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A FODPSO-Driven Multi-Layer Control Strategy for Reliable Grid Integration of DFIG Wind Energy Conversion Systems

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Abstract: This work presents an effective optimisation framework to improve Fault Ride-Through (FRT) performance of Doubly-Fed Induction Generator (DFIG)-based Wind Energy Conversion Systems using the Fractional Order Darwinian Particle Swarm Optimisation (FODPSO) technique. The performance improvement strategy uses the FODPSO technique and various grid-support schemes, such as Series Transformer Fault Current Limiter (STFCL), Superconducting Magnetic Energy Storage (SMES), Dynamic Voltage Restorer (DVR), and the SVPWM control strategy for the inverter. In the FODPSO method, particle dynamics are enhanced via fractional-order dynamics, leading to faster convergence. A simulation study indicates that the FODPSO strategy reduces Total Harmonic Distortion, improves Transient stability, and provides faster response times than PI, FLC, PSO-FLC, ANFIS-GA-PSO, ALO-RNN, and the standard DVR-based control strategy. Based on the simulation study, the proposed control strategy maintains grid voltage stability, reduces rotor overcurrent, and maintains constant DC link voltages. In both symmetric and asymmetrical faults, the performance improvement strategy stabilises grid voltages, reduces rotor currents, and maintains constant DC link voltages. In addition, the FODPSO and the SVPWM control strategy provide effective reactive control and continuous connection capabilities for the wind turbine during severe low-voltage dips.

Keywords: System Reliability; Voltage Stability; Fault Ride-Through (FRT); Electromagnetic Torque Ripples; Grid-Support Scheme; Dynamic Voltage Restorer (DVR); Simulation Study.

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1. Introduction

The global transition towards the development and integration of low-carbon energy resources and electric networks has driven the expansion of medium- and extra-large wind farms. Among available wind turbine technologies, the Doubly Fed Induction

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Generator (DFIG) wind turbine system has gained increasing popularity, as it effectively utilises wind speed, efficiently extracts wind energy, and requires a lower capacity rating. As DFIG-based Wind Energy Conversion Systems (WECS) gain widespread popularity for grid integration, the growth of these electric power generation resources, along with their integration and accessibility into already fragile and fault-prone electric power distribution networks, poses many new technical challenges. These new problems and challenges include, but are not limited to, maintaining strict observance and compliance with Fault Ride Through (FRT) capabilities, such as Low Voltage Ride Through (LVRT) and High Voltage Ride Through (HVRT) [1]. In the event of grid faults, the major problems faced by the DFIG are high rotor currents, DC-link voltages, torque instability, and voltage instability, which can cause converter disconnection and system shutdown due to protection system triggering [2].

To overcome these drawbacks, grid codes require wind turbines to remain connected to the grid during both symmetrical and asymmetrical faults. This necessitates the development of efficient control schemes that mitigate the adverse effects of faults. In the conventional control method, the dynamic response, harmonic elimination, and robustness against severe faults tend to be slow. For the conventional optimisation method, the standard Particle Swarm Optimisation, while robust against faults and capable of handling adaptive search spaces, can pose an obstacle to the development of the control system. These limitations raise the potential for designing advanced control architectures based on an optimisation technique that can improve grid support and reliable FRT performance [3]. In the last few years, there has been an increasing trend in research on the use of metaheuristic algorithms, especially their potential to optimise nonlinear systems and improve dynamic control performance. On the other hand, due to their extended memory properties and high flexibility for modelling actual dynamic processes, there has been increasing interest in the use of fractional-order mathematical algorithms [4]. As an important breakthrough, the development of the Fractional Order Darwinian Particle Swarm Optimisation (FODPSO) leverages the advantages of fractional calculus and the swarm's evolutionary adaptive capabilities [5].

This research explores the use of FODPSO across various coordinated control schemes to enhance LVRT and HVRT, and the fault-resilient performance of DFIG-based WECS. In this study, various FODPSO-improved schemes are designed and analysed, including (i) an STFCL-SC scheme for LVRT improvement, (ii) an STFCL-SMES method for the simultaneous improvement of LVRT and HVRT, (iii) an STFCL-DVR and energy storage system for the stabilisation of the grid, and finally, (iv) an FODPSO-based space vector PWM control strategy for the grid-side inverters, which are designed for the reduction of the transient currents during grid faults. These FODPSO-based solutions are applied to enhance voltage regulation, reduce harmonic distortion, reduce rotor overcurrents, maintain DC-link voltage stability, and support the reactive power component during faults. Simulation analyses indicate that the control schemes based on the optimisation algorithms proposed here are much superior to PI, FLC, PSO-FLC, ANFIS-GA-PSO, ALO-RNN, and other algorithms considered across various indices. Improvements have been observed in transient response time, fault recovery, Total Harmonic Distortion, and power stability [6]. By leveraging FODPSO's sophisticated capabilities, the present study offers a unified, comprehensive strategy to enhance the fault-tolerance of DFIG-based wind power generation. With evolving grid codes and the growing integration of wind power into the grid, such optimised, intelligent control schemes will play an increasingly critical role in ensuring grid stability and the service life of wind power generation.

