Direct Method for Transient Stability Assessment of a Power System with a SSSC

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Abstract—**This paper proposes the energy function of a power system with a Static Synchronous Series Compensator (SSSC). They make it possible for the direct method to acquire the transient stability or critical clearing time assessment of a power system. The proposed energy function of a power system with a SSSC is first derived and then it is used for SSSC control design. The proposed method is tested on the single machine infinite bus (SMIB) and multimachine system.**

Index Terms—**power system, transient stability, FACTS, SSSC, energy function, Lyapunov**

I. INTRODUCTION

Because of variety of factors, such as environmental legislation, rights of way issues, capital investment, deregulation policies, etc. constrain the construction of new transmission lines, electric utilities are now forced to operate their system in such a way that makes better utilization of existing transmission facilities. It is well known that the power flow through transmission line is a function of line impedance, magnitude and phase angle. If these parameters can be controlled, the power flow through the transmission line can be controlled in a predetermined manner. Flexible AC Transmission System (FACTS) uses advanced power electronics to control the parameters in the power system in order to fully utilize the existing transmission facilities [1].

There are various forms of FACTS devices, some of which are connected in series with the line and the others are connected in shunt or a combination of series and shunt [2]. A Static Synchronous Series Compensator (SSSC) is a member of FACTS family which is connected in series with a power system. It consists of a solid state voltage source converter which generates a controllable alternating current voltage at fundamental frequency. When the injected voltage is kept in quadrature with the line current, it can emulate as inductive or capacitive reactance so as to influence the power flow through the transmission line [3-4].

While the primary purpose of a SSSC is to control power flow in steady state stability, it can also improve transient stability of a power system. Now power engineers are much more concerned about transient stability problem due to blackout in northeast United States, Scandinavia, England and Italy.

One of the most important parts of transient stability analysis is to estimate the critical clearing time (CCT). Many previous researches present CCT improvement of power system with FACTS devices by using time domain simulation. Time domain simulation is the conventional method of analyzing the CCT. In this method, the generator stability is determined by observing the swing curves generated through numerical integration of the system dynamic equations. To assess the CCT by using time domain simulation method, it is time consuming process because it requires numerous of scenarios of the fault occurrence [5-7]. The Lyapunov's second method or direct method is known to be a very powerful tool of assessing CCT of a power system without solving the system dynamics equations at post fault. The direct method is capable of providing the information about the degree of stability (or instability). The difficulty in this method is to find the suitable energy function of power system with FACTS devices.

The energy function of a power system with a phase shifting transformer is presented in [8]. Recently, Reference [9] presents the energy function of muti-machine system with a Unified Power Flow Controller (UPFC). Reference [10] presents the transient stability assessment (direct method) of power system with a Static Synchronous Series Compensator (SSSC). However, in reference [10], the energy function of SSSC is in the function of time and is used for a simple system.

This paper proposes the energy function of a power system with a SSSC. It is independent of function of time. The proposed energy is in the function of variable on the system and parameter on a SSSC. The CCT of the system with a SSSC is estimated from the proposed

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energy function and it is compared with the time domain simulation method. In addition, this paper will further develop control strategy of the SSSC. The proposed method is then tested on the single machine infinite bus and new England system comprising 10 machines and 39 buses.

