Improvement of First Swing Stability Limit by Utilizing Full Benefit of Shunt FACTS Devices

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***Abstract*—This paper proposes a new control strategy of shunt flexible ac transmission system (FACTS) devices to improve the first swing stability limit of a simple power system. It is shown that the speed based bang-bang control (BBC) is unable to use the entire decelerating area in maintaining stability. The proposed control strategy improves the stability limit first by maximizing the decelerating area and then fully utilizing it in counterbalancing the accelerating area. This requires to continue the operation of shunt FACTS devices at full capacitive rating until the machine speed reaches a reasonable negative value during the first return journey. Afterwards, the control can be switched to continuous type to improve system damping in subsequent swings. The proposed control strategy is then applied to both static var compensator and static synchronous compensators placed in a single machine infinite bus system. The same control strategy is also used for some faults in a multimachine system. In both the systems, it is found that the proposed control can provide significantly higher stability limit than that of the BBC. The mechanism of improving the stability limit is also described.**

***Index Terms*—Dynamic analysis, equal area criterion (EAC), flexible ac transmission system (FACTS), first swing stability, static synchronous compensator (STATCOM), static var compensator (SVC).**

I. Introduction

TRANSIENT stability is the main factor that limits the power transfer capability of long distance transmission lines. Power utilities are now placing more emphasis on improving the transient stability, especially the first swing stability limit, to increase the utilization of existing transmission facilities. A power system can be considered as first swing stable if the post-fault angle of all machines in center of angle (COA) reference frame increases (decreases) until a peak (valley) is reached when the angle starts returning [1], [2]. In other words, existence of zero speed (maximum or minimum angle) of all machines guarantees the first swing stability of the system. In general, a first swing stable system is considered as stable because system damping, governor, etc. usually help to damp oscillation in subsequent swings [3].

The first swing stability limit of a single machine infinite bus (SMIB) system can be determined through equal area criterion (EAC) [4] that depends on the difference between input mechanical power and output electrical power of the machine. During faulted period, the output power of the machine reduces drastically while the input mechanical power remains more or less constant and thus the machine accelerates. The turbine delivers excess energy to the machine and that can be represented by an area called accelerating area. To maintain the first swing stability, the machine must transfer the excess energy to the network once the fault is cleared. The excess energy transferring capability of the machine can be represented by another area called decelerating area and it depends on post-fault network condition. The stability limit can be improved by enlarging the decelerating area in early part of post-fault period. Initially, it was considered that the network condition cannot be controlled fast enough to enlarge the decelerating area dynamically. However, recent development of power electronics introduces the use of flexible ac transmission system (FACTS) devices in power systems [5]. FACTS devices are capable of controlling the network condition in a very fast manner and this unique feature of FACTS devices can be exploited to enlarge the decelerating area and hence improving the first swing stability limit of a system.

Static var compensators (SVC) and static synchronous compensators (STATCOM) are members of FACTS family that are connected in shunt with the system [5]. Even though the primary purpose of shunt FACTS devices is to support bus voltage by injecting (or absorbing) reactive power, they are also capable of improving the transient stability and damping of a power system. The stability or damping can be improved by increasing (decreasing) the power transfer capability when the machine angle increases (decreases) and this can be achieved by operating the shunt FACTS devices in capacitive (inductive) mode [5], [6].

Continuous and discontinuous types of control are very commonly used for shunt FACTS devices to improve the transient stability and damping of a power system [6]–[10]. The continuous control may not utilize the full capability of the device. On the other hand, the discontinuous control operates the device at its full rating to provide the maximum benefit. The continuous control is found to be very effective in improving the dynamic stability problem caused by small disturbances. However, to improve the transient stability, much larger control action is needed and it is suggested that the discontinuous control (also called bang-bang control, or BBC) should be used for this purpose [6]. In BBC, the mode of operation of the device is changed (from full capacitive to full inductive or vice versa) at some discrete points. Usually the machine speed signal is used to change the mode of operation [5], [6] but any signal that is dynamically related to machine speed can also be used. References [7] and [11] used some locally measured signals to estimate the machine angle and speed of a simple radial system. However, the same techniques may not be applied to a general multimachine system.

Manuscript received March 23, 2004. Paper no. TPWRS-00197-2003.

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Digital Object Identifier 10.1109/TPWRS.2004.836243

The BBC maximizes the power transfer capability or decelerating area by operating the shunt FACTS devices at full capacitive rating. However, it is found in this study that, the speed based BBC is unable to utilize the entire decelerating area in improving the first swing stability limit. In fact, the use of last portion of decelerating area causes chattering action and that may eventually lead to instability. Such a situation occurs when the fault clearing time t_c approaches the actual critical clearing time $t_{\rm cr}$.

This paper proposes a new control strategy of shunt FACTS devices to improve the first swing stability limit by maximizing the decelerating area and fully utilizing it in counterbalancing the accelerating area. The proposed control strategy is then applied to both SVC and STATCOM placed in a single machine and multimachine systems. The results obtained with the proposed control strategy are also compared with those found with conventional BBC.

II. Background

This section provides the basis of EAC of a SMIB system. The dynamics of the machine, in classical model, can be expressed as

$$\frac{d\delta}{dt} = \omega \quad (1)$$

$$M\frac{d\omega}{dt} = (P_m - P_e) \equiv P_a. \quad (2)$$

Here, δ and ω are the machine angle and speed, respectively, with respect to the synchronously rotating reference frame. M, P_m, P_e, and P_a are the moment of inertia, input mechanical power, output electrical power and accelerating power, respectively, of the machine. By eliminating dt from (1) and (2), the relationship between $d\delta$ and $d\omega$ can be written as

$$M\omega d\omega = (P_m - P_e)d\delta. \quad (3)$$

Consider the system is initially operating in steady state and the corresponding system states are $\delta = \delta_0$ and $\omega = 0$. For a first swing stable, the angle first reaches a maximum value (δ_m) and then starts decreasing. The system states at the maximum angle point are $\delta = \delta_m$ and $\omega = 0$. Integration of (3) from pre-fault operating point to the maximum angle point provides

$$\int_{\omega=0}^{\omega=0} M\omega\, d\omega = \int_{\delta_o}^{\delta_m} (P_m - P_e)\, d\delta. \quad (4)$$