2. Literature Review

Doubly Fed Induction Generator (DFIG)-based wind system integration poses fewer challenges in scaling back-to-back converters, enabling efficient operation across varying wind speeds. Nevertheless, grid-connected fault conditions, whether asymmetrical or symmetrical, in the DFIG are significant sources of severe fault currents that threaten the stability and performance of the grid [7]. In fact, current grid code regulations require that DFIG wind turbines remain connected to the grid and ride through low- and high-voltage fault currents during LVRT and HVRT conditions. As such, enhancing the fault ride-through performance of the DFIG-based wind turbine system integration has become the focal point [8]. In traditional control schemes, proportional integral control and fuzzy logic control (FLC) are widely applied to the doubly fed wind turbines. Proportional-integral control is simple and effective for steady-state performance, but ineffective for dynamic performance. FLC control enhances the processing of nonlinearity but requires expert system rule bases. These are difficult to generate for general conditions. More advanced intelligent control, such as ANFIS and feed-forward backpropagation networks, was designed, but their robustness and speed during fast grid faults remain major limitations [7]. To address the above problems associated with the process of controlling the control, optimisation algorithms such as Particle Swarm Optimisation and various variants, including PSO, are widely popular.

While global search capability for nonlinear control optimisation, as provided by standard PSO, can be effective, the potential for suboptimal search termination and limited adaptive potential, as observed with standard PSO, poses certain problems. To address such problems, variants such as PSO-FLC, GA, ANFIS-PSO, and multi-swarm PSO have been proposed. More recently, Fractional-Order Darwinian PSO, as one of the variants that leverage the properties of memory in the mathematical model of the process known as 'fractional calculus,' shows potential for effective control. Apart from control algorithms, extensive research has focused on hardware-based protection devices to enhance DFIG fault-ride-through capability. The Series

Transformer Fault Current Limiter (STFCL) helps prevent high fault currents from entering the generator and converters. Superconducting Magnetic Energy Storage (SMES) systems can rapidly absorb and inject power during faults, thereby facilitating control of rotor voltages [9]; [10].

A Dynamic Voltage Restorer (DVR), along with an energy storage component, is effective for supporting terminal voltages during faults and for providing grid-side control capabilities. Studies clearly demonstrate that the combination of the above-mentioned devices and control algorithms can improve the ability to suppress rotor currents, enhance DC-link stability, and enhance grid support [11]. Converter modulation schemes are also important for the reliable accomplishment of fault ride-through. For many years, the reasons for using the space vector pulse width modulation scheme have been improved use of the DC-link, reduced harmonic distortion, and high dynamic performance [12]. In addition, when the optimal FODPSO tuning strategy is applied to the control scheme, the system provides reactive power support and fast voltage regulation during the fault [13]. Despite such progress, some gaps remain unfilled by the existing literature. Most research articles rely on simulations and are not validated with hardware, making it difficult to implement the findings [14]. The computational complexity and convergence behaviour of fractional-order optimisation algorithms are aspects that need to be investigated. There are no standards for comparisons for LVRT and HVRT control schemes.

3. Methodology

3.1. FODPSO (Fractional Order Darwinian Particle Swarm Optimisation)

The fitness function has been used to analyse the objective function. The major goal of this method is to track maximum wind power while minimising inaccuracies in turbine mechanical power output. Using an optimisation technique, such as the FODPSO algorithm, the preferred minimum and maximum values are obtained (stimulated by the PSO algorithm). The Particle Swarm Optimisation algorithm is a computational technique that enhances the search for optimal solutions by iteratively evaluating potential solutions. The potential solutions, called particles, in the PSO process move through the search space to find the optimal solution. Every step, the particle maintains the best position that belongs to it, as well as the best position for the whole cluster. Particles are stuck to the optimal solution available in the search space as a result of the computation process initiated by the use of the PSO algorithm. As a result, the challenges are addressed by incorporating Darwinian PSO (DPSO). This DPSO (Darwinian PSO) employs a multi-simultaneous parallel PSO method, with each swarm in the search space having its own. This optimisation technology has a downside: while the search is considered suboptimal, it is effectively denied in that region, and a new location is sought. For this DPSO, an inactivity issue reduces uptime and automatically deletes items in the search space. A very long convergence time is therefore required. To overcome the difficulty and control the convergence rate of DPSO, fractional-order DPSO was considered. These mathematical properties are suited to the dynamics of particle trajectories, since this fractional order requires an unlimited number of circumstances. The FODPSO equation is as follows:

$$\mathrm{v}_{\mathrm{n1}}^{\mathrm{s1}}[\mathrm{t}+1] = \mathrm{w}_{\mathrm{n1}}^{\mathrm{s1}}[\mathrm{t}+1] + \rho_1 \mathrm{r}_1(\hat{\mathrm{g}}_{\mathrm{n1}}^{\mathrm{s1}}[\mathrm{t}] + \rho_2 \mathrm{r}_2(\hat{\mathrm{x}}_{\mathrm{n1}}^{\mathrm{s1}}[\mathrm{t}] - \mathrm{x}_{\mathrm{n1}}^{\mathrm{s1}}[\mathrm{t}])) \qquad (1)$$

$$\mathrm{w}_{\mathrm{n1}}^{\mathrm{s1}}[\mathrm{t}+1] = \alpha \mathrm{v}_{\mathrm{n1}}^{\mathrm{s1}}[\mathrm{t}] + \frac{1}{2}\alpha(1-\alpha)\mathrm{v}_{\mathrm{n1}}^{\mathrm{s1}}[\mathrm{t}-1] + \frac{1}{6}\alpha(1-\alpha)(2-\alpha)\mathrm{v}_{\mathrm{n1}}^{\mathrm{s1}}[\mathrm{t}-2] + \frac{1}{24}\alpha(1-\alpha)(2-\alpha)(3-\alpha)\mathrm{v}_{\mathrm{n1}}^{\mathrm{s1}}[\mathrm{t}-3] \qquad (2)$$

Here, the number of times the particles shift their position in the multidimensional space is denoted as n, the position as xn1[t], the velocity as vn[t], the position of the best solution as [t], and the global optimal solution as planet Given that the inertial factor inertial weight for the global superior solution and the local excellent solution are1 and 2, respectively. r1 and r2 represent the weights applied to regulate the inertial influence of globally good and locally outstanding solutions. The letters s stand for the number of search swarms, the fractional coefficient, and the fractional coefficient, respectively:

$$\mathrm{x}_{\mathrm{n1}}[\mathrm{t}+1] = \frac{1}{1+\mathrm{e}^{-\mathrm{v}_{\mathrm{n1}}[\mathrm{t}+1]}} \qquad (3)$$

$$\mathrm{x}_{\mathrm{n1}}[\mathrm{t}+] = \begin{cases} 1, & \Delta \mathrm{x}_{\mathrm{n1}}[\mathrm{t}+1] \geq \mathrm{r}_{\mathrm{x}} \\ 0, & \Delta \mathrm{x}_{\mathrm{n1}}[\mathrm{t}+1] < \mathrm{r}_{\mathrm{x}} \end{cases} \qquad (4)$$

Where rx represents a random vector having a uniform random number ranging from 0 to 1 and a uniform random number ranging from 0 to 1.

4. Simulation Analysis

Figure 1 shows the Total harmonic distortion in current using the FODPSO method.

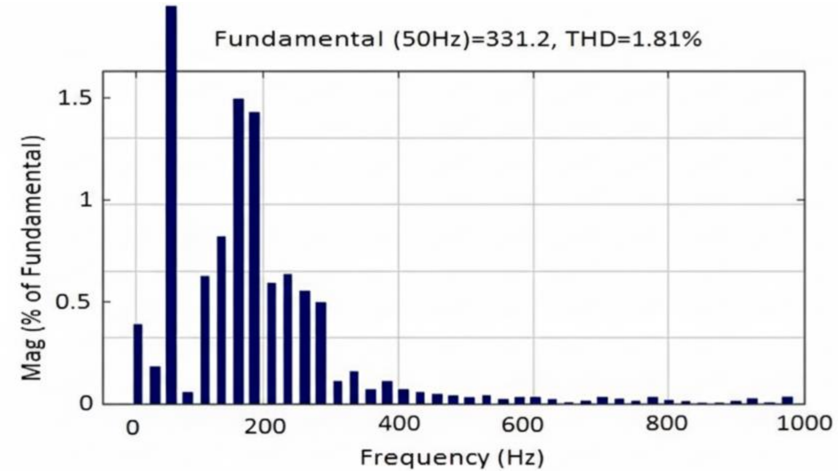

Figure 1: Total harmonic distortions using the FODPSO method

The following Figure 2 shows the total harmonic distortion in voltage using a PI controller.

