

Fractional fuzzy based static var compensator control for damping enhancement of inter-area oscillations

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ABSTRACT

Over time, the insertion of flexible alternating current transmission system (FACTS) components in the power grid became primordial to maintain the overall system stability. This paper proposed an innovative approach called hybrid auxiliary damping control based wide-area measurements for the static var compensator (SVC). The presented controller is a fractional-order fuzzy proportional integral derivative (FOFPID). Its principal task is to damp inter-area low frequency oscillations (LFOs) and to improve the power system stability over the transient dynamics. Then, a metaheuristic grey wolf optimization (GWO) method is applied to adjust the controller's gains. The SVC-based FOFPID control scheme is implemented in a two-area four-machine test system employing the rotor speed deviations of generators as input signal. A comparative analysis of the elaborated controller with the integer PID and the fractional-order PID (FOPID) is performed to emphasize its effectiveness under a three-phase perturbation. Furthermore, a load variation effect test is completed to attest the control strategy robustness. Based on dynamic simulation results and performance indices, the suggested controller shows its robustness and provides increased efficiency for inter-area oscillations damping.

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1. INTRODUCTION

Sustaining the stability of the electric energy systems has become an essential obligation due to the significant increase in electricity consumption across various sectors. Oscillatory stability, a major concern in interconnected power grids, contributes to stability analysis and control [1] by addressing the damping of inter-area low frequency oscillations (LFOs), typically occurring within 0.1 to 1 Hz [2]. These oscillations are caused by defaults, fluctuation in load demand, generation altering and disturbances [3]. Therefore, there is strong incentive to develop enhanced methods for effective damping of inter-area oscillations to avoid instability and blackouts caused by undamped swings.

The fast growth of power electronics has indeed resulted in the incorporation of flexible alternating current transmission system (FACTS) elements in power networks [4] FACTS devices equipped with appropriate auxiliary damping controller (ADC) can actively counteract inter-area oscillations by modulation of active and reactive power, adjusting voltage levels, and optimizing power flow distribution. This helps enhancement of power oscillations damping and overall system stability [5]. On the whole, static var compensator (SVC) is an essential shunt part of FACTS controllers that contribute to the stability and

efficiency of power networks. SVC helps ensure electrical systems well operating by regulating voltage levels and reducing transmission losses. It also provides oscillations damping when connected to an additional regulator [6].

Indeed, several conventional solutions have been tested to design SVC type damping controller. A frequently applied approach involves linear control techniques, such as the design of lead-lag [7] and proportional integral derivative (PID) [8] controllers. Another conventional strategy relies on the application of a linear quadratic regulator (LQR) [9]. In addition, robust control methods have been employed including μ -synthesis [10], polynomial control [11] and loop shaping [12].

Furthermore, a considerable amount of research has examined intelligent approaches to develop more efficient control strategies. Karpagam *et al.* [13] investigated the application of the fuzzy logic technique in. Abdulrahman and Radman [14] combined the strengths of fuzzy logic and neural networks to create powerful and adaptive control system in. A decentralized robust control technique to enhance the dynamic response of the network and mitigate electromechanical swings has been applied by [15]. Besides, author in [16] explored deep reinforcement learning (RL) algorithm to design a complementary controller for SVC in order to guarantee an adaptive parameter adjusting and system robustness. Additionally, new optimizations strategies have been applied to coordinate SVC and power system stabilizer (PSS) for optimal damping of the LFOs [17].

A major part of recent studies is focused on fractional-order proportional integral derivative (FOPID) controllers [18]. Overall, these class of controllers offer improved performance and great robustness for LFOs damping using FACTS devices as demonstrated by FOPID-based thyristor-controlled series capacitor (TCSC) [19], FOPID type static synchronous series compensator (SSSC) [20]–[22] and fractional PI controller applied to unified power flow controller (UPFC) [23]. Moreover, an FOPID-SVC in coordination with FOPID-PSS is reported in [24] to mitigate low-frequency oscillations using a single-machine infinite bus (SMIB) network. This control scheme has shown good results for damping local swings but not verified for inter-regional modes that represent a vital concern in stability and reliability of present interconnected power grids. Hence, a wide-area FOPID type SVC is introduced as first purpose in this work to ameliorate the damping of inter-area LFOs in multi-generators network.

Alternatively, an hybrid control technique that merges the benefits of fuzzy logic and fractional calculus reveals an original controller scheme called fractional-order fuzzy PID (FOFPID) [25], which attracted considerable research concern in power and energy system engineering [26]–[29]. Investigation of current literature has revealed that the FOFPID-based SVC controller has not been sufficiently examined for inter-area LFOs damping study. This inspired us to develop a FOFPID using remote signals-based phasor measurement units (PMU) [30], [31] for inter-area oscillations damping mitigation.

Additionally, various optimization algorithms have been applied by many researchers to obtain the gains of fractional controllers. The most popular and efficient techniques are ant lion optimizer (ALO) [32], modified salp swarm algorithm (MSSA) [33], grey wolf optimizer (GWO) [22], and moth flame optimization (MFO) [24]. Therefore, in this work, the GWO algorithm is adopted and implemented for tuning the parameters of the developed controllers. Moreover, integral time absolute error (ITAE)-objective function is used as performance index in this work. It is considered to be the best criteria to optimize the regulators gains [34].

Regarding the above motivations, this study aims to enhance inter-area oscillations damping in interconnected power grid by designing a robust SVC-based FOFPID controller that utilizes wide-area measurements. The major highlights of this research are listed in this way:

- a. Using of speed deviations difference of all generators from dispersed areas of multi-machine network as input control signal. These measurements offer highest observability of inter-area oscillations modes.
- b. Development of a wide-area FOPID based-SVC to improve the damping of inter-area LFOs.
- c. Calculation of fractional order operators (integral and derivative) by Charef's approximation algorithm using MATLAB software and implementation of FOPID controller by Simulink block.
- d. Combining the efficiency of fuzzy logic controller (FLC) with flexibility and additional performance of fractional calculus (FC) based control scheme, a hybrid GWO-optimized fractional-order fuzzy PID type SVC damping controller is designed and tested to restrain inter-area oscillations.
- e. Introduction of the decay ratio index (DRI) as a performance measure to quantify power oscillations speed decreasing.