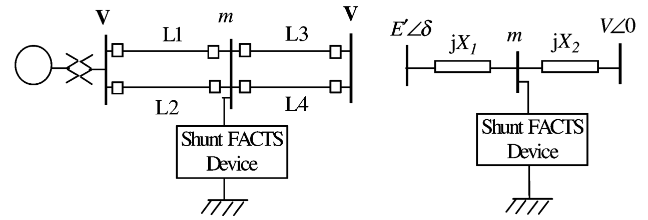
Equation (4) can be expressed as

$$0 = \int_{\delta_o}^{\delta_c} \left(P_m - P_e^f\right) d\delta + \int_{\delta_c}^{\delta_m} \left(P_m - P_e^p\right) d\delta. \quad (5)$$

Here, δ_c is the machine angle at fault clearing and superscripts "f" and "p" represent faulted and post-fault conditions, respectively. The above equation can be rewritten as

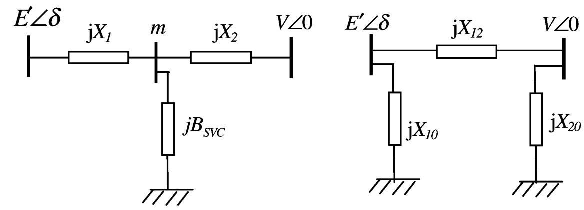
$$\int_{\delta_o}^{\delta_c} \left(P_m - P_e^f\right) d\delta = \int_{\delta_c}^{\delta_m} \left(P_e^p - P_m\right) d\delta \Rightarrow A_a = A_d. \quad (6)$$

Equation (6) represents the well-known EAC.



(a) (b)

Fig. 1. A SMIB system with a shunt FACTS device: (a) single line diagram and (b) equivalent circuit.



(a) (b)

Fig. 2. A SMIB system with a SVC.

III. Improvement of First Swing Stability Limit by Shunt FACTS Devices

Consider a lossless SMIB system with a shunt FACTS device as shown in Fig. 1(a). The equivalent circuit of the system is shown in Fig. 1(b) where E' and V represent the machine internal voltage and infinite bus voltage, respectively. X_1 is the reactance between bus m and the machine internal bus, and X_2 is the reactance between bus m and the infinite bus. The mechanism of improving the first swing stability limit by utilizing the full benefit of shunt FACTS devices (SVC and STATCOM) is described in the following.

A. SVC

A SVC can be modeled by a variable shunt susceptance $B_{\rm SVC}$ as shown in Fig. 2(a) [5]. For a given $B_{\rm SVC}$, the transfer reactance X_{12} in Fig. 2(b) can be written as

$$X_{12} = X_1 + X_2 - B_{\rm SVC}X_1X_2. \quad (7)$$

The electrical output power P_e of the machine in Fig. 2(b) is

$$P_e = \frac{E'V}{X_{12}}\sin\delta. \quad (8)$$

The power-angle $(P{-}\delta)$ curve of the system with a SVC is shown in Fig. 3(a). When a fault occurs, P_e suddenly decreases from point a to point b and thus the machine starts accelerating along $b{-}c$ where both ω and P_a are positive. At fault clearing, P_e suddenly increases and the area $a{-}b{-}c{-}d{-}a$ represents the accelerating area A_a as defined in (6).

If the SVC operates in capacitive mode (at fault clearing), P_e increases to point e where $P_a < 0$ and $\omega > 0$. Thus the machine starts decelerating but its angle continues increasing along $e{-}f$ until reaches a maximum value δ_m at point f, for a stable situation. The area $e{-}f{-}g{-}d{-}e$ represents the decelerating area A_d as defined in (6) and it must be the same as A_a. The unused decelerating area $f{-}h{-}g{-}f$ is a measure of stability margin (SM). Note that both A_d and SM can be increased by raising the power curve as much as possible and which can be achieved by operating the SVC at its full capacitive rating.

For critically stable situation ($t_c = t_{\rm cr}^-$), almost the entire unused decelerating area is needed to counterbalance the accelerating area. In this case, the maximum angle occurs almost at point h. When the BBC changes the mode of operation of the SVC (from capacitive to inductive) at point h (or when $\omega = 0$), P_e suddenly decreases to point k and that makes the system first swing unstable. If the maximum angle occurs before reaching the point m, switching the operation of SVC to inductive mode (at $\omega = 0$) would not allow to increase the angle further. Such a situation occurs when t_c is significantly less than $t_{\rm cr}$. However, if the maximum angle occurs in between m and h, the BBC decreases P_e below P_m and that may not guarantee the first swing stability of the system. In other words, the BBC is unable to utilize the last portion of decelerating area (area $m-h-n-m$) to counterbalance the accelerating area.

1) Proposed Control: Unlike the conventional BBC, the proposed control maximizes the first swing stability limit by fully utilizing the last portion of decelerating area in counterbalancing the accelerating area. This requires to continue the operation of SVC at its full capacitive mode until the machine speed reaches a reasonable negative value during the first return journey. To the best knowledge of the author, such a control has not been reported in the literature to improve the stability limit.

Fig. 3(b) shows the return journey of the machine after reaching the maximum angle at point h (or fully utilizing the area $m-h-n-m$ of Fig. 3(a)). First consider the SVC is switched off at point p during the first return journey. Thus, P_e suddenly decreases to point q but δ continue to decrease along $q-r-s$ because of negative speed. In this case, the angle over swing the SEP s and reaches a minimum value at point t to satisfy the following EAC:

$$\text{area } h-p-q-h + \text{area } q-r-s-q = \text{area } s-t-u-s. \tag{9}$$

The back swing of the machine can be reduced by decreasing the area $q-r-s-q$ and which is possible by operating the SVC in inductive mode. One way of achieving the above is by applying a continuous control (proportional to ω) at point p instead of switching off the SVC. The continuous control will also reduce the peak angle in subsequent swings. Thus, the post-fault-control strategy of SVC that maximizes the first swing stability limit and improves damping in subsequent swings can be considered as

$$B_{\rm SVC} = \begin{cases} B_{\rm SVC}^{\max}\text{: until the machine reaches the point} \\ \quad\quad \text{p during the first return journey} \\ B_{\rm SVC}^{\min} \leq K\omega \leq B_{\rm SVC}^{\max}\text{: afterwards.} \end{cases} \tag{10}$$

Here, K is a positive constant and $B_{\rm SVC}^{\min}$ and $B_{\rm SVC}^{\max}$ are the minimum and maximum susceptances, respectively, of the SVC. The simulation block diagram of the system with a SVC is shown in Fig. 4.

