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Power Generation and Voltage Regulation of 132kV Karbala grid using DFIG Wind Turbine Generator

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Abstract

Due to increasing demand on electrical energy in Iraq and to have clean energy that is environmental friendly, wind energy would be one of the most important and promising sources of renewable energy to achieve this goal. This paper discussed the reasons to use the Doubly-Feed Induction Generator (DFIG) amongst the available types of wind turbine generators, and in section (4) illustrate Motivations to select place to the wind farm construction. using decupling method (the vector control strategy) to change reactive power of DFIG 2MW connected to middle of the 132KV transmission line (Karbala north – Alahkader) without effect about the active power generated from DFIG itself with fixed wind speed value assumed to provide the voltage regulation, and control of the transmission line In addition to power generating. By using PSCAD/EMTDC, different simulation results are presented based on various scenarios.

Keywords: *wind energy conversion systems (WECS), DFIG, AC/DC/AC Converters, GRS, RSG*

1. Introduction

Due to increasing demand of electrical energy of Iraq and to get environmental better, the integration of the Wind power into power grid will be a good option due to the fact that is clean and renewable energy source and non-polluting. There are many features of wind power conversion system compared with the conventional power generation such as thermal power generation, nuclear power, gas power, and diesel power. Wind power conversion system can decrease the emissions of CO2 and other harmful gases emission from conventional power generation units. Each 1-MW wind power generator reduces 6 tons of NO2, 10 tons SO2, and 2000 tons CO2 emissions to the atmosphere per year. the main advantage a considerable the efforts is being made to generate electricity from renewable energy sources are abundance, Amongst the renewable energy conversion systems, the wind power has the most commercial prospects [1]. Especially in the last few years due to the rapid development of wind power industries and Wind is the one of the most abundant of energy nature sources. The wind energy can be exploited by using a wind energy conversion system (WECS), composed of a wind turbine with gear box to regulate speed, electrical generator, and power electronic converters and control system.

The Large-size wind turbines divided into two types depends to the behaviour of the wind turbine during the variations of wind speed: fixed-speed wind turbines and variable-speed wind turbines [3]. In fixed-speed wind turbines, three phase squirrel cage induction generators are generally used, since the generator output is directly connected to the grid, the rotation speed of the generator is fixed (in practice, it can be vary a little a range of typically 2 to 3 %), and so is the rotation speed of the wind turbine rotor should be fixed by use gear box. Any fluctuation in wind speed naturally causes stresses the mechanical components (specially the gear box) for the wind turbine. In variable-speed wind turbines, rotation speed of the wind turbine rotor is allowed to vary as the wind speed varies. This prevents the use of asynchronous generators in such wind turbines as the rotation speed of the generator is inconstant when its output is directly connected to the grid. The same is true for synchronous generators which operate at constant speed when directly connected to the grid. Therefore the doubly-fed induction generators come into allow the generator output voltage and frequency connected to grid to be maintained at constant values, no matter the turbine rotor speed fixed or variable (and

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thus, don't care to the wind speed), this is achieved by feeding AC currents of variable frequency and amplitude into the generator rotor windings, to be capable to keep the amplitude of frequency and the voltages produced by the generator (at stator) constant, despite the variations in the turbine rotor speed caused by fluctuations in wind speed [2].

