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Performance analysis of reactive power control management for doubly fed induction generator wind turbines

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Abstract

The efficient operation of the Doubly Fed Induction Generator (DFIG) in wind power systems is significantly affected by reactive power flow. Depending on its excitation, the DFIG's reactive power drawn either from the grid or fed into the grid, affects the voltage quality and stability of the wind turbine systems. In addition, an increase in DFIG excitation through the Machine Site Converter (MSC) above or below the rated excitation results in over-excited or under-excited operations of the generator respectively. Therefore, reactive power control management for DFIG wind turbines is crucial to overcoming these problems, thus, enhancing the performance of the DFIG wind turbine systems. The performance analysis of reactive power control management for DFIG wind turbines using the Lucas Nulle Wind Power Plant (LNWPP) WindSim software is presented.

Keywords: Doubly Fed Induction Generator (DFIG); Reactive Power Control Management; Machine Site Converter (MSC); Reactive Power Flow; Lucas Nulle Wind Power Plant (LNWPP) WindSim Software

1. Introduction

The wind energy system is one of the fastest-growing renewable energy resources in the world because it's clean and sustainable. Aside, generating electrical power from wind energy increasingly reduces greenhouse gas emissions [1]. The rising demand for wind power usage resulting in the continuous penetration of wind power into the grid has drawn significant attention to the DFIG wind turbine technologies amongst all other available wind energy conversion systems because of its many advantages, such as operating variable wind speed with minimum converters ratings [2-5]. However, the efficient operation of the DFIG wind turbine is greatly affected by the reactive power it draws from the grid or feeds to the grid, thereby limiting the voltage quality of the wind turbine systems [6]. Thus, solving the problem requires efficient DFIG model improvement strategies to provide reactive power control.

Numerous reactive power control techniques based on achieving optimum voltage quality efficiency of the DFIG wind turbine systems have been reported. M. Hallack et al. [7] present the modeling and control strategy for a grid-connected DFIG-based wind turbine system. Their control strategy incorporates Maximum Power Point Tracking (MPPT) by developing different elements conversion chains. At the same time, the simulation results give a better insight into the dynamic operation of the DFIG wind turbine systems in a Matlab/Simulink environment. J. Hu et al. [8] report the regulation of DFIG-based wind turbine systems' direct active and reactive power control using a sliding-mode control approach that eliminates the instantaneous active and reactive power errors by directly calculating the rotor control voltage. Their simulation results show enhanced transient performance and keep the steady-state harmonic spectra at the same level as other vector control strategies.

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The vector control strategy in active and reactive power control of a DFIG-based wind energy conversion system achieves efficient results by using the simple PI controller, according to A. R Kumhar [9]. S. Demirbas et al. [10] present the control of active and reactive power of DFIG, successfully controlling the rotor voltages at each switching period using the direct power control technique. The active and reactive power control techniques of the DFIG are independently unstable. However, there is a need to develop a fast reactive power control management that can maintain and enhance voltage stability and quality.

Thus, this paper presents the performance analysis of reactive power control management for DFIG wind turbines using the LNWPP system; section II describes the DFIG over-excited and under-excited operations; section III expresses the equations of DFIG; section IV deals with the DFIG reactive power control management; section V focuses on the simulation results and discussions, while section VI presents the conclusions.

2. Material and methods

2.1. Reactive Power Control Management of DFIG Wind Turbine

The DFIG wind turbine is a wound rotor induction generator with a back-to-back AC/DC/AC IGBT-based PWM converter [11]. The DFIG reactive power control management is achieved using the LNWPP system, a modular system equipped with training panels and system software support to perform specific tasks much shorter than other software support systems. The Lucas Nulle (LN) scope displays the LNWPP system results of the performance analysis of DFIG reactive power control management.

2.2. DFIG Mode of Operation

In Figure 1, the DFIG stator is connected to the power contactor Q1, and in between the MSC and the Line Site Converter (LSC) are the DC chopper, crowbar, and the DC link. The DC chopper and crowbar resistance arrangement help the system mitigate fault-related disturbances such as voltage dip or voltage sag. In addition, in the DFIG system, the rotor windings are connected to the MSC via the slip rings to overcome the problems of unwanted fluctuations in the entire control system and for the system to operate at various speeds in response to the changing wind speeds. The line inductors (choke) connect the LSC to the grid to minimize the effects of the converter-generated harmonics. Aside from this, the back-to-back converter (AC/DC/AC), Insulated Gate Bipolar Transistor (IGBT) – based Pulse Width Modulation (PWM) converter reduces harmonics in the DFIG wind turbine system using the sinusoidal PWM method.

