Optimizing Grid Stability through the Integration of Wind Energy

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Abstract. It has become increasingly apparent that wind energy can contribute to reducing carbon emissions and reducing fossil fuel reliance. In spite of this, wind's intermittent nature makes it challenging for grids to maintain stability. The objective of this paper is to review the current state of wind energy integration, highlighting key research findings on the potential of wind power, turbine performance, and approaches to enhance grid stability. A particular part of the research focuses on the modelling of DFIG systems, which includes the rotor control mechanism as well as the grid control mechanism at the grid side of the generator. Voltage fluctuations, transients in the power system, and reactive power management are among the technical challenges associated with wind power integration. SFCLs (Superconducting Fault Current Limiters) are also explored in the paper as innovative solutions for improving grid stability. As a result of simulations, it is demonstrated that SFCLs can mitigate power deviations and improve overall system stability to an extremely high degree.

Keyword-: Renewable energy, wind energy, power generation, limitations, power grids.

1 Introduction

It is undeniable that wind energy has gained popularity as a renewable and cost-effective source of energy. It is difficult to restore power networks after interruptions due to wind's inherent variability and unpredictability. Continuous power supply depends on self-healing

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power systems that can recover from disruptions quickly and efficiently [1]. Increasingly, intermittent renewable energy resources (RER), like wind energy, have been integrated into the power grid as a result of efforts to improve electricity supply and reduce greenhouse gas emissions. The Fig. Although integrating grids is beneficial, it presents several operational and control challenges, compromising grid stability and reliability.

Energy and power companies have been focusing their research and development efforts on generating electricity using renewable energy sources (RE). A longstanding dependency on fossil fuels for power generation has exacerbated global climate change impacts due to the escalating global energy demand. Consequently, renewable energy conversion systems are currently being designed, developed, and deployed throughout the world as alternatives to traditional fossil fuel-based methods. There has been an investment of billions of dollars across continents to advance renewable energy technologies, including in the United States, Europe, Asia, and Brazil. As seen in Kenya, where a significant portion of electricity is generated through hydro and geothermal energy, efforts are also underway in Africa and the Middle East to harness renewable resources. As a result, renewable energy is increasingly being integrated into the grid on a local and global scale.

A significant shift is being made towards sustainable energy solutions with wind and solar power leading the way. Among the top renewable energy technologies for 2018, Wind Energy Conversion System (WECS) was recognized as the most impressive with an installed capacity of 591 gigawatts at year's end, according to the Global Wind Energy Council report for 2018. Moreover, this document estimates that new offshore and onshore wind projects will generate more than 55 gigawatts annually between 2014 and 2023 [4]. As we move toward a renewable energy-dominated future, this projection underscores the vigorous expansion of wind energy

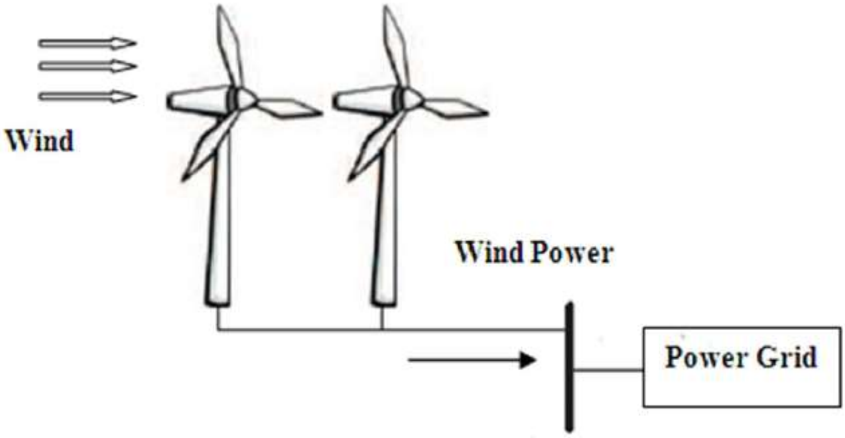

Fig. 1: Wind farm integration in power grid

A WAsP program was used to evaluate three commercial wind turbines for electricity generation using wind speed data over 10 years. The most economical site was Tiaret based on a cost per kWh evaluation. The use of Milliana, Skikda, and Tlemcen was found to be more profitable than the use of diesel generators in a study of non-connected applications [5]. Despite its obstacles, wind energy has been shown to be a viable renewable energy source when incorporated into electric grids. Researchers at Dumlupnar University in Kütahya, Turkey, examined wind's ability to substitute fossil fuels for eco-friendly ones. At an elevation of 30 meters, an average wind velocity of 4.62 meters per second gave a 36.62 watt per square meter energy density for the study, which ran from July 2001 to February 2003. According to the findings, under current conditions, the wind velocities may not be sufficient to generate electric power economically, indicating the need for further advancements in technology and economic models.