Note that, it is not absolutely necessary to switch the control of SVC (from its full capacitive mode to continuous type) at point p. In fact, it can be done at any point when ω reaches a

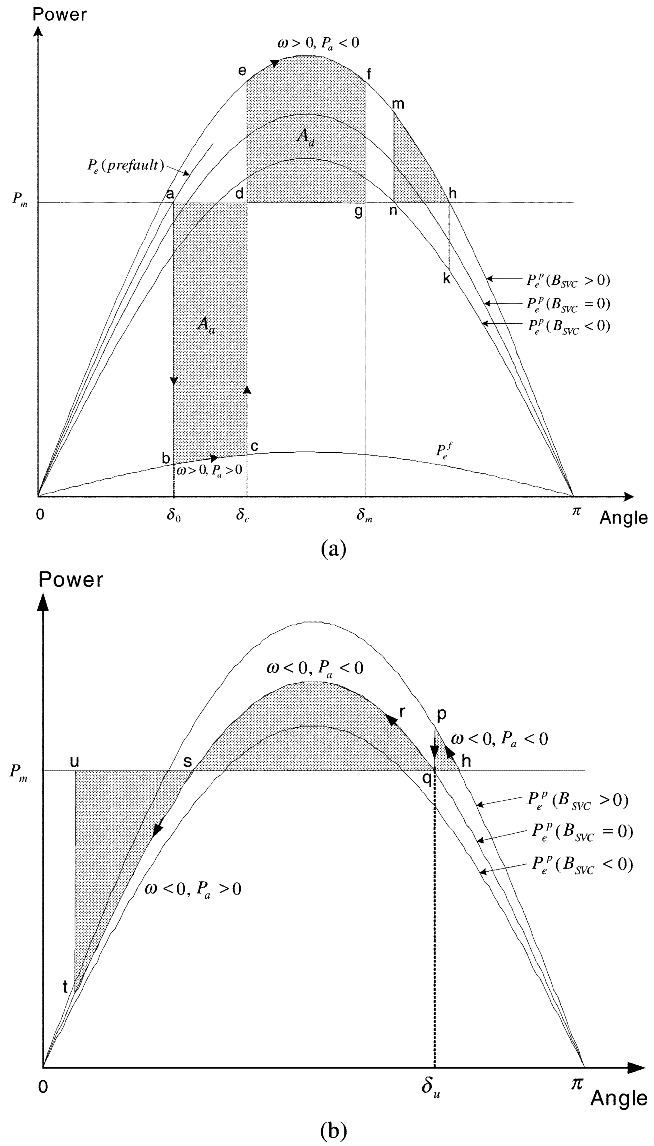


Fig. 3. $P-\delta$ curves for various operating conditions of SVC: (a) areas when the angle increases and (b) areas when the angle decreases.

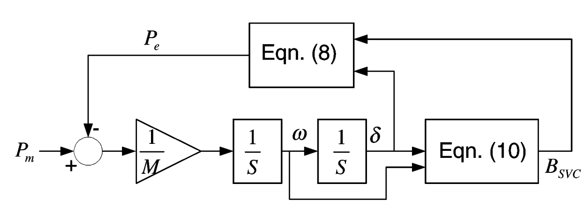


Fig. 4. Simulation block diagram of the system with a SVC.

reasonable negative value during the first return journey. When $t_c \ll t_{\rm cr}$, the angle may not even reach the point p. For such a case, the continuous control can immediately be applied when the angle reaches the maximum value or ω becomes zero.

The above control strategy requires the information of machine speed and which may not be locally available. Thus, it may be necessary to find a signal that is dynamically related to machine speed and readily available from some local measurements. A technique of finding such a signal is described in the following.

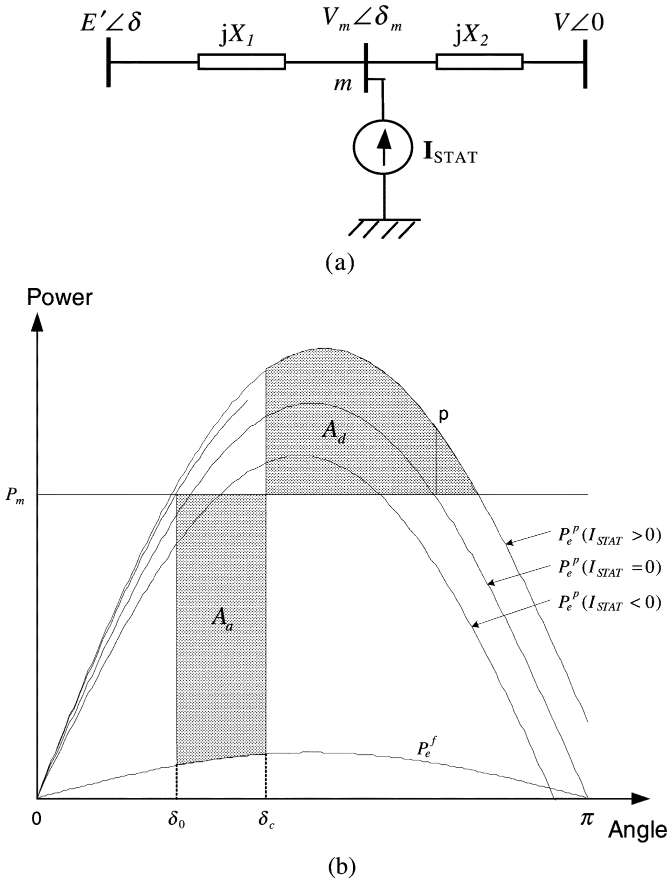


Fig. 5. System with a STATCOM: (a) equivalent circuit and (b) $P-\delta$ curve.

