Research Article
Optimal Fractional Order Based on Fuzzy Control Scheme for Wind Farm Voltage Control with Reactive Power Compensation

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Voltage stability margin is ensured through the reactive power resources. In order to generate the reactive power references and ensure the low-voltage ride-through (LVRT) control of a wind farm system based on squirrel cage induction generator, this paper proposed an optimal control approach based on fractional-order (FO) PI-fuzzy-PI (FOPI-fuzzy-FOPI) controller. The proposed control method ensures, also, the demand for active and reactive power predetermined by the transmission system operator (TSO) and satisfies the grid code recommendations. In order to achieve a faster tracking of state variables of the system, the FO operators are optimized using the particle swarm optimization algorithm (PSOA). Using FO operator and PSOA, the responses of the system can be improved. The proposed controller provides additional parameters for better tracking performance and faster convergence can be achieved. Numerical simulation results are presented to analyze the advantages of the proposed control approach to design a physically, realizable controller. The present results are compared with various control methods to show the superiority of the method proposed in this paper.

1. Introduction

Nowadays, the increased integration of wind energy sources in the grid [1] is leading to the establishment of grid codes. The wind farms (WFs) are more demanded to control the active and reactive power and to participate in the service system. Therefore, the research in the field of wind energy conversion systems (WECSs) is oriented towards designing supervision systems with the aim of distributing references of active and reactive powers among wind turbines using the supervision algorithm [2–6].

The central and local units of the supervision system are set up for controlling and injecting active and reactive power into the grid. These powers are produced according to one of the control modes [5].

For stable and reliable operation of WECS, most grid codes impose for the grid connected WFs to inject the reactive power during faults (for voltage support) and stipulate that WFs must keep connected to the grid [7, 8].

In weakly grids connected WFs, it is not efficient to transfer reactive power over a long-distance transmission line. The reactive power shortage should be compensated locally to avoid losses. Accordingly, the European Network of Transmission System Operators for Electricity (ENTSO-E) (Policy 3: Operational Security) indicates that the measurements must be taken to maintain reactive power near the point of consumption to ensure the minimal transfer of reactive power through the network [8]. The reactive power is also required for voltage stability of power systems and satisfies the Grid Code Requirements (GCRs) [5].

For solving the problem of WF reactive power control at Point of Common Coupling (PCC), various control methods are proposed recently in the literature, such as hierarchal fuzzy controller [9], nonlinear fuzzy controller [10], and fractional-order controller (FOC) [11].

The first work on FO derivatives is started in the last centuries and the theory of fractional calculus has been developed mostly by mathematicians. Moreover, in recent decades, considerable interest has been shown in fractional calculus through the application of these concepts in different fields of physics and engineering, and the idea of employing fractional calculus in system control loops has
appeared. The FOCs [12, 13], such as fractional-order PID controller (FOPID), are used in many applications to overcome the problem related to the dynamic system response and performances. This controller type can be used for renewable system control [14, 15], and it can be used also for designing observer-based control [16] and intelligent control system.

In the field of control engineering, the control strategy is intelligent if it is based on artificial intelligence computing approaches like neural networks, fuzzy logic, machine learning, genetic algorithms, and the improved version PSO algorithm based on Intelligent Particle Number Control for Optimal Design [17, 18].

Many works propose the fuzzy fractional-order controllers to improve the control performance for grid-connected Variable Speed Wind Energy Conversion System [19–27], and it is employed to obtain a robust control system for Quadrotor Unmanned Aerial Vehicle [28–30]. The response of the controllers can be improved using the particle swarm optimization (PSO) algorithm [14] invented by Russel Eberhart (electrical engineer) and James Kennedy (sociopsychologist) in 1995 [31]. In most references, the PSO is investigated for controller parameter optimization. It is used to enhance PI controller performance [32] and to optimize a simple fuzzy controller [33] and fractional high-order controller [34].

This paper presents the application of FO fuzzy PI (FOFPI) controller using the PSO algorithm to adjust their parameters to obtain an optimal intelligent control for a wind farm voltage control [35]. This proposed control method combines the FOC, fuzzy logic, and PI controller to improve the PCC voltage and reactive power responses. The suggested control method allows the WF based on the squirrel cage asynchronous generator (SCAG) to participate in the service system.