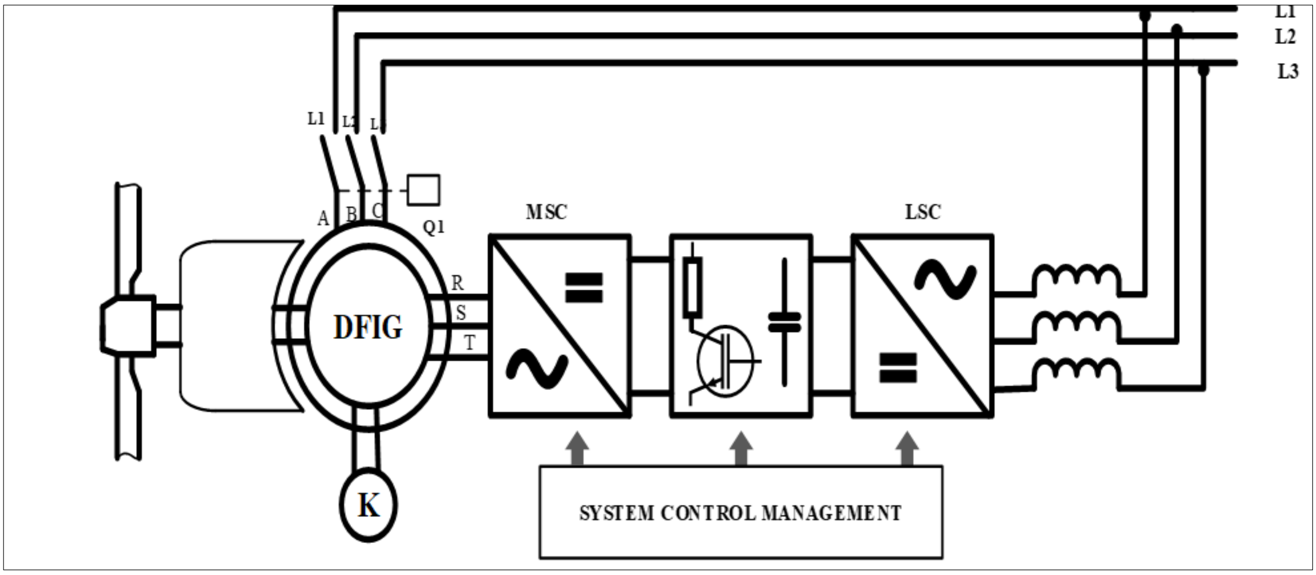

Figure 1 Block Diagram of Reactive Power Control Management for DFIG Wind Turbine

The DFIG achieves dual-feed by connecting the stator to the rotor. The controller uses the dual-feed to optimize the inductance of the rotor making it easier for the inverter to rectify AC in both directions and convert DC into AC at the specified frequency. Since the DFIG wind turbine excitation occurs through the converters, the generator's control system delivers capacitive and inductive reactive power relative to the system's operational requirement to achieve power grid stability. In this reactive power control management, the MSC autonomously controls and regulates the generated active power and the reactive power of the DFIG wind turbine while LSC simultaneously maintains the DC link voltage and keeps it constant. The contactor Q1 is an automatic switching device that enhances the DFIG operation to provide a significant amount of electric power through the stator to the grid [12].

The reactive power control management DFIG wind turbine maintains the generator's voltage at a constant frequency and amplitude by regulating the rotor current with the help of the MSC and also facilitates the exchange of the required reactive and active power output of the stator [13]. Hence, it permits varying the rotor's speed to 30% of the rated speed resulting in an increase in power levels under changing wind conditions [11]. The grid-side inverter of the DFIG controller can operate as a Static Synchronous Compensator (STATCOM) to facilitate the exchange of inductive or capacitive reactive power with the grid. At the same time, the phase shift between the current and voltage is possible through the smart control of the inverter [11].

2.3. Over-excited Operation

The DFIG's operation depends on its excitation. The process of reactive power being drawn from the electrical power grid or fed into it makes the generator operate mechanically in an idle state, and an increase in the generator's excitation beyond the rated excitation through the MSC, this results in the generator supplying the grid with reactive power. Then, the generator behaves like a capacitor. Figure 2, over-excited operation, shows that an increase in the rotor current results in the generator supplying reactive power to the grid.