To achieve this goal, the paper is ordered in this way: section 2 discusses the power system investigation and SVC modeling. Section 3 presents the control strategy including the design of the damping controllers. The optimization formulation and performance criteria are elaborated in section 4, followed by the implementation of GWO algorithm in section 5. Section 6 provides the optimization and simulation results together with their explanations. Finally, section 7 presents the conclusion derived from this study.

2. OVERALL SYSTEM DESCRIPTION

2.1. Power system investigated

The configuration shown in Figure 1 illustrates the test power network examined in this study. The system is made up of two symmetrical areas inter-connected by two tie-lines of 200 km length. Each region has two synchronous generators rated 20 kV/900 MVA, arranged G1 and G2 for area 1, G3 and G4 for area 2. Every generator is described by its two-axis model and supplied with internal regulators.

Power system stabilizers (PSSs) are installed for only one generator in each area (G1 for area 1 and G3 for area 2) to damp local modes while other generators (G2 and G4) are without stabilizers. An SVC of ± 200 MVAR rating is positioned at bus 8 to damp inter-area oscillations. The test system is available in Simscape Electrical within MATLAB/Simulink software and its parameters are given in [35].

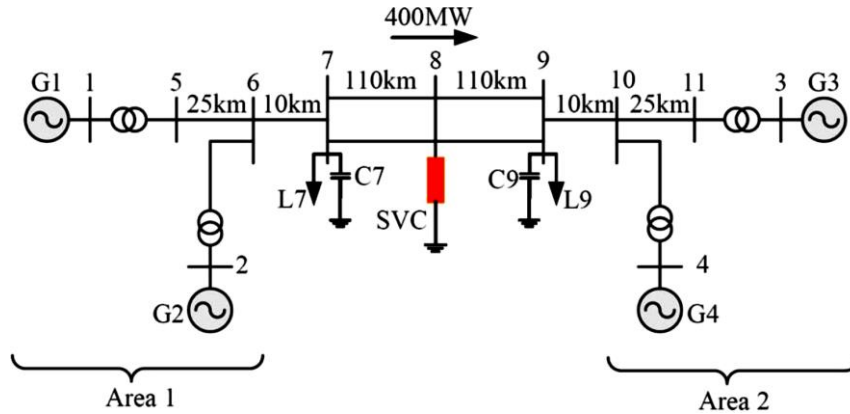


Figure 1. Two-area four-machine power network with SVC [35]

2.2. Static var compensator model

The static var compensator belongs to the shunt category of FACTS equipment's. A thyristor controlled reactor (TCR) is joined in parallel with a FC bank [36] to form the structure of the SVC as presented in Figure 2. The main role of a SVC is voltage control in electric power network, and can contribute to damp inter-area oscillations by additional control equipment. Figure 3 depicts the SVC model with an ADC. The supplementary control signal U_{SVC} is added to the sum of the SVC bus magnitude voltage V_{t_SVC} and the SVC reference voltage V_{ref_SVC} . B_{SVC} denotes the equivalent susceptance of SVC. The gain K_{SVC} and time constant T_{SVC} describe the compensator firing regulator which can be expressed by the next equation [37].

$$\dot{B}_{SVC} = \frac{1}{T_{SVC}} (K_{SVC} (-V_{t_SVC} + V_{ref_SVC} + U_{SVC}) - B_{SVC}) \quad (1)$$

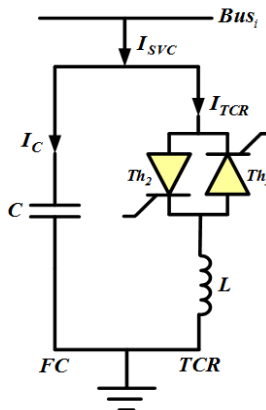


Figure 2. Circuit diagram of SVC

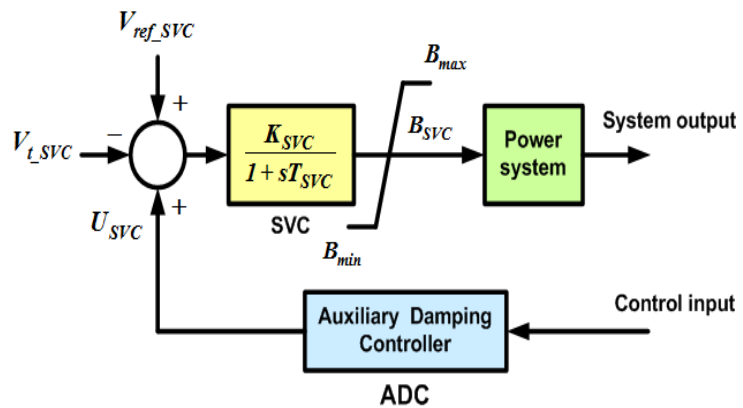


Figure 3. Control block scheme of SVC with an ADC

3. SUGGESTED CONTROL STRATEGY

The framework of this study is focused on the improving of inter-area LFOs. The solution to satisfy such constraint is by adding a complementary regulator to SVC internal control using global measurements that offer highest observability of inter-area swings as control input. The main proposed strategy is based on fractional-order fuzzy PID, then compared with the classical PID and fractional-order PID. The general control structure is presented in Figure 4 and the input signal is based on speed deviations difference of generators from scattered areas as expressed by (2).

$$\Delta w = \sum_{i \in \text{Area1}} dw_i - \sum_{j \in \text{Area2}} dw_j \quad (2)$$

dw_i and dw_j are the speed deviation of the i^{th} and j^{th} generator respectively.

