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Application of Lyapunov Theory and Fuzzy Logic to Control Shunt FACTS Devices for Enhancing Transient Stability in Multimachine System

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Abstract – This paper proposes the control strategy of the shunt Flexible AC Transmission System (FACTS) devices to improve transient stability in multimachine power system. The multimachine power system has high nonlinear response after severe disturbance. The concept of Lyapunov energy function is applied to derive nonlinear control strategy and it was found that the time derivative of line voltage is not only can apply to control the shunt FACTS devices in multimachine system but also is locally measurable signal. The fuzzy logic control is also applied to overcome the uncertainty of various disturbances in multimachine power system. This paper presents the method of investigating the effect of the shunt FACTS devices on transient stability improvement. The proposed control strategy and the method of simulation are tested on the new England power system. It was found that the shunt FACTS devices based on the proposed nonlinear control strategy can improve transient stability of multimachine power system.

Keywords: Power system, Transient stability, FACTS devices, Lyapunov, Fuzzy logic control

1. Introduction

In the early days, power system used only radial lines to supply power to a specified load center. Nowadays, the demand has dramatically increased and a modern power system becomes a complex network of transmission lines interconnecting the generating stations and the major load points in the overall power system in order to support the high demand of consumers. Since the environmental regulatory and economical constraints are often the obstacle to build new transmission lines, the challenge facing the power system engineers today is to use the existing transmission facilities to a greater extend.

The power system stability is concerned with the behavior of the synchronous machines after a disturbance. The power system stability is generally divided into three major categories [1]. Steady state stability refers to the stability of the power system subjects to small and gradual changes in load, and system remains stable with conventional excitation and governor controls. Dynamic stability refers to the stability of the power system subjects to a relatively small and sudden disturbance. Transient stability refers to the stability of a power system subjects to a sudden and severe disturbance.

It is well known that the power flow through an AC transmission line is a function of line impedance, magnitude and phase angle of the sending and receiving end voltages. If these parameters can be controlled, the power flow through the transmission line can be controlled in a predetermined manner [2]. This can be achieved and the natural behavior of the network can be modified through the application of power flow control devices placed at strategic location. Thus the power transfer capability can be improved and the need for additional network facilities can be reduced.

Flexible Alternating Current Transmission Systems (FACTS) concept, initiated by Electric Power System Research Institute (EPRI), uses power electronics based devices to control or change the system parameters in order to fully utilize the existing transmission facilities. There are various forms of FACTS devices, some of them are connected in series with the line and others are connected in shunt or a combination of series and shunt [3].

The development of FACTS controllers has followed two distinctly different technical approaches. The first group of controllers includes the Static Var Compensator (SVC), Thyristor Controlled Series Capacitor (TCSC) and Thyristor Controlled Phase Shifter Transformer (TCPST). All of them employ conventional thyristors and can act on only one of the three parameters that dictate the power flow through a line. The SVC controls the voltage magnitude, TCSC controls the line impedance and TCPST controls the phase angle [4].

The second group of FACTS controller employs self-commutated, voltage source switching converters to realize rapidly controllable, static, synchronous ac voltage or current sources. This approach, when compared with the first group of controller, generally provides superior performance characteristics and uniform applicability for power transmission control. The second group of FACTS

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devices includes the Static Synchronous Series Compensator (SSSC), Static Synchronous Compensator (STATCOM), Unified Power Flow Controller (UPFC) and Interline Power Flow Controller (IPFC) [5, 6].

Static Var Compensator (SVC) and Static Synchronous Compensator (STATCOM) are considered as the shunt FACTS devices and they are used for controlling the line voltage by supplying or absorbing the reactive power. Most of previous researches use the remote signal such as machine speed to control the shunt FACTS devices for improving transient stability of the power system [7-9]. However, the machine speed may not be available at the optimal placement of the shunt FACTS devices [10]. Thus, in multimachine power system, the remote signal may not be practical.

In modern power system, it is very large scale and complex network. The disturbance may results in nonlinear response. The second method of the Lyapunov second method or called the Lyapunov energy function is the concept of nonlinear system. The successful application of Lypunov energy function of series FACTS devices have been reported in [11].

The uncertainty of various disturbances often happening in power system provides the difficulty of control. The fuzzy logic control provides very powerful to handle this difficulty. Reference [12, 13] represents the application of fuzzy logic to control UPFC and STATCOM in a single machine infinite bus.