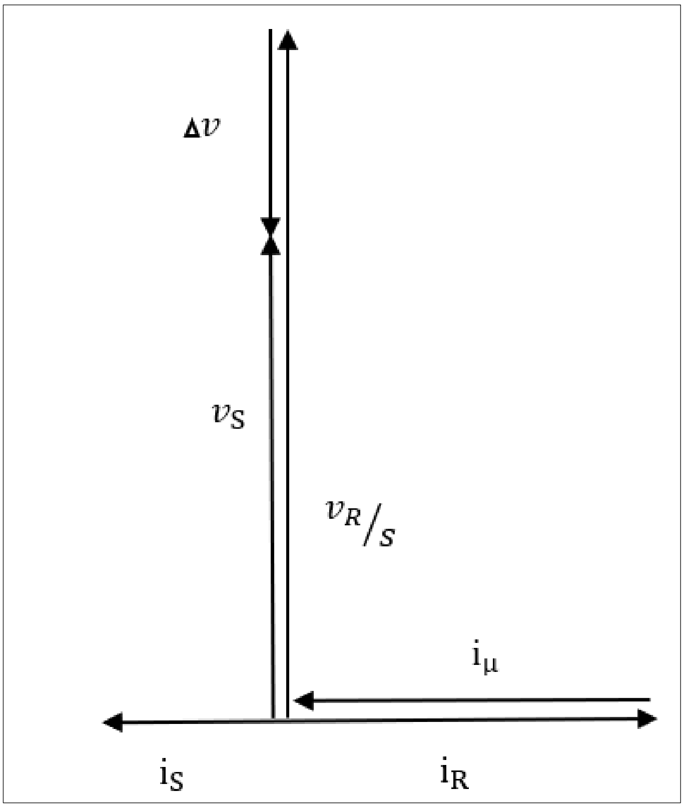

Figure 2 Over-excited operation mode vector diagram [11]

2.4. Under-excited Operation

The reduction of the DFIG excitation below the rated value makes the generator draw part of its required reactive power from the grid, thereby acting as a choke. Figure 3 shows that the rotor current drop makes the generator absorb reactive power from the grid.

The DFIG wind turbine can supply to the grid or receive from the grid inductive reactive current throughout its operating range. It is undesirable to operate the generator when it outputs reactive power since this reduces the active power output to prevent the generator from overloading. However, for the generator to meet the reactive power demand, it is pertinent to run it in the over-excited mode.

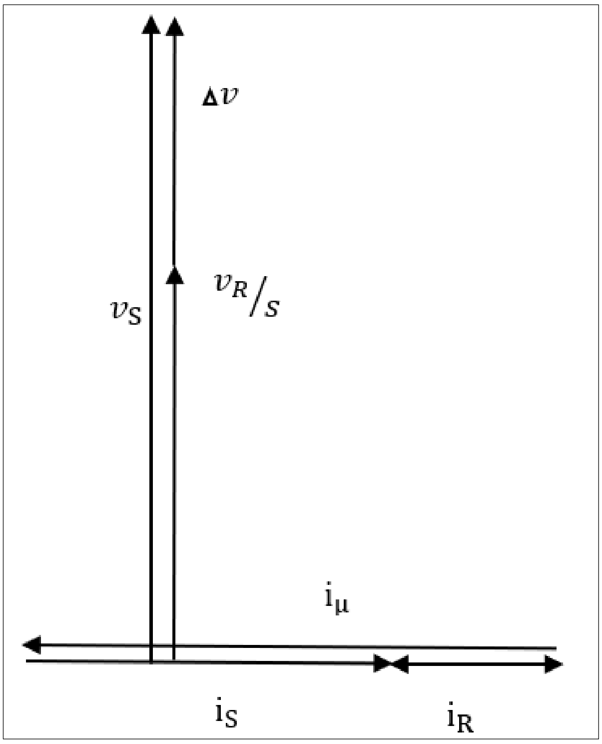

Figure 3 Under-excited operation mode vector diagram [11]