II. SINGLE MACHINE INFINITE BUS SYSTEM

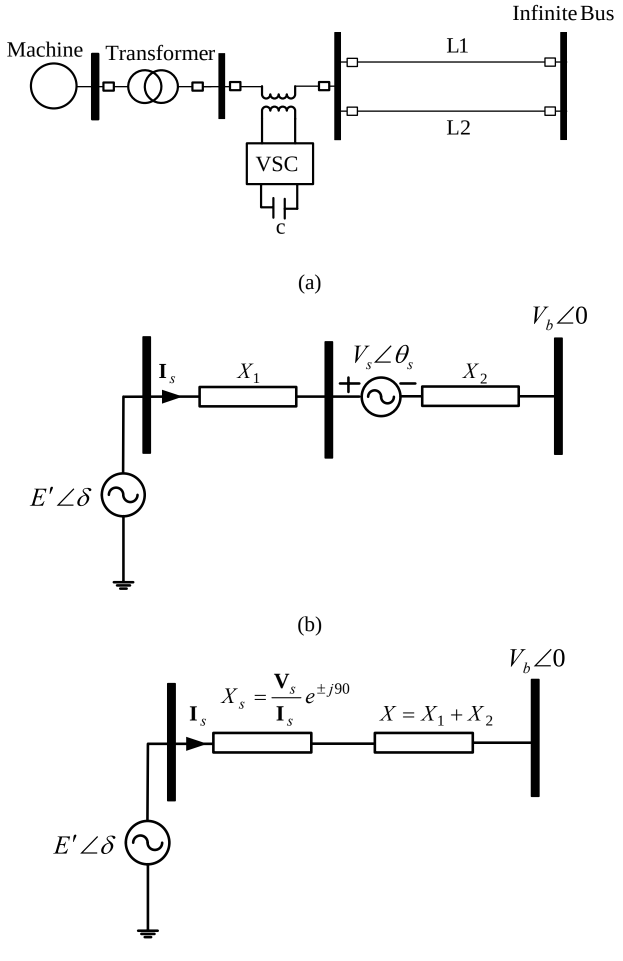
A. Mathematical Model

The dynamic equations of single machine infinite bus system (SMIB) with a SSSC can be expressed by the following differential equations

$$\dot{\delta} = \omega \qquad (1)$$

$$\dot{\omega} = \frac{1}{M}\left[P_m - P_e^s\right] \qquad (2)$$

Here δ, ω, P_m and M are the rotor angle, speed, input mechanical power and moment of inertia, respectively, of the generator. P_e^s is output electrical power of generator with the SSSC.



(a)

(b)

(c)

Figure 1 Single machine infinite bus system with a SSSC (a) Single line diagram (b) Equivalent circuit of a system with a SSSC represented by a series injected voltage (c) Equivalent circuit of a system with a SSSC represented by a variable reactance.

From Fig. 1 (a), the general equation of the current can be written as

$$\begin{aligned} \boldsymbol{I}_s &= \frac{\boldsymbol{E}' - \boldsymbol{V}_s - V_b}{jX} \\ &= \left[\frac{\boldsymbol{E}' - V_b}{jX}\right] + \left[\frac{-\boldsymbol{V}_s}{jX}\right] \\ &= \boldsymbol{I}_0 + \Delta\boldsymbol{I} \end{aligned} \qquad (3)$$

Here $\Delta\boldsymbol{I}$ is an additional term because of the SSSC voltage ($\boldsymbol{V}_s$).

A SSSC, limited by its voltage and current ratings, is capable of emulating a compensating reactance, X_s (both inductive and capacitive in series with the transmission line

$$X_s = \frac{\boldsymbol{V}_s}{\boldsymbol{I}_s} e^{\pm j90} \qquad (4)$$

The output electrical power of a Power system with a SSSC (P_e^s) is given by

$$P_e^s = \frac{E'V_b}{X - X_s} \sin\delta \qquad (5)$$

B. Energy Function

This Section derives the energy function of a power system with a SSSC. The energy function (V) of a power system with a SSSC written by [11]

$$V(\delta,\omega) = V_k(\omega) + V_p(\delta) + V_c(\delta) \qquad (6)$$

Here V_k is kinetic energy, V_p is the potential energy of the system a SSSC and V_c is the constant energy at the post fault equilibrium point of machine angle(δ_s) and speed ($\omega_s = 0$). The first integral of the motion of equation (1), equation (2) and equation (5) constitutes a energy function given by

$$V\ (\delta,\omega) = [\int_0^{\omega} M\omega d\omega] - [\int_{\delta_s}^{\delta} (-Pm + P_e^s) d\delta] \qquad (7)$$

