STATCOM control strategy based on Lyapunov energy function and fuzzy logic control for improving transient stability of multimachine power system

PRECHANON KUMKRATUG
Electrical Engineering Dept.
Kasetsart University at Si Racha Campus
Si Racha, Chonburi
THAILAND
pc475601@gmail.com

Abstract: - This paper proposes a nonlinear control strategy of a Static Synchronous Compensator (STATCOM) for improving transient stability of multimachine power system. The large scale and the complexity of modern power system require the nonlinear control strategy of the STATCOM. The concept of Lyapunov energy function is applied to derive the nonlinear control strategy and the proposed control based on Lyapunov energy function is locally measurable signal. The fuzzy logic control is also applied to overcome the uncertainties of various disturbances in the multimachine power system. This paper presents the method of investigating the transient stability of the multimachine power system equipped with the STATCOM. The proposed control strategy and the method of simulation are tested on the Kundur's inter-area power system and new England power system. It is found that the proposed nonlinear control strategy can improve transient stability of the multimachine power system.

Key-Words: - Flexible ac transmission system, power system, static synchronous compensation (STACOM), , fuzzy logic control, transient stability, Lyapunov, nonlinear control.

1 Introduction

In the early days, power system used only radial lines to supply power to a specified load center. Nowadays, 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.

The power system stability is concerned with the behaviour 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 behaviour 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 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 Synchronous Compensator (STATCOM) is considered in the second group of FACTS controller used for reactive power compensation to overcome the technical limitations and high cost of the first group of FACTS controller such as SVC. The development of STATCOM is based on the use of Gate-Turn-Off (GTO) thyristors, which can electrically mimic reactor or capacitor by injecting a current in quadrature with line voltage.

Currently, power system stability is a concerned issue of power system engineers due to the widespread blackout of North America in 2003 and Europe. FACTS devices have been proposed to improve steady sate stability, dynamic stability and transient stability of power system [7-10].

STATCOM has capability of controlling the line voltage in the power system not only at steady state but also dynamic state. The applications of the STATCOM for improving transient stability were reported in [10-11]. Most of previous researches used the remote signal such as generator speed deviation. However, the optimal placement of a STATCOM in a simple system is at the midpoint of power system [12]. Thus, in multimachine power system, the remote signal may not be practical.

Modern power system is very large scale and complex network. The disturbance in modern power system causes in nonlinear response and then the control strategy of FACTS devices should be nonlinear control. The second method of the Lyapunov or called the Lyapunov energy function is the concept of the nonlinear system. The successful applications of Lypunov energy function to control a SVC, TCSC, TCPST, SSSC and series part of UPFC for enhancing stability of power system were reported in [13-15].

The uncertainties of various disturbances in power system provide the difficulty of controlling the FACT devices. The fuzzy logic control is very powerful method to handle the uncertainties in the controlled nonlinear system. The applications of the fuzzy logic to control FACTS devices were reported in [16-17].

It is well known that the time domain simulation method is widely used for simulating power system with/without FACTS devices. There are two possible ways to carry out the time domain. The first method is referred to as the momentary mode. In this mode, electric power system including FACTS devices has to be modeled in detailed [17]. Traditional tools for momentary mode such as EMTP, PSCAD and EMTDC require coding in conventional programming languages and are optimized for speed and efficiency. However, implementation of new components, especially soft computing ones, within these packages can be very difficult and error prone [18-19]. The second approach is called stability mode. In this mode power system and FACTS devices are modeled as single phase, and electric quantities are represented with their effective values. Since sine quantities are not dealt with, the integration step is much shorter and modeling is simpler and the simulation procedure is faster than in the momentary mode. In this mode, the suitable mathematical models of power system and FACTS devices are required.

This paper applies the concepts of Lyapunov energy function and fuzzy logic to determine control strategy of a STATCOM for enhancing stability of multimachine power system. Due to the drawbacks of the momentary method, this paper aims to develop computation method of the power system with a STATCOM in stability mode. The outline of this paper is as follows: Section 2 reviews the power system model and Lyapunov energy function. Section 3 describes the principle operating of the STATCOM and presents its mathematical model. Section 4 proposes the STATCOM control strategy based on Lyapunov energy function and fuzzy logic control. Section 5 investigates the proposed method by testing on multimachine power system.

