PERFORMANCE EVOLUTION OF DOUBLY-FED INDUCTION GENERATOR DRIVEN BY A WIND TURBINE

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ABSTRACT

The paper focuses on managing grid frequency by controlling the operation of a Doubly Fed Induction Generator (DFIG). These generators play a crucial role in wind energy conversion systems, particularly variable speed wind turbines. Unlike fixed-speed turbines, variable speed turbines offer several advantages. They connect to the grid via Voltage Source Converters (VSC), enabling flexible operation. In this paper, the DFIG-based variable speed wind generation system is analyzed. The rotor-side converter (RSC) handles active and reactive power control, it's typically more efficient to use the RSC for this purpose. The paper also covers the introduction of the DFIG, control of the AC/DC/AC converter, and SIMULINK/MATLAB simulations for both isolated induction generators and grid-connected DFIGs. It contributes to enhancing grid stability and optimizing wind energy utilization. The results are compared with experiment setup.

KEYWORDS: *DFIG, Rotor-Side Converter, Grid-Side Converter, Converter Control Diagram, Simulink Diagram, Wind Turbine Modeling, Wind Energy.*

INTRODUCTION

In today's world, the demand for electrical energy is steadily rising. However, traditional sources such as coal and fossil fuels are depleting. It is crucial to explore alternative method of electricity generation[1]. Wind energy, a non-conventional source, is controlled in remote rural areas. These regions often have weak grids, voltage imbalances, and under-voltage conditions. Recent research and development efforts have focused on wind energy, especially with the increased integration of wind power into electrical grids[2-4]. Doubly Fed Induction Generator (DFIG) wind turbines, known for their variable speed capability, play a significant role in this context. Researchers are actively developing suitable models for DFIG integration into power system studies. As wind power penetration continues to rise, grid codes are being updated to ensure wind turbines contribute to voltage and frequency control while remaining connected to the network during disturbances[5-6]. Wind power, which does not contribute to the greenhouse effect, is becoming a vital component of overall energy generation. Understanding the dynamic behavior of wind energy systems is essential for further advancements. These models utilize rotor voltage components in an appropriate reference frame to regulate voltage efficiently.

DOUBLY FED INDUCTION GENERATOR

Wind turbines utilize a Doubly Fed Induction Generator (DFIG), which comprises a wound rotor induction generator and an AC/DC/AC IGBT-based PWM converter. Here's how it works: The stator winding directly connects to the 50 Hz grid, while the rotor receives variable-frequency power through the AC/DC/AC converter. The DFIG technology maximizes energy extraction from low speeds by optimizing turbine speed and minimizing mechanical stress during gusts. The ideal turbine speed for maximum mechanical energy production at a given wind speed is directly proportional to that wind speed. Another advantage of DFIG technology lies in the power electronic converters ability to generate or absorb reactive power. This eliminates the need for installing capacitor banks, as required for squirrel-cage induction generators[7-8].

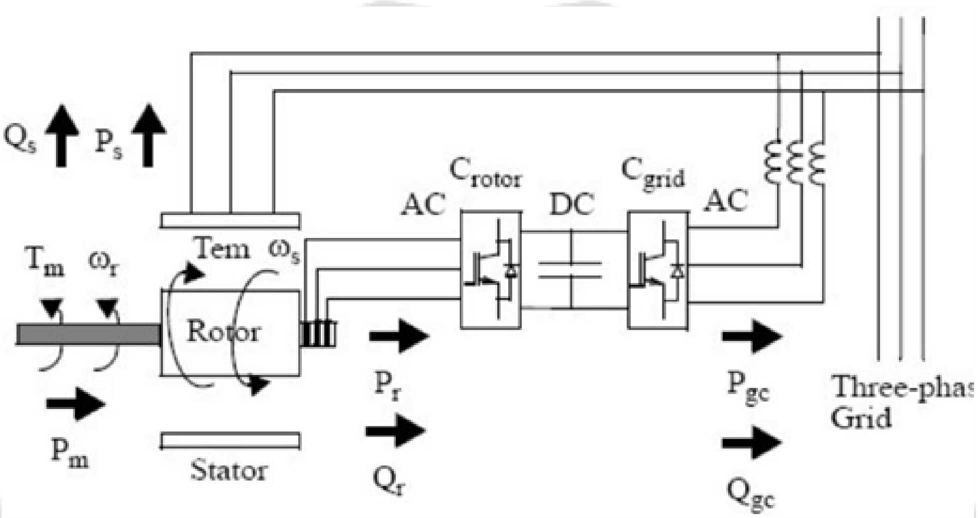

Figure1: DFIG and its power flow

In practical terms, the stator remains connected to the AC grid. Meanwhile, the wound rotor receives power from the power Electronic Converter via slip rings, allowing the DFIG to operate at various speeds in response to changing wind conditions. The fundamental concept involves inserting a frequency converter between the variable-frequency induction generator and the fixed-frequency grid. To achieve precise grid current control, the DC-link voltage must exceed the grid line-to-line voltage amplitude. The slip power can flow in both directions-either from the supply to the rotor or vice versa. Consequently, the machine's speed can be controlled using either the rotor-side or stator-side converter, enabling four distinct operating modes: generator or motor in both super and sub-synchronous ranges.

