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Performance Analysis of Photovoltaic and Wind Turbine Grid-Connected Systems under LVRT Conditions

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ABSTRACT

The integration of grid-connected renewable energy systems has gained significant attention and introduces several challenges and considerations. One of these challenges is ensuring the reliable and stable operation of these systems under various grid conditions. For example, faults at the grid could lead problems such as DC-link over-voltage and AC over-current that may cause disconnection or damage to inverter. This paper presents a comprehensive analysis of the performance of photovoltaic (PV) and doubly-fed induction generator (DFIG) wind turbine grid-connected systems under low voltage ride-through (LVRT) conditions. The study aims to investigate their behavior, and stability during LVRT events and provide insights for enhancing their grid integration capabilities. The PV and DFIG systems are modelled and simulated using MATLAB Simulink under three difference conditions, with and without using reactive current injection and DC chopper circuit. Various performance parameters, including grid voltage, grid current, DC-link voltage, active power, and reactive power, are analyzed to assess the system's behavior and compare their responses. The principal results reveal distinct performance characteristics of the PV and DFIG systems. The PV system shows higher overshoot currents, over-voltage, and significant drops in active power during fault occurrences, while the DFIG system exhibits lower overshoot currents and better stability in the DC-link voltage. Reactive power responses differ between the systems, with the PV system demonstrating a higher capability for support. The implementation of DC chopper shows more effective in the reduction of DC-link voltage and overshoot grid current in the PV system compared to the DFIG system.

1. Introduction

Renewable energy systems, such as photovoltaic (PV) and wind turbine installations, have gained significant attention in recent years due to their potential to reduce greenhouse gas emissions, enhance energy sustainability, and diversify the energy mix. Grid-connected renewable energy

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systems play a crucial role in integrating clean energy sources into the existing power grid infrastructure. These systems enable the efficient utilization of renewable energy resources and facilitate the transition towards a more sustainable and environmentally friendly energy generation paradigm [1-3]. The deployment of grid-connected PV and wind turbine systems has seen remarkable growth worldwide, driven by advancements in technology, policy support, and the increasing global demand for clean energy. PV systems harness solar energy, converting it into electricity through the photovoltaic effect, while wind turbines capture the kinetic energy of wind and convert it into electrical power. Both PV and wind turbine systems are highly scalable, offering flexibility in deployment for various applications, ranging from residential and commercial installations to utility-scale power plants [1,4-6]. The integration of grid-connected renewable energy systems introduces several challenges and considerations, one of which is the reliable and stable operation of these systems under various grid conditions. Faults at the grid such as voltage dips or sags could lead problems such as DC-link over-voltage and AC over-current that may cause disconnection or damage to inverter. It is essential for renewable energy systems to remain connected, continue operating and protect electrical components during these faults to ensure grid stability and reliability [7,8].

In this study, doubly fed induction generator (DFIG) is chosen among wind turbine system due to its advantages in variable-speed operation and power quality management [8,9]. Numerous studies have explored low voltage ride-through (LVRT) capability of DFIG-based wind turbines and proposed control strategies to enhance their performance during grid disturbances [10-12]. The analysis of DFIG-based wind turbines specifically allows for a comprehensive examination of the control methods and challenges unique to this system configuration. On the other hand, PV systems also face challenges during LVRT events. Voltage dips can adversely affect the output power and stability of PV systems. To address these challenges, various control techniques and grid-support functionalities have been investigated, including maximum power point tracking (MPPT) control, voltage regulation, and reactive power injection strategies [13-17]. These studies have explored methods to improve the performance of PV systems and ensure their compliance with LVRT requirements.