2.5. DFIG Model Equation Analysis

The DFIG operates by feeding its slip power into the electrical power grid and from the electrical power grid back into the rotor. These modes of operations are super-synchronous and sub-synchronous [11]. In sub-synchronous operation mode, the MSC behaves as an inverter while the LSC acts as a rectifier, and the flow of active power is from the grid to the rotor [6]. In the super-synchronous mode of operation, the MSC behaves as a rectifier. In contrast, the LSC acts as an inverter, and active power flows from the rotor to the electrical power grid [6]. The control of the rotor current injection in these two operational modes is effective with the help of the controlled converters [2]. The control method used to examine the behavior of the DFIG is derived from the direct and quadrature, d-q, stationary and synchronous reference frame [14, 15, 16] as presented in the equations (1- 4).

$$v_{ds} = \frac{d\varphi_{ds}}{dt} + r_s i_{ds} - \omega_s \varphi_{qs)} \ldots\ldots (1)$$

$$v_{qs} = \frac{d\varphi_{qs}}{dt} + r_s i_{qs} + \omega_s \varphi_{ds} \ldots\ldots (2)$$

$$v_{dr} = \frac{d\varphi_{dr}}{dt} + r_r i_{dr} - \varphi_{qr}(\omega_s - \omega_r) \ldots\ldots (3)$$

$$v_{qr} = \frac{d\varphi_{qr}}{dt} + r_r i_{qr} - \varphi_{dr}(\omega_s - \omega_r) \ldots\ldots (4)$$

$$\varphi_{ds} = (L_{Is} + L_m) i_{ds} + L_m i_{dr} \ldots\ldots (5)$$

$$\varphi_{qs} = (L_{Is} + L_m) i_{qs} + L_m i_{qr} \ldots\ldots (6)$$

$$\varphi_{dr} = (L_{Ir} + L_m) i_{dr} + L_m i_{ds} \ldots\ldots (7)$$

$$\varphi_{qr} = (L_{Ir} + L_m) i_{qr} + L_m i_{qs} \ldots\ldots (8)$$

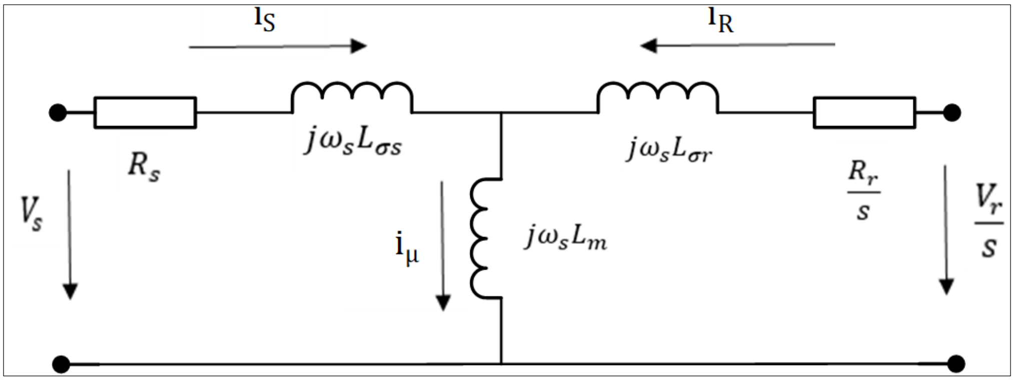

Figure 4 Generator simplified equivalent circuit diagram [17]

Applying Kirchhoff's voltage law to Fig. 4, the voltage equation [11, 17] is as follows:

$$V_S = R_s i_S + j\omega_s L_{\sigma s} i_s + j\omega_s L_m (i_s + i_R) \ldots\ldots\ldots (9)$$

$$\frac{V_r}{s} = \frac{R_r}{s} i_R + j\omega_s L_{\sigma r} i_R + j\omega_s L_m (i_s + i_R) \ldots\ldots\ldots (10)$$

$$\varphi_S = L_s i_S + L_m i_R \ldots\ldots\ldots (11)$$

$$\varphi_r = L_r i_R + L_m i_S \ldots\ldots\ldots (12)$$

In the above equations V_s is the stator voltage, i_S is the current flowing through the stator, R_s is the stator resistance, $L_{\sigma s}$ is the stator self-inductance, L_m is the mutual inductance, V_r is the voltage across the rotor, i_R is the current flowing through the rotor circuit, $L_{\sigma r}$ is the rotor self-inductance, s is the system slip, L_S is the total stator inductance, φ_s and φ_r are stator flux and rotor flux respectively.