WIND TURBINE MODELING

Initially, wind turbines relied on direct grid-coupled synchronous generators with pitch-controlled rotor blades. These designs aimed to limit mechanical power output during high wind speeds. Subsequent modeling efforts focused on this concept. Later, the synchronous generator was replaced by a directly grid-coupled asynchronous squirrel cage induction generator. To reduce power extraction at high wind speeds, pitch control or stall control mechanisms were employed. Numerous research papers explore modeling wind turbines with directly grid-coupled squirrel cage induction generators, considering both pitch and stall control for mechanical power.

In recent times, modern variable-speed wind turbines equipped with Doubly Fed Induction Generators (DFIGs) have replaced the traditional constant-speed wind turbines. DFIGs allow efficient extraction from varying wind speeds. Since power output is proportional to the cube of wind speed, strategically locating electricity-generating turbines in areas with high mean annual wind speeds is crucial. Wind turbine rotors, rated for a specific capacity, are significantly larger than those of hydro-turbines.

ROTOR EQUATION

A wind turbine operates by extracting kinetic energy from the wind passing through its rotor.

The power developed by a wind turbine is given by:

$$P=1/2C_p\vartheta V_w 3A$$

Where

P	power (W),
A	swept area of rotor disc (m2),
ϑ	density of air (1.225kg=m3),
C_p	power coefficient,
V_w	Wind velocity (m/s).

The force exerted on the rotor is directly proportional to the square of wind speed. Consequently, wind turbines must be robustly designed to withstand substantial forces during storms. Most modern wind turbine designs feature three-bladed horizontal-axis rotors. This configuration not only achieves a favorable peak power coefficient (C_p) but also results in an elegant pleasing appearance.

The power coefficient (C_p) quantifies how much energy the turbine extracts from the wind. It depends on the rotor design and the relative speed between the rotor and the wind. Typically, C_p reaches a practical maximum value of approximately 0.4. Since aerodynamics and precise computations are involved, numerical approximations have been developed to address these complexities.

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

$$\frac{1}{\lambda_i} = \frac{1}{\lambda+0.08\beta} - \frac{0.035}{\beta^3+1}$$

Figure2: Shows C_p (¸;µ) versus ʎ ¸ characteristics for various values of ʎ. Using the actual values of the wind and rotor speed. The maximum value of C_p (C_p max=0.48) is achieved for¯ = 0± and for¸ = 8:1. This particular value of¸ is defined as the nominal value (ʎ¸nom).

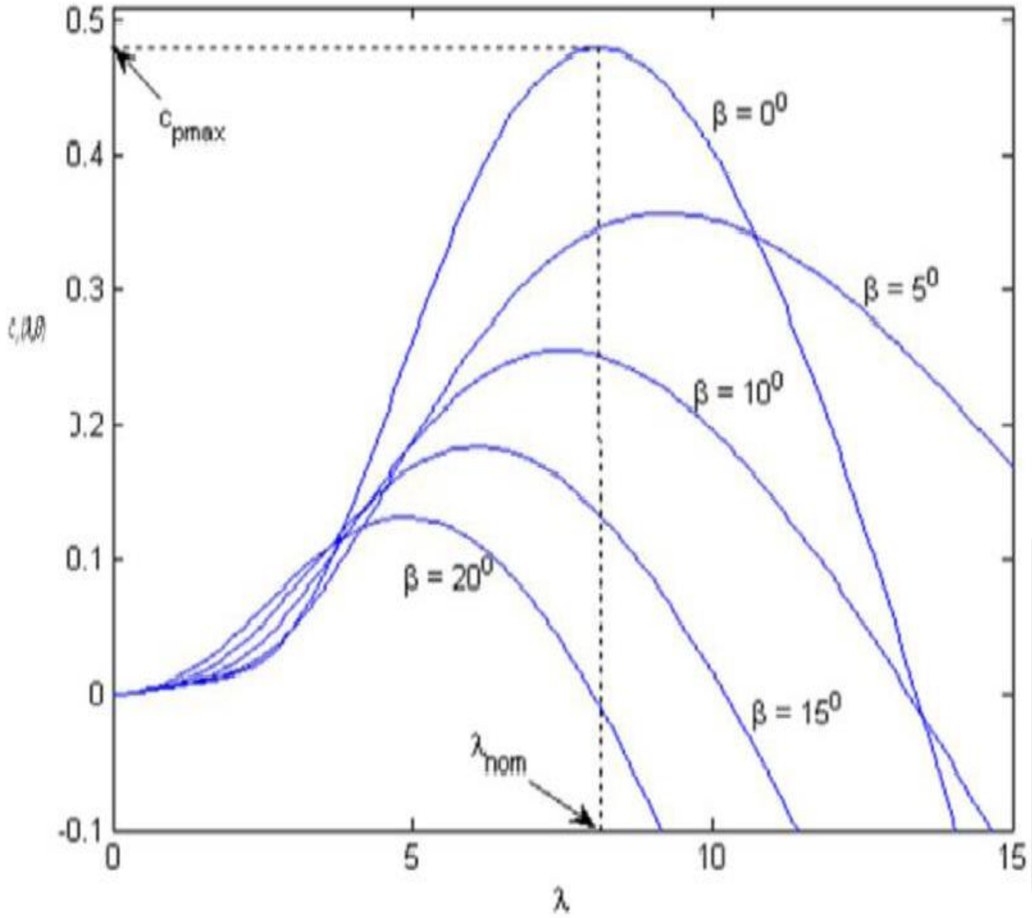

Figure2: C_p Vs ʎ characteristics

Performance coefficient CC_p as a function of the tip speed ratio¸ with p it change l ʎ as a parameter.