2 Power system model and Lyapunov energy function

This Section will briefly review the power system model and the Lyapunov energy function.

2.1 Power system model

A single line diagram of a multimachine power system consisting n_g generators is shown in Fig. 1a.

Fig. 1b shows the equivalent circuit of Fig. 1a. Here the E'_{qi} and x'_{di} are the 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 the direct axis transient synchronous reactance can be represented by the reduced admittance matrix of all physical load buses ($\mathbf{Y}_{bus}^{red}$) as shown in Fig. 1c. The dynamic equations of the multimachine power system in the Center Of Inertia (COI) are given by [20]

$$\dot{\tilde{\delta}}_i = \tilde{\omega}_i \tag{1}$$

$$\dot{\tilde{\omega}}_i = \frac{1}{M_i}[P_i - P_{ei} - \frac{M_i}{M_T}P_{COI} - D_i\tilde{\omega}_i], i=1,2\ldots n_g \tag{2}$$

$$P_i = P_{mi} - E_i'^2 G_{ii} \tag{3}$$

$$P_{ei} = \sum_{j=1;\neq i}^{ng}(F_{ij}\sin\theta_{ij} + H_{ij}\cos\theta_{ij}) \tag{4}$$

$$P_{COI} = \sum_{i=1}^{ng}(P_{mi} - F_{ij}) - 2\sum_{i=1}^{ng}\sum_{j=i+1}^{ng} H_{ij}\cos\theta_{ij} \tag{5}$$

$$M_T = \sum_{i=1}^{ng} M_i \tag{6}$$

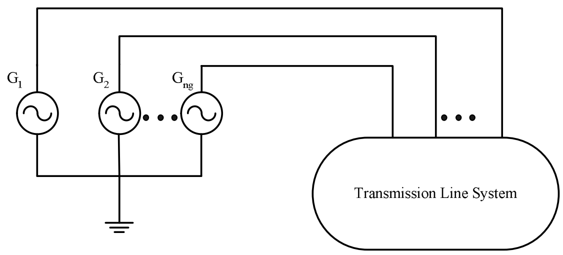
Here $\theta_{ij} = (\theta_i - \theta_j)$, $F_{ij} = E'_{qi}E'_{qj}B_{ij}$,

$H_{ij} = E'_{qi}E'_{qj}G_{ij}$ and $\mathbf{Y}_{bus}^{red} = G + jB$

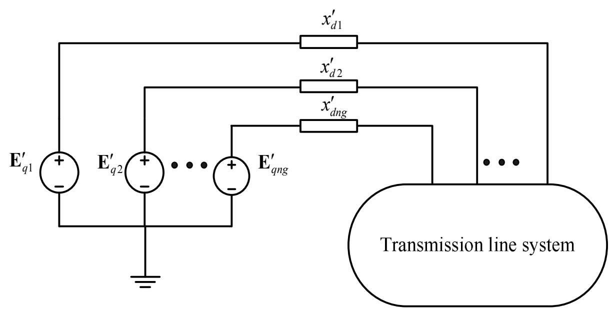
where,

$\tilde{\delta}_i$: machine angle of the *i*-th machine
$\tilde{\omega}_i$: machine speed of the *i*-th machine
D_i : damping constant 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
M_T : summation of moment inertia
$\mathbf{Y}_{bus}^{red}$: reduced admittance matrix of all physical load buses
G : conductance
B : susceptance
ng : number of generator

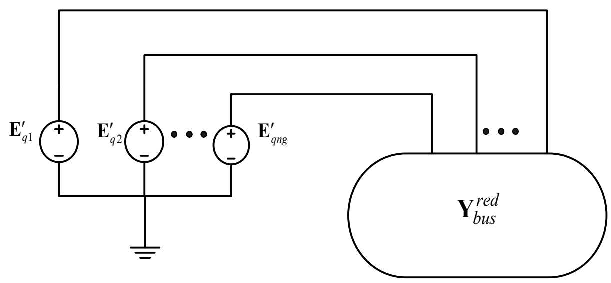
The first objective in this paper is to derive control strategy of a STATCOM in the multimachine power system. For the simplicity of analysis, let the bus *m* is the location of a STATCOM. Consider a sample load bus at bus *m* as shown in Fig. 2. Here $\mathbf{Y}_{bus}^{par}$ is the reduced admittance matrix of all physical load buses except bus *m*. The summation of the complex power injection ($\boldsymbol{S}_{\boldsymbol{F}\mathrm{m}}$) and the complex power load ($\boldsymbol{S}_{\boldsymbol{L}\mathrm{m}}$) are equal to zero.