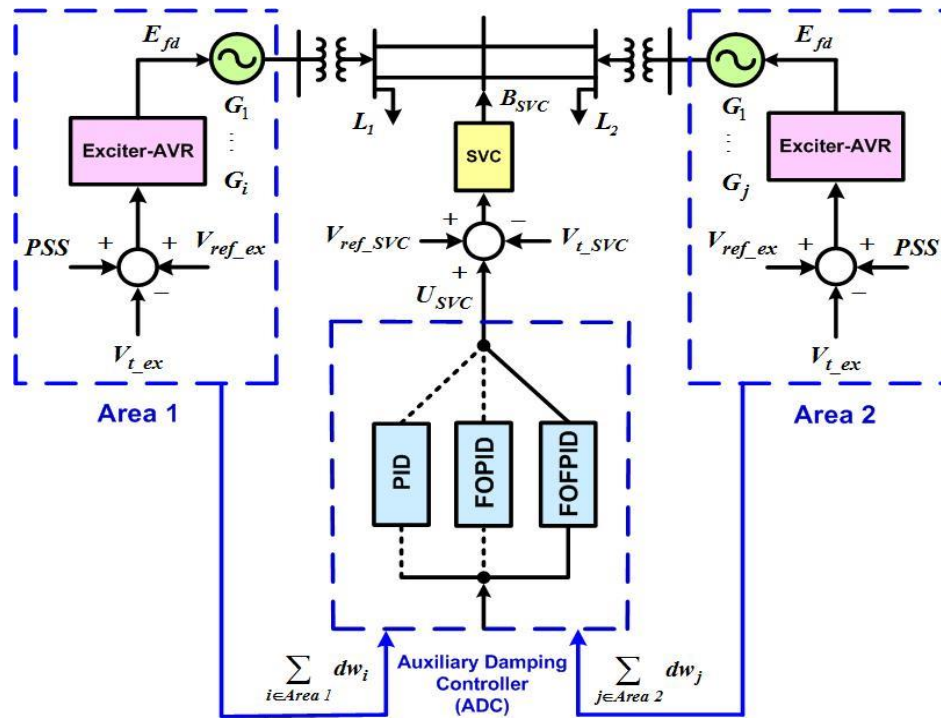


Figure 4. Inter-area power network with SVC type damping controller

3.1. SVC-PID controller

The conventional PID controller presented in Figure 5 is ranked as the most widely used regulator in industrial processes. The PID output formula consists of three terms based on its control gains: proportional (G_P), integral (G_I) and derivative (G_D) as expressed in (3).

$$U_{SVC}(S) = \left(G_P + \frac{G_I}{S} + G_D S \right) \Delta w(S) \quad (3)$$

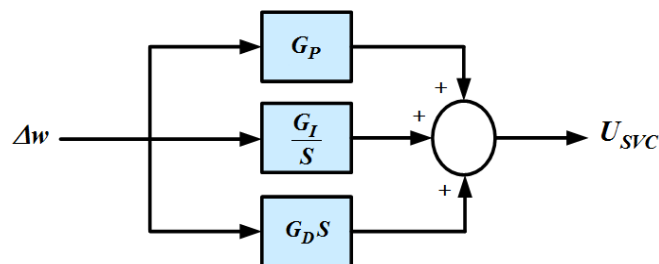


Figure 5. PID controller

3.2. SVC-FOPID controller

Podlubny [38] proposed a generalization of the integer-order PID to a new one designated fractional-order PID as depicted in Figure 6. FOPID controllers are established by fractional calculus [39] which become a popular part of mathematical analysis over the past few decades. It is intended for the computation of non-integer derivation and integration operators. To implement these controllers both in simulation and in hardware implementation, an approximation with integer order transfer functions is needed. In this work, the approximation algorithm proposed by Charef *et al.* [40] has been used for calculation of fractional order operators.

The transfer function of this sort of control structure is expressed in (4). G_{PF} , G_{IF} and G_{DF} symbolize in order, the proportional, integral, and derivative gains. λ and μ represent integrator and differentiator orders respectively ($0 < \lambda, \mu < 1$).

$$G(S) = G_{PF} + \frac{G_{IF}}{S^\lambda} + G_{DF}S^\mu \quad (4)$$

Figure 7 shows the arrangement of the fractional controller $PI^\lambda D^\mu$ in the plane (λ, μ) . Noting from (4) that for $\lambda = \mu = 1$ the fractional controller becomes the classical PID. The interest in this kind of controller is justified by better flexibility, since plus the three traditional parameters of PID corrector adjustment, it has two other gains, the order of integration λ and the one of differentiation μ . These two factors can be used to fulfill additional characteristics such as precise control and robustness [41], [42].

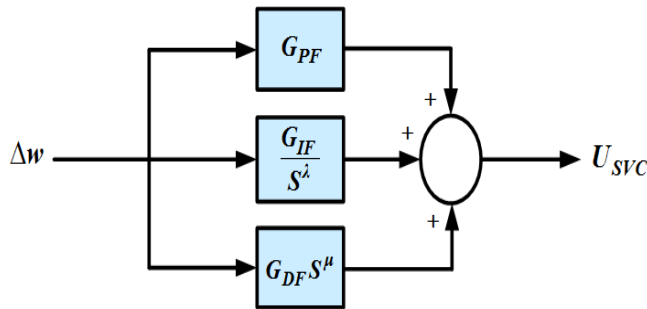


Figure 6. FOPID controller

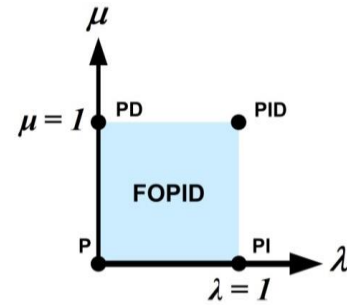


Figure 7. Graphic illustration in λ - μ plane

3.3. SVC-FOFPID controller

Benefiting from the capability of fuzzy PID for dealing with complex nonlinear systems along with the flexibility and robustness of FOPID, a hybrid type FOFPID controller is introduced in this work. The adopted control strategy is based on Mamdani fuzzy inference class. Rotor speed deviation (Δw) and its fractional order derivative ($\Delta \dot{w} = \frac{d^\mu \Delta w}{dt^\mu}$) are the inputs and the auxiliary signal (U_{SVC}) is generated as output of the FOFPID as depicted in Figure 8. The error input (Δw) includes the speed deviations difference of remote generators. The FLC integral output has a fractional order coefficient (λ). G_E and G_{DE} representing inputs scaling factors with G_{PI} and G_{PD} output ones are optimized by the GWO algorithm as well as the fractional order operators λ and μ .

