Optimal fractional SSSC auxiliary controller for power system low frequency oscillations damping improvement

Khadidja Benayad, Tarik Zabaiou, Amar Bouafassa
Laboratoire Génie Électrique Polytech Constantine (LGEPC), Département d'Électronique, Électrotechnique et Automatique (EEA), École Nationale Polytechnique de Constantine (ENPC), Constantine, Algeria

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ABSTRACT

This work presents a new controller design to improve inter-area low frequency electromechanical oscillations (LFEOs) damping and enhance the overall stability of the electrical network. The control strategy used the static synchronous series compensator (SSSC) based flexible AC transmission systems (FACTS) series-type device mainly performed for power flow and voltage regulation. Then, a fractional order proportional integral derivative (FOPID) is introduced as an auxiliary controller for the SSSC using the difference of rotor speed deviations of generators as input signal to improve the oscillations damping. Moreover, genetic algorithm (GA) is applied to seek for optimum controller gains. The proposed control approach is examined on two-area four-machine (2A4M) test system. The FOPID performance is compared with the integer order proportional integral derivative (PID). Obtained results show that the proposed SSSC-based FOPID controller achieves high performance for enhancement of inter-area low frequency oscillations damping.

Corresponding Author:

Khadidja Benayad
Laboratoire Génie Électrique Polytech Constantine (LGEPC)
Département d'Électronique, Électrotechnique et Automatique (EEA)
École Nationale Polytechnique de Constantine (ENPC)
Constantine, Algeria
Email: benayadkhadidja@gmail.com

1. INTRODUCTION

One of the serious problems that face today's interconnected power systems is small signal stability, which concerns the damping of low frequency oscillations varying from 0.1 Hz to 2 Hz, principally divided into local and inter-area modes [1]. The inter-area oscillatory modes, if not damped properly, have caused instability and blackouts in the power systems [2]. Flexible AC transmission systems (FACTS) equipments lately developed, help significantly on enhancing the transient stability margin [3] and offer a further technique for power oscillations damping improvement when supplied with auxiliary controllers [4], [5]. Among several FACTS controllers, more attention is focused on static synchronous series compensator (SSSC). SSSC varies its operations modes from capacitive to inductive without modifying the line intensity, what makes it useful in the control of power flow [6]. Also, an additional control signal is connected to the SSSC voltage block to suppress inter-area low frequency oscillations [7].

Extensive studies were performed on the effect of SSSC to dampen low frequency electromechanical oscillations (LFEOs) and ensure the dynamic stability of large grid. A variety of conventional regulators have been notified in the scientific publications comprising lead-lag [8] and proportional integral (PI) [9]. Several studies have proposed new techniques for designing SSSC-based damping controllers. Sahu *et al.* [10] presented a SSSC fuzzy lead-lag controller. Truong *et al.* [11] proposed an adaptive neural fuzzy inference system compensator to enhance the damping of a grid connected wind farms. Nonlinear robust controller based-SSSC for oscillations damping improvement is developed in [12]. Furthermore, new optimization algorithms are applied for best tuning of a SSSC controller to mitigate power swings [13]. On the other hand, the optimal coordination of SSSC and other FACTS controllers with photovoltaic and wind farms to ameliorate the transient stability of a multi-generators electric network is discussed in [14]. Additionally, SSSC-bassed network predictive control (NPC) is used in coordination with a wide-area damping control system (WADCS) including wind generation to enhance the damping of inter-area modes while dealing with diverse uncertainties [15].

Recently, fractional order proportional integral derivative (FOPID) controller [16] has received a great interest due to its more flexibility to satisfy design specifications, its better performances, and robustness compared to the conventional proportional integral derivative (PID) [17]. As consequence, FOPID controllers have been successfully extended to modern electrical power networks [18], [19]. Moreover, wide-area measurement system (WAMS) technology has facilitate the availability of remote generators speed deviations [20] as input for the proposed controller and then enable the application of wide-area damping control to eliminate inter-area LFEOs [21].

