UDC 621.3 https://doi.org/10.20998/2074-272X.2023.1.08

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Indirect adaptive fuzzy finite time synergetic control for power systems

Introduction. *Budget constraints in a world ravenous for electrical power have led utility companies to operate generating stations with full power and sometimes at the limit of stability. In such drastic conditions the occurrence of any contingency or disturbance may lead to a critical situation starting with poorly damped oscillations followed by loss of synchronism and power system instability. In the past decades, the utilization of supplementary excitation control signals for improving power system stability has received much attention. Power system stabilizers (PSS) are used to generate supplementary control signals for the excitation system in order to damp low-frequency oscillations caused by load disturbances or short-circuit faults.* ***Problem.*** *Adaptive power system stabilizers have been proposed to adequately deal with a wide range of operating conditions, but they suffer from the major drawback of requiring parameter model identification, state observation and on-line feedback gain computation. Power systems are nonlinear systems, with configurations and parameters that fluctuate with time that which require a fully nonlinear model and an adaptive control scheme for a practical operating environment. A new nonlinear adaptive fuzzy approach based on synergetic control theory which has been developed for nonlinear power system stabilizers to overcome above mentioned problems.* ***Aim.*** *Synergetic control theory has been successfully applied in the design of power system stabilizers is a most promising robust control technique relying on the same principle of invariance found in sliding mode control, but without its chattering drawback. In most of its applications, synergetic control law was designed based on an asymptotic stability analysis and the system trajectories evolve to a specified attractor reaching the equilibrium in an infinite time. In this paper an indirect finite time adaptive fuzzy synergetic power system stabilizer for damping local and inter-area modes of oscillations for power systems is presented.* ***Methodology.*** *The proposed controller design is based on an adaptive fuzzy control combining a synergetic control theory with a finite-time attractor and Lyapunov synthesis. Enhancing existing adaptive fuzzy synergetic power system stabilizer, where fuzzy systems are used to approximate unknown system dynamics and robust synergetic control for only providing asymptotic stability of the closed-loop system, the proposed technique procures finite time convergence property in the derivation of the continuous synergetic control law. Analytical proofs for finite time convergence are presented confirming that the proposed adaptive scheme can guarantee that system signals are bounded and finite time stability obtained.* ***Results.*** *The performance of the proposed stabilizer is evaluated for a single machine infinite bus system and for a multi machine power system under different type of disturbances. Simulation results are compared to those obtained with a conventional adaptive fuzzy synergetic controller.* References 20, table 1, figures 9.

Key words: **adaptive fuzzy systems, synergetic control theory, finite time convergence, power system stabilizer, multi-machine power system.**