The main reasons of DFIG to get more attention and application in WECS to used amongst the available types of wind turbine generators can briefly describe, its used instead of asynchronous generators: (a) DFIG-based WECS are highly controllable, allowing maximum power extraction over a large range of wind speeds. (b) the active and reactive power control is fully decoupled by independently controlling the rotor currents. (c) Ability to supply power at constant voltage and frequency while the rotor speed varies, Rotor speed may vary according to wind speed in order to improve wind generator efficiency, (d)Mechanical stress is reduced as well as torque oscillations are not transmitted to the grid; gusts of wind can be absorbed as energy is stored in the mechanical inertia of the turbine. Finally, (e) the DFIG- based WECS can either inject or absorb reactive power from the grid, hence effectively participating at voltage control [2-5]. Using synchronous generator in wind turbines offers the same advantages (above) as when DFIG is used. Both types of power generator require AC/DC/ AC converters. However, the converters in doubly-fed induction generators are significantly smaller than those in synchronous generators, this is because the converters in doubly-fed induction generators convert about 30% of the nominal output power while in the synchronous generators convert 100% of the nominal output power [3]. The synchronous nature of PMSG may cause problems during start-up, synchronization and voltage regulation and they need a cooling system, since the magnetic materials are sensitive to temperature, the temperature in Iraq its so high specially at summer season, they can lose their magnetic properties. Hence DFIG is dominantly used when compared among asynchronous generator and PMSG [2]. Many papers presented study about DFIG control to extract maximum active power different cases such generator output during various wind speed and another papers explained of DFIG wind turbine generator performance during the disturbance of main grid. For these cases and others it's had been achieved by kept reactive power of DFIG to be or near to zero. In this paper, focus to change the reactive power of DFIG and kept the active power as nominal rated to get another benefit as well as active power generation to voltage regulation and control; interested from the DFIG capability to reactive power exchange between the wind turbine generator and the grid. Ordered to produce or absorb an amount of reactive power to or from the grid, with the purpose of voltage control. Use vector control strategy based on which, the active and reactive power can be controlled independently. This paper organized, DFIG wind turbine performance its explained with mathematical equations in section 2 .In section 3, DFIG with Converters Controller mathematical Model introduced on which, the active and reactive power can be controlled independently. The case study it be illustrated in section 4. Control strategy is proved to be effective by the simulation results in section 5. in section 6 conclusion based in simulation results.

2. DFIG Wind Turbine Performance

It considers a network with Wind turbine catches the wind energy through blades of its rotor and transfers it to the rotor hub system. The rotor hub is connected to a low speed shaft through a gear box. The high speed shaft drives the electric generator which converts the mechanical power to electric power and delivers it to the grid .as shown in Figure1.

The technical performance of DFIG allows to extracting maximum energy from the wind, during the low wind speeds, while minimizing mechanical stresses on the turbine during gusts of wind. For the wind speeds lower than rated the rotor is running at sub-synchronous speed and for high wind speed it is running at super-synchronous speed. The model of the wind turbine is based on the steady state power characteristics, where the generator coupled to the turbine. The output power of the turbine is given by the following equation: And according to [3, 6], and [7].

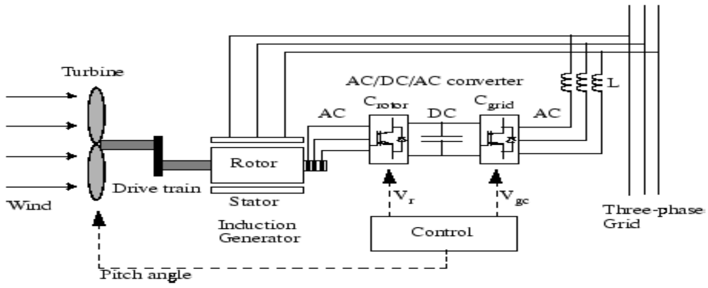

Figure 1. Structure of DFIG Coupled to Wind Turbine

$$P_W = \frac{1}{2}\rho A_t C_P(\lambda,\beta)V_w{}^3 \quad (1)$$

$$\lambda = \frac{Rw_m}{V_w} \quad (2)$$

$$T_w = \frac{P_w}{w_m} \quad (3)$$

Let At = π R2, And Substituting (1) and (2) to (3) to get:

$$T_w = \frac{\rho\pi R^3 C_P(\lambda,\beta)V_w{}^2}{2\lambda} \quad (4)$$

The performance coefficient of turbine Cp (λ, β) is a function of the tip speed ratio (λ), and the pitch angle of the rotor blades (β). It is determined by aerodynamic laws and it will be changed from turbine to other.

$$C_P(\lambda,\beta) = 0.5176\left[\frac{116}{\lambda_i} - 0.4\beta - 5\right]e^{-21/\lambda_i} + 0.0068\lambda \quad (5)$$

$$\lambda_i = \left[\frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1}\right]^{-1} \quad (6)$$

Where, pw is Mechanical power of wind turbine, ρ is the air density in Kg/m3,At is the area covered by the rotor blades in m2, Cp is Performance coefficient of the turbine, Vw is Wind speed (m/s), λ is Tip speed ratio of the rotor blade tip speed to wind speed, β is Blade pitch angle (deg), ωm is the mechanical speed of the wind turbine□(rad/s), R is the radius of the area covered by the blades (m).