The purpose of this work is to design a SSSC-based fractional order PID controller using global signals to improve inter-area oscillations damping of interconnected power grid. For that, this paper is structured in this manner: SSSC modeling and internal control are discussed in section 2. The wide-area damping controller design is explained by section 3, while the optimization formulation is detailed in section 4. The test network is illustrated in section 5. To assess the performance of the developed controller, optimization and simulation results with their interpretations are provided in sections 6 and 7, respectively. Finally, section 8 outlines the general conclusion.

2. MODELING AND CONTROL CONCEPT OF SSSC

2.1. Modeling of static synchronous series compensator

Gyugyi *et al.* [6] introduced SSSC compensator in 1989. Figure 1 shows that it contains a DC capacitor and a voltage source converter (VSC) coupled in series with the electrical line using a transformer. Compared to the TCSC, the SSSC offers the advantage of removing the passive component (inductance and capacitance) of reactors and capacitors. Moreover, it possesses a symmetrical aptitude in both inductive and capacitive modes. This compensator injects a controllable voltage $V_q = V_{SSSC}$ in series to change the flow of energy, as illustrated in Figure 2. Furthermore, V_q must be in quadrature with the line intensity to provide series compensation and DC link voltage regulation [22]. This voltage is expressed in (1):

$$V_q = V_{SSSC} = \pm j V_{SSSC}(\beta)\left(\frac{I}{I}\right) \quad (1)$$

Where $V_{SSSC}(\beta)$ represents the injecting voltage magnitude, β is a control factor, and I is the transmission line current.

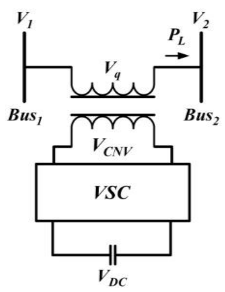

Figure 1. Principle configuration of SSSC

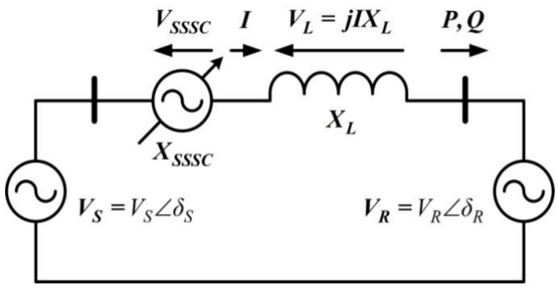

Figure 2. Two-machine system with SSSC [22]

2.2. SSSC internal control system

The SSSC-based VSC control structure is shown in Figure 3. First, a phase-locked loop (PLL) is utilized to calculate the angle $\theta = wt$ needed to obtain the direct and quadrature voltages and currents. Then, measurement blocks produce the measured quadrature and DC voltage. Finally, by comparing the obtained voltages with a reference values, the regulators provide the quadrature and direct (V_{dcnv} and V_{qcnv}) elements of the converter required for obtaining the desired DC and injected voltage.

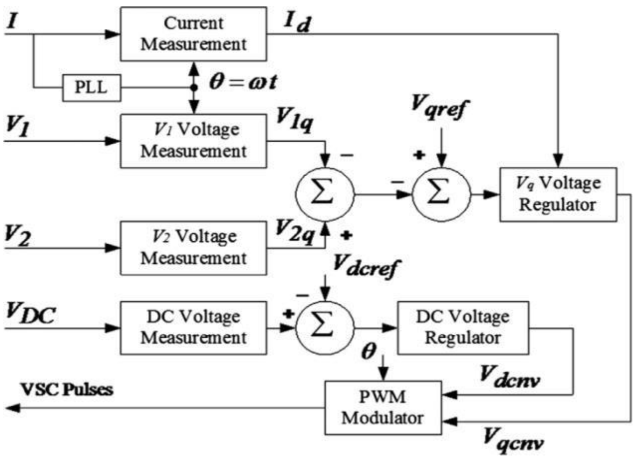

Figure 3. Structure of SSSC internal control

In addition to the aforementioned command blocks, power oscillations damping is achieved by modulation of the series injected voltage V_q during dynamics behavior. For this aim, the injected voltage variation ΔV_q of SSSC provided by the damping controller is combined with the reference voltage V_{qref} to obtain the required V_q given as in (2):

$$V_q = V_{qref} + \Delta V_q \tag{2}$$

Where $U_{SSSC} = \Delta V_q$ is the auxiliary damping signal from SSSC controller.