a) Single line diagram



b) Equivalent circuit



c) Reduced admittance matrix

Fig.1. Multimachine power system: a) Single line diagram b) Equivalent circuit c) Reduced admittance matrix

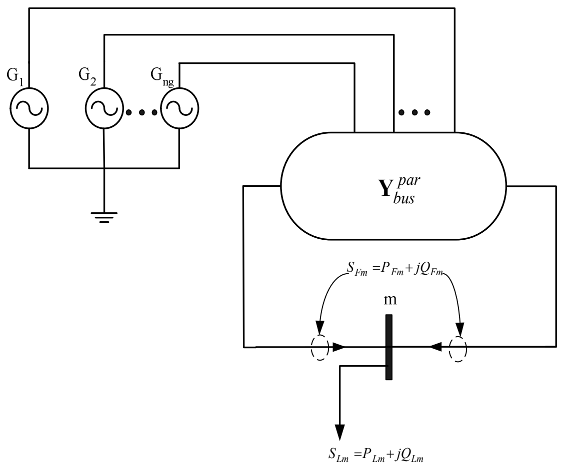


Fig.2. The complex power balance of bus m

The active power balance at bus m is given by

$$P_{Fm} + P_{Lm} = 0 \tag{7}$$

And the reactive power balance at bus m is given by

$$Q_{Fm} + Q_{Lm} = 0 \tag{8}$$

The summations of complex power balance as given in (7) and (8) are the fact happening in all load buses of power system.

2.2 Lyapunov energy function

The energy function of the power system (E) is written by [20]

$$E = E_k + E_p + E_C \tag{9}$$

Here E_k is the kinetic energy, E_p is the potential energy and E_c is the constant energy at the equilibrium point.
The kinetic energy (E_k) is given by

$$E_k = \frac{1}{2}\sum_{i=1}^{ng} M_i \tilde{\omega}_i^2 \tag{10}$$

The potential energy (E_p) is given by

$$E_p = \sum_{i=ng+1}^{ng+nb} \int \frac{Q_{Li}}{V_i} dV_i + \sum_{i=ng+1}^{ng+nb} P_{Li}\tilde{\theta}_i -$$

$$\sum_{i=1}^{ng} P_{mi}\tilde{\theta}_i - \frac{1}{2}\sum_{i=1}^{ng+nb}\sum_{j=1} B_{mn}V_iV_j \cos\tilde{\theta}_{ij} \tag{11}$$

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

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

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

$$\sum \left(Q_{Fng+i} + Q_{Lng+i}\right)\frac{\dot{V}_{ng+i}}{V_{ng+i}} \tag{12}$$

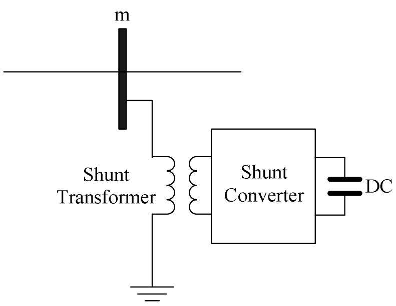
From (7) and (8), the second and the third bracket of (12) are zero. Thus the time derivative of energy function is

$$\dot{E} = \sum_{i=1}^{ng} D_i \tilde{\omega}_i^2 \tag{13}$$

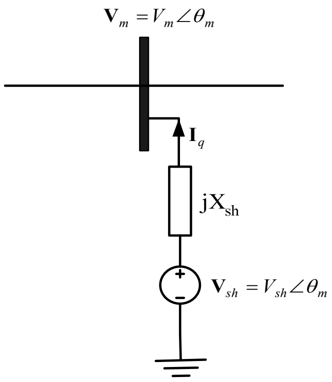
In the second method of Lyapunov, the energy function (E) is in positive and the time derivative of the energy function ($\dot{E}$) is in the semi-negative definite as can be seen in (9)-(13). This paper will apply this concept to derive control strategy of STATCOM.

