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# Finite-Time Fuzzy Synergetic Power System Regulator

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**Abstract:** A finite-time fuzzy synergetic power system stabilizer (FFSPSS) is proposed based on the concept of terminal attractor, adaptive fuzzy synergetic control, and Lyapunov synthesis approach. Enhancing existing adaptive fuzzy synergetic PSS, where fuzzy systems are used to approximate unknown system dynamics and robust synergetic control 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. Performance of the proposed stabilizer is evaluated for a single-machine infinite-bus power system, subjected to different types of disturbances. Simulation results are compared to those obtained with a conventional fuzzy synergetic PSS confirming the prevalence and effectiveness of FFSPSS developed.

**Keywords:** Power system stabilizer; Synergetic control; Terminal attractor; Adaptive fuzzy systems; Finite time convergence.

## 1. Introduction

Power systems are one of the most complex 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. 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 [2-3]. Adaptive stabilizers have been proposed to provide better dynamic performance over a wide range of operating conditions [4-6], 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 (SCT) has been developed for nonlinear power system stabilizers [1,7] (FSPSS) to overcome above mentioned problems. Synergetic control (SC), a potent mean for nonlinear system control [6, 8-9] is a most propitious approach based on the invariance feature found SMC, yet devoid of its short coming: inherent chattering. Robust and easy to implement SC has been advocated in PSS [1, 7, 10]. However SC law was considered for asymptotic convergence in which system dynamics reach the equipoise point in unbounded time. Numerous propositions, using a terminal methodology leading to a rapid convergence based on terminal attractor procedures, [11-14] have been made; it is obvious that attaining rapidly the evident that reducing the time required in reaching the equilibrium point reinforces convergence as well as dwarfs disturbance impacts.

In the present paper, a nonlinear power system model consisting of a single machine connected to an infinite bus (SMIB) is used to assess performance and effectiveness of the proposed controllers. Performance obtained with the proposed fuzzy finite time synergetic PSS (FFSPSS) is compared to those obtained using a fuzzy synergetic power system stabilizer (FSPSS) [1], under different operating conditions. FFSPSS will guarantee finite-time stability of power system, and ensure closed-loop system overall robustness.

## 2. Synergetic power system stabilizer

In order to design the power system stabilizer proposed in this paper, a power system configuration is shown in Fig. 1, contents of which are addressed in the last section. The power system dynamics can be expressed in a canonical form given in [1, 7, 10, 15], using speed variation $\Delta\omega = \omega - \omega_0$ and the accelerating power $\Delta P = P_m - P_e$ as measurable input variables to the PSS.

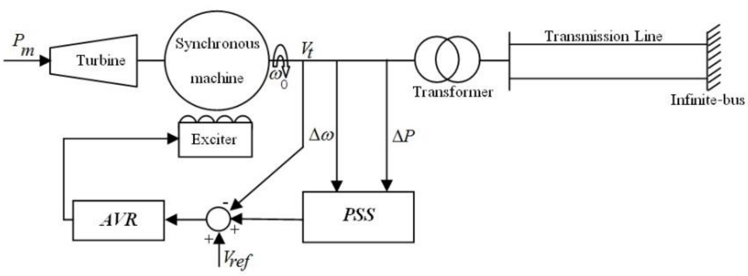


**Fig.1.** Single-machine infinite-bus power system.

The synchronous machine system model can be represented in the following nonlinear state-space equations form [1,7,15]:

$$\begin{cases} \Delta\dot{\omega} = \dfrac{1}{2H}\Delta P \\ \Delta\dot{P} = f(\Delta\omega, \Delta P) + g(\Delta\omega, \Delta P)u \end{cases} \tag{1}$$

Where $\omega$ is the angular speed in per units, $P_e$ is delivered electrical power, $P_m$ is the mechanical input power treated as a constant in the excitation controller design and $H$ is the per unit machine inertia constant. Equation (1) represents the machine model during a transient period after a major disturbance occurrence in the system. It has been assumed that two nonlinear functions

$f(\Delta\omega,\Delta P)$ and $g(\Delta\omega,\Delta P)$ can be found from system dynamics analysis [15-16]. Synthesis of a synergetic controller begins with a choice of a state variables function called a macro-variable (2):

$$\sigma = \lambda\,\Delta\omega + \Delta P\,;\ \lambda > 0; \tag{2}$$

Desired dynamic evolution of the macro-variable can be designer chosen such as (3):

$$\dot{\sigma} + \tau\,\sigma = 0 \tag{3}$$

$\tau$ is a positive constant imposing a designer chosen speed convergence to the desired manifold. Differentiating the macro-variable (2) along (1) leads to (4):

$$\begin{aligned}\dot{\sigma} &= \lambda\,\Delta\dot{\omega} + \Delta\dot{P} \\ &= \frac{\lambda}{2H}\Delta P + \left( f(\Delta\omega,\Delta P) + g(\Delta\omega,\Delta P)\,u \right)\end{aligned} \tag{4}$$