Вступ. *Бюджетні обмеження у світі, жадібному до електроенергії, змушують комунальні підприємства експлуатувати станції, що генерують, на повну потужність, а іноді і на межі стабільності. У таких різких умовах виникнення будь-якої позаштатної ситуації або збурення може призвести до виникнення критичної ситуації, що починається з погано згасаючих коливань з подальшою втратою синхронізму та нестійкістю енергосистеми. В останні десятиліття велика увага приділялася використанню додаткових сигналів, керуючих збудження, для підвищення стійкості енергосистеми. Стабілізатори енергосистеми (СЕС) служать для вироблення додаткових сигналів керування системою збудження з метою гасіння низькочастотних коливань, спричинених збуреннями навантаження або короткими замиканнями.* ***Проблема***. *Адаптивні стабілізатори енергосистем були запропоновані для того, щоб адекватно справлятися з широким діапазоном робочих умов, але вони страждають від основного недоліку, що полягає в необхідності ідентифікації моделі параметрів, спостереження за станом та обчислення коефіцієнта посилення зворотного зв'язку в режимі реального часу. Енергетичні системи є нелінійними системами з конфігураціями та параметрами, які змінюються з часом, що потребує повністю нелінійної моделі та схеми адаптивного управління для практичного операційного середовища. Новий нелінійний адаптивно-нечіткий підхід, заснований на синергетичній теорії управління, розроблений для нелінійних стабілізаторів енергосистем для подолання вищезазначених проблем.* ***Мета***. *Теорія синергетичного управління успішно застосовувалася під час проєктування стабілізаторів енергосистем. Це найбільш перспективний надійний метод управління, заснований на тому ж принципі інваріантності, що і в ковзному режимі управління, але без його недоліку, пов'язаного з вібрацією. У більшості своїх програм синергетичний закон управління був розроблений на основі аналізу асимптотичної стійкості, і траєкторії системи еволюціонують до заданого атрактора, що досягає рівноваги за нескінченний час. У статті подано непрямий адаптивний нечіткий синергетичний стабілізатор енергосистеми з кінцевим часом для гасіння локальних та міжзонових мод коливань енергосистем.* ***Методологія.*** *Пропонована конструкція регулятора заснована на адаптивному нечіткому управлінні, що поєднує синергетичну теорію управління з атрактором кінцевого часу та синтезом Ляпунова. Удосконалюючи існуючий стабілізатор адаптивної нечіткої синергетичної енергосистеми, де нечіткі системи використовуються для апроксимації динаміки невідомої системи та надійного синергетичного управління тільки для забезпечення асимптотичної стійкості замкнутої системи, запропонований метод забезпечує властивість збіжності за кінцевий час при виведенні безперервного синергетичного закону керування. Наведено аналітичні докази збіжності за кінцевий час, що підтверджують, що запропонована адаптивна схема може гарантувати обмеженість сигналів системи та отримання стійкості за кінцевий час.* ***Результати***. *Працездатність пропонованого стабілізатора оцінюється для одномашинної системи з нескінченними шинами і багатомашинної енергосистеми при різних типах збурень. Результати моделювання порівнюються з результатами, отриманими за допомогою звичайного нечіткого адаптивного синергетичного регулятора.* Бібл. 20, табл. 1, рис. 9.

Ключові слова: **адаптивні нечіткі системи, синергетична теорія управління, збіжність за кінцевий час, стабілізатор енергосистеми, багатомашинна енергосистема.**

Introduction. Power systems are one of the most complex and nonlinear systems, with configurations and parameters fluctuating with time thus require a fully nonlinear model and an adaptive control scheme for adequate and sound operating environment [1-4]. Therefore, guaranteeing system stability for all operating condition is a major concern for utility companies. It is a recognized fact that hindering low frequency oscillations often occur in power networks upon advent of perturbations and power system stabilizers (PSS) have been developed to suppress them and to enhance overall system dynamic stability. PSS are used to generate supplementary control signals for the excitation system in order to damp low-frequency oscillations during disturbances [3-5]. Adaptive stabilizers have been proposed to provide better dynamic performance over a wide range of operating conditions [3, 4], but they suffer from the major drawback of requiring parameter model identification, state observation and on-line feedback gain computation. However, a nonlinear adaptive fuzzy approach based on synergetic control theory (SC) has been developed for nonlinear power system stabilizers [6, 7] to overcome above mentioned problems.

Synergetic control, a powerful tool for nonlinear system control [8-12] is a most promising robust control approach relying on the same principle of invariance found in sliding mode control, but devoid of its shortcoming: inherent chattering. Its robustness and its ease in implementation have put forth this recent control technique. Synergetic control has been successfully applied in the design of power system stabilizers [6-8]. In most of these papers, synergetic control law was designed based on an asymptotic stability analysis in which system trajectories reach the equilibrium point in infinite time. Several papers have proposed a so called terminal approach resulting in a finite time convergence based on terminal attractor techniques [13-15]; it is evident that reducing the time required in reaching the equilibrium point reinforces convergence as well as dwarfs disturbance impacts.

In the present paper, the first contribution lies in investigating the efficiency and robustness of indirect finite time adaptive fuzzy synergetic PSS (ITFSC-PSS) to control partially known or unknown systems and the second one consists in determining a new dynamic evolution of the synergetic attractor, such that system trajectories evolve to a specified attractor reducing the time required in reaching the equilibrium point and reinforcing the convergence as well as faster attenuation of disturbances. A nonlinear power system model consisting of a single machine connected to an infinite bus and a nonlinear multi-machine power system model, are used to assess performance and effectiveness of the proposed controllers. Performances obtained with the proposed ITFSC-PSS are compared to those obtained using an indirect adaptive fuzzy synergetic power system stabilizer (IFSC-PSS) [6], under different operating conditions.

