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Review TEE

Enhancement of LVRT Capability in DFIG-Based Microgrids Using STATCOM

Swati Sajan Sangamnere[1,*], Rupesh Chandrakant Pawaskar[2]

Abstract

The improvement of a grid-connected wind microgrid's low voltage ride-through (LVRT) capability using a static synchronous compensator (STATCOM) is investigated in this research. The increasing penetration of wind energy into modern power systems necessitates advanced control strategies to maintain grid stability during voltage disturbances and fault conditions. In this study, STATCOM is employed with an effectively tuned PI controller to provide enhanced dynamic response, voltage regulation, and reactive power support during grid disturbances. The improved STATCOM controller demonstrates superior performance under both symmetrical and asymmetrical fault conditions compared to conventional tuning techniques. A 16 MW wind microgrid based on Doubly fed induction generators (DFIGs) is modeled and simulated in MATLAB/Simulink to evaluate system behavior under various grid fault scenarios. The performance of the STATCOM is analyzed in terms of voltage recovery, reduction of peak voltage sag, reactive power compensation, damping of post-fault oscillations, and overall system stability during LVRT events. Simulation results indicate that a properly tuned STATCOM significantly enhances the voltage profile at the Point of Common Coupling (PCC), improves fault ride-through capability, ensures compliance with grid code requirements, and contributes to the reliable and stable operation of grid-connected wind-based microgrids under severe fault conditions effectively and sustainably.

Keywords: DFIG, LVRT, STATCOM, microgrid, wind energy

INTRODUCTION

The global energy industry is undergoing a major transition owing to environmental considerations, depletion of fossil fuels, and increasing demand for electricity. Wind energy has emerged as the primary renewable energy source, with a total installed capacity of approximately 1136 GW by the end of 2024 [1]. However, for large wind power mergers, particularly in weak grids, stability issues arise because of the occasional nature of wind power. Microgrids are a good solution to this problem as they enable localized generation, controlled coordination, and higher system resilience [2]. Because of its high efficiency and partial-scale power converter structure, which allows for the independent management of active and reactive power, the Doubly Fed Induction Generator (DFIG) is widely used in wind turbine technology [3]. Despite these advantages, DFIG systems are particularly sensitive to grid outages because the stator is directly connected to the grid. If sufficient (LVRT) capacity is not guaranteed, voltage dips during faults may result in rotor overcurrents, DC link overvoltages, and even disconnection [4, 5], and [6]. Grid rules mandate that wind turbines remain connected and offer reactive power support during brief voltage sags. For instance, in Germany, these requirements are 150 ms fault tolerance at zero

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voltage, whereas in the Indian grid codes, it is required to operate at 0.15 pu for 0.3s [7, 5]. Conventional hardware-based protection methods, such as crowbar circuits, braking resistors, and Dynamic Voltage Restorers (DVRs), have shortcomings, such as increased losses, thermal stress, and limited adaptability [8−11]. A preferable option is to use Flexible AC Transmission System (FACTS) devices, particularly static synchronous compensators (STATCOM). Without requiring significant turbine modifications, a STATCOM can quickly offer dynamic reactive power assistance, enhance voltage stability, reduce post-fault oscillation, and improve LVRT performance [12, 13]. The goal of this design is to use a STATCOM to enhance the LVRT capability of a DFIG-based wind microgrid. The system model was created in MATLAB/Simulink and evaluated under symmetrical and asymmetrical failures to assess the system stability, reactive power supply, and voltage recovery.

LITERATURE REVIEW

The sudden switch to renewable energy worldwide has made wind energy a mainstay in today's power systems because of its scalability, technological maturity, and declining cost. Comprehensive studies on the global energy transition emphasize the need for the large-scale deployment of renewable energy sources to combat climate change and achieve sustainable development goals. However, the increasing penetration of wind energy, particularly in developing and weak grid areas, has raised major technical challenges, such as grid stability, voltage regulation, and fault ride capability [1, 2]. The variable-speed operation, high efficiency, and separate control of the active and reactive power of DFIG-based wind turbines have led to their widespread adoption. Numerous investigations on the steady-state and dynamic behaviors of DFIG under different control and magnetization schemes have been conducted, demonstrating that an effective control design can significantly improve the operational reliability and efficiency [3]. Despite these benefits, DFIGs are prone to grid disturbances, particularly voltage sags. Such disturbances may lead to excessive rotor currents, DC link overvoltages, and converter stress, and may lead to disconnection from the grid, thus violating modern grid code requirements [4, 5, 8]. To meet the Low-Voltage Ride-Through (LVRT) requirements, various protection and check strategies have been suggested. Conventional methods, such as crowbar circuits and braking resistors, are efficient in protecting power converters from faults; however, they come at the cost of reactive power control ability, which results in reduced voltage support and adversely affects the overall system stability [8, 11].

Advanced control-based solutions, such as disturbance feedforward control, nonlinear rotor-side control, and coordinated converter control, have demonstrated improvements in transient performance without the need for additional hardware. However, these methods are often characterized by complex control structures and sensitivity to parameter variations under uncertain operating conditions [4, 6, 14]. External compensation devices, especially Flexible AC Transmission System (FACTS) controllers, have attracted considerable interest in enhancing LVRT. Devices such as Dynamic Voltage Restorers (DVRs), Fault Current Limiters (FCLs), and Static Synchronous Compensators (STATCOMs) have been widely studied to reduce voltage sags and enhance fault tolerance in DFIG-based wind energy systems [9, 11, 15]. Among these, STATCOM is the most popular because of its fast dynamic response, better reactive power compensation capability, and ease of integration at the point of common coupling (PCC). Several studies have shown that STATCOM-assisted DFIG systems have improved voltage recovery, fewer post-fault oscillations, and better compliance with grid codes in the case of symmetrical and asymmetrical faults [12, 13].

PROBLEM STATEMENT

Because of frequent voltage dips and grid faults, Doubly Fed Induction Generator (DFIG)-based wind turbines (WT) connected to weak AC grids are prone to considerable Low-Voltage Ride-Through (LVRT) problems. Any voltage sag has a direct impact on the generator because the stator of the DFIG is directly connected to the electrical grid. This can cause excessive rotor currents, DC link overvoltages, and converter tripping. These faults may cause the wind turbine to be disconnected from the grid, violating current grid code regulations [4, 5, 8]. The problem becomes more severe in wind-based microgrids, where a low short-circuit capacity is another factor that worsens voltage instability during fault conditions [9].