Combining equations (3) and (4), leads to (5):

$$\frac{\lambda}{2H}\Delta P + f(\Delta\omega,\Delta P) + g(\Delta\omega,\Delta P)\,u = -\tau\,\sigma \tag{5}$$

Solving for the control law $u$, leads to (6):

$$u = -\left( \frac{\lambda}{2H}\Delta P + f(\Delta\omega,\Delta P) + \tau\,\sigma \right)\left( g(\Delta\omega,\Delta P) \right)^{-1}; \qquad g(\Delta\omega,\Delta P) \neq 0 \tag{6}$$

The power system under synergetic control stabilizer (6) provides only asymptotic stability; robust operating conditions may not be satisfied leading to a system prone to instability under minor perturbations. These issues are addressed via a terminal synergetic technique which provides finite time convergence as well as a better steady-state performance.

## 3. Finite time synergetic stabilizer

Achieving desired performance described in previous section, a different constraint defined by (7) will now be employed:

$$\dot{\sigma} + \tau\,\sigma^{n/m} + \alpha\,\sigma = 0 \tag{7}$$

Where $\alpha > 0$ is constant and $n$, $m$ are odd positive integers. Finite time to reach the equilibrium point is given by [11-14]:

$$t^* = \frac{1}{\alpha(1-m/n)}\ln\frac{\alpha|\sigma(0)|^{1-n/m}+\tau}{\tau} \tag{8}$$

$t^*$ has a definite value as opposed to the enormous value it may take to attain $\sigma=0$, resulting in the previous scheme. Thus a new controller is obtained, motivated by [14], expressed as:

$$u = -\left(\alpha\sigma + \frac{\lambda}{2H}\Delta P + f(\Delta\omega,\Delta P) + \tau\sigma^{n/m}\right)\left(g(\Delta\omega,\Delta P)\right)^{-1} \tag{9}$$

A new stabilizer articulated by (9)is thus developed providing finite time convergence given by (8).

## 4. Stability and robustness analysis

Power system state trajectories reach the attractor $\sigma=0$ in finite time through the use of (9) and (7) as can be proved by the following theorem:

**Theorem** [11-14]: Let there be a positive definite continuous function $v(t)$ with positive real numbers $\rho$, $\beta$ and $0<\gamma<1$, satisfying the differential inequality:

$$\dot{v}(t)\le -\rho v(t) - \beta v^{\gamma}(t) \tag{10}$$

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

$$t_f = \frac{1}{\rho(1-\gamma)}\ln\frac{\rho|v(0)|^{1-\gamma}+\beta}{\beta} \tag{11}$$

**Proof**: let's consider the following Lyapunov function candidate:

$$v = \frac{1}{2}\sigma^2 \tag{12}$$

with $\sigma$ defined as in (2). The derivative of (12) with respect to time is given in (13).

$$\begin{aligned}\dot{v} &= \sigma\dot{\sigma}\\ &= \sigma\left(\frac{\lambda}{2H}\Delta P + \left(f(\Delta\omega,\Delta P) + g(\Delta\omega,\Delta P)u\right)\right)\end{aligned} \tag{13}$$

Substituting (9) into (13), one can obtain

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$$\dot{v} \leq -\tau\, \sigma^{1+n/m} - \alpha\sigma^2 \tag{14}$$

and using (10),(14) becomes

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

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

$$\dot{v} \leq -\beta v^{\gamma} - \rho v \tag{16}$$

Thus according to the theorem above, state trajectories of system of (1) reach equilibrium point $\sigma = 0$ in a time $t^*$ given in (8) and finite time stability is assured that which concludes the proof. However, nonlinear power system models are imprecisely known; therefore implementing control (9) for such models may lead to unreliable results. A fuzzy logic system will now be used to address this latter concern.