3. PROPOSED CONTROL STRATEGIES

In this section, two controllers for SSSC are proposed to improve power oscillations damping. As illustrated in Figure 4, the controllers generate the compensation signal $U_{SSSC} = \Delta V_q$ that will be adding to the reference V_{qref} of the voltage regulator. The input signal is the remote generator speed deviation.

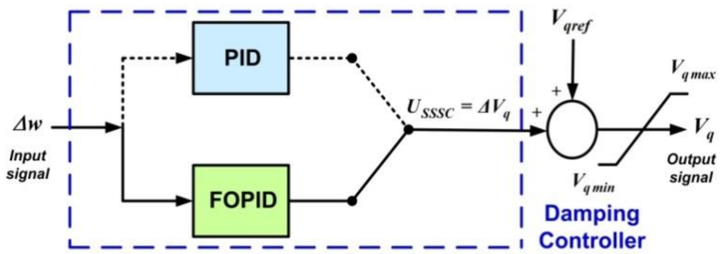

Figure 4. Structure of proposed controllers

For wide-scale electric system as represented in Figure 5, the damping controller uses speed deviations difference of generators from dispersed regions to implement the control laws. The proposed controller input based wide-area signals is very efficient in reducing low frequency swings and it is expressed as in (3):

$$\Delta w = \sum_{i \in Area1} dw_i - \sum_{j \in Area2} dw_j \tag{3}$$

dw_i and dw_j represent the rotor speed deviation of the ith and jth generator respectively.

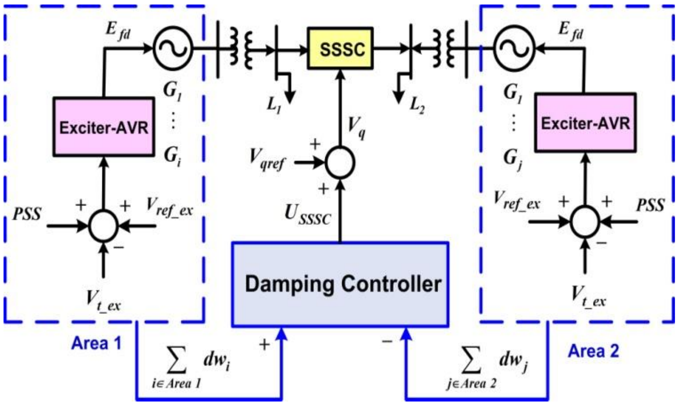

Figure 5. Inter-area multi-machine network with SSSC and auxiliary controller

3.1. PID type SSSC controller

The PID regulator is a simple device commonly used in most industrial control applications. The transfer function representing the PID is shown in Figure 6 and can be expressed as in (4). Where G_p, G_i and G_d are representing the proportional, integral and derivative parameters, respectively.

$$U_{SSSC}(S) = \left(G_p + \frac{G_i}{S} + G_d S\right) \Delta w(S) \quad (4)$$

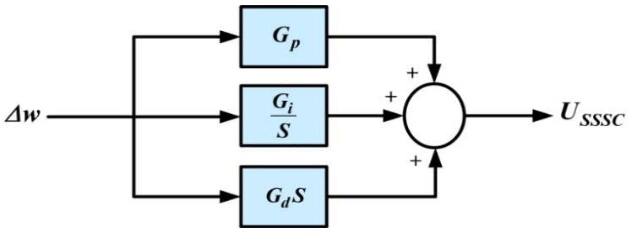

Figure 6. Block diagram of PID controller

3.2. FOPID type SSSC controller

3.2.1. Fractional computation concept

In fractional-order computation, the integer order integral and differential of classical calculus are extended to a fractional order operator $\mathrm{a}\mathrm{D}_{\mathrm{b}}^{\mathrm{r}}$. The variables a, b are the operator upper and lower limits and $r \in R$ represents the fractional order. Three most important suggestions for fractional order calculation were reported in [23]. Mathematically, it is formulated as in (5):

$$aD_b^r = \begin{cases} \frac{d^r}{dt^r} r > 0 \\ 1 \quad r = 0 \\ \int_a^b (d\tau)^{-r} r < 0 \end{cases} \quad (5)$$

