The Study of FACTS Impacts for Probabilistic Transient Stability

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Abstract - This paper proposes a probabilistic evaluation for the transient stability of electrical power systems incorporating FACTS devices. The uncertainties of the fault location and relay operation time play important keys in power system instability evaluation. The TCSC and SVC are employed for the reduction of system instability probability. This method is demonstrated by the WSCC test system and the results are compared with and without FACTS by means of Monte Carlo simulation.

Keywords: FACTS, Monte Carlo simulation, SVC, TCSC, Transient stability

1. Introduction

Currently, the electric power utility industry in many countries is undergoing a tremendous change. Transient stability [1, 2], which is the ability of power systems to maintain synchronism when subjected to a large disturbance, is a principal component in dynamic security analysis. Any loss of synchronism may result in additional outages and cause the present steady state analysis of the post-contingency condition to become inadequate for unstable cases. To maintain system stability, most utilities use deterministic criterion with a safety margin to cover all uncertainties such as fault type, fault location, etc. Utility companies prepare themselves for the worst case using the deterministic criterion. The deterministic criterion indicates whether a system is stable during certain outages. The calculation of this criterion is simple and concise. However, it cannot explain the stochastic nature of the fault system. Even though the preparation for the worst case has served the industry well, the worst case scarcely occurs in real systems. Also, utilities need to know the risk level of their system by means of probabilistic evaluations [3 - 6].

The flexible AC transmission systems (FACTS) devices have received much attention. They are used to control power flow and to enhance transient stability. One of the critical purposes of FACTS devices in power systems is to improve transient stability. There are other ways to enhance power system transient stability but FACTS is more cost effective and has less environmental impact. It can be hooked up to existing AC transmission systems easily. There are three kinds of FACTS devices; series controllers, shunt controllers and combined series-shunt controllers. The TCSC (Thyristor Controlled Series Compensator), SSSC (Static Synchronous Series Compensator), and TCPAR (Thyristor Controlled Phase Angle Regulators) are series controllers, which are connected in sequence with the transmission line. The SVC (Static Var Compensator) and STATCOM (Static Synchronous Compensator) are shunt controllers, which are connected in shunt with the transmission line. The UPFC (Unified Power Flow Controller) is connected in series and shunt combination. Since the UPFC is a more expensive device than other FACTS devices, this paper investigates the impacts of series controller TCSC and shunt controller SVC on power system transient stability. The contribution of this paper is how the probabilistic technique can be applied to the risk level evaluation of power systems.

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2. The Characteristics of FACTS Devices

2.1 SVC control

2.1.1 The Fundamentals of SVC

Power electronics technology together with advanced control methods made possible the development of the rapid SVC in the early 1970's. The SVC can provide voltage support in a power system. Fig. 2 shows a common case of SVC control to compare the level of transient stability with and without the SVC. Suppose the total reactance of a transmission line is X. The SVC is installed

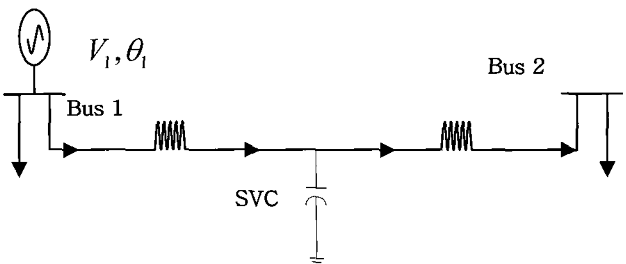


Fig. 1. Common case of SVC control

in the middle of the transmission line. Buses 1 and 2 have sufficient voltage support to maintain the voltage as constant during the process. When there is no resistance or shunt of the transmission line, the voltage at bus 2 without the SVC is as follows.

$$|V_2|^2 = \frac{|V_1|^2}{2} - \beta P_D X \pm \left[\frac{|V_1|^4}{4} - P_D X(P_D X + \beta |V_1|^2) \right]^{\frac{1}{2}} \quad (1)$$

$$P_{12} = \frac{|V_1||V_2|}{X} \sin \theta_{12} \quad (2)$$

where $\beta = \tan \phi$, and $\cos \phi$ is the power factor of the load.