## 5. Fuzzy finite time synergetic power system stabilizer

The control law (9) for power system (1) can be modified as:

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

Where $x = [\Delta\omega\ \Delta P]^T$ is a vector of measurable states. Real-world functions $f(x)$ and $g(x)$ are never known with great accuracy, thus they may be replaced by their fuzzy estimates [6,7]:

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

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

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

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

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

$$\dot{\theta}_f = \eta_f\, \sigma\, \xi(x) \tag{21}$$

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

where $\eta_f$ and $\eta_g$ represent adaptive positive learning rates. Fuzzy systems sets can provide up to desired accuracy approximation as detailed in [19-20] based on operators expertise and enable one to express the new control law as:

$$u = -\left( \alpha\,\sigma + \frac{\lambda}{2H}\Delta P + \hat{f}(x/\theta_f) + \tau\,\sigma^{n/m} \right) \hat{g}(x/\theta_g)^{-1} \tag{23}$$

The system model depicted in Fig.1 is again used in assessing the proposed stabilizer (23) performance and results obtained are compared to those obtained with a FSPSS [6]. Simulation of several operating scenarios are considered and results are discussed in the next section.

## 6. Simulation results

A schematic diagram of a single-machine power system, with PSS location defined is shown in Fig. 1. A synchronous machine connected to an infinite bus through a transformer, a double transmission line and automatic voltage regulator (AVR) make up the system considered which is represented by a four order model [2-3]. 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 different fault cases are envisaged:

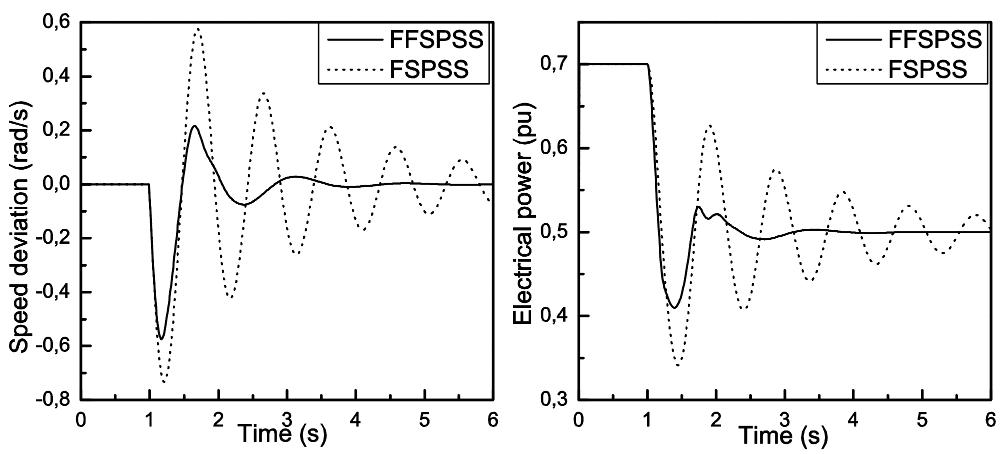


**Fig.2** System response for case 1.

- 0.2 p.u. mechanical torque disturbance at $t = 1s$ .
- three-phase to ground fault on the transmission line of 0.06 s duration at $t = 1s$ .
- reference voltage stet up of 0.1 0.1 p.u. at $t = 1s$ .

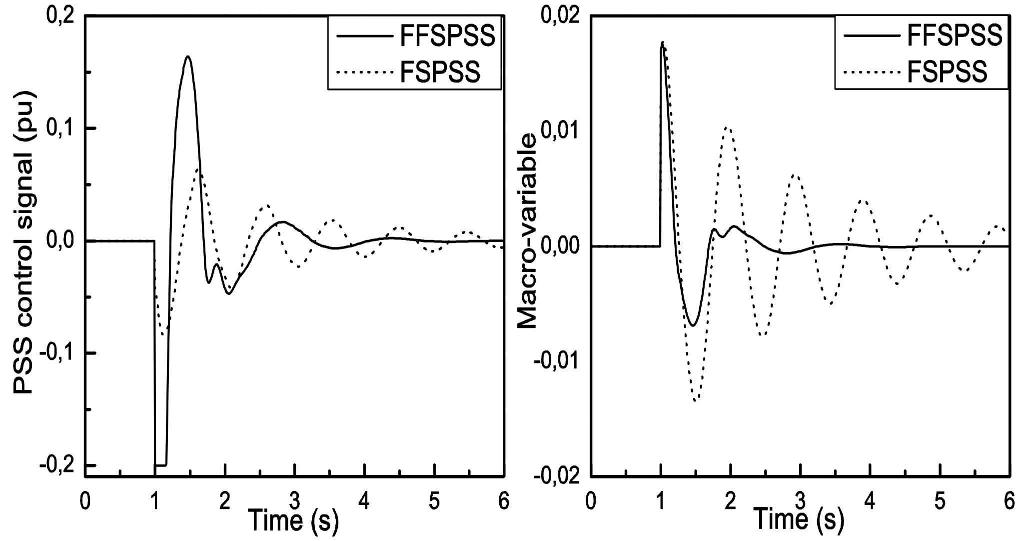


**Fig.3** Controller output and macro-variable evolutions for case 1.

Faster oscillations damping occur, directly observed in Fig.2 and Fig.3, for FFSPSS than for the traditional fuzzy synergetic stabilizer 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.