AC/DC/AC CONVERTER

The choice of model type and structure typically depends on specific analysis requirements, such as steady-state or fault studies. In the context of Doubly Fed Induction Generator (DFIG) modeling, a common approach involves simulating converters based on expected controller responses rather than directly modeling power Electronics devices. In this approach, converters are assumed to be ideal, and the DC-link voltage remains constant. Depending on the converter control strategy, a controllable voltage (or current) source can represent the rotor-side operation in the model.

On the other hand, a physical model considers individual system components separately and accounts for interrelationships among different elements within the system. The choice of model type and structure typically depends on specific analysis requirements, such as steady-state or fault studies. In the context of Doubly Fed Induction Generator (DFIG) modeling, a common approach involves simulating converters based on expected controller are assumes to be ideal, and the

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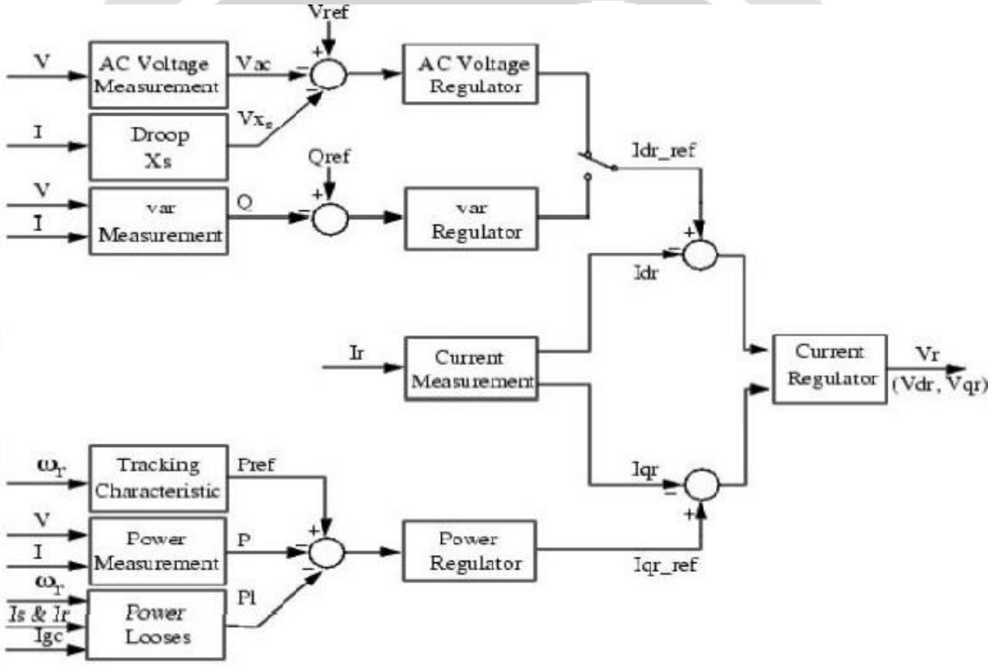
CONVERTER CONTROL SYSTEM

Back-to-Back PWM converter consists of two converters --- one connected to the rotor side and the other to the grid side. In this context, we discuss control strategies for both converters. The rotor-side converter plays a crucial role in regulating wind turbine output power and monitoring the voltage at the grid terminals. Its primary objective is to maintain alignment with a pre-defined power-speed characteristic, commonly referred to as the tracking characteristic.

ROTOR-SIDE CONVERTER CONTROL SYSTEM

Figure3: Rotor converter control block diagram.