From equation (5), the equation (7) can be written as

$$V\ (\delta,\omega) = \left[\int_0^{\omega} M\omega d\omega\right] + \left[\int_{\delta_s}^{\delta} [-P_m + \frac{E'V_b}{X - X_s}\sin\delta] d\delta\right]$$

(8)

From equation (8), the energy function (V) of a power system with a SSSC is given by

$$V(\delta,\omega)=\left[\frac{1}{2}M\omega^2\right]+\left[-P_m\delta-\frac{E'V_b}{X-X_s}\cos\delta\right]+[V_c] \tag{9}$$

The first bracket of equation (9) represents the kinetic energy (V_k), the second bracket represents the potential energy (V_p) with a SSSC, and the third bracket represents the constant energy. The proposed potential energy function V_p of SSSC given by

$$V_p=\left[-P_m\delta-\frac{E'V_b}{X-X_s}\cos\delta\right]+[V_c] \tag{10}$$

The proposed energy function will be used for transient stability assessment of a power system with a SSSC and it is also used for deriving the control strategy.

C. Control strategy

It was established previous research that the continuous nonlinear control of the SSSC is given by [8]

$$V_s=k\omega\sin\delta \tag{11}$$

However, in this paper, the proposed potential energy will be further used for develop the control strategy of a SSSC. Fig. 2 shows variation of V_p against δ. Suppose that the system with a SSSC is subjected to severe disturbance. With V_s=0 machine angle will increase from prefault stable equilibrium point (δ_0) to any machine angle ($\delta>\delta_s>\delta_0$) corresponding the potential gets increase.

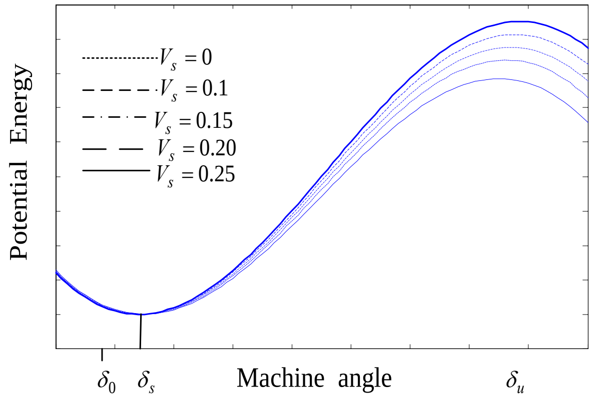


Figure 2 Energy function against machine angle with various cases.

If machine angle reaches at the unstable equilibrium point ($\delta=\delta_u$) the potential energy function has the maximum value. The system is considered as unstable when $\delta>\delta_u$ and $V_p(\delta)<V_p(\delta_u)$. It can be seen from the Fig. 2 that the maximum potential energy and unstable equilibrium point gets increase as the V_s is increased. Thus for the first swing stability improvement the maximum of V_s should be used and then the control of V_s is given by

$$V_s=\begin{cases}V_s^{\max} & \text{for first swing}\\ k\omega\sin\delta & \text{afterwards}\end{cases} \tag{12}$$

III. MULTIMACHINE SYSTEM

The dynamic equations of multimachine system with a SSSC can be expressed by

$$\dot{\tilde{\delta}}_i=\tilde{\omega}_i \tag{13}$$

$$\dot{\tilde{\omega}}_i=\frac{1}{M_i}[P_i-P_{ei}^s-\frac{M_i}{M_T}P_{COI}] \tag{14}$$

Here P_{ei}^s is the output electrical power of a system with a SSSC

$$P_{ei}^s=E_i'E_j'B_{ij}\sin(\delta_{ij})-E_i'E_j'G_{ij}\cos(\delta_{ij}) \tag{15}$$

It may be mentioned here that the B_{ij} of equation (15) is not constant because the X_s of a SSSC is controlled and changed values during transient period. The energy function of a power system with a SSSC can be expressed by

$$V=[V_k]+[V_p]+[V_c]$$
$$=\left[\frac{1}{2}\sum_{i=1}^{n_g}M_i\tilde{\omega}_i^2\right]-\left[\sum_{i=1}^{n_g}P_i\tilde{\delta}_i-\sum_{i=1}^{n_g-1}\sum_{j=i+1}^{n_g}E_i'E_j'B_{ij}\cos(\delta_{ij})\right]+[V_c] \tag{16}$$

The given control strategy of a SSSC in SMIB system can be applied to multimachine system. For the most of the faults in multimachine system, it was observed that only one machine (or critical group) is responsible to initiate instability for an unstable situation.