3. DFIG with Converters Mathematical Model

A DFIG is basically a standard, as wound rotor induction machine with its stator windings directly connected to the grid and its rotor windings connected to the grid through a converter. The AC/DC/AC IGBT voltage-source Converter is divided to two components: the rotor side converter and the grid side converter with a common DC bus, [8].

3.1 The Rotor-Side Converter (RSC)

The RSC with PWM it is possible applies the voltage to the rotor windings of DFIG. The purpose of the RSC is to control the rotor currents such that the rotor flux position is optimally oriented with respect to the stator flux in order that the desired torque is developed at the shaft of the machine. The RSC uses a torque (or speed) controller to regulate the wind turbine output power and the stator terminals voltage (or reactive power) measured at the machine. The power is controlled in order to follow a pre-defined turbine power-speed characteristic to track the maximum power point. The actual electrical output power from the generator terminals, added to the total power losses (mechanical and electrical) is compared with the reference power obtained from the wind turbine characteristic. Usually, a Proportional-Integral (PI) controller is used at the outer control loop to reduce the power error to zero. The generic power control loop is illustrated in the Fig.2.The RSC provides the excitation of the rotor for the induction machine in order to control the torque, hence the speed of the DFIG and the power factor at the stator terminals. The RSC provides a varying excitation frequency depending on the wind speed conditions. The DFIG induction machine is controlled in a synchronously rotating dq-axis frame, with the d-axis oriented along the stator-flux vector position in one common implementation and this is called stator-flux orientation (SFO) vector control. In this way, a decoupled control between the rotor excitation current and the electrical torque is obtained. Consequently, the active and reactive powers are controlled independently from each other. The general Park's model of an induction machine is introduced. Using the static stator-oriented reference frame, without saturation, the vector equations of The Stator and rotor voltage Equations with constant coefficient in the d-q frame are [4, 9], and [10]:

$$\begin{aligned} V_{sq} &= R_s i_{sq} + \omega_s \psi_{sd} + \frac{d\psi_{sq}}{dt} \\ V_{sd} &= R_s i_{sd} - \omega_s \psi_{sq} + \frac{d\psi_{sd}}{dt} \end{aligned} \tag{7}$$

$$\begin{aligned} V_{rq} &= R_r i_{rq} + \omega_{slip} \psi_{rd} + \frac{d\psi_{rq}}{dt} \\ V_{rd} &= R_r i_{rd} - \omega_{slip} \psi_{rq} + \frac{d\psi_{rd}}{dt} \end{aligned} \tag{8}$$

The stator and Rotor fluxes are related to the stator and rotor currents in the d-q frame as:

$$\begin{aligned} \psi_{sq} &= L_s i_{sq} + L_m i_{rq} \\ \psi_{sd} &= L_s i_{sd} + L_m i_{rd} \end{aligned} \tag{9}$$

$$\begin{aligned} \psi_{rq} &= L_r i_{rq} + L_m i_{sq} \\ \psi_{rd} &= L_r i_{rd} + L_m i_{sd} \end{aligned} \tag{10}$$

Where, Rs, Rr, Ls, and Lr are the resistances and self-inductances of the stator and rotor windings Respectively, and Lm is the mutual inductance between a stator and a rotor windings when they are fully aligned with each other. ωs is the synchronously frequency and ωslip is the slip frequency, ωslip = ωs-ωe where, ωe = Pωm, P is pole pairs and ωm is the rotor's mechanical speed. Vs is the stator voltage imposed by the grid. The rotor voltage Vr is controlled by the rotor-side converter and used to perform generator control. The vector control strategy applied to the DFIG consists on making the stator flux in quadrature with the q-axis of the Park reference frame, therefore

$$\begin{cases} \psi_{sd} = L_s i_{sd} + L_m i_{rd} = \psi_s = L_m i_{ms} \\ \psi_{sq} = 0 \end{cases} \tag{11}$$