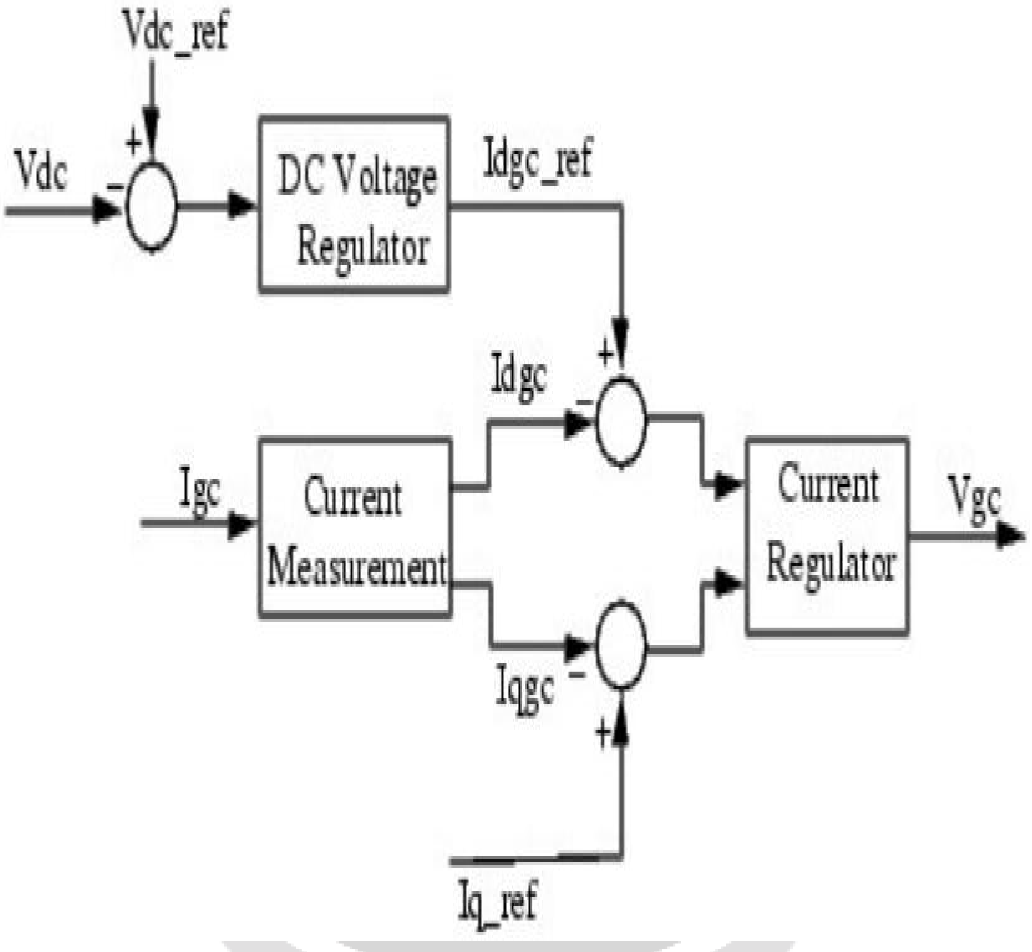


The rotor-side controller aligns the d-axis of the rotating reference frame with the air-gap flux during d-q transformation. It measures the actual electrical output power at the wind turbine's grid terminals, accounting for both mechanical and electrical losses. This measured power is then compared to a reference value. To minimize any power error, a Proportional-Integral (PI) regulator is employed. The regulator's output provides the reference rotor current (Iqr ref), which is injected into the rotor by the C rotor converter

GRID SIDE CONVERTER CONTROL SYSTEM

The Grid side converter is used to regulate the voltage of the DC bus capacitor. For the grid side controller the d-axis of the rotating reference frame used for d-q transformation is aligned with the positive sequence of grid voltage.

Figure4: Grid side converter control



SIMULINK DIAGRAM

This is the Simulink diagram for a doubly fed induction generator connected to grid side with wind turbine protection schemes involved for protection from single phase faults and ground faults. The system is connected to a 120KV, 3 phase source which is connected to a 9MW wind farm (6 of 1.5 MW each) via Step down transformers, fault protection and pi-transmission line.