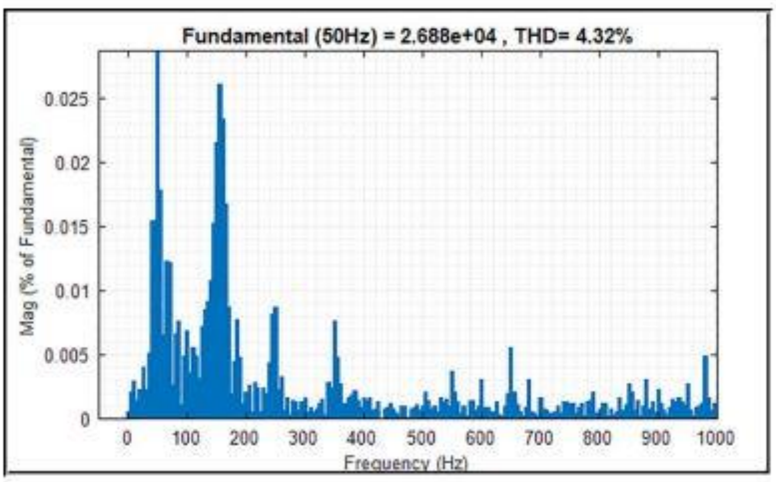

Figure 2: Total harmonic distortions using PI controller

Figure 3 indicates the 3D graph of the comparative analysis of THD current for the FLC and PSO-FLC controllers.

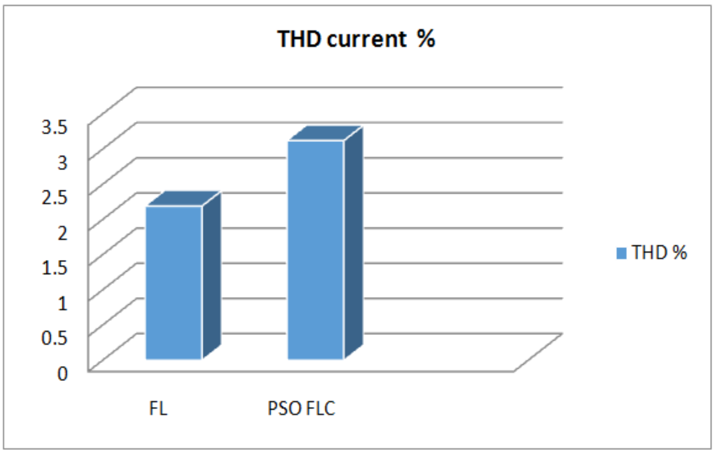

Figure 3: Comparative analysis of THD current for FLC and PSO-FLC controller

Tables 1, 2, and 3 show the comparison analysis and THD values for wind speeds of 12m/sec, 10m/sec, and 6m/sec (Table 1).

Table 1: Comparison analysis of THD value under wind speed (12 m/sec)

Parameters	Wind Speed (m/sec)	Output Power (W)	Time Response (sec)	THD (%)
PI Controller	12	290	0.48	4.32
FL Controller	12	295	0.42	3.12
PSO FLC	12	310	0.4	2.19
Proposed FODPSO	12	350	0.23	1.81

Table 2 compares different controllers operating at a constant wind speed of 10 m/s. The PI controller has the lowest output power, the highest THD, and a slow response time. The FL controller improves performance, and the PSO–FLC makes it even better. The PSO–FLC delivers higher output power, lower harmonic distortion, and faster dynamic response. The suggested FODPSO controller outperforms all other approaches by producing the most power, responding the fastest, and having the lowest THD. This means it is more efficient, more stable, and of higher quality.

Table 2: Comparison analysis of THD value under wind speed (10 m/sec)

Parameters	Wind Speed (m/sec)	Output Power (W)	Time Response (sec)	THD (%)
PI Controller	10	285	0.48	4.38
FL Controller	10	290	0.42	3.22
PSO FLC	10	305	0.4	2.22
Proposed FODPSO	10	340	0.23	1.92

Table 3 shows how different controllers perform at a wind speed of 6 m/s, with respect to output power, time response, and total harmonic distortion (THD). The PI controller has the lowest output power (273 W), the largest THD (4.56%), and the slowest response time (0.48 s). The FL controller improves a bit, with output power rising to 282 W and THD and response time decreasing. The PSO–FLC controller further improves the system, producing 301 W with a lower THD (2.23%) and a faster response time of 0.40 s. The suggested FODPSO controller is superior to the others, as it delivers the maximum output power (313 W), the shortest response time (0.23 s), and the lowest THD (1.95%). This shows that it is more efficient, dynamic, and of higher quality.

Table 3: Comparison analysis of THD value under wind speed (6 m/sec)

Parameters	Wind Speed (m/sec)	Output Power (W)	Time Response (sec)	THD (%)
PI Controller	6	273	0.48	4.56
FL Controller	6	282	0.42	3.29
PSO FLC	6	301	0.4	2.23
Proposed FODPSO	6	313	0.23	1.95

From the above compression, the proposed optimisation method provides better harmonic elimination (%THD) in the current waveform and reduces the tracking time to 0.3 seconds. The following Figure 4 shows the FODPSO flowchart. There are certain steps to follow the FODPSO algorithm:

- **Step 1:** Adjust the speed and position of all FODPSO limits.
- **Step 2:** High iteration estimate; it represents i = 1:1, the maximum number of iterations.
- **Step 3:** Fix the number of swarm matrices, denoted by n = 1:1 no. Herd matrix.
- **Step 4:** Adjust the parameters of the lowest-fitness function.
- **Step 5:** Estimate the difference between the maximum fitness valuesof I and i1.
- **Step 6:** Update the positions and velocities of all particles.
- **Step 7:** Repeat step 3 several times.