Equations of the stator active and reactive power are derived as follows,

$$P_S = 3R_s|i_S|^2 + 3\omega_s L_m Im\{i_S i_R{}^*\} \ldots\ldots\ldots (13)$$

$$Q_S = 3\omega_s L_s|i_S|^2 + 3\omega_s L_m Re\{i_R i_S{}^*\} \ldots\ldots\ldots (14)$$

The equations of the rotor active and reactive power are derived as follows,

$$P_R = 3R_r|i_R|^2 - 3s\omega_s L_m Im\{i_S i_R{}^*\} \ldots\ldots\ldots (15)$$

$$Q_R = 3s\omega_s L_r|i_s|^2 + 3s\omega_s L_m Re\{i_S i_R{}^*\} \ldots\ldots\ldots (16)$$

Assuming the rotor and stator resistances $R_S = R_R = 0$

$$S_S = (P_S + jQ_S) = V_s i_S^* \ldots\ldots\ldots (17)$$

$$S_R = (P_R + jQ_R) = v_R i_R^* \ldots\ldots\ldots (18)$$

$$P_S = 3R_S|i_S|^2 + 3s\omega_s L_m Im\{i_S i_R{}^*\} \ldots\ldots\ldots (19)$$

$$P_R = 3R_r|i_R|^2 - 3s\omega_s L_m Im\{i_S i_R{}^*\} \ldots\ldots\ldots (20)$$

where.

$$i_s = i_m + i_{\sigma s} \text{ and } i_R = i_m + i_{\sigma r} \ldots\ldots\ldots (21)$$

Therefore,

$$P = P_S + P_R = P_S(1 - s) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (22)$$

Simplifying equation (22) gives,

$$P_R = -sP_S \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (23)$$

The equations (5-12) show that in the sub-synchronous mode, the rotor consumes power while it outputs power in the super-synchronous mode [2, 13]. In addition, controlling the rotor current injection using controlled converters enhances the effective operation of the DFIG in both the sub-synchronous and the super-synchronous modes [2]

3. Results and discussion

Figure 5 illustrates the experimental setup of the LNWPP for the proposed reactive power control management of the DFIG wind turbine using the WindSim software.

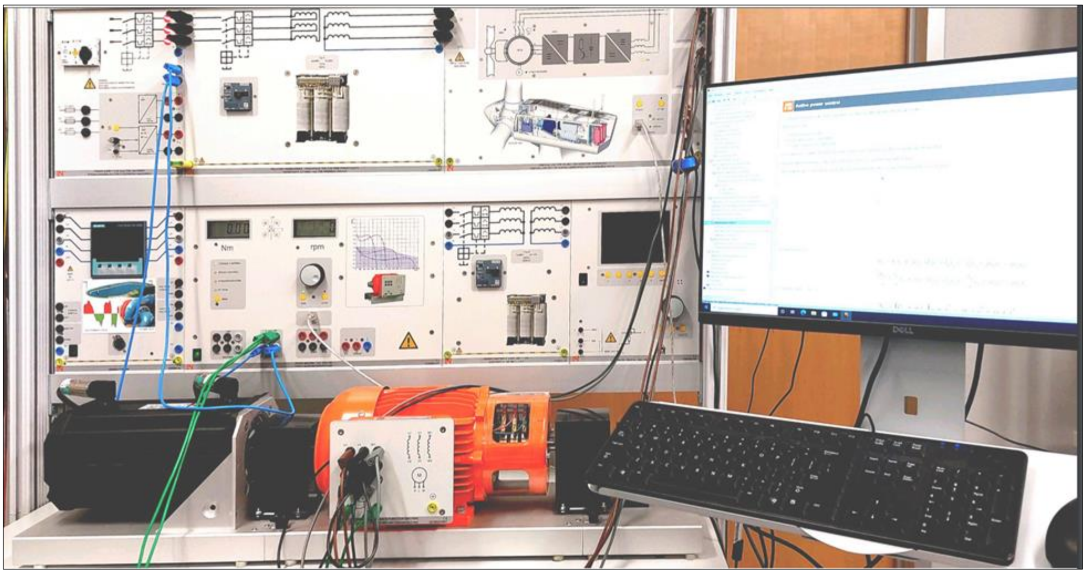

Figure 5 Experimental setup of LNWPP for DFIG reactive power control management [11]

Table 1 shows the LNWPP equipment for the reactive power control management for DFIG wind turbine experimental setup. The virtual instruments facilitate the system's operation by recording experimental measurements.