Grid codes and regulations define the LVRT requirements for grid-connected renewable energy systems, including PV and wind turbine systems. These standards ensure the safe and reliable integration of renewable energy into the grid. LVRT events pose several challenges for both PV and DFIG-based wind turbine systems. Reactive current and power injection during faults is essential to stabilize the grid voltage. Control strategies, such as voltage control and current injection techniques, have been proposed to enhance the LVRT capability of PV and DFIG-based wind turbines [18-24]. These strategies aim to ensure seamless operation and grid stability during voltage dips. Another challenge is related to the protection and control mechanisms within the DFIG system. The rotor-side converter (RSC) of the DFIG plays a crucial role in maintaining system stability during LVRT events. Control strategies, such as DC chopper, crowbar protection, rotor current control, and grid synchronization techniques, have been investigated to enhance the LVRT capability of DFIG-based wind turbines [25-27]. These methods enable the DFIG system to ride through voltage dips and maintain stable operation. Previous studies mainly focused on the performance analysis of individual systems. However, there has been no study conducted for a comparative analysis of electrical performances for both PV and DFIG systems during grid fault conditions. Such a comparative analysis becomes crucial when planning the design and development of a hybrid generation system or studying an energy management system. For example, it helps in deciding which power source needs to be turned on or off during specific times and conditions. Therefore, this paper proposes a comprehensive analysis of electrical performances for both PV and DFIG systems.

2. Methodology
2.1 Modelling and Simulation Conditions

In this study, the performance analysis of a grid-connected photovoltaic (PV) system and a doubly fed induction generator (DFIG) wind turbine system under low voltage ride-through (LVRT) conditions was conducted using MATLAB Simulink. The simulation platform allows for a detailed investigation of the system behavior and control strategies during LVRT events. Both the PV and DFIG grid-connected systems were configured with parameters aligned with the utility grid. Figure 1 and Figure 2 show the block diagram of grid-connected PV system and DFIG system, respectively, while Table 1 presents the relevant parameters of the PV system and DFIG system. The PV system was designed to generate 1.5 MW of power with a DC-link voltage of 800 V. The DFIG system, on the other hand, generated 1.5 MW of power with a DC-link voltage of 575 V. All these parameters have been converted into per unit values in the simulation results in order to make appropriate comparison.

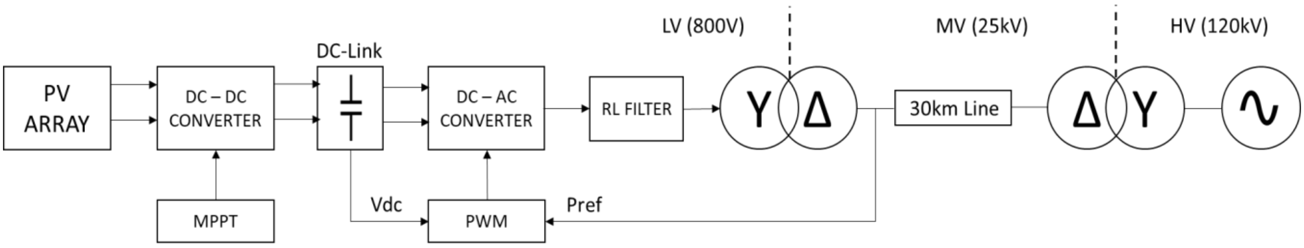


Fig. 1. Block diagram of grid-connected PV system

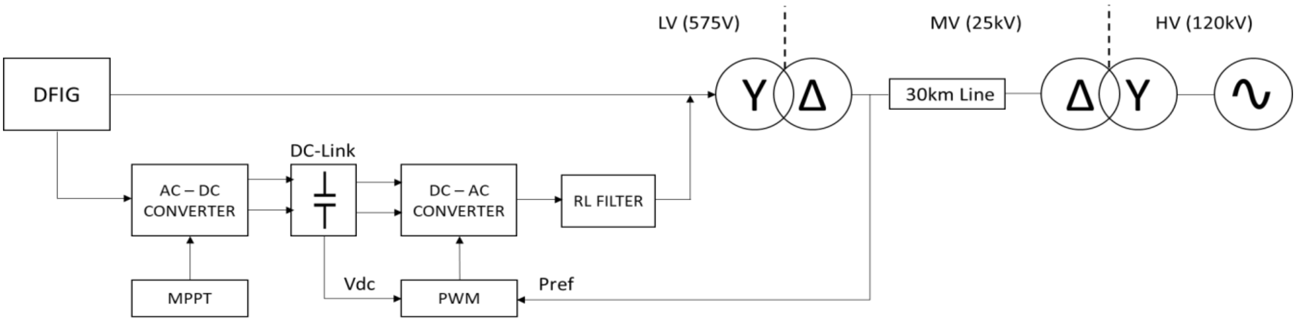


Fig. 2. Block diagram of grid-connected DFIG system

Table 1
Parameters of PV system and DFIG system

PV system	Value	DFIG system	Value
Maximum power	1.5 MW	Maximum power	1.5 MW
Maximum voltage	800 V	Maximum voltage	575 V
Maximum current	1.88 kA	Maximum current	2.61 kA
DC-link voltage	800 V	DC-link voltage	575 V
Irradiance	1000 W/m^2	Wind speed	10 m/s
Temperature	25^{o}C		