Based on the FODPSO optimisation technique, the STFCL and SC for LVRT Capability in a Doubly-Fed Induction Generator system are improved, and the results are analysed.

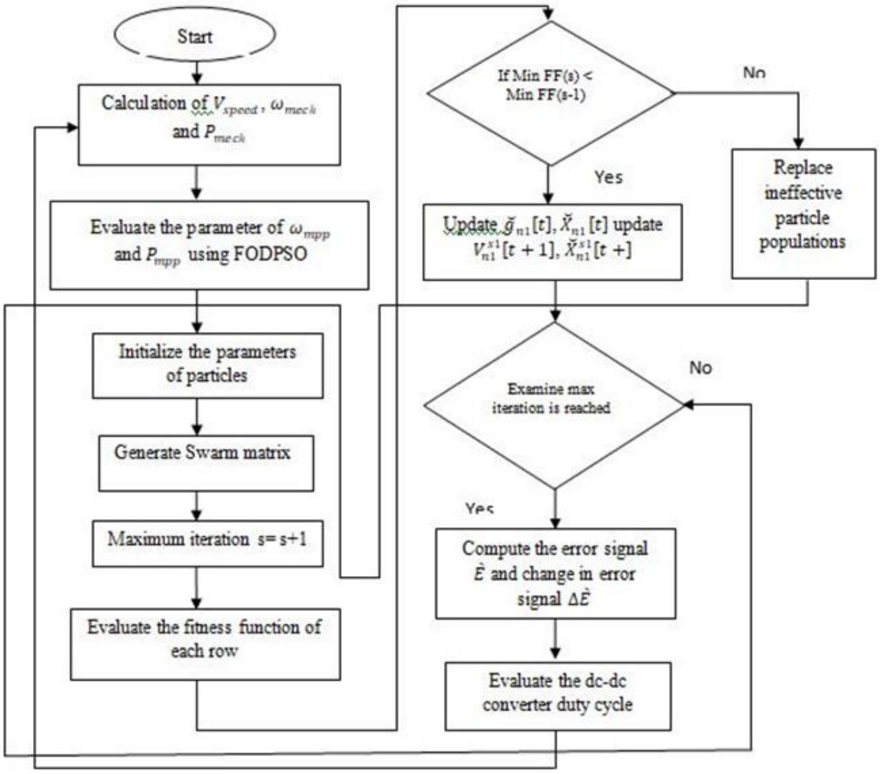

Figure 4: FODPSO flowchart

4.1. FODPSO Optimisation-Based STFCL and SC for LVRT Capability in DFIG

The primary goal of this research is to develop an LVRT control system that enables the design of a controller capable of rectifying fault signals. This study presents a new approach for LVRT, termed FODPSO optimisation, for STFCL and SC. It also compares the proposed system to conventional approaches. As a consequence, it examines the simulation findings through qualitative analysis during normal operation and fault conditions. As a result, the suggested FODPSO-based STFCL and SC for the LVRT system outperform the conventional methods. The proposed FODPSO-LVRT's active power more correctly rectifies the fault signal than the systems with minimum and maximum constant gain, as well as the typical LVRT system. The reactive power, real power, and voltage of the grid area unit are now coordinated using the planned technique. The proposed FODPSO-based STFCL-SC method was used to improve LVRT capabilities, and its results were compared with those of the hybrid ANFIS-GA-PSO and ALO-RNN methods. The anticipated approach's performance analysis is explained further below.

Table 4: Control action performance comparative analysis

Control Actions	ALO-RNN	ANFIS-GA-PSO	Proposed Method
Active power	0.21 s	0.22 s	0.20 s
Reactive power	0.20 s	0.21 s	0.20 s
Voltage	0.2-0.32 s	0.22-0.33 s	0.2-.30 s
Current	0.2-0.30 s	0.2-0.31 s	0.2-0.30 s

The control action performance comparison analysis reported in Table 4 shows that the grid-side reactive power is balanced and steady before the voltage lowers. When a grid failure occurs at a specific moment, the grid-side power begins to decline, and the control strategy immediately reduces the GSC output power to maintain system stability. As a result, researchers can conclude that the suggested approach has strong LVRT performance.