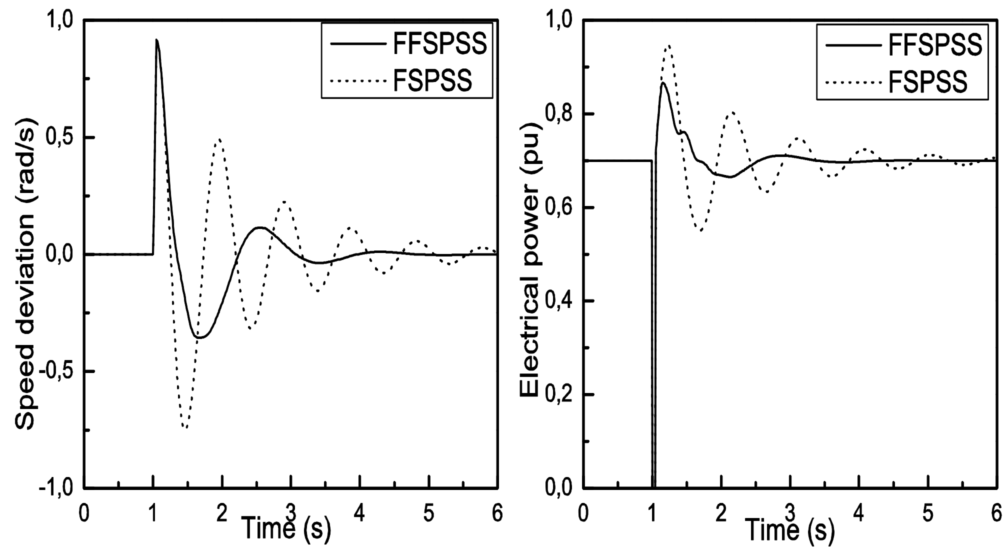


**Fig.4** Speed deviation and electrical power evolutions for case 2.

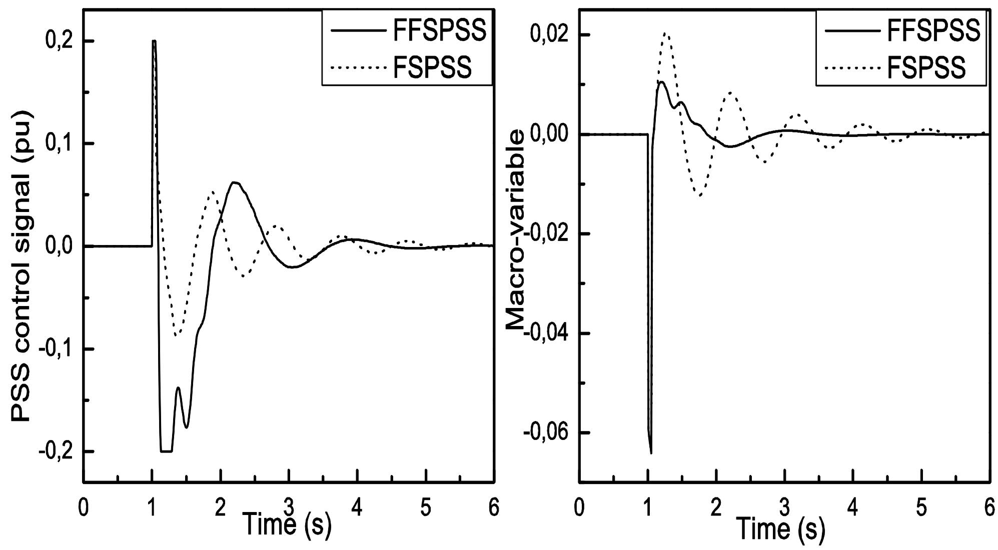


**Fig.5** Controller output and macro-variable evolutions for case 2.

Even in the case of severe three-phase short circuit, the proposed stabilizer demonstrate its prevalence in providing finite time convergence as plainly illustrated in Figs. 4-5, compared to FSPSS.