Synergetic power system stabilizer. In order to design the power system stabilizer proposed in this paper, a power system dynamics can be expressed in a canonical form given in [6, 7, 16, 17], using speed variation $\Delta\omega_i = \omega_i - \omega_{0i}$ and the accelerating power $\Delta P_i = P_{mi} - P_{ei}$ as measurable input variables to the PSS. The synchronous machine system model can be represented in the following non linear state-space equations form [8, 16, 17]:

$$\begin{cases} \Delta\dot{\omega}_i = \dfrac{1}{2H_i}\Delta P_i \\ \Delta\dot{P}_i = f_i\left(\Delta\omega_i, \Delta P_i\right) + g_i\left(\Delta\omega_i, \Delta P_i\right)u_i \end{cases} \quad (1)$$

where ω_i is the angular speed in per units; P_{ei} is the delivered electrical power; P_{mi} is the mechanical input power treated as a constant in the excitation controller design and H_i is the per unit machine inertia constant; u_i is the necessary control signal to be designed, i.e. the PSS output; f_i (.) and g_i (.) are the nonlinear functions with $g_i (.) \neq 0$ in the controlled region.

It has been assumed that two nonlinear functions can be found from system dynamics analysis [6, 7, 16, 17]. In generic terms, the equation set (1) for the i^{th} generator is:

$$\begin{cases} \dot{x}_1 = \Delta\dot{\omega} = \dfrac{1}{2H}x_2 \\ \dot{x}_2 = \Delta\dot{P} = f\left(x_1, x_2\right) + g\left(x_1, x_2\right)u \end{cases} \quad (2)$$

Synthesis of a synergetic controller begins with a choice of a state variables function called a macro-variable:

$$\sigma = \lambda x_1 + x_2; \qquad \lambda \succ 0. \quad (3)$$

Desired dynamic evolution of the macro-variable can be designer chosen such as (4):

$$\dot{\sigma} + \tau\sigma = 0, \quad (4)$$

where τ is the positive constant imposing a designer chosen speed convergence to the desired manifold.

Differentiating the macro-variable (3) along (2) leads to (5):

$$\begin{aligned} \dot{\sigma} &= \lambda\dot{x}_1 + \dot{x}_2 \\ &= \frac{\lambda}{2H}x_2 + \left(f\left(x_1, x_2\right) + g\left(x_1, x_2\right)u\right) \end{aligned} \quad (5)$$

Combining equations (4) and (5), leads to (6):

$$\frac{\lambda}{2H}x_2 + f\left(x_1, x_2\right) + g\left(x_1, x_2\right)u = -\tau\sigma. \quad (6)$$

Solving for the control law u, leads to (7):

$$u = -\left(\frac{\lambda}{2H}x_2 + f\left(x_1, x_2\right) + \tau\sigma\right)\left(g\left(x_1, x_2\right)\right)^{-1}. \quad (7)$$

The power system under synergetic control stabilizer (7) has an asymptotic stability and its trajectories converge to the equilibrium point in infinite time. Therefore, robust operating conditions may not be satisfied and even slight disturbances can destabilize the system. To improve robust tracking and finite time convergence, a terminal synergetic controller leading to fast response and more robust performance is proposed.

Finite time synergetic power system stabilizer. In this new approach, aiming to reinforce robustness and better tracking, a reformulation of the dynamic evolution of the macro-variable (4) is adopted by defining a new nonlinear functional equation given in (8).

$$\dot{\sigma} + \tau\,\sigma^{n/m} + \alpha\sigma = 0 \quad , \quad (8)$$

where $\alpha > 0$ is the constant and n, m are the odd positive integers.

It can be derived that the time to reach the equilibrium $\sigma = 0$ is [13-15]:

$$t^* = \frac{1}{\alpha\left(1 - m/n\right)}\ln\frac{\alpha\left|\sigma\left(0\right)\right|^{1-n/m} + \tau}{\tau}, \quad (9)$$

where t^* is the finite expressing a finite time convergence as opposed to the asymptotic infinite time convergence to the attractor $\sigma = 0$ resulting in the previous scheme.