IV. SIMULATION RESULTS

The proposed technique of transient stability assessment of a power system with a SSSC is tested on a single machine infinite bus system (SMIB) and the 10 machine New England system.

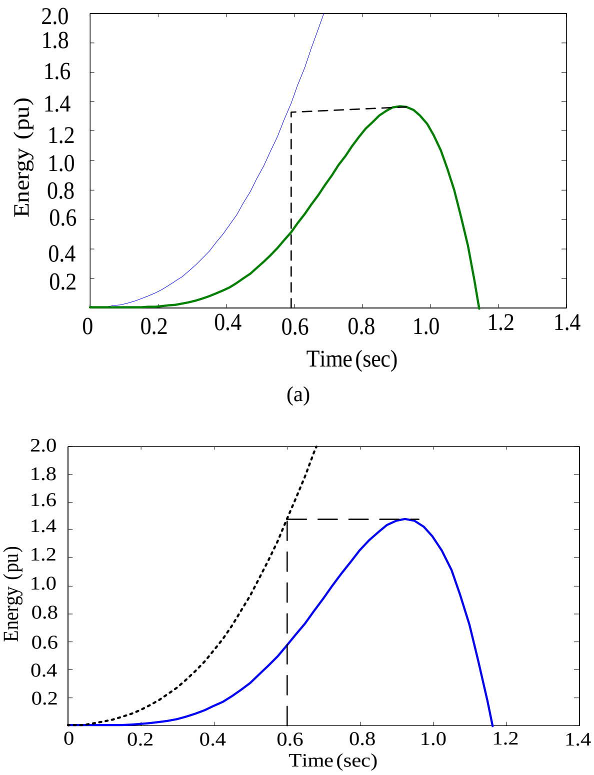
A. SMIB System

The energy function and control strategy of the SMIB sytem with a SSSC are tested on system of Fig. 1(a). The data of the system is given in [9]. It is considered that a three-phase self-clearing type fault appears at bus *m*. For the critical clearing time (CCT) assessment, this paper used the potential-energy boundary surface (PEBS) method. The detail of PEBS method is given in [9].

Fig. 3 (a) shows variation curve of the total energy (V) and potential energy (V_p) for the system without a SSSC (V_s=0). The maximum of V_p and CCT are around 1.37 pu and 590 msec, respectively. However, with V_s=0.1 pu, the CCT is improve to 620 msec because of the V_s help the system increases the potential energy V_p to 1.47 pu as can be seen in Fig. 3(b).

Table I summarizes the CCT and maximum of V_p for various ratings of Vs. It can be seen from the Table that CCT and maximum of V_p gets increase as the V_s is increased. With V_s = 0.9 pu , the CCT is increased to 650 msec.

It was found that by using the time domain simulations, the CCT from direct method of proposed energy function is around that from time domain simulations. Fig. 4 shows the variation of potential energy against machine angle with clearing time of fault (t_{cl}) for 600 msec with various cases of V_s. The system with V_s=0 is considered as unstable. However, with V_s=0.1 pu, the system is considered as stable because the magnitude of potential energy with Vs =0.1 pu is around 1.49 pu and it is in the limit of maximum V_p (1.54 pu).



