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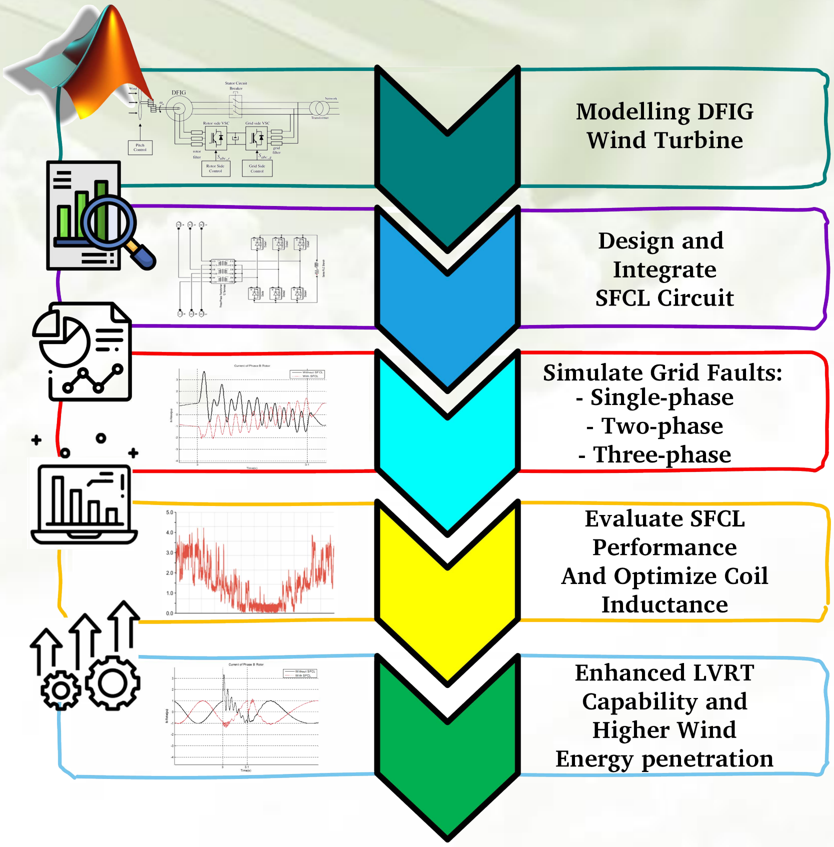
# Improving Low Voltage Ride-Through Capability of Doubly-Fed Induction Generator Wind Farms Using Superconducting Fault Current Limiter

**Seyed Ehsan Aminoroayaye yamani, Mohammad Amin Bahramian and Ali Asghar Ghadimi**

## Highlight

- **Enhancing DFIG Wind Turbines with SFCL for better Low Voltage Ride-Through**
- **Tuning SFCL Coil Inductance for Optimal Current Control**
- **Assessing SFCL-DFIG Performance in Grid Faults via Simulation**
- **Boosting Wind Energy Integration with Advanced LVRT and Stability**

## Graphical Abstract



Modelling DFIG Wind Turbine

Design and Integrate SFCL Circuit

Simulate Grid Faults:
- Single-phase
- Two-phase
- Three-phase

Evaluate SFCL Performance And Optimize Coil Inductance

Enhanced LVRT Capability and Higher Wind Energy penetration

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Citation

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# Improving Low Voltage Ride-Through Capability of Doubly-Fed Induction Generator Wind Farms Using Superconducting Fault Current Limiter

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## ABSTRACT

Doubly-fed induction generators (DFIGs) are crucial in wind turbines due to their advanced control features and efficient power conversion, but they're vulnerable to grid issues like voltage dips and short circuits. This study explores enhancing DFIGs' low voltage ride-through (LVRT) capabilities using a superconducting fault current limiter (SFCL) system. The SFCL's superconducting coil plays a key role by limiting fault current to stabilize power output, reducing excessive currents during faults, and mitigating voltage fluctuations, protecting the rotor-side converter and gearbox. The research focuses on optimizing the coil's inductance to improve SFCL performance, showing through MATLAB/Simulink simulations that adjusting inductance can lessen rotor current oscillations during short circuits. The results indicate significant enhancements in LVRT capabilities, reducing electrical and mechanical stress on generators and converters, preventing severe voltage drops, and maintaining torque levels. Incorporating an SFCL into DFIG systems greatly increases stability, reliability, and fault tolerance, supporting more wind energy integration.

## Nomenclature

| Variable | Description | Variable | Description |
|---|---|---|---|
| $V_s, V_r$ | Stator and Rotor voltage | $T_e$ | Torque electromagnetic axis |
| $i_s, i_r$ | Stator and Rotor current | $w_s$ | Synchronous speed |
| $i_{sc}$ | The fault current | $w_r$ | Rotor speed |
| $i_{ms}$ | Magnetizing component of stator current | $w_{slip}$ | Slip speed |
| $i_{rqref}$ | Reference rotor current | $V_{rd}, V_{rq}$ | d-q components of rotor voltage |
| $a_s, a_r$ | Stator and Rotor flux | $i_{rd}, i_{rq}$ | d-q components of rotor current |
| $L_s, L_r$ | Stator and Rotor self-inductance | $R_s, R_r$ | Stator and Rotor resistance |
| $L_m$ | Magnetizing inductance | $T_e$ | Torque electromagnetic axis |
| $L_{ls}, L_{lr}$ | Stator and Rotor leakage inductance | $w_s$ | Synchronous speed |
| $R_s, R_r$ | Stator and Rotor resistance | $w_r$ | Rotor speed |

## 1. Introduction

The DFIG stands as a premier solution for integrating wind turbines with the electrical grid, owing to its superior control features and the efficiency of its compact converter design. DFIGs are distinguished by their exceptional ability to manage and adapt power output, making them highly suitable for renewable energy applications. However, it is imperative to acknowledge that these generators exhibit a heightened sensitivity to voltage fluctuations, particularly in instances of grid faults. This vulnerability is especially pertinent given the geographical positioning of many wind power installations in isolated locales, where they are frequently connected to less robust power grids. Consequently, these systems are more susceptible to disturbances, including voltage sags and short circuits, necessitating sophisticated management and protection strategies to ensure grid stability and reliability.