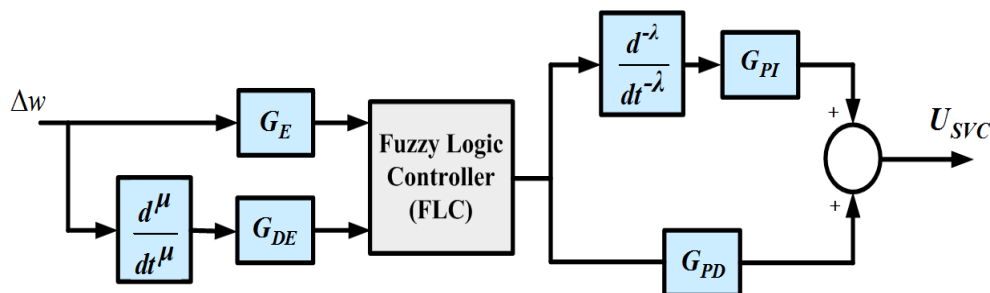


Figure 8. FOFPID controller

Thus, five Gaussian symmetrical linguistic variables namely (negative big, negative small, zero, positive small, and positive big) are selected as membership functions for both inputs and output as represented in Figures 9 and 10 respectively. The extraction of the proposed input-output rules is based on the principle of acceleration/deceleration control of the system. Examining the case with (Δw) and $(\Delta \dot{w})$ are positive big (PB). This signifies that the difference of speed deviations increases, and therefore $(dw_1 + dw_2)$ of generators (G_1, G_2) in area 1 is greater than $(dw_3 + dw_4)$ of generators (G_3, G_4) in area 2. Consequently, the system decelerates and the transmitted active power flow between the two areas is decreased. At this moment, by applying an auxiliary signal (U_{SVC}) , the static var compensator (SVC) injects reactive power and provides positive susceptance (B_{SVC}) at the output of the voltage regulator in Figure 3. In the contrary situation known as acceleration, (Δw) and $(\Delta \dot{w})$ are taken as negative big (NB), this means that the speed deviations $(dw_1 + dw_2)$ is lower than $(dw_3 + dw_4)$. Hence, the output signal (U_{SVC}) is used such as SVC absorbs reactive power (inductive mode) and supplies negative susceptance to the power grid. When (Δw) and its derivative are zero (Z), the generators are rotating with equal speed, no power oscillations situation. Thus, the SVC supplementary control is not necessary and the output is zero. Using similar interpretations, a 5×5 rule base matrix can be established and listed in Table 1. Moreover, the inference process is made on the min-max technique and defuzzification on the center of gravity.

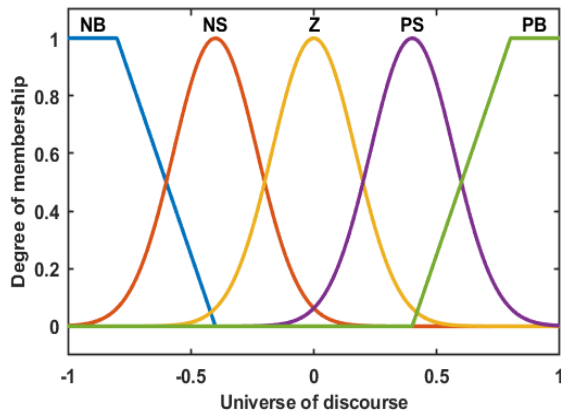


Figure 9. Membership function for output

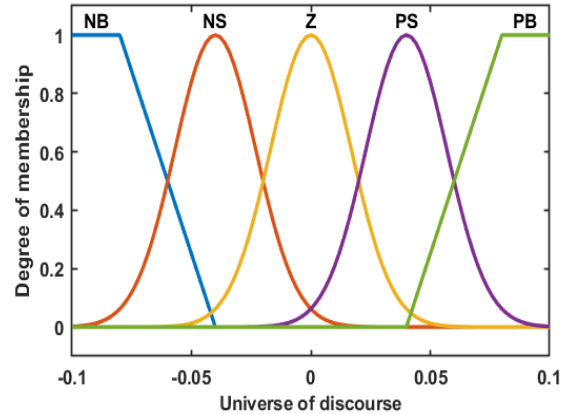


Figure 10. Membership function for inputs

Table 1. FOFPID controller rule base

$\frac{d^{\mu} \Delta w}{dt^{\mu}}$	Δw				
	NB	NS	Z	PS	PB
NB	NB	NB	NB	NS	Z
NS	NB	NB	NS	Z	PS
Z	NB	NS	Z	PS	PB
PS	NS	Z	PS	PB	PB
PB	Z	PS	PB	PB	PB

4. PERFORMANCE CRITERIA

4.1. Objectif function

To improve the operating conditions of the damping controller and increase its performance, parameters tuning is inevitable. For this aim, ITAE is approved as objective criterion and expressed by (5):

$$J = \int_0^{t_{sim}} |\Delta w_{Inter-area}| \cdot t \cdot dt \quad (5)$$

where t_{sim} is simulation time and $\Delta w_{Inter-area} = \sum_{i \in area1} w_i - \sum_{j \in area2} w_j$. w_i and w_j are the i th and j th speed generator from distinct zones.