(a)

(b)

Figure 3 Variation of energy function of a power system (a) without SSSC (b) with a SSSC

It can be seen from Fig. 4 that without SSSC, after machine angle reaches maximum, machine angle increases as the potential energy decreases where as the system with V_s=0.1 pu, the machine angle decreases as potential energy decreases. The maximum and minimum of machine angle are summarized in Table II It can be seen from the Table that the maximum of machine angle is improved as the rating of V_s is increased. However, the minimum of machine angle is not improved.

TABLE I.

IMPROVEMENT OF CCT FOR VARIOUS RATINGS OF SSSC

V_s (pu)	V_p (pu)	δ_u (pu)	CCT (msec)
0.10	1.37	150.00	590-591
0.150	1.54	151.35	608-609
0.20	1.62	152.12	618-619
0.20	1.71	152.67	630-631
0.25	1.74	154.36	633-634

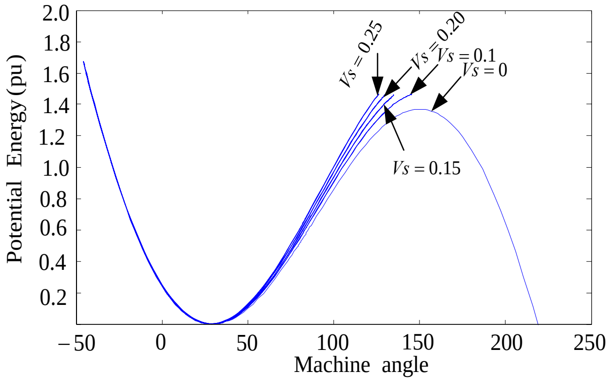


Figure 4 Potential energy against machine angle with various constant V_s.

This paper used the nonlinear control $k\omega \sin\delta$ for the multi-swing improvement. Fig. 5 shows the swing curve of the system with constant V_s=0.1 and with proposed control. It can be seen from the Fig. 5 that with the proposed control the minimum machine angle is around -32.12 whereas with constant V_s=0.1pu the mimimum machine angle is around -30.

TABLE II.

DAMPING WITH CONSTANT RATING OF SSSC

V_s (pu)	δ_{max} (degree)	δ_{min} (degree)
0.10	145.26	-44.05
0.15	135.26	-46.71
0.20	134.91	-48.20
0.25	133.17	-49.37

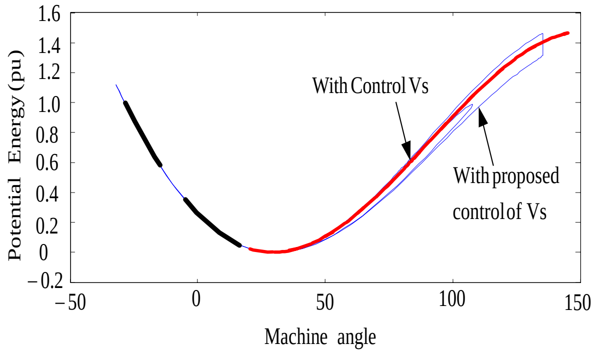


Figure 5. Variation of Potential energy with constant and proposed control of V_s.

TABLE III.

DAMPING WITH PROPOSED CONTROL OF SSSC

Vs (pu)	With constant V_s		With proposed control V_s	
	δ_{max} (degree)	δ_{min} (degree)	δ_{max} (degree)	δ_{min} (degree)
0.10	145.26	-44.05	145.26	-30.09
0.15	135.26	-46.71	135.26	-29.12
0.20	134.91	-48.20	134.91	-28.01
0.25	133.17	-49.37	133.17	-27.83

Table III summarizes the improvement of the swing curve of a power system. It can be seen from the Table that with the proposed control the improvement of swing curve is better that of constant V_s.

B. Multimachine system

The single line diagram of the 10 machines, 39 bus New England system is shown in Fig. 6. A 3 phase fault on bus 29 cleared by opening the line between buses 29 and 26 is considered. Fig. 7 shows the generator rotor angle of all machines in the system with fault clearing time 60 msec. It can be observed from the Fig. 7 that machine 9 is the most severely disturbed and can be considered the critical machine.

