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Research Article

Control of DFIG-based wind power generation system under unbalanced grid voltage conditions

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Abstract:

Double Fed Induction Generator (DFIG)-based wind turbines have become increasingly popular in recent years due to their capacity to operate at varying speeds. Weaknesses in the DFIG system can arise from issues with the power grid due to the stator's direct connection and the excitation converter's power rating limitation. Under situations of unbalanced grid voltage, this study aims to explore the efficacy of the Direct Power Control (DPC) approach in managing wind turbine systems based on DFIG. Throughout the experimental investigation, we evaluated the system in standard and unbalanced grid voltage settings. MATLAB/SIMULINK simulations implement DPC, specifically tailored for a 9 MW DFIG-based wind farm. The results of these simulations show that the changed control method effectively reduces torque oscillations by making it possible to create active and reactive power references for the rotor-side converter. This eliminates the requirement for sequence component excitation, which was previously necessary. Furthermore, the research highlights the intrinsic link between control techniques and grid circumstances, showing this connectivity's crucial role in improving wind energy systems' stability and operational efficiency based on DFIG.

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1. Introduction

It has become increasingly common for large-scale wind power generation to be accomplished by wind turbines that make use of Doubly Fed Induction Generators (DFIGs). DFIG-based wind turbines have gained popularity due to their numerous advantages in wind power generation. These turbines feature a wound rotor induction generator with a power converter connected between the generator and the grid. The converter allows variable speed operation and controls active and reactive power. DFIG-based turbines offer improved efficiency, enhanced grid integration capabilities, and better performance in low and high wind speeds compared to fixed-speed wind turbines. Additionally, they enable smoother power output and reduce mechanical stress on the turbine components, contributing to their growing adoption in the wind energy industry. Wind energy is increasingly integrating into power networks worldwide (Liu *et al.*, 2011). The DFIG's direct connection between the stator and the grid makes it more sensitive to imbalanced grid voltage compared to generators with full-sized grid-connected converters like the permanent magnet synchronous generator. There is the potential for the stator and rotor currents inside the DFIG to become significantly imbalanced, even when there are only slight variations in the grid voltage balance. An imbalance in currents causes the generator's power output and electromagnetic torque to produce double-supply frequency oscillations (Abed *et al.*, 2013; Miao, 2013). The compromised power output quality and reduced operational lifespan of the mechanical components result from this. In addition, the uneven heating that happens in the stator and rotor windings because of these imbalanced currents puts the insulation of the windings at risk, which makes the problems that could arise from deterioration even worse (Flannery & Venkataramanan, 2009; Hu & He, 2009).

DFIGs without complete, unbalanced voltage management systems risk disconnection from the grid if network voltage imbalances exceed 6%. In accordance with the revised grid standards, DFIG needs to maintain uninterrupted operation, regardless of the steady-state voltage imbalances that are now in place (Kearney *et al.*, 2009; Zhou *et al.*, 2013). Recent academic research has thus focused on the development of enhanced operation and control approaches that have been devised, mainly to handle the issues that are faced by DFIG systems that are operating in situations that are characterised by unbalanced grid voltage circumstances (Phan & Lee, 2011; Zhou *et al.*, 2008).

Voltage imbalances in the stator primarily cause current imbalances in the stator and rotor, changes in electromagnetic torque, and power pulsations within the DFIG. It is of utmost importance to address the negative-sequence voltage component that is located at the generator's stator terminal. It is possible to lessen the harmful effects that network imbalance has on the DFIG system by taking out this part and making sure that only balanced positive-sequence voltage is left over when the network is off balance (Tavner & Penman, 1987; Chaudhary *et al.*, 2012). The Rotor-Side Converter (RSC) and the Grid-Side Converter (GSC) are two crucial components of DFIG-based wind turbines, and various approaches are used to regulate their function by regulating their operation. These converters play a vital role in managing the flow of electricity between the wind turbine and the grid. Vector Control (VC) and Direct Torque Control (DTC) or Direct Power Control (DPC) are the two basic ways to control these converters.

VC enables the wind turbine to regulate its speed and torque by changing the voltage and current vectors, ensuring effective power production. Alternatively, DTC direct power control

DPC systems can directly regulate the turbine's torque or power output without requiring complex transformations (Zhou *et al.*, 2009a; Brekken & Mohan, 2007; Phan & Lee, 2011). This allows for precise control over the turbine's operation. These control approaches are essential for optimising the efficiency, stability, and overall performance of wind turbines that are based on DFIG. This enables the wind turbines to efficiently adapt to changing wind conditions and grid requirements (Zhou *et al.*, 2009b; Morren *et al.*, 2005; Pena *et al.*, 2007; Flannery & Venkataramanan, 2008; Nian *et al.*, 2011; González *et al.*, 2022; Shehata, 2023).

DFIG systems play a pivotal role in wind energy generation, offering advantages such as variable-speed operation and improved power quality. DFIG ensures a consistent voltage output, irrespective of wind turbine speed, and supplies electricity to the grid using both its rotor and stator (Salam *et al.*, 2020). However, they are susceptible to vulnerabilities stemming from grid-related issues and excitation converter limitations. Grid disturbances like voltage sags, swells, and asymmetrical faults can induce torque oscillations in DFIG systems, jeopardising the mechanical integrity of wind turbines. These oscillations affect turbine performance and pose risks to reliability and longevity. Furthermore, the excitation converter's finite response time and bandwidth exacerbate the system's vulnerability by impeding rapid adjustments to sudden grid fluctuations. Thus, addressing these vulnerabilities becomes paramount for ensuring the effective and sustainable operation of DFIG-based wind turbine systems.

The study aims to tackle these vulnerabilities by assessing the efficacy of DPC in managing DFIG systems under unbalanced grid voltage conditions. DPC offers a promising solution by regulating electrical power flow through control strategies implemented for both the RSC and GSC. The study aims to stabilise torque output and facilitate seamless power exchange with the grid by generating appropriate references for active and reactive power within the DPC framework. This objective aligns with the pressing need to develop robust control techniques capable of mitigating mechanical issues like torque oscillations while ensuring the reliable and efficient performance of DFIG systems, especially under challenging grid conditions. Moreover, the study conducts a theoretical analysis to delve deeper into the effects of grid voltage unbalance on various parameters within the DFIG system. By examining how grid voltage unbalance influences parameters such as flux, torque, and power disturbances, the analysis offers valuable insights into devising effective control strategies to alleviate these effects. This theoretical groundwork is crucial for understanding the intricate dynamics of DFIG systems under varying grid conditions and lays the foundation for designing optimised control techniques that can enhance system resilience and performance.

In essence, the significance of DFIG systems in wind energy generation cannot be overstated, but addressing their vulnerabilities stemming from grid-related issues and excitation converter limitations is essential for ensuring their optimal performance and reliability. The study's objective to evaluate DPC's efficacy underscores the importance of advancing control strategies to mitigate mechanical issues and enhance the integration of DFIG systems into the power grid, ultimately contributing to the advancement of sustainable wind energy solutions.