The main contributions of this paper are given as follows:

(i) Unlike in [9, 15] that present the PI, PIFPI, and FOPPID methods without a fractional-order operator, the proposed control methods utilize PIFPI with fractional dynamics and more degree of freedom to allow the control structure to be more flexible.

(ii) Unlike in [9, 15], the control parameters are obtained using only the traditional trial and error method, and the fractional-order operators of the proposed control are tuned based on the particle swarm optimization algorithm.

(iii) Using the proposed controller, the Low Voltage Ride-Through (LVRT) control is guaranteed. Also, its tracking performance is superior compared to the PI regulator, hierarchal fuzzy controller (PIFPI) [9], and the FOPPID proposed in [15] and that proposed in [36].

(iv) Develop the model of the grid with possible parametrization of the reactive power-voltage control.

The control method proposed in this paper is validated through the simulation of WF consisting of three WTs using the three control modes.

The remaining sections of this paper are as follows: Section 2 addresses the configuration of the supervision system and WECS; then its management, according to the grid code recommendations, is developed in Section 3. In Section 4, the proposed control technique is presented. The validation using the simulation results is discussed in Section 5. In the final section (Section 6) the main contribution points are concluded.

2. The Supervisory System of the WECS

The global scheme of the WECS and the system control are illustrated in Figure 1. In this figure, \( i_d \) and \( i_q \) are the reference values of the current, \( \bar{v}_d \) and \( \bar{v}_q \) are the voltage control voltages. \( \Phi_{ref} \) is the desired value of the estimated d-axis rotor flux \( \Phi_{rd-estim} \).

To achieve and respect the TSO power requirements, the supervision system should be configured as that given in Figure 2(b). The central supervision unit receives the power reference from the TSO (\( P_{WF-ref} \) and \( Q_{WF-ref} \)) and sends to it at the same time the information about the maximum power capacity (\( P_{WF-max} \) and \( Q_{WF-max} \)). The local supervision unit computes the power references necessary for the operation of each WT, using one of the three control types (MPPT, PQ, or fault control), and sends the information about the WTs maximum power production (\( P_{WG-max,i} \) and \( Q_{WG-max,i} \)) to the central supervisory unit, as illustrated in Figure 2(a) [5, 6].

The protection of the WTs is ensured by the automatic system protection to avoid the damage of its equipment. The protection of WTs is achieved by the automatic disconnection from the grid and the connection of the load protection (LP1) for dissipating the power underproduction. It also indicates and sends the information about the problem type to the TSO (Figure 2(a)). The turbine protection system decides to disconnect the WTs based on the level of the voltage sag, the fault clearance time, the location, and the type of fault [37]. The limits, period, and types of protection are listed in Table 1.

The power references of each WT (\( P_{WG-ref,i} \) and \( Q_{WG-ref,i} \)) are computed using the WF references (\( P_{WF-ref} \) and \( Q_{WF-ref} \)) following the instructions of PDA given in Algorithm 1 which is summarized in Figure 2(b) [5].

2.1. The Electrical Network Modeling. The grid model is developed for possible parameterization of reactive power-voltage control using two synchronous generators (SG1 and SG2) feeding the loads as shown in Figure 3. Each SG is connected to a steam turbine controlled by a power governor system for delivering the required electrical power [9, 38, 39]. For power network stability and control of power flow, the voltage and the frequency are controlled as illustrated in Figure 3 [9].

The excitation system of the synchronous generator unit regulates its terminal voltage during the normal operation [40]. But when the load power increases (\( P_L \) and \( Q_L \) are connected) and the voltage control is deactivated (Switch SW is on position 2, \( V_L = 1.36 \) in Figure 3), the grid voltage drops from the nominal value. Therefore, the
WF should start to take part in fault voltage and reactive power control, because the voltage level is directly related to the reactive power control. The level of the voltage sag and fault clearance time is decided by the turbine protections system, taking into consideration the location and the fault type.