Upon the occurrence of a grid short circuit, there is an alteration in grid voltage, precipitating elevated induced voltages within the DFIG rotor circuit. In the absence of effective control measures, this scenario can provoke the generation of high currents within the rotor circuit, endangering the integrity of the rotor-side converter (RSC). Amid such a fault, the magnitude and frequency of induced voltage in the rotor circuit undergo significant shifts, surging to levels substantially above the norm. In these situations, the DFIG's standard control system is inept at furnishing suitable control signals for the RSC converter, owing to the Proportional-Integral (PI) controllers in the control loops being unadjusted for these extreme scenarios and lacking the requisite agility for managing such states. Consequently, the DFIG's protective system initiates a block to avert damage to the electronic converters within the RSC, culminating in the disconnection of the wind turbine from the circuit [1]. However, DFIG's disconnection from the circuit contradicts grid regulations, which stipulate that large wind farms must remain connected to the grid during faults and not be disconnected from service. Therefore, it is essential to quickly detect faults in the grid and implement appropriate control actions to keep the wind turbine connected to the grid without being disconnected from service.

Numerous strategies have been proposed to improve the LVRT capability of the DFIG. The rotor crowbar circuit is commonly utilized to safeguard the RSC. Furthermore, the significance of the grid-side converter has been highlighted, with its role being integral to the Energy Conversion System (ECS) of the DFIG or operating independently as a unified voltage restorer. The introduction of an additional resistive circuit, serving as a current limiter in conjunction with the stator resistance and a passive resistive network, has been suggested. This resistive circuit plays a pivotal role in limiting the surge current in the rotor and mitigating electromagnetic torque oscillations. Additionally, the incorporation of an energy storage device is instrumental in stabilizing the DC-Link voltage, thereby offering a protective mechanism for the RSC. Moreover, a specialized control strategy has been developed to augment the LVRT capacity of DFIG, with subsequent validation indicating enhanced LVRT performance.

During a network fault connected to a wind turbine equipped with a DFIG, two crucial issues arise. One is fault detection, and the other is restricting the fault effects to protect stator windings, especially the electrical converters in the rotor. So far, the "crowbar" has been widely used to limit fault current. The crowbar is a set of resistances connected in parallel with the rotor windings, short-circuiting the rotor winding circuit during faults and preventing fault current from flowing through the Rotor-Side Converter. However, with the introduction of the crowbar, the DFIG transforms into a conventional induction generator, absorbing reactive power from the grid and limiting the control capability of the wind turbine's power. In [2] and [3], methods have been proposed to improve the crowbar's response speed; however, the issue of reactive power absorption still persists. In [4], a control method for the grid-side converter to enhance DFIG performance during faults is presented, which suffers from control scheme complexity and inconsistency in fault and normal DFIG operation. [5] proposes the use of dynamic series resistors with the rotor, introducing system reliability concerns, thermal issues, and generating high voltages that can disrupt RSC performance when fault current passes through these resistors.

Also, the integration of renewable energy, particularly wind power, calls for innovative strategies to ensure grid stability. Recent studies have focused on improving DFIG systems' fault ride-through capabilities and reducing grid disturbances through advanced control strategies [6], fault current limiters [7,8], and power flow controllers [9]. Additionally, research into limiting fault currents [10,11], enhancing proactive stabilization [12], and integrating systems for better frequency regulation [13], alongside developing multifunctional limiters for power management [14], highlights a concerted effort towards robust wind power integration. The literature has investigated multiple solutions to enable higher penetration levels of renewables, notably forecasting and scheduling optimization for resilience [15], incorporating energy storage for stability [16-18], advanced power electronics interfaces, dynamic demand response, and virtual synchronous machines. Recent researches have also delved into enhancing the efficiency and reliability of renewable and hybrid systems. Studies have introduced optimal operation models for multi-energy microgrids [19], innovative short-term load forecasting techniques sensitive to weather changes [20], and advanced power flow analysis methods for AC microgrids [21], showcasing the evolving landscape of smart grid optimization and management.

In this article, we propose integrating a SFCL into the rotor circuit of DFIG wind turbines to enhance their LVRT capability. The SFCL serves three key functions: acting as a fault current limiter during normal operation, restricting excess stator and rotor currents during grid faults, and attenuating voltage fluctuations in the rotor circuit to protect the converter and gearbox. We examine tuning the SFCL coil inductance to optimize its current limiting performance. The effectiveness of the SFCL-enhanced DFIG system is evaluated under various grid fault scenarios through simulations in the MATLAB/Simulink environment. The results demonstrate substantial improvements in LVRT capability, reduced electrical/mechanical stresses, avoidance of severe voltage drops, and prevention of torque drops to zero, highlighting the potential of this solution to enable higher wind energy penetration levels.

The remainder of the article is structured as follows: Section 2 provides details on the wind turbine structure and modeling of the DFIG and its control circuits, as well as the operating principles of the SFCL. Section 3 presents the simulation setup and results evaluating the performance of the proposed SFCL-integrated DFIG system under different grid fault conditions. Finally, Section 4 concludes the article and outlines potential future research directions.

## 2. Wind Turbine Structure

Here, the problem of planning the presence of EV charging stations in smart distribution systems is discussed to enhance the power output and electrical parameters of the distribution system.

### 2.1. Modeling Doubly-fed Induction Generators

A wind turbine equipped with a doubly-fed induction generator consists of three main components: the turbine blades, the DFIG generator, and the power electronic converter. The turbine blades capture wind energy and transform it into mechanical rotation, which is then transmitted to the DFIG generator through a gearbox. The DFIG generator receives the mechanical energy and converts it into electrical energy. Figure 1 illustrates the structure of a DFIG. In this model, the stator coil is directly connected to the network through an electronic converter, and the rotor coil is also connected to the network through an electronic converter. The electronic converter, consists of two converters: the Rotor-Side Converter and the Grid-Side Converter. They are connected back-to-back, and a capacitor is placed in the DC link between them as shown in Figure 2. The Grid-Side Converter maintains a constant voltage in the DC link, while the Rotor-Side Converter controls the current and voltage in the rotor circuit.