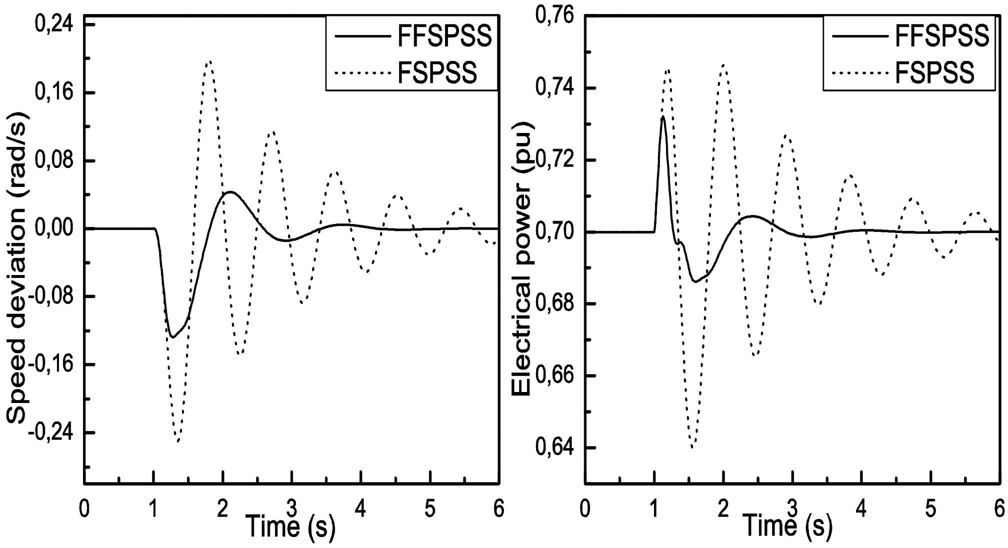


**Fig.6** System response in case 3.

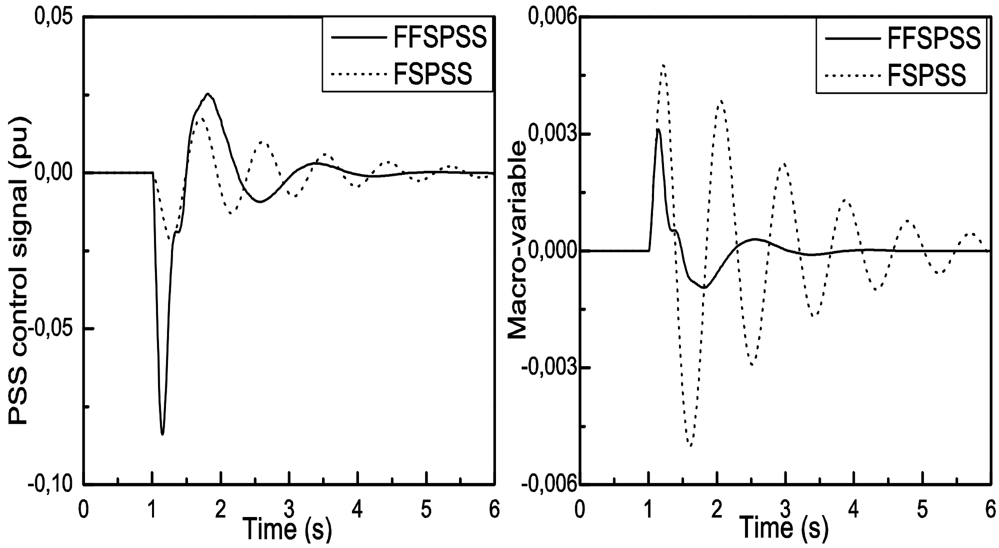


**Fig.7** Controller output and macro-variable evolutions for case 3.

It is obvious that FSPSS responses show the great impact due to the reference voltage step up as opposed to the rapidly damped oscillations upon the use of the proposed PSS. One can but conclude that FFSPSS reinforce system robustness and provide better transient response over its considered counterpart in different and severe operating conditions.

## 7. Conclusion

A fuzzy finite time synergetic power system stabilizer has been presented and its performance evaluated by simulation using nonlinear power system model. Furthermore results have been compared to simple fuzzy synergetic PSS showing great improvement of the proposed stabilizer in transient as well as in steady-state performance. Despite the critical conditions the power system considered has been subjected to, the overall performance using the finite time fuzzy synergetic power system stabilizer shows remarkable fast suppression of undesirable oscillations.

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