3 STATCOM and its model

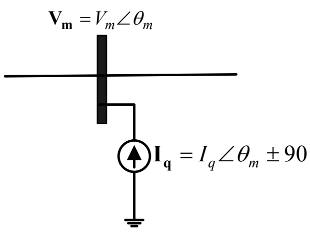
Static Synchronous Compensator (STATCOM) is used for reactive or capacitive power compensation to power system. The STATCOM consists of a solid-state voltage source converter (VSC) with GTO thyristor switches or other high performance of semi-conductor switches, a DC capacitor, and transformer as shown in Fig. 3a. The VSC converts the DC input voltage into a three-phase AC output voltage at fundamental frequency. The solid-state voltage source converter and transformer is in the shunt with power system are called the shunt converter and transformer, respectively. The basic diagram of a STATCOM placed at bus m in power system is shown in Fig. 3a. Fig. 3b shows the equivalent circuit of Fig. 3a where a STATCOM is represented by a synchronous voltage source ($\boldsymbol{V_{sh}}$) in series with a transformer leakage reactance (X_{sh}).



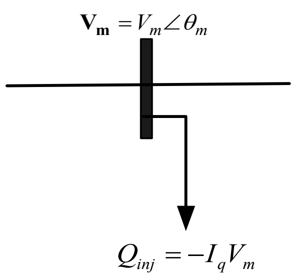
a) Configuration



b) Basic equivalent circuit



c) Shunt current injection



d) Reactive power load injection

Fig.3. Static Synchronous compensator (STATCOM): a) Configuration b) Basic equivalent circuit c) Shunt current injection model d) Reactive power load injection

The synchronous voltage source and the associated transformer leakage reactance can be represented by a shunt current source as shown in Fig. 3c. The shunt current ($\mathbf{I}_q$) is given by

$$\mathbf{I_q} = \frac{\mathbf{V}_{sh} - \mathbf{V}_m}{jX_{sh}} \tag{14}$$

The angle of synchronous voltage source is kept in phase with the line voltage. The magnitude of synchronous voltage source determines the direction of the shunt current ($\mathbf{I}_q$) and the direction of the reactive power compensation. When $V_{sh}>V_m$, the I_q flows into the bus m, the STATCOM supplies reactive power to power system and STATCOM is operated as capacitive mode; when $V_{sh}<V_m$, the I_q flows out the bus m, the STATCOM absorbs the reactive power from the power system and the STATCOM is operated as reactive mode.

$$\mathbf{I_q} = I_q \angle(\theta_m \pm 90) \tag{15}$$

With capacitive mode of the STATCOM operation, the capacitive power load injection model as shown in Fig. 3d is written by

$$Q_{inj} = \mathrm{Im}\left\{\mathbf{V_m}(-\mathbf{I_q})^*\right\}$$

$$= -V_m I_q \tag{16}$$

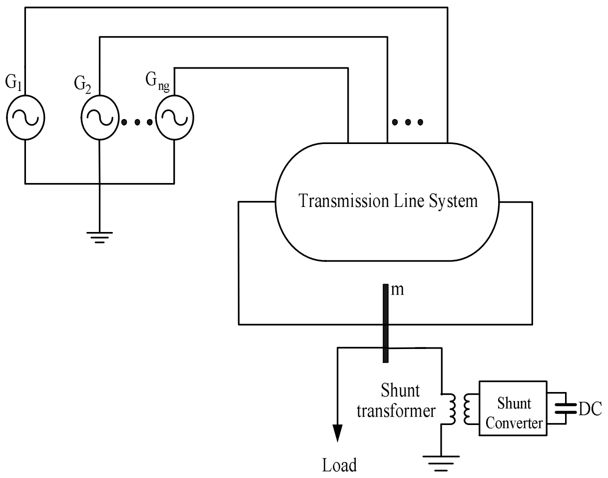
The degree and the direction of control reactive power injection are determined by I_q. It can be mentioned here that the STATCOM can improve stability of power system if it is carefully controlled.

