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Research Article

Performance Evaluation of MG Systems Interfaced with Wind Turbines Employing DFIG Technology

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Abstract: The Doubly-Fed Induction Generator (DFIG) technology's capacity to adjust the rotor frequency depending on wind conditions greatly enhanced the wind farm's total energy collection. Adaptability is crucial for maximizing the efficiency of power generation, especially in regions with variable wind patterns. This article does a comprehensive examination of a 9 MW wind farm of six 1.5 MW wind turbines. The turbines are designed to optimize power generation and reduce mechanical strain. The wind farm is linked to a 25 kV distribution system, which transmits power to a 120 kV grid by a 30 km, 25 kV feeder. The primary advancement is in the use of Doubly Fed Induction Generator (DFIG) technology in every turbine. This method utilizes a wound rotor induction generator in conjunction with an AC/DC/AC IGBT-based PWM converter. The stator winding is directly linked to the 60 Hz Microgrid, whilst the rotor is supplied with electricity of varying frequency via the converter. DFIG technology optimizes the energy extraction from low wind speeds by dynamically regulating the turbine's rotational speed, resulting in optimal use of wind power. The capacity to adjust is essential for keeping a constant power production under different wind conditions. Furthermore, the technique significantly contributes to the reduction of mechanical strains on the turbines when exposed to strong gusts of wind, hence improving their durability and decreasing the expenses associated with maintenance. The article assesses the whole performance of the wind farm, analyzing power generation, effectiveness, connection to the Microgrid, and the influence of DFIG technology on energy extraction and reduction of mechanical stress. The results highlight the efficacy of the suggested approach in attaining substantial energy production and maintaining consistent performance.

Keywords: Global carbon dioxide, Microgrid, Power quality, Wind turbine, DFIG.

1. Introduction

The imperative for aligning the global energy infrastructure with the ambitious 1.5°C target has never been more compelling. August 2023 marked a historical apex in global temperatures, surpassing previous records by a significant margin, and clearly, ranking as the hottest month on record subsequent to 2023 [1-3]. The frequency and severity of climate change-induced events are escalating, underscoring the urgent need for decisive action. In 2022, global carbon dioxide emissions from the energy sector soared to an unprecedented high of 37 billion tonnes (Gt), exceeding pre-pandemic levels by 1%. Despite this concerning trajectory, there is a glimmer of hope as projections indicate an imminent peak in emissions within this decade [4-6]. Within this domain, the accelerated adoption of pivotal clean energy technologies has led the International Energy Agency to forecast a plateau in demand for coal, oil, and natural gas, even absent additional climate mitigation policies [7-9]. While this development is encouraging, it falls short of the requisite trajectory to achieve the 1.5°C goal, highlighting the imperative for intensified efforts.

The global landscape is poised to witness an unprecedented infusion of financial resources, with an anticipated record allocation of USD 1.8 trillion towards clean energy initiatives in the year 2023. However, to align with our trajectory, this figure must escalate substantially to approximately USD 4.5 trillion annually by the early 2030s [10-14]. Obviously, investments in clean energy engender long-term returns manifested through diminished fuel expenditures. Projections indicate that by the year 2050, both energy sector investments and associated fuel costs will constitute a reduced proportion of global Gross Domestic Product (GDP) relative to contemporary benchmarks. The imperative for heightened investment in clean energy is particularly pronounced within emerging market and developing economies, excluding China. Within the framework of the Net Zero Emissions (NZE) Scenario, these regions necessitate a sevenfold surge in clean energy investment by the early 2030s. Attaining such ambitious targets demands a confluence of robust domestic policies and augmented international support mechanisms. To facilitate this transition, it is imperative to bolster annual concessional funding directed towards clean energy initiatives in emerging market and developing economies, with figures projected to reach approximately USD 80-100 billion by the early 2030s [15-17].

A microgrid refers to a localized energy system comprising interconnected distributed energy resources (DERs), such as renewable energy sources, energy storage systems, and conventional generators, operating independently or in conjunction with the main grid [18-23]. Microgrids also play a pivotal role in enhancing energy resilience and reliability by providing localized power generation and distribution capabilities, particularly in areas susceptible to grid disruptions or natural disasters. They facilitate the integration of renewable energy sources, optimize energy use, and reduce costs by generating electricity close to the point of consumption, thereby supporting the transition to a low-carbon energy system [24-27]. Microgrids also address energy access challenges by providing reliable power to remote or off-grid areas and offer grid support services, enhancing the stability and flexibility of the broader electricity grid. Besides, microgrids contribute to a more resilient, sustainable, and efficient energy infrastructure, fostering energy security and enabling greater control over energy generation, distribution, and consumption [28-32].