According to a separate study conducted in Gharo, Sindh, Pakistan, which analyzed five years of wind data, average wind speeds consistently exceeded 5 meters per second, with projected energy costs at US$0.0255 per kilowatt-hour. Because of the substantial power and energy densities recorded in the region [9], wind energy endeavors in the region appear to have a bright future.

Additionally, DFIG-WECS were integrated into electric circuits to examine the effects of their operation. According to the results, such an integration could potentially enhance the grid's loadability, but with a practical limitation due to the risk of transmission line overloading at around 28.06 percent.

Nevertheless, strategic enhancements and adjustments in reactive power through Flexible AC Transmission Systems (FACTS) devices could mitigate this constraint [10-12].

A particular analysis concerning the 52-bus, 330 kV Nigerian power grid with DFIG-WECS integration pinpointed an optimal wind energy penetration rate of 35%, a level at which the grid's stability is maintained without infrastructure overload [13]. Moreover, the introduction of an innovative virtual inertia control strategy aimed at bolstering the rotor angle stability within interconnected power systems illustrated marked improvements in both reliability and support from wind turbines [14].

2 DFIG Modeling

With a 2 MW capacity and a 690V voltage, the wind farm (as shown in Fig. 2) is modeled with MATLAB/SIMULINK. A Doubly Fed Induction Generator (DFIG), which transforms kinetic energy into electrical energy, is mechanically connected to a wind turbine. The produced electricity is integrated into the electrical grid via a step-up transformer. This guarantees dependable and steady operation. Engineers may optimize the design and operation for optimal efficiency, safety, and sustainability by evaluating parameters like power output, voltage stability, and grid integration requirements using the MATLAB/SIMULINK simulation.

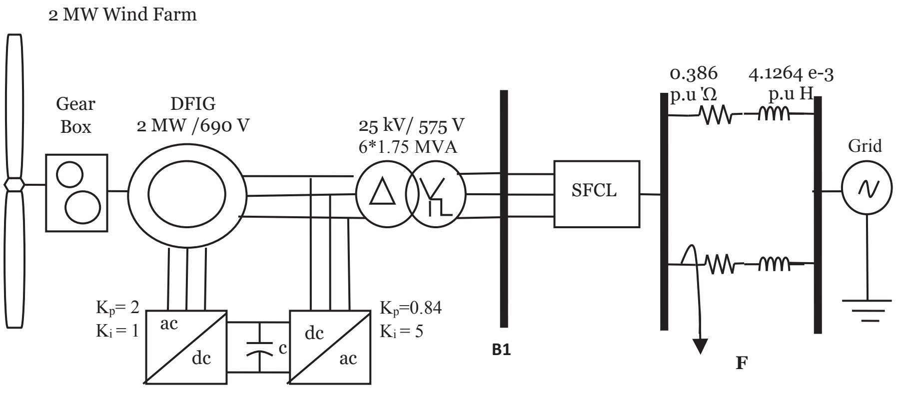

Fig. 2: Model of wind turbine to be simulated

The parameters of the wind turbine and Doubly Fed Induction Generator (DFIG) are as follows: The turbine is of the horizontal axis type with three blades, designed to operate optimally at a rated wind speed of 14 meters per second. The DFIG has a rated power output of 2 MW, with a rated stator voltage of 690 volts and a frequency of 50 Hz. Its stator resistance is 0.00488 per unit (pu), while the rotor resistance referred to the stator is 0.00549 pu. The stator leakage inductance is 0.09231 pu, and the rotor leakage inductance referred to the stator is 0.09955 pu. The magnetizing inductance is 3.95279 pu, contributing to the generator's magnetic properties. The DFIG's lumped inertia constant is 3 seconds, representing its rotational inertia. Additionally, the DC link voltage is 1200 volts, and it is supported by a DC link capacitor with a capacitance of 14,000 microfarads. These parameters collectively define the operational characteristics and performance capabilities of the wind turbine and DFIG within the system.