4 The proposed control strategy

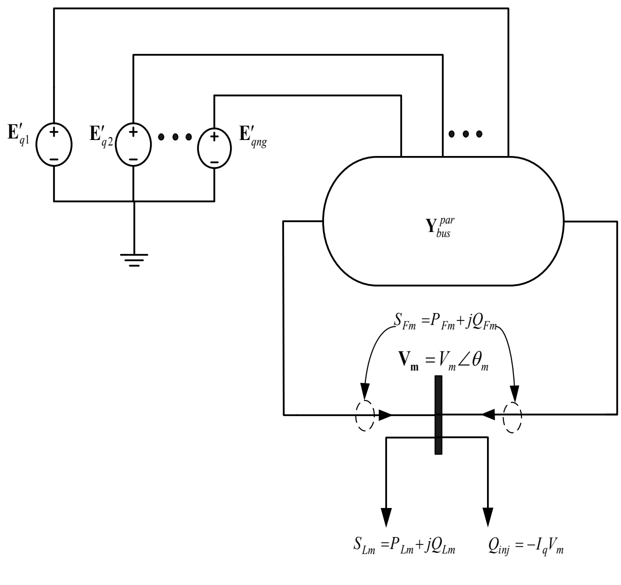
This Section will first derive control strategy of the STATCOM in the Multimachine power system by using Lyapunov energy function. Then the concept of fuzzy logic control will be applied to determine the control rule of the STATCOM.

4.1 Lyapunov control

Fig. 4a shows the multimachine power system equipped with a STATCOM. Fig. 4b shows its equivalent circuit. Consider the complex power balance at bus m. It can be seen from Fig. 4b that the STATCOM doesn't affect on the active power balance equation as given in (7). However, the STATCOM affects on reactive power balance equation as given in (8) because of the additional component of the reactive power injection Q_{inj}. Our objective is to control the STATCOM in the way that satisfies the concepts of the second method of Lyapunov.



a) Configuration



b) Equivalent circuit

Fig.4. Multimachine power system with a STATCOM: a) Configuration b) Equivalent circuit

By observing the third term of (12), the time derivative of the potential energy at bus m can be written by

$$(Q_{Fm} + Q_{Lm})\frac{\dot{V}_m}{V_m} = -\frac{Q_{inj}}{V_m}\dot{V}_m \tag{17}$$

The right hand side of (17) is called the additional component of the time derivative of the potential energy from a STATCOM. Based on the second method of Lyapunov, the (17) can be expressed by

$$-\frac{Q_{inj}}{V_m}\dot{V}_m \le 0 \tag{18}$$

From (16) and (18), the proposed control strategy of STATCOM based on Lyapunov energy function is given by

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

Consider the variation of the line voltage (V_m) and its time derivative ($\dot{V}_m$) of a faulted system as shown in Fig. 5a and Fig. 5b, respectively. The system is subject to a disturbance during *a* to *b* period. After the disturbance is cleared, the line voltage is continuously oscillation. From (19), when the time derivation of the line voltage at bus *m* is negative sign ($\dot{V}_m$<0), I_q is controlled in positive sign (I_q>0) and the STATCOM supplies reactive power or is called capacitive mode when the time derivation of line voltage at bus *m* is positive sign ($\dot{V}_m$>0), I_q is controlled in negative sign (I_q<0) and the STATCOM absorbs reactive power or is called reactive mode.

4.2 Fuzzy logic control

This paper will further apply the concept of the fuzzy logic to suitable control the STATCOM for various degrees of the line voltage oscillations. Consider Fig. 5a and Fig. 5b. The period from *b-c* to *c-d* may be called big oscillation with $\dot{V}_m$ negative big and positive big, respectively; whereas the period from *d-e* to *e-f* can be called oscillation with $\dot{V}_m$ negative and positive, respectively.