Ensuring the power quality of microgrids is a top priority on the agenda due to its critical importance in guaranteeing reliable and stable electricity supply [33-37]. As microgrids incorporate diverse distributed energy resources (DERs) like wind turbines, solar panels, and energy storage systems, maintaining power quality becomes paramount to mitigate issues such as voltage fluctuations, frequency variations, and harmonics [38-44]. Given this context, poor power quality can lead to equipment damage, operational inefficiencies, and even safety hazards, highlighting the necessity for stringent monitoring, control, and management strategies within microgrid operations [45-48]. Addressing power quality concerns requires robust technical solutions, including advanced control algorithms, voltage regulation mechanisms, and real-time monitoring systems, alongside comprehensive standards and regulations to ensure compliance and reliability across microgrid deployments [49-52]. By prioritizing power quality, microgrid operators can enhance system performance, optimize energy utilization, and ultimately deliver dependable electricity services to end-users [53-58].

The burgeoning apprehensions surrounding future global energy requisites and environmental degradation have prompted concerted efforts among international communities. To alleviate these concerns, diverse strategies, technologies, and alternative energy sources are being sought and implemented across various sectors reliant on energy derived from disparate sources. Within this framework, the advancement of wind energy emerges as a pivotal contributor poised to address future energy demands while mitigating environmental pollution to a notable extent. In the year 2022, wind-generated electricity witnessed an unprecedented surge, recording a remarkable increase of 265 TWh (equating to a 14% rise), thereby exceeding 2,100 TWh in total generation [59,60]. This growth, although substantial, ranked second only to solar photovoltaic technology in terms of renewable power advancements. However, to align with the ambitious Net Zero Emissions by 2050 Scenario, which anticipates approximately 7,400 TWh of wind electricity generation by 2030, there is an imperative to augment the average annual generation growth rate to approximately 17%. Realizing these objective mandates, a substantial escalation in annual capacity additions, elevating from approximately 75 GW in 2022 to a projected 350 GW by 2030 [61,62].

Within this perspective, wind power is a highly appealing clean energy source that has the potential to address the current energy and global warming challenges facing the planet. DFIG wind turbines, which are widely utilized, often exhibit a consistent pattern of rising oscillation damping. When not effectively regulated, the extensive integration of wind energy would amplify oscillation and disrupt the management and dynamic interaction of the linked generators. In this, direction, Numerous studies have discussed the wind turbine using a DFIG [63-65]. It is worth mentioning that, electricity production from fossil fuels contributes to 35.29% of all releases of pollutants that lead to climate change as well as global warming. Wind energy is a prominent clean energy source globally, reducing dependence on fossil fuels. The evaluation of the life cycle of wind energy facilitates the comprehension of the environmental and economic impacts associated with the production of power utilizing wind energy. Moreover, the energy outputs of 100 MW capacity wind farms at twelve different places were predicted using the System Advisor Model tool. On top of that, a new eco-environmental estimate called the Life Cycle Levelized Cost of Energy (LCLCOE) has been developed. This indicator takes into account all the expenses associated with environmental harm across the whole lifetime of wind energy facilities [66-72].

According to [73], The power flow simulation for a node with DFIG has been developed by referencing the reactive power control loop of the rotor side converter in the suggested technique. Furthermore, the suggested method addresses many constraints linked to the Doubly Fed Induction Generator (DFIG). The suggested technique is validated by research studies conducted on an experiment 6-bus system and a 418-bus similar network of the Indian southern network. This article [74] focused on the optimum control of a DFIG using a rotor-side converter (RSC). The objective is to guarantee the transmission of electricity in a three-phase network with suitable characteristics while functioning in an isolated power system. Typically, this kind of grid is distinguished by an imbalanced distribution of load over each phase. Furthermore, the burden of these stages fluctuates unpredictably throughout time. The use of optimum control with a square expense function is used to guarantee that the presumed variables are related to line voltages. This guarantees that the voltage waveform aligns precisely with the reference voltage. In this particular context, other harmonics with a certain frequency are identified and decreased. The run simulations validate adherence to the output voltage parameter criteria in the islanded grid. The oscillations in the power flowing through the RSC received significant attention. The techniques for expediting the mitigation of these oscillations are outlined.