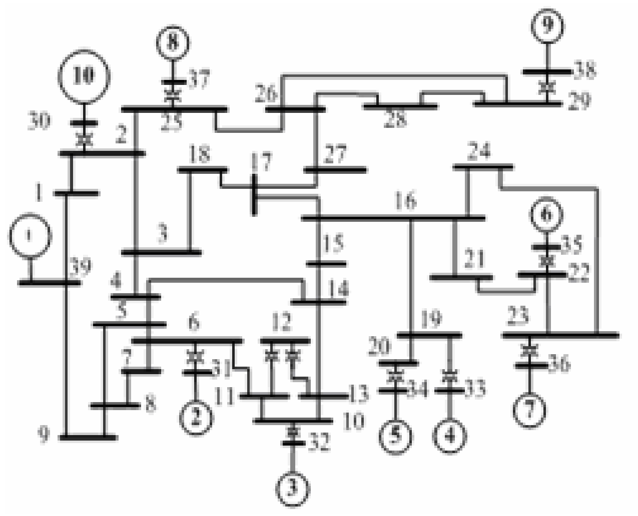


Figure 6 Single line diagram of new England system.

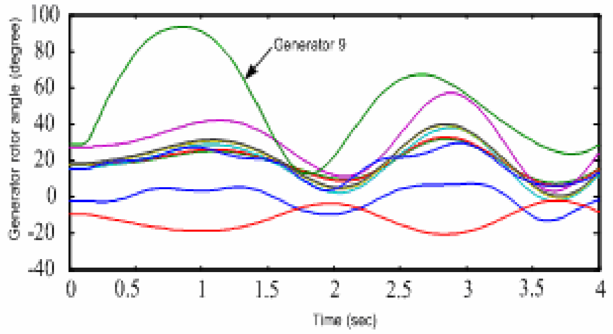


Figure 7 Generator rotor angle of new England system.

The CCT of the system without FACTS devices is around 67 msec. Fig. 8 show the swing curve of a machine 9 with clearing time 70 mess for various case of SSSC. Table IV summarizes the damping improvement of Fig. 8. The proposed of energy function is applied to determine the CCT of the new England system with a SSSC as summarized in Table V.

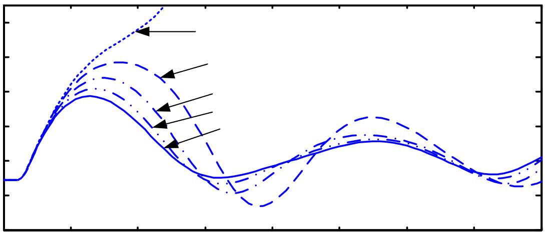


Figure 8 Generator rotor angle of machine 9 at various case of a SSC

TABLE IV
DAMPING IMPROVEMENT OF MACHINE 9

case	K_{sh}	I_{sh}^{max} (pu)	δ_{max} (degree)	δ_{min} (degree)
1	0.1	0.1	-	-
2	0.2	0.3	97.32	13.46
3	0.4	0.6	87.96	21.32
4	0.6	0.9	81.62	26.71
5	0.8	1	77.46	30.17

TABLE V
IMPROVEMENT OF CCT OF NEW ENGLAND SYSTEM

K_{sh}	I_{sh}^{max} (pu)	t_{cr} (msec)
0	0	67-68
0.1	0.1	107-108
0.3	0.2	126-127
0.6	0.4	137-138
0.9	0.6	147-148
1.2	1.2	147-148

V. CONCLUSION

This paper presents the energy function of a power system with a SSSC for estimation the CCT. The parameter of the SSSC is modeled in the potential energy of a power system. It was found that the SSSC can improve stability of the power system because it can increase the maximum the potential energy and unstable equilibrium point. This paper developed the control strategy of the SSSC. The maximum of rating is used for the first swing and non-linear control based on the Lyapunov's stability criterion is used for damping improvement. The proposed energy function is then tested on the simple system and multimachine system. It was found that the SSSC can improve stability of the power system.

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