From the Equation (9) and (11):

$$i_{sq} = -\frac{L_m}{L_s} i_{rq} \tag{12}$$

$$i_{sd} = \frac{L_m\left(i_{ms} - i_{rd}\right)}{L_s} i_{rq} \tag{13}$$

By Substituting (12) and (13) in (10), to obtain

$$\psi_{rd} = (L_r - L_m^2) i_{rd} + \frac{L_m^2}{L_S} i_{ms}$$
$$\psi_{rq} = L_r (1 - \frac{L_m^2}{L_S L_r}) i_{rq} \tag{14}$$

By introducing the leakage coefficient σ with:

$$\sigma = 1 - \frac{L_m^2}{L_s L_r} \tag{15}$$

Then:

$$\begin{cases} \psi_{rd} = \frac{L_m^2}{L_S} i_{ms} + \sigma L_r i_{rd} \\ \psi_{rq} = \sigma L_r i_{rq} \end{cases} \tag{16}$$

Substitute (16) in to (8) to get the rotor Voltage and flux equations are (scaled to be numerically equal to the ac per-phase values):

$$\begin{cases} V_{rd} = R_r i_{rd} + \sigma L_r \frac{di_{rd}}{dt} - \omega_{slip} \sigma L_r i_{rq} \\ V_{rq} = R_r i_{rq} + \sigma L_r \frac{di_{rq}}{dt} + \omega_{slip}\left(L_o i_{ms} + \sigma L_r i_{rd}\right) \end{cases} \tag{17}$$

Where, Lo equivalent inductance is:

$$L_O = \frac{L_m^2}{L_S} \tag{18}$$

Assuming that the stator flux is stationary in the frame (the d-axis is aligned with the stator-flux-linkage vector) and neglecting the stator's resistive voltage drop, and from so:

$$\psi_{sd} = \psi_s, and\, \psi_{sq} = 0 \tag{19}$$

And,

$$V_{sd} = 0, and V_{sq} = V_s \tag{20}$$

Substitute (19), (20) to (7) $V_{sq} = V_s = R_s i_{sq} + \omega_s \psi_s$, from which obtain:

$$\psi_s = \frac{V_s - R_s i_{sq}}{\omega_s} \tag{21}$$

From (11), (21) to get:

$$i_{ms} = \frac{(V_{sq} - R_s i_{sq})}{\omega_s L_m} \tag{22}$$

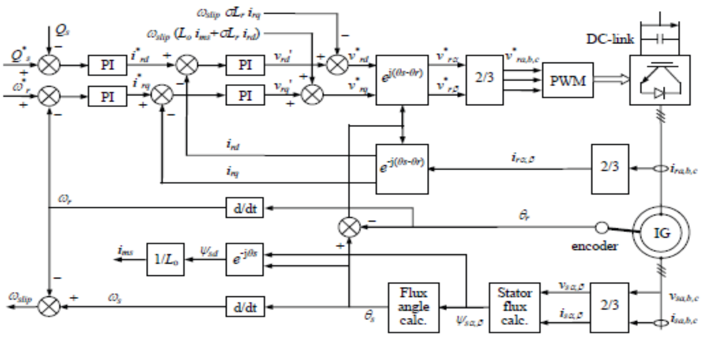

Figure 2. Vector Control Structure for RSC

From the rotor voltage (17) and from Figure 2 then:

$$\begin{cases} v'_{rd} = R_r i_{rd} + \sigma L_r \dfrac{di_{rd}}{dt} \\ v'_{rq} = R_r i_{rq} + \sigma L_r \dfrac{di_{rq}}{dt} \end{cases} \quad (23)$$

To ensure best tracking of the rotor dq-axis currents, vrd and vrq compensation terms are added to obtain the reference voltages vrd* and vrq* as shown in Figure 2 according to Equation (24)

$$\begin{cases} v^*_{rd} = v'_{rd} - w_{slip} \sigma L_r i_{rq} \\ v^*_{rd} = v'_{rq} + w_{slip} (L_m i_{ms} + \sigma L_r i_{rd}) \end{cases} \quad (24)$$