When a SVC is installed in the middle of a transmission line, the voltage at the middle point of the line will be supported by the SVC. The length between the load and the SVC site is x/2, so we have

$$|V_2|^2 = \frac{|V_{SVC}|^2}{2} - \beta P_D X/2 \pm \left[\frac{|V_{SVC}|^4}{4} - P_D X/2(P_D X/2 + \beta |V_{SVC}|^2) \right]^{\frac{1}{2}} \quad (3)$$

The real power transfer from sending bus 1 to receiving bus *SVC* is

$$P_{1SVC} = \frac{|V_1||V_{svc}|}{X/2} \sin \theta_{1svc} \quad (4)$$

From equations (3) and (4), the loadability of the system with the SVC will be better than the system without the SVC. After installing the SVC, if the voltage magnitude at the load is the same as before, then the real power will increase. Therefore, the SVC increases both the voltage and loadability of the system. This is for the steady state study not considering the dynamic process of the SVC. The dynamics of the TCSC, however, can be studied by the same manner as for transient stability.

2.1.2 SVC control model

SVC is a reactive power compensator. Its function is to dampen power oscillations and it can overcome the voltage problem due to reactive power deficit. After the SVC begins to act, it uses the terminal voltage where the SVC is installed as the feedback signal to adjust the susceptance value. This paper shows a thyristor-controlled reactor/fixed capacitor with the SVC control scheme widely used in the industry. In the transient study, the SVC can adjust its susceptance. The differential equations are described as follows [7, 8]

$$\frac{dX_1}{dt} = \frac{1}{T_m}(V_t - X_1) \quad (5)$$

$$\frac{dX_3}{dt} = \frac{1}{T_1}(K_1(V_{ref} - X_1) - X_3) \quad (6)$$

$$\begin{cases} X_3' = A_{max}, & When \quad X_3 > A_{max} \\ X_3' = A_{min}, & When \quad X_3 < A_{min} \\ X_3' = X_3, & When \quad A_{min} < X_3 < A_{max} \end{cases} \quad (7)$$

$$\frac{dX_5}{dt} = \frac{1}{T_{th}}((X_3' + X_0) - X_5) \quad (8)$$

$$\begin{cases} X_{SVC} = A_{max}, & When \quad X_5 > X_{max} \\ X_{SVC} = A_{min}, & When \quad X_5 < X_{min} \\ X_{SXC} = X_5, & When \quad X_{min} < X_5 < X_{max} \end{cases} \quad (9)$$

The parameters used in the equations are described in [8] The detailed discussion of the SVC control scheme is beyond the scope of this paper.

2.1.3 Network Effect of SVC

When the SVC is installed in the transmission line *ij* with λ distance from *i* at *m* connection point, then the elements of *Y* matrix are changed into equation (10). Only the self-admittance of the bus will be changed. When the SVC is installed on the bus *i*, the elements of *Y* matrix are changed into equation (11). When a new bus is introduced, there are several elements that need to be revised.

$$Y_{new} = \begin{array}{c} 1 \\ \vdots \\ i \\ m \\ j \\ \vdots \\ n+1 \end{array} \begin{bmatrix} Y_{11\_old} & \cdots & Y_{1i\_old} & 0 & Y_{1j\_old} & \cdots & Y_{1n\_old} \\ \vdots & \ddots & & \vdots & \vdots & \ddots & \vdots \\ Y_{i1\_old} & \cdots & Y_{ii\_old} - Y_{line\_ij} + \lambda Y_{line\_ij} & \lambda Y_{line\_ij} & 0 & \cdots & Y_{in\_old} \\ 0 & \cdots & \lambda Y_{line\_ij} & Y_{line\_ij} & (1-\lambda) Y_{line\_ij} & \cdots & 0 \\ Y_{j1\_old} & \cdots & 0 & (1-\lambda) Y_{line\_ij} & Y_{ii\_old} - Y_{line\_ij} + (1-\lambda) Y_{line\_ij} & \cdots & Y_{jn\_old} \\ \vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots \\ Y_{(n+1)1\_old} & \cdots & Y_{(n+1)i\_old} & 0 & Y_{(n+1)j\_old} & \cdots & Y_{(n+1)(n+1)\_old} \end{bmatrix} \quad (10)$$