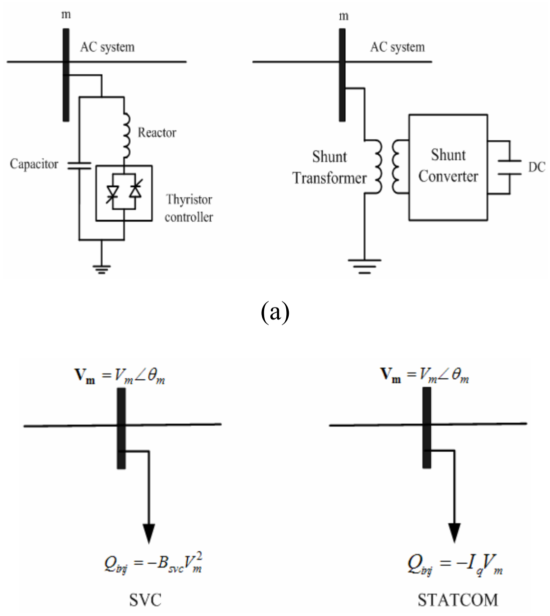
Traditional tool for evaluating transient stability of power system is called the momentary mode. In this mode, power system and the FACTS devices are modeled in detail. The examples of working in this mode are PSS/E, Eurostag, and PSCAD, EMTP/EMTDC. However, implementation of new components, especially soft computing ones, within these packages can be very difficult and it is very time consuming for evaluating transient stability of the multimachine power system [14-16].

This paper applies the concepts of Lyapunov energy function and fuzzy logic to determine control strategy of the shunt FACTS devices for enhancing stability of multimachine power system. Due to the drawbacks of the momentary mode, this paper aims to develop computation method of power system equipped with the shunt FACTS devices. The outline of this paper is as follows: Section 2 reviews the shunt FACTS devices model, power system model and Lyapunov energy function. Section 3 proposes the shunt FACTS devices control strategy based on Lyapunov energy function and fuzzy logic control. Section 4 presents the method of simulations. Section 5 investigates the proposed control strategy.

2. Mathematical Model and Lyapunov Energy Function

2.1 Model of shunt FACTS devices

Fig. 1 shows the configurations and the model of the shunt FACTS devices equipped at bus m. The Static Var Compensator (SVC) consists of the fixed capacitor with a thyristor controlled reactor whereas the Static Synchronous Compensator (STATCOM) consists of a solid-state voltage source converter (VSC) with GTO thyristor switches or other high performances of semi-conductor switches, a DC capacitor, and transformer as shown in Fig. 1(a). They are used for exchanging reactive power from power system. The load injections of both the SVC and STATCOM are shown in Fig. 1(b).



(a)

(b)

Fig. 1. Shunt FACTS devices: (a) Configurations; (b) Reactive power load injection models.

The capacitive power load injection model of the SVC is given by

$$Q_{inj} = -B_{svc}V_m^2 \tag{1}$$

The capacitive power load injection model of the STATCOM is given by

$$Q_{inj} = -V_m I_q \tag{2}$$

The degree and the direction of control reactive power injections are determined by variable susceptance (B_{svc}) on the SVC or shunt current injection (I_q) on the STATCOM, respectively. When the controlled parameters (B_{svc} , I_q) are positive, they supply reactive power into the system; when the controlled parameters are negative, they absorb reactive power from the system.

2.2 Power system model

A single line diagram of a multimachine power system consisting n_g generators is shown in Fig. 2(a). Fig. 2(b) is shows the equivalent circuit of Fig. 2(a). Here the E'_{qi} and x'_{di} are quadrature axis voltage behind transient reactance and direct axis transient synchronous reactance of the i-th machine, respectively. The load bus in transmission line and direct axis transient synchronous reactance can be represented by reduced admittance matrix of all physical load buses ($\mathbf{Y}_{bus}^{red}$) as shown in Fig. 2(c). The dynamic equations of multimachine system are given by

$$\dot{\delta}_i = \omega_i \tag{3}$$

$$\dot{\omega}_i = \frac{1}{M_i}[P_{mi} - P_{ei} - D_i\omega_i], \quad i=1,2\ldots n_g \tag{4}$$

$$P_{ei} = \sum_{j=1;\neq i}^{ng} (F_{ij}\sin\theta_{ij} + H_{ij}\cos\theta_{ij}) \tag{5}$$

Here $\theta_{ij} = (\theta_i - \theta_j)$, $F_{ij} = E'_{qi}E'_{qj}B_{ij}$, $H_{ij} = E'_{qi}E'_{qj}G_{ij}$ and $\mathbf{Y}_{bus}^{red} = G + jB$

where

δ_i : machine angle of the i-th machine
ω_i : machine speed of the i-th machine
M_i : moment of inertia of the i-th machine
P_{mi} : input mechanical power of the i-th machine
P_{ei} : output electrical power of the i-th machine
D_i : damping constant of the i-th machine
G : conductance
B : susceptance