2.2 DC Chopper as DC-link Protection

During grid faults, there is an imbalance between the grid and the PV or wind turbine. This will lead to an increase in the DC-link voltage and may damage the power electronic devices. According to the LVRT requirement, it is necessary to reduce the DC-link voltage of the systems to ensure stable operation and avoid damage of electrical components. To achieve this, a DC chopper circuit is implemented. Figure 3 shows the schematic diagram of the DC chopper circuit. The DC chopper is a simple protection device connected in parallel with DC-link capacitors. It comprises of a switch such as the insulated-gate bipolar transistor (IGBT) with a series of high-power resistor ($R_{chopper}$). This braking chopper is effective to protect the inverter against over-voltage that happens due to the increase in the DC-link voltage during faults. It will be activated when the fault is detected. Therefore, the gate pulse of the IGBT will be switched on, whereby the excess energy generated by PV or wind turbine will be absorbed by the high-power resistor and keep the power balance between DC and AC sides of the inverter.

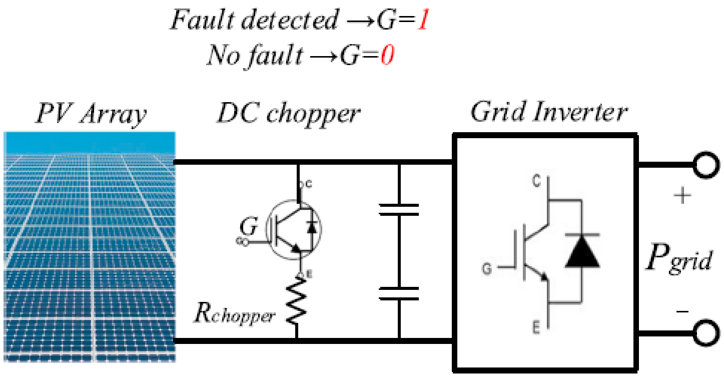


Fig. 3. DC chopper circuit for DC-link protection

2.3 Reactive Current Injection for Grid Voltage Support

The LVRT requirements are specified in the modern grid codes (GCs). It requires the grid-connected system to withstand grid voltage dip to a certain percentage of the nominal voltage (down to 0 in some GCs) for a specific duration. In this duration, the grid-connected system should operate normally. After fault clearance, the grid-connected system must restore active and reactive power fast enough to the pre-fault value. In some countries, the grid-connected system is required to operate like traditional synchronous generators where reactive current should be fed into the grid to support voltage stability. Normally, the LVRT requirements are characterized with a voltage-vs-time graph as shown in Figure 4, which illustrates general LVRT requirements for the grid-connected system. The grid-connected system is required to work continuously in area A, which represents the nominal voltage at the connection point, that so-called point of common coupling (PCC). If the voltage is in area B, the systems have to withstand voltage dip and remain connected to the system for a period of time ($t_0 \rightarrow t_1$). Otherwise, it has to be disconnected. In case the voltage at the connection point in area C is recovered to V_1 within time t_2 after fault occurrence, it is mandatory for the grid-connected system to remain under continuous operation without disconnection. The values of V_0, V_1, t_1, and t_2 differ from one GC to another based on the standards and characteristics of the national grid. LVRT requirements imposed by different grid codes from several countries are discussed in detail [12].