The parameter values are given in the appendix. In Figure 3, where the prefix $\Delta$ indicates the deviation from the initial value, $\omega_s$ is the Laplace operator. $\omega_{r-1}$ and $\omega_{r-2}$ are the rotor speeds of SG1 and SG2, respectively. $y$ is the valve/gate position and $R$ is the droop for speed/frequency regulation.

### 3. Wind Farm Management according to Grid Code Recommendations

#### 3.1. Grid Code Requirements

For managing and controlling the WF to behave like a conventional power plant, the TSOs established specific recommendations. According to the ENTSO-E Network Code requirements for grid connection applicable to all generators, the WF should be stable and still connected to the grid during the voltage drop [8, 41]. This grid code imposes for the WF control system to react within 20 ms after the beginning of a voltage dip less than 95% of
the rated value. The voltage dip should be regulated after 500 ms and return to the dead-band $\pm 5\% V_n$ [41–43].

The power references are generated using one of the three operating modes: MPPT, fault, or PQ control mode [5].

3.2. MPPT Control Mode. When the grid voltage is between the allowable band of $[95\% V_n, 105\% V_n]$, the MPPT or the PQ control mode is activated manually, while the fault control is activated automatically during the fault.

4. The Proposed Fault Control Strategy

4.1. PCC Voltage Control. During the existence of the voltage fault ($V_g \leq 95\% V_n$), the grid-side converter can be adjusted into a nonunity power factor to meet the requirement and provide reactive power up to its rated value to help the fault ride through. The undervoltage is caused by a reactive power shortage when an inductive load is connected to or near a PCC bus. The active and reactive power references required for PCC voltage control are generated as illustrated in Figure 4(a). To eliminate the oscillations, it is preferable to use block “sum” for the combination of the voltage control mode and other control modes, instead of the block “switch.” $I_{\text{max}}$ is the current maximum value.

4.2. Design Layout of Fractional-Order PIFO-Fuzzy-PIFO. Design layout of fractional-order PIFO-Fuzzy-PIFO controller is developed using structure based on PI controller and follows the following steps:

(i) The PI controller, with a constant parameter, is adopted to generate reactive power references for voltage control given in Figure 4. The PI gains are tuned using the trial and error method. But the better response cannot be obtained.

(ii) The better response demands the use of the fuzzy logic to ensure the variation of the integrator gain for improved dynamic response compared to PI [9]. In this case, there are two additional parameters of the PIFPI controller ($k_i$, $k_{pe}$), which can be determined using the check step response characteristics of the Simulink Design Optimization tools to check that the step response satisfies the specified characteristics.
(iii) For the superior performance, the integrator term is replaced by the fractional-order operator to propose the FOPI-fuzzy-FOPI controlled based on the fractional-order operator with two other degrees of freedom $\lambda_1$ and $\lambda_2$. The order of the fractional term is optimized using PSO to obtain the optimal parameters $\lambda_1$ and $\lambda_2$ given in Figure 4. The PSO algorithm proposed by [44] for PD optimization can be adapted for fractional-order controller optimization using the flow chart proposed in Figure 5.

4.3. Fractional-Order Preliminaries. Fractional-order (FO) controller is quite popular among scientists, researchers, and engineers for the last years. Using the FO operators, two degrees of freedom are provided compared with integer orders.

Let us define the operator fractional of derivative and integral as follows:

\[
D^\lambda_t f(t) = \begin{cases} \frac{d^\lambda}{dt^\lambda} f(t), & \Re > 0, \\ 1, & \Re = 0, \\ \int_{t_0}^{t} (\tau - t)^{-\lambda} f(\tau) d\tau, & \Re < 0, \end{cases}
\]

where $\lambda \in \Re$ is FO operator.

In the literature, several methods of FO derivatives and integrals have been reported. In this paper, the Riemann–Liouville derivative and integral are used to implement the control method proposed in this work as given in the following equations for a function $f(t)$ [45, 46].

For the FO derivative,

\[
P_{\text{ref}} = \sqrt{((V_{\text{pcc}}^\text{max})^2 - (Q_{\text{ref}})^2) + \text{PQ control}}
\]

where $m$, $m$ and $t_0$ is the initial time, and $\Gamma(\cdot)$ is the Gamma function.