In the analysis of the rotor angle stability, the focus of attention is on the behavior of the machine angles with respect to each other. To clearly distinguish between the forces that accelerate the whole system and those that tend to separate the system into different parts. The dynamic equations as given in (3) and (4) are transformed into Center Of Inertia (COI). The dynamic equations of multimachine system in COI are given by [11, 17]

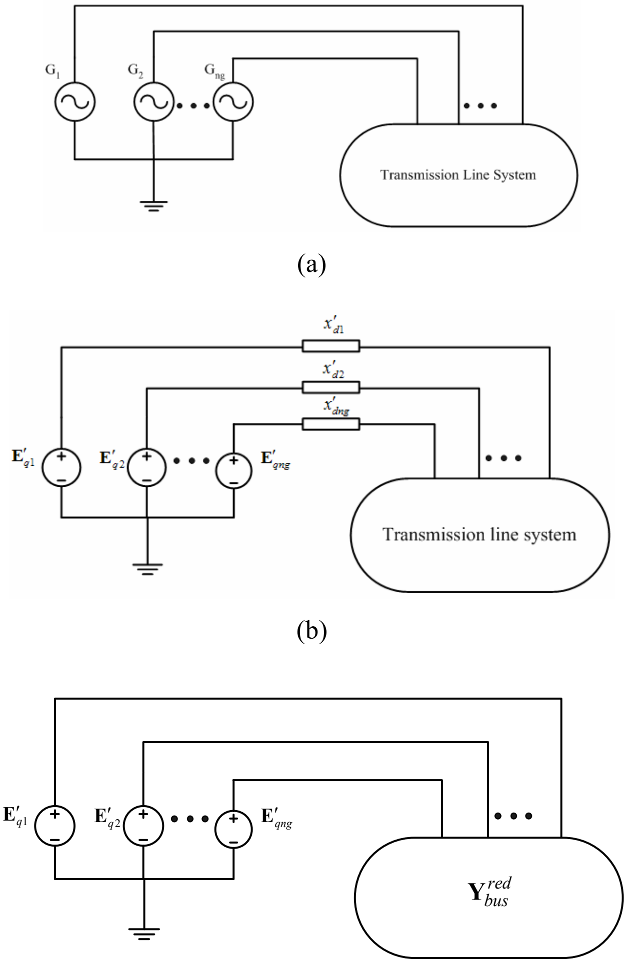
$$\dot{\tilde{\delta}}_i = \tilde{\omega}_i \tag{6}$$

$$\dot{\tilde{\omega}}_i = \frac{1}{M_i}[P_i - P_{ei} - \frac{M_i}{M_T}P_{COI} - D_i\tilde{\omega}_i] \tag{7}$$

$$P_i = P_{mi} - E_i'^2 G_{ii} \tag{8}$$

$$P_{COI} = \sum_{i=1}^{ng}(P_{mi} - F_{ij}) - 2\sum_{i=1}^{ng}\sum_{j=i+1}^{ng} H_{ij}\cos\theta_{ij} \tag{9}$$

$$M_T = \sum_{i=1}^{ng} M_i \tag{10}$$



(a)

(b)

(c)

Fig. 2. Multimachine power system: (a) Single line diagram; (b) Equivalent circuit; (c) reduced admittance matrix.

where,

$\tilde{\delta}_i$: machine angle in COI of the i-th machine
$\tilde{\omega}_i$: machine speed in COI of the i-th machine
M_T : summation of moment inertia

The first objective in this paper is to derive control strategy of the shunt FACTS devices in the multimachine power system. For the simplicity of analysis, let the bus m is the location of the shunt FACTS devices. Consider a sample load bus at bus m as shown in Fig. 3. Here $\mathbf{Y}_{bus}^{par}$ is the reduced admittance matrix of all physical load buses except bus m. The summation of the complex power injection ($\boldsymbol{S}_{F\mathrm{m}}$) and the complex power load ($\boldsymbol{S}_{L\mathrm{m}}$) are equal to zero.