The active and reactive power at stator terminals are given by:

$$\begin{aligned} P_S &= V_{sd} i_{sd} + V_{sq} i_{sq} \\ Q_S &= V_{sq} i_{sd} - V_{sd} i_{sq} \end{aligned} \quad (25)$$

The active and reactive power at rotor terminals is given by:

$$\begin{aligned} P_r &= V_{rd} i_{rd} + V_{rq} i_{rq} \\ Q_r &= V_{rq} i_{rd} - V_{rd} i_{rq} \end{aligned} \quad (26)$$

The electromagnetic torque equation:

$$T_e = \psi_{sd} i_{sq} - \psi_{sq} i_{sd} \quad (27)$$

3.2. The Grid-Side Converter (GSC)

The GSC controls the flow of real and reactive power to the grid, through the grid interfacing inductance. The objective of the GSC is to keep the dc-link voltage level constant regardless of the magnitude and direction of the rotor power. The vector control method is used as well, with a reference frame oriented along the stator voltage vector position, enabling independent control of the active and reactive power flowing between the grid and the converter. The PWM converter is current regulated, with the d-axis current used to regulate the dc-link voltage and the q-axis current component to regulate the reactive power. A similar analysis of the d-q currents control carried out for the GSC can likewise be done for the control of the converter d-q currents [10]:

$$\begin{cases} V_{Cd} = Ri_{Cd} + L_{choke}\dfrac{di_{Cd}}{dt} - w_e L_{choke} i_{Cq} + V_{Cd1} \\ V_{Cq} = Ri_{Cq} + L_{choke}\dfrac{di_{Cq}}{dt} - w_e L_{choke} i_{Cd} + V_{Cq1} \end{cases} \quad (28)$$

The angular position of the grid voltage in Figure 3 is calculated as:

$$\theta_e = \int w_e dt = \tan^{-1}(\frac{v_{c\beta}}{v_{c\alpha}}) \quad (29)$$

Where, Vcα and Vcβ are the converter grid-side voltage stationary frame components. The d-axis of the reference frame is aligned with the voltage angular position θe of grid.

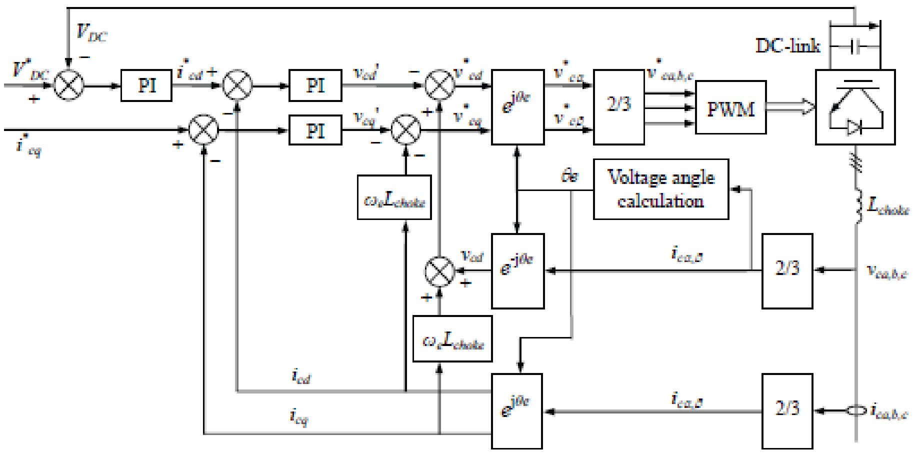

Figure 3. Vector Control Structure for GSC

Since the amplitude of the grid voltage is constant, Vcd is constant, and Vcq is zero. so the converter active and reactive power flow It will be proportional to icd and icq respectively. To realize decoupled control of Figure 3, similar compensations are introduced likewise of RSC in Equation (24):

$$\begin{cases} v_{cd}^{*} = (w_e L_{choke} i_{cq} + v_{cd}) - v_{cd}^{'} \\ v_{cq}^{*} = w_e L_{choke} i_{cd} - v_{cq}^{'} \end{cases} \quad (30)$$