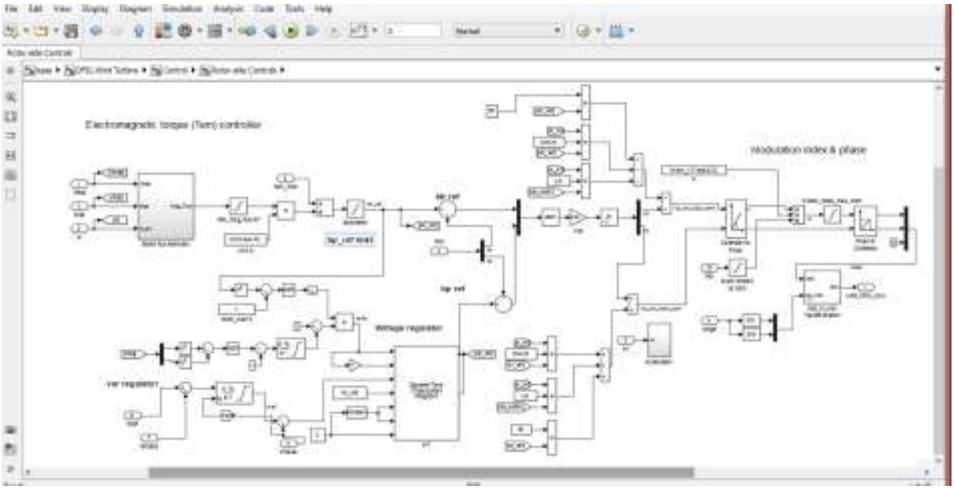

Fig.3: System for regulating the rotor side

The rotor side controlling system as shown in Fig. 3 utilizes a Universal Bridge (3Φ Power Converter) within MATLAB/SIMULINK, featuring a snubber resistance of 1e3 ohms. This Universal Bridge block enables the simulation of converters employing various power electronic devices, including both naturally commutated (or line-commutated) devices such as diodes or thyristors, and forced-commutated devices like GTO, IGBT, or MOSFET. In this setup, the Rotor-Side Converter (RSC) employs IGBTs as gate-controlled devices, requiring gate pulses for control. Two PI controllers with gains Kp=2 and Ki=1 regulate the RSC, as depicted in the figure. The voltage and flux vector equations for RSC are defined, considering rotor-side voltage (Vr), rotor current (Ir), rotor winding resistance (rr), rotor flux vector (ψr), magnetizing inductance (Lm), stator current (Is), and rotor windings self-inductance (Lr). The rotor self-inductance (Lr) is determined by adding the magnetizing inductance (Lm) to the rotor leakage inductance (Llr). Additionally, compensation terms are incorporated into the RSC controller to ensure accurate tracking of the dq axis current, resulting in the calculation of reference voltages (Vdr’ and Vqr’). Through MATLAB/SIMULINK, these reference voltages are used to generate gate pulses for the insulated-gate bipolar transistors (IGBTs) on the rotor side.