4.2. FODPSO Optimisation-Based STFCL-SMES for HVRT and LVRT Capability of DFIG

The purpose of this examination is to improve the LVRT capability of the Doubly-Fed Induction Generator by utilising FODPSO-based SMES and STFCL, along with a few changes to the framework. It is necessary that the voltage ride through, even at a value below 10-15% of the correct value, during voltage droops. In this proposed model, the RSC and the GSC have been controlled using FODPSO-based SMES and STFCL. The proposed Doubly-Fed Induction Generator Wind Energy Conversion System comprises a SEPIC converter, a wind turbine, a Bidirectional converter, recirculating converters, and a drive train, all of which are connected to the framework via transformers. The control techniques and the operation of the proposed framework are discussed. The following Figure 5 shows the block diagram of the FODPSO-based STFCL-SEMS system.

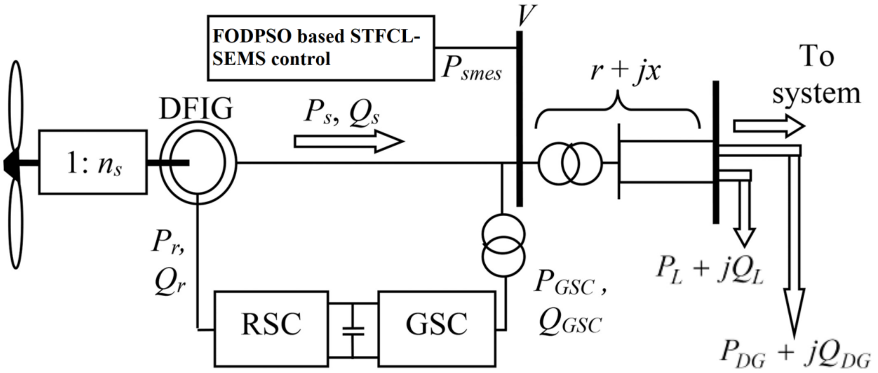

Figure 5: Block diagram of FODPSO-based STFCL-SEMS system

When a grid failure occurs, the series SEMS system on the rotor side is used to create the desired output voltage while also absorbing energy. Compared with other methods for improving LVRT capability with FODPSO-based STFCL, this strategy can directly control the SMES output voltage to suppress the transient AC voltage component in the rotor, making it more effective and faster. The simulation results presented in this paper demonstrate the efficiency of the fully modified model in handling network voltage variations, including the ability to reduce voltage and prevent high-voltage wind turbine operation. In LVRT and HVRT conditions, the complete control method is employed to connect the Doubly-Fed Induction Generator to the grid. As a result, this approach can be used to reduce both low- and high-voltage transients. Because conventional safety measures do not control the rotor current or framework separation during die voltage drop, frequent checks are required to prevent poor framework performance. FODPSO-based STFCL-SMES framework improves performance and encourages the use of wind turbines to keep internet connections up and running during power outages, while enhancing LVRT and operational control in imbalanced, unstable shortage conditions.

4.3. FODPSO Optimisation Based STFCL, DVR, and Energy Storage System of DFIG

This work presents an FODPSO-based DVR with STFCL for wind turbine generators composed of a Doubly-Fed Induction Generator to meet LVRT criteria in grid systems. The in-statement position, simulation, and strategies for improving LVRT performance are all represented. A collaborative, link-based approach that integrates STFCL with a mix of inductance-emulation control and reactive power control enables the Doubly-Fed Induction Generator to generate reactive power while ensuring the system remains safe even when the grid is down. A variety of fault conditions are investigated, both in the regular situation and when the projected system is connected. The following Figure 6 shows the block diagram of the FODPSO-based Doubly-Fed Induction Generator.

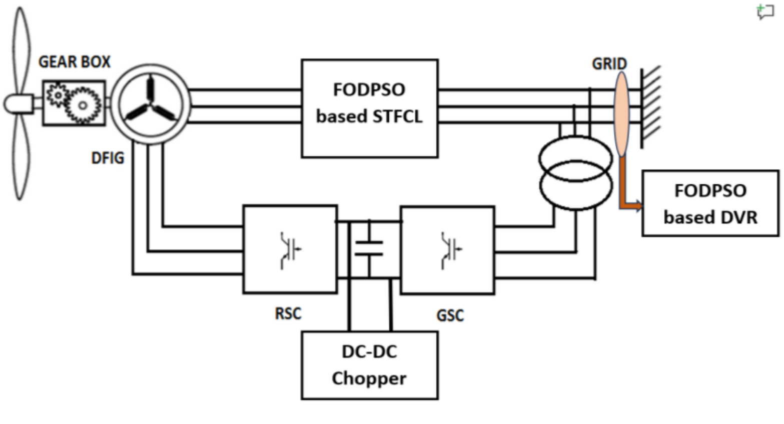

Figure 6: Block diagram of FODPSO-based DFIG

The proposed system is capable of dealing with a variety of faults. The following fault types were investigated: LLL, LL, LLLG, LG, and LLG. All of these defects are investigated under two conditions: initially, when the STFCL is off, and second, when it is on. When a failure occurs, the FODPSO-based DVR calculates the required grid voltage and supplies it to the system. At typical supply voltage levels, the FODPSO-based DVR is adjusted to minimise losses. When a voltage sag is detected due to a fault, the FODPSO-based DVR responds instantly by injecting AC into the grid. As a rule, the FODPSO-based DVR distinguishes between the reference voltage and the infused voltage and produces the heap-appraised voltage. Table 5 shows a comparison of several approaches on the Doubly-Fed Induction Generator subject to symmetrical and asymmetrical faults.