This approach inspired from sliding mode techniques [13-15] will be used to express the finite time synergetic control law u. Using (5), (8), the synergetic control law is then obtained as:

$$u = -\begin{pmatrix} \alpha\sigma + \dfrac{\lambda}{2H}x_2 + f\left(x_1, x_2\right) \\ + \tau\sigma^{n/m} \end{pmatrix}\left(g\left(x_1, x_2\right)\right)^{-1}. \quad (10)$$

Equation (10) is used in the design of a synergetic power system stabilizer which assures finite time stability of the system, in which $\sigma = 0$ is guaranteed in finite time

Stability and robustness analysis. Under the control law (10) and macro-variable design constraint (8), the state trajectories of the power system (2) can be driven onto the manifold $\sigma = 0$ in a finite time (9) thus ensuring finite time stability.

Theorem 1 [13-15]: suppose that there exists a positive definite continuous function $v(t)$ with positive real numbers ρ, β and $0 < \gamma < 1$, such that $v(t)$ satisfies the differential inequality:

$$\dot{v}(t) \le -\rho v(t) - \beta v^{\gamma}(t) . \quad (11)$$

Then the positive definite continuous function $v(t)$ will converge to the origin in finite time given by:

$$t_f = \frac{1}{\rho(1-\gamma)} \ln \frac{\rho\left|v(0)\right|^{1-\gamma} + \beta}{\beta} . \quad (12)$$

Proof: let's consider Lyapunov function candidate: $v = \sigma^2 / 2$, where σ defined as in (3). Then the time derivative of v leads to:

$$\dot{v} = \sigma\dot{\sigma} = \sigma\left(\frac{\lambda}{2H}x_2 + \left(f\left(x_1, x_2\right) + g\left(x_1, x_2\right)u\right)\right). \quad (13)$$

Substituting (10) into (13), one can obtain

$$\dot{v} \le -\tau\, \sigma^{1+n/m} - \alpha\sigma^2 . \quad (14)$$

Using (11), (14) becomes

$$\dot{v} \le -\tau\, 2^{(1+n/m)/2}\, v^{(1+n/m)/2} - 2\alpha v . \quad (15)$$

Defining constants: ρ and β as: $\rho = 2\alpha$ and $\beta = \tau \cdot 2^{(1+n/m)/2}$, if the parameter $\gamma = (1+n/m)/2$ is chosen such that $0<(1+n/m)/2<1$, therefore, (15) can be further simplified as:

$$\dot{v} \le -\beta v^{\gamma} - \rho v . \quad (16)$$

Thus according to Theorem 1, the stability of the power system (1) is guaranteed and the state trajectories can be driven onto the manifold $\sigma = 0$ in a finite time t^* given in (9). Therefore, $\sigma = 0$ is achieved in finite time, and the proof is complete. However, power system parameters for nonlinear functions are not well known and imprecise; therefore it is difficult to implement the control law (10) for unknown nonlinear system model. A fuzzy logic system will now be used to address this latter issue.

Finite time adaptive fuzzy synergetic power system stabilizer. The control law (10) for power system (1) can be modified as:

$$u = -\left(\alpha\sigma + \frac{\lambda}{2H}x_2 + f(x) + \tau\sigma^{n/m}\right)\left(g(x)\right)^{-1} . \quad (17)$$

In a practical real case where $f(x)$ and $g(x)$ are unknown functions, they are replaced by their fuzzy estimates [6, 7, 16, 17]:

$$\hat{f}(x/\theta_f) = \theta_f^T \xi(x) ; \quad (18)$$

$$\hat{g}(x/\theta_g) = \theta_g^T \xi(x) , \quad (19)$$

where $\xi(x)$ is the fuzzy basis functions defined as:

$$\xi_l(\underline{x}) = \frac{\prod_{i=1}^{n} \mu_{F_i^l}(x_i)}{\sum_{l=1}^{M}\left(\prod_{i=1}^{n} \mu_{F_i^l}(x_i)\right)} , \quad (20)$$

where $\mu_{F_i^l}(x_i)$ is the membership function value of x_i in labels of fuzzy sets F_i^l in $U = \prod_{i=1}^{n} U_i \in R^n$ and the parameters vectors θ_f and θ_g of the fuzzy logic systems (18) and (19), can be continuously updated as [6, 7, 16, 17]:

$$\dot{\theta}_f = \eta_1 \sigma \xi(x) ; \quad (21)$$

$$\dot{\theta}_g = \eta_2 \sigma \xi(x) u , \quad (22)$$

where η_1 and η_2 are the positive constants that will be used as learning rates in the adaptation procedure.