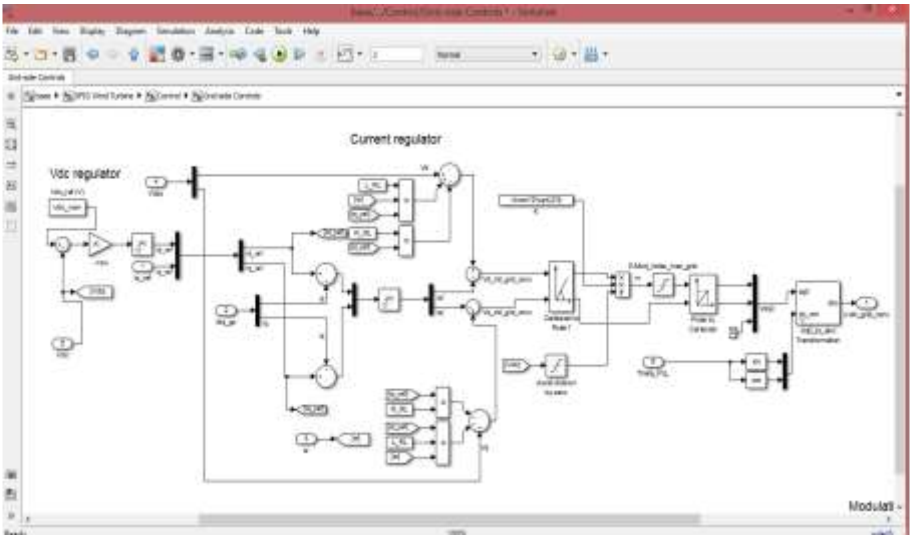

Fig. 4: Grid-side mechanism for controlling

The primary function of the Grid-Side Converter (GSC), shown in Fig.4 in the system is to maintain a constant DC link voltage and ensure a fixed power factor. By implementing vector control methodologies, this can be achieved. The GSC is essential for balancing the energy on both sides of the DC link capacitor in DFIG setups by regulating the DC link voltage. It was decided that the gain parameters of the GSC controller would be set at Kp = 0.844 and Ki = 5 so that we could make use of two series PI controllers to build the controller. In the GSC controller, the power electronic devices are IGBTs with snubber resistances of 1e3 ohms and universal bridge converters simulated in MATLAB/SIMULINK. With the use of gate pulses, the IGBTs are controlled in order to turn on and off. Several inputs are taken from the rotor line, including the DC link voltage (vdc) and the reactive power (Qs). PI controllers process signals and modulate at the carrier frequency to generate desired output. By regulating the DC link voltage and power factor, these signals ensure the stability and efficiency of the system.

DC current (IB1) flows through the semiconductor IGBT switch in the proposed design because it is normally closed. Both during normal operating conditions and during transient events, IB1 is continuously compared with a preset reference current (Iref). Comparators output high pulses if IB1 slightly exceeds Iref, indicative of slight deviation from the desired current level. A comparator outputs a low pulse when the voltage at the Point of Common Coupling (PCC) (Vpcc) approaches the predefined maximum acceptable voltage at the Point of Common Coupling (PCC) (Vref). Taking advantage of these comparator signals determines the IGBT gate signal's control action.

An abnormal increase in current is detected by the controller when IB1 exceeds Iref during a fault scenario. When this signal goes low, the IGBT gate signal is also signaled to go low. This action connects the IGBT switch to a shunt path with high impedance (Rsh), instantly limiting the fault current. The fault must be addressed before normal operation can be restored.

The terminal voltage must be controlled in order to accomplish this. After a fault has been detected, the controller ensures that both the PCC voltage (VB1) as well as the predefined reference voltage (Vref), a percentage of 0.90 pu of the nominal voltage, are taken into account in its post-fault operation. The duration of Rsh remains in series with the line for the duration determined by Vref when VB1 and Vref are compared. In order to signal a return to normal voltage levels, the controller raises the gate signal when VB1 slightly exceeds Vref. IGBT switches disconnect the shunt path when the switch is activated, restoring the pre-fault state.

3 Stabilizing the grid with wind power

Power quality (PQ) can be significantly affected by the integration of wind energy into the electrical grid due to its intermittent nature. Increasing wind energy penetration into the grid presents a number of technical challenges, affecting the grid's efficiency and stability. The issues with reactive power include voltage fluctuations, power system transients, harmonics, and harmonics, among others. As well as electromagnetic interference, switching operations, and accurate synchronization, integration is complicated by the need for precision. Managing the load and scheduling power generation to meet demand are challenging due to the long distances over which electricity must be transmitted.

Additionally, wind power generation usually uses asynchronous induction generators that complicate the integration process. Reactive power management within these generators is limited, which is key to maintaining grid stability. It is possible for feeder regulation to be disrupted by a sudden increase in torque coupled with voltage dips at the point of common connection (PCC). As a result of this disruption, the grid's demand for reactive power may exceed its supply, leading to a voltage collapse, which may threaten the entire grid's stability.

4 Result and Discussion

We present the new idea of a Superconducting Fault Current Limiter (SFCL), which functions normally as a rectifier-type SFCL as well as through symmetrically and asymmetrical faults as a resistive-type SFCL, namely an IGBT-Bridge-type SFCL. In case 1 and case 2, the voltage deviation is significantly lower when SFCL is used than in example 1, when SFCL is not used. The drop in fault current at the bus terminal is the cause of this reduction. The complete schematic diagram of a DFIG with SFCL is shown in Fig. 5.