Table 5: Comparison of several approaches on the DFIG subject to symmetrical and asymmetrical faults

Type of Fault	Parameter	With DVR	Without Auxiliary	With the FODPSO-DVR
Symmetrical fault	DC link voltage	1.23 KV	1.94 KV	1.19 KV
	Stator current	2.1 pu	4.1 pu	1.49 pu
	Terminal voltage (RMS)	0.36 pu	0.05 pu	0.37 pu
	Rotor current	2.31 pu	3.49 pu	1.4 pu
	Electromagnetic torque	1.71 pu	2.25 pu	0.97 pu
Asymmetrical fault	DC link voltage	1.21 KV	1.31 KV	1.19 KV
	Stator current	1.54 pu	3.28 pu	1.39 pu
	Terminal voltage (RMS)	0.54 pu	0.38 pu	0.56 pu
	Rotor current	2.03 pu	3.64 pu	1.35 pu
	Electromagnetic torque	1.88 pu	3.12 pu	1.17 pu

According to the findings, the combined FODPSO-DVR makes the greatest contribution to the stabilisation of Doubly-Fed Induction Generators. The combined FODPSO-DVR can significantly reduce fault currents in the Doubly-Fed Induction Generator stator and rotor, and provide visible voltage stabilisation at the generator terminal and the DC-link. As a result, the risk of converter damage is minimised, and appropriate LVRT performance is achieved for the Doubly-Fed Induction Generator under both fault scenarios. Therefore, LVRT improved, and electromagnetic force motions decreased. Additionally, energy pulverisation is diminished.

4.4. FODPSO Optimisation-Based SVPWM Inverter Control for the FRT Method of DFIG

The study focuses on decreasing the transient current throughout the instant of fault. The converters connected to the Doubly-Fed Induction Generator to the grid, consisting of an AC-to-DC converter, a boost converter, and an FODPSO with a space-vector pulse-width modulation-based DC-AC converter. Modelling and control approaches were also discussed in this study. The performance of the SVPWM controller is analysed under symmetrical and unsymmetrical fault conditions. The reactive power flow is also analysed, and the effectiveness of the proposed controller is verified using MATLAB/SIMULINK.

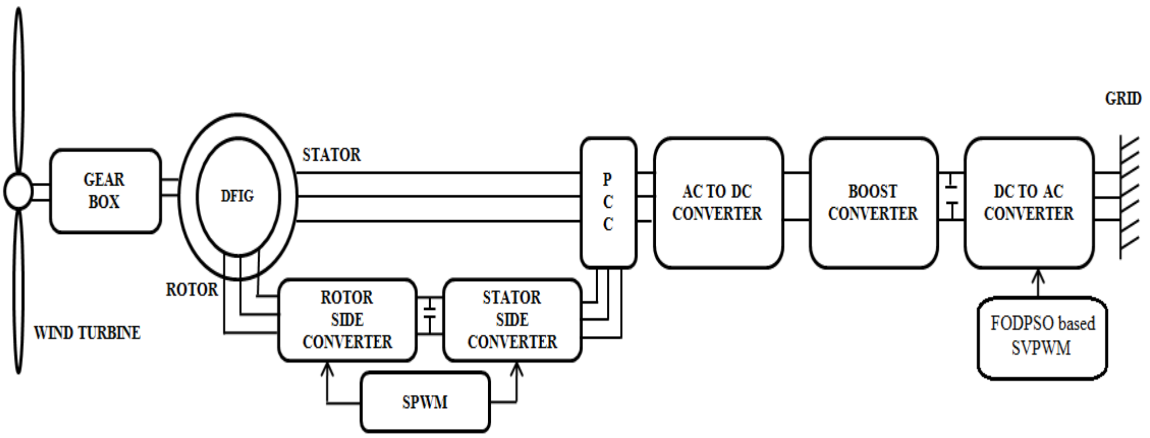

Figure 7: Block diagram of the proposed circuit

The anticipated control method, as shown in Figure 7, improves the voltage and current waveform. The reactive power variation is also greater than that under the conventional control scheme. With the conventional control scheme, the entire system suffers a significant voltage drop and draws more reactive power from the grid, leading to the plant being disconnected from the System. The implemented schemes facilitate the plant's connection to the system. Hence, the simulation results show that the proposed control enhances the LVRT capability of the Doubly-Fed Induction Generator and provides adequate reactive support to the grid during balanced and unbalanced fault conditions. Table 6 presents a comparison of SVPWM and FODPSO-SVPWM.