$$Y_{new} = \begin{array}{c} 1 \\ \vdots \\ i \\ \vdots \\ n \end{array} \begin{bmatrix} Y_{11\_old} & \cdots & Y_{1i\_old} & \cdots & Y_{1n\_old} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ Y_{1i\_old} & \cdots & Y_{ii\_old} + jB_{SVC} & \cdots & Y_{in\_old} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ Y_{n1\_old} & \cdots & Y_{ni\_old} & \cdots & Y_{nn\_old} \end{bmatrix} \quad (11)$$

where

$$Y_{old} = \begin{array}{c} 1 \\ \vdots \\ i \\ \vdots \\ n \end{array} \begin{bmatrix} Y_{11\_old} & \cdots & Y_{1i\_old} & \cdots & Y_{1n\_old} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ Y_{1i\_old} & \cdots & Y_{ii\_old} & \cdots & Y_{in\_old} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ Y_{n1\_old} & \cdots & Y_{ni\_old} & \cdots & Y_{nn\_old} \end{bmatrix}$$

From equations (10) and (11), note that the dimension of Y matrix is different. When the SVC is installed in the transmission line *ij*, the SVC bus is added to the dimension of Y matrix.

Since the electronic process is much faster than the mechanical one, we can assume that the SVC can act without delay for simplicity here. The interaction variables are the terminal voltages of the point where the SVC has been installed. Once the SVC has received its feedback signals solving its differential equations, the shunt susceptance of the SVC will be put into the system. The newly introduced SVC susceptance will change the Y matrix and Jacobian matrix of the network equations.

2.2 TCSC control

2.2.1 The Fundamentals of TCSC [9 -11]

The TCSC has received a great deal of attention due to various roles in the operation and control of power systems, such as scheduling power flow, reducing net loss, providing voltage support, limiting short-circuit currents, decreasing unsymmetrical components, mitigating subsynchronous resonance (SSR), damping the power oscillation, and enhancing transient stability.

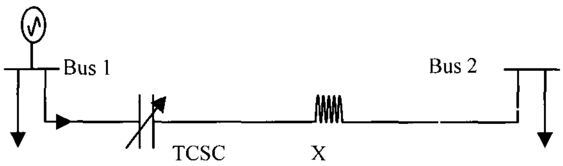


Fig. 2. A Common Case of TCSC control

When a TCSC is installed in the transmission line, the impedance of that transmission line is controlled within its limit. Normally, the TCSC will have the capacitor characteristics. As such, the TCSC can decrease the impedance of the transmission line in Equation (1).

$$|V_2|^2 = \frac{|V_1|^2}{2} - \beta P_D X' \pm \left[\frac{|V_1|^4}{4} - P_D X'(P_D X' + \beta |V_1|^2)\right]^{\frac{1}{2}} \quad (12)$$

$$P_{12} = \frac{|V_1||V_2|}{X'}\sin\theta_{12} \quad (13)$$

where $X' = X_{TCSC} + X$

Obviously we can see that the load ability of the system with the TCSC will be better than the system without the TCSC. Because the TCSC is a series-connected device, the position of the TCSC does not matter.

2.2.2 TCSC Characteristics

A typical TCSC consists of three parts, thyristor controlled reactor (TCR), parallel capacitor and metal oxide varistor (MOV). The TCSC can operate in the capacitive or inductive range. There are 4 kinds of operating range limits, e.g. impedance limits, capacitor limits, voltage limits, and thyristor current limits [9]. Its operating range is limited by the firing angle of the thyristors (impedance limits), the protection (over-voltage) of the MOV (voltage limits) and the current limitation of the capacitors.

Through the control of the reactance of the line installed, the TCSC can control the power flow of the system. With the firing control of the thyristor, the TCSC can change its apparent reactance smoothly and rapidly between capacitive and inductive range. Typically, the capacitor and inductor reactance can vary between $X_{TCSCmax}$ and $X_{TCSCmin}$. It can increase the power transfer capability of a line, if the thermal limit permits, while maintaining the same degree of stability.