The active power balance is given by

$$P_{Fm} + P_{Lm} = 0 \tag{11}$$

And the reactive power balance is given by

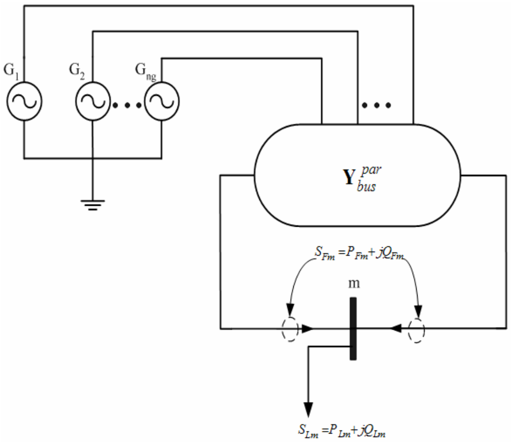


Fig. 3. The complex power balance of bus m.

$$Q_{Fm}+Q_{Lm}=0 \tag{12}$$

The summation of complex power balance as given in (11) and (12) is the fact happening in all load buses of power system.

2.3 Lyapunov energy function

The energy function of the power system (E) is written by [17]

$$E=\frac{1}{2}\sum_{i=1}^{ng}M_i\tilde{\omega}_i^2+\sum_{i=ng+1}^{ng+nb}\int\frac{Q_{Li}}{V_i}dV_i+\sum_{i=ng+1}^{ng+nb}P_{Li}\tilde{\theta}_i-\sum_{i=1}^{ng}P_{mi}\tilde{\theta}_i-\frac{1}{2}\sum_{i=1}^{ng+nb}\sum_{j=1}B_{mn}V_iV_j\cos\tilde{\theta}_{ij}+E_c \tag{13}$$

Here

E_c is constant energy at equilibrium point.

V, θ and n_b are the line voltage magnitude, line voltage angle and number of non-generator bus, respectively.

The derivative of energy function ($\dot{E}$) is given by

$$\dot{E}=\frac{dE}{dt}=\sum_{i=1}^{ng}D_i\tilde{\omega}_i^2+\sum\left(P_{Fng+i}+P_{Lng+i}\right)\dot{\tilde{\theta}}_{ng+i}+\sum\left(Q_{Fng+i}+Q_{Lng+i}\right)\frac{\dot{V}_{ng+i}}{V_{ng+i}} \tag{14}$$

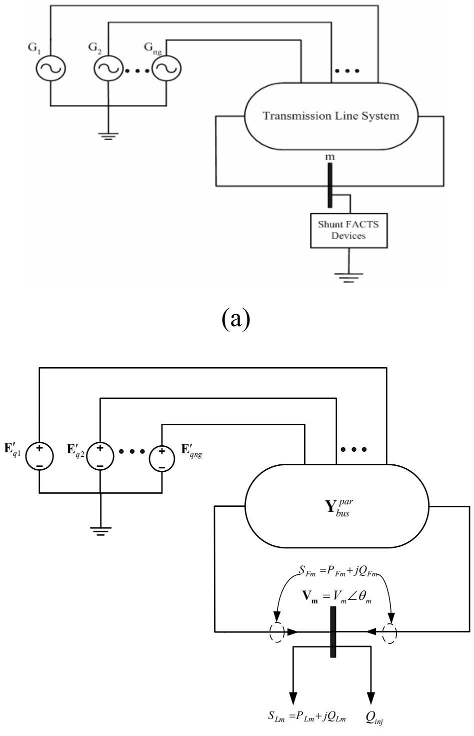
From (11) and (12), the second and the third term of (14) are zero. Thus the derivative of energy function is

$$\dot{E}=\sum_{i=1}^{ng}D_i\tilde{\omega}_i^2 \tag{15}$$

In the second method of Lyapunov, the energy function (E) is in positive and time derivative of energy ($\dot{E}$) is in semi-negative definite as can be seen in (13)-(15). This paper will apply this concept to derive control strategy of SVC and STATCOM.

3. The Proposed Control Strategy

This Section will first derive control strategy of the shunt FACTS devices in the Multimachine power system by using the Lyapunov energy function. Then the concept of the fuzzy logic control will be applied to determine the control rule of the shunt FACTS devices.



(a)

(b)

Fig. 4. Multimachine system with the shunt FACTS devices: (a) configuration; (b) equivalent circuit.

Fig. 4(a) shows the multimachine power system equipped with the shunt FACTS devices. Fig. 4(b) shows its equivalent circuit. Consider the complex power balance at bus m. It can be seen from the Fig. 4(b) that the shunt FACTS devices don't affect on the active power balance equation as given in (11). However, the shunt FACTS devices affect on the reactive power balance equation as given in (12) because of the additional component of a reactive power injection from a shunt FACTS device (Q_{inj}). Our objective is to control the shunt FACTS devices in the way that satisfies the concepts of the second method of Lyapunov. By observing the third term of (14), the time derivative of the energy at bus m can be written by

$$(Q_{Fm}+Q_{Lm})\frac{\dot{V}_m}{V_m} = -\frac{Q_{inj}}{V_m}\dot{V}_m \tag{16}$$