Table 1 Equipment of the LNWPP [11]

Equipment Serial Number	Equipment Name	Quantity
CO3208-3A	Controller for wind power plant DFIG	1
SE2662-6W	Three-phase, multi-function machine (DFIG)	1
CO3208-3B	Three-phase isolating transformer 1 KVA	1
SE2662-5T	Incremental position encoder with 1024 pulses 1 KW	1
CO3636-6W/CO2663-6U	Servo test stand for 1 KW machines	1
CO3212-5U	Power supply for electric machine	1
SE2662-6A	Coupling sleeve for 1 KW	2
SE2667-6B	Coupling guard for 1 KW	2
CO5127-1Z	Analog/digital multimeter, power, and power-factor meter	1

In Figure 5, the three-phase multi-phase machine (DFIG) is connected to the grid to investigate the reactive power control based on the rotor current's response to variation in reactive power and operation in over and under-excited modes. The speed is varied between 1400 rpm and 1900 rpm, while the MSC's reactive power is varied to measure and record the corresponding rotor currents, as in Table 2. The performance analysis of the reactive power control management using the LNWPP system is verified based on the DFIG operating conditions such as over-excited mode, under-excited mode, and the relationships between the generator's reactive power, rotor current, and torque. In addition, the smart control of the LSC enhances the phase shift between the current and the voltage, thereby making the reactive power control of the inverter more efficient. The controller of the LNWPP enhances the control and operation of the variable speed DFIG under laboratory conditions. The control unit allows the LNWPP to emulate and study all conditions of practical significance. It also incorporates the WindSim software that makes its operation easy and convenient to visualize all measured values and results.

Table 2 Reactive Power Control of DFIG Wind Turbine in the Over-excited Mode

DFIG Reactive Power Q, [VAR]	I Rot [A] @ n= 1400 rpm	I Rot [A] @ n= 1900 rpm
-300	0.2	0.2
-200	0.6	0.5
-100	1.1	1.1
0	1.7	1.8
100	2.4	2.4

Table 2 shows the variations in DFIG reactive power and the corresponding rotor currents responses

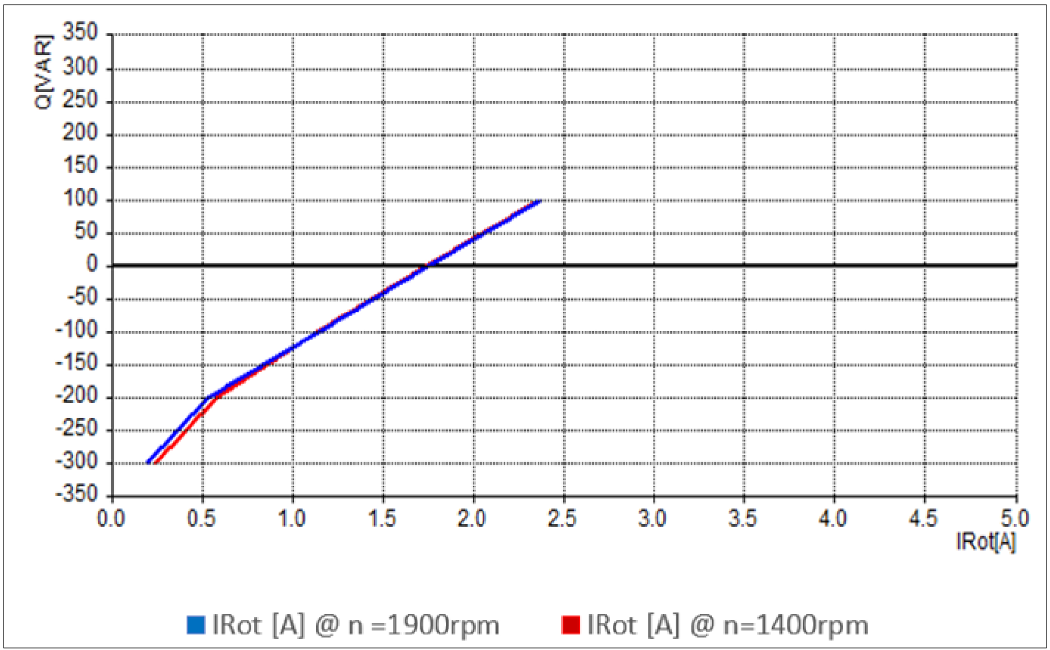

Figure 6 Simulation result of reactive power control management of DFIG Wind Turbine in Over-excited Mode and Under-excited Mode

The results of Figure 6 describe the reactive power control of the DFIG wind turbine in the over-excited mode operation, where the increase in rotor current causes the generator to supply reactive power to the grid and changes in mechanical power have no effects on the reactive power of the DFIG wind turbine in the under-excited Mode. In addition, the DFIG can supply and receive inductive reactive current over its entire operating range.