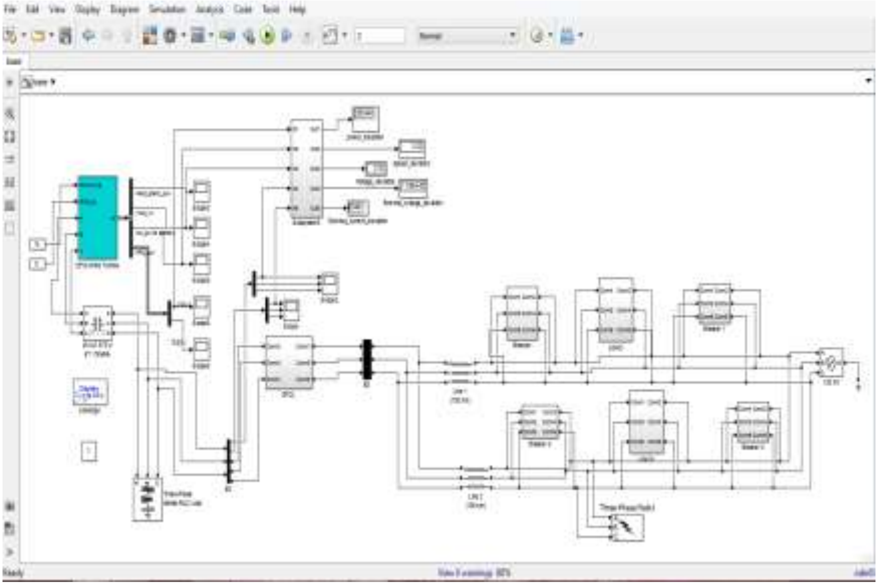

Fig. 5: Model using Resistive type SFCL

A wound rotor inductive generators and an AC/DC/AC IGBT-based the pulse width modulation based converter, portrayed as the sources of voltage, are combined to form a DFIG turbine for wind power. While the rotating component receives adjustable frequency power through the AC/DC/AC conversion, its stator winding has a direct connection to the 50 Hz grid. With DFIG technological advances, mechanical strains throughout gusts are reduced and the greatest amount of energy may be extracted from wind speeds that are low by maximizing turbine speed. The wind speed in the particular instance stays at 14 m/s.

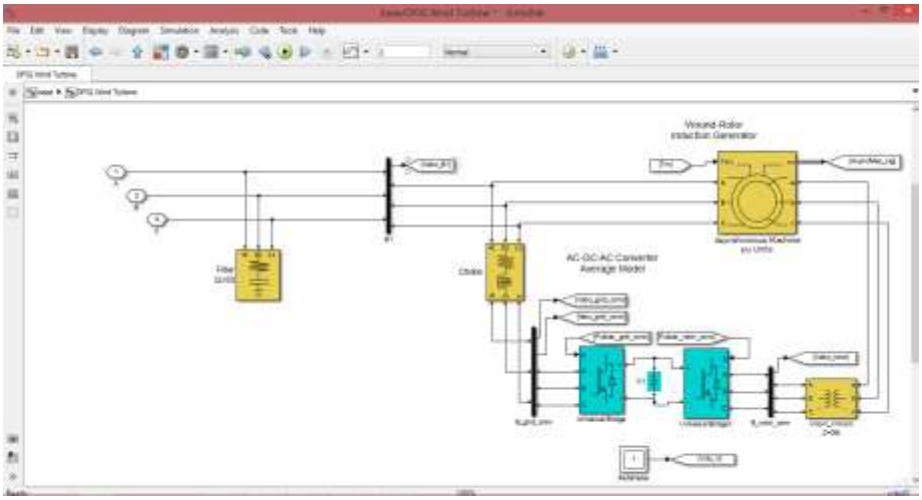

Fig.6: As an adaptable three-phase power conversion, the Standard Bridge block integrates up to six power switching devices arranged in a bridge pattern.

Whereas the additional set of switches serves as an inverter, the initial set serves as a rectifier. These switches are used to form three bridge arms throughout the converter by using forced communication devices such as IGBTs. To improve achievement, a 1000 ohm Snubber Resistance continues to be used. To create a resistive snubber having an inside resistance equal to 1 x 10^{-3} ohms of the chosen device, the snubber capacitance is also set to infinity. A coordinating system provides independent controlled pulses for the rotor and grid-side conversion devices, as shown in Fig. 6.