In this study, for a multi-generators system the fitness function is defined by (6):

$$J = \int_0^{t_{sim}} |(w_1 + w_2) - (w_3 + w_4)| \cdot t \cdot dt \quad (6)$$

Thus, the problem formulation is stated as:

Minimize J subject to

– PID controller

$$J(G_P, G_I, G_D) \begin{cases} G_{P_min} \leq G_P \leq G_{P_max} \\ G_{I_min} \leq G_I \leq G_{I_max} \\ G_{D_min} \leq G_D \leq G_{D_max} \end{cases}$$

– FOPID controller

$$J(G_{PF}, G_{IF}, G_{DF}, \lambda, \mu) \begin{cases} G_{PF_min} \leq G_{PF} \leq G_{PF_max} \\ G_{IF_min} \leq G_{IF} \leq G_{IF_max} \\ G_{DF_min} \leq G_{DF} \leq G_{DF_max} \\ \lambda_{min} \leq \lambda \leq \lambda_{max} \\ \mu_{min} \leq \mu \leq \mu_{max} \end{cases}$$

– FOPID controller

$$J(G_E, G_{DE}, G_{PI}, G_{PD}, \lambda, \mu) \begin{cases} G_{E_min} \leq G_E \leq G_{E_max} \\ G_{DE_min} \leq G_{DE} \leq G_{DE_max} \\ G_{PI_min} \leq G_{PI} \leq G_{PI_max} \\ G_{PD_min} \leq G_{PD} \leq G_{PD_max} \\ \lambda_{min} \leq \lambda \leq \lambda_{max} \\ \mu_{min} \leq \mu \leq \mu_{max} \end{cases}$$

The limits of the optimized settings are given by $\{G_P, G_I, G_D, G_{PF}, G_{IF}, G_{DF}, G_E, G_{DE}, G_{PI}, G_{PD}\} \in [0,100]$ and $\{\lambda, \mu\} \in [0,1]$.

4.2. Performance measure indices

With the aim of assessing the supremacy of the developed FOPID controller, a comparative analysis based transient performance indices (settling time, overshoot and undershoot) is considered. In addition, an indicator called decay ratio index (DRI) is introduced in this study, presented by (7). It gives a measure of how rapidly the power oscillations are decreasing. Minimizing ITAE and other performance indices are a good indication of dynamic response improvement. So, the power system response becomes faster and the oscillations damping is increased.

$$DRI = \frac{SOS}{FOS} \quad (7)$$

where FOS is the first overshoot and SOS is the second overshoot.

5. OPTIMIZATION COMPUTATION

Various algorithms for optimizing swarm intelligence have been introduced by simulating the behavior of living beings in nature. One of the optimization approaches is GWO [43] which is adapted using MATLAB environment for our application. This technique is inspired by a wolf type called grey wolf which has a special hierarchy and great organization. The optimization algorithm depends on the social hierarchy and the hunting mechanism of the grey wolves.

- Social hierarchy: The pack is shared on four levels as depicted in Figure 11(a): Alpha α , Beta β , Delta δ and Omega ω in the base. The strongest wolf is the alpha leader and the domination decrease from α to ω .
- Hunting mechanism: The principal steps of wolf hunting presented by [44] are as follows: tracking, encircling, and attacking the prey.

Compared to other known metaheuristic algorithms, GWO is characterized by its simplicity, its ease of application and mainly its use of no specific input parameters to operate. The general evolution steps of the used algorithm are summarized by the following flowchart illustrated in Figure 11(b).