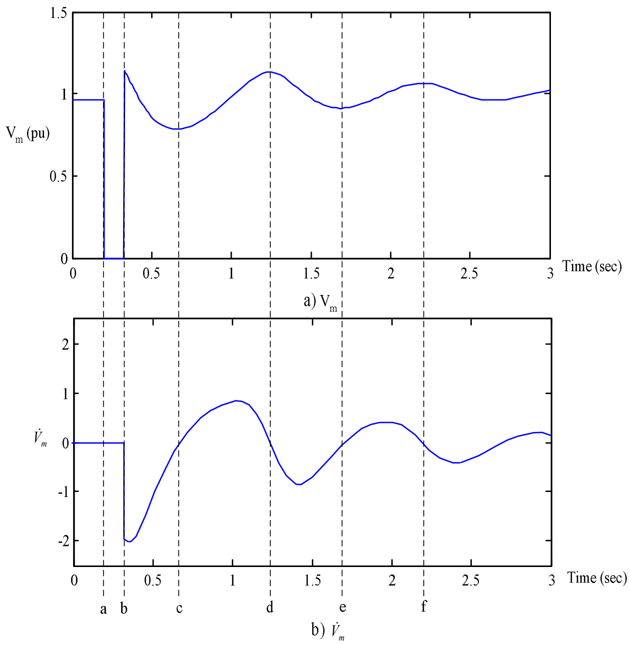
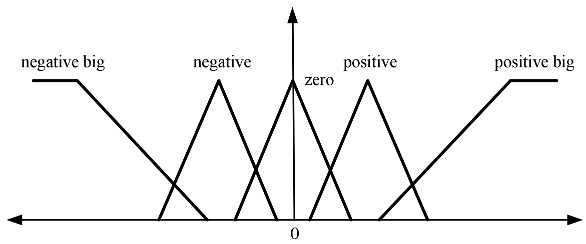
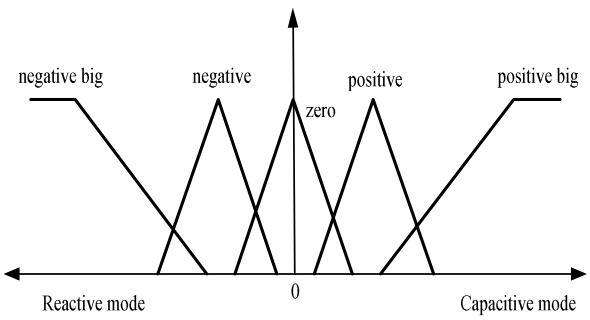


Fig.5. Variation curve of a faulted system: a) V_m b) $\dot{V}_m$



a) Output I_q



b) Output I_q

Fig.6. Membership functions: a) Input b) Output I_q

This paper uses the fuzzy rules based on human reasoning of Mamdani inference engine [22-23]. Fig. 6a and Fig.6b show the membership functions of the input ($\dot{V}_m$) and the output I_q. The rules are defined as follows:

a) If $\dot{V}_m$ is negative big then I_q is positive big.
b) If $\dot{V}_m$ is negative then I_q is positive.
c) If $\dot{V}_m$ is zero then I_q is zero.
d) If $\dot{V}_m$ is positive then I_q is negative.
e) If $\dot{V}_m$ is positive big then I_q is negative big.

5 Algorithm

This Section will present the method of evaluating the transient stability of the multimachine power system equipped with a STATCOM in stability mode. The computation steps of the transient response of power system equipped with a STATCOM 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 a constant admittance and add in $\mathbf{Y}_{bus}^{par}$.

b) Evaluate the V_m as given by

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

Here I_{gng} is the current injection of the i-th machine

c) Evaluate the I_q based on the proposed control strategy

d) Calculate the susceptance equivalent of a STATCOM (y_{mi}) by

$$\mathbf{y}_{mi} = \frac{\mathbf{I}_q}{\mathbf{V}_m} \tag{21}$$

f) Incorporate the y_{mi} into the $\mathbf{Y}_{bus}^{par}$ as shown in Fig. 7.

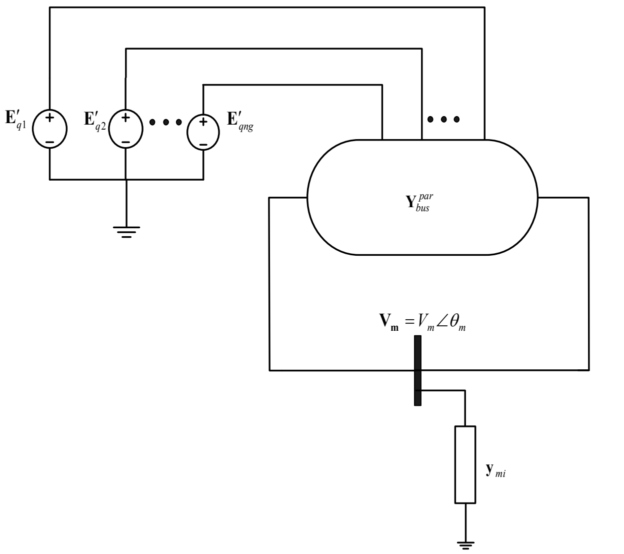


Fig.7. Equivalent circuit of multimachine power system equipped with a STATCOM represented by susceptance y_{mi}

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

g) Evaluate the machine angles and speeds from (1) and (2).