In order to implement the fractional operators, the CRONE toolbox is used [47]. Then, FO terms in the proposed controller are approximated using 5-order Outaloup’s modified filter and the frequency range is set as 0.01 to 100 rad/s.

4.4. Proposed Hierarchical FOPI-Fuzzy-FOPI Controller. The hierarchical FOPI-fuzzy-FOPI controller proposed in Figure 4(b) combines the fuzzy logic and fractional-order PI controllers in one structure to improve the voltage and reactive power responses. The inputs are the error $e = V_{\text{nom}} - V_{\text{pcc}}$ and error fractional-order integral ($I^\lambda_t (e)$). The output ($U$) is used to generate the reference of the reactive power ($Q_{\text{WF-ref}}$) [9].

The fuzzy logic rules for voltage controller are expressed in a form of if-then as shown in Table 2 using the center of gravity defuzzification method. The inputs and output variables are fuzzified using the Gaussian membership functions presented [9].

5. Validation and Discussion

The WF model and control system are both simulated in MATLAB/Simulink software. The grid is modeled as depicted in Figure 3. The total capacity of the WF is 9 MW and consists of three WTs connected to the PCC. The parameters of the WF system and controller are given in the appendix.
The control approaches like fractional-order PI controller and fuzzy control could have been used which might give better performance over the PID controller for the voltage control of the wind energy conversion system.

Most industrial control systems still rely on the PID controller due to its simple structure, ease of implementation, and satisfactory performance of the control system. But, with the advanced technology in the last years, the controller based-fuzzy logic and fractional-order do not face any problem for implementation [14].

The objective of introducing the PI controller in a comparative study of the simulation results is solely to serve as a benchmark of traditionally accepted industrial practices.

The focus of the present study is to make a comparison between the fractional-order fuzzy PI controller, hierarchal fuzzy controller (PIFPI) [9], and the FOFPID proposed in [15] and that proposed in [36].

On one hand, the simulation strives to demonstrate the performances of the proposed FOPI-fuzzy-FOPI controller for LVRT control in comparison with the PI-fuzzy-PI controller [9], PI controller, and constant reactive power control (CRPC) proposed in [36] (the reactive power ratio \( K_q = 0.7 \)). On the other hand, it is carried out to clarify the behavior of the WF supervision system and the WTs under the variable wind speed.

To determine the optimal value of the fractional-order parameter \( \lambda \), Figure 6 presents the voltage response of FOPI-fuzzy-FOPI for different values of fractional-order parameters. It can be seen that the optimal value \( \lambda \) is 0.8, where \( \lambda = \lambda_1 = \lambda_2 \). But the determination of optimal values of \( \lambda_1 \) and \( \lambda_2 \) needs the optimization algorithm program such as the PSO algorithm.

The PSO functionality is elaborated using MATLAB/ Simulink software. The optimization is applied to a Simulink model using MATLAB commands to adjust variables that define the parameters of the simulation (\( \lambda_1 \) and \( \lambda_2 \)). The particle swarm optimization (PSO) is used to obtain the best parameters of the PID controller Simulink [44], in this view, the PSO algorithm can be used to select the best values of FO parameters (\( \lambda_1 \) and \( \lambda_2 \)) of the proposed controller. The simulation can be run using the sim command to generate the output of the model. The PSO target function is defined, based on the integral of the square error (ISE) Index [48], by the following function:

\[
F = \beta \cdot \int e^2 + \alpha \cdot (\text{overshoot}),
\]  

### Table 2: Fuzzy logic rules for voltage controller.

| \( I^\lambda (e) \) | PB | PM | EZ | NB | NB | NB |
|---------------------|----|----|----|----|----|----|
| PB                  | PB | PB | PM | PM | PM | EZ |
| PM                  | PB | PM | PM | EZ | NB | NB |
| EZ                  | PB | PM | EZ | NM | NB | NB |
| NM                  | PM | EZ | NM | NM | NB | NB |
| NB                  | EZ | NM | NM | NB | NB | NB |

NB is negative big, NM is negative medium, EZ is equal zero, PM is positive medium, and PB is positive big.
where $\alpha$ and $\beta$ are the constant numbers. The error $e = y_{out} - 1$, $y_{out}$ is the system variable to tune and overshoot $= \max(y_{out}) - 1$.