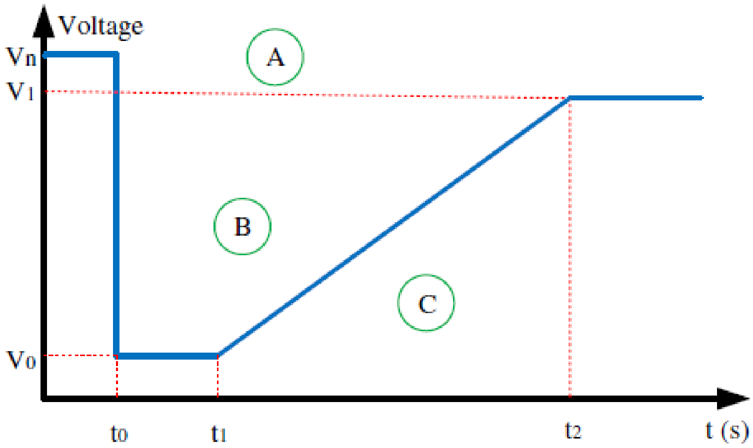


Fig. 4. General curve limits for low-voltage ride-through requirements [12]

In LVRT requirements, grid-connected system also require to support grid voltage recovery by injecting reactive current during grid faults. For instance, German GC defines the injection of reactive current as fast as possible to support the grid voltage according to the standard requirements shown in Figure 5. It specifies that the amount of reactive current should be injected based on the depth of voltage sag. Typically, the voltage works in a band of ±10% of the nominal voltage. Thus, when the rated voltage is between 0.9 and 1.1 pu, the system is in a steady-state operation, and therefore, no change is required. For voltage drop between 10% and 50% from its nominal value, the amount of injected reactive current should be 2% of the rated current for each percent of the voltage drop. In case the amplitude of grid voltage drops under 50% of the rated value, the grid-connected system should inject the rated amount of reactive current (1.0 pu). As a result, according to Figure 5, the required amount of injected reactive current can be obtained using the following equation

$$I_q = \begin{cases} 0 & , 0.9\ \text{pu} \leq V < 1.1\ \text{pu}, \\ \mathrm{k}\dfrac{V - V_0}{V_\mathrm{n}} + 2 & , 0.5\ \text{pu} \leq V < 0.9\ \text{pu}, \\ -I_\mathrm{n} + I_{q0} & , V < 0.5\ \text{pu}, \end{cases} \tag{1}$$

where V, V_0, and V_n are the amplitude values of the present voltage during the fault, voltage before fault, and the nominal grid voltage; I_{q0} and I_n are the reactive current before the disturbances and the nominal current, respectively.

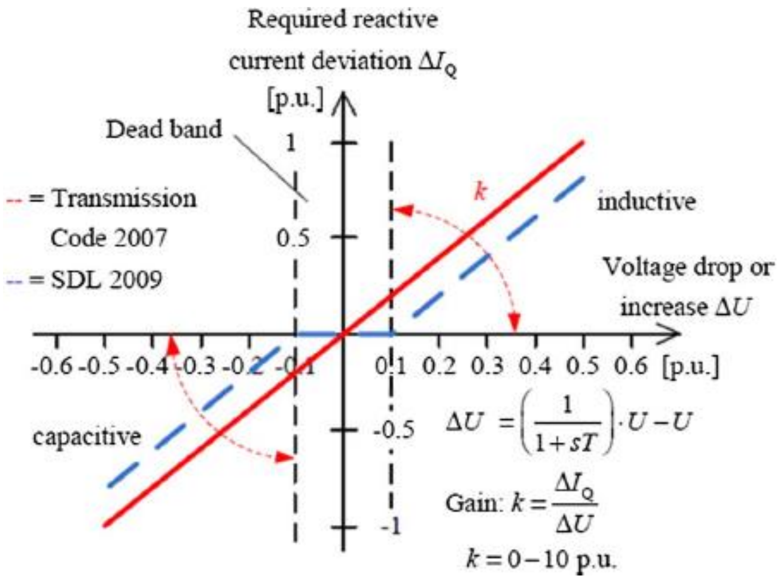


Fig. 5. Reactive current requirement during grid fault in various grid conditions [12]

3. Results and Analysis

To assess the LVRT capability of the PV and DFIG systems, fault conditions were simulated by injecting three-phase fault (phase-A, phase-B and phase-C are shorted) into the medium voltage (MV) grid at 25 kV. A voltage dip of approximately 50% from the nominal voltage was considered. The fault is occurring in very short duration of 0.1s between the time of 0.3s to 0.4s. In the results, various performance parameters were observed and analyzed, including the MV grid voltage, MV grid current, DC-link voltage, active power, and reactive power. Data acquisition and measurement techniques were employed to capture and analyze the system's behavior during LVRT events. Additionally, a performance comparison between the PV and DFIG systems was conducted to evaluate their respective responses and LVRT capabilities.