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

6 Simulations

The proposed control strategy of the STATCOM is tested on Kundur's inter-area power system and new England power system. Fig. 8 shows a single line diagram of Kundur's inter-area power system equipped with a STATCOM at bus 8. The detail of the system data and initial operating point are given in [21]. It is considered that a 3 phase fault appears near bus 8 at 100 msec and it is cleared at 140 msec. It can be seen from Fig. 9a that, without STATCOM (I_q=0) the different of generator rotor angle of area 1 (Generator 1 and Generator 2) and area 2 (Generator 3 and Generator 4) increases monotonically and thus the system can be considered as unstable. However, with a STATCOM, the system is considered as stable as can be seen in Fig. 9b.

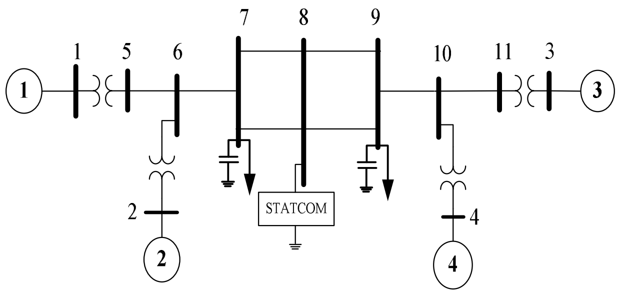
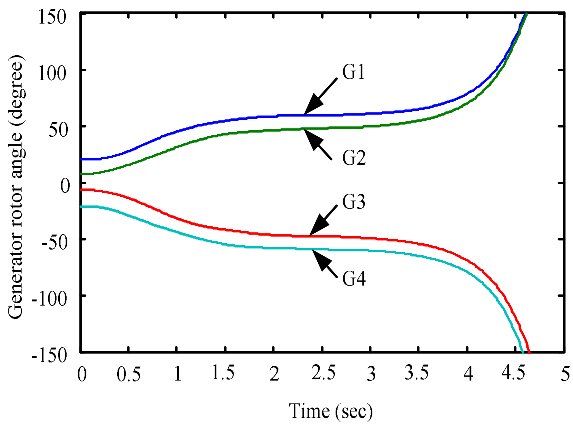
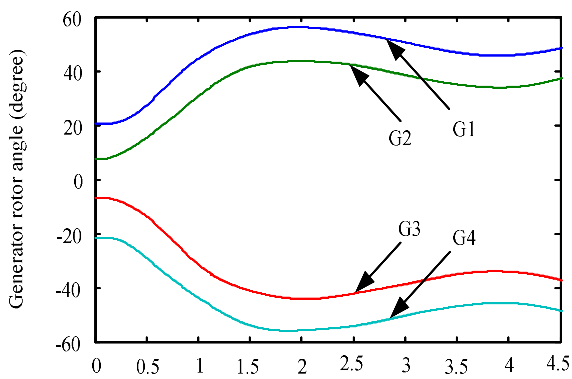


Fig.8. Single line diagram of Kundur's inter-area power system equipped with a STATCOM



a) Without STATCOM



b) With a STATCOM

Fig.9. Generator rotor angle of Kundur's inter-area system: a) Without STATCOM b) With a STATCOM

Fig. 10 shows the single line diagram of new England power system. The detail of system data and initial operating point are given in [20]. It is considered that a 3 phase fault occurs near bus 23 and it is cleared by opening the line between buses 23 and 24 is considered. Fig. 11 and Fig. 12 show the generator rotor angle of all machines in the system with fault clearing time (t_{cl})=190 msec and 191 msec, respective. It can be noticed from the Fig. 11 that the maximum and the minimum rotor angle are machine 5 and machine 10, respectively. The critical clearing time (t_{cr}) of system is around 190-191 msec. With t_{cl}=191 msec, the new England system without a STATCOM is considered as unstable. It can be seen from the results that the machine 10 is critical machine. The system with a proposed nonlinear control strategy of a STATCOM equipped at bus 16 can be considered as stable as can be seen in Fig. 13.

