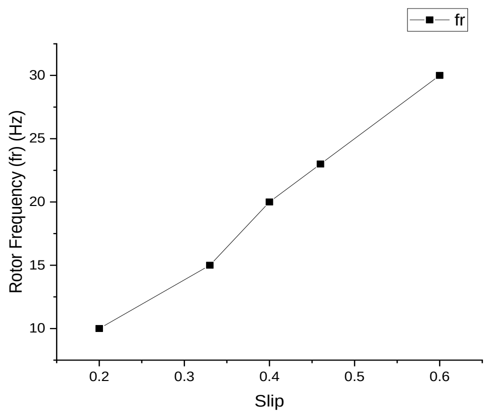

Fig. 5: Variations of Rotor Frequency w.r.t Slip Values

The above curve illustrates that the rotor frequency is different from the grid frequency (f=50 Hz). Its values vary with the different values of slip. The following table shows the other parameters which are computed as:

Table 3: Mechanical Parameters of Wind Turbine

Slip	Ws (rad/s)	Wm (rad/s)	Mechanical Power, Pm (w)	Torque (N.m)
0.2	314	150.72	78743	522.51
0.3	314	628	35167.7	55.99
0.4	314	37.6	25982.1	691.01
0.46	314	25.12	20333.9	809.47
0.6	314	12.56	11547.6	919.39

The following curve shows the variations of stator rotational speed with the varying values of slips:

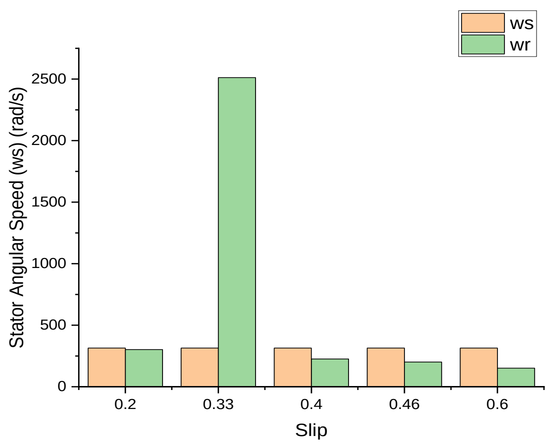

Fig. 6: Variations of Stator Angular Speed w.r.t Slip Values

Similarly, the mechanical torque [8] is produced in the machine and the values of the mechanical torque will change with respect to different reference points of slips as depicted in the following curve:

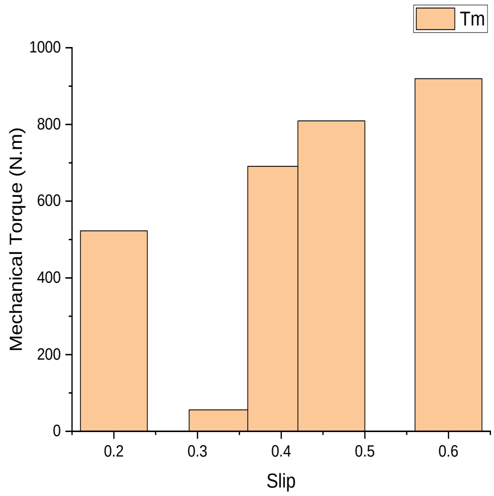

Fig. 7: Variations of Mechanical Torque w.r.t Slip Values

The mechanical power [9] produced will vary with different values of the slips. It can be shown in the following figure when the value of the slip increase the mechanical power decreases almost linearly:

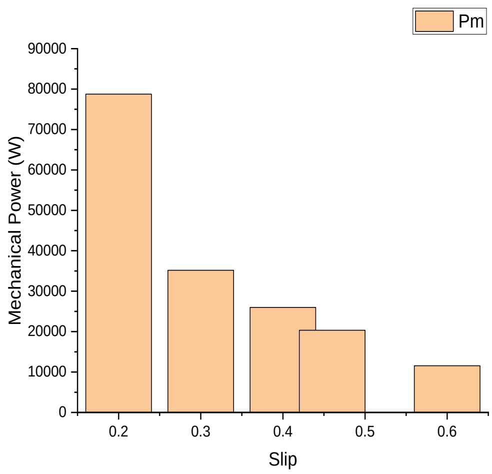

Fig. 8: Variations of Mechanical Power w.r.t Slip Values

The stator harmonics in stator winding become the cause of production of rotor harmonics in the rotor. The harmonics are the multiples of the fundamental frequencies. By using the harmonics table, the stator harmonics and rotor harmonics may be plotted by keeping the values of n=1;3 (odd harmonics) [10] and m=1;3 (odd). It can be clearly shown in the following curve that the impact of odd harmonics is very prominent. It can disturb the performance of wind energy system. These harmonics cannot be measured by ordinary power factor measuring meters. It can be measured by power quality analyzer. The quality of power cannot be improved in the presence of harmonics. Harmonics internally degrade the performance of the electrical power system and are not visible. Therefore; mitigation of harmonics is indispensible for the smooth running of the power system. The following plot shows the stator harmonics (S_h) and the rotor harmonics (R_h) at n=1; 3 and m=1;3 [10]:

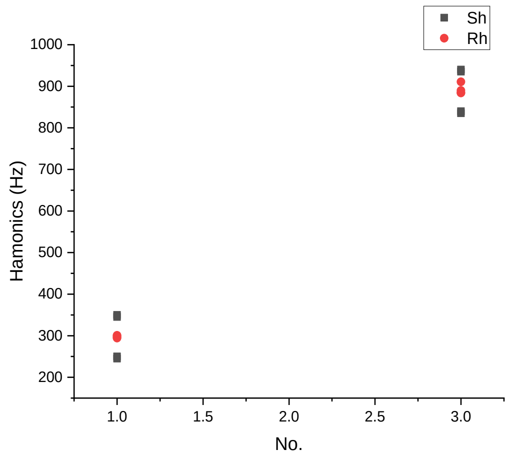

Fig. 9: Stator Harmonics and Rotor Harmonics at different values of N

Both stator harmonics (S_h) and rotor harmonics (Rh) at n=1;3 and m=1;3 are dangerous for the electrical system. These are considered as the "silent killers" of the smooth functioning of the power system. These harmonics can be mitigated by the installation of filters at both ends of DFIG. . In first case, Wind energy conversion system is connected to the electrical network. Distorted voltage in the stator generate harmonics wind energy conversion system which can produce ripple voltage, torque pulsation, overheating, increased losses in the stator winding and low power factor [11]. While in the second case, injection of harmonic components of voltage or current into electrical equipment can excessive heating of transformer and conductors [11]. At one end from where the harmonics distortion is from electrical network and at another end in which harmonic distortion is from Wind energy conversion system.

IV. Conclusion

Conclusively, this research has presented a novel approach in the form of a wind turbine system based on the DFIG system. The study has shed light on critical aspects of wind energy generation. Our findings emphasize that both harmonic and non-harmonic currents can coexist within the generator windings, with their presence contingent upon slip and the fundamental frequency in the voltage sources. These variables, if left unaddressed, have the potential to trigger detrimental power quality issues within the electrical system. To mitigate these challenges and ensure the robustness of the system, we recommend the strategic installation of filters at both ends of the DFIG. These filters act as guardians and suppressing disturbances.

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