The primary aim of this research [75] is to enhance the energy efficiency obtained from a variable-speed wind turbine that utilizes a DFIG. Initially, the system's many components are subjected to dynamic modelling. The electrical machine is shown in the PARK reference frame. Subsequently, the control approach is further upon. The use of fuzzy logic controllers (FLC) in indirect field-oriented control is employed to regulate the rotor currents, hence effectively managing the actual and reactive powers of the stator generator.

This research article [76] investigates the role of wind energy conversion systems (WECS), specifically wind turbines with variable speeds (VSWT) that use DFIG for regulation and frequency optimization efforts. The investigation also investigates the impact of different levels of wind permeation on an isolated structure that includes both traditional thermal and non-thermal factories. The DFIG has the ability to generate power at various mechanical speeds and regulate the instantaneous speed, therefore dissipating stored mechanical energy. Additionally, it may assist in the adjustment of frequency in conventional tuning systems.

Controlling the DFIG at various amounts of wind penetration is feasible by choosing the required speed. This approach employs the particle swarm optimization (PSO) algorithm. The simulation results have been evaluated against the integral of squared error (ISE). An investigation is conducted to determine the best integration of wind energy conversion systems (WECSs) in a MG by taking into account the varying characteristics of the MG frequency. Wind turbines have been demonstrated to enhance the oscillation frequency and, specifically, the degree of penetration of wind energy in the MG. Consequently, the generating businesses' economic production and the consumers' productivity would decline. To achieve the necessary speed and interconnect all generators, it is important to effectively regulate the whole system. Given these difficulties, there has been a significant focus on using DFIG wind turbines to mitigate power system oscillations. This study focuses on the DFIG, which is considered the optimal and economical approach for implementing complex demand loads.

2. Microgrid

The concept of MG is subject to variation based on factors such as its size, level of connection to the primary grid, and method of functioning. The operating modes and features of a microgrid (MG) can vary depending on how the demands and supplies are connected to the MG network [77-79]. MG can potentially be categorized into three distinct groupings according to their types such as (i) DC MG, (ii) AC MG, and (iii) hybrid MG. Figure 1 demonstrates the types of MG.

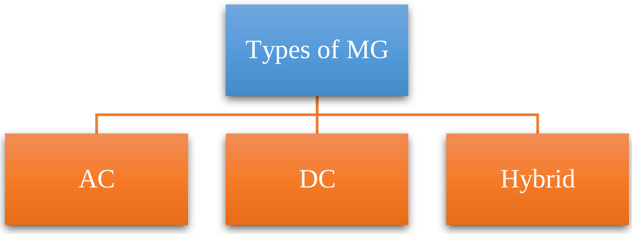

Figure 1. Types of MG

A. AC MG

An alternating current (AC) MG refers to a microgrid where the loads and sources have a connection to the AC MG, as demonstrated in Figure 2. The AC MG system is a popular option because of its ability to travel great distances, generate significant amounts of power, and adapt to various levels and tasks. Because most loads and the main grid operate on AC, this MG can be completely interconnected to the main grid.