The complex voltage at bus m in Fig. 2(a) can be written as

$$V_m\angle\delta_m = \frac{X_2E'\angle\delta + X_1V\angle 0}{X_1+X_2-B_{\rm SVC}X_1X_2}. \tag{11}$$

The square of the voltage magnitude can be expressed as

$$V_m^2 = \frac{X_1^2V^2+X_2^2E'^2+2X_1X_2E'V\cos\delta}{(X_1+X_2-B_{\rm SVC}X_1X_2)^2}. \tag{12}$$

By differentiating on both sides of (12), the relationship between the machine speed and derivative of SVC bus voltage can be found as

$$\omega = -\left[\frac{(X_1+X_2-B_{\rm SVC}X_1X_2)^2V_m}{X_1X_2E'V\sin\delta}\right]\frac{dV_m}{dt}. \tag{13}$$

Note that the term within the square bracket of (13) is always positive when the machine angle δ oscillates in between zero and π. Thus, $-dV_m/dt$ can be considered as dynamically related to machine speed ω. This suggests that ω in the proposed control can be replaced by $-dV_m/dt$ and which is locally available. Reference [8] used the derivative of V_m^2 (instead of V_m) as control signal of SVC in a multimachine system and it was derived from the basis of Lyapunov's stability criterion. These two derivatives are related through $2V_m$ and which is again a positive quantity. Thus, it may be fair to assume that $-dV_m/dt$ can also be used as control signal of SVC in a multimachine system.

B. STATCOM

A STATCOM can be represented by a shunt current source as shown in Fig. 5(a) [5]. The STATCOM current is always in quadrature with its terminal voltage and can be written as (for capacitive mode of operation)

$$\mathbf{I}_{\rm STAT} = I_{\rm STAT}e^{j(\delta_m-90^\circ)}. \tag{14}$$

The voltage magnitude and angle of bus m are given by [12]

$$V_m = \frac{E'X_2\cos(\delta-\delta_m)+VX_1\cos\delta_m+X_1X_2I_{\rm STAT}}{X_1+X_2} \tag{15}$$

$$\delta_m = \tan^{-1}\left(\frac{E'X_2\sin\delta}{VX_1+E'X_2\cos\delta}\right). \tag{16}$$

For an inductive mode of operation, $I_{\rm STAT}$ in (14) and (15) is to be replaced by $-I_{\rm STAT}$. The electrical output power P_e of the machine in Fig. 5(a) can be written as

$$P_e = \frac{E'V_m}{X_1}\sin(\delta-\delta_m). \tag{17}$$

The $P-\delta$ curve of the system with a STATCOM is shown in Fig. 5(b). For capacitive mode of operation ($I_{\rm STAT}>0$), the $P-\delta$ curve is not only raised but also shifted toward right (see Fig. 5(b)) and that provides more decelerating area and hence higher stability limit. Similar to SVC, the control strategy of STATCOM that maximizes the first swing stability limit and improves damping in subsequent swings can be considered as

$$I_{\rm STAT} = \begin{cases} I_{\rm STAT}^{\max}\text{: until the machine reaches the point} \\ \quad\text{p during the first return journey} \\ I_{\rm STAT}^{\min} \le K\omega \le I_{\rm STAT}^{\max}\text{: afterwards.}\end{cases} \tag{18}$$

The simulation block diagram of Fig. 4 can also be used for the system with a STATCOM. In this case, (8) and (10) in Fig. 4 are to be replaced by (17) and (18), respectively. Analogous to SVC, the speed signal in (18) can also be replaced by $-dV_m/dt$.

Note that the above control strategies of shunt FACTS devices (SVC and STATCOM) are derived for a SMIB system. The author believes that the same control strategies can also be used for some faults in a multimachine system where the severely disturbed machine (SDM) feeds power to rest of the system through radial lines and the shunt FACTS device is placed in the main power transfer path of the SDM. For such a case, the behavior of the SDM, with respect to rest of the system, can be considered very similar to that the SMIB system. However, if the shunt FACTS device is not placed in the main transfer power path of the SDM, it may not improve the stability limit significantly.

IV. Simulation Results

The proposed control strategy of shunt FACTS devices is tested on both SVC and STATCOM placed in the SMIB system and 10-machine New England system. In all cases, it is considered that the inductive rating of the SVC is half of its capacitive rating ($B_{\rm SVC}^{\min} = -0.5B_{\rm SVC}^{\max}$). However, for the STATCOM, inductive and capacitive ratings are considered to be the same ($I_{\rm STAT}^{\min} = -I_{\rm STAT}^{\max}$). For the SMIB system, only the machine speed is used as control signal. However, for the New England system, both ω and $-dV/dt$ are used as control signals to investigate the stability improvement.

TABLE I
CCT FOR VARIOUS RATINGS OF SVC AND STATCOM.

Results of SVC		Results of STATCOM	
B_{SVC}^{max} (pu)	CCT (ms)	I_{STAT}^{max} (pu)	CCT (ms)
0.00	67.7	0.00	67.7
0.25	96.9	0.25	104.5
0.50	119.2	0.50	130.4
0.75	137.9	0.75	151.1
1.00	154.5	1.00	168.4

A. Single Machine Infinite Bus System

The single line diagram of the SMIB system is shown in Fig. 1(a). The system data including initial operating conditions are given in the Appendix. A 3-phase fault on line L3 near bus m is considered and it is cleared by opening the line at both ends. First the critical clearing time (CCT) of the fault is determined through EAC for various ratings of shunt FACTS devices and the results found are given in Table I. In determining the CCT, it is considered that the shunt FACTS devices operate at full capacitive rating in early part of the post-fault period to maximize the decelerating area and then the entire decelerating area is used in counterbalancing the accelerating area. Results of Table I indicate that the CCT of the fault, without a shunt FACTS device (when $B_{\mathrm{SVC}} = 0$ or $I_{\mathrm{STAT}}^{\max} = 0$), is only 67.7 ms and it increases as the rating the device is increased. It may be mentioned here that the reactive power associated with a SVC (STATCOM) can be represented by $V_m^2 B_{\mathrm{SVC}}$ $(V_m I_{\mathrm{STAT}})$. However, at a higher angle, V_m decreases significantly and thus a STATCOM injects more reactive power (or transfers more active power through the line) than that of a SVC of similar rating. That is why a STATCOM is capable of providing higher values of CCT than that of a SVC (see Table I).