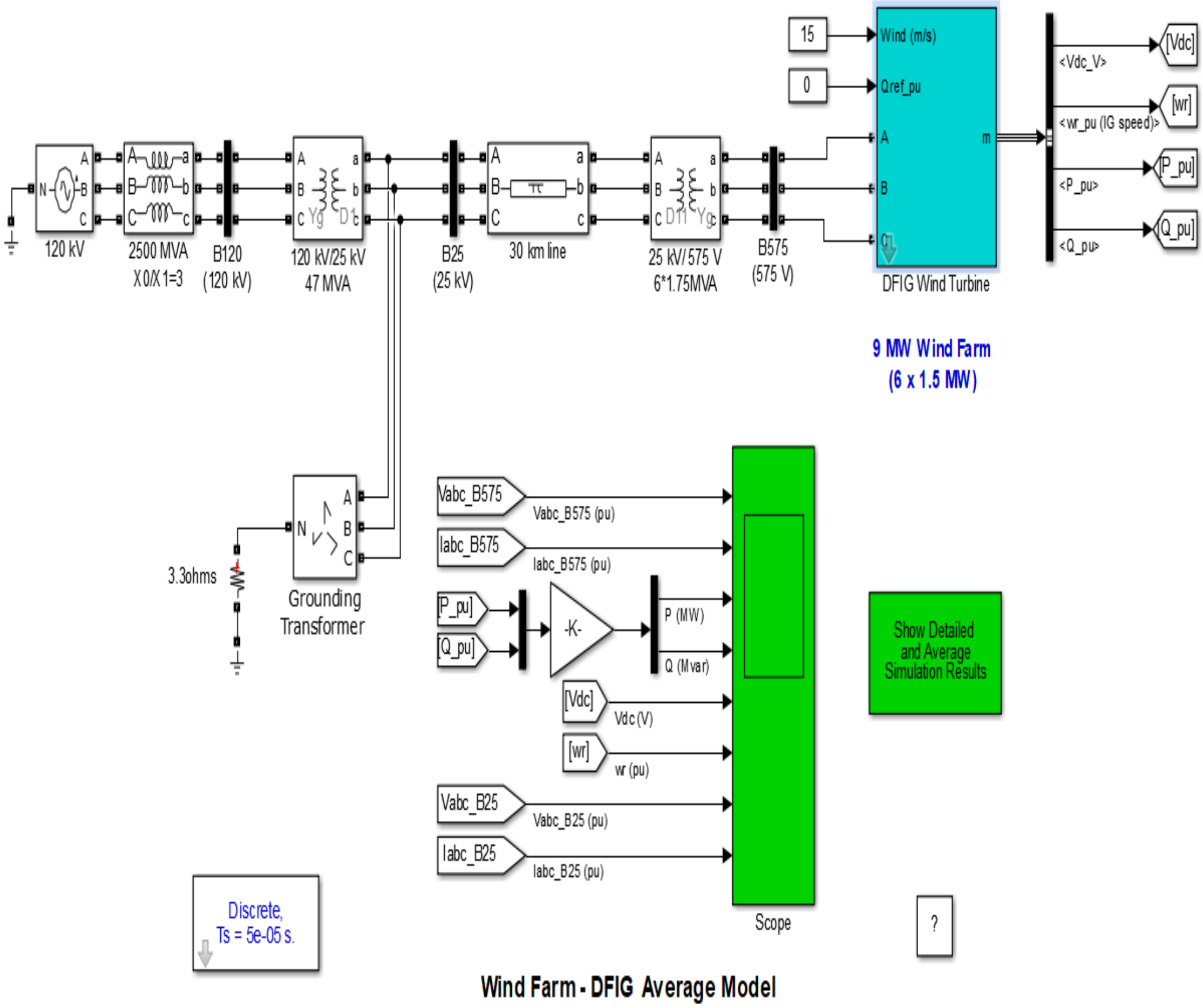


Figure 5: Wind Farm- DFIG Average Model

SIMULINK MODEL OF ROTOR SIDE AND GRID SIDE CONVERTER CONTROLLER

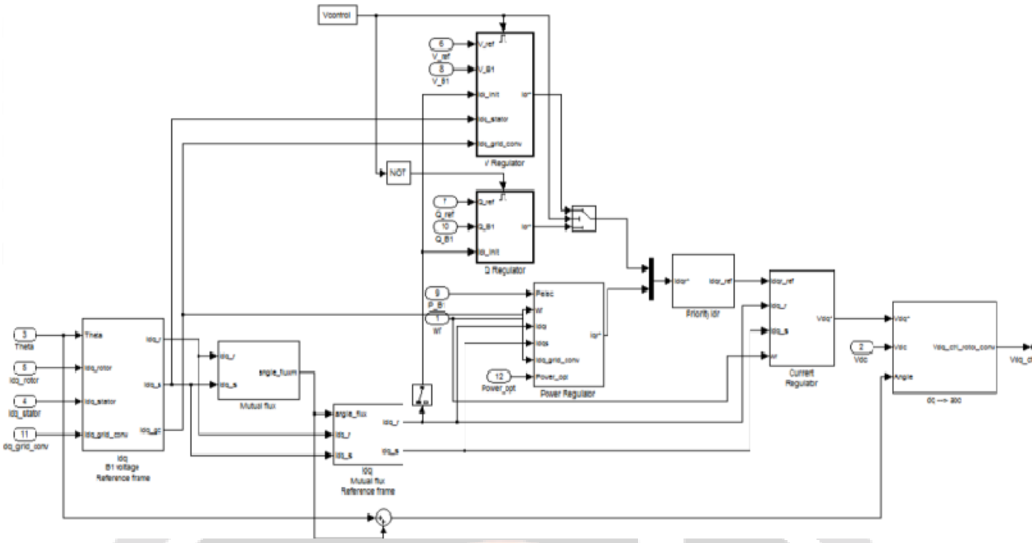


Figure6: SIMULINK diagram of rotor side converter control system

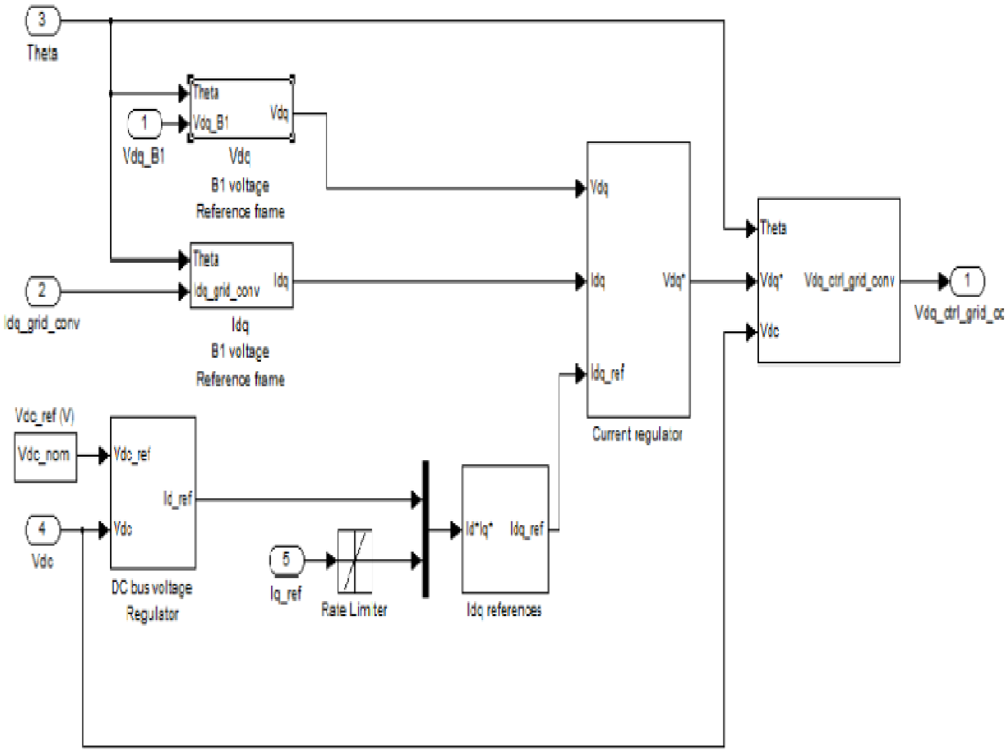


Figure7 : SIMULINK diagram of grid side converter's controller

SIMULATION RESULTS

Turbine response to a change in wind speed “Wind Speed” step block specifying the wind speed. Initially, wind speed is set at 8 m/s, then t = 0.03s, wind speed increases suddenly at 14 m/s. Start simulation and observe the signals on the “Wind Turbine” scope monitoring the wind turbine voltage, current, generated active and Reactive powers, DC bus voltage and turbine speed.