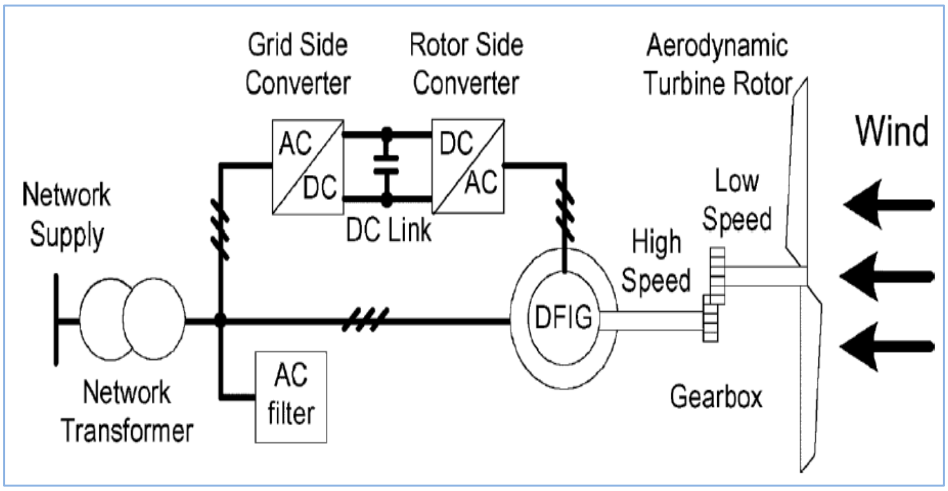
2. DFIG-based wind farm

The integration of electricity generated by wind turbines based on DFIG into the grid has highlighted the urgent need to address control and operational issues faced by DFIG systems in the presence of unbalanced grid voltage situations, particularly in recent years. Over the past decade, this issue has garnered significant attention, underscoring the importance of implementing efficient control strategies for DFIG operation under various grid conditions.

The discussion also includes the presentation of two important diagrams, namely Figure 1 and Figure 2, intended to elucidate the construction and behaviour of DFIG systems. Figure 1 illustrates the basic components of a DFIG, depicting the connection of the stator to the grid via a star-delta transformer and the connection of the rotor to a four-quadrant pulse width modulation converter. This graphical representation aids in understanding the interplay between the DFIG and its control mechanisms within the grid.

Figure 2 illustrates the equivalent circuit of a DFIG in the rotor reference frame, which is essential for comprehending the generator's electrical behaviour. This circuit depiction facilitates theoretical analysis and modelling of the DFIG's performance, particularly concerning fluctuations in rotor flux. Overall, the discussion underscores the importance of addressing control and operational issues in DFIG systems operating under unbalanced grid voltage conditions. Additionally, it provides visual aids to enhance understanding of the system's setup and behaviour.

Figure 1: Schematic of a DFIG-based wind generation system



The presented Equation (1) explains how the applied rotor voltage directly influences the change in rotor flux. The rotor flux direction aligns with the applied voltage vector, and its velocity is directly proportional to the voltage magnitude. In a three-phase, two-level converter system, the use of six power devices generates eight distinct voltage vectors inherent to the system's features. By finding the position of the stator flux during each sample period, it is possible to figure out how each voltage vector affects the changes in the rotor flux components. This allows for an evaluation of the impact that each voltage vector has. As a result, it is now possible to measure each voltage vector's impact on the variations in responsive and reactive power. Constructing an ideal switching table can determine the most effective rotor voltage vector, ultimately reducing power disparities.

$$\frac{d\psi_r^r}{dt} = V_r^r - R_r I_r^r \approx V_r^r \tag{1}$$

This article primarily focuses on the direct relationship between variations in rotor flux and the voltage supplied to the rotor in a three-phase, two-level converter system. This highlights how important it is to have a solid grasp of the influence that different voltage vectors have on rotor flux variations and the impact of these influence vectors on active and reactive power fluctuations. Furthermore, it emphasises the importance of developing an adequate switching strategy to reduce the risk of power errors (Hu & He, 2009).

Figure 2: Equivalent circuit of a DFIG in the rotor reference frame

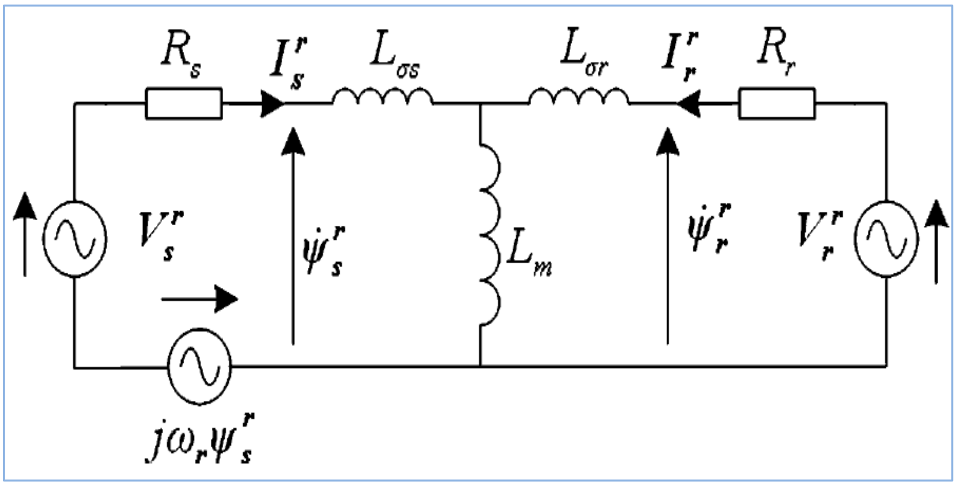
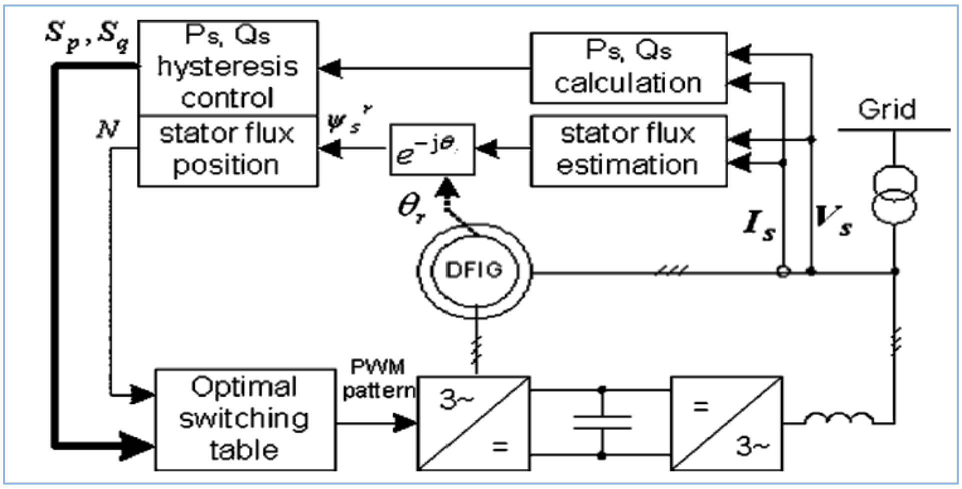


Figure 3 diagrammatically shows the DPC approach configuration. Researchers meticulously find and apply the optimal rotor voltage vector during each sample period to achieve hysteresis control of active and reactive power. This is achieved by meticulously selecting and applying the vector. These actions achieve the desired outcomes within the sample timeframe. A sufficiently high sample frequency, often in the region of tens of kilohertz, ensures successful management of these power characteristics.