Table 6: Comparison analysis of SVPWM and FODPSO-SVPWM

Parameters	Symmetrical Fault with SVPWM Method	Symmetrical Fault with FODPSO- SVPWM Method	Unsymmetrical Fault with SVPWM Method	Unsymmetrical Fault with FODPSO-SVPWM Method
Grid Voltage	11kV	11kV	11kV	11kV
Grid current	78A	80A	77A	80A
Reactive power	598kvar	599kvar	594kvar	597kvar

Appropriate control techniques are implemented in both the DC-DC converter and the FODPSO-SVPWM-based DC-AC converter for the performance of the Doubly-Fed Induction Generator under various network disturbances. The proposed system performs satisfactorily under symmetrical and unsymmetrical fault conditions and during normal operation. In the end, it is shown that projected control techniques can enhance the LVRT performance of a Doubly-Fed Induction Generator-based Wind Energy Conversion System during network disturbances.

5. Result and Discussion

The proposed control system, based on the FODPSO optimiser, consistently and significantly outperforms the other schemes across all test cases. The harmonic analysis clearly indicates that the FODPSO optimiser provides the minimum values for the total harmonic distortion, which are 1.81%, 1.92%, and 1.95% for the wind velocities of 12, 10, and 6 m/s, respectively, and are significantly less compared to the values of the other schemes, which are above 2-4%. Additionally, the settling times are reduced by 0.23 s. In the case of LVRT, the FODPSO-STFCL-SC scheme required the least time for active and reactive power stabilisation (0.20 s), compared to the ALO-RNN and ANFIS-GA-PSO control schemes, which required up to 0.33 s. This quick stabilisation helps the DFIG operate stably during low-voltage conditions and supports the grid. The optimised FODPSO design for the STFCL-SMES system improved the LVRT and HVRT capabilities. The SMES system significantly reduced transient currents and stabilised the rotor voltage. This indicates the advantages of the designed system over traditional protection schemes, which do not limit the stresses experienced by the rotor during deep sags and swells. The stabilisation impacts were achieved most prominently by the FODPSO-DVR method. In the case of symmetric faults, the DVR reduced the DC link voltage to 1.19 kV, down from 1.94 kV without auxiliary support, and the stator and rotor currents decreased to 1.49 pu and 1.40 pu, respectively. Comparable effects were observed for the asymmetrical faults, including damping of Electromagnetic Torque Oscillations and improved terminal voltage.

5.1. FODPSO-SVPWM Inverter

Both the FODPSO-SVPWM Inverter and the Fuzzy–PID-SVPWM Inverter demonstrated their effectiveness in improving voltage and current quality. In both symmetric and asymmetric fault cases, the FODPSO-SVPWM Inverter maintained the grid's constant voltage of 11 kV and provided higher reactive support (599 kVAR) than the standard SVPWM. In total, the experiments confirm that integrating FODPSO optimisation into the control layers of the converter, auxiliary equipment, and modulation significantly improves stability, harmonic distortion, and overcurrent, as well as LVRT and HVRT compliance. This indicates the appropriateness of the FODPSO intelligent control strategy.

6. Conclusion

This work demonstrated that integrating the Fractional Order Darwinian Particle Swarm Optimisation (FODPSO) technique with DFIG-based Wind Energy Conversion Systems substantially improves both LVRT and HVRT capabilities under a wide range of grid disturbances. The optimisation framework improved transient behaviour, harmonic suppression, and power stability across all tested wind speeds. The proposed FODPSO controller consistently achieved the lowest THD levels—1.81% at 12 m/s, 1.92% at 10 m/s, and 1.95% at 6 m/s— outperforming PI, FLC, and PSO-FLC schemes. In addition, it produced the highest maximum power output (up to 350 W at 12 m/s) and the smallest response time of 0.23 seconds. For improving LVRT characteristics based on STFCL and SC, the FODPSO-based control strategy showed faster stabilisation times for active and reactive power (0.20 s) than ANFIS-GA-PSO and ALO-RNN. Additionally, it worked well with SMES to control rotor voltage and improve low- and high-voltage ride-through capabilities. The FODPSO-DVR produced marked improvements during symmetric and asymmetric faults by suppressing the stator current to 1.49 pu, the rotor currents to 1.40 pu, and the DC-link voltage to 1.19 kV, while maintaining the terminal voltages close to their rated values. Equally, the FODPSO-SVPWM inverter performed well, delivering approximately 599 kVAR of reactive support and ensuring stability during both symmetric and asymmetric faults. In essence, the experiment validates that the FODPSO control strategy provides an effective, rapid solution for ensuring seamless grid integration of the DFIG-based wind energy system.

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