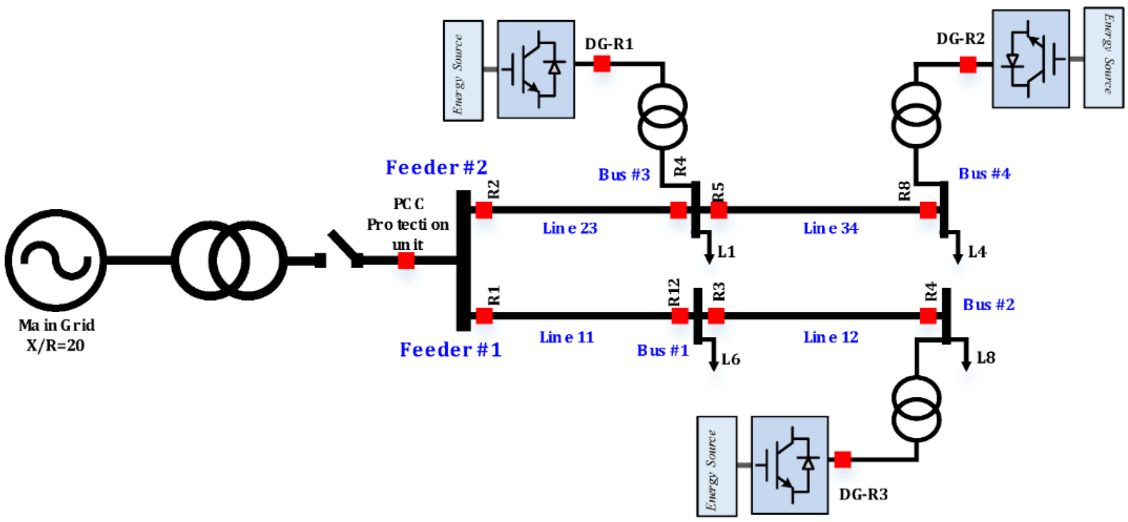

Figure 2. Configuration of AC MG system.

To operate efficiently, an AC MG requires the synchronization of all renewable energy sources and grid connections, as well as the capacity to reduce harmonics along with inrush current. In this context, integrating wind turbines into AC microgrids offers numerous advantages, including the generation of renewable energy without greenhouse gas emissions, diversification of energy sources to reduce reliance on fossil fuels, and increased energy resilience by harnessing consistent wind patterns [80-84]. This integration promotes local energy production, fostering community independence from external suppliers and strengthening local economies. Additionally, by generating electricity close to where it is consumed, transmission losses are minimized, enhancing overall energy efficiency. The scalability and modularity of wind turbines allow for flexible integration into microgrid systems of various sizes and configurations, while their environmental benefits contribute to sustainability goals and mitigate climate change [85-88]. In essence, the utilization of wind power can lead to cost savings compared to traditional fuels, further incentivizing the adoption of wind turbines within AC microgrid infrastructures.

B. DC MG

Direct current (DC) microgrids offer vast potential across various power applications, including small-scale generation, backup for energy storage systems, data centers, marine operations, sensitive loads, and industrial settings. When compared to traditional alternating current (AC) power systems, DC microgrids present several advantages, particularly in terms of power density and efficiency. Due to their inherent characteristics, DC microgrids exhibit higher power density, enabling more compact and space-efficient installations. Additionally, they boast greater efficiency levels compared to AC systems, resulting in reduced energy losses during transmission and distribution [89,90]. These advantages make DC microgrids particularly well-suited for applications where space constraints, energy efficiency, and reliable power delivery are paramount, thus positioning them as a promising solution for a wide range of modern power needs. Figure 3 illustrates the configuration of DC MG.

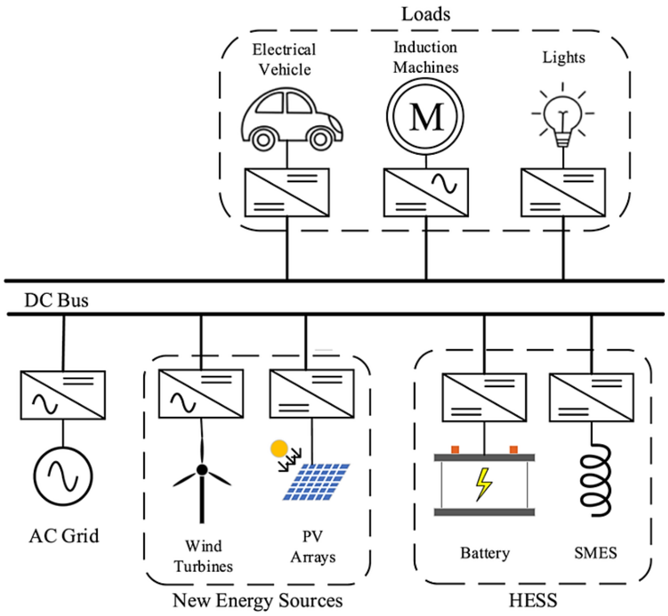

Figure 3. Configuration of DC MG

Incorporating wind turbines into direct current (DC) microgrids presents several significant advantages. Firstly, it enhances efficiency by eliminating the need for AC to DC conversion, reducing energy losses and streamlining control and management processes due to the inherent compatibility of wind turbines with DC power systems. Secondly, the scalability and modularity of DC microgrids allow for easy integration of wind turbines as energy demands evolve, offering flexibility and cost-effectiveness in system expansion [91]. Additionally, the compatibility of wind turbines with DC microgrids facilitates seamless integration with energy storage solutions, enhancing overall system reliability and stability while enabling efficient utilization of surplus energy. Furthermore, DC microgrids are well-suited for remote or off-grid applications, making wind turbines an ideal renewable energy source for providing reliable electricity access in such areas, thus contributing to environmental sustainability by reducing greenhouse gas emissions and promoting clean energy adoption.