The control scheme includes a transient control loop, a power swing damping loop, a limitation loop and an output loop. The limitation loop and output loop simulate capacity, operating range, output range and output characteristics of the TCSC controller. The transient control loop is used to improve transient stability. When there is a certain fault detected in a power system, it acts in a manner that leads to the maximum compensation level during a certain time (T_{forced}). The control is then transferred to the damping loop to suppress the subsequent power oscillation. Damping control is a transfer function-based linear control with an input signal of line active power. The two control functions are combined based on the time switching. It can be seen from this control scheme that the TCSC stability controller is used for power swing damping control, for transient stability control, and for either one in conjunction with a co-ordination scheme. The detailed discussion of control scheme is beyond the scope of this paper. According to the control scheme, the differential equations of the TCSC are as follows [12].

$$\text{When } t < t_r, \quad X_{TCSC} = X_{TCSC\max} \quad (14)$$

When $t \geq t_r$

$$\frac{dX_{desired}}{dt} = (K_1 \frac{dP_{line}}{st} - X_{desired}) / T_1$$

$$\frac{dX_{TCSC}}{dt} = \frac{1}{T_{TCSC}}(X_{desired} - X_{TCSC}) \quad (15)$$

For transient stability study, these differential equations are solved together with the swing equations of the generators. The reactance of the TCSC from the differential equations is used to solve the network equations.

2.2.3 Network Effect of TCSC

Suppose the TCSC is installed in line *ij*, then, the following elements of Y matrix are changed in Equation (16). The elements that have been influenced are the self-admittance of the two end buses of the line and the mutual admittance between the two end buses.

$$Y_{new}=\begin{bmatrix} Y_{11\_old} & - & Y_{1i\_old} & Y_{1j\_old} & - & Y_{1n\_old} \\ | & \backslash & | & | & \backslash & | \\ Y_{i1\_old} & - & Y_{ii\_old}-Y_{line\_ij}+1/(Z_{line\_ij}+jX_{TCSC}) & 1/(Z_{line\_ij}+jX_{TCSC}) & - & Y_{in\_old} \\ Y_{j1\_old} & - & 1/(Z_{line\_ij}+jX_{TCSC}) & Y_{jj\_old}-Y_{line\_ij}+1/(Z_{line\_ij}+jX_{TCSC}) & - & Y_{jn\_old} \\ | & \backslash & | & | & \backslash & | \\ Y_{n1\_old} & - & Y_{ni\_old} & Y_{nj\_old} & - & Y_{nn\_old} \end{bmatrix} \quad (16)$$

Since the Y matrix has been changed, the Jacobian matrix is also changed.

3. Probabilistic Transient Stability Study with FACTS Devices

3.1 Transient Stability Algorithm with FACTS Device

The first-swing stability model in a power system is a simple and efficient model to evaluate transient stability [13]. The power system is considered stable if a fault is cleared before the critical clearing time (CCT). The CCT is defined as the maximum value of fault clearing time (CT), which consists of the operation time of the relay and circuit breaker. Although a three-phase-fault has a lower probability of occurrence, it has larger impact on a system. Utility companies prepare themselves for the worst case. It is a common practice to use three-phase-faults for transient stability studies. The basic algorithm for transient stability with FACTS devices can be briefly described as follows.

STEP 1: The first step in transient analysis is to calculate load flow prior to disturbance. The diagonal admittance equals the sum of the admittances directly contented to bus k and the off-diagonal element equals the negative of the net admittance connected between bus j and k.

STEP 2: Calculate machine current including initial condition. Steps 1 and 2 are just the same as the conventional transient stability calculations.

STEP 3: Set fault line, location, breaker time, re-closing time and FACT type. At starting point, simulation time is set as $t=0$. Here, maximum time for simulation is set as $t=10$. Time interval is set as 1/600.

STEP 4: According to events, Y matrix is different. Suppose that the FACTS devices do not take effect until the disturbance happens. There are 3 events as follows.

a) Event 1: At $t=0$, a fault is selected. According to fault location, Y matrix is different. For a faulted bus, there is a fault at the selected line near one end. Since the voltage of the faulted bus is zero, it can be treated as constant impedance load. For the middle line fault, the admittance in the faulted line is also changed. The admittance element between faulted lines is zero. The diagonal element connecting the faulted line is also changed.
b) Event 2: At $t= t_r$, the faulted line is isolated with breakers. Y matrix is treated as an open faulted line.
c) Event 3: At $t= t_r$, the fault is cleared and the line is back to service. At $t= t_r$, the fault is cleared and the line is back to service. It's the same as Y matrix in a pre-fault state.