Figure 3: Schematic of the original DPC control strategy



The converter's working conditions, such as active and reactive powers, hysteresis bandwidth, and rotor slip, significantly influence its switching frequency. This is one of the factors that results in significant variation. As a result, estimating the rotor-side converter's power loss and loading conditions and constructing a sufficient cooling system are both highly challenging jobs. Both tasks are incredibly complex. The design of the AC filter is complicated because it must reduce the proportion of broadband-frequency components to prevent them from entering the grid. This makes the design of the AC filter exceptionally challenging. Highlighting the challenges associated with the DPC method involves managing active and reactive power within each sample period and implementing the strategy. It highlights the need for a high sample frequency for effective control and draws attention to operating variables' influence on the converter's switching frequency. It examines the complexities involved in estimating power loss, creating cooling systems, and designing the AC filter to prevent broadband-frequency components from entering the grid. Topics covered also include constructing cooling systems.

2.1. Under normal condition

When positioned in the d-q reference frame, the DFIG rotates at a synchronous speed of ω_s. These equations characterise the voltage and flux vectors of DFIG based on their characteristics. These equations encompass both the stator and the rotor.

$$V_s^+ = R_s I_s^+ + \frac{d\Psi_s^+}{dx} + j\omega_s \psi_s^+ \tag{2}$$

$$V_r^+ = R_r I_r^+ + \frac{d\Psi_r^+}{dx} + j\omega_{slip} \psi_r^+ \tag{3}$$

$$\psi_s^+ = L_s I_s^+ + l_m I_r^+ \tag{4}$$

$$\psi_r^+ = L_m I_s^+ + l_r I_r^+ \tag{5}$$

Where $\omega_{slip} = \omega_s - \omega_r$

The instantaneous active and reactive power can be calculated using Equation (6).

$$P_s + jQ_s = \frac{3}{2} V_s^+ \times \hat{I}_s^+ = \frac{3}{2} V_s^+ \times \frac{L_m}{L_s L_r - L^2{}_m} \left(\frac{L_r}{L_m} \hat{\psi}_s^+ - \hat{\psi}_r^+ \right) \tag{6}$$

Certain conditions must be met for the stator flux of a DFIG to be considered constant within a particular reference frame, known as the positive synchronous reference frame. In this frame, it is assumed that the rate of change of the stator flux is zero, indicating that the flux remains unchanged over extended periods, typically spanning several seconds.

Moreover, it is recommended that the d-axis of this reference frame align with the stator's voltage vector. This alignment signifies the direction in which the stator voltage vector acts, facilitating analysis and enhancing understanding of the system's dynamics. Simultaneously, the voltage decreases as it traverses the stator resistance. This simplification, aimed at focusing on the system's fundamental impacts and dynamics, is commonly employed in theoretical assessments, mainly when the stator resistance is relatively low compared to other parameters.

$$V_s^+ = j\omega_s \psi_s^+ = -\omega_s \psi_{sq}^+ = V_{sd}^+ = V_s \tag{7}$$

The amplitude of the voltage in the stator is represented by the symbol V_s. Equations (8) and (9) can be used to construct the stator's active and reactive power formulas, respectively.

$$P_s = -k_\sigma V_s \psi_{rd}^+ \tag{8}$$

$$Q_s = k_\sigma V_s \left(\psi_{rd}^+ + \frac{L_r}{L_m}\frac{V_S}{\omega_S}\right) \tag{9}$$

Where $k_\sigma = 1.5L_m/(L_sL_r - L^2{}_m) = 1.5/(L_{\sigma s}+L_{\sigma r})$.

In accordance with the provided equations, over a consistent sampling period denoted as T_s. Equations (10) and (11) can be used to describe the fluctuations in rotor flux.

$$\frac{d\psi_{rd}^+}{dt} = \frac{1}{k_\sigma V_S}\frac{dP_S}{dt} = -\frac{1}{k_\sigma V_S}\frac{P^*{}_s - P_S}{T_S} \tag{10}$$

$$\frac{d\psi_{rq}^+}{dt} = \frac{1}{k_\sigma V_S}\frac{dQ_S}{dt} = -\frac{1}{k_\sigma V_S}\frac{Q^*{}_s - Q_S}{T_S} \tag{11}$$

Where $P^*{}_S$, and $Q^*{}_S$ describe the references for the stator active power and the stator reactive power, respectively. Within the context of the stator-voltage-vector-oriented reference frame, Equations (12) and (13) provide the necessary rotor control voltages for the d-axis and the q-axis, respectively.

$$V_{rd}^+ = -k_p(P^*{}_s - P_s) - \omega_{slip}\left(\frac{Q_s}{k_\sigma V_s} - \frac{L_r}{L_m}\frac{V_s}{\omega_s}\right) + R_r i_{rd}^+ \tag{12}$$

$$V_{rq}^+ = -k_p\left(Q^*{}_s - Q_s\right) - \omega_{slip}\left(\frac{Q_s}{k_\sigma V_s}\right) + R_r i_{rq}^+ \tag{13}$$

Developing a proportional controller helps reduce the impact of power faults, with the value k_p representing the gain of the controller. Several key operational characteristics define its performance and behaviour in a DFIG-based wind farm operating under normal conditions with a standard grid voltage scenario, as follows.

- Variable-speed operation: DFIG systems are known for their ability to operate at variable speeds, allowing them to capture wind energy efficiently across a range of wind speeds. In normal conditions, the wind turbine rotor rotates at a speed determined by the wind speed and the desired power output. In contrast, the RSC's power electronics control the generator rotor speed independently. This decoupling of the generator rotor speed from the wind turbine rotor speed enables optimal energy conversion and enhances the system's overall efficiency.
- Power control: The DFIG system regulates the power output to match the grid requirements. The GSC's power electronics adjust the active and reactive power exchanged with the grid based on grid conditions and control commands from the wind farm's central control system. This allows the wind farm to contribute to the grid's power supply while maintaining stability and reliability.
- Pitch control: Modern wind turbines often incorporate pitch control mechanisms to optimise power production and protect the turbine from excessive wind loads. Under normal conditions, the pitch angle of the turbine blades may be adjusted dynamically to maximise energy capture while ensuring the turbine operates within safe mechanical limits.

- Grid synchronisation: DFIG systems rely on grid synchronisation to ensure seamless integration with the electrical grid. The system's control algorithms continuously monitor grid frequency and voltage, adjusting the rotor speed and converter control signals to maintain synchronisation with the grid. This synchronisation enables the wind farm to operate in parallel with the grid and deliver power reliably.
- Fault monitoring and protection: DFIG systems are equipped with various monitoring and protection mechanisms to detect and respond to faults or abnormalities. Under normal conditions, these systems continuously monitor parameters such as voltage, current, and temperature to detect any deviations from expected values. In the absence of faults, the system operates smoothly, with built-in protection mechanisms ensuring safe and reliable operation.

Overall, under normal operating conditions, a DFIG-based wind farm demonstrates efficient energy conversion, grid integration, and reliable operation. Its components work in tandem to maximise power output while ensuring stability and safety, contributing to the effective utilisation of wind energy resources for sustainable power generation.