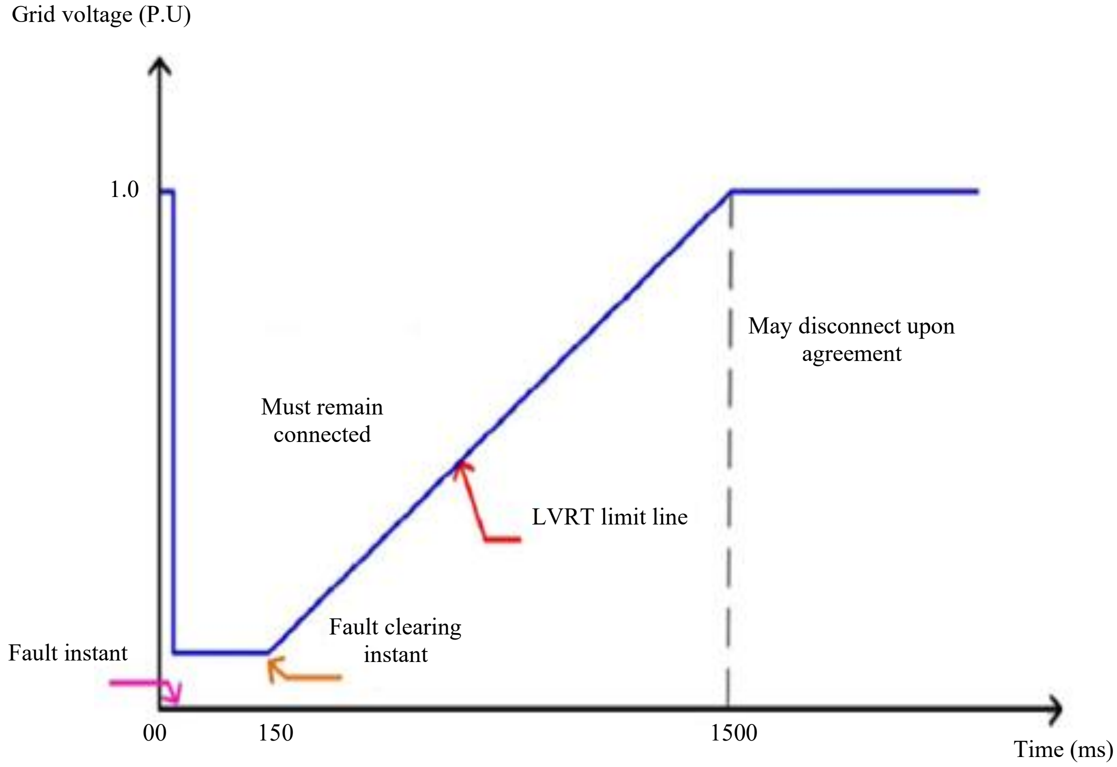

Figure 1. Standard low-voltage ride through (LVRT) characteristics.

To overcome the problems of LVRT, various hardware-based protection schemes have been used, such as crowbar circuits, braking resistors, and fault current limiters. Although these approaches are effective for protecting the converter in fault situations, they often cause a loss of reactive power control or introduce extra losses, which reduce the voltage support capacity and compromise the changing performance of the system [8, 11, 15]. Control-based methods, such as nonlinear control strategies and disturbance feedforward approaches, have also been proposed for better fault response.

However, these techniques usually have complicated control structures and suffer from parameter variations, which reduce their robustness under practical operating conditions [4, 6, 14]. FACTS devices, mainly Static Synchronous Compensators (STATCOMs), have been widely used to upgrade the LVRT capability because of their fast dynamic response and excellent reactive power compensation capability [7, 12, 13]. By delivering fast sensitive power support at the point of common coupling (PCC), the stability of the voltage and fault recovery performance are improved significantly using STATCOM. Therefore, there is a great need for the design and development of an optimized and robust STATCOM control strategy that can ensure balanced active and reactive power support, PCC voltage stabilization, reduction of power oscillations, and reliable LVRT performance under symmetrical and unsymmetrical grid fault conditions [1, 2, 7].

LVRT REQUIREMENTS AND FAULT SCENARIOS

Figure 1 shows the LVRT conditions, which specify the minimum voltage magnitude and time that wind turbines should be linked to the grid in the case of a malfunction and are subject to extremely strict regulations in modern grid standards. These LVRT profiles are aimed at preventing the large-scale disconnection of wind generation and facilitating grid voltage stability in the case of disturbances [7, 5]. In this study, the DFIG-based microgrid was tested with symmetrical and unsymmetrical faults to thoroughly examine the LVRT performance of the microgrid. Severe symmetrical faults, such as three-line-to-ground (3LG), are worst-case scenarios because of their serious consequences on the collapse of the voltage and power oscillations. One-sided faults, such as single line-to-ground (SLG) faults, are also considered, as this type of fault is more frequent in practical distribution systems and causes unbalanced voltage conditions [4, 9, 14]. The depth of the voltage sag and fault clearing period were chosen in compliance with the popularly adopted international grid code requirements for wind energy systems. These conditions ensure that the suggested control strategy is tested in realistic and stringent operational scenarios pertinent to wind-based microgrids that operate in a weak grid environment [5, 7, 15].

STATCOM CONFIGURATION AND CONTROL

The compensating device, as shown in Figure 2, a STATCOM, is located at the PCC of the microgrid to achieve fast and dynamic reactive power assistance during grid disturbances. It mainly comprises a voltage source converter (VSC), a DC link capacitor, and coupling inductors to interface the converter with the grid [9, 10]. Owing to its shunt-connected configuration, the STATCOM can put in or grip reactive current independent of the grid voltage, thereby making it very effective for voltage regulation under fault conditions [12, 13]. The operation of the STATCOM is based on a synchronous dq-axis control approach, in which the DC-link voltage is maintained by assuring reactive power with the d-axis current and active power exchange with the q-axis current [7]. This control structure enables the independent regulation of reactive power and DC link voltage. This feature is Essential during LVRT events to ensure that the system remains stable despite weak grid conditions [9, 12]. Proportional-integral (PI) controller: Because of its simplicity, ease of construction, and excellent performance in real-world power system applications, proportional-integral controllers are frequently employed for controlling STATCOM control loops [8, 15]. However, proper tuning of the proportional and integral gains is critical to ensure fast voltage recovery, reduced oscillations, and stable operation during symmetrical and unsymmetrical faults [4, 8]. The theoretical basis of the design of the STATCOM controller is the reactive power correction and voltage regulation principle. The control architecture usually has a hierarchical loop structure [10, 12]. The outer voltage control loop ensures the stability of the PCC voltage by comparing the measured voltage with its reference and providing the corresponding reactive current reference. The inner current control loop tracks this reference while simultaneously regulating the inverter switching signals to manage the reactive power injection. Furthermore, a DC-Link Volt Control loop is employed to guarantee voltage balance between the DC capacitor [9] by regulating the active power exchange through the converter.

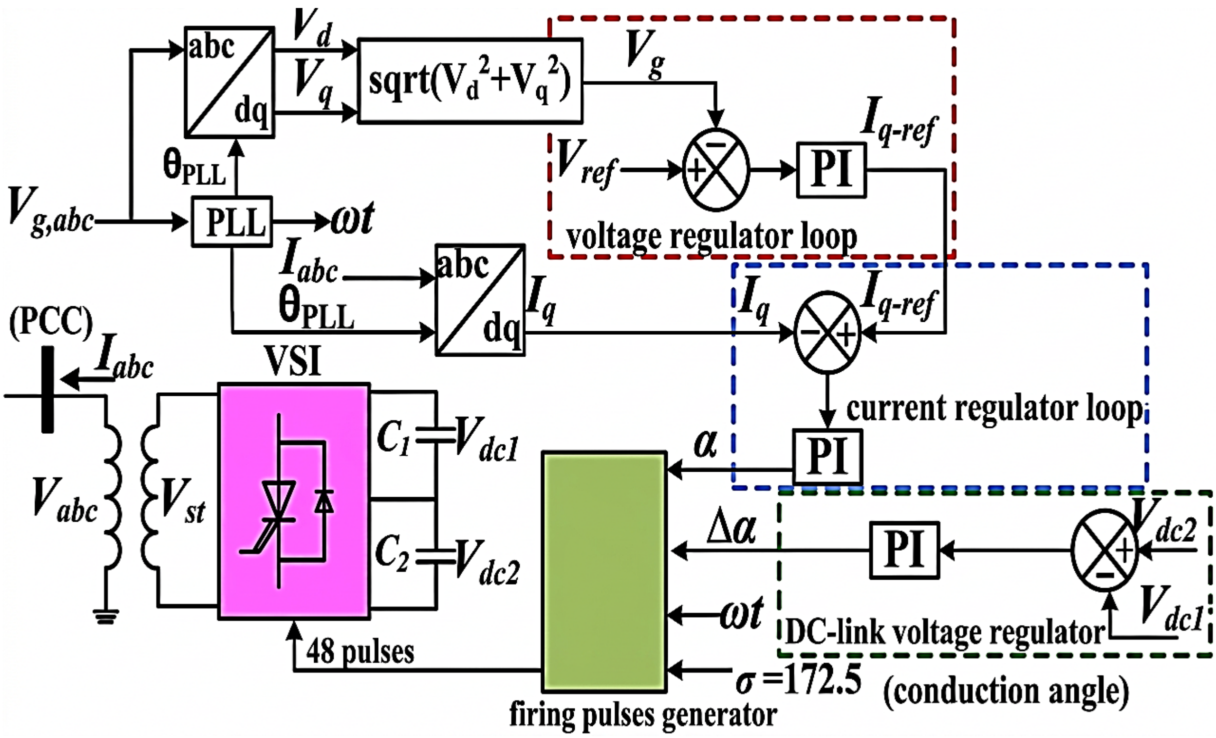

Figure 2. Static synchronous compensator (STATCOM) control scheme.