3.2.2. Fractional controller and its approximation

Numerical simulations and practical application of fractional order controllers require technique for approximating them through integer order functions. According to Charef *et al.* [24], one of the first used methods formulates the fractional order integrator in frequency domain as in (6):

$$H(S) = \frac{1}{\left(1 + \frac{S}{p_T}\right)^r} \quad (6)$$

Where p_T is the transitional frequency and r is a real number bounded by 0 and 1. The transfer function represented in (6) could be substituted with a structure of poles and zeros:

$$H(S) = \frac{1}{\left(1+\frac{S}{p_T}\right)^r} \approx \frac{\prod_{i=0}^{N-1}\left(1+\frac{S}{z_i}\right)}{\prod_{i=0}^{N}\left(1+\frac{S}{p_i}\right)} \quad (7)$$

Poles and zeros shown in (7) are determined by: $p_0 = p_T\sqrt{b}$, $p_i = p_0(ab)^i$ and $z_i = ap_0(ab)^i$ with: $a = 10^{[y/10(1-r)]}$, $b = 10^{[y/10r]}$, $ab = 10^{[y/10r(1-r)]}$ and $N = integer\left[\frac{log(\omega_{max}/p_0)}{log(ab)}\right] + 1$. Where: y represents the error and w_{max} the frequency bandwidth.

The fractional order PID controller is represented in (8). G_p, G_i, and G_d symbolize the gains of the FOPID. λ and μ indicate the fractional order of integrator and differentiator, respectively, with a range for 0 to 1. The above fractional controller has been implemented by the Charef approximation [24]. The schematic structure of FOPID is shown in Figure 7.

$$U_{SSSC}(S) = \left(G_p + \frac{G_i}{S^\lambda} + G_d S^\mu\right) \Delta w(S) \quad (8)$$

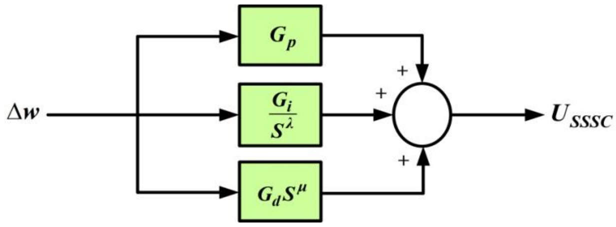

Figure 7. Block diagram of FOPID controller

Figure 8 shows that for classical PID controller $\lambda = \mu = 1$. However, for the FOPID controller λ and μ can have any value. Consequently, the stabilizing set of the FOPID is wider than that of the integer order PID, which makes it more robust against system uncertainties [25].

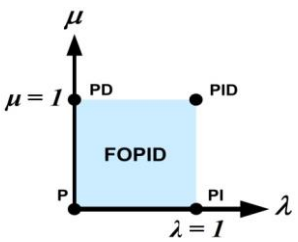

Figure 8. Graphical illustration in $\mu - \lambda$ plane

4. CONTROLERS TUNING METHOD

A well-tuned damping controller parameters necessitated a suitable performance criteria. Thus, the integral time absolute error (ITAE) of the generator speed deviation is considered as the cost function and it is calculated by:

$$f = \int_0^{t_{sim}} |\Delta w| \times t \times dt \quad (9)$$

Where Δw is the variation in generator speed and t_{sim} the simulation time. This work proposes a new performance function defined in (10):

$$f = \int_0^{t_{sim}} |\Delta w_{Inter-Area}| \times t \times dt \quad (10)$$

With $\Delta w_{Inter-Area} = \sum_{i\in Area1} w_i - \sum_{j\in Area2} w_j$, w_i, and w_j represent rotor speed of the ith and jth generator from different areas. Therefore, the problem formulation is given as follows:

Minimize f Subject to

$$G_p^{min} \le G_p \le G_p^{max}$$
$$G_i^{min} \le G_i \le G_i^{max}$$
$$G_d^{min} \le G_d \le G_d^{max}$$
$$\lambda^{min} \le \lambda \le \lambda^{max}$$
$$\mu^{min} \le \mu \le \mu^{max}$$

The limits of the optimized gains G_p, G_i and G_d are taken between 0.1 and 100, the fractional factors λ and μ are within the interval 0 to 1. The best controller coefficients are determined using genetic algorithm (GA) technique using MATLAB optimization toolbox-optimtool.

5. SYSTEM DESCRIPTION

Kundur's two-area four-machine (2A4M) network (Figure 9) was selected as test case. The system has two identical areas related by a long parallel transmission lines. Area 1 comprises two synchronous machines G1 and G2, where the second one incorporates generators G3 and G4. Each one rated 20 kV/900 MVA and provided with conventional regulators.

The test network has two local modes representing respectively areas 1 and 2, and the third one is an inter-area oscillation under what, machines in area 1 swing in opposition with those of area 2. The later is characterized by a little damping coefficient with lower oscillation frequency of 0.62 Hz [26]. Conventional power system stabilizers (CPSSs) are implanted on both generators G1 and G3 to help damping of local oscillations, the reminder generators are without stabilizers. The SSSC is centrally located on the line connecting buses 8 and 9 as depicted in Figure 9. The control algorithm and tests are implemented using SimPowerSystems toolbox [27] and the power network parameters are presented in [28].

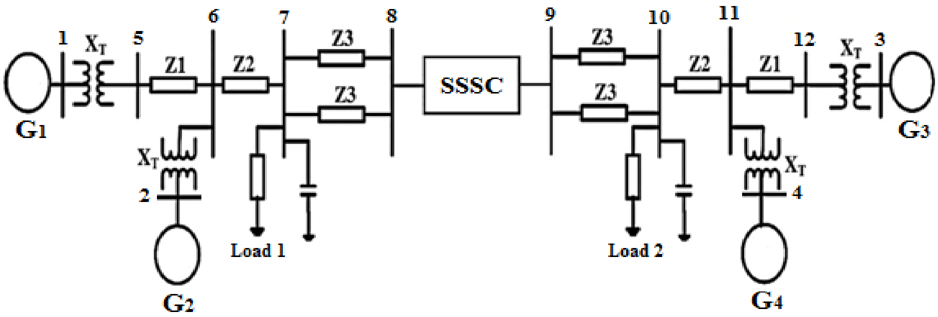

Figure 9. Simulation diagram of the two-area four-machine test network with SSSC [28]

6. OPTIMIZATION RESULTS

The ITAE-based objective function considered for study is expressed in (11). The optimized controller gains and fitness function values obtained by the GA algorithm are reported in Table 1.

$$f = \int_0^{t_{sim}} |(w_1 + w_2) - (w_3 + w_4)| \times t \times dt \qquad (11)$$

Table 1. Controller parameters and objective function optimal values

Controller	G_p	G_i	G_d	λ	μ	f
PID	95.892	72.234	10.024	-	-	0.345
FOPID	74.276	93.346	82.389	0.269	0.173	0.295

Figure 10 exhibits the variation of objective function ITAE with the classical and the fractional order PID controllers. Obviously, the results show that the FOPID type SSSC damping controller acts more significantly in minimizing the final value of fitness function. Therefore, it may be concluded from the preceding results that the FOPID provides more optimal controller settings compared to the PID.