The simulation for both PV and DFIG systems are divided into three conditions as follows

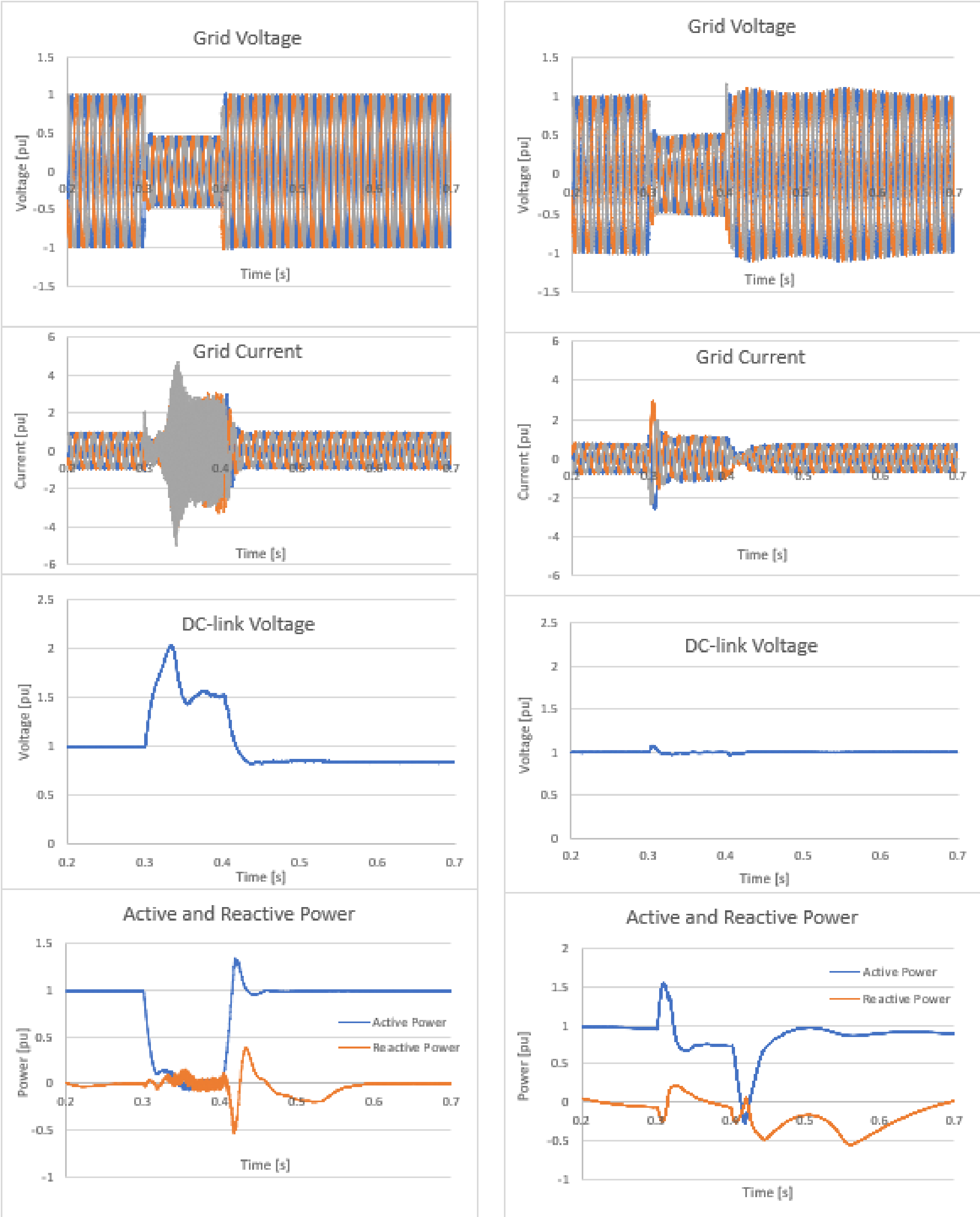
Condition A: Without Reactive Current Injection and without DC Chopper
Condition B: With Reactive Current Injection and without DC Chopper
Condition C: With Reactive Current Injection and with DC Chopper

The simulation results are shown in Figure 6, Figure 7 and Figure 8.