The CCTs of the fault are also determined through repetitive time domain simulations of system dynamic equations with the proposed control strategy and the results found are observed to be in exact agreement with those given in Table I. Fig. 6(a) shows the swing curve of the machine for critically stable ($t_c =$ 119 ms) and unstable ($t_c = 120$ ms) situations with a SVC of $B_{\mathrm{SVC}}^{\max} = 0.5$ pu. The variation of machine speed and SVC susceptance, for critically stable case, is shown in Fig. 6(b). Unlike the BBC, the proposed control operates the SVC at its full capacitive rating beyond the zero speed [see Fig. 6(b)] to use the entire decelerating area. Afterwards, the control is switched to continuous type to improve damping and which depends on the value of K used in (10) and (18). Fig. 7 shows the swing curve of the machine for critically stable case ($t_c = 168$ ms with a STATCOM of $I_{\mathrm{STAT}}^{\max} = 1.0$ pu) for different values of K and it indicates that the system damping improves as the value of K is increased.

When the BBC is applied, the CCT of the fault is found as 114–115 ms (with $B_{\mathrm{SVC}}^{\max} = 0.5$ pu) and which is 5 ms lower than that obtained with the proposed control. Fig. 8 shows the $P-\delta$ curve and swing curve of the machine for $t_c = 114$ ms. Some chattering actions of machine output power around the maximum angle can be observed in Fig. 8(a). Such changes in output power cause to operate the machine around the unstable equilibrium point (UEP) for a long time [see Fig. 8(b)]. However, with the proposed control, the machine smoothly returns to the SEP as can be seen in Fig. 9, which is plotted for critically stable situation ($t_c = 119$ ms).

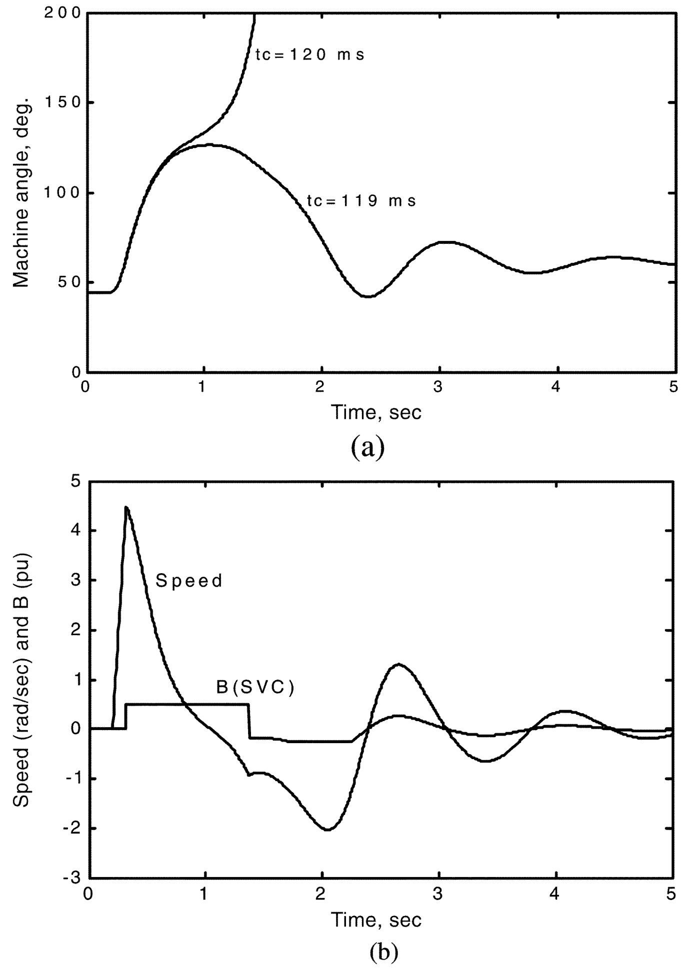


Fig. 6. Results of SMIB system: (a) swing curves for critically stable and unstable situations; (b) variation of machine speed and SVC susceptance.

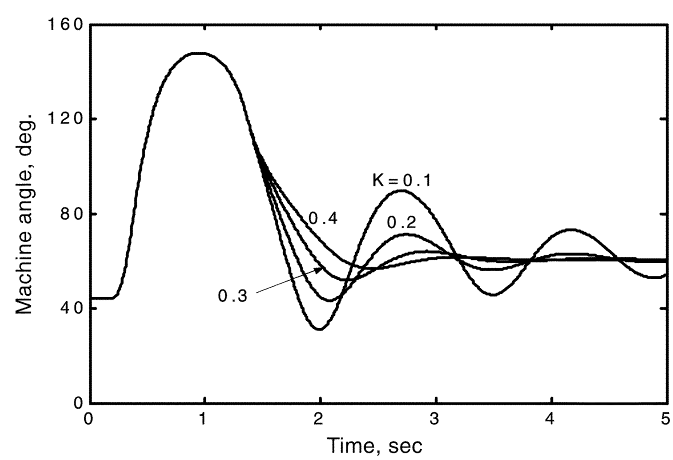


Fig. 7. Swing curve of the SMIB system for various values of K.