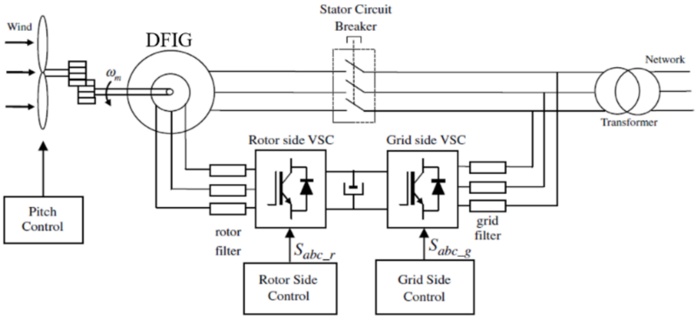


**Figure 1**. Wind turbine structure equipped with DFIG.

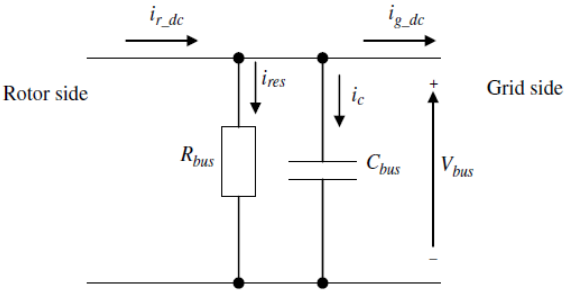


**Figure 2**. DC-link System.

By adjusting these, the active and reactive power produced by the Doubly Fed Induction Generator can be controlled. The dynamic model of DFIG examines the behaviour of its variables in transient and steady states, essential for the proper design and control of DFIG.

Dynamic behaviour of machines is usually studied using their "dynamic model." By utilizing the dynamic model of a machine, the behaviour of its variables, such as torque, currents, and fluxes at all times (not just in a steady state) when a specified supply voltage is applied, becomes apparent. Information obtained from the dynamic model allows the identification of unsafe machine conditions, such as instability or extreme transient currents. Additionally, the dynamic model provides more insights into the performance of the stable system, such as dynamic oscillations, torque ripple, flux variations, and more. The dynamic model is presented in the form of a compact set of ordinary differential equations, enabling computer simulation, often referred to as "simulation model." Using this model, the analysis of the behaviour of all machine variables at every moment of machine operation becomes possible.

### 2.2. Dynamic Modeling of Doubly-Fed Induction Generator

Deep analysis of DFIG provides a profound understanding of its behaviour in transient and steady-state conditions. This information is essential for the proper design and control of DFIGs. The dynamic behaviour of DFIGs is typically examined using a mathematical model that encompasses complex relationships between machine variables, such as torque, currents, and fluxes. Through model simulation, engineers can accurately predict machine behavior across a wide spectrum of operational scenarios. The dynamic analysis of DFIGs pursues two objectives: it aids in identifying potential issues, such as instability or extreme transient currents, while optimizing machine performance, including reducing oscillations and enhancing efficiency.

The dynamic model of DFIGs is usually presented as a compact set of ordinary differential equations, facilitating computer simulation. Hence, it is often referred to as a "simulation model." Using this model, engineers can scrutinize the intricate behavior of all machine variables throughout the entire operational cycle. In summary, the dynamic analysis of DFIGs forms the foundation for their proper design and control, providing engineers with the capability to anticipate potential issues, optimize performance, and ensure the stability and efficiency of the machine under various operational conditions.

### 2.3. Control Circuit of the Rotor-Side Converter

The purpose of the Rotor-Side Converter is to control the rotor currents. The Rotor-Side Converter serves as a torque controller for adjusting the output of the wind turbine and measuring the active or reactive power at the stator terminal. To minimize the error in power or rotor speed towards zero, a PI controller is employed in an external control loop. The output of the current controller, the reference rotor current, should be injected into the rotor coil by the Rotor-Side Converter. This component controls the torque electromagnetic axis. The real part of the rotor current is compared with the reference rotor current, and the error is driven to zero by the PI current controller in the inner control loop. The output of this current controller is the voltage, generated by the Rotor-Side Converter and combined with other similar controllers for $(i_{rd})$, $(v_{rd})$, and the required three-phase voltage applied to the rotor coil. The voltage equations are as follows:

$$V_s = i_s * R_s + {}^{d\alpha}/_{dt} \tag{1}$$

$$V_r = i_r * R_r + {}^{d\alpha}/_{dt} \tag{2}$$

Here, $V_s$ represents the applied stator voltage to the network. The rotor voltage $V_r$ is controlled by the rotor-side converter and is used to control the generator's performance. The flux equations are as follows:

$$\alpha_s = L_s * i_s + L_m * i_r \tag{3}$$

$$\alpha_r = L_m * i_s + L_r * i_r \tag{4}$$

$L_s$ and $L_r$ will be driven, respectively.

$$L_s = L_m + L_{ls} \; and \; L_r = L_m + L_{lr} \tag{5}$$

The leakage coefficient is defined as:

$$\sigma = 1 - \frac{L_m^2}{L_r} * L \tag{6}$$

$$L_0 = L_m^2 / L_s \tag{7}$$

$$V_{rd} = i_{rd} * R_r + \sigma L_r * \frac{d_{ird}}{dt} - w_{slip} * \sigma L_r * i_{rq} \tag{8}$$

$$V_{rq} = i_{rq} * R_r + \sigma L_r * \frac{d_{irq}}{dt} - w_{slip}(\sigma L_r * i_{rd} + L_0 * i_{ms}) \tag{9}$$

$$w_{slip} = w_s - w_r \tag{10}$$

The stator flux angle is calculated using the following formula:

$$\alpha_{st} = \int (V_{st} - i_s * R_s) dt \tag{11}$$

$$\alpha_{sb} = \int (V_{sb} - i_s * R_s) dt \tag{12}$$

$$\theta_s = tan^{-1}\left({}^{\alpha_{st}}/_{\alpha_{sb}}\right) \tag{13}$$

The calculated parameters obtained from the above equations in the PI controller system are employed to enable the controller to regulate speed and torque in the generator. This allows the controller to have dual-mode functionality instead of directly adjusting the active power. The fundamental operation of the Superconducting Fault Current Limiter involves limiting the fault current in a unidirectional manner. During normal operation, the fault current is regulated to be within the peak range of $ni_{rabc}$ or $ni_{sabc}$, representing the rotor current and stator current, with 'n' being the transformer ratio. Under normal conditions, the SC exhibits a non-inductive impedance, with the voltage drop across the unidirectional rectifier and the voltage drop from the resistance of the winding and leakage inductance of the isolated transformer being the only significant impedances in the circuit. During a fault, when the current magnitude reaches $\frac{i_{sc}}{n}$, the SFCL enters the circuit. The impedance of the fault circuit increases, limiting the fault current to a predetermined level. When the fault current is cleared, and the rotor or stator current drops below $\frac{i_{sc}}{n}$, the SFCL automatically exits the circuit.