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SIMULATION AND RESULTS

The PI controller transfer method is given by

$$G(s) = Kp + \frac{K_i}{s}$$

where Kp and Ki stand for integral and relative gains, respectively. In the case of STATCOM applications, these parameters should be carefully selected to address the nonlinear dynamics of the grid and fault-induced transients. Poor tuning can lead to instability, excessive overshoot, or long voltage recovery under LVRT conditions [4, 8].

Simulation of the Grid Connected Microgrid

Figure 3 shows the Simulink model of our DFIG-based wind microgrid integrated with a STATCOM for LVRT analysis. Starting from the left side, we have the main grid source, which provides 69 kV at 60 Hz. This is the utility grid connected to our microgrid system. Next, the power passes through a 100 MVA transformer that reduces the voltage from 69 kV to 25 kV. This transformer helps connect the high-voltage grid to the lower-voltage microgrid. We have several lines (Line 1, Line 2, Line 3, etc.) that connect different buses from Bus 1 to Bus 12. Each line and bus exists for different parts of the microgrid network that carry power or 25 kV or 0.48 kV. The microgrid system is shown in the blue shaded area. Here, several distribution transformers (T2, T3, T4, T5, and T6) are connected to step down the voltage to 0.48 kV and 0.6 kV for different loads and wind turbines. On the bottom right, we have the 16 MW Wind Farm, which is eight 2 MW DFIG-based wind turbines. These DFIGs convert wind energy into electrical energy, and the output of these DFIGs is connected to Bus 12 using a 25/0.6 kV transformer. The DFIG Wind Turbine block provides important electrical outputs, such as DC-link voltage (V_{dc}), rotor speed (ω_r), active power (P), and reactive power (Q). Moving slightly upward, the fault block connected at Bus 2 can be observed; this is used to simulate different kinds of grid faults, such as LLLG, LLG, or LG faults, to test the LVRT capacity of the method. The STATCOM system is shown on the left side of the diagram. In a two-phase system, the following functions are performed: -

- The STATCOM measures the voltage (V_{abc}), current (I_{abc}), and DC link voltage (Vdc) from Bus 2.
- Consequently, the output of the HMI could be read within a +-667 V range. Consequently, a Phase-Locked Loop (PLL) was utilized to synchronize the grid frequency and phase.
- The control system calculates the active (P) and reactive (Q) power, and the PI controllers inside the STATCOM are used to generate the control signals based on the results of this calculation.
- At the grid voltage in response to faults, the Voltage Source Inverter (VSI) injects or absorbs reactive power as required; therefore, these signals control this.

At the center bottom, the Scope and PowerGUI blocks are used to monitor the waveform and control the simulation parameters with a discrete step size of 5e-6 s. Therefore, this complete Simulink model represents how the DFIG-based wind microgrid interacts with the main grid, how faults affect the stability of the system, and how the use of STATCOM helps to maintain voltage stability as well as LVRT performance.

The steady-state performance of the wind farm is illustrated through the three-phase voltage and current waveforms at the wind farm bus, PCC voltage profile, and active/reactive power responses under normal operating conditions (Figures 4–8). The system behavior under fault conditions without STATCOM compensation, including L–G, L–L–G, and L–L–L–G faults, is presented in Figures 9–14, showing a significant voltage sag at the PCC. The effectiveness of the STATCOM in enhancing fault ride-through capability, voltage support, and power compensation during L–G, L–L–G, and L–L–L–G faults is shown in Figures 15–22.

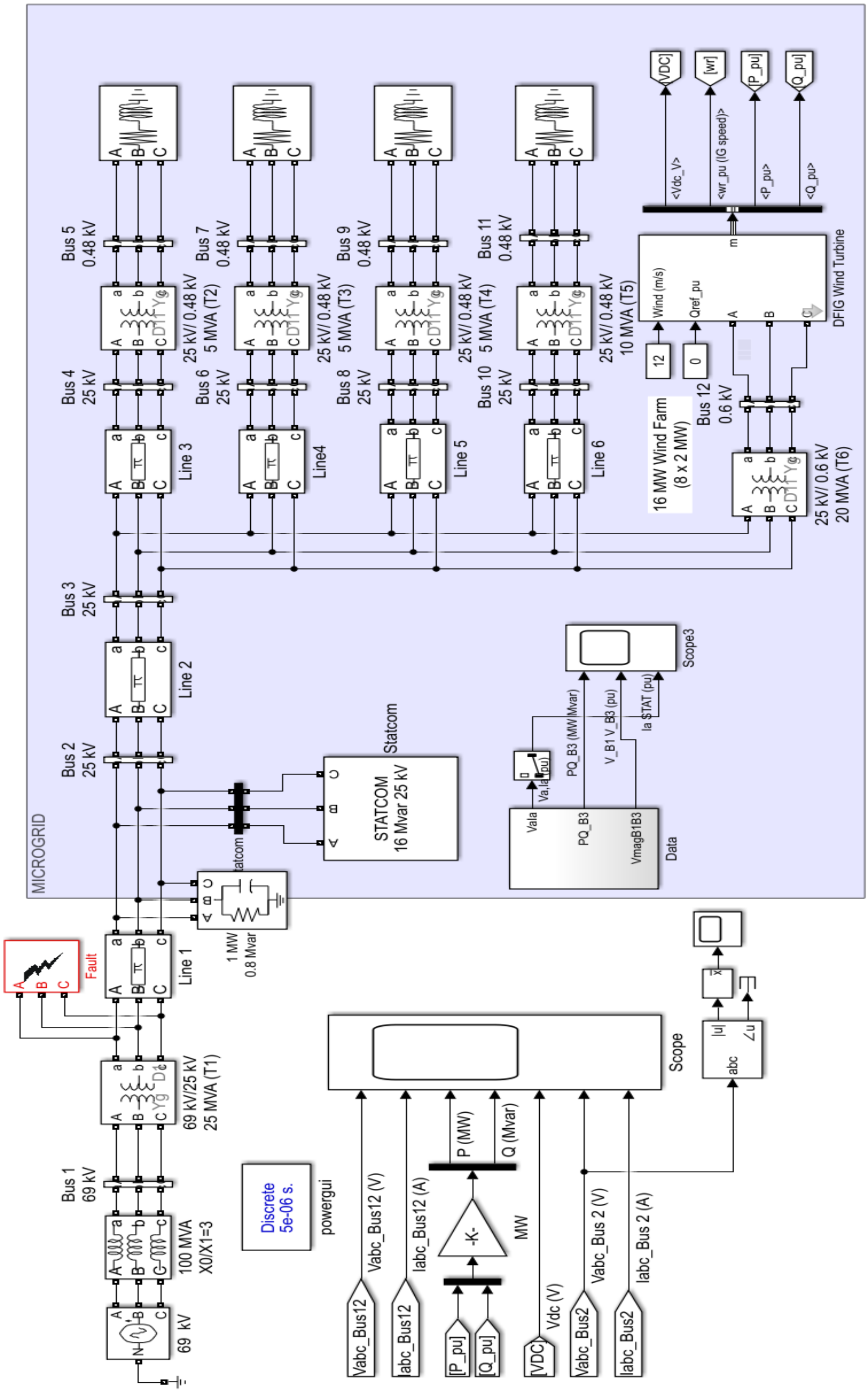

Figure 3. MATLAB/simulink model of the grid connected microgrid.