The right hand side of (16) is called the additional component of derivative of potential energy from the shunt FACTS device. Based on the second method of Lyapunov, the (16) can be expressed by

$$-\frac{Q_{inj}}{V_m}\dot{V}_m \le 0 \tag{17}$$

From (1) and (17), the proposed control strategy of the SVC based on Lyapunov energy function is given by

$$B_{svc}V_m\dot{V}_m \le 0 \tag{18}$$

From (2) and (17), the proposed control strategy of the STATCOM based on Lyapunov energy function is given by

$$I_q\dot{V}_m \le 0 \tag{19}$$

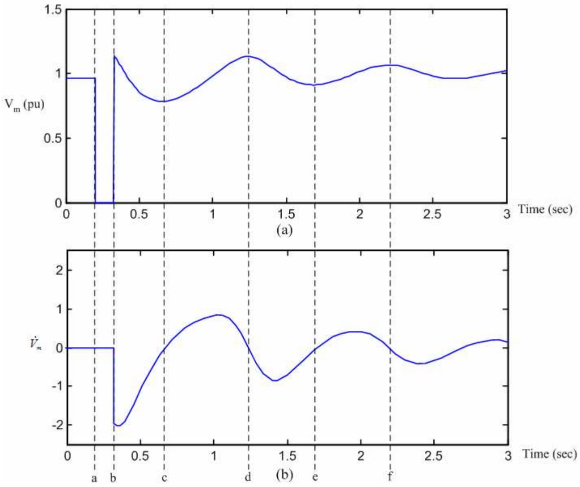
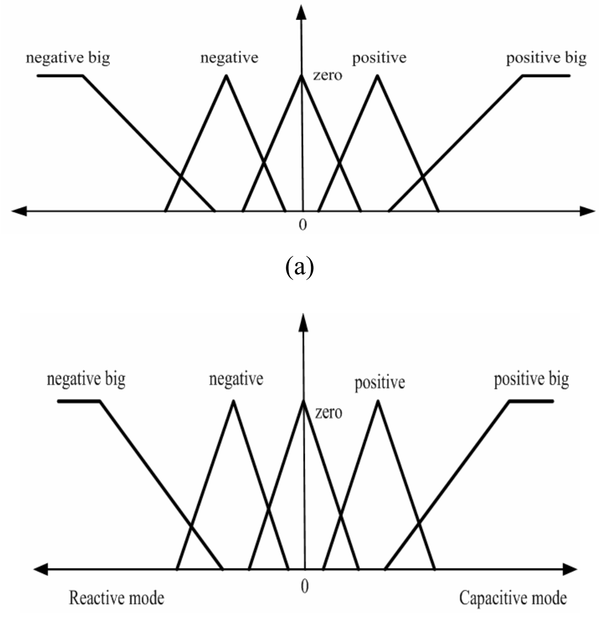


Fig. 5. Variation curve of the faulted system: (a) V_m; (b) $\dot{V}_m$.

Consider the variation of the line voltage (V_m) and the derivative of the line voltage ($\dot{V}_m$) of the faulted system as shown in Fig. 5(a) and Fig. 5(b), respectively. The system is subject to the disturbance during *a* to *b* period. After the disturbance is cleared, the line voltage is continuously oscillation. It can be noted that the value of the V_m is always in the positive sign whereas the value and the sign of the $\dot{V}_m$ are changed. Thus the Lyapunov stability criterion of the system equipped with shunt FACTS devices as given in (18) and (19) depends on the sign of the control parameter of shunt FACTS devices (B_{svc} or I_q) and $\dot{V}_m$. From (18) and (19), when the $\dot{V}_m$ is in negative sign ($\dot{V}_m$<0), the parameter of the shunt FACTS devices (B_{svc} or I_q) should be controlled in positive sign, shunt FACTS devices supplies reactive power to the system; when the $\dot{V}_m$ is in positive sign ($\dot{V}_m$>0), the parameter of the shunt FACTS devices (B_{svc} or I_q) should be controlled in negative sign, the shunt FACTS devices absorbs reactive power from the system.



(a)

(b)

Fig. 6. Membership functions: (a) input ($\dot{V}_m$); (b) controlled parameter (B_{svc} or I_q).