### 2.4. Control Circuit of the Grid-Side Converter

The purpose of the Grid-Side Converter is to regulate the voltage of the DC link capacitor. Therefore, it is authorized to generate or absorb the reactive power required to support the voltage. This function is achieved through two internal control loops and an external regulating loop. The measured current at the output is utilized by a voltage controller to regulate the current. The internal current control loop consists of a current controller to control the magnitude and phase of the voltage produced by the converter.

### 2.5. Superconducting Fault Current Limiter

The use of current limiters during short-circuit events contributes to optimal current control. Almost all current limiters during short-circuits operate by introducing a significant impedance in series with the system. The introduction of this impedance has led to the development of various current limiters for power systems, demonstrating significant advancements over the past three decades. The Superconducting Fault Current Limiter is one of the most effective types. However, during a network fault, the SFCL impedance rapidly transitions from a superconducting state to a normal state, swiftly limiting the fault current and reducing various fault types. These limiters do not require control circuits and automatically increase impedance during a short-circuit incident, restricting the fault current in less than half a cycle.

Nevertheless, due to challenges such as lengthy recovery and high costs at high voltage levels, the practical use of these limiters is not feasible and requires further research. In this article, the implementation of a diode-bridge-type superconducting fault current limiter is examined, reducing associated weaknesses such as extended recovery time and high costs. In practical operation, the current passing through the superconductor during continuous network operation remains almost constant. Consequently, it acts as an equivalent short circuit to a secondary transformer, leading to a substantial reduction in voltage drop across the secondary transformer and, as a result, almost eliminating the voltage drop in the primary transformer series. Thus, the current limiter has no significant effect on restricting fault current during normal network operation, which is one of its main advantages. In the event of a fault on the load side, the impedance circuit resulting from the superconductor limits the fault current. The main advantage of this limiter is its ability to prevent a sudden increase in fault current during a short-circuit incident, with the fault current gradually increasing with the rise in superconductor current. The research methodology is outlined through a process flowchart in Figure 3, depicting the sequential integration of the Superconducting Fault Current Limiter into Doubly-Fed Induction Generator wind turbine systems and subsequent optimization in MATLAB/Simulink.

## 3. Simulation and Results

In this section, to examine the performance of the presented system, an SFCL circuit in a 1.5 MW dual-fed induction generator connected to the grid is simulated using the Simulink environment in MATLAB. Table 1 will present the parameters of the DFIG under study and the network connected to it. Subsequently, the performance of the DFIG under normal grid voltage conditions and with the proposed method added to the circuit will be investigated. Furthermore, the performance of the proposed method will be examined under various network fault scenarios. For this purpose, the system's performance will be evaluated under single-phase to ground faults, two-phase to ground faults, and three-phase to ground faults. During the analysis of the DFIG performance, wind blows at a constant speed of 15 meters per second, and the reactive power generated by the DFIG is set to zero per unit. The graphical representation of the system in the DFIG is connected to the grid through a transformer 25 KV / 575 V and two parallel 30-kilometer lines. These lines are arranged in parallel to each other so that in the event of a fault in one of them, the other line maintains the DFIG's connection to the grid, enhancing the system's reliability. The 25-kilovolt network is also connected to the main 120 KV network through a transformer 120 KV / 25 KV. The graphical representation of the DFIG system connected to the grid along with the SFCL circuit is shown in Figure 4. The SFCL circuit employed, illustrated in Figure 5, is a diode-bridge type configuration comprising a superconducting coil connected to a rectifier bridge. This SFCL design serves the dual purpose of limiting fault currents during grid disturbances and attenuating voltage fluctuations in the DFIG's rotor circuit.

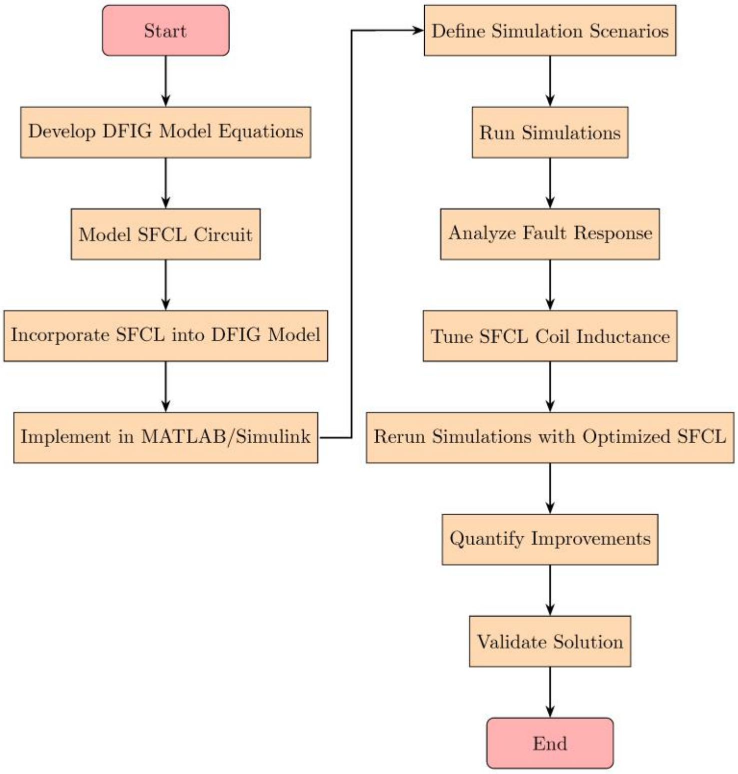


**Figure 3**. Process flowchart for the integration of SFCL into DFIG systems and optimization in MATLAB/Simulink.

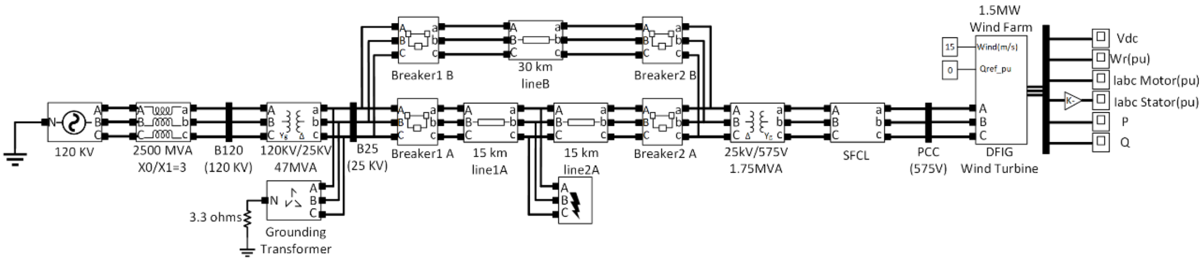


**Figure 4**. Wind turbine circuit with SFCL.

**Table 1.** Doubly Fed Induction Generator and Grid Information**.**

| Parameter | Value |
|---|---|
| Grid Voltage | 575 volts |
| Frequency | 60 Hz |
| Rated Power | 1.5 MVA |
| $R_s$ | 0.023 PU |
| $L_{ls}$ | 0.18 PU |
| $R_r'$ | 0.016 PU |
| $L_r'$ | 0.16 PU |
| $L_m$ | 2.9 PU |
| $H$ | 0.685 PU |
| $p$ | 3 Pairs of Poles |
| C | 10 mF |