RESULTS WITHOUT STATCOM

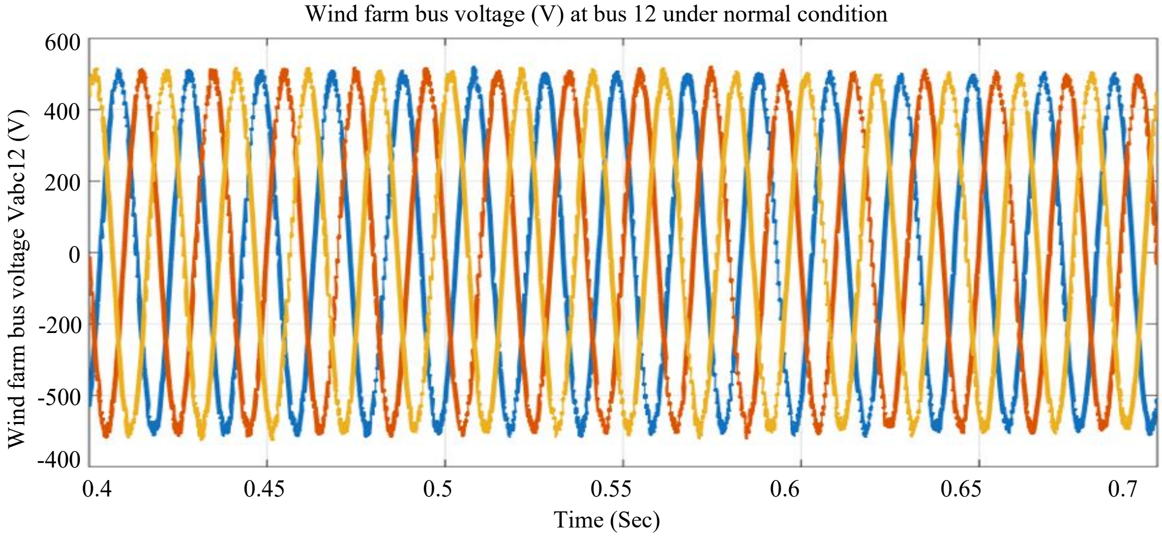

Figure 4. Three phase voltage at wind farm bus beneath normal conditions.

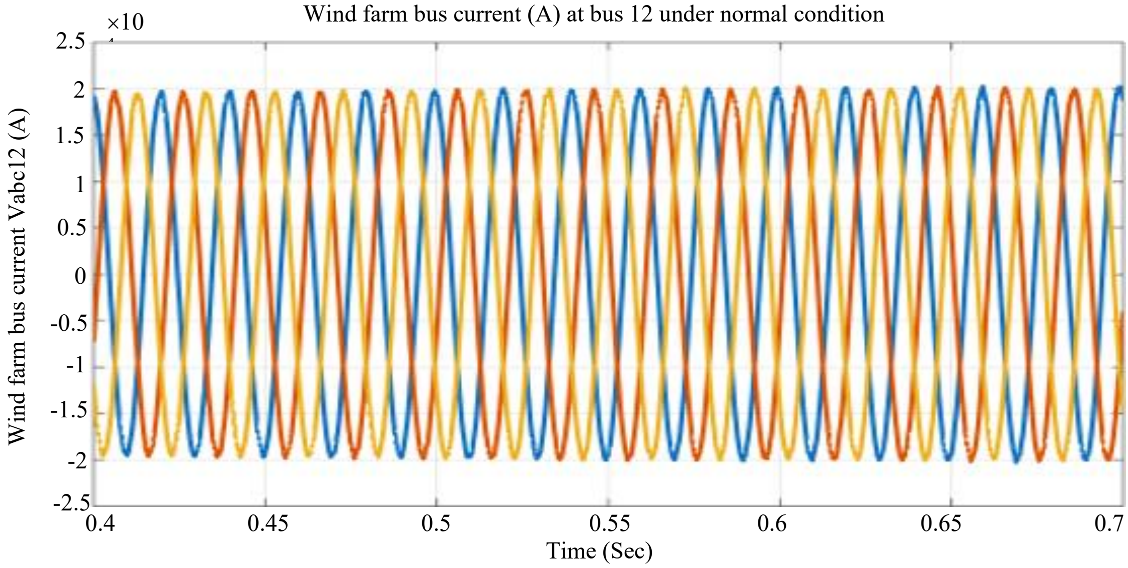

Figure 5. Three phase current at wind farm bus beneath normal condition.

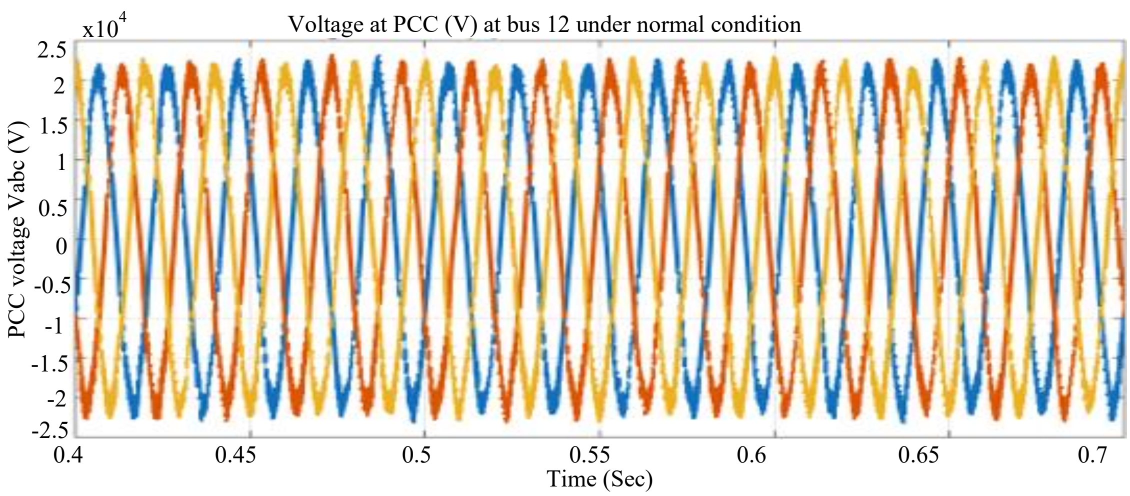

Figure 6. Under typical circumstances, three-phase voltage at the point of common coupling (PCC).

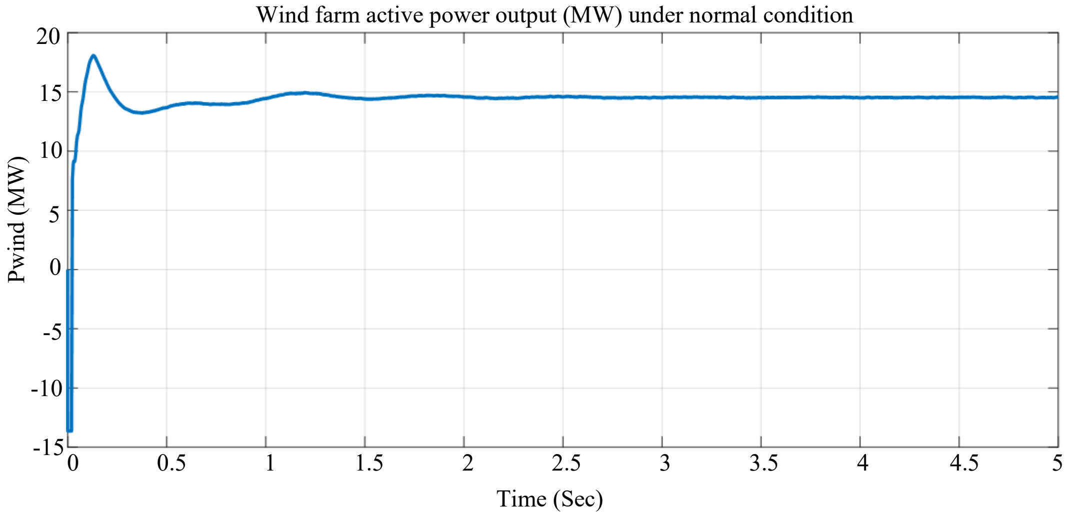

Figure 7. Active power communicated by wind farm beneath normal conditions.