STEP 5: When solving a network equation, FACTS control is required. The inserted reactance of the TCSC is zero during a fault period (Event 1). When the fault is isolated by the breakers (Event 2), the TCSC is inserted into the line with the maximum reactance. When the line is back to service (Event 3), the TCSC is in the damping control mode.

STEP 6: This step is based on the Modified Euler's method, which considers the slope at both the beginning and the end point of the interval to compensate for the drawback of the Euler's method. The generators can be modeled using any of three models namely, the classical model, two-axis model and one-axis model. The classical model is the simplest and we will assume this model for stability studies.

STEP 7: Repeat Steps 5 and 6 until maximum time is satisfied. The differential equation and algebraic equations are solved alternatively to obtain the state variables. The angle curve of each generator is obtained

3.2 Probabilistic Transient Stability Study

The instability probability under a given contingency is, in general, defined by the relationship of the critical clearing time and the fault clearing time. We can calculate the probability of successfully clearing a fault ($\mathbf{B}_{ts}$) for the contingency k using probability density function of clearing time. That is, for the contingency k,

$$B_{ts}(k) = P[CT \leq CCT] \quad (17)$$

CCT is used to select some dominant contingencies. The random nature of the operation time of relay and circuit breaker, however, result in different system status at the same fault and location. Since CCT depends on both clearing time and reclosing time, it is impossible to acquire exact CCT. The probabilistic nature of reclosing time as well as clearing time should be taken into account for probabilistic transient stability. Moreover, the location of the fault is an important parameter for this study. The clearing time and reclosing time greatly affect the system stability as well as the location of the fault. The more quickly the relays and breakers can clear the fault in the system, the better chance the system has of maintaining the stability. To ensure the stability of the system, quick clearing and reclosing of the fault are necessary.

Probability density function (p.d.f.) for the fault clearing time, reclosing time, and fault distance is shown in Fig. 3. Fault clearing time and reclosing time can be represented by normal distribution functions. Fig. 3 shows that probability density function of fault clearing time has a mean of 0.2 [sec] and a standard deviation of 0.02 [sec]. The probability density function of reclosing time has a mean of 0.4 [sec] and a standard deviation of 0.02 [sec]. The fault location can be described by uniform function.

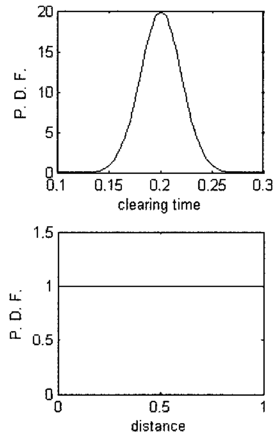


Fig. 3 Probability Density Function for the fault clearing time, reclosing time, and fault distance.

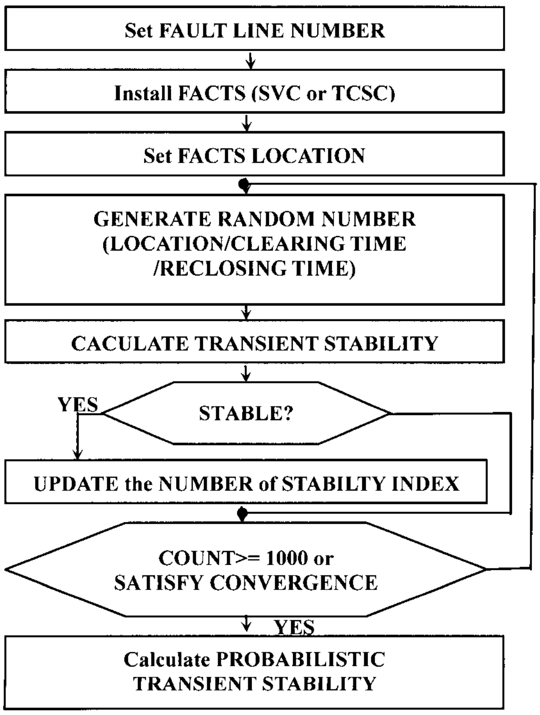


Fig. 4 Flowchart for probabilistic transient stability with FACTS devices

In the probabilistic criterion, either analytical method or Monte Carlo simulation can be used. The analytical method is based on conditional probability; however, it is somewhat cumbersome when applied to a system with many components. The Monte-Carlo simulation is suitable for the analysis of a complicated system such as a bulk power system.