It is to be noted that the approximation issue has been addressed in great details in [18] where the universal approximation theorem is used to prove that fuzzy systems can approximate any continuous real function on a compact set to any arbitrary accuracy, while fuzzy rules are derived based on experts' recommendations. Therefore the new control law is rewritten as:

$$u = -\begin{pmatrix} +\alpha\sigma + \dfrac{\lambda}{2H}x_2 + \hat{f}\left(x/\theta_f\right) \\ + \tau\sigma^{n/m} \end{pmatrix}\left(\hat{g}\left(x/\theta_g\right)\right)^{-1} . \quad (23)$$

The power system models shown in Fig. 1, Fig. 5 are used to evaluate performance of the terminal adaptive fuzzy synergetic stabilizer (23) and results obtained are compared with a IFSC-PSS [6]. Different operating conditions are used in a simulation study and results are given and discussed in the next section.

Simulation results. The basic function of a PSS is to damp power oscillations that occur upon perturbations such as sudden change of loads or in the event of short-circuit occurrence. In this study, we will investigate the performance of the proposed power system stabilizer as it is applied to both single machine infinite-bus and multi-machine power systems. The success of the proposed PSS, with the single-machine infinite-bus case, motivates us to test its capability on a multi-machine model.

Application to the single-machine infinite bus model. A simplified schematic diagram of a single-machine infinite-bus system, which illustrates the position of a PSS, has been shown in Fig. 1.

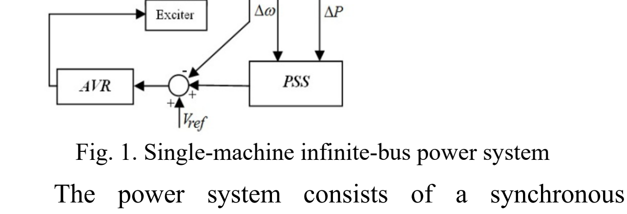

Fig. 1. Single-machine infinite-bus power system

The power system consists of a synchronous machine connected to an infinite bus through a transformer, a double transmission line and automatic voltage regulator (AVR) is represented by a four order model [3, 4]. The power system equations and parameters can be found in [4]. When the power system is operating with a leading power factor, the stability margin is reduced and, thus, the PSS faces adverse operating conditions. This scenario is now considered and power system simulation is carried out under the following severe fault cases:

Case 1. 0.2 p.u. disturbance in mechanical torque occurring at *t* = 1 s.

Faster oscillations damping occurs, as can be seen in Fig. 2, for the ITFS-PSS than for the traditional fuzzy synergetic stabilizer IFSC-PSS under a mechanical torque disturbance. A larger control effort is solicited by FFSPSS but only as a transient that rapidly dies out as opposed to its counterpart.

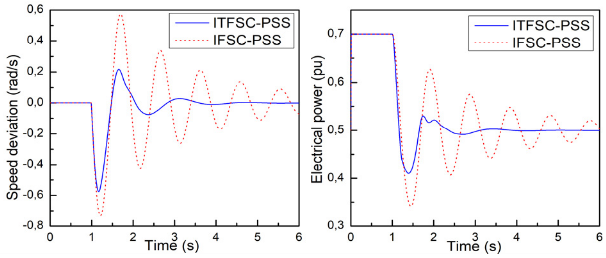

Fig. 2. System response for case 1

Case 2. Three-phase fault to ground on the transmission line occurring at *t* = 1 s with 0.06 s duration.