C. Hybrid MG

The implementation of an innovative MG structure, known as a hybrid AC/DC MG, aims to improve power quality, local accuracy, support for voltage, and efficiency, and reduce feeder losses, voltage sag, and harmonics [92]. This MG incorporates highly intelligent design as well as management techniques for sources of information, loads, and connections to each other. Figure 4 depicts the diagram of a hybrid MG.

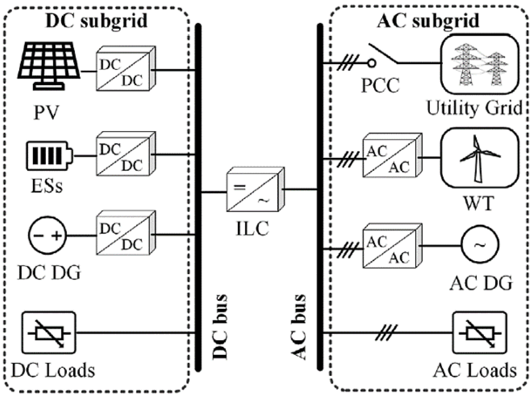

Figure 4. Hybrid MG

Hybrid microgrids offer a multifaceted contribution to energy systems by combining various energy sources such as solar, wind, diesel generators, and energy storage systems. This integration ensures enhanced reliability and resilience, minimizing the risk of power outages and providing continuous electricity supply even in the face of fluctuations or failures in individual sources. With sophisticated control and management systems, hybrid microgrids optimize energy utilization, dynamically balancing generation and consumption based on real-time demand and resource availability, thus promoting efficient energy management and cost savings. By integrating renewable energy sources, hybrid microgrids reduce reliance on fossil fuels, lower greenhouse gas emissions, and foster environmental sustainability [93-95]. Furthermore, they enable communities and businesses to achieve greater energy independence, enhance energy security, and support electrification efforts in remote or underserved areas, ultimately contributing to socio-economic development and improved quality of life.

3. DFIG Model

The mathematical description of the doubly fed induction generator (DFIG) in the reference structure could potentially be represented as a fifth-order model when expressed in matrix form. All the changes in flow and the significant relationships between characteristics are considered. In order to simplify the machine, some fundamental assumptions are taken into account [96,97]. The effect of magnetic saturation is disregarded and it is assumed that the machine windings have an equal distribution in a sinusoidal manner. The effects of electromagnetic magnitudes are given by the Eq. (1) that follows the matrix.

$$\frac{d}{dt}\begin{bmatrix}\Phi_{sd}\\ \Phi_{sq}\\ \Phi_{rd}\\ \Phi_{rq}\end{bmatrix}=\begin{bmatrix}-\frac{R_s}{\sigma L_s} & \omega_g & \frac{R_s M}{\sigma L_s L_r} & 0\\ -\omega_g & -\frac{R_s}{\sigma L_s} & 0 & \frac{R_s M}{\sigma L_s L_r}\\ \frac{R_r M}{\sigma L_s L_r} & 0 & -\frac{R_s}{\sigma L_r} & \omega_g-\omega_m\\ 0 & \frac{R_r M}{\sigma L_s L_r} & -(\omega_g-\omega_m) & -\frac{R_s}{\sigma L_r}\end{bmatrix}\begin{bmatrix}\Phi_{sd}\\ \Phi_{sq}\\ \Phi_{rd}\\ \Phi_{rq}\end{bmatrix}+\begin{bmatrix}V_{sd}\\ V_{sq}\\ V_{rd}\\ V_{rq}\end{bmatrix} \tag{1}$$