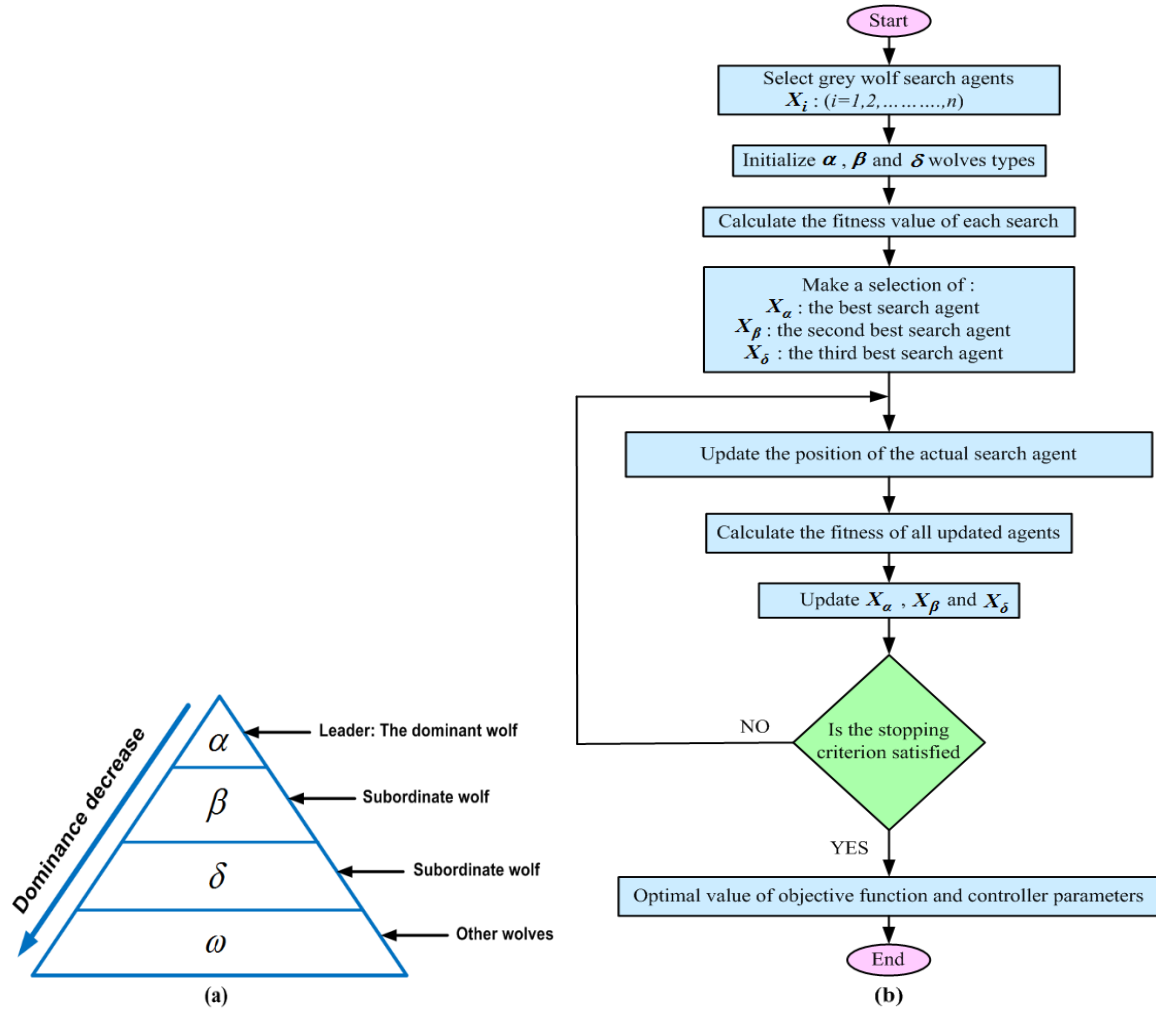


Figure 11. GWO algorithm [43]: (a) social hierarchy of grey wolves and (b) flow diagram

6. OPTIMIZATION AND SIMULATION RESULTS

In the context of assessing the performance of the proposed FOPID controller to mitigate inter-area LFOs and emphasizing its superiority over other regulators, this work covers two case studies. Note that the fractional controllers [40] are implemented using MATLAB/Simulink and the main configuration employed by the GWO algorithm is 40 search agents and 100 iterations.

6.1. Case 1: Six-cycle three-phase fault

For the first test, a six-cycle three-phase fault is occurred in the center of the transmission line between buses 7 and 8 of the test system. The disturbance is started at the time $t=1$ s and deleted after 0.1 s through the breaker's circuits. The values of the fitness function and the optimum controllers' gains acquired after optimization with the GWO method are noticed in Table 2.

Table 2. Controllers gains and ITAE optimal values for case 1

Controller	Case 1 Parameters						ITAE
	G_P	G_I	G_D	λ	μ	J	
PID	100.00	0.3870	16.3276			0.4051	
FOPID	G_{PF} 39.4723	G_{IF} 0.1587	G_{DF} 99.8596	λ 0.1289	μ 0.1955	J 0.3556	
FOFPID	G_E 5.3802	G_{DE} 59.7073	G_{PI} 2.6090	G_{PD} 57.7609	λ 0.1850	μ 0.3214	0.3229

The obtained convergence curve is illustrated in Figure 12. It is apparent, that the ITAE has its minimal value $J=0.3229$ for the GWO-based FOPID controller versus $J=0.3556$ for FOPID and $J=0.4051$ for PID. Hence, the developed FOPID has the best efficiency in reducing the objective function value and scores extra desired oscillations damping in comparison with the PID and FOPID.

After computer simulation, the dynamics performance of the test power grid is provided in Figures 13 and 14. These figures show the responses of the rotor speed difference between generators of area 1 (G1 and G2) and those of area 2 (G3 and G4). The disturbance produces a poor inter-area low frequency oscillation ($f=0.63$ Hz). Noticeably, the FOPID controller effectively and rapidly attenuate the damping of the undesirable oscillation. Despite the assets of the FOPID noticed by the literature, the novel fractional-order fuzzy PID gives higher performances.