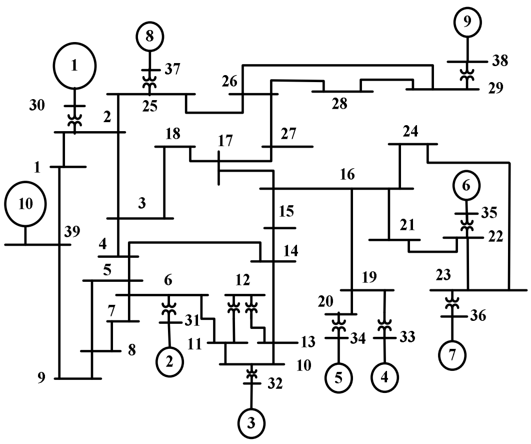


Fig.10. Single line diagram of new England system equipped with a STATCOM

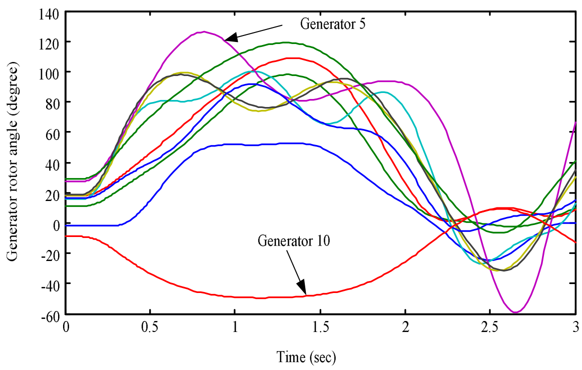


Fig.11. Generator rotor angle of new England system without STATCOM for t_{cl}=190 msec

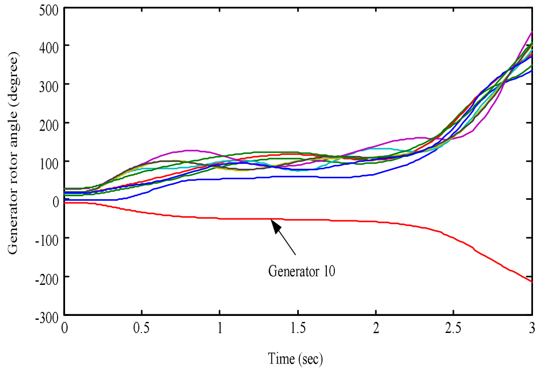


Fig.12. Generator rotor angle of new England system without STATCOM for t_{cl}=191 msec

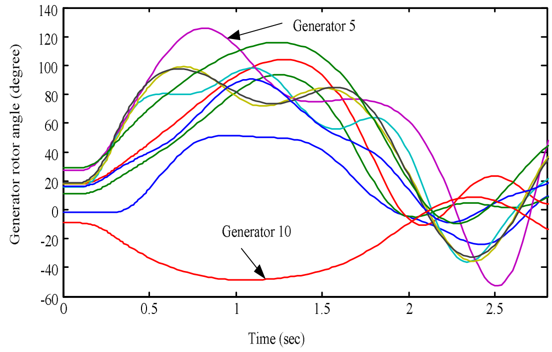


Fig.13. Generator rotor angle of new England system with a STATCOM for t_{cl}=191 msec

7 Conclusion

This paper presented the nonlinear control strategy of a STATCOM for improving stability of multimachine power system and presents the method of investigating the transient stability of the multimachine power system equipped with the STATCOM. The concept of the Lyapunov energy function was applied to derive the nonlinear control of the STATCOM. It was found that the use of the time derivative of line voltage to STATCOM controller is satisfied the concept of the Lyapunov energy function and it is the locally measurable signal. The fuzzy logic control was further applied to suitable control for various sizes of disturbances. The successive method of simulation in stability mode was presented in this paper. The simulation results were tested on the Kundur's inter-area power system and new England power system. It was found from the simulation results that the proposed control strategy of the STATCOM can improve transient stability of multimachine power systems.

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