In Figure 6 (Condition A), the PV system exhibits a significant overshoot in current at the grid side, with a value three times higher than the nominal current. Additionally, it demonstrates a considerable over-voltage, reaching twice the nominal DC-link voltage. The active power output drops nearly to zero, while the reactive power experiences a delay of approximately 0.2s to achieve a steady state following the occurrence of the fault. When compared to the DFIG system, the grid current in the PV system shows a lower overshoot, reaching a value of about three times the nominal current. The DC-link voltage, on the other hand, demonstrates excellent performance with minimal overshoot. This behavior is attributed to the configuration of the DFIG system, which allows power flow through the back-to-back converter and DC-link with only 20-30% of the power. The active power experiences a drop to approximately 0.3pu but exhibits significant overshoot at the beginning and end of the fault occurrence. Additionally, the reactive power shows an unstable performance, with a longer delay of approximately 0.3s to achieve a steady state after the fault occurrence.

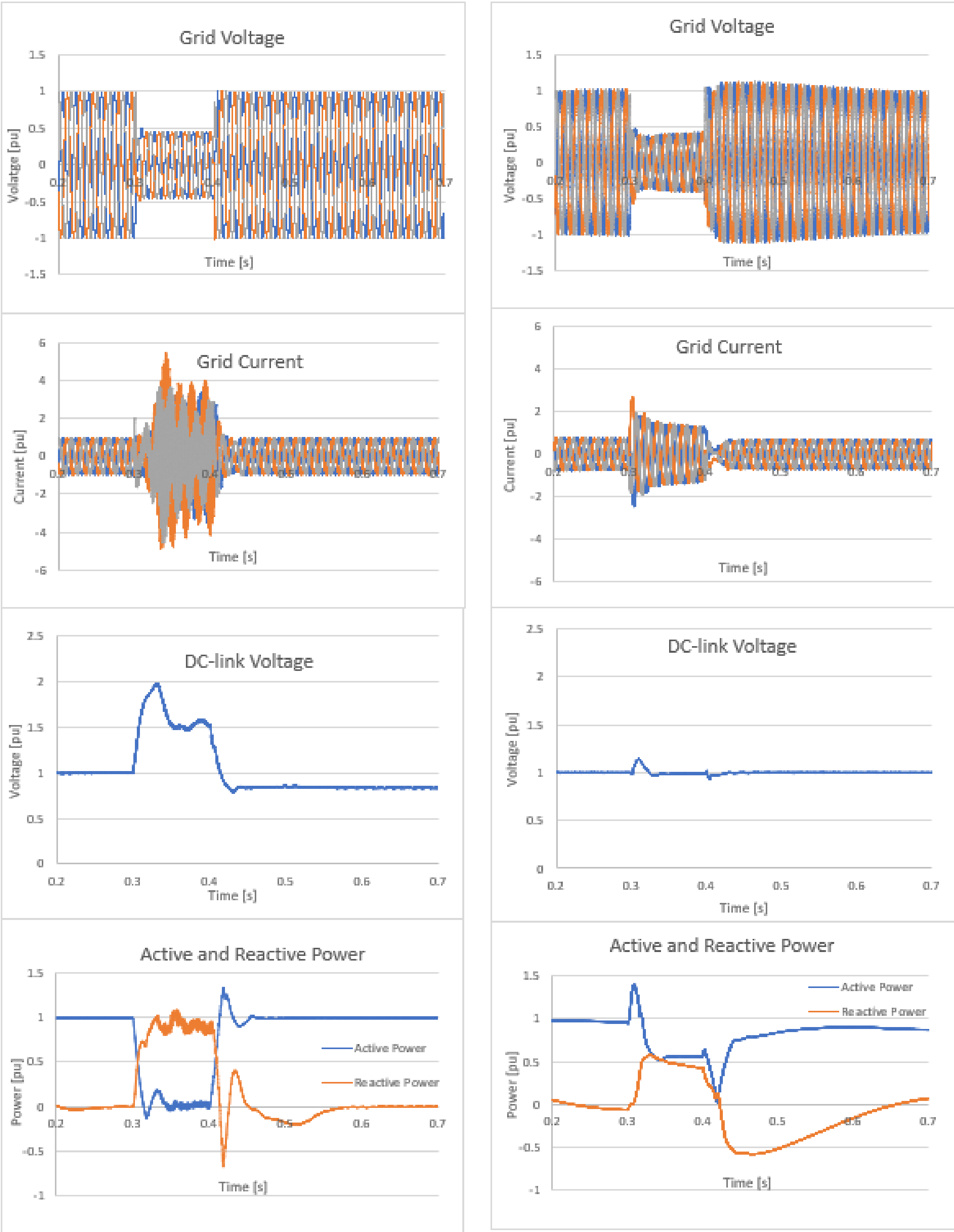
In Figure 7 (Condition B), the PV system demonstrates similar performance in terms of grid current and DC-link voltage compared to Condition A. During the fault duration, a voltage dip of approximately 50% occurs at the grid. Following the LVRT requirement depicted in Figure 5, the PV system injects 100% (1.0pu) of reactive current into the grid. Consequently, Figure 7 shows an increment of approximately 1.0pu in reactive power. On the other hand, the DFIG system maintains a consistent performance in terms of grid current and DC-link voltage, which closely resemble the values observed in Condition A. Despite the injection of 1.0pu reactive current during the fault duration, the DFIG system exhibits a relatively lower increase in reactive power, achieving approximately 0.5pu.

