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 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 for 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.

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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
\[ \Delta \omega_i = \omega_i - \omega_0 \] and the accelerating power
\[ \Delta P_i = P_{mi} - P_{ci} \] 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{align*}
\Delta \omega_i &= \frac{1}{2H_i} \Delta P_i \\

\Delta P_i &= f_i(\Delta \omega_i, \Delta P_i) + g_i(\Delta \omega_i, \Delta P_i)u_i
\end{align*}
\]  

where \(\omega_i\) is the angular speed in per units; \(P_{mi}\) 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{align*}
\dot{x}_i &= \Delta \omega_i = \frac{1}{2H_i} x_i \\

\dot{x}_2 &= \Delta P_i = f(x_i, x_2) + g(x_i, x_2)u
\end{align*}
\]  

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

\[ \sigma = \lambda x_i + x_2; \quad \lambda > 0 . \]  

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

\[ \sigma = \sigma^0 + \tau \sigma = 0 , \]  

where \(\tau\) is the positive constant imposing a designer
closed speed convergence to the desired manifold.
Differentiating the macro-variable (3) along (2)
leads to (5):

\[ \dot{\sigma} = \dot{\lambda} x_i + \dot{x}_2 = \frac{\lambda}{2H} x_i + \left( f\left(x_i, x_2\right) + g\left(x_i, x_2\right)u \right) \]  

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

\[ \frac{\lambda}{2H} x_i + f\left(x_i, x_2\right) + g\left(x_i, x_2\right)u = -\tau \sigma . \]  

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

\[ u = -\frac{\lambda}{\left( \frac{\lambda}{2H} x_i + f\left(x_i, x_2\right) + \tau \sigma \left( g\left(x_i, x_2\right) \right) \right)^2} \]  

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).

\[ \dot{\sigma} + \tau \sigma = 0 , \]  

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]:

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

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:
\[ u = -\left[ \alpha \sigma + \frac{\lambda}{2H} x_2 + f(x_1, x_2) \right] \left( g(x_1, x_2) \right)^{-1}. \]  

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 function \( V(t) \) defined as in (3). Then the time derivative of \( V \) leads to:

\[ \dot{V} = \sigma \dot{\sigma} \left( \frac{\lambda}{2H} x_2 + f(x_1, x_2) + g(x_1, x_2)u \right). \]  

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

\[ \dot{V} \leq - \tau \sigma^{1+n/m} - \alpha \sigma^2. \]  

Using (11), (14) becomes

\[ \dot{V} \leq - \tau \sigma^{1+n/m} - \alpha \sigma^2. \]  

Defining constants \( \rho \) and \( \beta \) as: \( \rho = 2\alpha \) and \( \beta = \tau^{2(1+n/m)} \), 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:

\[ \dot{V} \leq - \beta \sigma^2 - \rho \sigma. \]  

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:

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

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]:

\[ \hat{f}(x/\theta) = \theta f(x); \]

\[ \hat{g}(x/\theta) = \theta g(x). \]

where \( \theta \) is the fuzzy basis functions defined as:
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.

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

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.

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.

![Multi machine power system](image)

**Fig. 5.** Multi machine power system

**Table 1**

<table>
<thead>
<tr>
<th></th>
<th>Nominal</th>
<th>Heavy</th>
<th>Light</th>
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<tr>
<td>Gen</td>
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<td>Q</td>
<td>P</td>
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<td>0.27</td>
<td>2.1</td>
</tr>
<tr>
<td>G2</td>
<td>1.63</td>
<td>0.07</td>
<td>1.92</td>
</tr>
<tr>
<td>G3</td>
<td>0.85</td>
<td>0.11</td>
<td>1.28</td>
</tr>
<tr>
<td>Load</td>
<td>P</td>
<td>Q</td>
<td>P</td>
</tr>
<tr>
<td>A</td>
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<td>0.50</td>
<td>2.0</td>
</tr>
<tr>
<td>B</td>
<td>0.9</td>
<td>0.30</td>
<td>1.80</td>
</tr>
<tr>
<td>C</td>
<td>1.0</td>
<td>0.35</td>
<td>1.50</td>
</tr>
</tbody>
</table>

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.

![Response of W1-2, W2-3 and W3-1 in nominal operating condition without PSS](image)

**Fig. 6.** Response of W1-2, W2-3 and W3-1 in nominal operating condition without PSS
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.

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.

**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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