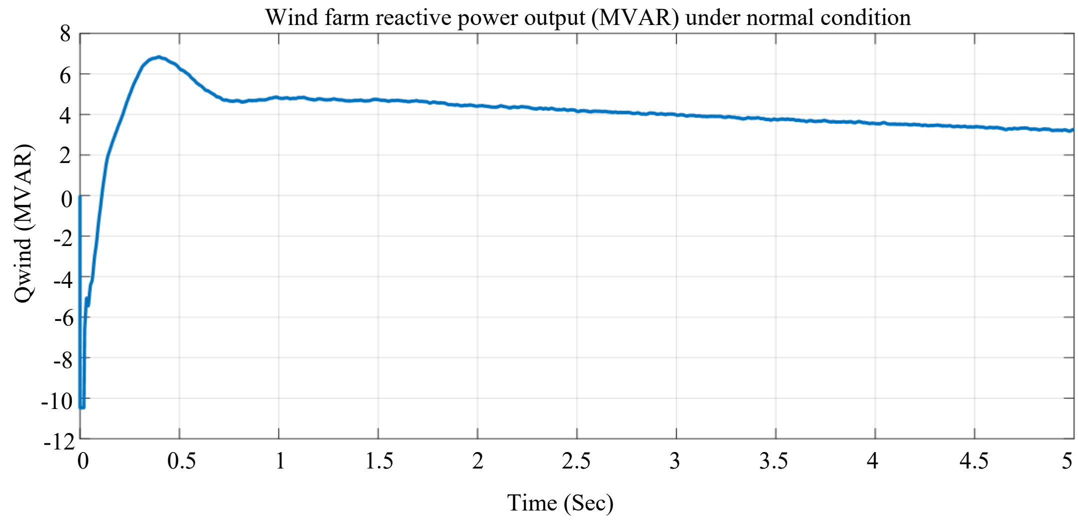

Figure 8. Reactive power delivered by wind farm under normal conditions.

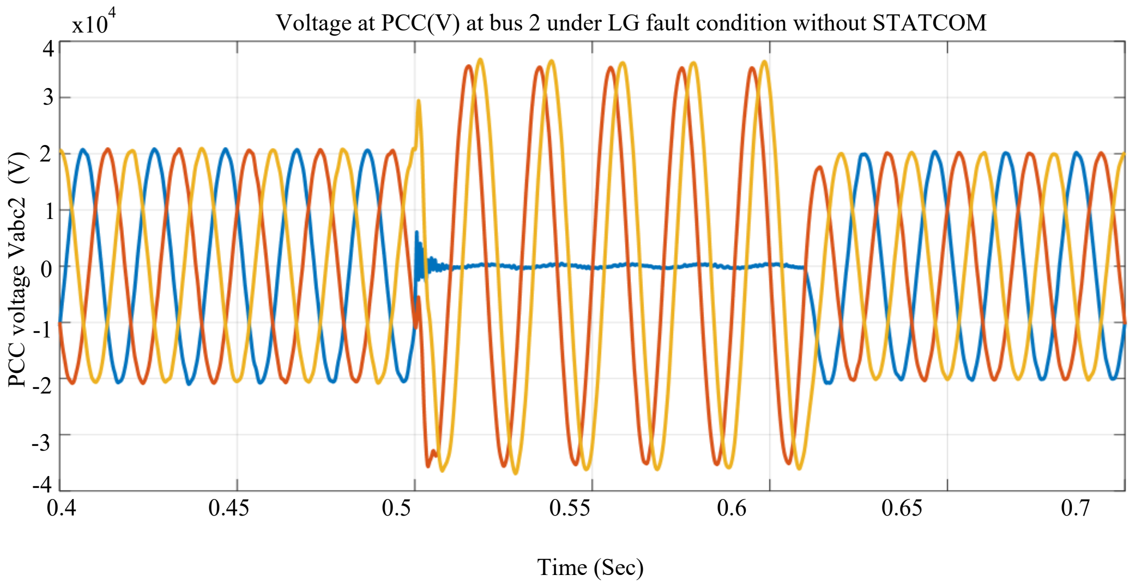

Figure 9. Three phase voltage at wind farm bus under L-G fault (0.5–0.6 sec) condition.

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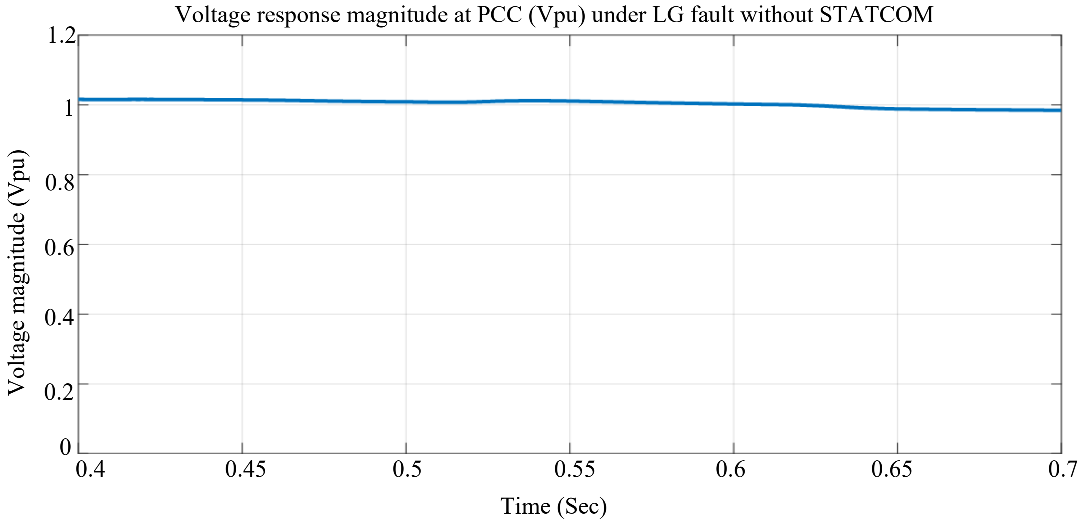

Figure 10. Magnitude of voltage response (pu) at PCC beneath L-G fault without STATCOM.

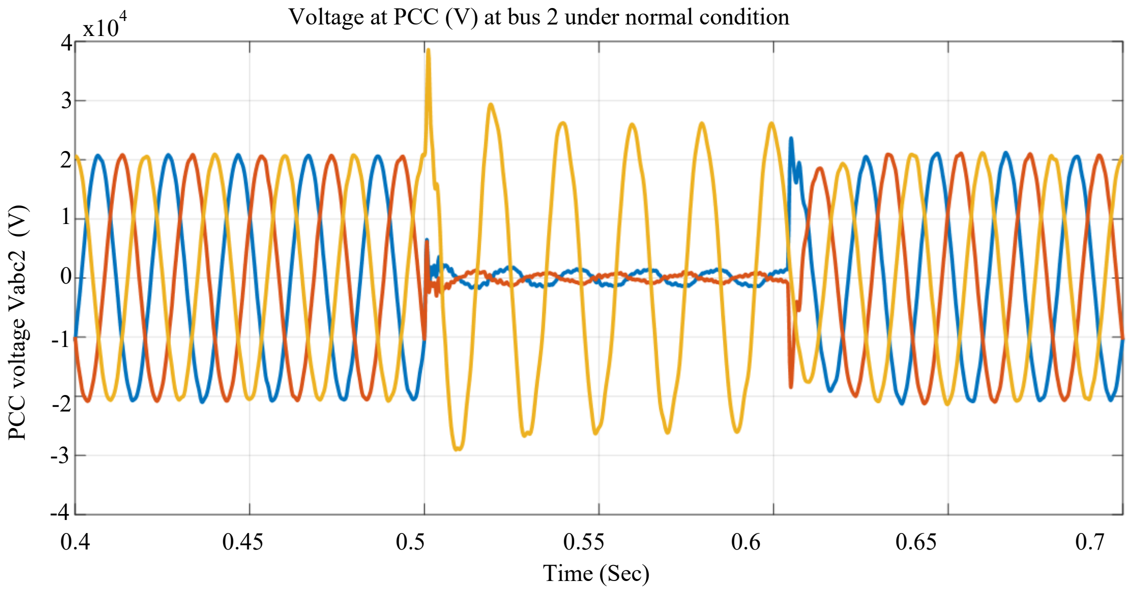

Figure 11. Three phase V at wind farm bus under L-L-G fault (0.5–0.6 sec).