In this regard, the symbol σ indicates the leakage coefficient aspect. ω_g and ω_m represent the angles and higher frequencies of the stator flux as well as the rotor shaft. The symbols $\Phi_{sd,q}$, and $\Phi_{rd,q}$ represent both the stator and rotor fluxes, accordingly. $\Phi_{sd,q}$, and $\Phi_{rd,q}$ represent the stator and rotor voltages. Moreover, R_s and R_r represent the stator and rotor resistances. L_s, L_r, and even M represent the stator, rotor, and magnetizing inductances. For the purpose of linking the electrical and mechanical components of the machine., the electromagnetic torque, which is additionally referred to as C_{em}, serves as the glue. In connection to fluxes, it comes with the possibility of being acquired as the following Eq. (2):

$$C_{em} = \left(\frac{3}{2}\ p\right)\left(\frac{M}{L_r\ L_s\sigma}\right)\left(\Phi_{sq}\ \Phi_{rd} - \Phi_{sd}\ \Phi_{rq}\right) \tag{2}$$

The mathematical representation of a Doubly Fed Induction Generator (DFIG) can potentially be stated in the following Eq. (3). Where J represents the inertia of the framework, whereas f_v refers to the viscous friction. To finalize the computational framework, it is important to calculate both the actual and reactive power. They could have been expressed as Eq. 4 and Eq. 5.

$$C_g - C_{em} - f_v \, \Omega_{mec} = \vartheta \left(\frac{d \, \Omega_{mec}}{dt}\right) \tag{3}$$

$$P_s = \frac{3}{2} \left(V_{sq} I_{sq} + V_{sd} \, I_{sd} \right) \tag{4}$$

$$Q_s = \frac{3}{2} \left(V_{sq} I_{sq} - V_{sd} \, I_{sd} \right) \tag{5}$$

In this direction, in contemporary wind power conversion systems, DFIGs play an essential function in shifting speed innovation. This machine has several benefits as it has the capability to run at different speeds (either below or above the synchronous speed) by modifying the phase and frequency of the rotor voltages. There is much room for improvement in terms of reducing the size of the power converter. The design can potentially be configured to transmit just 30% of the maximum power rating of the DFIG [98-100]. These factors enhance the efficiency, reduce the weight, and lower the cost of the wind turbine. Furthermore, the DFIG can independently regulate both the active and reactive power. This feature enhances the machine's suitability for Microgrid integration, making it a very competitive option.

4. Result and Discussion

The article investigates the efficiency of a 9 MW wind farm consisting of six 1.5 MW wind turbines that use the doubly fed induction generator (DFIG) technology. Figure 5 presents modelling of MG interfaced with wind turbines using a DFIG. Figure 6, illustrates the result of the 3-phase voltage and 3-phase current during MG interfaced with wind turbines using a DFIG.

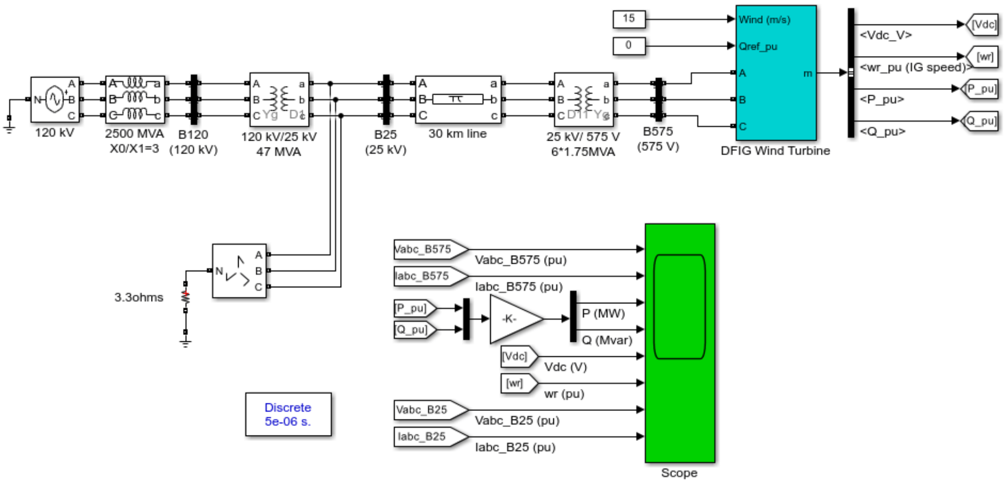

Figure 5. Modeling of MG interfaced with wind turbines using a DFIG.