It may be mentioned here that the chattering action of BBC occurs when the machine speed approaches the zero value (minimum or maximum angle) near the stable or unstable equilibrium point. The chattering action near the SEP can be eliminated (or the control can be terminated) by using a dead-band. Use of such a dead-band near the UEP may not eliminate the

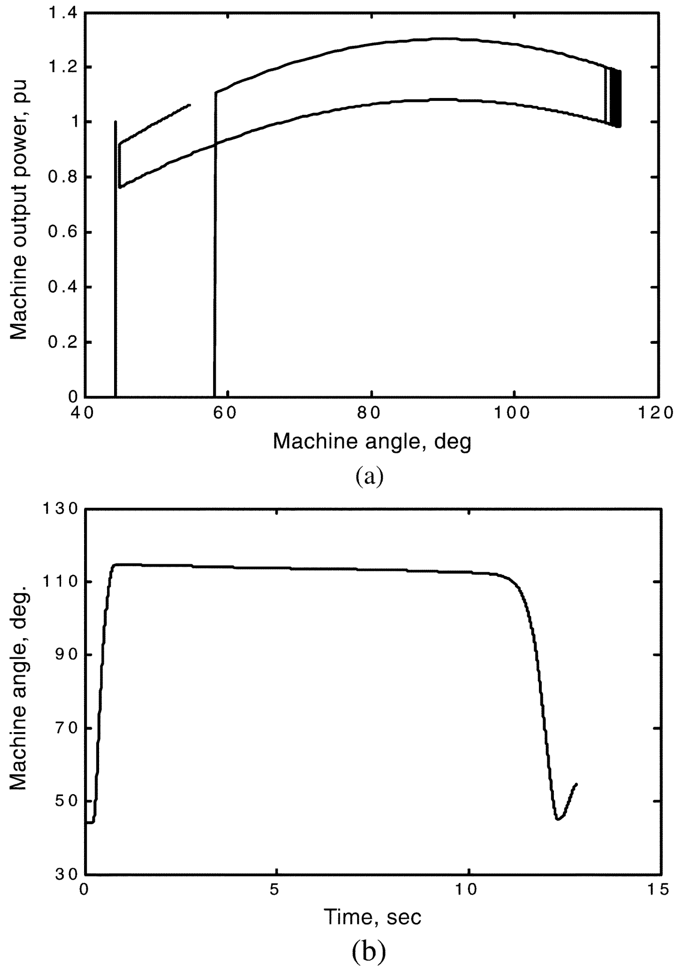


Fig. 8. System response with BBC: (a) $P-\delta$ curve and (b) swing curve.

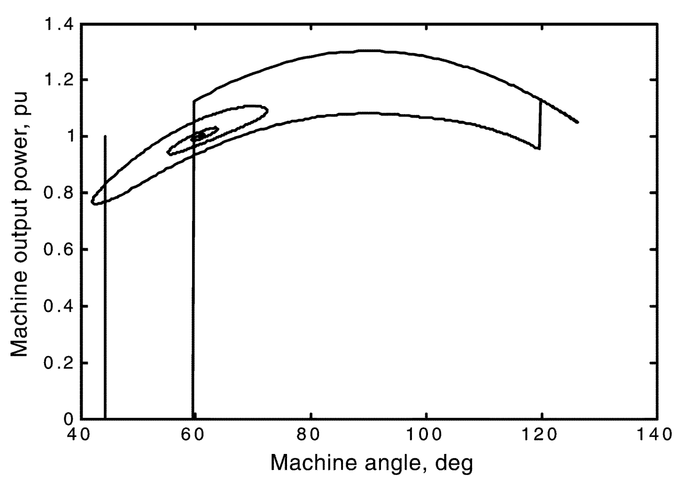


Fig. 9. $P-\delta$ curve with the proposed control strategy.

chattering action. However, for critical cases, the machine speed approaches the zero value (at the first swing) near the UEP and that is why the BBC forced to operate the machine near the UEP for a prolong period.

In generating Figs. 6, 7, and 9, the control was switched from full capacitive mode to continuous type $(K\omega)$ when the machine reached the point p [see Figs. 3(b) and 4(b)] during the first return journey. However, the above switching operation can be

TABLE II
CCT OF THE SMIB SYSTEM FOR VARIOUS VALUES OF α.

Value of α	CCT (ms)
0.0	147-148
0.1	151-152
0.2	154-155
0.3	154-155
0.4	154-155
0.5	154-155
0.6	154-155

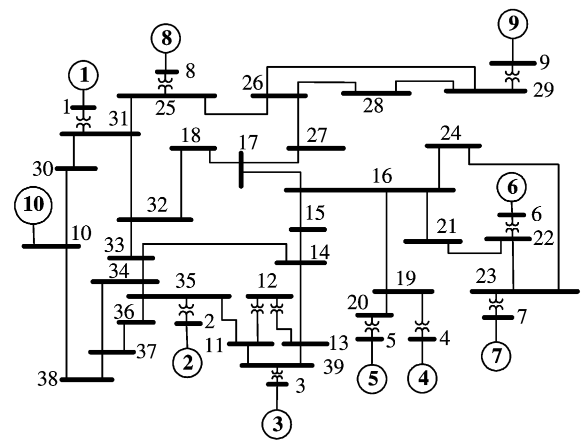


Fig. 10. Single line diagram of the New England System.

performed at any point when the machine speed reaches a reasonable negative value, say $-\alpha\omega_m$. Here α is a positive constant and ω_m is the maximum speed and it usually occurs at fault clearing. To verify that, the CCTs of the fault are also determined for various values of α (with $B_{\text{SVC}}^{\max} = 1.0$ pu) and are given in Table II. Results of Table II clearly indicate that the same value of CCT (154–155 ms) can be obtained when $\alpha \geq 0.2$ is used and is in exact agreement with that given in Table I. One of the advantages of using the above criterion is that it does not require the knowledge of the point p and that would be very useful for multimachine power systems.

B. New England System

The proposed control strategy of shunt FACTS devices is then applied to the 10-machine New England system. The single line diagram of the system is shown in Fig. 10. A 3-phase fault near bus 26 cleared by opening the line between buses 26 and 29 is considered. For this fault, machine 9 is found to be the most severely disturbed and is responsible to initiate the instability for an unstable situation. A shunt FACTS device is placed at bus 28 to improve the first swing stability of the system. The configuration of the system, for the above fault case, can be considered to be very similar to that of Fig. 1 when the infinite bus is replaced by rest part of the system. Thus, analogous to SMIB system, the speed of machine 9 in COA reference frame or the derivative of SVC bus voltage can be used to control the SVC. To generate the swing curves, first all physical buses of the system, except the SVC bus, are eliminated. During each integration step, the value of SVC susceptance is evaluated using the proposed control law and placed at the SVC bus. The SVC bus is then eliminated to reduce the system to the machine internal buses.