Figure 6 demonstrates that using the PSO algorithm improves the voltage response in terms of time response and small overshoot.

5.1. Comparative Study of Voltage and Reactive Power Responses. The voltage control is verified using the test system of Figure 1. The grid voltage drop is simulated using the system in Figure 3. The inductive load ($Q_L$) of 6.5 MVAR is connected to the grid through the bus $B_{2,2}$ at $t = 10$ s.

The grid voltage drops to a value lower than 0.95 pu during the step increase in load, as shown in Figure 7(a). The LVRT control based CRPC strategy (C4) depicts the most severe ripple oscillations during fault control, which means that the robustness of the CRPC control approach is relatively low. Table 3 presents the combination between the voltage and reactive power controllers. For example, C2 indicates that the PIFPI is used for LVRT control and PI used for reactive power control. The C1 and C3 controllers have slow dynamics of voltage and power responses compared to the proposed controller (C2) as shown in Figure 7. The use of C1 (PIFPI for both LVRT and reactive power control) increases the system complexity. Indeed, 4 fuzzy logic blocks are executed simultaneously, which leads to poorer performance.

The PI-fuzzy-PI is one of the best controllers for wind turbine control in terms of settling time and maximum deviation [9]. Unlike PI and PIFPI control methods without a fractional-order operator, the proposed control methods utilize PIFPI with fractional dynamics offering more degree of freedom to allow the control structure to be more flexible and to obtain better performances.

The use of the fractional-order integral in the PIFPI to obtain the proposed FOPI-fuzzy-FOPI (C6), with PSO optimization of $\lambda_1$ and $\lambda_2$, improves the voltage and the reactive power responses (Figures 7(a) and 7(b)). This proposed controller presents a better response compared to C7 (the FOFPID proposed in [15]).

From Figure 7, it can be seen that the best responses of the voltage and output power are achieved using the proposed FOPI-fuzzy-FOPI controller for the LVRT control and the PI regulator for reactive power control in terms of fast response, deviation from the reference value, and the accomplishment of the RCRs (fault clearance time $< 0.2$ s).

As shown in Figures 7(c) and 7(d), when the fault control mode is deactivated, the automatic system protection disconnects one-third of the WTs from the grid at 10.2 sec, at 11.8 sec, and at 12.1 sec, respectively. The PCC power decreases gradually to reach 0 MW.

5.2. Supervision System Performances. To prove the performance of the supervisory system, a simulation scenario, divided into three periods, has been carried out. In each period one of the three operating modes is activated under variable wind speed (Figure 8(a)). The inductive load of 6.5 MVAR connected into the grid near to the PCC causes a voltage drop at 10 s as shown in Figure 7(b).

From 2 s to 6 s, the “PQ” control mode is activated. Despite the variable wind speed, the PCC active and reactive powers track their references as shown in Figures 8(c) and 8(d). The WF consumes $Q_{ref} = 3$ MVAR [2 s to 4 s] and generates 4 MVAR [4 s to 6 s] for satisfying the requested power plant production. The WTs participate in a proportional way, according to their available powers. In Figure 8(c), the missing power in the 3rd WT is ensured by the two other generators.

As presented in Figure 8(c), the MPPT control mode is activated [6 s to 10 s] to extract the maximum power from the wind which is the sum of the three WTs optimal active powers. While the PCC reactive power is set to zero as shown in Figure 8(d).
The voltage dip is caused by the excessive increase of reactive power when an inductive load connected to the grid at 10 s activates the voltage control automatically (Figure 7(a)). As shown in Figures 8(c) and 8(d), the WF sacrifices an amount of active power to generate the required reactive power and all WTs participate with their available maximal power.