The reference voltage Vcd* and Vcq* are then transformed by inverse-Park transformation to give3-phase voltage Vabc* for the final PWM signal generation for the converter IGBT switching.

$$\begin{cases} P_C = 3(V_{cd} i_{cd} + V_{cq} i_{cq}) = 3V_{cd} i_{cd} \\ Q_C = 3(V_{cd} i_{cq} + V_{cq} i_{cd}) = 3V_{cd} i_{cq} \end{cases} \quad (31)$$

From Equation (31) demonstrates that the active and reactive powers from the grid-side converter are controlled by the icd and icq current components.

4. Case Study

132kv Karbala north transmission network connected to Alahkader transmission network by two transmission line type teal (thermal rating 120MVA) with distance 90km. the site

which passes through it, these transmission lines, its desert and Elevated area to obtain a higher wind speed or (i.e. its open place to get max wind speed and no effect of the noise obtained from generators to the live of urban city).Consider Alahkader network is the terminal network consists of two transformers 132/33kv, 63MVA, and feeders 33 KV, feeds cement factory beside the network, and residential areas nearby, the largest load is taken from this network which does not exceed 75MW.since the load is low, most time Alahkader network supplied by one of transmission lines and another work as off line from one side and because of distance, this make the transmission line suffer from over voltage and its effect to insulations and some time damage of voltage transforms connected on it. From above mention there are two reasons to select wind turbine generator at this place, one satiation of the transmission line and second thermal rated of transmission lines with low load consumption. So can be exploitation to construction wind turbine farm to achievement power generation and to protection the transmission line from over voltage Influences. With ability of DFIG wind turbine to obtain these two cases. The rated power size of DFIG wind turbine farms unlimited in this paper it's depending to economics and politics reasons, consequence used single DFIG wind turbine. To study the impact of DFIG wind turbine to 132KV transmission line voltage, and active power by interconnection of DFIG 0.69kv, 2MW to middle of transmission line as shown in Figure 4 across two step of transformers one 0.69kv/11kv, then transfer throw 11kv feeder to second transformer 11kv/132kv which connected to transmission line. In this study suppose the wind speed its 5m/s according to NASI monthly data of wind at Karbala city, the load at Alakhder network 10MW, supplied from Karbala north grid.
The system parameters of the interconnection are shown below:

1) Transmission line parameters: 132kV, 120MVA, 50Hz, with R1=0.097Ω/km, X=0.387Ω/km,R0=0.3275 Ω/km, X0=1.274 Ω/km
2) DFIG Parameters: 2MW, 0.69kV, 50Hz, IGBT AC/DC/AC PWM converters, vector control model.

Different cases studies were conducted using PSCAD/EMTDC to demonstrate the power flow and voltage magnitude of transmission line by change reactive power of DFIG shown in section 5.

5. Simulation with Result and Discussion

The simulation done for 132KV, 120MVA, 50HZ, three phases Transmission line connected of Karbala north to Alahkader network with distance of 90km supply the load 10MW at Alahkader network. Assuming the load is low and pure resistive, to show the effect of change in reactive power of DFIG with rated 2MW to voltage profile and the active power transfer of transmission line between two networks ,the total time of the simulation it is 10 sec. different cases of simulation are done as shown below:

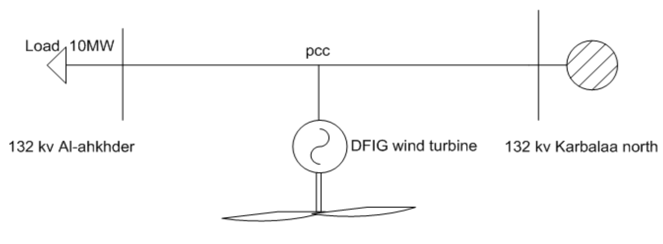

Figure 4. Circuit Diagram for Simulation Model

5.1. Active Power Supply to Load without DFIG.

The simulation done for circuit diagram is in Figure 4 without DFIG connection. From the Simulation result in Figure 5 the active power supplied from Karbala north network, to the load at Alahkehder network across transmission line is 10MW, since Alahkader terminal network and load is low at it so, the transmission line supply reactive power around 1.8 MVAR to Karbala north network. And Simulation result in Figure 6 Represent transmission line voltage magnitude value little more than rated (131.80- 132.2) KV.