The Monte-Carlo simulation method [9] for probabilistic transient stability obtains the result by collecting and analyzing sample data based on statistical experiments. Non-sequential simulation called random sampling is applied for probabilistic transient stability. In non-sequential simulation, a system state can be determined by random sampling based on the probability distributions of the component states regardless of the sequences of occurrence. A flowchart for probabilistic transient stability is shown in Fig. 4.

4. Case Study

A one line diagram of the Western System Coordinating Council (WSCC) 3-machine and 9-bus system is shown in Fig. 5. The base MVA is 100 and system frequency is 60 Hz. Detailed data of transmission lines and generators are presented in Tables 4 and 5 of the Appendix. The parameters of the SVC and TCSC used in this simulation are given in Tables 6 and 7. The parameters used in the tables are described in [13].

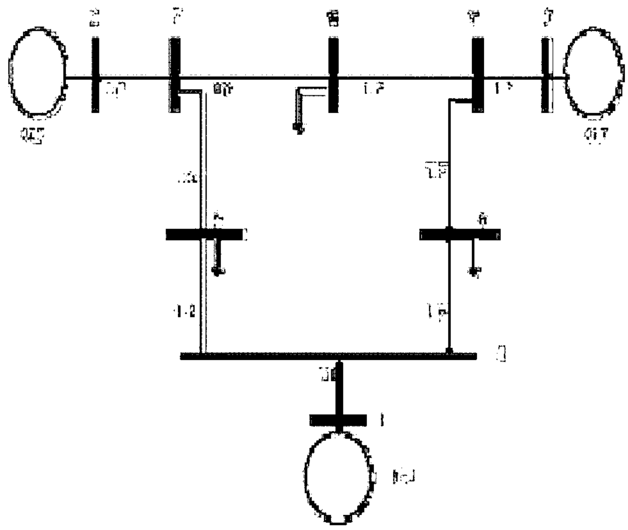
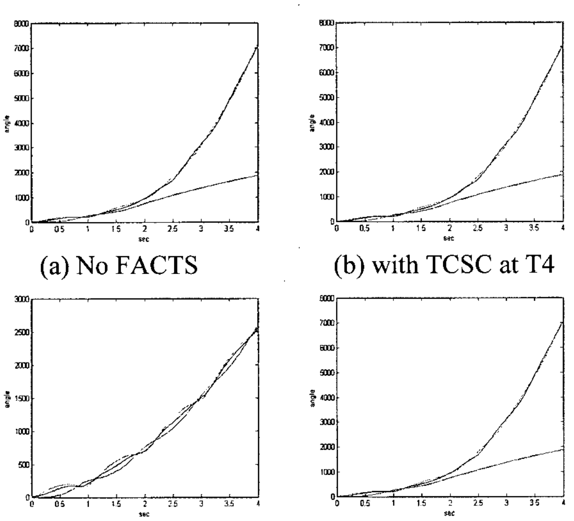


Fig. 5 WSCC system

A fault on transmission line T6 near Bus 7 is assumed with clearing time 0.18 and reclosing time 0.4. It is found that the system is unstable in Fig. 5-(a).

When the TCSC is installed at transmission line T8, the system is still unstable as indicated in Fig. 5-(b). Under the same conditions, a FACTS device is installed at transmission line T5. The series controller TCSC contributes to system stabilization, as shown in Fig. 5-(c). The location of the TCSC controller is an important parameter for a transient stability study. Even though shunt controller SVC is installed in the middle of transmission line T4 and T5, the system is still unstable. The TCSC has a better chance to make the system stable than the SVC, as indicated in Fig. 5-(d).



(a) No FACTS (b) with TCSC at T4

(c) with TCSC at T5 (d) with SVC at T5

Fig. 6 Plot of generator angles

The probability density function of relay operation time and fault location is shown in Table 1. Clearing time and reclosing time are described as normal distribution functions with their mean values and standard deviation, which can be changed by the characteristic of relay operation at each contingency line. On the other hand, the fault occurring point for each contingency is supposed as uniform function.