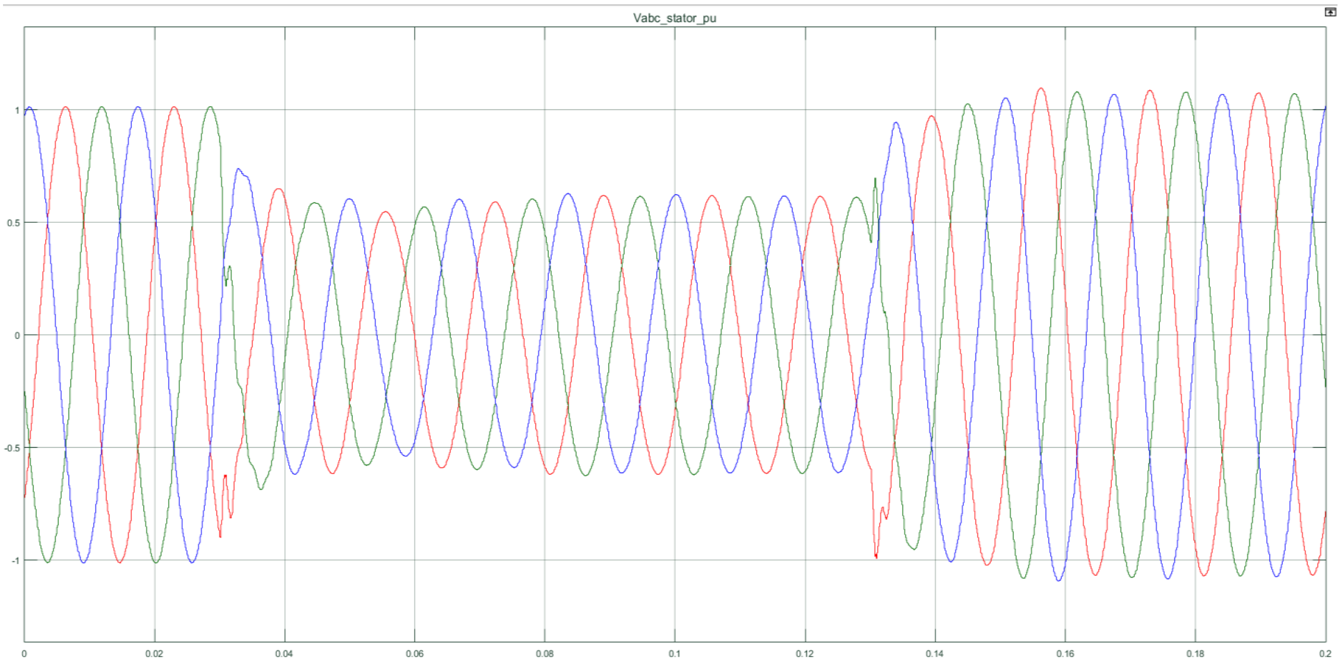


Figure 8: Stator voltage

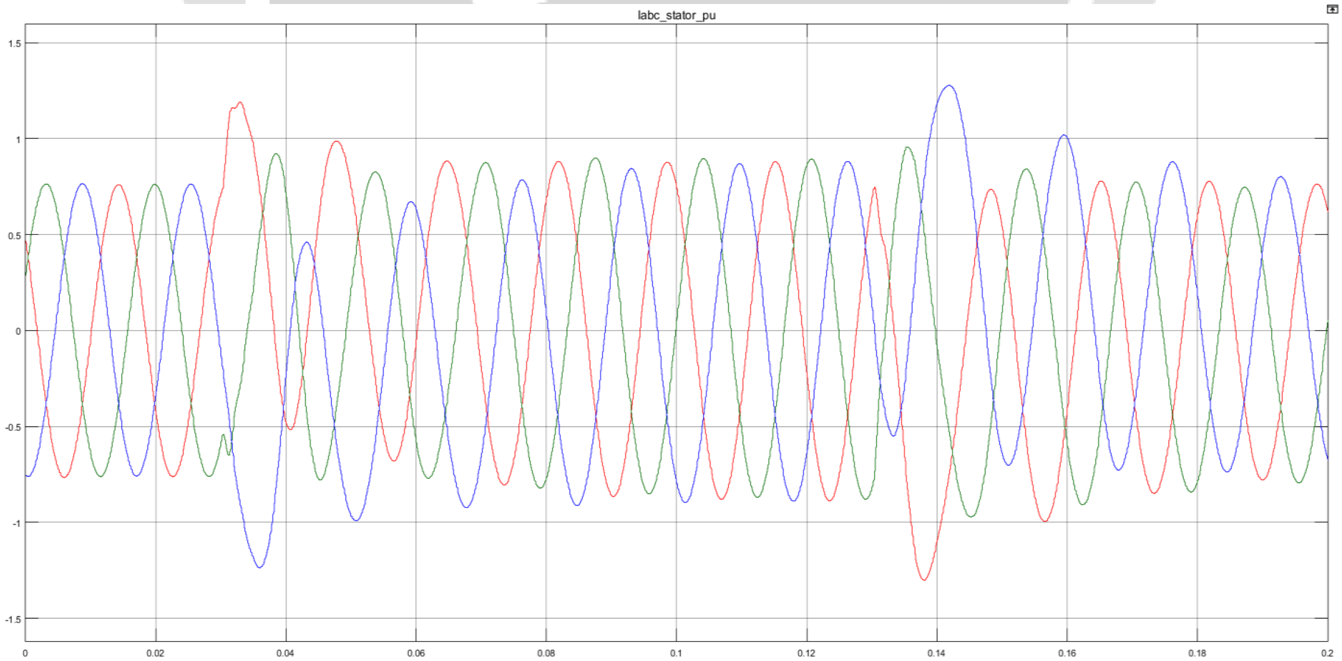


Figure 9: Stator Current

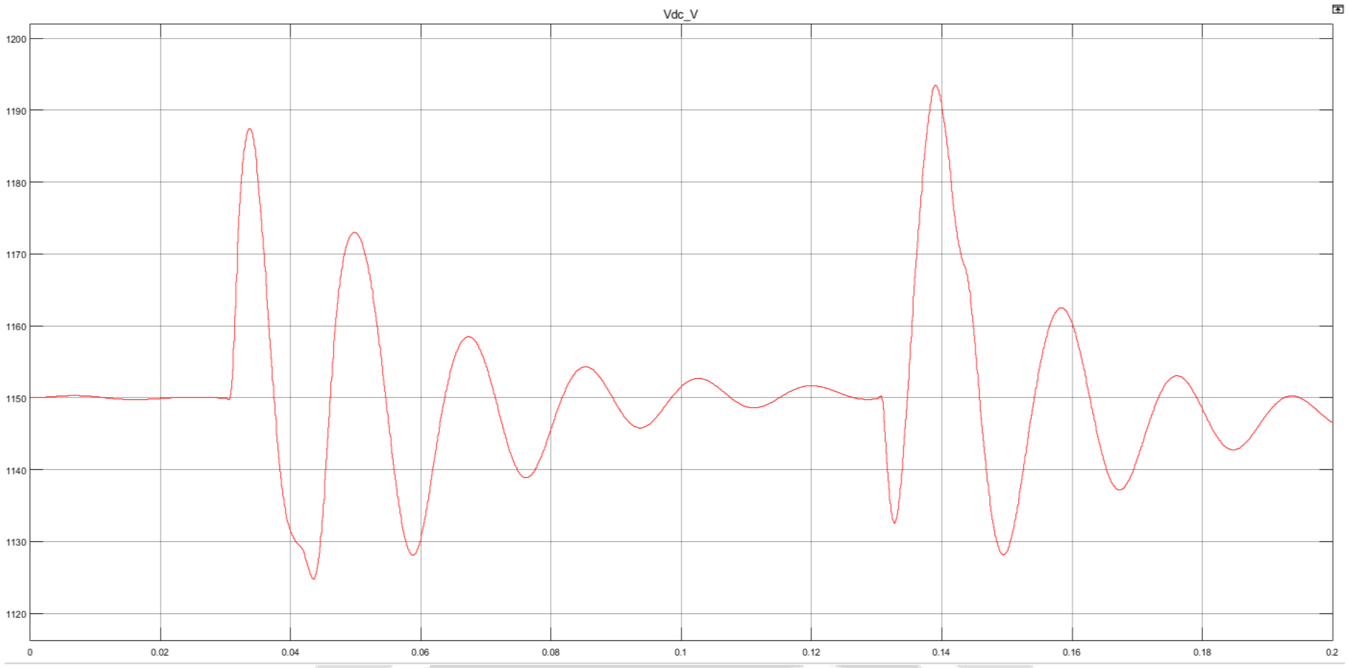


Figure 10: Dc Link Voltage

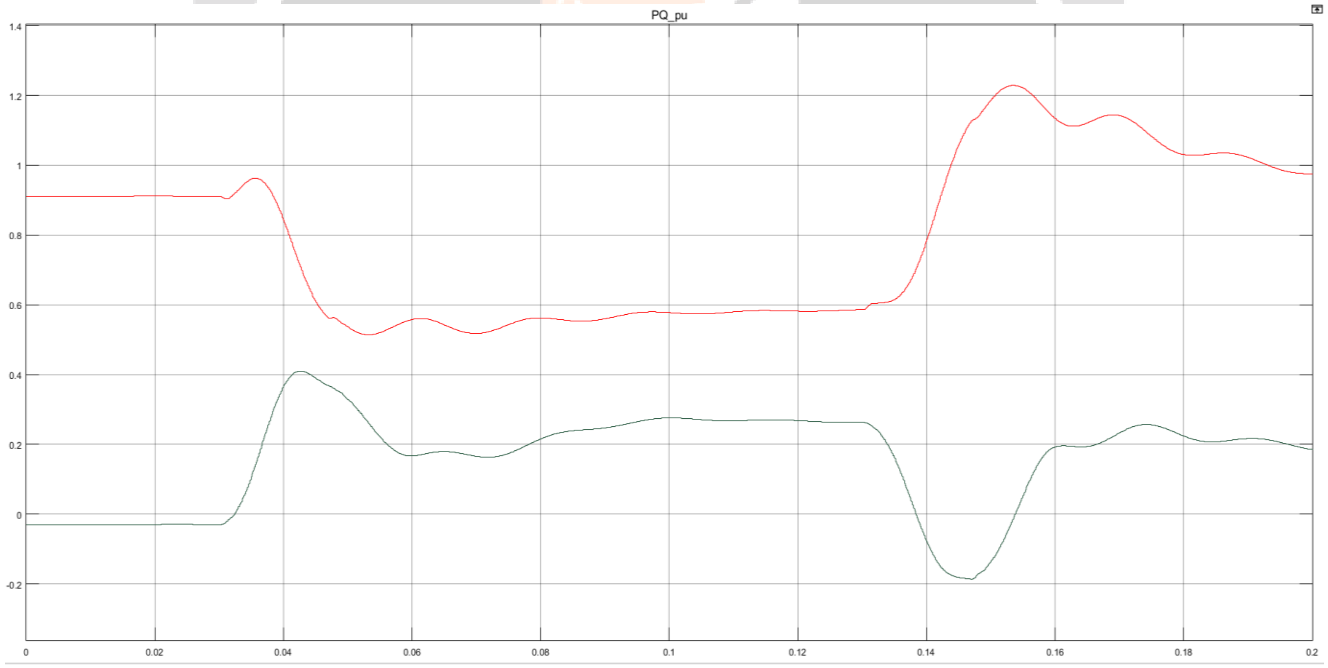


Figure 11: Active and Reactive Power

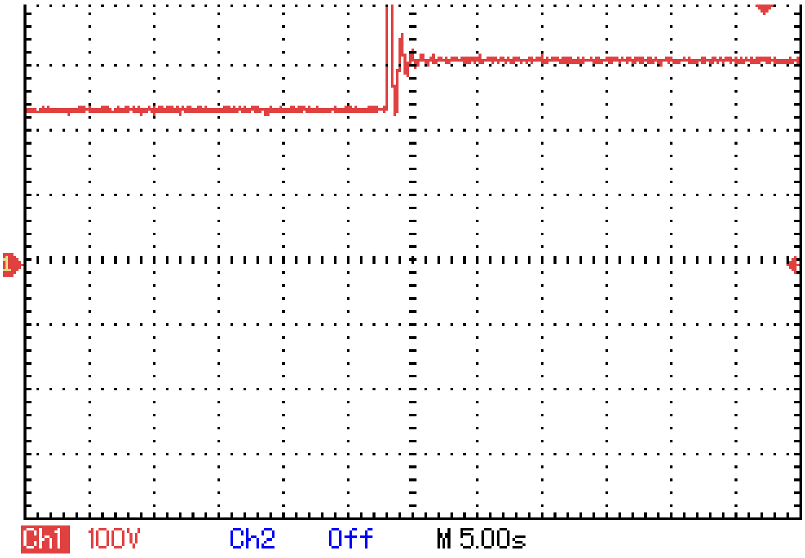


Figure 12: Dc Link Voltage(Experimental)

CONCLUSION

The Doubly Fed Induction Generator (DFIG) system, which is connected to the grid side, offers improved control and efficiency. The rotor-side converter (RSC) primarily handles active and reactive power control for the machine. While the grid-side converter (GSC) maintains a constant voltage on the DC-link. We conducted simulations using grid-side and wind turbine parameters, and the corresponding results were displayed. Faults may occur due to low wind speeds or persistent fluctuations. Particularly, the DFIG system significantly contributes to grid voltage support during short circuit events. Overall, when properly connected to the grid side with appropriate converter control systems, the DFIG proves to be a reliable and stable solution.

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