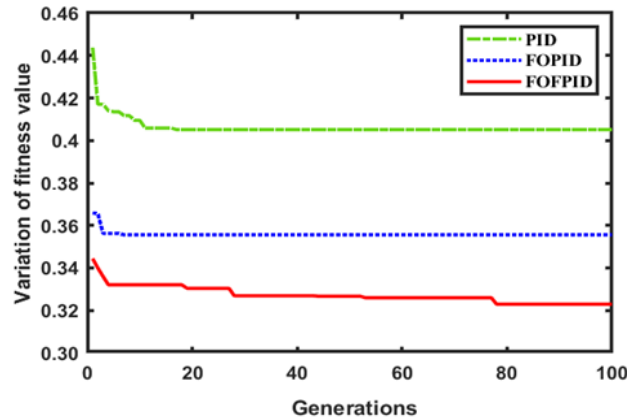


Figure 12. Objective function variation graph for case 1

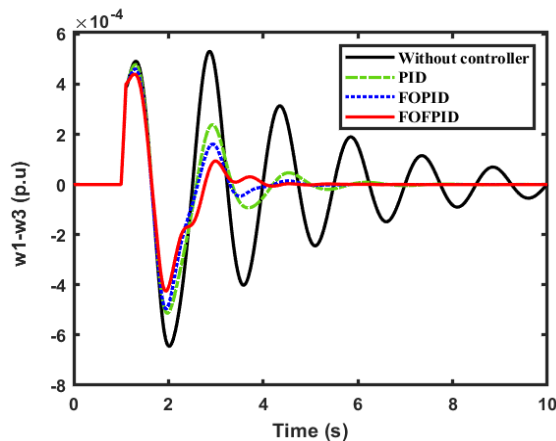


Figure 13. Speed difference of G1-G3 - case 1

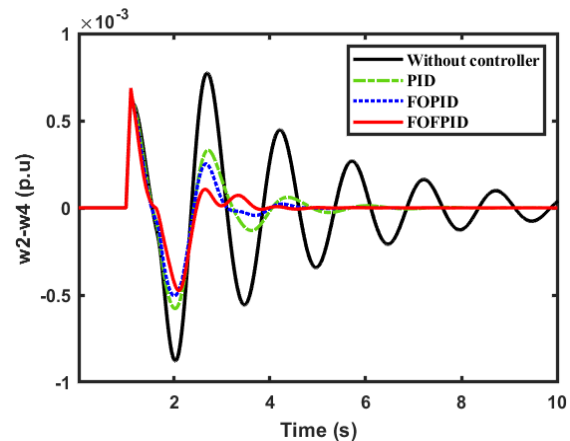


Figure 14. Speed difference of G2-G4 - case 1

The various transient performance indexes noted settling time (ST), overshoots: first overshoot (FOS), second overshoot (SOS), and undershoot (US) extracted from the previous figures are mentioned in Table 3. The settling time (ST) of speed deviation ($w1-w3$) with the SVC-based FOPID is detected at 3.9456 s, which is less than other settling times obtained with FOPID (4.6435 s) and PID (5.5914 s). Furthermore, the first and second overshoots are (FOS = 4.3958, 4.6057, 4.7743) and (SOS = 0.9368, 1.6119, 2.3832) for the FOPPID, FOPID and PID, respectively. The undershoot is decreased to a lower value of 4.2462 given by the FOPPID and varies at 4.9514 and 5.1183 for the FOPID and PID, subsequently. The same remarks are conducted for speed deviation ($w2-w4$), for all transient measures, the FOPPID achievement is superior to the FOPID and PID controllers. From this comparative study, it is concluded that the designed GWO-FOPPID performs better in term of minimizing the settling time, lowering over/under shoots and therefore provides effective damping of inter-area low LFOs.

Table 3. Transient parameters of speed difference for case 1

w1-w3					w2-w4				
Controller	ST (s)	FOS ($\times 10^{-4}$)	SOS ($\times 10^{-4}$)	US($\times 10^{-4}$)	Controller	ST (s)	FOS ($\times 10^{-4}$)	SOS ($\times 10^{-4}$)	US($\times 10^{-4}$)
PID	5.5914	4.7743	2.3832	5.1183	PID	5.4576	6.8641	3.3021	5.7776
FOPID	4.6435	4.6057	1.6119	4.9514	FOPID	4.3748	6.8645	2.5187	5.0445
FOFPID	3.9456	4.3958	0.9368	4.2462	FOFPID	3.6135	6.8616	1.0618	4.7427

6.2. Case 2: Load variation

In the second scenario, the robustness verification of the designed controller is performed by changing load conditions. For that, a test is carried out by increasing the load L9 at bus 9 by 20 % from 1767 MW to 2120.40 MW at $t=1$ s [45]. The minimalized values of the obtained ITAE criteria and the GWO-optimized parameters of the PID, FOPID, and FOFPID controllers are provided in Table 4.

Figure 15 illustrates the variation of objective function. It is evident that the FOFPID displays the best fitness value $J=0.4041$ compared to FOPID and PID with $J=0.4305$ and $J=0.5501$, respectively. Reducing ITAE is a good sign of power oscillations diminution and system dynamic response amelioration.

Table 4. Controllers gains and ITAE optimal values for case 2

Case 2						
Controller	Parameters					
PID	G_P 100	G_I 0.4296	G_D 3.2542	ITAE J 0.5501		
FOPID	G_{PF} 92.2706	G_{IF} 82.8238	G_{DF} 83.9285	λ 0.4353	μ 0.1454	J 0.4305
FOFPID	G_E 0.4635	G_{DE} 67.3110	G_{PI} 92.9847	G_E 96.0470	λ 0.1193	μ 0.2476
						J 0.4041

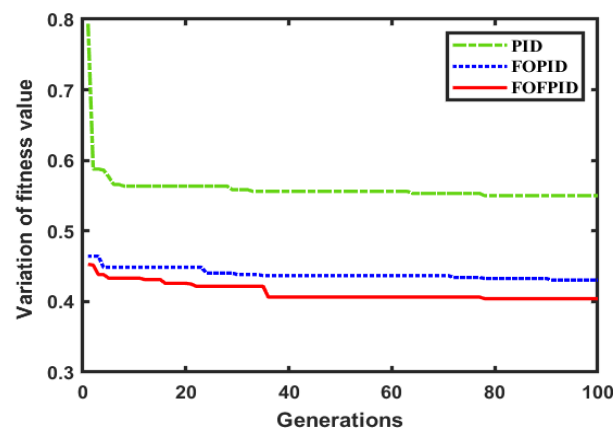


Figure 1. Objective function variation graph for case 2

The rotor speed difference of generators from scattered regions are shown in Figures 16 and 17. During the load variation, the power system becomes expose to great poorly damped inter-area swings. Evidently, the system equipped with the FOFPID returns to its steady state and can suppress oscillations as rapidly and more efficiently than with other controllers.

The obtained values of transient performance parameters (settling time, overshoot and undershoot) of case 2 are listed in Table 5. It is apparent that for speed difference (w1-w3), the little settling time 3.0011 s is obtained with the FOFPID strategy, compared to FOPID (3.1995 s) and PID (4.7170 s). The results reveal approximately a similar first overshoot (FOS). However, the recommended control scheme exhibits the lower second overshoot (SOS = 0.0151), surpassing the findings of FOPID (0.0904) and PID (0.2685). Again, the undershoot is further reduced to a small amount 0.6954 using FOFPID compared to the values attained by FOPID (0.8002) and PID (0.9011). The same remarks for speed deviation (w2-w4), the results indicate the supremacy of the FOFPID with a good enhancement of transient performance measures.