The control strategy of the shunt FACTS devices based on the Lyapunov's method is to maintain the negative sign of (18) and (19). This concept doesn't provide the justification of controlling the amplitude of B_{svc} or I_q such as big or small. Thus this paper further applies the concept of the fuzzy logic control. The control rule based on fuzzy logic contains all possible combinations of the input and suitable controlled parameter for each of them [18]. The $\dot{V}_m$ derived from the concept of Lyapunov stability criterion is the input and B_{svc} or I_q is the controlled parameter. It is noted that the amplitude of the $\dot{V}_m$ related to the size of the oscillation as can be seen in Fig. 5. Fig. 6(a) and Fig. 6(b) show the membership functions of the input and controlled parameter. They consist of the negative big, negative, zero, positive and positive big, respectively. The proposed rules are defined as follows:

(a) If $\dot{V}_m$ is negative big then B_{svc} or I_q is positive big.
(b) If $\dot{V}_m$ is negative then B_{svc} or I_q is positive.
(c) If $\dot{V}_m$ is zero then B_{svc} or I_q is zero.
(d) If $\dot{V}_m$ is positive then B_{svc} or I_q is negative.
(f) If $\dot{V}_m$ is positive big then B_{svc} or I_q is negative big.

4. Algorithm

This Section will present the evaluation method for investigating the proposed control strategy of the shunt FACTS devices on transient stability of the multimachine power system. The computation steps of the transient response of power system equipped with the shunt FACTS devices are given in the following:

(a) Perform the reduced admittance matrix of all physical load buses except bus m ($\mathbf{Y}_{bus}^{par}$). Here the constant load at bus m ($\mathbf{S}_{Lm}$) is converted into constant admittance and add in $\mathbf{Y}_{bus}^{par}$.

(b) Evaluate the V_m as given by

$$\begin{bmatrix} \mathbf{I}_{g1} \\ \mathbf{I}_{g2} \\ \vdots \\ \mathbf{I}_{gng} \\ 0 \end{bmatrix} = \begin{bmatrix} & & \\ & \mathbf{Y}_{bus}^{par} & \\ & & \end{bmatrix} \begin{bmatrix} \mathbf{E}'_{q1} \\ \mathbf{E}'_{q2} \\ \vdots \\ \mathbf{E}'_{qng} \\ \mathbf{V}_m \end{bmatrix} \qquad (20)$$

Here $\boldsymbol{I}_{gng}$ is the current injection of machine of the i-th machine

(c) Evaluate the B_{svc} or I_q based on the proposed control strategy

(d) Calculate the susceptance equivalent of the shunt FACTS devices ($\boldsymbol{y}_{mi}$) as shown in Fig. 7 and given by

$$\mathbf{y}_{mi} = \begin{cases} \pm jB_{svc} \;\; for\ SVC \\ \pm j\dfrac{\mathrm{I}_q}{\mathrm{V}_m} \;\; for\ STATCOM \end{cases} \qquad (21)$$

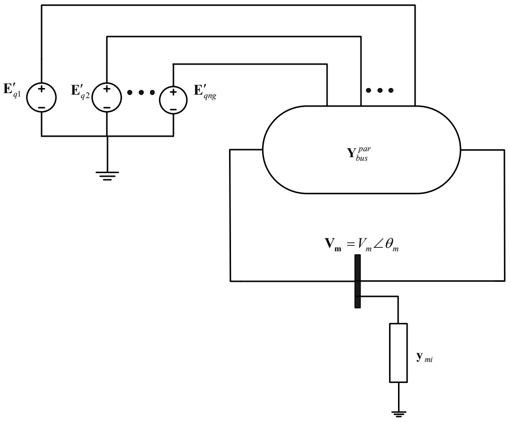


Fig. 7. Equivalent circuit of multimachine power system equipped with the shunt FACTS devices represented by susceptance $\boldsymbol{y}_{mi}$.

(e) Incorporate the $\boldsymbol{y}_{mi}$ into the $\mathbf{Y}_{bus}^{par}$ as shown in Fig. 7.

(f) Perform the reduced admittance matrix of all physical load buses ($\mathbf{Y}_{bus}^{red}$).

(g) Evaluate the machine angles and speeds from (6) and (7).

(h) Repeat steps b)-g) until the maximum period of investigation is reached.