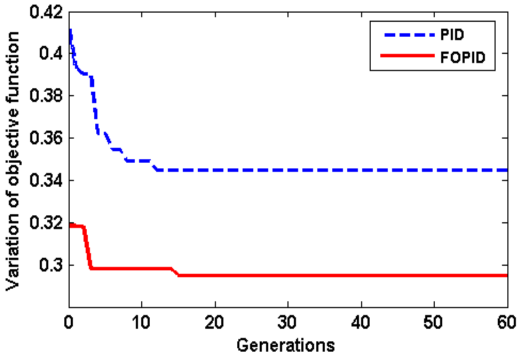

Figure 10. ITAE convergence curve

7. SIMULATION RESULTS AND DISCUSSION

In the following, the effectiveness of the designed FOPID is illustrated by considering the 2A4M network (Figure 9). The test consists of three-phase-to-ground disturbance arising between buses 7 and 8 at 1 s, cleared at 1.1 s. Figures 11-14 exhibit the dynamic behavior of the faulty system. These results represent the speed and angle deviation of generators (G1, G3) and generators (G2, G4). In this case, an inter-regional mode with low frequency (f=0.63 Hz) is appeared representing a power oscillation of generators (G1, G2) from area 1 toward those from area 2 (G3, G4). The transient performance indices regarding settling time, overshoot and undershoot of Figures 11-14 are shown in Tables 2-5, respectively. Noticeably, the FOPID controller provides lower indices values indicating improvement of dynamic response and thus attenuation of inter-area LFEOs.

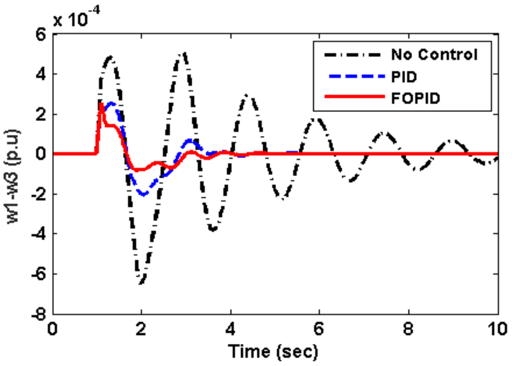

Figure 11. Speed deviation w1-w3

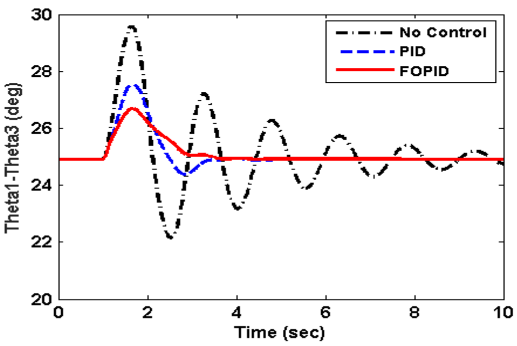

Figure 12. Angle deviation theta1-theta3

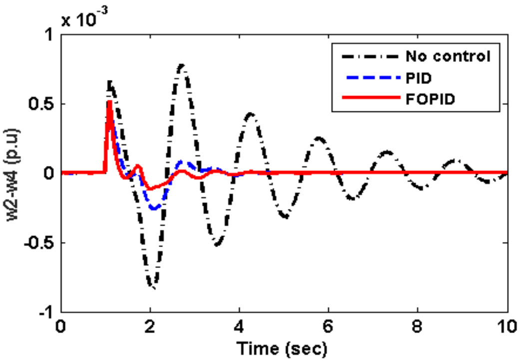

Figure 13. Speed deviation w2-w4

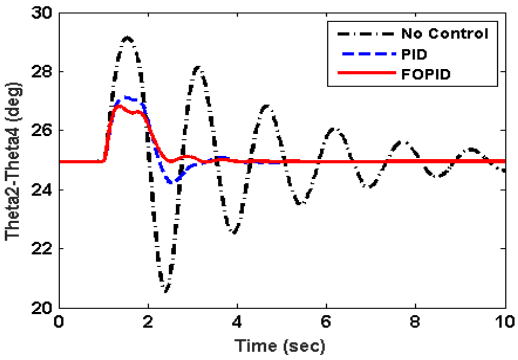

Figure 14. Angle deviation theta2-theta4

Table 2. Comparison of various performance indices of speed deviation (w1-w3)

Controller	Settling time (s)	Overshoot ($\times 10^{-4}$)	Undershoot ($\times 10^{-4}$)
No control	10.00	4.81	6.45
PID	3.40	2.55	2.04
FOPID	2.92	2.55	0.82