From Table 1, clearing time, reclosing time and fault location occur at random when contingency occurs at transmission line T1. An example for stability result is shown in Table 2. The more quickly the relays and breakers can clear the fault in the system, the better chance the system will have to maintain stability.

A fault location is an important factor for system instability as indicated in Case 3. When the fault occurs farther away from the generator, transfer reactance is smaller. The required time to clear the fault is longer. Therefore, the required fault clearing time to maintain the stability of the system is different. For the fault at the beginning of the line, the required clear time should be shorter than that for the fault at the middle point of the line.

Table 1 Probability distribution of clearing time, reclosing time , and fault location

	Clearing Time			Reclosing Time			Fault Loc.
Tr. No.	Dist. Type	Mean (s)	SD* (s)	Dist. Type	Mean (s)	SD* (s)	Dist. Type
T1	Norm	0.20	0.05	Norm	0.60	0.02	Uni
T2	Norm	0.10	0.05	Norm	0.20	0.02	Uni
T3	Norm	0.10	0.05	Norm	0.25	0.02	Uni
T4	Norm	0.10	0.02	Norm	0.20	0.02	Uni
T5	Norm	0.10	0.02	Norm	0.20	0.02	Uni
T6	Norm	0.10	0.02	Norm	0.20	0.02	Uni
T7	Norm	0.10	0.02	Norm	0.20	0.02	Uni
T8	Norm	0.10	0.02	Norm	0.20	0.02	Uni
T9	Norm	0.10	0.02	Norm	0.20	0.02	Uni

SD*: Standard Deviation

Table 2 An Example of Transient Stability result from random sampling for contingency T1

Case No.	Fault Loc.	Clearing Time	Reclosing Time	Result
1	0.4692	0.1293	0.5923	stable
2	0.0648	0.1771	0.5942	stable
3	0.9883	0.1849	0.5682	unstable
4	0.5828	0.2547	0.6265	stable
5	0.4235	0.1937	0.5853	stable
6	0.5155	0.2107	0.5920	stable
7	0.3340	0.2032	0.5648	stable
8	0.4329	0.2843	0.6065	unstable
9	0.2259	0.2358	0.6320	stable
10	0.5798	0.0968	0.5851	stable
11	0.7604	0.2088	0.6106	stable
12	0.5298	0.1723	0.6060	stable
13	0.6405	0.1387	0.5962	stable
-	-	-	-	-
200	0.3798	0.1733	0.5820	stable
-	0.7833	0.1554	0.6056	stable
300	0.6808	0.1627	0.6321	stable
-	-	-	-	-
500	0.5678	0.1924	0.6063	stable
-	-	-	-	-
1000	0.0592	0.2646	0.5924	unstable

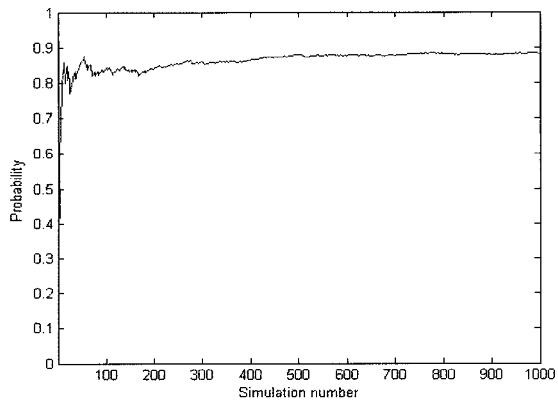


Fig. 7 The probability of transient stability by simulation (faulted line T1)

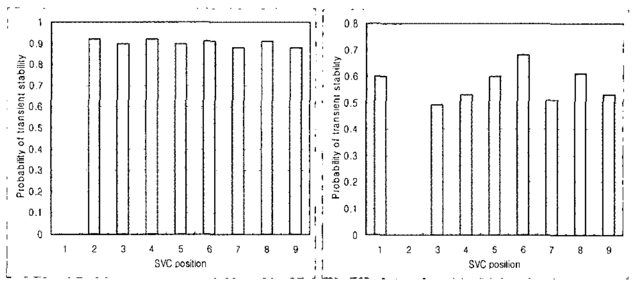
When a contingency occurs at transmission line T1, the probability of transient stability by Monte-Carlo simulation is presented in Fig. 7. The maximum number for simulation is set at 1000. This simulation result shows that the probability for faulted line T1 converges 0.88. Using the same procedure, the simulation results of other contingencies are indicated in Table 3. For contingency from T4 to T9, the fast response of relay operation makes the system stable.