2.2. Unbalanced grid voltage condition

The purpose of this study is to investigate the amount of time that DFIGs take to react to momentary imbalances in the grid. When there is a difference in the generation and distribution of electricity, it can lead to oscillations in voltage, which can eventually lead to the grid's collapse in the electrical system. When issues arise, the DFIG stator voltage, a crucial element of wind turbines, can have two components: the positive sequence component, illustrating normal voltage behaviour, and the negative sequence component, showing how the fault alters its behaviour. Both components are critical to wind turbine operation. A solid understanding of how the DFIG reacts to issues of this nature is necessary to maintain the stability and dependability of grid-connected wind power systems.

$$V_s(t) = V_{s+} + V_{s-} = V_{s+}^{+} e^{jw_s t} + V_{s-}^{-} e^{-j\omega_s t} = \left(V_{sd+}^{+} + jV_{sq+}^{+}\right) e^{-j\omega_s t} + \left(V_{sd-}^{-} + jV_{sq-}^{-}\right) e^{-j\omega_s t} \quad (14)$$

In scenarios where the grid voltage is balanced, the stator flux vector, denoted as Ψ_s , rotates at the synchronous angular speed of ω_s. This rotation signifies that Ψ_s is purely comprised of a positive component. However, in the event of an abrupt imbalance in the stator voltage due to a sudden fault in the grid, additional negative and zero sequence components emerge within the stator flux. These supplementary components represent deviations from the standard behaviour of the stator flux and manifest because of the grid fault. Assuming the occurrence of the grid fault at time t = 0, the transient behaviour of the stator flux vector can be mathematically expressed. This transient analysis is pivotal for comprehending how the DFIG reacts to grid faults and for implementing appropriate control strategies to alleviate their impact.

$$\psi_s(t) = \psi_{sdc} + \psi_{s+} + \psi_{s-} = \frac{V_s(0-) - V_{s+}(0+) + V_{s-}(0+)}{j\omega_s} e^{-\frac{t}{T_s^T}} + \frac{V_{s+}(0+)}{j\omega_s} e^{j\omega_s t} + \frac{V_{s-}(0+)}{-j\omega_s} e^{-j\omega_s t} \quad (15)$$

In this context, $V_s(0-)$ represents the stator voltage prior to the occurrence of a fault, whereas $V_{s+}(0+)$ and $V_{s-}(0+)$ signifies the positive and negative components of the stator voltage immediately following the fault event. Additionally, Ψsdc denotes the stator flux's zero sequence (DC) component. This component is governed by the principle of constant flux linkage and experiences attenuation over time, with its decay regulated by the stator's transient time constant T_s^-. This time constant reflects the duration required for the stator flux to return to its original state subsequent to the fault-induced disturbance.

Unbalanced grid voltages can significantly affect the performance and stability of a DFIG-based wind farm. When the voltage levels across different phases of the grid are unequal, asymmetry is introduced into the system, leading to several detrimental impacts, as follows:

- Increased torque oscillations: Unbalanced grid voltages can induce variations in the electromagnetic torque produced by the DFIG generator. This phenomenon occurs due to asymmetrical stator currents caused by the imbalance in grid voltages. As a result, the generator experiences torque pulsations, leading to mechanical stress on the turbine shaft. These increased torque oscillations reduce energy conversion efficiency and pose risks to the structural integrity of the wind turbine components.
- Imbalanced power exchange: In an unbalanced grid voltage scenario, the power exchanged between the DFIG system, and the grid may become uneven across different phases. This imbalance can lead to issues such as overloading of certain components, inefficient energy transfer, and reduced system reliability. Asymmetrical power exchange can also affect the grid's stability, potentially causing voltage fluctuations and frequency deviations.
- Control instability: The control algorithms implemented in DFIG systems may struggle to maintain stability and synchronisation with the grid under unbalanced voltage conditions. The mismatch between the expected and actual grid voltages can lead to instability in the control loops governing the operation of the RSC and GSC. This instability can result in erratic system behaviour, including fluctuations in power output and potential grid disconnection events.
- Component overloading: Unbalanced grid voltages may cause certain components of the DFIG system, such as converters and transformers, to experience uneven loading. This uneven loading can lead to overheating and accelerated wear and tear on these components, reducing their lifespan and overall reliability. Component failures may occur in extreme cases, resulting in costly downtime and maintenance efforts.

Overall, unbalanced grid voltage conditions pose significant challenges to DFIG-based wind farms, including increased torque oscillations, imbalanced power exchange, control instability, and component overloading. Addressing these challenges requires advanced control strategies and grid management techniques to ensure wind energy systems' reliable and efficient operation in the presence of grid voltage asymmetry.

2.3. Torque of DFIG under transient unbalanced grid fault

The process by which consecutive flux components are induced in a DFIG by the interaction of the stator and rotor windings' magnetic fields. Fundamentally, because of their magnetic connection, fluctuations in the stator flux cause comparable changes in the flux of the rotor windings. These components of induced flux cause changes in the stator and rotor currents. As a result, as shown in Figure 4, which shows the link between the electromagnetic torque and the various components caused by the flux fluctuations, these current variations have an impact on the electromagnetic torque generated by the DFIG.

Furthermore, it highlights that the occurrence of unbalanced stator voltage and fault current intensifies fluctuations in stator power. Essentially, variations in the voltage supplied to the stator and disturbances in the current flowing through it contribute to fluctuations in the generated power, which can impact the system's overall performance.

$$P_s + jQ_s = \frac{3}{2}V_s\hat{I}_s = \frac{3}{2}\left(V_{s+}^{+}e^{j\omega_s t} + V_{s-}^{-}e^{-j\omega_s t}\right) \times \left(\hat{I}_{s+}^{+}e^{-j\omega_s t} + \hat{I}_{s-}^{-}e^{j\omega_s t} + \hat{I}_{sdc}\right) \quad (16)$$

Subsequently, the expressions for reactive power and stator active can be delineated as follows.

$$P_S = P_{sa} + P_{s2\omega_s} + P_{s\omega_s} \quad (17)$$

$$Q_S = Q_{sa} + Q_{s2\omega_s} + Q_{s\omega_s} \quad (18)$$

Where $P_{sa} + jQ_{sa} = \frac{3}{2}\left(V_{s+}^{+} \times \hat{I}_{s+}^{+} + V_{s-}^{-} \times \hat{I}_{s-}^{-}\right)$

$$P_{s2\omega_s} + jQ_{s2\omega_s} = \frac{3}{2}\left(V_{s+}^{+} \times \hat{I}_{s-}^{-}e^{j2\omega_s t} + V_{s-}^{-} \times \hat{I}_{s+}^{+}e^{-j2\omega_s t}\right) \quad (19)$$

$$P_{s\omega_s} + jQ_{s\omega_s} = \frac{3}{2}\left(V_{s+}^{+} \times \hat{I}_{sdc}e^{j\omega_s t} + V_{s-}^{-} \times \hat{I}_{sdc}e^{-j\omega_s t}\right) \quad (20)$$

The phenomenon of stator power fluctuations that arise during transitory periods of imbalanced grid supply. More precisely, it states that apart from the usual variations, these fluctuations also consist of oscillations occurring twice the grid frequency (100 Hz) and the fundamental grid frequency (50 Hz). The fluctuations occur due to differences in the voltage and current of the grid produced by transitory events like faults or disturbances. Moreover, the statement presents the notion of electromagnetic power, which refers to the total power produced by voltage sources of equal magnitude. The power in Equation (21) denotes the amount of energy sent by the generator's electromagnetic field. It is crucial for comprehending the system's overall performance and behaviour.