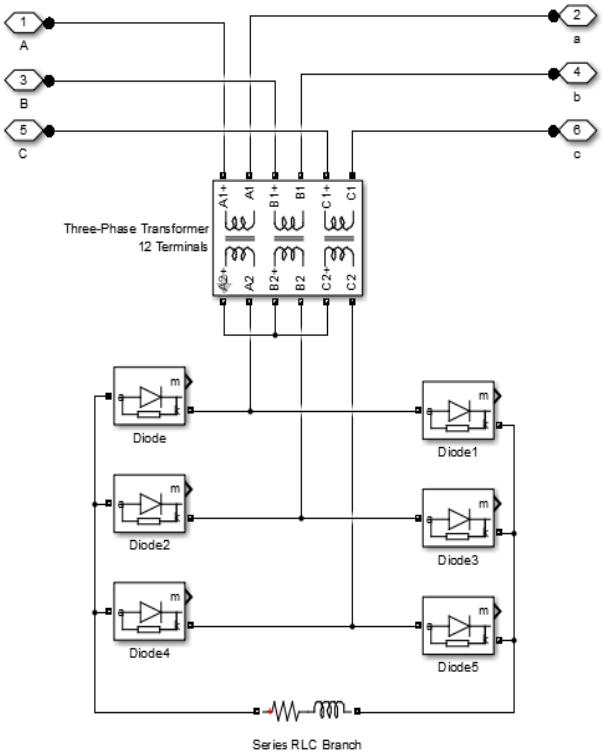


**Figure 5**. The SFCL circuit.

In this study, the performance of SFCL in the event of single-phase, two-phase, and three-phase short circuits has been investigated. Furthermore, the impact of the coil value used in the SFCL circuit has been evaluated. Figure 6 illustrates the results of simulating a single-phase fault. As evident, in this scenario, the presence of SFCL has a negligible effect on limiting the short-circuit current in the rotor and stator windings. The dashed line waveform corresponds to the circuit with SFCL. However, the results indicate that the presence of SFCL reduces transient and sub-transient oscillations in the rotor current, resulting from the occurrence of a two-phase short circuit to the ground in the system, to an acceptable level as shown in Figure 7. Since decreasing the peak value of sub-transient oscillations reduces the likelihood of triggering the wind turbine's trip and its disconnection from the circuit, employing the SFCL circuit in wind turbines is justified.

Similarly, to Figure 7, Figure 8 illustrates the effect of the SFCL on limiting the current, but this time for the stator phase b current during a two-phase-to-ground fault scenario. The figure presents two waveforms: the dashed line waveform corresponds to the circuit with the SFCL integrated, while the solid line waveform represents the circuit without the SFCL. Analogous to the rotor current behavior observed in Figure 7, the results in Figure 8 demonstrate that the presence of the SFCL significantly reduces the magnitude and range of oscillations in the stator current compared to the circuit without the SFCL. The dashed line waveform, which includes the SFCL, exhibits a smaller oscillation amplitude and a quicker damping of the oscillations in the stator current than the solid line waveform without the SFCL. This damping effect on the stator current oscillations is beneficial as it helps prevent potential damage to the circuit and generator windings caused by excessive current levels during the two-phase-to-ground fault condition. As mentioned, the presence of SFCL results in all three stator phase currents having smaller oscillation amplitudes. This prevents damage to the circuit and the generator windings. Figure 9 illustrates that the presence of SFCL further limits the oscillations in the rotor current during a three-phase short circuit to the ground, reducing the likelihood of wind turbine disconnection and increasing the possibility of its recovery after a fault occurs.