Table 3 Reactive Power Control of DFIG Wind Turbine Electrical Power and Mechanical Power

DFIG Reactive Power, Q [VAR]	Torque, M [Nm]	DFIG Active Power, P [W]	Torque, M [Nm]
-300	-0.5	-4	-0.5
-200	-0.5	-3	-0.5
-100	-0.5	0	-0.5
0	-0.5	2	-0.5
100	-0.5	3	-0.5
200	0.5	5	-0.5
300	-0.6	8	-0.6

Table 3 shows the variations in DFIG electrical power and the corresponding mechanical power (torque) by varying the MCS reactive and active power

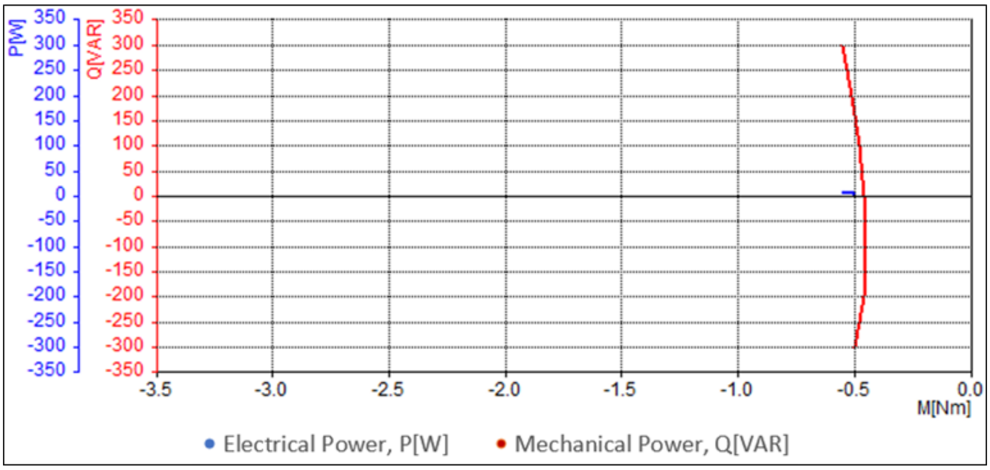

Figure 7 Simulation result of reactive power control management of DFIG Wind Turbine Electrical Power and Mechanical Power (torque)

The result of Figure 7 shows that in the under-excited mode operation, the rotor current diminishes to make the generator draw reactive power from the grid. In contrast, changes in active power at constant speeds result in a relative change in the torque. Therefore, operating the generator while it outputs reactive power is disadvantageous because that reduces the generator speed. In the exchange of power between LSC and the grid, the voltage and current are in phase during purely active power consumption, and the orientation of the current vector is in the positive and negative direction with respect to the q-axis.

4. Conclusion

The performance analysis of reactive power control management of the DFIG wind turbine using the LNWPP WindSim software has been presented. The results of the experiments performed based on the generator's operating modes are observed on the LN scope. Based on the results, it can be deduced that the control management has better control of the reactive power exchange of the DFIG wind turbine because it incorporates a better controller for improved voltage quality compared to other existing techniques. The mechanical fluctuations are reduced by connecting the rotor windings to slip-rings, and system fault-related disturbances are minimized using DC Chopper and crowbar resistance. In addition, the MSC controls active and reactive powers, and the presence of a power contactor enhances smooth switching capability between the stator and the grid. Moreover, the LSC controls the DC link voltage and the reactive power with the grid, and the line inductors reduce the converters' generated harmonics. The entire enhanced operation of the control unit contributes significantly to the performance analysis of the reactive power control management of the DFIG wind turbine.

Compliance with ethical standards

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Disclosure of conflict of interest

The authors declare that no conflict of interest exists between them.

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