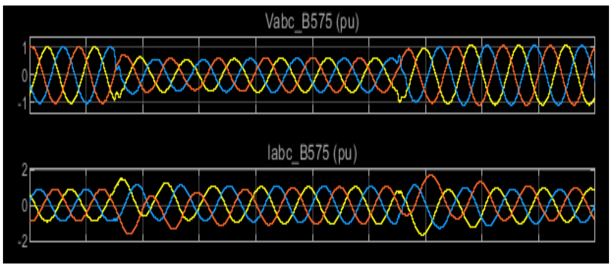

Figure 6. The result of the 3-phase voltage and 3-phase current during MG interfaced with wind turbines using a DFIG.

The wind farm is linked to a 25 kilovolt (kV) distribution system and transmits electricity to a 120 kilovolt (kV) Microgrid via a 30-kilometre (km) feeder operating at 25 kV. The DFIG technology employs a wound rotor induction generator and an AC/DC/AC IGBT-based PWM converter to increase energy extraction from the wind and reduce mechanical strains on the turbines. Figure 7 shows the outcome of the active power and reactive power during MG interfaced with wind turbines using a DFIG. Figure 8 presents the result of the DC voltage, wind, 3-phase voltage during MG interfaced with wind turbines using a DFIG.

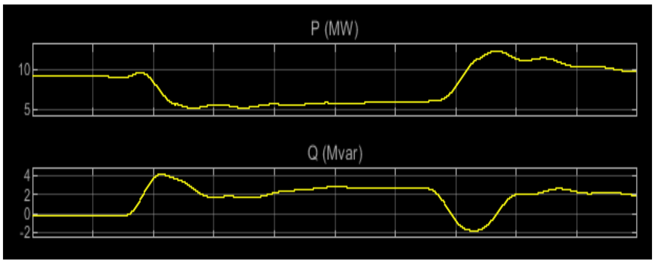

Figure 7. The outcome of the true power and reactive power during MG interfaced with wind turbines using a DFIG.

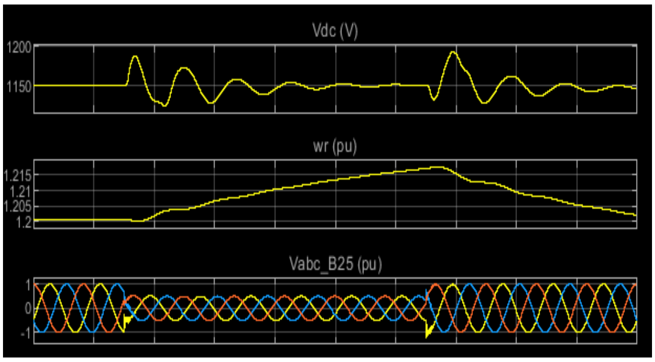

Figure 8. The result of the DC voltage, wind, and 3-phase of voltage during MG interfaced with wind turbines using a DFIG.

5. Conclusion

The doubly fed induction generator (DFIG) technology's capacity to modify the rotor frequency in response to wind conditions greatly enhanced the wind farm's total energy collection. The capacity to adjust is essential for optimizing power-generating efficiency, particularly in areas with fluctuating wind patterns. This feature was especially advantageous in maximizing energy extraction when wind conditions were unfavourable, resulting in a greater total capacity factor. The DFIG wind farm generates a power output of 9 MW. The turbine speed corresponds to 1.2 per unit (pu) of the generator's synchronous speed. It is important to point out that the direct current voltage is maintained at a controlled level of 1150 volts, while the reactive power is maintained at zero megavolt-amperes (Mvar). At a time of 0.03 seconds, the positive-sequence voltage experiences a dramatic decrease to 0.5 per unit, resulting in oscillations in both the DC bus voltage and the output power of the DFIG. During the occurrence of voltage sag, the control system endeavours to maintain the direct current voltage and reactive power at their designated values of 1150 V and 0 Mvar, respectively. The system undergoes recovery in around 4 cycles. Moreover, the research work investigates possible obstacles in incorporating the microgrid and proposes directions for future investigation and advancement to improve DFIG technology and tackle changing energy requirements. This study provides significant findings that contribute to the progress of wind energy technology, with a particular focus on the function of DFIG in enhancing performance, improving dependability, and fostering sustainable wind power production.

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A. K., and S. K.; resources, author; data curation, author; writing—original draft preparation, S. A., M. E., K. M., A. K., and S. K.; writing—review and editing, author; visualization, author; supervision, author; project administration, S. A., M. E., K. M., A. K., and S. K.;.; author has read and agreed to the published version of the manuscript.

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