TABLE III
CCT OF THE NEW ENGLAND SYSTEM FOR VARIOUS VALUES OF α.

Value of α	CCT (ms) obtained by using SVC	CCT (ms) obtained by using STATCOM
0.0	123-124	129-130
0.1	125-126	132-133
0.2	126-127	134-135
0.3	126-127	134-135
0.4	126-127	134-135
0.5	126-127	134-135
0.6	126-127	134-135

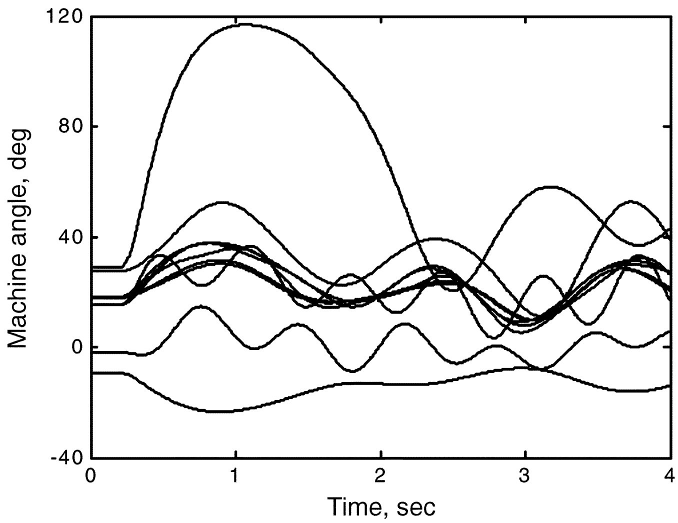


Fig. 11. Swing curves of the New England system with proposed control.

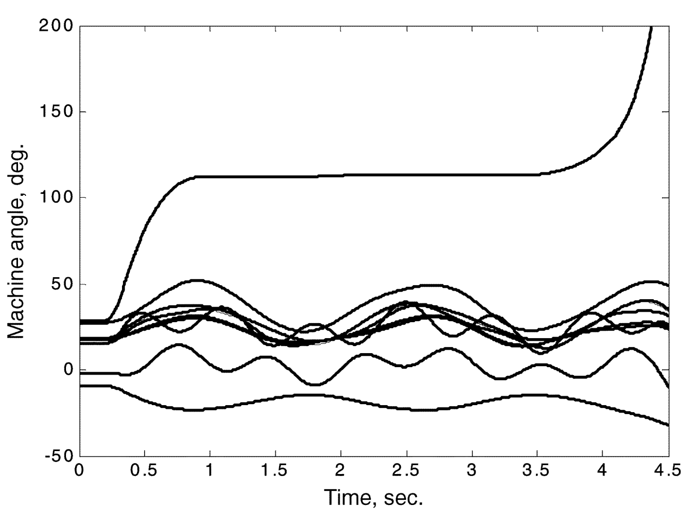


Fig. 12. Swing curve of the New England system with BBC.

The CCTs of the fault are first determined by using the machine speed as control signal and the results found, for various values of α, are given in Table III. In determining the CCT, both $B_{\rm SVC}^{\rm max}$ and $I_{\rm STAT}^{\rm max}$ are considered to be 2.0 pu. Results of Table III again indicate that the same value of CCT can be obtained when $\alpha \geq 0.2$ is used. Fig. 11 shows the swing curve of all machines of the system for critically stable situation ($t_c = 126$ ms with a SVC).

With conventional BBC, the CCT of the fault is found as 122–124 ms and is much less than that obtained with the proposed control. Fig. 12 shows the swing curves of all machines

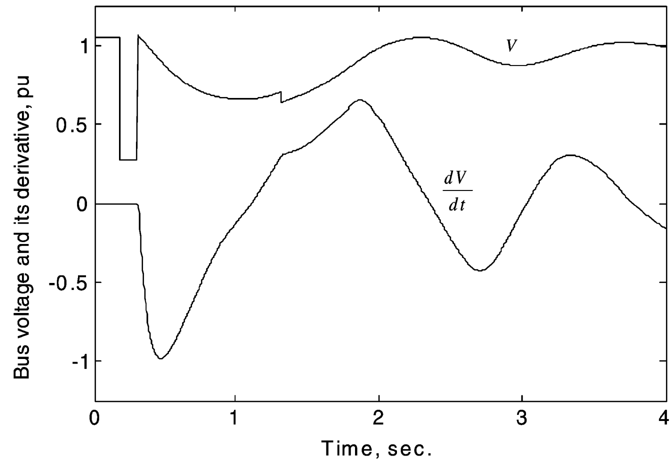


Fig. 13. Variation of SVC bus voltage (bus 28) and its derivative.

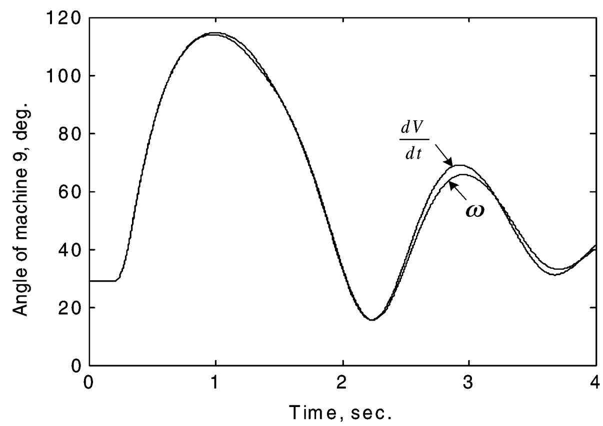


Fig. 14. Swing curve of the most severely disturbed machine (machine 9) obtained by using ω and $-dV/dt$ as control signals.

for critically unstable case ($t_c = 124$ ms) and it indicates that machine 9 initially operates around the UEP for a long time due to chattering action of BBC but ultimately the machine fails to remain in synchronism.