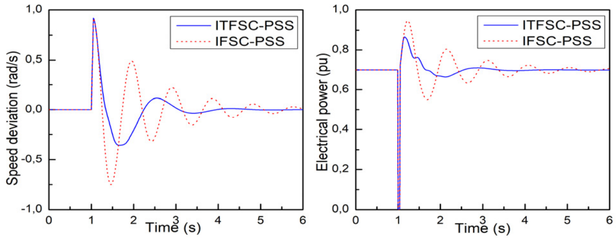

Fig. 3. System response for case 2

Even in the case of severe three-phase short circuit , the proposed controller effectively exhibits and confirms superior performance in improving finite time convergence of the system responses as clearly shown in Fig. 3, compared to IFSC-PSS.

Case 3. 0.1 p.u. step increase in reference voltage applied at *t* = 1 s.

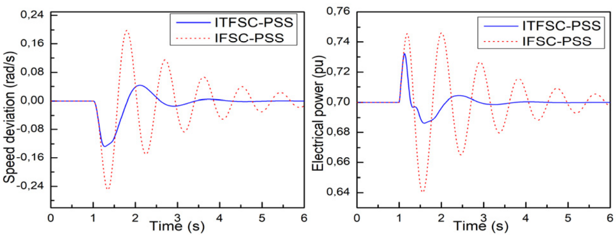

Fig. 4. System response in case 3

Simulation results show that the output responses of the IFSC-PSS are considerably affected by the step change in reference voltage as shown in Fig. 4, while oscillations are rapidly damped with the use of proposed PSS. It can be easily concluded that the latter achieves better robustness and has satisfactory time response under these types of disturbance and uncertainties over its presented counterpart.

Application to the multi-machine model. In this study, the three-machine nine-bus power system shown in Fig. 5 is considered. Details of the system data are given in [3, 4]. To identify the optimum location of PSS's in multi-machine power system the participation factor method [19] and the sensitivity of PSS effect method [20] were used. Both methods result indicate that G2 and G3 are the optimum location for installing PSS's in WSCC system. To assess the effectiveness and robustness of the proposed method over a wide range of loading conditions, three different cases designated as nominal, lightly and heavily loading are considered. The generator and system loading levels at these cases are given in Table 1.

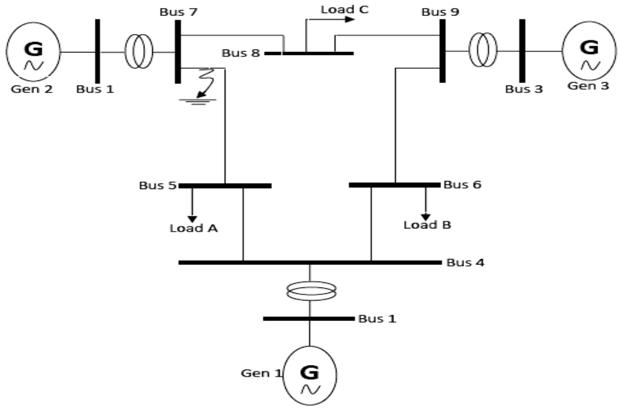

Fig. 5. Multi machine power system

Table 1

Loading operating conditions for the system (in p.u)

	Nominal		Heavy		Light	
Gen	*P*	*Q*	*P*	*Q*	*P*	*Q*
G1	0.72	0.27	2.1	1.09	0.36	0.16
G2	1.63	0.07	1.92	0.56	0.80	0.11
G3	0.85	0.11	1.28	0.36	0.45	0.20
Load	*P*	*Q*	*P*	*Q*	*P*	*Q*
A	1.25	0.50	2.0	0.80	0.65	0.55
B	0.9	0.30	1.80	0.60	0.45	0.35
C	1.0	0.35	1.50	0.60	0.50	0.25

The performance of the proposed controller under transient conditions is verified by applying a 6-cycle three-phase fault at *t* = 1 s, on bus 7 at the end of line 5-7 [4]. The fault is cleared by permanent tripping of the faulted line. System response under the nominal, lightly and heavily loading conditions are shown in Figs. 7-9. Figure 6 shows the system response without PSS. It is clear that the system response without PSS is highly oscillatory and eventually becomes unstable.