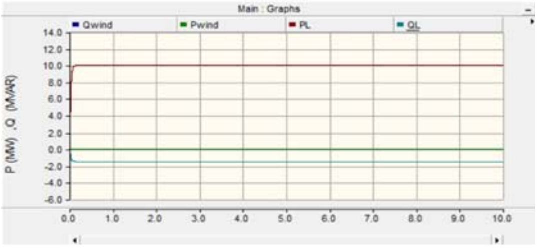

Figure 5. Active and Reactive Power Flow in Transmission Line without DFIG

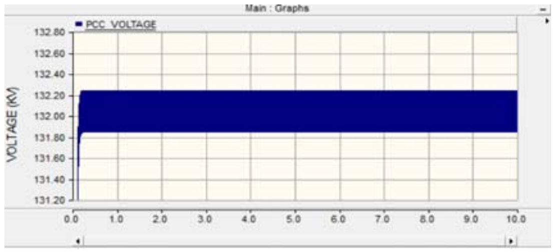

Figure 6. Voltage at Interconnection Point without DFIG Connection

5.2. Active Power Supply to Load with DFIG.

In this case the simulation done for circuit diagram is in Figure 4 for three cases of reactive power supplied or injection from DFIG to transmission line without effected to its active power supplier to load:

5.2.1. DFIG Supply Active Power and Reactive Power (Q wind =0)

The Simulation result of Figure 7 shows the active power supplied from Karbala north network, to the load in cased (5.1) decreased from 10 MW to 8MW, result from the DFIG supply 2MW. The reactive power supply at the transmission line to Karbala north network it be less than case(A) result from reactance of transformers which connect of DFIG to transmission line, this is decrease in reactive power and leads to balance transmission line voltage at rated value (131.80- 132.20) KV as shown in simulation result of Figure 8.

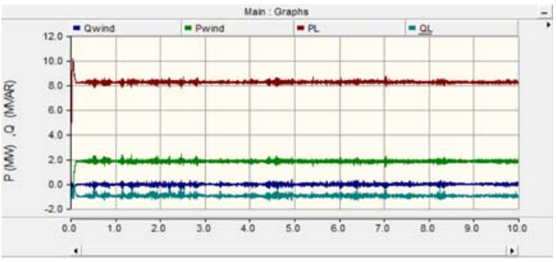

Figure 7. Active and Reactive Power Flow in transmission line with DFIG Reactive Power (Q = 0MVAR)

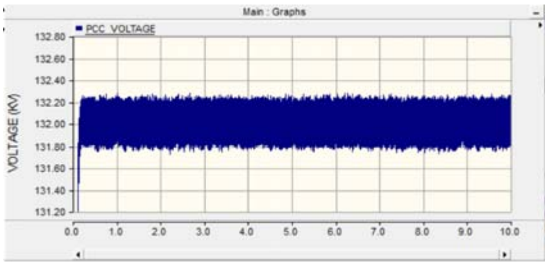

Figure 8. Voltage at Interconnection Point with DFIG Reactive Power (Q = 0MVAR)

5.2.2. DFIG Supply Active Power and Absorb Reactive Power (Q wind = -1MVAR)

The Simulation result of Figure 9 shows the active power transferred from Karbala north network at it be same in case (5.2.1) it 8MW, while the reactive power it be decrease to zero since the reactive power control of DFIG regulated to absorb 1Mvar so, this lead to reduce in transmission line voltage rated to (131.60- 132.00) KV as shown in simulation result of Figure 10.