Discrete 3-phase PWM Generators are employed to generate pulses, with a sampling time (Ts) set at 5.000 x 10^{-3}.
The DFIG model is configured without the presence of any Superconducting Fault Current Limiter (SFCL). When simulated for a duration of 2 seconds in MATLAB/SIMULINK, the model exhibits the following outputs: Power Deviation of 0.0004936%, Speed Deviation of 0.02%, Terminal Current Deviation of 0.0004663%, and Terminal Voltage Deviation of 1.123e-8%. These values represent the deviations observed in various parameters of the DFIG system during the simulation period.

The design of the resistive Superconducting Fault Current Limiter (SFCL) is illustrated in the provided Fig. 5. When simulated for a duration of 2 seconds in MATLAB/SIMULINK, the system exhibits the following outputs: Power Deviation of 0.0004936%, Speed Deviation of 0.02%, Terminal Current Deviation of 0.0004663%, and Terminal Voltage Deviation of 1.123e-8%. In addition, the measurements of both reactive and active power using the resistive-type SFCL are shown below, together with visual depiction of the voltage at the terminus, terminals current, speed of the rotor, and the voltage of the DC output from the DFIG simulation.

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4.1 Comparative Assessment

We compare the DFIG with a Bridge-Type SFCL with the DFIG without any controller. Simulations are conducted for intervals of 0.5, 1, 1.5, and 2 seconds and the resulting results are comparedThe metrics of power variation, voltage at the terminal variation, current divergence, speed variance, throughout every interval have been recorded and represented against the period of time. By comparing the DFIG model to the SFCL over varying time periods, we can evaluate how the SFCL affects the model's performance.

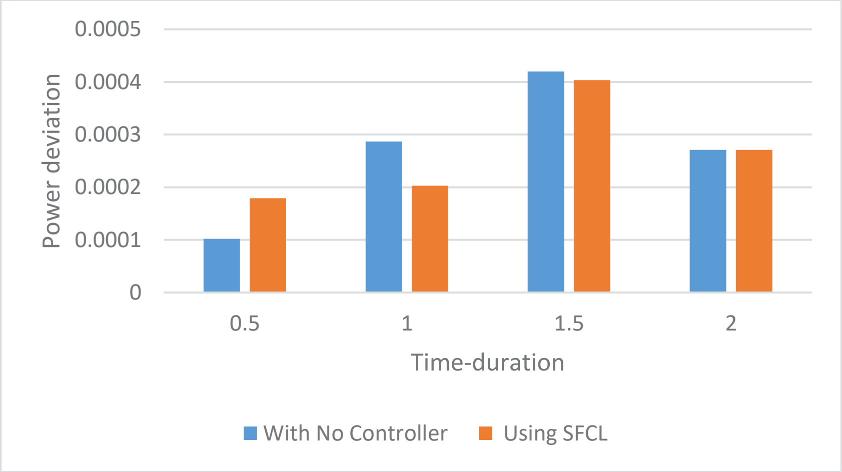

Fig. 7: Deviations in power generation with and without controllers in DFIG-based systems

The graph in Fig .7 shows that the implementation of the SFCL essentially results in higher values of power deviation compared with when no controller is used, with the exception of the 0.5 mark, where the deviations appear to match, and the largest deviation from either saw the same result at 1.5 seconds, where the SFCL recorded a higher deviation than no controller setup. Scenarios return to closer deviation values at 2 seconds that shows the impact caused due to the SFCL may also vary in case of different times.