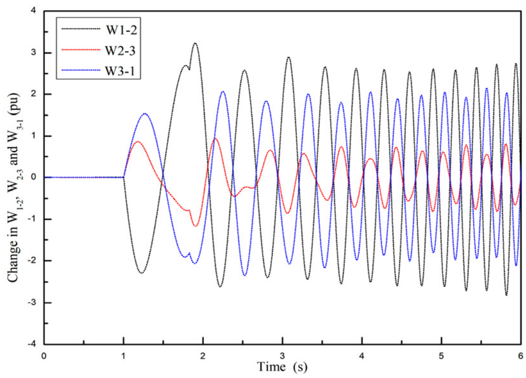

Fig. 6. Response of W_{1-2}, W_{2-3} and W_{3-1} in nominal operating condition without PSS

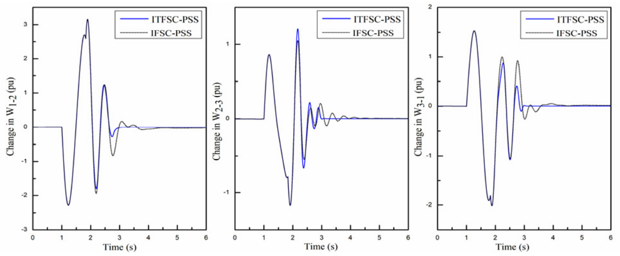

Fig. 7. Response of W_{1-2}, W_{2-3} and W_{3-1} in nominal operating condition

It is evident from the results in Figs. 7-9, that the damping of the low frequency oscillations in IFSC-PSS requires more time and has more oscillations before the speed deviation response is stabilized. The indirect adaptive fuzzy synergetic PSS improves the damping of oscillations in the change of operating conditions.

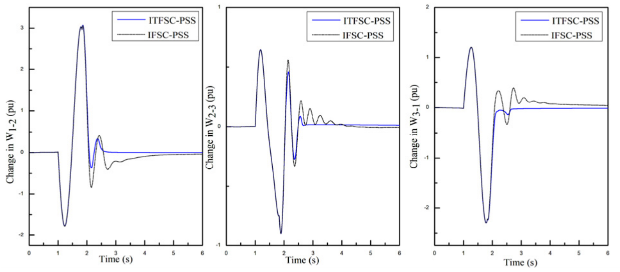

Fig. 8. Response of W_{1-2}, W_{2-3} and W_{3-1} in heavy operating condition

However, the superiority performance is clear with the proposed controller. The proposed controller provides significantly better damping enhancement in the power system oscillations. It is possible to observe that the overshoot and the settling time are reduced.

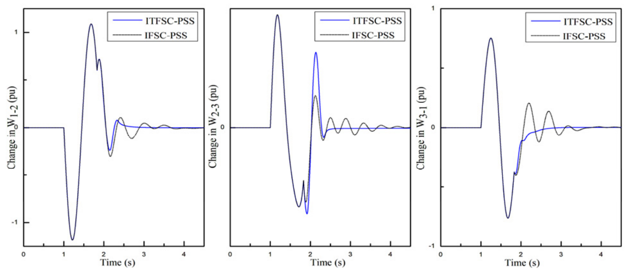

Fig. 9. Response of W_{1-2}, W_{2-3} and W_{3-1} in light operating condition

Conclusion. An indirect finite time adaptive fuzzy synergetic power system stabilizer has been presented and its performance evaluated by simulation using nonlinear power system models. Furthermore results have been compared to simple adaptive fuzzy synergetic PSS showing the pre-eminence of the proposed approach in both time response and steady-state performance. Despite the critical conditions, power systems considered have been subjected to the overall performance using the indirect adaptive finite time fuzzy synergetic power system stabilizer shows remarkable fast suppression of undesirable oscillations.

Conflict of interest. The authors declare that they have no conflicts of interest

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Received 25.06.2022
Accepted 12.09.2022
Published 06.01.2023

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How to cite this article:
Khatir A., Bouchama Z., Benaggoune S., Zerroug N. Indirect adaptive fuzzy finite time synergetic control for power systems. *Electrical Engineering & Electromechanics*, 2023, no. 1, pp. 57-62. doi: https://doi.org/10.20998/2074-272X.2023.1.08