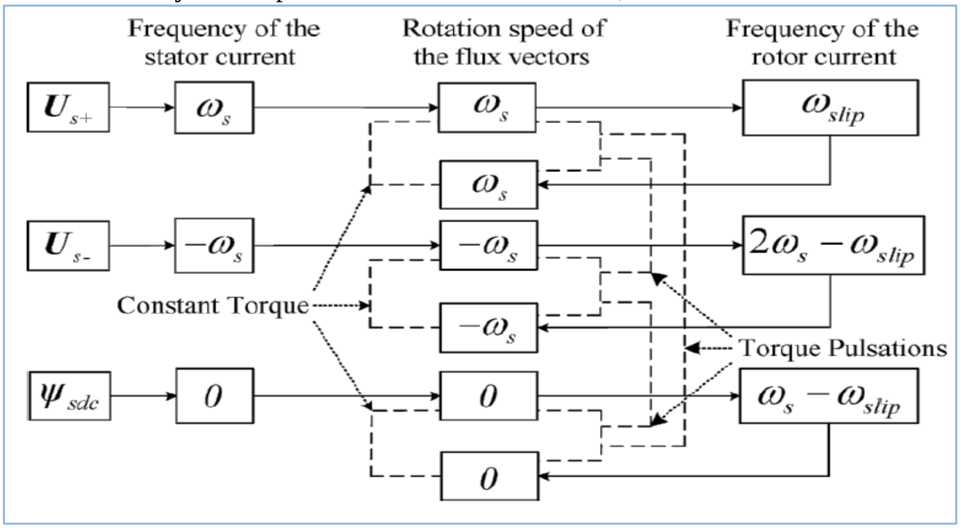
$$\mathrm{P}_e = \mathrm{P}_{es} + \mathrm{P}_{er} = \frac{3}{2}\mathrm{Re}\left[\mathrm{j}\omega_\mathrm{s}\psi_\mathrm{s} \times \hat{\mathrm{I}}_\mathrm{s} + \mathrm{j}\omega_\mathrm{slip}\psi_\mathrm{r}\hat{\mathrm{I}}_\mathrm{r}\right] = -\mathrm{k}_\sigma\omega_\mathrm{r}\frac{\mathrm{L_m}}{\mathrm{L_s}}\mathrm{Re}[\mathrm{j}\psi_\mathrm{s} \times \psi_\mathrm{r}] = \mathrm{P_{ea}} + \mathrm{P}_{\mathrm{e}2\omega_\mathrm{s}} \quad (21)$$

Hence, the calculation of the electromagnetic torque of the DFIG can be presented by Equation (22).

$$T_e = \frac{P_e}{\omega_r} = T_{ea} + T_{e2\omega_s} + T_{e\omega_s} \quad (22)$$

As depicted in Figure 4, the electromagnetic torque exhibits pulsations at both 100 Hz and 50 Hz frequencies. Conventional unbalanced control methods aimed to address these pulsations typically focused on either the average stator power P_{sa} andQ_{sa}, or the 100 Hz active or reactive power pulsations represented by r$P_{s2\omega_s}$ or $Q_{s2\omega_s}$ However, it was observed that $P_{s2\omega_s}$and $Q_{s2\omega_s}$ could not be simultaneously eliminated due to the limitation of only four controllable rotor current components. Furthermore, the control targets $P_{s\omega_s}$ and $Q_{s\omega_s}$ were not considered control targets since no extra control variables were to govern them. In light of this, the pulsations of the stator power, which occur at a frequency of 50 Hz, naturally decrease over time, as indicated by the stator time constant T_S^-. On the other hand, the attenuation rate of the 50 Hz pulsations is noticeably slow because of the comparatively large value of T_s^-, which is about a few seconds for a DFIG of the MW class.

Figure 4: A diverse array of components characterises the flux, rotor current and stator within the system



During transient unbalanced grid faults, the torque response of a DFIG system undergoes significant variations, which can impact the overall performance and stability of the DFIG-based wind farm. Let us explore these aspects in detail.

- Torque response: When a transient unbalanced grid fault occurs, asymmetrical voltages are introduced across the stator windings of the DFIG generator. As a result, the rotor currents become unbalanced, leading to uneven distribution of electromagnetic torque. The torque response of the DFIG system during these faults typically exhibits oscillatory behaviour, with torque pulsations occurring at twice the grid frequency. These torque oscillations are primarily influenced by the asymmetrical components of the stator currents and can result in mechanical stress on the turbine shaft.
- Impact on performance: Transient unbalanced grid faults can have detrimental effects on the performance of the DFIG-based wind farm. Firstly, the faults' torque oscillations may lead to fluctuations in the wind turbine's mechanical output, affecting its power generation capacity and efficiency. These torque fluctuations can also result in dynamic responses in the drive train and mechanical components, potentially causing fatigue damage and reducing the system's overall reliability.
- Stability concerns: Transient unbalanced grid faults can compromise the stability of the DFIG system and wind farms' stability. The faults' torque oscillations may destabilise the control loops governing the operation of the RSC and GSC, leading to instability in the power electronic control system. Additionally, the mechanical vibrations caused by torque oscillations can affect the structural integrity of the wind turbine and the tower, further exacerbating stability concerns.
- Grid integration challenges: Transient unbalanced grid faults pose challenges for integrating the DFIG-based wind farm with the electrical grid. The uneven distribution of torque and power during fault conditions may lead to unbalanced power exchange with the grid, potentially causing voltage and frequency deviations. This can impact the overall stability and reliability of the grid, as well as the quality of power supplied by the wind farm.

Transient unbalanced grid faults significantly influence the torque response of DFIG systems, with implications for the performance, stability, and grid integration of DFIG-based wind farms. Addressing these challenges requires advanced control strategies and grid management techniques to mitigate torque oscillations and ensure wind energy systems' reliable and efficient operation under transient fault conditions.

3. Simulation

We conduct the simulations in the MATLAB environment using the SIMULINK tool. These simulations aim to determine the success of the recommended strategy. Figure 5 presents both the simulation sets and the Simulink model that is associated with them. Table-1 provides information on the simulation settings that apply to the simulations. In a 9 MW wind farm, the simulated system consists of six 1.5 MW wind turbines connected to one another. Through the utilisation of a 25 kV distribution infrastructure, the system can accommodate this wind farm. Through a feeder that is thirty kilometres in length and has a voltage of twenty-five kilovolts, these turbines supply power to a grid that works at a voltage of one hundred twenty kilovolts. The wind turbines employ a DFIG arrangement in their operation. A wound rotor induction generator in this system connects to an AC/DC/AC IGBT-based Pulse Width Modulation (PWM) converter. The stator winding directly connects to a grid operating at 60 Hz. The rotor receives a variable frequency by converting alternating current to direct current and back to alternating current. By adjusting the turbine speed, the double-fed approach increases energy collection from low wind speeds while limiting mechanical stress during gusts. Exploring essential control parameters such as the DC voltage regulator, direct power control parameters, and pitch control response is necessary. We conducted these simulations under both normal and unbalanced grid voltage conditions. Additionally, the simulations evaluate the voltages, currents, and apparent power (both active and reactive) injected into the grid. This includes both active and reactive power.