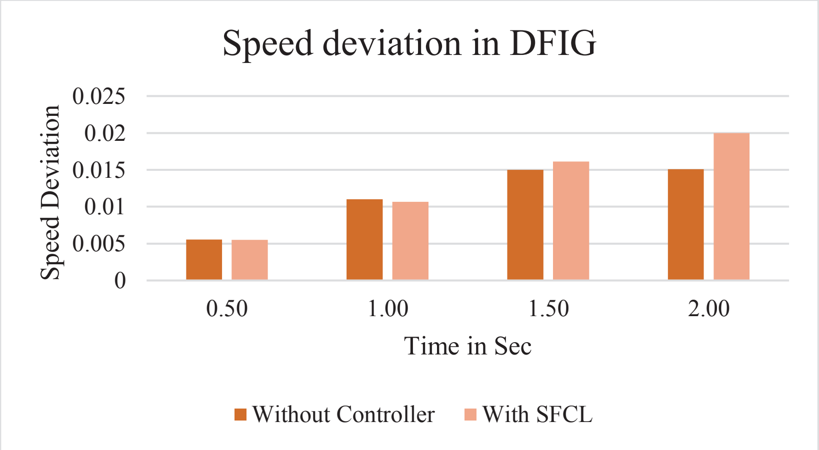

Fig. 8: Differences in speed deviation between DFIG-based power systems controlled with and without controllers

Fig.8 depicts that in all time instances,the SFCL always gives a higher speed deviation compared to no controller. The minimum deviation occurs at 0.5 seconds and it is still higher in the case of SFCL. From the figure, it can be seen that as time goes on, both cases depict an increase in deviation but still, SFCL gives the highest deviation. This trend shows that, though SFCL enhances the other operational parameters, it somehow introduces more variation in the speed in this setup of DFIG. All this is more pronounced at the last time point of 2 seconds.

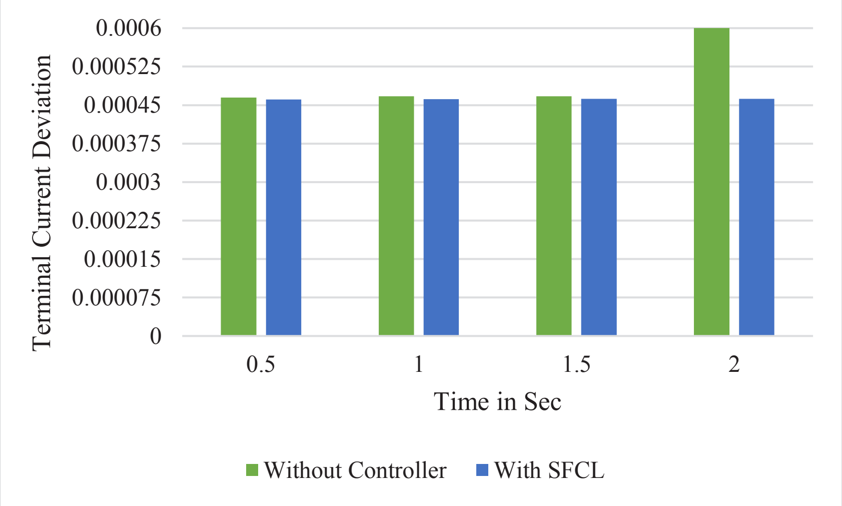

Fig. 9: In DFIG-based power systems with and without controllers, terminal voltage deviation can be observed

Based on a comparison of various parameters in the model after 2 seconds of simulation, the scenarios without a controller and with a Superconducting Fault Current Limiter (SFCL) exhibit notable differences as seen in Fig. 7-10. SFCL reduces the power deviation from 0.0004137 to 0.0002512 when compared to the absence of a controller. As a result of the SFCL, the terminal voltage deviation decreases from 37.1E-08 in the absence of a controller to 14.4E-08 when the controller is employed. A reduction of 0.0006081 in terminal current deviation is also observed when SFCL is implemented from 0.0006181 to 0.0004524. Additionally, while the speed deviation remains relatively constant at 0.01508 without a controller, it slightly increases to 0.02 with the SFCL. Based on these comparisons, it can be seen that the SFCL mitigates deviations across various parameters, thus improving model performance and stability.

5 Conclusion

Power grids can be integrated with wind energy in both positive and negative ways. If wind power is not properly managed, it can destabilize the grid. Wind power offers sustainable alternatives to fossil fuels. The purpose of this paper is to shed light on the technical challenges associated with the integration of wind energy, including voltage fluctuations, power system transients, and managing reactive power, through comprehensive research and simulation studies. To enhance grid stability in the presence of wind power, the paper proposes innovative solutions like Superconducting Fault Current Limiters (SFCLs). Power deviations can be mitigated and overall system stability improved with SFCLs according to simulation results. In order to integrate wind energy into power grids with more efficiency and resilience, these challenges must be addressed and advanced control systems implemented. For wind energy to be seamlessly integrated into the grid, research and development efforts must be continued.

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