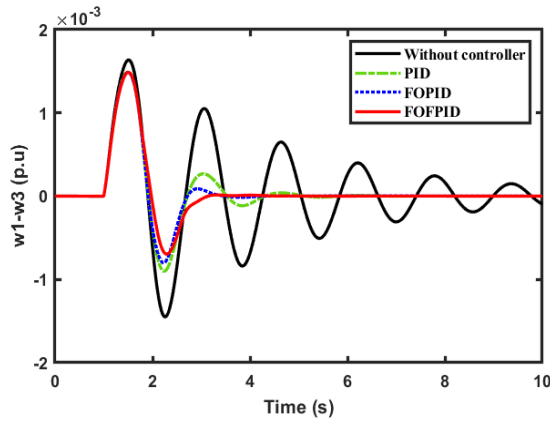


Figure 16. Speed difference of G1-G3 - case 2

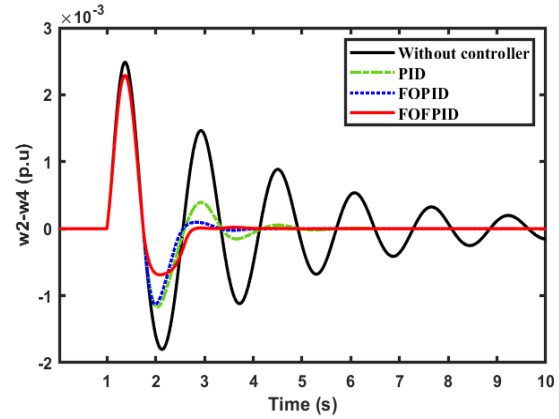


Figure 17. Speed difference of G2-G4 - case 2

Table 5. Transient parameters of speed difference for case 2

Controller	ST (s)	w1-w3			Controller	ST (s)	w2-w4		
		FOS ($\times 10^{-4}$)	SOS ($\times 10^{-4}$)	US($\times 10^{-4}$)			FOS ($\times 10^{-4}$)	SOS ($\times 10^{-4}$)	US($\times 10^{-4}$)
PID	4.7170	1.4900	0.2685	0.9011	PID	4.0080	2.2900	0.3927	1.1680
FOPID	3.1995	1.4880	0.0904	0.8002	FOPID	3.0945	2.2900	0.0987	1.1280
FOFPID	3.0011	1.4870	0.0151	0.6954	FOFPID	2.6959	2.2900	0.0210	0.6876

For more quantitative interpretation of dynamic response amelioration by the suggested controller, the DRI index values for the abovementioned measured variables (case 1 and case 2) are plotted in bar plot, as depicted in Figures 18 and 19. Obviously, the minimum index values are given by the proposed FOFPID controller, demonstrating the successful and fast suppression of inter-area low-frequency oscillations.

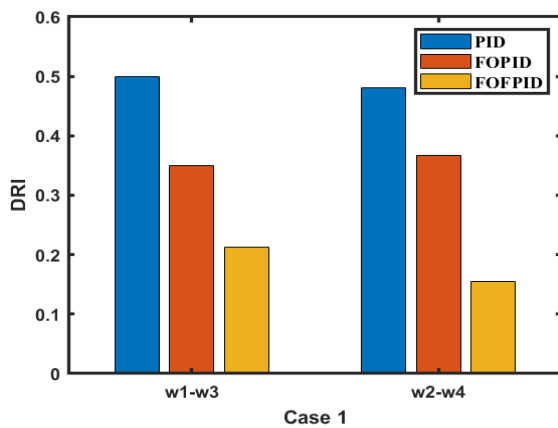


Figure 18. DRI values for case 1

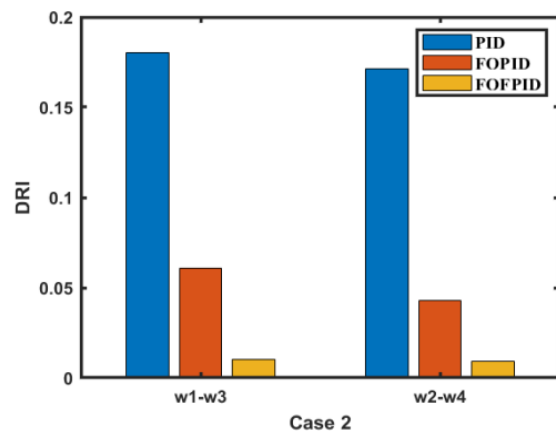


Figure 19. DRI values for case 2

7. CONCLUSION

A novel robust approach is introduced to improve the damping of inter-area LFOs using a wide-area auxiliary FOFPID controller with SVC. The suggested control technique integrates the benefits of fuzzy logic and fractional calculus. The controller parameters are efficiently optimized utilizing GWO, taking into account the ITAE index based remote generators speed deviation as an optimization criterion. The simulation is conducted on Kundur two-area power network. Moreover, the implemented control scheme efficiency is demonstrated and compared to integer and fractional PIDs through different performance indicators (ITAE, settling time, overshoot, undershoot and DRI). Then, following the application of diverse test cases, the designed FOFPID accomplishes excellent results and gives proof of robustness against disturbances

including load variation. It successfully mitigates inter-area LFOs and increases stability limit of the power system. Further expansion of our future work will consider the incorporation of high penetration of various forms of renewable energy sources (RES). In addition, coordination of robust FACTS type damping controllers with other system equipment's such as large-scale wind-PV farms (LWPF) and energy storage system (ESS) could be interesting. Furthermore, an important implication of this work is the practical application of the proposed controllers. Primary, a feasibility testing is confirmed using the OPAL-RT real-time simulator and then an initial implementation phase is performed.

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AUTHOR CONTRIBUTIONS STATEMENT

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C : Conceptualization

M : Methodology

So : Software

Va : Validation

Fo : Formal analysis

I : Investigation

R : Resources

D : Data Curation

O : Writing - Original Draft

E : Writing - Review & Editing

Vi : Visualization

Su : Supervision

P : Project administration

Fu : Funding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

The authors confirm that the data supporting the findings of this study are available within the article.

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