Figure 5: Simulink model of the system

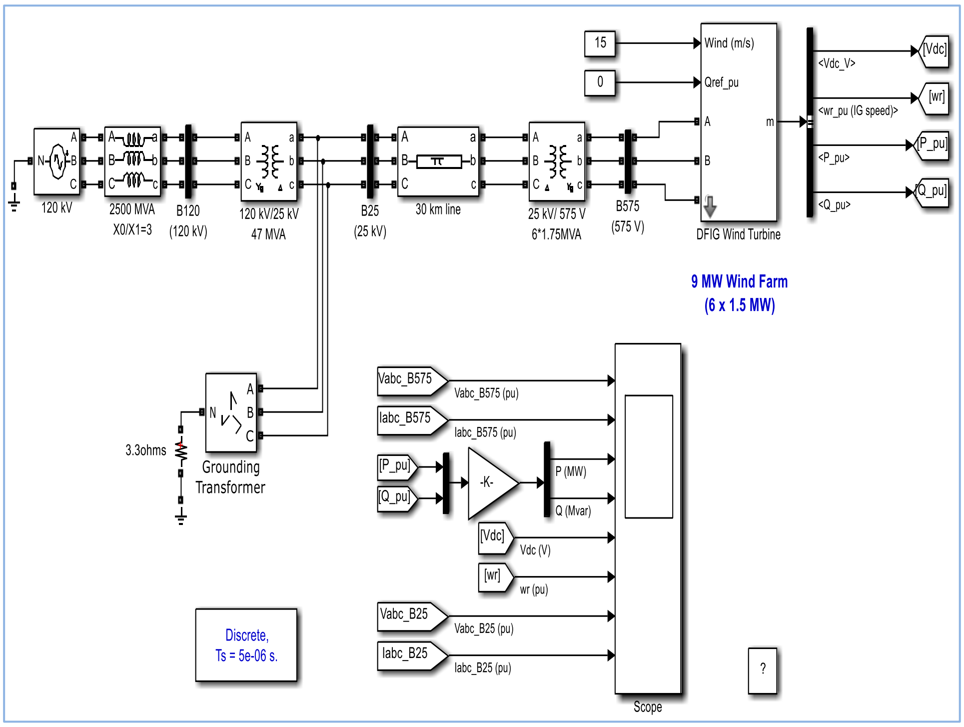


Table-1: System parameters

S. No	Parameter	Value
1	Rotor power	1.5 MW
2	Rotor stator voltage	575 V
3	Rated frequency	50 Hz
4	Stator resistance	0.23 pu
5	Rated DC link voltage	1150 V
6	Stator leakage inductance	0.18 pu
7	Rotor leakage inductance	0.16 pu
8	Magnetising inductance	2.9
9	No of pole pairs	3
10	Lumped inertia constant	0.685 s
11	DC link capacitance	10000 uf

3.1. Normal condition

Several key aspects need to be considered when simulating the DPC's performance under normal or standard grid voltage conditions to accurately evaluate its impact on the behaviour and performance of the DFIG-based wind farm.

3.1.1. Simulation setup

The steps of the simulation procedure are as follows:

- Modelling: The simulation begins with the creation of a detailed model representing the DFIG-based wind farm, including the wind turbine, DFIG generator, converters RSC and GSC, control systems, and the electrical grid.
- Grid conditions: The simulation assumes normal or standard grid voltage conditions, typically characterised by balanced and sinusoidal voltages with nominal values.
- Control implementation: Implement the DPC algorithm within the simulation environment. This involves programming the control logic to calculate the appropriate active and reactive power references based on the measured grid parameters and desired system operation.
- Performance metrics: Define performance metrics such as power quality indices (voltage deviation, harmonic distortion), system stability (torque oscillations, rotor speed fluctuations), and efficiency (active power output, reactive power exchange).

3.1.2. Implementation of DPC

The DPC is implemented using the procedure as follows:

- Reference generation: DPC generates references for active and reactive power directly based on error between these parameters measured and desired values. This eliminates the need for coordinate transformations typically used in traditional control methods.
- Voltage control: DPC adjusts the references for active and reactive power to regulate voltage within specified limits at grid connection point, ensuring stable grid integration.

- Dynamic response: Assess the dynamic response of the DPC system to changes in wind speed, load variations, and grid disturbances. Evaluate how quickly and accurately DPC adjusts the power output to maintain system stability and performance.
- Comparison with other control strategies: Compare the performance of DPC with other control strategies such as field-oriented control or vector control to determine its effectiveness in managing the DFIG system under normal grid conditions.

3.1.3. Impact on system behaviour and performance

The impact of DPC on the system's behaviour and performance is analysed by considering the key factors described below:

- Stability: Evaluate the stability of the DFIG-based wind farm under the influence of DPC. Assess the system's ability to maintain synchronisation with the grid and avoid instability issues such as voltage or frequency deviations.
- Power quality: Analyse the power quality indices to ensure that the DPC implementation maintains grid voltage within acceptable limits and minimises harmonic distortion.
- Efficiency: Measure the efficiency of the DFIG system in converting wind energy into electrical power under the control of DPC. Compare the active power output with the available wind energy to assess the system's performance.

Simulating DPC performance under normal grid voltage conditions involves setting up a comprehensive simulation environment, implementing the DPC algorithm, and analysing its impact on system behaviour and performance metrics such as stability, power quality, and efficiency. This evaluation provides insights into the effectiveness of DPC in managing DFIG-based wind farms and optimising their operation under standard grid conditions.

In this scenario, we put the system through its paces to evaluate its performance under typical operational conditions. Under these conditions, a Power Factor (PF) of 1 indicates that the injected power perfectly meets the capacity demand. Energy transmission is guaranteed to be effective under these conditions. In addition, the Point of Common Coupling (PCC), which acts as the interface between the wind farm and the electrical grid, is responsible for injecting reactive power at a rate of three megavolts per revolution. The simulation produces results that apply to the operation of two essential controllers, specifically the direct axis current controller and the DC link voltage controller. Generated results from the simulation. Controllers are critical system components because they regulate essential electrical characteristics such as current and voltage. This ensures that the system operates consistently and performs at its strongest levels. The Figures 6 and 7 present the controllers' responses in their respective orders.

Figure 8 presents additional statistics on the wind farm's mechanical properties and power generation. The information includes the mechanical torque generated by the rotor turbine, the rotor speed controlled by the rotor speed controller (expressed in revolutions per minute, rpm), and the amounts of active and reactive power present at the PCC. Additionally, the metrics provide vital information on the operational characteristics of the wind farm, notably its capacity to maintain consistent power output and its contribution to the grid's active and reactive power demands.