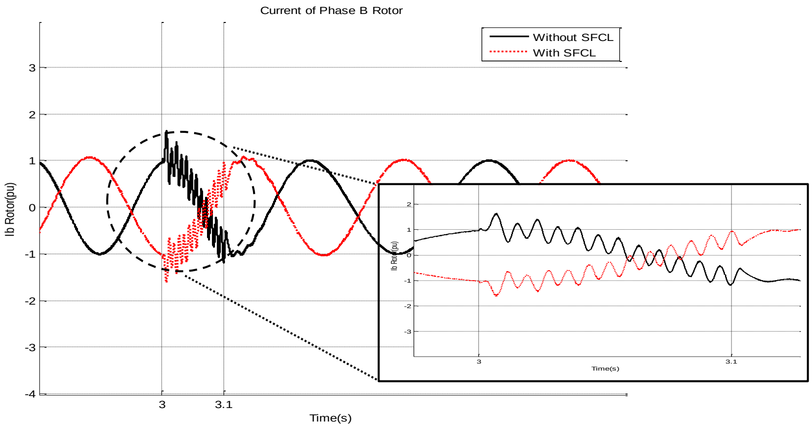


**Figure 6**. The effect of SFCL on limiting the phase a current of the rotor in a single phase to ground fault.

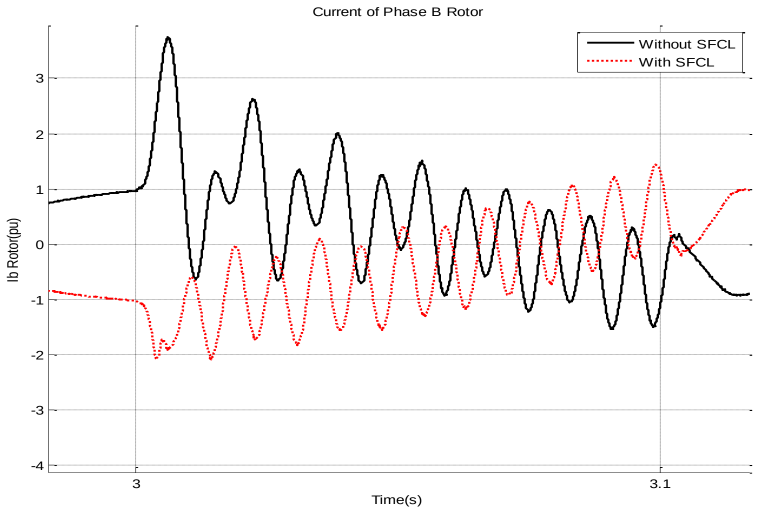


**Figure 7**. The impact of SFCL on limiting the phase b current of the rotor in a two-phase to ground fault.

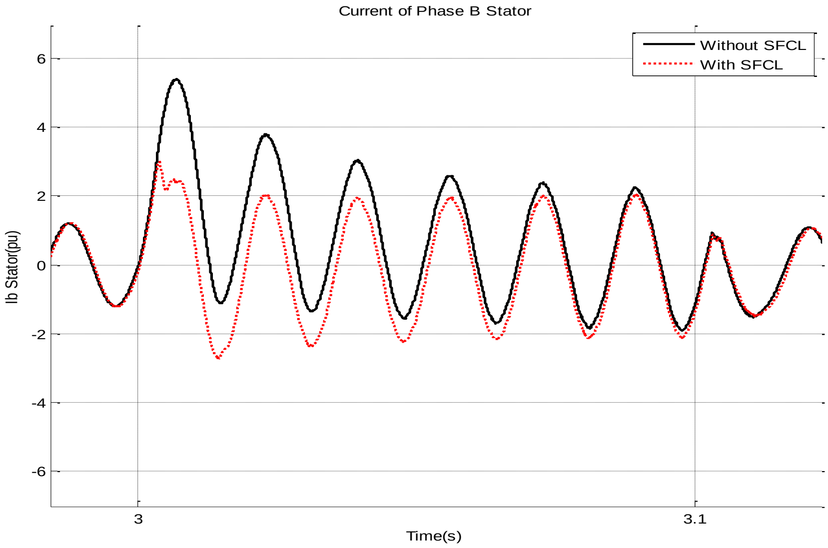


**Figure 8**. The effect of SFCL on limiting the phase b current of the stator in a two-phase to ground fault.

Further investigation examined the impact of varying the SFCL circuit's coil inductance value on the rotor current oscillations during short circuit events. The results, as depicted in Figures 10 and 11, indicate that determining the coil value in a way that places the coil current in continuous conduction mode (CCM) yields the maximum reduction in rotor current oscillations.

Figure 10 shows the rotor phase 'b' current with an SFCL coil inductance of 0.1 Henry during a three-phase to ground fault. While the dashed line waveform (with SFCL) exhibits reduced oscillations compared to the solid line waveform (without SFCL), further optimization is possible. Figure 11, on the other hand, illustrates the rotor phase 'b' current when the SFCL coil inductance is set to the calculated optimal value of approximately 0.2 Henry for the studied system.

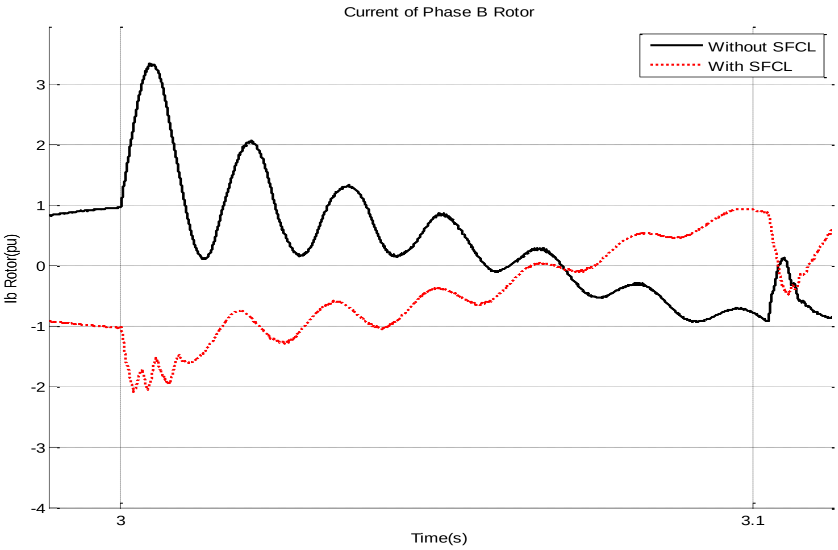


**Figure 9.** The effect of SFCL on limiting the phase b current of the stator in a three-phase to ground fault.

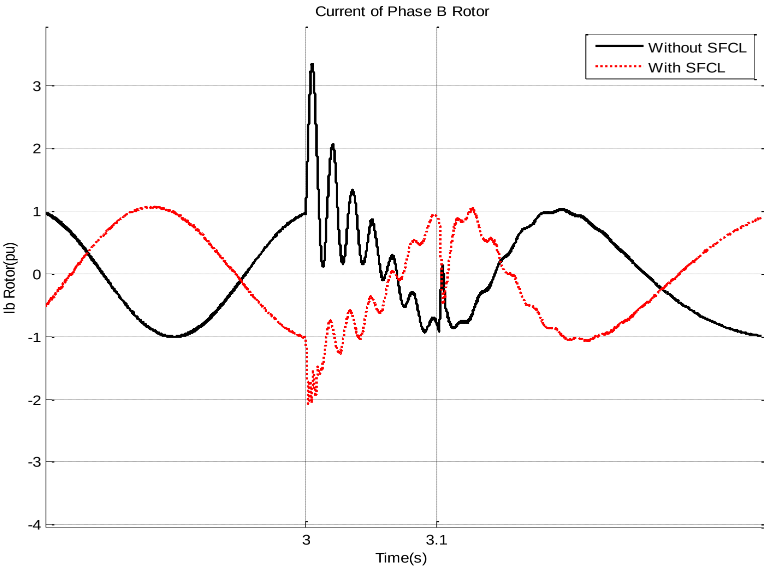


**Figure 10**. Phase b current of the rotor during three-phase-to-earth fault in two states with SFCL and without SFCL, when the value of the inductor is 0.1 H.