Table 3 The probability of transient stability for each transmission line cotingency

	The Line Number of Contingency								
	T1	T2	T3	T4	T5	T6	T7	T8	T9
Prob.	.88	.49	.45	.98	.99	.98	.99	.98	.98

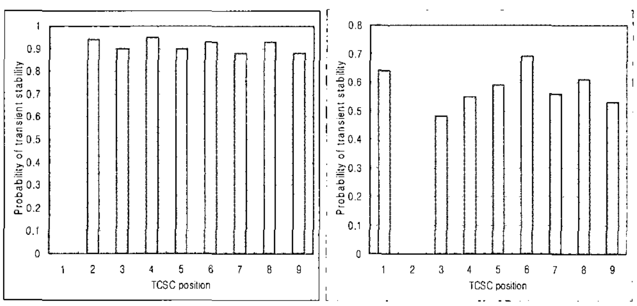
The effect of FACTS device is shown in Fig. 8. From Table 3, the probability of transient stability is 0.88 when contingency occurs at transmission line T1.

The effects of the SVC and TCSC are shown in Fig. 8 and 9, respectively. The TCSC has a slightly better result for the probability of transient stability than the SVC. When FACTS is installed at each transmission line, FACTS installed transmission line T4 results in optimal probability of transient stability as can be seen in Fig. 8-(a) and 9-(a). The probability of transient stability increases from 0.88 to 0.92 for the SVC and from 0.88 to 0.94 for the TCSC, when FACTS is installed at transmission line T2. On the other hand, in case of contingency T2, FACTS installed transmission line T6 has optimal probability as indicated in Fig. 8-(b) and 9-(b).



(a) faulted line T1 (b) faulted line T2

Fig. 8 The probability of transient stability with SVC



(a) contingency T1 (b) contingency T2

Fig. 9 The probability of transient stability with TCSC

5. Conclusion

This paper proposes a probabilistic approach to evaluate the transient stability of electrical power systems incorporating FACTS devices. FACTS devices can be applied for power flow control and transient stability enhancement. This paper is only focused on probabilistic transient stability. It can also be helpful for integrated problem analysis, such as security analysis including dynamic and steady state problems.

The probabilistic evaluation of transient stability can explain the uncertainties of the fault location and relay operation time. From the case study demonstrated by the WSCC test system, FACTS devices such as TCSC and SVC can be used to improve power system transient stability. Moreover, the location of the TCSC and the SVC is an important key in a power system instability evaluation. This information can be useful for power system planning.

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Appendix

Table 4 The Parameters of Generators

	Generator1	Generator 2	Generator 3
H (Sec.)	23.64	6.4	3.01
X'_d	0.0608	0.1198	0.1813

Table 5 Branch data

Tr. No.	R (p.u.)	X (p.u.)	B/2 (p.u.)	Limit (MVA)
T1	.0000	.0576	.0000	300
T2	.0000	.0625	.0000	300
T3	.0000	.0586	.0000	300
T4	.0100	.0850	.0880	300
T5	.0170	.0920	.0790	300
T6	.0320	.1610	.1530	300
T7	.0390	.1700	.1790	300
T8	.0085	.0720	.0745	300
T9	.0119	.1008	.1045	300

Table 6 The SVC Parameter

T_m	V_{ref}	T_I	K_I	T_{th}
0.05	1.0	0.05	0.3	0.001
A_{max}	A_{min}	X_{max}	X_{min}	X_0
1.1	-1.1	1.1	-1.1	0

Table 7 The TCSC Parameter

K_I	T_I	T_{tcsc}	$X_{TCSCmax}$
0.5	0.05	0.05	0.5

The parameters used in Table 4 and 5 are described in [13].

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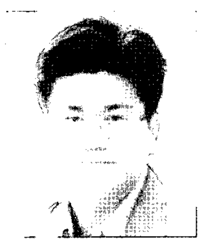

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