5. Results and Discussion

The proposed control strategy of the shunt FACTS devices is tested on the new England power system. Its single line diagram is shown in Fig. 8. The detail of system data and initial operating point are given in [17]. First consider a 3-phase fault occurred near bus 29 and it is cleared by opening the line 26-29 (between bus 26 and bus 29). Fig. 9(a) and Fig. 9(b) show the rotor angles in Center Of Inertia (COI) of all generators in the system with the fault clearing time (t_{cl}) =90 and 91 msec, respectively. It can be observed from Fig. 9 that with this fault and without FACTS devices, the generator 9 have the most severe disturbance and the critical clearing time (CCT) of the system is around 90-91 msec. With t_{cl}=91 msec, the system is considered as unstable. First a SVC is arbitrary equipped at bus 27. The system can be considered as stable with the rating of SVC (B_{svc}^{R}) ≥ 0.03 pu. With this fault and B_{svc}^{R} = 0.03 pu, the maximum rotor angle of generator 9 is around 116.97 degree as shown in Fig. 10. The simulations show that with this fault the suitable location of the shunt FACTS devices for improving CCT is the bus 29 or bus 38. Table 1 summarizes the CCT of the system with various ratings of a SVC (B_{svc}^{R}) and a STATCOM (I_q^R) equipped at bus 29. The simulations have shown that the capability of the shunt FACTS devices for enhancing transient stability of power system depends on their ratings, locations and fault occurrence. If the fault occurs near bus 23 and it is cleared by opening the line 23-24, the best location of shunt FACTS for enhancing transient stability of the system would not be bus 29 as can be seen in Fig. 11. The first maximum ($\tilde{\delta}_{\max}$) and minimum swing curve ($\tilde{\delta}_{\min}$) of the system with SVC (B_{svc}^{R} = 1 pu) at bus 29 are 115.03 and -44.12, respectively whereas that of the SVC at bus 21 are 113.24 and -42.20, respectively. Thus the better location of the SVC with the new fault occurrence should be bus 21.

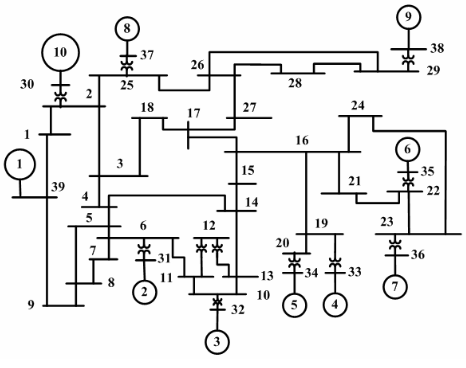
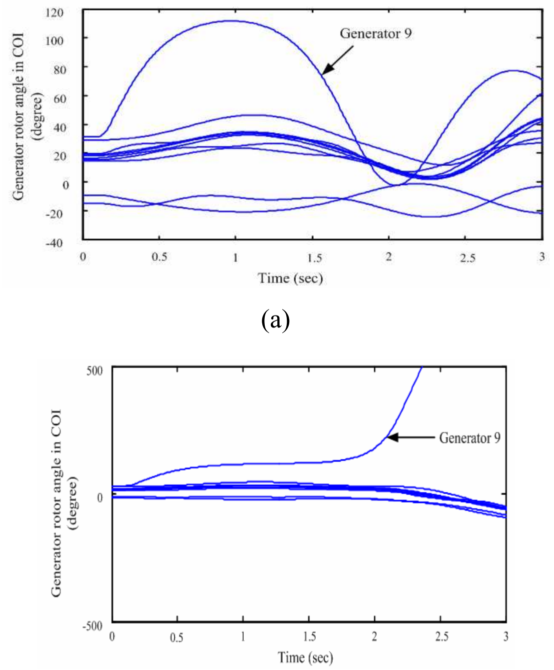


Fig. 8. Single line diagram of the new England system.



(a)

(b)

Fig. 9. Generator rotor angle in COI of the new England system without the shunt FACTS devices and with fault near bus 29: (a) t_{cl}=90 msec; (b) t_{cl}=91 msec.

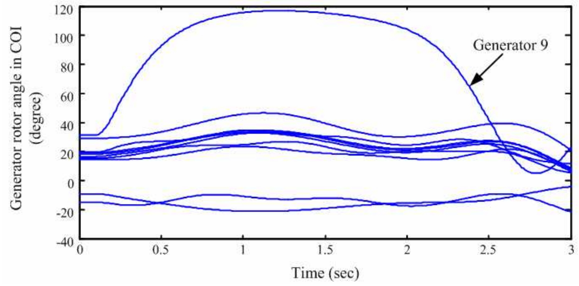
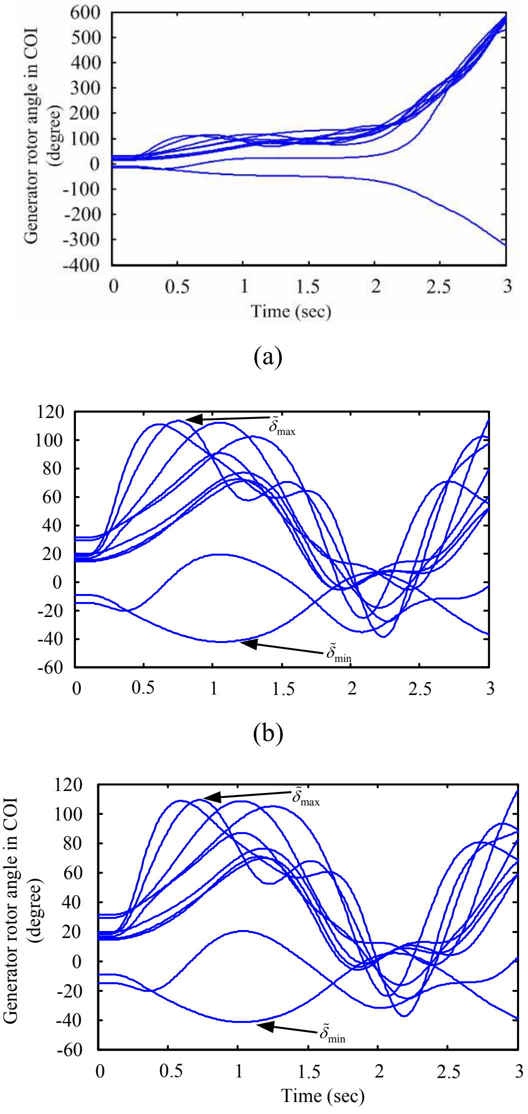