In Figure 8 (Condition C), the PV system exhibits an improved performance in the grid current, which is reduced to approximately 2.0pu from the previous value of 5.0pu. This improvement is attributed to the implementation of the DC chopper, which effectively reduces the DC-link voltage and the overshoot grid current about 70%. The active and reactive power of the PV system remain consistent with their previous performances. On the other hand, the DFIG system demonstrates similar performance as observed in the previous conditions, as the DC chopper does not directly affect the DC-link voltage. Since the DC-link voltage of the DFIG system already exhibits excellent performance, there is no significant impact of the DC chopper on its behavior.



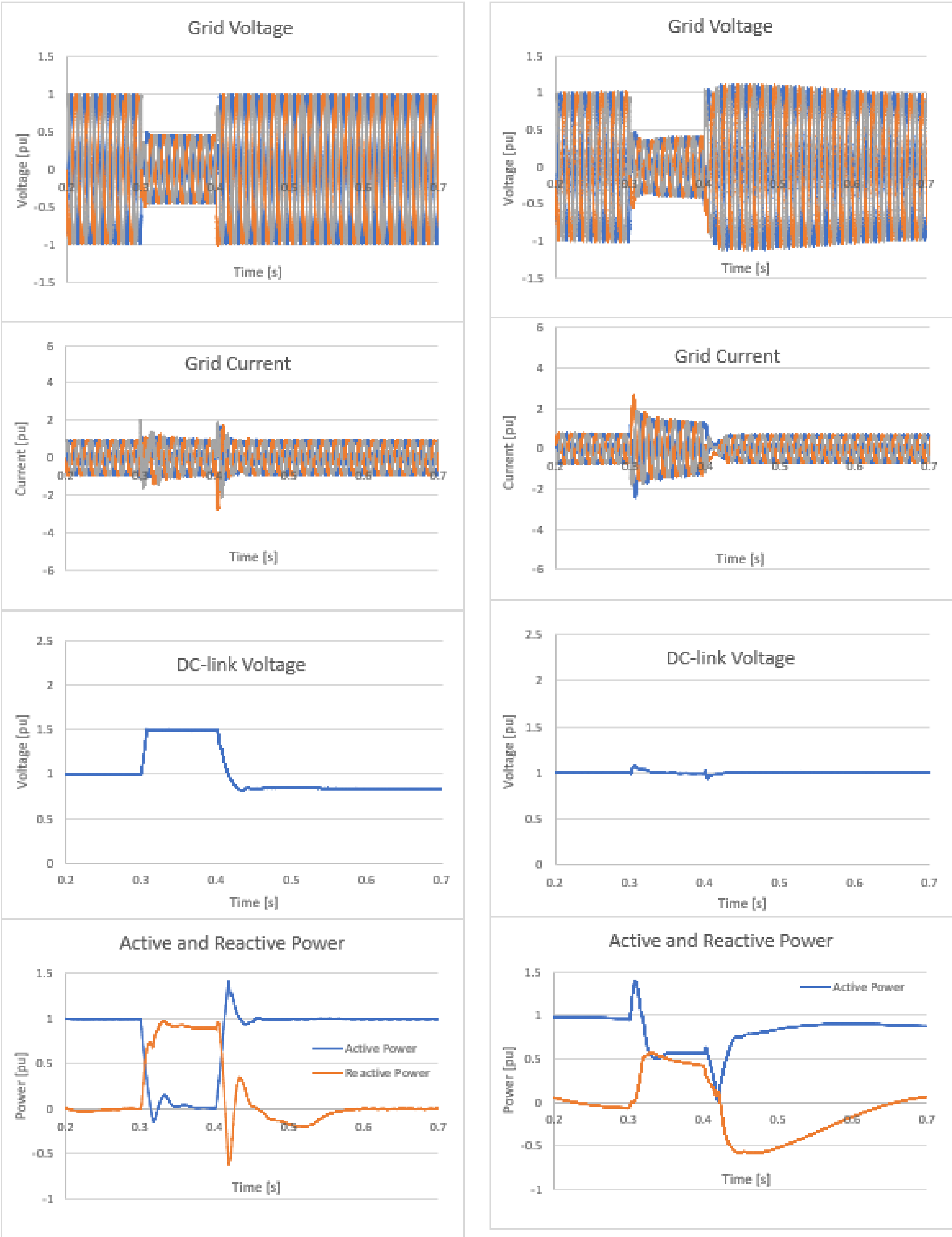
PV system DFIG system

Fig. 6. Condition A: Without Reactive Current Injection and without DC Chopper



PV system DFIG system

Fig. 7. Condition B: With Reactive Current Injection and without DC Chopper



PV system DFIG system

Fig. 8. Condition C: With Reactive Current Injection and with DC Chopper

4. Conclusion

This paper presented a comprehensive analysis of the performance of photovoltaic (PV) and doubly-fed induction generator (DFIG) wind turbine systems under low voltage ride-through (LVRT) conditions. By examining their response to voltage dips and evaluating system stability, valuable insights were gained into the behavior and capabilities of these renewable energy systems during LVRT events. The study investigated the impact of fault condition, that is three-phase fault with voltage dips of approximately 50% from the nominal voltage, on various performance parameters of the PV and DFIG systems. The analysis considered different scenarios, with and without reactive current injection and the implementation of a DC chopper for DC-link voltage protection during faults. Through simulation studies using MATLAB Simulink, the responses of the systems were evaluated and compared. The results revealed distinct performance characteristics of the PV and DFIG systems under LVRT conditions. The PV system exhibited higher overshoot