Figure 6: DC link voltage controller response

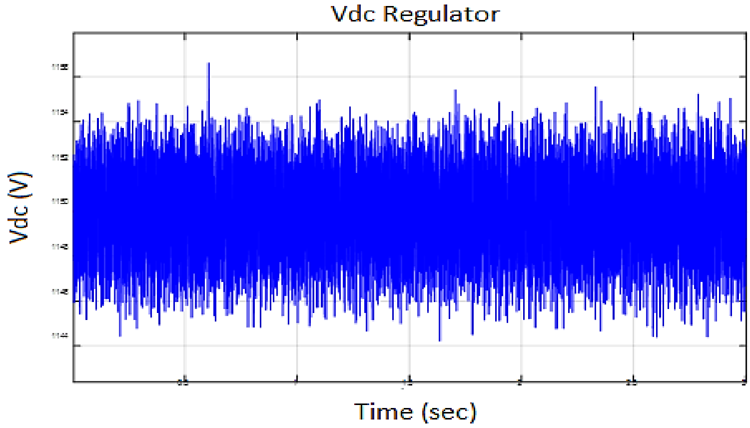


Figure 7: Direct axis current controller response

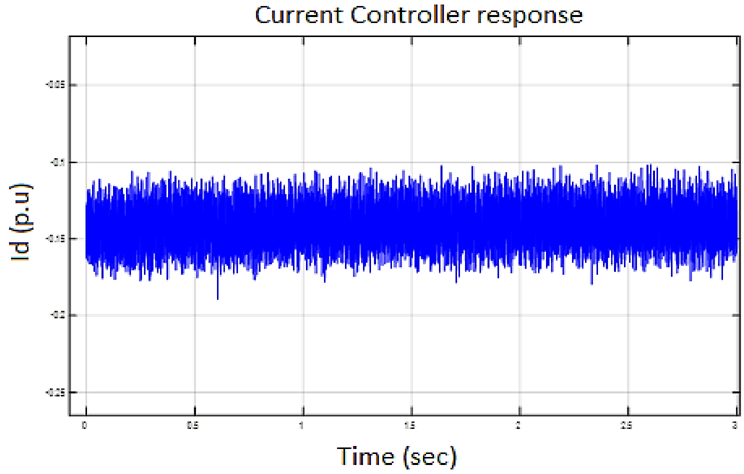
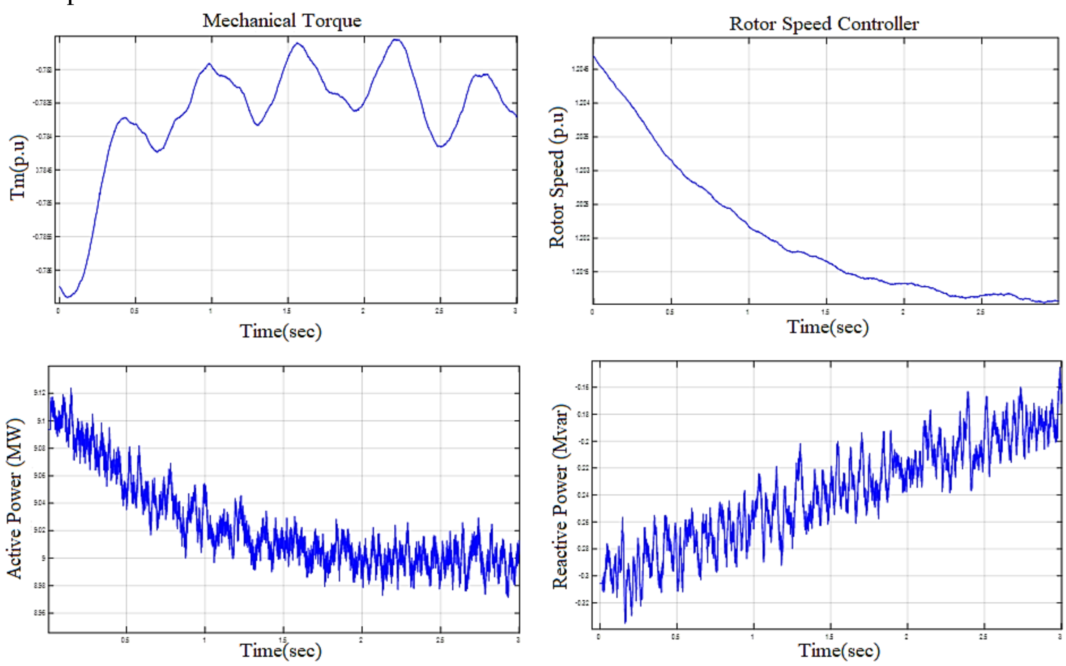


Figure 8: Mechanical torque of the rotor turbine, rotor speed controller (rpm), active and reactive power at the PCC



3.2. Unbalance grid voltage conditions

A comprehensive simulation setup is essential to evaluate the effectiveness of DPC under unbalanced grid voltage conditions. Here is a detailed outline of the simulation setups.

- Modelling the DFIG-based wind farm: Develop a detailed model of the DFIG-based wind farm using appropriate simulation software or tools like MATLAB/Simulink and PSCAD. Include models for the wind turbine, DFIG generator, RSC, GSC, and associated control systems. Ensure that the model accurately represents the dynamic behaviour of the DFIG system under normal and fault conditions.
- Modelling unbalanced grid voltage conditions: Introduce asymmetrical voltage disturbances into the grid model to simulate unbalanced grid voltage conditions. Vary the magnitudes and phase angles of grid voltages across different phases to represent realistic unbalanced scenarios. Consider different types of grid faults such as line-to-line faults, line-to-ground faults, and phase imbalances.
- Implementation of DPC: Implement the DPC algorithm within the DFIG model's control system. Develop the control logic to calculate the active and reactive power references based on the measured grid parameters and desired system operation. Ensure that the DPC algorithm can dynamically adjust to changes in grid voltage conditions and maintain stable operation of the DFIG system.
- Simulation scenarios: Define various simulation scenarios to evaluate DPC effectiveness under different unbalanced grid voltage conditions. Consider scenarios with varying degrees of grid unbalance, ranging from mild asymmetry to severe voltage disturbances. Include transient simulations to assess the dynamic response of the DFIG system to unbalanced grid faults.
- Parameter settings: Specify the parameters for the DFIG model, converters, and control systems. Tune the control parameters of the DPC algorithm to optimise its performance under unbalanced grid conditions. Document all parameter settings and provide a rationale for their selection based on literature review or experimental data.
- Performance metrics: Define performance metrics to evaluate the effectiveness of DPC under unbalanced grid voltage conditions. Include metrics such as power quality indices (voltage deviation, harmonic distortion), system stability (torque oscillations, rotor speed fluctuations), and efficiency (active power output, reactive power exchange).
- Simulation execution: Execute the simulation for each defined scenario, capturing the behaviour of the DFIG system under unbalanced grid voltage conditions. Record simulation results, including system variables, control signals, and performance metrics, for further analysis.

In this case, the system is tested under an unbalanced three-phase grid voltage, which is 10% of the nominal voltage. Figure 9 shows the simulation result of the DC link voltage controller response for a 9 MW wind farm under unbalanced three-phase grid voltage. At t = 0.75 seconds (time of unbalance) and diminished at 1 second (occurred for 250 ms), unbalance is 10% of the nominal value, which means that the grid voltage of the 120 kV source is reduced to 10% (12 kV). To simulate the unbalance, we observed that the DC link is affected and quickly returned to its new steady state. Also, the system responds quickly to its original steady state after clearing time. At t = 0.75 seconds (time of unbalance), we observed that the voltages decreased to 10% of the nominal value and continued in the new steady state. At t = 1 second (clearing time), the voltages gradually increase to the original steady state.