The dashed line waveform in this figure demonstrates significantly diminished rotor current oscillations during the three-phase fault, highlighting the importance of tuning the coil inductance to achieve maximum effectiveness in mitigating transient phenomena and enhancing the low voltage ride-through capability of the DFIG wind turbine.

Tables 2 and 3 comprehensively present the peak stator and rotor currents for various inductor values under different fault conditions, with and without the SFCL. The tabulated data validates the SFCL's ability to substantially reduce peak currents, thereby mitigating electrical and mechanical stresses on the generator and converters during grid disturbances. Collectively, these results demonstrate the proposed SFCL system's viability in bolstering the low voltage ride-through capabilities of DFIG-based wind farms, paving the way for higher renewable energy penetration levels.

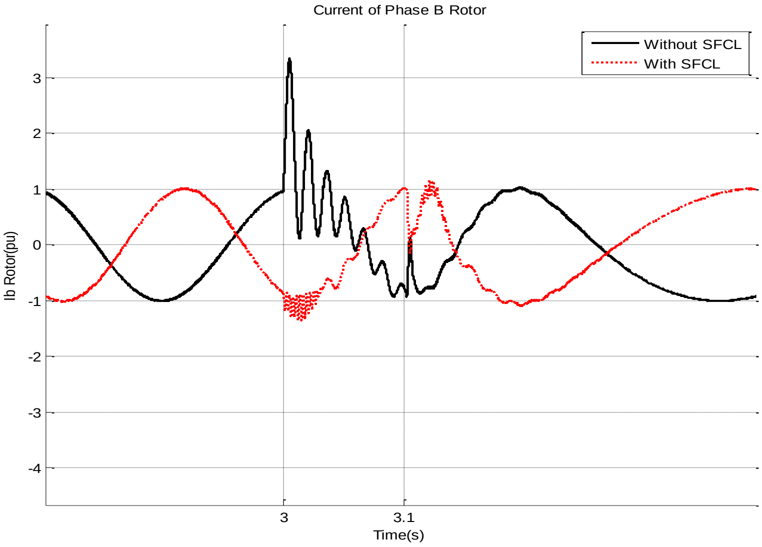


**Figure 11**. Phase b current of the rotor during three-phase-to-earth fault in two states with SFCL and without SFCL, when the value of the inductor is 0.2 H.

**Table 2**. Peak current of the stator for different inductor values.

**Stator Current (PU)**

**Type of short circuit**

| SFCL Value (H) | Three-phase to ground | | Two-phase to ground | | Single-phase to ground | |
|---|---|---|---|---|---|---|
| | Without SFCL | With SFCL | Without SFCL | With SFCL | Without SFCL | With SFCL |
| 0.1 | 4.77 | 2.54 | 4.77 | 2.54 | 1.79 | 1.76 |
| 0.2 | 4.77 | 1.81 | 4.77 | 1.81 | 1.79 | 1.55 |
| 0.3 | 4.77 | 2.05 | 4.77 | 2.05 | 1.79 | 1.72 |
| 0.5 | 4.77 | 1.90 | 4.77 | 1.90 | 1.79 | 1.75 |
| 0.9 | 4.77 | 2.89 | 4.77 | 2.70 | 1.79 | 2.60 |
| 1.2 | 4.77 | 3.26 | 4.77 | 3.29 | 1.79 | 3.30 |

**Table 3**. Peak current of the rotor for different inductor values.

**Rotor Current (PU)**

**Type of short circuit**

| SFCL Value (H) | Three-phase to ground | | Two-phase to ground | | Single-phase to ground | |
|---|---|---|---|---|---|---|
| | Without SFCL | With SFCL | Without SFCL | With SFCL | Without SFCL | With SFCL |
| 0.1 | 3.35 | 1.76 | 3.35 | 1.75 | 1.64 | 1.53 |
| 0.2 | 3.35 | 1.17 | 3.35 | 1.17 | 1.64 | 1.24 |
| 0.3 | 3.35 | 1.45 | 3.35 | 1.45 | 1.64 | 1.33 |
| 0.5 | 3.35 | 1.59 | 3.35 | 1.44 | 1.64 | 1.38 |
| 0.9 | 3.35 | 2.08 | 3.35 | 2.11 | 1.64 | 2.03 |
| 1.2 | 3.35 | 2.34 | 3.35 | 2.32 | 1.64 | 2.36 |

## 4. Conclusions

In this study, we have demonstrated the effectiveness of integrating Superconducting Fault Current Limiters with Doubly-Fed Induction Generator wind farms to significantly enhance their Low Voltage Ride-Through capabilities. Our findings highlight the potential for SFCL technology to mitigate the adverse effects of grid disturbances, thereby improving the reliability and stability of wind power generation systems. Through comprehensive simulations conducted in MATLAB/Simulink, we have validated the improved performance of DFIG systems under various fault conditions, underscoring the viability of SFCL as a robust solution for enhancing wind farm resilience. The successful implementation of SFCL in DFIG systems not only addresses current challenges in wind power generation but also sets a foundation for the future integration of renewable energy sources into the power grid. Our study contributes to the body of knowledge by providing a detailed analysis of the SFCL-DFIG interaction and its impact on system performance, offering valuable insights for researchers, engineers, and policymakers involved in the renewable energy sector.

While this study provides a comprehensive assessment of SFCL integration with DFIG wind farms, several avenues for future research emerge from our work. These include:

1. Broadening SFCL use in renewables like solar and hydro needs exploration for wider benefits and challenges.

2. More sophisticated SFCL-DFIG control algorithms could significantly enhance performance and efficiency under variable grid conditions.

3. It's crucial to conduct a comprehensive economic analysis on SFCL integration in renewables to understand its cost-benefit, including potential savings from enhanced reliability.

4. Examining SFCL's impact on grid stability, quality, and resilience is essential for its sustainable and secure expansion.

These directions will help further renewable energy integration, contributing to a more sustainable and resilient future. By pursuing these future research directions, the scientific community can build upon the foundational insights provided by this study, driving forward the integration of renewable energy into the global power grid and advancing the pursuit of a more sustainable and resilient energy future.

## References

**[1]** W. Qiao, G. K. Venayagamoorthy, and R. G. Harley, "Real-Time Implementation of a STATCOM on a Wind Farm Equipped with Doubly Fed Induction Generators," *IEEE Transactions on Industry Applications*, vol. 45, no. 1, pp. 98-107, 2009.