Figure 9(a) shows that the grid current does not exceed the maximum value despite the fault. Figure 9(b) demonstrates that the DC bus voltages of the three WTs follow

| Voltage controller | Reactive power controller |
|--------------------|---------------------------|
| PIFPI [9]          | PIFPI                     |
| PI                 | C1                        |
| CRPC [36]          | 0                         |
| No control         | C2                        |
| FOPI-F-FOPI (proposed) | 0         |
| FOFPID [15]        | C3                        |
|                    | C4                        |
|                    | 0                         |
|                    | C5                        |
|                    | 0                         |
|                    | C6                        |
|                    | C7                        |
|                    | 0                         |

The voltage dip is caused by the excessive increase of reactive power when an inductive load connected to the grid at 10 s activates the voltage control automatically (Figure 7(a)). As shown in Figures 8(c) and 8(d), the WF sacrifices an amount of active power to generate the required reactive power and all WTs participate with their available maximal power.

Figure 7: The reactive power and voltage response for different controllers: (a) the PCC voltage, (b) reactive response, (c) active power response, and (d) zoom of active power response.
Figure 8: Simulation results for the scenario: PQ control from 2 s to 6 s, MPPT control from 6 s to 10 s, and voltage drop at 9 s. (a) PCC voltage, (b) the three wind profiles, (c) active power, and (d) reactive power.

Figure 9: Simulation results for the scenario: PQ control from 2 s to 6 s, MPPT control from 6 s to 10 s, and voltage drop at 9 s. (a) PCC current and (b) the DC bus voltages of the 3 WTs.
accurately their references ($V_{dc\text{-ref}} = 1400$ V). But, a peak of less than 5% $V_{dc\text{-ref}}$ has appeared without any threat to the DC bus capacitance.

On the basis of the above-mentioned analysis, it can be shown that the adopted control system based on the fractional-order fuzzy controller guarantees better performances for voltage stability and power dispatching.

6. Conclusion

The present work deals with LVRT control for WF and its power management:

(1) A fractional-order fuzzy controller (FOPI-fuzzy-FOPI) for LVRT control of the uncompensated power network, which improves the response of voltage and reactive power.

(2) The PSO algorithm adopted to obtain the optimal parameters of the FO operators.

(3) A supervisory system based on PDA associated with three operating modes for power management and control.

The simulation results have shown that, with the proposed tuning procedure, the settling time is reduced considerably, deviation from rated value is limited and oscillations are damped out faster compared to the conventional PI controller, fractional-order PID controller, and constant reactive power control. The combination between the supervision system, the proportional distribution algorithm, the FOPI-fuzzy-FOPI voltage controller, and the PI reactive power controller allows the WF to compensate the grid voltage and exhibit a behavior similar to that of the conventional power plant. The adopted supervision system drives all the wind turbine generators to work under different wind velocities and quite far from their saturation zones.

Appendix

The base values are rated frequency $f_r = 50$ Hz; nominal voltage $V_b = 690$ V, rated power $P_b = 3.10^6$ W, and rated apparent power $S_b = P_b/0.9$.

Filter resistance $R_f = 0.027$ (pu). Filter inductance $L_f = 0.186$ (pu).

Parameters of the SCIG:

Stator resistance, $R_s = 0.004843$ (pu)

Stator leakage inductance, $L_s = 0.1248$ (pu)

Rotor resistance, $R_r = 0.004347$ (pu)

Rotor leakage inductance, $L_r = 0.1791$ (pu)

Mutual inductance, $L_m = 6.77$ (pu)

The parameters of reactive power controllers:

PI: $k_i = 12.21$ and $k_p = 0.063$

PIFPI: $k_c = 0.5$, $k_{pu} = 0.4$, $k_i = 12.21$, and $k_p = 0.063$

The parameters of voltage controllers:

PIFPI: $k_c = 0.4$, $k_{pu} = 0.8$, $k_i = 120$, and $k_p = 6$

FOPI-fuzzy-FOPI: $k_c = 0.4$, $k_{pu} = 0.08$, $k_i = 120$, and $k_p = 6$

FOPI-fuzzy: $k_c = 0.4$, $k_{pu} = 0.08$, $k_i = 120$, and $k_p = 6$

FOFPI: $k_c = 0.4$, $k_{pu} = 0.08$, $k_i = 120$, and $k_p = 6$

PI: $k_p = 120$ and $k_i = 6$

Data Availability

All data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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