Figure 9: DC link voltage controller, DC regulator, Quadrature current regulator, and Three-phase current at PCC response

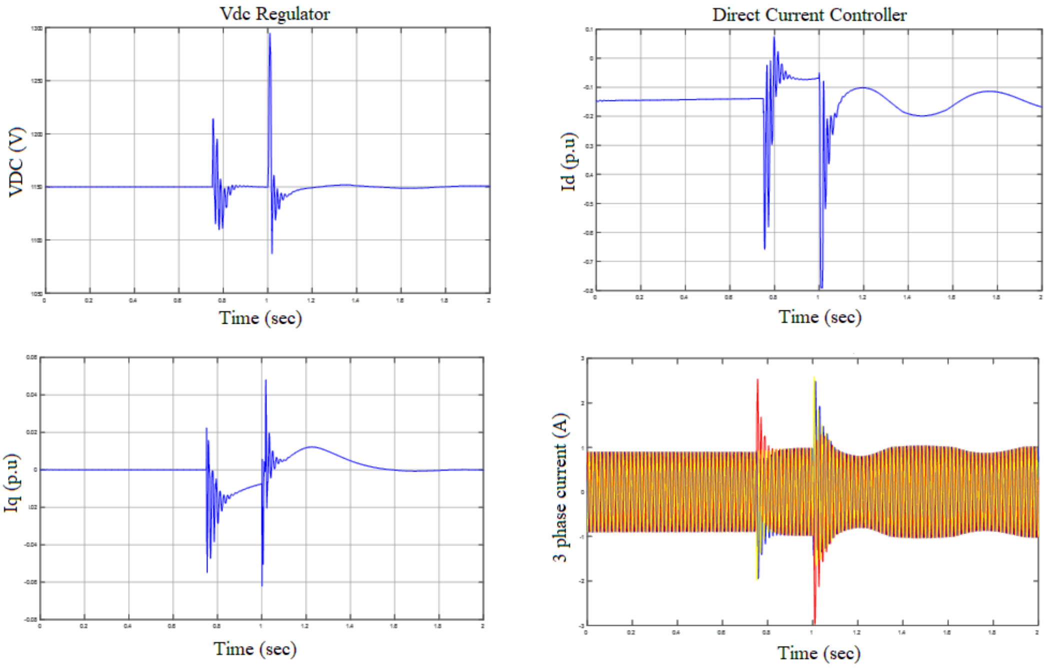
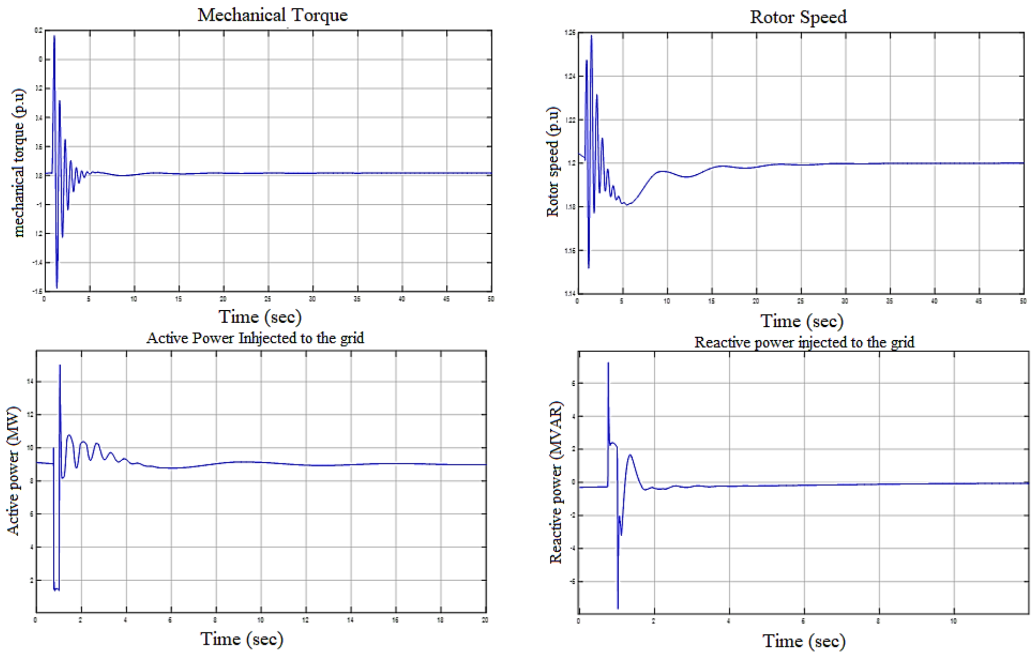


Figure 10 illustrates the behaviour of significant parameters, such as mechanical torque, active power, and reactive power, at the PCC, where the wind farm connects to the grid. An unbalanced three-phase grid voltage is a scenario in which the voltage levels across the various phases of the grid are not equal. We investigated these properties under unbalanced three-phase grid voltage conditions.

Figure 10: The parameters examined include the mechanical torque generated by the rotor turbine, rotor speed and as well as the active and reactive power at the PCC under unbalanced three-phase grid voltage conditions



Following the occurrence of oscillations in active power, reactive power, and mechanical torque at the beginning of the experiment, which takes place at t = 0.75 seconds, the graph reveals that these oscillations are present. By the time t equals one second, however, these changes have ceased, and the values of active power, reactive power, and torque have stabilised, bringing themselves closer to their respective reference values. This is because these variables' values have aligned themselves. This stabilisation occurs relatively quickly after a time interval of one second, suggesting that the system adapts to the unequal grid voltage in a relatively short time. After considering the data, the research concludes that the direct power management technique effectively regulates the effects of uneven grid voltage. After considering the data, we reach this conclusion. The technique demonstrates robust performance by quickly restoring stability and ensuring the parameters closely match their goal references. Even though one can achieve this accomplishment despite the initial oscillations in the process, after considering the data, we conclude that the described control strategy effectively addresses the issues arising from unbalanced grid situations in wind energy systems. The fact that this is the case demonstrates this.

4. Conclusion

This study aimed to explore and apply the Direct Power Control (DPC) approach in a wind-power generation system utilising a Doubly Fed Induction Generator (DFIG) framework. Specifically, we examined the DPC technique within the context of unbalanced grid voltage, characterised by uneven voltage distribution across grid phases. The study focused in investigating the performance of the DFIG system under both conventional grid voltage conditions and scenarios with unbalanced grid voltage. We conducted simulations using the SIMULINK tool in MATLAB to assess the effectiveness of a modified control approach utilising DPC. These simulations, developed specifically for a 9 MW wind farm based on DFIG, create a virtual environment to explore the system's behaviour and performance in various scenarios. Examining the simulation's outcomes leads to several significant inferences. After the change, the DOC control strategy effectively reduces the torque oscillations in the system. Creating active and reactive power references for the rotor-side converter accomplishes this goal. This not only simplifies the control approach but also eliminates the need to separate sequence components. The improved control strategy enables the stator currents to interchange with the grid-side converter in a sinusoidal fashion. The result is a smooth, sinusoidal pattern of currents flowing between the wind farm and the grid, which improves the system's stability and efficiency. When it comes to regulating torque oscillations and ensuring constant current exchange, the study demonstrates that the enhanced control approach works well in circumstances where the grid voltage is uneven. This is especially true regarding conditions where the grid voltage is uneven. These findings have practical implications for improving the efficiency and dependability of wind power generation systems based on DFIG. Through these tests, researchers can analyse the system's performance and its ability to adjust to variations in grid voltage.

Declaration of conflict of interest

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