**[2]** J. Lopez, E. Gubia, E. Olea, J. Ruiz, and L. Marroyo, "Ride Through of Wind Turbines with Doubly Fed Induction Generator Under Symmetrical Voltage Dips," *IEEE Transactions on Industrial Electronics*, vol. 56, no. 10, pp. 4246-4254, 2009.

**[3]** I. Erlich, J. Kretschmann, J. Fortmann, S. Mueller-Engelhardt, and H. Wrede, "Modeling of Wind Turbines Based on Doubly-Fed Induction Generators for Power System Stability Studies," *IEEE Transactions on Power Systems*, vol. 22, no. 3, pp. 909-919, 2007.

**[4]** P. S. Flannery, and G. Venkataramanan, "A Fault Tolerant Doubly Fed Induction Generator Wind Turbine Using a Parallel Grid Side Rectifier and Series Grid Side Converter," *IEEE Transactions on Power Electronics*, vol. 23, no. 2, pp. 1126-1135, 2008.

**[5]** Y. Jin, J. E. Fletcher, and J. O'Reilly, "A Series-Dynamic Resistor-Based Converter Protection Scheme for Doubly-Fed Induction Generator During Various Fault Conditions," *IEEE Transactions on Energy Conversion*, vol. 25, no. 2, pp. 422-432, 2010.

**[6]** N. R. Naguru, A. Karthikeyan, C. Nagamani, and V. S. Kumar, "Comparative Study of Power Control of DFIG Using PI Control and FeedBack Linearization Control," *International Conference on Advances in Power Conversion and Energy Technologies (APCET)*, pp. 1-6, 2012.

**[7]** A. R. Fereidouni, B. Vahidi, and T. H. Mehr, "The Impact of Solid State Fault Current Limiter on Power Network With Wind-Turbine Power Generation," *IEEE Transactions on Smart Grid*, vol. 4, no. 2, pp. 1188-1196, 2012.

**[8]** G. Rashid, and M. H. Ali, "Transient Stability Enhancement of Doubly Fed Induction Machine-Based Wind Generator by Bridge-Type Fault Current Limiter," *IEEE Transactions on Energy Conversion*, vol. 30, no. 3, pp. 939-947, 2015.

**[9]** M. Firouzi, G. B. Gharehpetian, and B. Mozafari, "Power-Flow Control and Short-Circuit Current Limitation of Wind Farms Using Unified Interphase Power Controller," *IEEE Transactions on Power Delivery*, vol. 32, no. 1, pp. 62-71, 2016.

**[10]** M. S. Alam, M. A. Abido, and I. El-Amin, "Fault Current Limiters in Power Systems: A Comprehensive Review," *Energies*, vol. 11, no. 5, p. 1025, 2018.

**[11]** G. M. Gomes Guerreiro, R. Sharma, F. Martin, P. Ghimire, and G. Yang, "Concerning Short-Circuit Current Contribution Challenges of Large-Scale Full-Converter based Wind Power Plants," *IEEE Access*, vol.11, pp. 64141 – 64159, 2023.

**[12]** P. Verma, and P. Gupta, "Proactive Stabilization of Grid Faults in DFIG Based Wind Farm Using Bridge Type Fault Current Limiter Based on NMPC," *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, vol. 45, no. 2, pp. 6062-6081, 2023.

**[13]** X. Liu, and W. Han et al., "Active Fault Current Limitation for VSC-MTDC Integrated Offshore Wind Farms Participating in Frequency Regulation," *IEEE Transactions on Sustainable Energy*, pp. 1 – 15, 2023.

**[14]** M. Ghorbani, M. Firouzi, B. Mozafari, and F. Golshan, "Power Flow Management and LVRT Enhancement by Using Multi-Functional Capacitive Bridge-Type Fault Current Limiter in DFIG System," *International Journal of Electrical Power & Energy Systems*, vol. 148, 108810, 2023.

**[15]** D. Baimel, "Transient Stability Enhancement of Steam Turbine-Based Power Plant by Using Improved Bridge Fault Current Limiter," *Engineering Science and Technology, an International Journal*, vol. 39, 101345, 2023.

**[16]** L. F. Azeredo, and I. Yahyaoui et al., "Study of Reducing Losses, Short-Circuit Currents and Harmonics by Allocation of Distributed Generation, Capacitor Banks and Fault Current Limiters in Distribution Grids," *Applied Energy*, vol. 350, 121760, 2023.

**[17]** B. Carbonell, and C. Cardozo et al., "An Open Source Modelica Implementation of The IEC 61400-27-1 Type 4 Wind Turbine Model for Power System Stability Assessment," *Electric Power Systems Research*, vol. 214, 108313, 2023.

**[18]** M. Sarwar, and M. Arshed et al., "Stability Enhancement of Grid-Connected Wind Power Generation System Using PSS, SFCL and STATCOM," *IEEE Access*, vol. 11, pp. 30832-30844, 2023.

**[19]** A. Mobasseri, M. Tostado-Véliz, A. A. Ghadimi, M. R. Miveh, and F. Jurado, "Multi-Energy Microgrid Optimal Operation with Integrated Power to Gas Technology Considering Uncertainties," *Journal of Cleaner Production*, vol. 333, 130174, 2022.

**[20]** A. Mansouri, A. H. Abolmasoumi, and A. A. Ghadimi, "Weather Sensitive Short Term Load Forecasting Using Dynamic Mode Decomposition with Control," *Electric Power Systems Research*, vol. 221, 109387, 2023.

**[21]** M. Bayat, M. M. Koushki, A. A. Ghadimi, M. Tostado-Véliz, and F. Jurado, "Comprehensive Enhanced Newton Raphson Approach for Power Flow Analysis in Droop-Controlled Islanded AC Microgrids," *International Journal of Electrical Power & Energy Systems*, vol. 143, 108493, 2022.

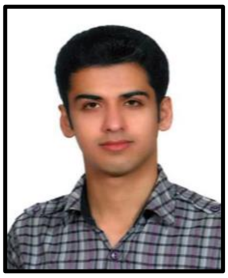
## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, redundancy, have been completely observed by the authors.

## Credit Authorship Contribution Statement

**Seyed Ehsan Aminoroayaye yamani:** Conceptualization, Data curation, Formal analysis, Methodology, Software, Roles/Writing - original draft. **Mohammad Amin Barhamian:** Resources, Visualization, Roles/Writing - original draft, Writing - review & editing. **Ali Asghar Ghadimi :** Conceptualization, Formal analysis, Methodology, Supervision, Validation Roles/Writing.

## Bibliography



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