Fig. 10. Generator rotor angle in COI of the new England system with the rating of SVC (B_{svc}^{R}) = 0.03 pu for t_{cl}=91 msec.

Table 1. The CCT of the system for the fault near bus 29 with various rating of a shunt FACTS devices equipped at bus 29

Shunt FACTS devices	B_{svc}^{R} (pu)	I_{q}^{R} (pu)	CCT (msec)
SVC	0.2	-	94-95
	0.4	-	98-99
	0.6	-	102-103
	0.8	-	105-106
	1.0	-	108-109
STATCOM	-	0.2	96-97
	-	0.4	100-101
	-	0.6	106-107
	-	0.8	109-110
	-	1.0	113-114



(a)

(b)

(c)

Fig. 11. Generator rotor angle in COI of the new England system with fault near bus 23 and t_{cl}=191 msec: (a) without FACTS devices; (b) with a SVC at bus 29; (c) with a SVC at bus 21.

It may be mentioned here that the shunt FACTS devices have been applied for controlling the line voltage in steady state and improving dynamic performance. The primary purpose of the shunt FACTS devices is to control voltage at steady state and it is also applied for enhancing the dynamic performance. To fully utilization of shunt FACTS devices, the applications of the shunt FACTS devices both steady state and dynamic state should be applied and considered. Suppose a STATCOM is installed at bus 15 to regulate the voltage at steady state. With the previous fault condition, the STATCOM (I_{q}^{R} =1 pu) based on the presented control strategy can improve transient stability as can be seen in Fig. 12. The simulation results indicate that with the presented control strategy, suitable ratings and location, the shunt FACTS devices can improve transient stability of the multimachine system.

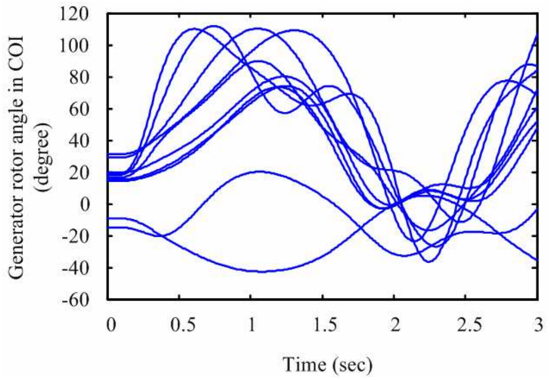


Fig. 12. Generator rotor angle in COI of the new England system with fault near bus 23, t_{cl}=191 msec and with a STATCOM at bus 15.

6. Conclusion

This paper presented the control strategy of the shunt FACTS devices for improving transient stability of multimachine power system and presented the method of investigating the effects of shunt FACTS devices on transient stability of multimachine power system. The concept of the Lyapunov energy function is applied to derive the nonlinear control of shunt FACTS devices. It was found that the time derivative of line voltage in the system equipped with shunt FACTS devices is satisfied the concept of the Lyapunov energy function and is the locally measurable signal. The fuzzy logic control was further applied to suitable control for various sizes of disturbances. This paper presented the mathematical model of multimachine power system equipped with shunt FACTS devices. It can be applied to investigate the transient stability improvement of power system. The successive model of shunt FACTS devices is represented by a variable susceptance and is incorporated into power system. The simulation results were tested on the new England power system. It was found from the simulation results that the presented control strategy can improve transient stability of multimachine systems. The capability of improvement depends on their ratings and locations.

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