currents, DC-link over-voltage, and significant drops in active power during fault occurrences. On the other hand, the DFIG system demonstrated lower overshoot currents and better stability in the DC-link voltage, but experienced delays in achieving steady-state operation for both active and reactive power. Comparative analysis between the PV and DFIG systems highlighted their respective strengths and limitations. The PV system showed a higher capability for reactive power support and better stability in active and reactive power responses, whereas the DFIG system showed acceptable stability in grid current and DC-link voltage without the need of DC chopper. In the PV system, the implementation of a DC chopper is necessary to improve its performance in terms of grid current and DC-link voltage reduction during fault conditions.

These findings emphasize the importance of understanding the behavior and performance of PV and wind turbine systems under LVRT conditions to enhance their grid integration capabilities and ensure the reliable operation of renewable energy systems. Furthermore, the comparative investigation between the PV and DFIG systems provides insights into the potential of implementing hybrid PV-wind turbine systems with appropriate control strategies, which can leverage the strengths of each system and address their respective limitations. It is recommended that further research and development focus on the optimization of current control strategies using artificial intelligent to enhance the performance and resilience of PV and wind turbine systems under LVRT conditions.

In conclusion, this study contributes to the understanding of PV and DFIG system performance under LVRT conditions, and it opens up avenues for future research and innovation in the design and energy management of grid-connected hybrid renewable energy systems. By addressing the challenges associated with LVRT, the reliability, stability, and overall efficiency of renewable energy integration into the grid can be enhanced, thus leading to a more sustainable and resilient energy future.

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