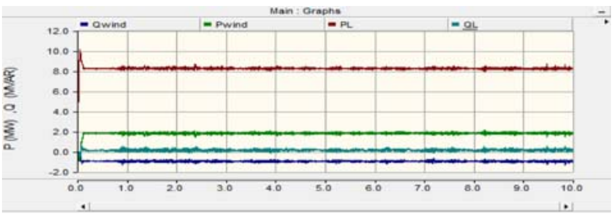

Figure 9. Active and Reactive Power Flow in Transmission Line with DFIG Absorb Reactive Power (Q = -1MVAR)

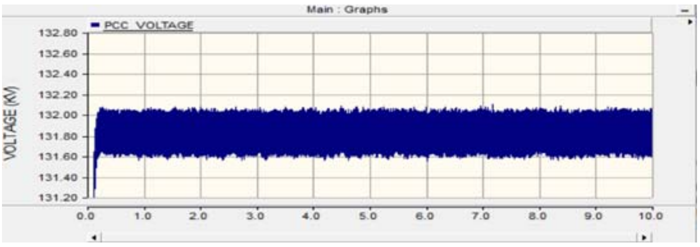

Figure 10. Voltage at Interconnection Point with DFIG Absorb Reactive Power (Q = -1MVAR)

5.2.3. DFIG Supply Active Power and Inject Reactive Power (Q wind = 1MVAR)

The Simulation result of Figure 11 shows the active power transferred from Karbala north network, to the load same in case (5.2.1), and case (5.2.2) it be 8MW, while the reactive power it be increase to -2Mvar since the reactive power control of DFIG setting to provide 1Mvar, and this resulted to increase in transmission line voltage (132.00- 132.40) KV as shown in simulation result of Figure 12

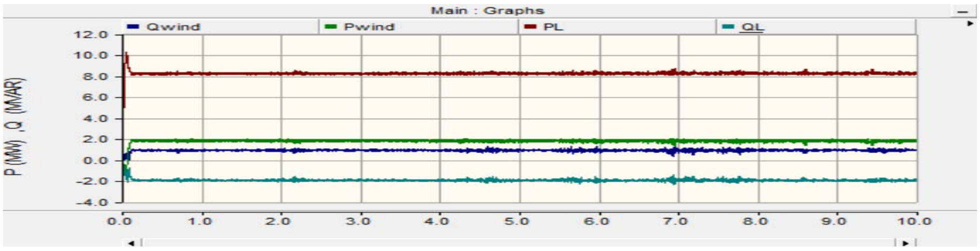

Figure 11. Active and reactive power flow in transmission line with DFIG inject Reactive power (Q = 1MVAR)

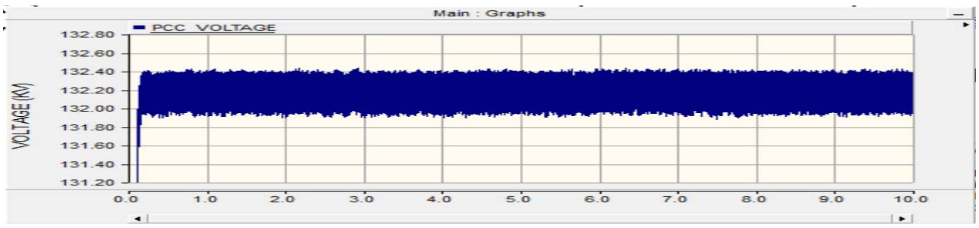

Figure 12. Voltage at Interconnection Point with DFIG Inject Reactive Power (Q = 1MVAR)

6. Conclusion

To increasing power generation of Iraq and environmental concerns needs to installing wind turbine generation farms, there two important things to construction new wind farms one type of generators and second the place to install it. This paper shows both and concludes use DFIG from others types of (WECS) and select 132KV transmission line connects between the Karbala north network and Alahkader network for construction wind farm without others places. The Control and operation of a DFIG-based wind power generation system under balanced supply voltage conditions with vector control strategy allows decoupled or independent control of both active and reactive power of DFIG have been investigated. Simulation results proved ability with effectively and efficiency of DFIG to do two options in transmission line one active power generation, and second reactive power control and this mean voltage profile control, without effected to change in active power produced from DFIG.

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