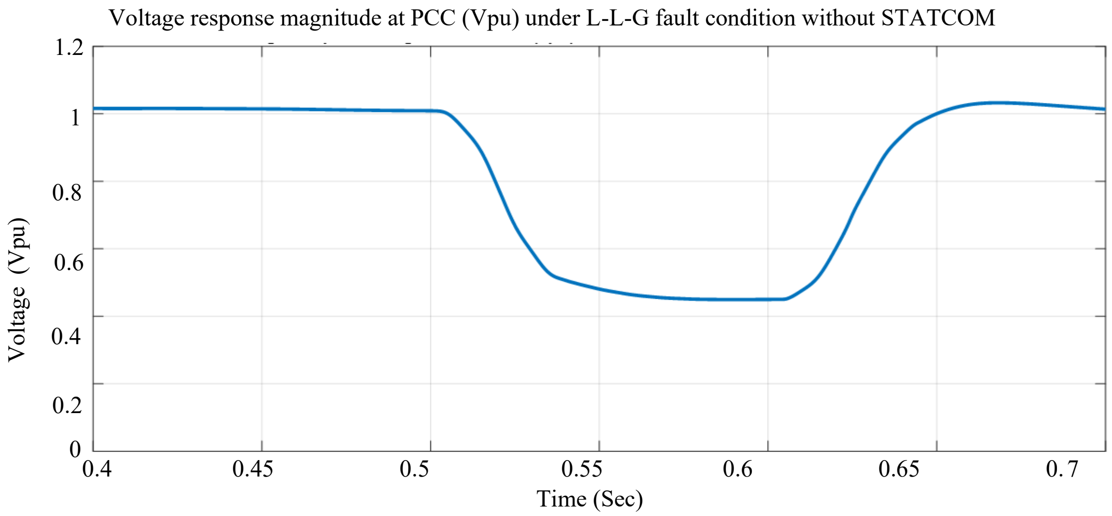

Figure 12. Magnitude of voltage response (pu) at PCC beneath L-L-G fault without STATCOM.

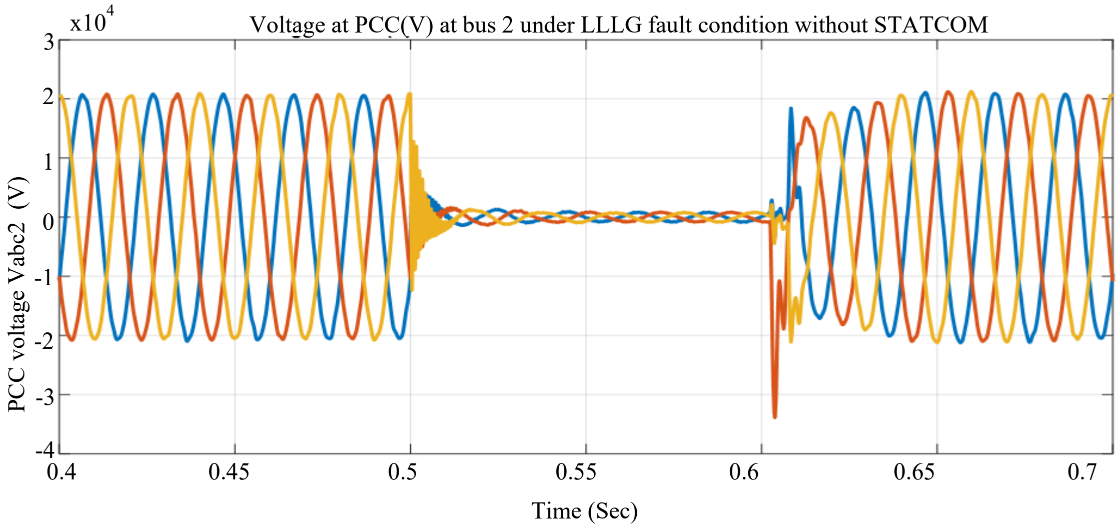

Figure 13. Three phase voltage at wind farm bus beneath L-L-L-G fault without STATCOM.

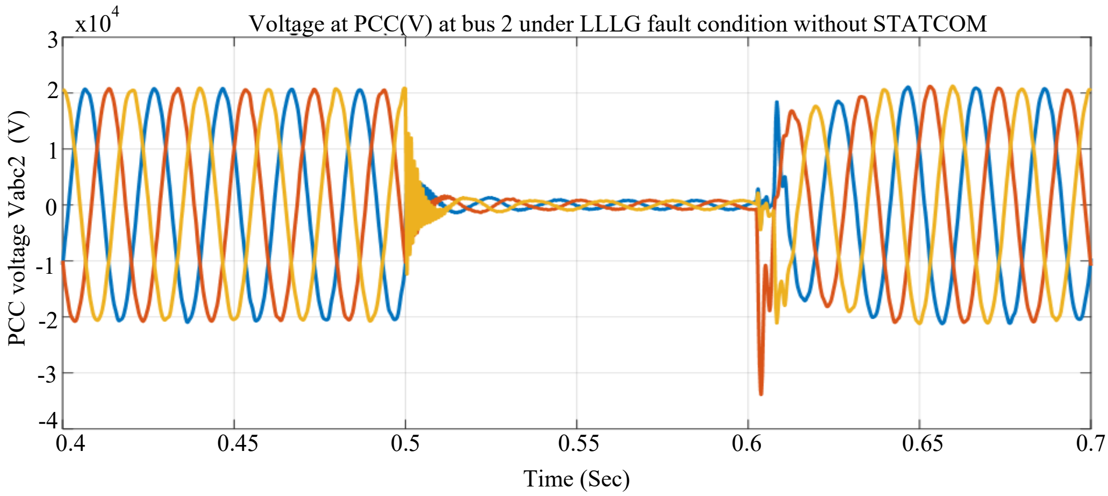

Figure 14. Magnitude of voltage response (pu) at PCC beneath L-L-L-G fault without STATCOM.

RESULTS WITH STATCOM

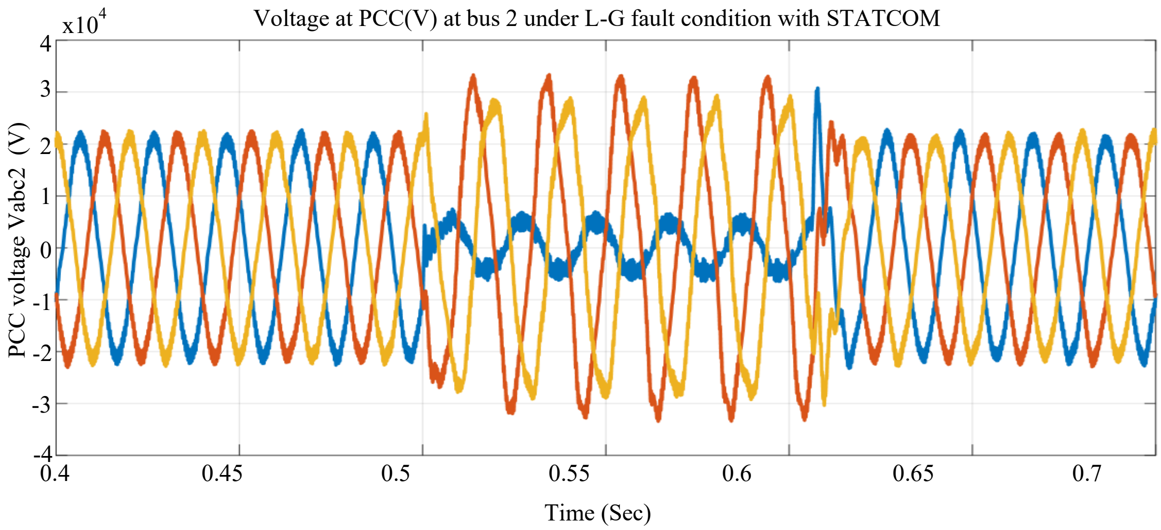

Figure 15. Three phase voltage at wind farm bus beneath L-G fault with STATCOM.