Table 3. Comparison of various performance indices of angle deviation (theta1-theta3)

Controller	Settling time (s)	Overshoot	Undershoot
No control	10.00	4.66	2.76
PID	3.39	2.64	0.54
FOPID	2.91	1.78	0.00

Table 4. Comparison of various performance indices of speed deviation (w2-w4)

Controller	Settling time (s)	Overshoot ($\times 10^{-4}$)	Undershoot ($\times 10^{-4}$)
No control	10.00	6.79	8.37
PID	3.14	5.23	2.59
FOPID	2.50	5.23	1.18

Table 5. Comparison of various performance indices of angle deviation (theta2-theta4)

Controller	Settling time (s)	Overshoot	Undershoot
No control	10.00	4.18	4.39
PID	3.12	2.17	0.72
FOPID	2.49	1.86	0.00

Previous results reveal that the proposed fractional PID controller outperforms the integer one. Oscillation and time damping have been decreased demonstrating mitigation of inter-area oscillations and increasing of power system stability. Finally, one can observe in Figure 15 that the damping signal U_{SSSC} provided by both the controllers lies within the limits imposed (± 0.2 p.u) without saturation. Even though, the FOPID controller offers the best damping and stability enhancement results.

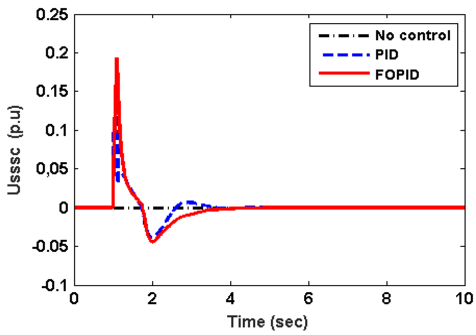

Figure 15. SSSC auxiliary damping signal

8. CONCLUSION

This paper has proposed a novel supplementary fractional order PID based-SSSC controller employing remote signals. The tuning gains of the designed controller were optimized by GA. ITAE index-based speed difference of dispersed generators is considered in the optimization problem. The performance of the FOPID SSSC controller was tested and analyzed for 2A4M power network, and a comparative study based different perfomance indices (ITAE, settling time, overshoot, and undershoot) has been performed with the classical PID. The proposed FOPID achieves the lowest indices values indicating enhancement of power system dynamic performance. Study results have verified the ability of the developed controller to enhance inter-area LFEOs damping and to increase the stability in a multi-machine electric network.

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BIOGRAPHIES OF AUTHORS

Khadidja Benayad was born in Jijel in October 1992. She received a master degree in automatic control from the university of Jijel, Algeria, in 2017. She is currently pursuing the Ph.D. at the National Polytechnic School of Constantine (ENPC), Algeria, within the Electrical Engineering Laboratory of the Polytechnic of Constantine (LGEPC). Her research interests include application of modern control techniques to power systems. She can be contacted at email: benayadkhadidja@gmail.com.

Tarik Zabaiou received the bachelor degree in automatic control from the university of Sétif, Algeria, in 1994, M.Ing. and Ph.D. in electrical engineering from École de Technologie Supérieure (ÉTS), Montreal, Quebec, Canada, in 2005 and 2010, respectively. During 2011–2014, he was a postdoctoral researcher in the Department of Electrical Engineering at ÉTS. In 2015, he joined the National Polytechnic School of Constantine (ENPC), Algeria, where he is currently an associate professor at the Department of Electrical, Electronic and Automatic Engineering. His current research interests include the application of modern robust nonlinear control techniques to large-scale power systems. He can be contacted at email: tzabaiou@gmail.com.

Amar Bouafassa was born in Sétif, Algeria, in 1988. He received his M.S. and Ph.D. degrees in Automatic Control from the University of Sétif-1, Sétif, Algeria, in 2011 and 2015, respectively. He is presently working as a lecturer at the National Polytechnic School of Constantine, Constantine, Algeria. His current research interests include modern control of power converters, PWM rectifiers, power factor correction, and energy efficiency. He can be contacted at email: amar.bouafassa@gmail.com.