The stability of the system is then investigated by using negative derivative of SVC bus voltage $(-dV/dt)$ as control signal. In this case, the CCT of the fault is found as 126–127 ms and which is exactly the same as obtained with the machine speed as control signal. Fig. 13 shows the variation of SVC bus voltage and its derivative for a fault clearing time of 125 ms. Note that a low pass filter is used to eliminate the sudden changes in dV/dt caused by the fault occurrence, fault clearance, etc. A comparison of swing curve of the most severely disturbed machine (machine 9) obtained by using ω and $-dV/dt$ as control signals is shown in Fig. 14 and it clearly indicates that both the signals provide almost the same results in early part of the transient period. A slight variation in machine angle can be observed in later part of the transient period but which is not so important in determining the first swing stability limit of the system.

Another 3-phase fault at bus 18 cleared by opening the line between buses 18 and 32 is also studied. The first swing stability limit or CCT of the fault, without any shunt FACTS device, is found as 235–236 ms. Fig. 15 shows the swing curve of all machines of the system for $t_c = 235$ ms and it indicates that

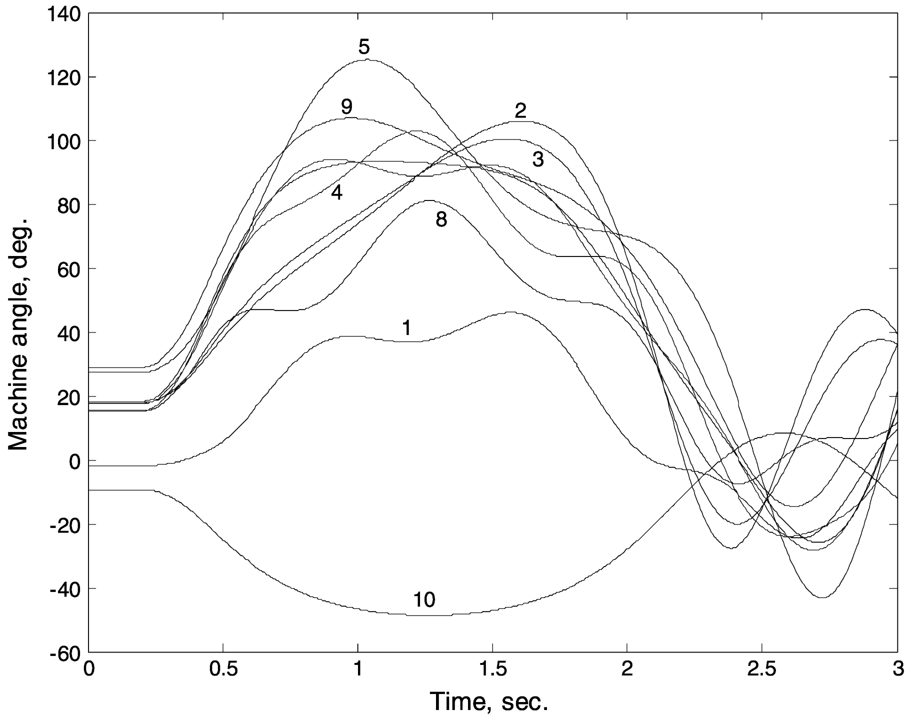


Fig. 15. Swing curves of all machines for a 3-phase fault at bus 18.

TABLE IV
IMPROVEMENT OF FIRST SWING STABILITY LIMIT FOR A FAULT AT BUS 18

SVC at bus	CCT (ms)	Improvement of CCT (ms)
19	254-255	19
28	258-259	23
30	241-242	6
38	242-243	7

machine 5 has the largest swing followed by machines 9, 2, and other machines. The first swing stability limit of the system is then determined with a SVC of $B_{\max} = 2.0$ pu placed at various locations and the results found are summarized in Table IV. Results of Table IV indicate that when the SVC is placed in the main power transfer path (buses 19 and 28) of the SDMs, it improves the first swing stability limit significantly. However, when the SVC is placed far away from the SDMs (buses 30 and 38), it may not improve the stability limit significantly.

V. CONCLUSION

A new control strategy of shunt FACTS devices (SVC and STATCOM) to improve the first swing stability limit of a power system is presented. The stability limit is improved by operating the FACTS devices at full capacitive rating in early part of post-fault period to maximize the decelerating area. The entire decelerating area is then used to counterbalance the accelerating area. This requires to continue the operation of shunt FACTS devices at full capacitive rating until the machine speed reaches a reasonable negative value during the first return journey. Afterwards, the control is switched to continuous type to improve system damping. The justification of using such a control strategy and the mechanism of improving the first swing stability limit are systematically described through EAC. An alternative control signal which is locally available is also suggested to replace the machine speed signal in controlling the shunt FACTS devices.

The proposed control strategy of shunt FACTS devices is then tested on a SMIB system. The same control strategy is also applied to some faults in the 10-machine New England system. Simulation results indicated that the critical clearing time (CCT) obtained with the proposed control is significantly higher than that found with the speed based BBC. It was also observed that a STATCOM can provide higher stability limit than that of a SVC of similar rating. In the New England system, the improvement of CCT is found to be very prominent when the shunt FACTS device is placed in the main power transfer path of the severely disturbed machine. However, use of the proposed control for a more general case in a multimachine system needs further investigation.

APPENDIX

Data of the SMIB system:

Generator: $\mathrm{H} = 5\,\mathrm{s}, \mathrm{f} = 60\,\mathrm{Hz}, \mathrm{X}' = 0.3\,\mathrm{pu}, (\mathrm{M} = \mathrm{H}/\pi\mathrm{f})$.

Transformer: $\mathrm{X} = 0.1$ pu.

Transmission line: $\mathrm{X} = 0.4$ pu of each line.

The machine delivers a power of 1.0 pu at the terminal voltage $\mathrm{V_t} = 1.0$ pu and infinite bus voltage $\mathrm{V} = 0.95$ pu. The internal voltage of the machine is found as $1.2065\angle 44.26°$ pu.

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