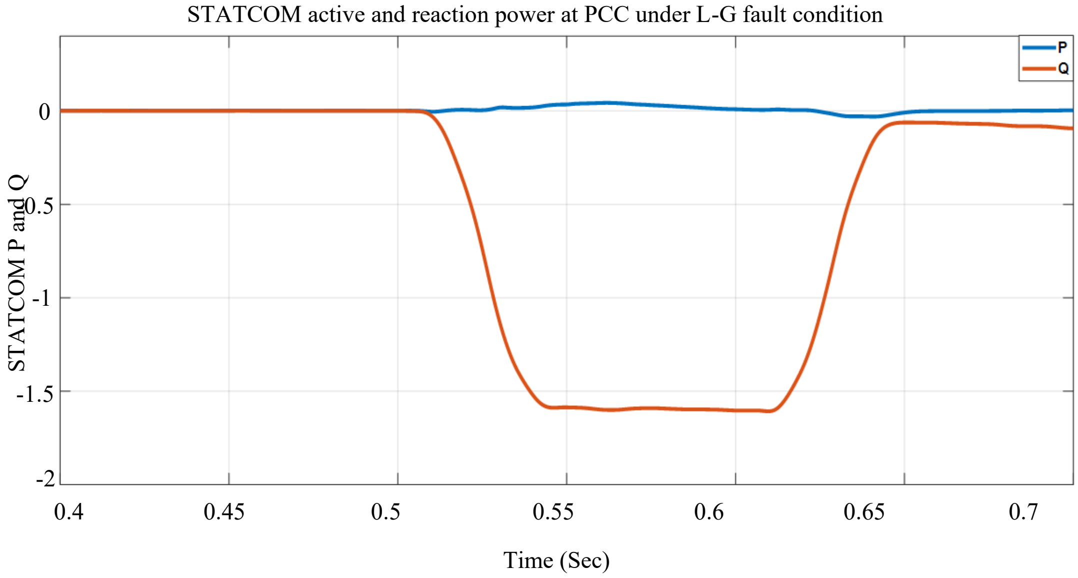

Figure 16. Active and reactive power injected at PCC beneath L-G fault with STATCOM.

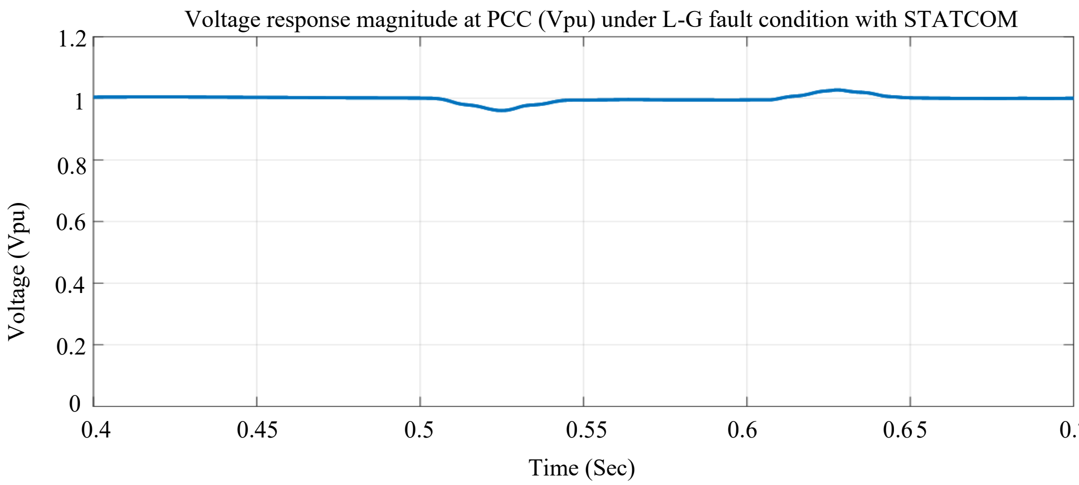

Figure 17. Magnitude of voltage response (pu) at PCC beneath L-G fault with STATCOM.

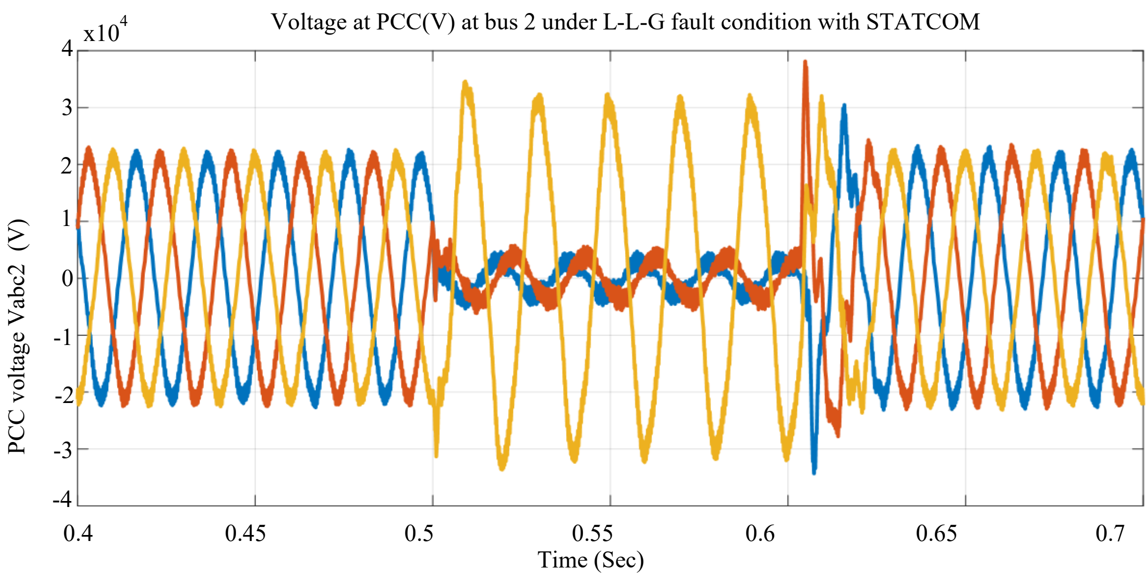

Figure 18. Three phase voltage at wind farm bus beneath L-L-G fault with STATCOM.

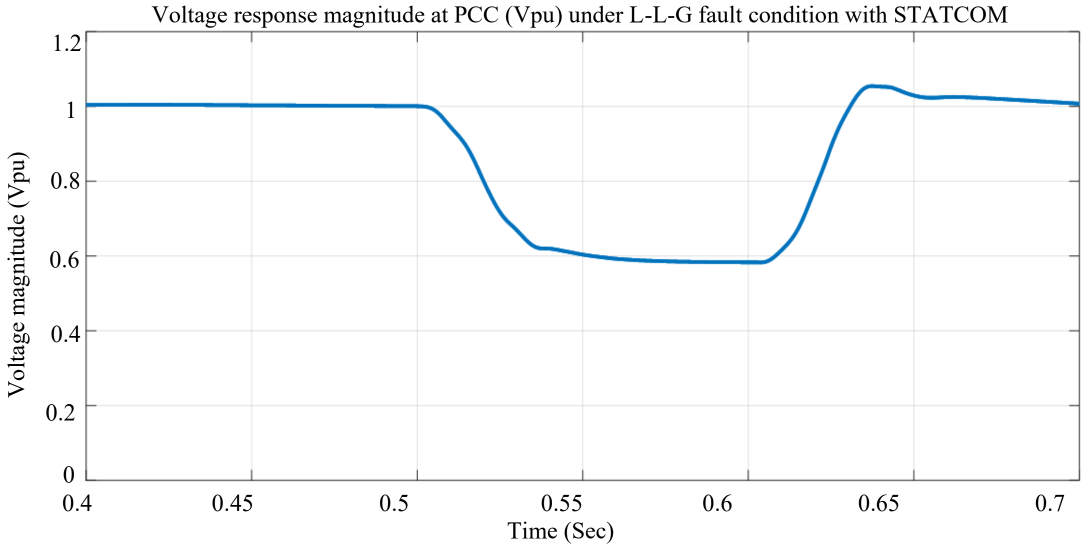

Figure 19. Magnitude of voltage response (pu) at PCC beneath L-L-G fault with STATCOM.

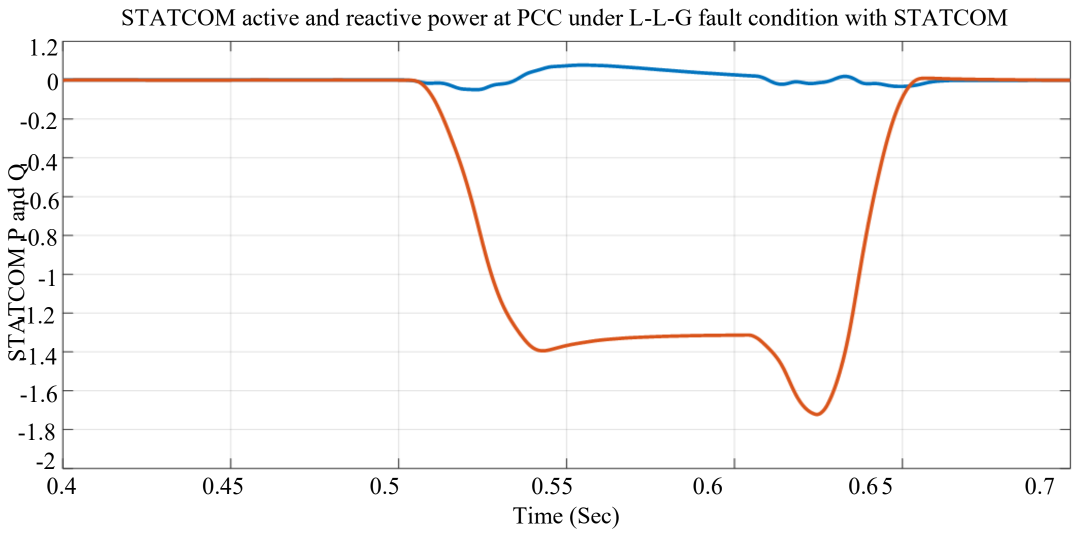

Figure 20. Active and reactive power put in at PCC beneath L-L-G fault with STATCOM.

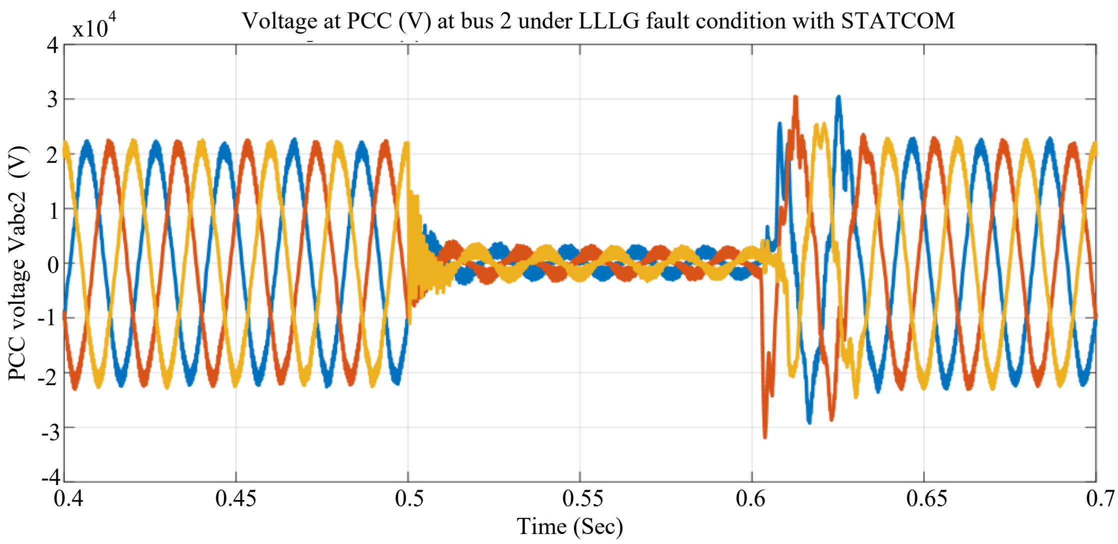

Figure 21. 3-phase voltage at wind farm bus beneath L-L-L-G fault with STATCOM.

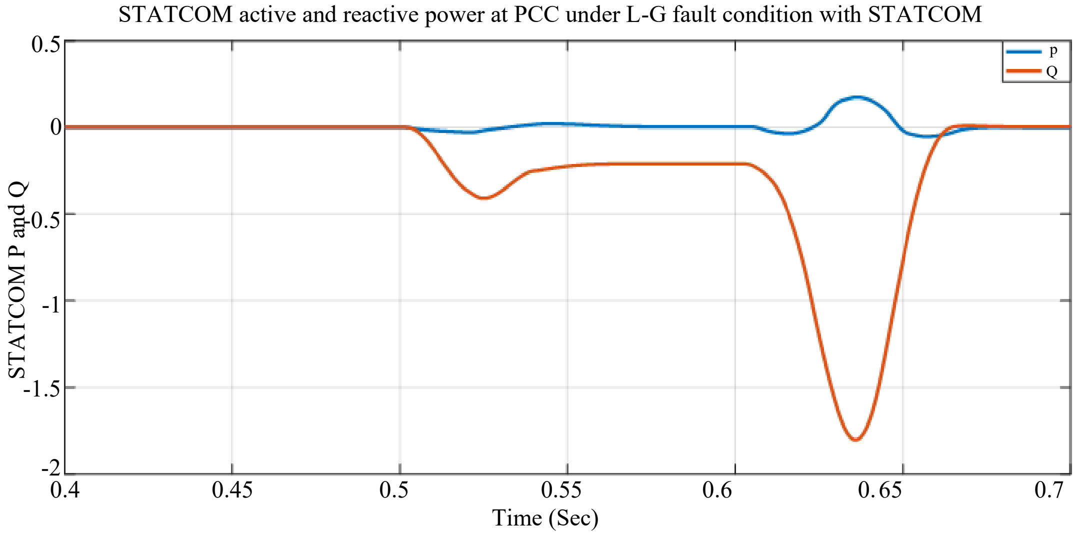

Figure 22. Active and reactive power put in at PCC beneath L-L-L-G fault with STATCOM.

CONCLUSION

This paper presents an effective approach for improving the low-voltage ride-through (LVRT) capability of a Doubly Fed Induction Generator (DFIG)-based wind microgrid using a Static Synchronous Compensator (STATCOM) with a PI controller. The proposed method successfully addresses the limitations of conventional LVRT enhancement techniques by providing improved voltage support and reactive power compensation during grid disturbances. A detailed simulation study was conducted under various fault conditions to evaluate the performance of the system. The results demonstrated significant improvements in voltage recovery, reduction in voltage sag, suppression of post-fault oscillations, and enhancement of overall system stability. Furthermore, the STATCOM-assisted control strategy enabled the wind microgrid to maintain operation during severe symmetrical and asymmetrical faults while satisfying the modern grid code requirements. The improved dynamic response and voltage regulation capability contribute to better fault ride-through performance and increased reliability of the grid-connected wind energy system. Overall, the findings confirm that the proposed STATCOM-based LVRT enhancement approach is an effective and reliable solution for strengthening the stability and resilience of DFIG-based microgrids under adverse grid conditions. The developed system can serve as a practical solution for ensuring the secure and continuous integration of renewable energy sources into modern power networks.

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