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Enhancement of Transient Stability in Transmission Line Using SVC Facts Controller

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Abstract :- This paper will discuss and demonstrate how Static Var Compensator (SVC) has successfully been applied to control transmission systems dynamic performance for system disturbance and effectively regulate system voltage. SVC is basically a shunt connected static var generator whose output is adjusted to exchange capacitive or inductive current so as to maintain or control specific power variable; typically, the control variable is the SVC bus voltage. One of the major reasons for installing a SVC in transmission line is to improve transient stability of a line.

Static VAR Compensator is a shunt connected FACTS devices, and plays an important role as a stability aid for dynamic and transient disturbances in power systems. UPFC controller is another FACTS device which can be used to control active and reactive power flows in a transmission line. The damping of power system oscillations after a three phase fault is also analyzed with the analyzation of the effects of SVC on transient stability performance of a power system. A general program for transient stability studies to incorporate FACTS devices is developed using modified partitioned solution approach. The modeling of SVC for transient stability evaluation is studied and tested on a 10-Generator, 39 - Bus, New England Test System.

Keyword: SVC Facts Controller, Transient stability, Matlab.

I. INTRODUCTION

A power system is a complex network comprising of numerous generators, transmission lines, variety of loads and transformers. As a consequence of increasing power demand, some transmission lines are more loaded than was planned when they were built. With the increased loading of long transmission lines, the problem of transient stability after a major fault can become a transmission limiting factor [1]. Transient stability of a system refers to the stability when subjected to large disturbances such as faults and switching of lines [2]. The resulting system response involves large excursions of generator rotor angles and is influenced by the nonlinear power angle relationship. Stability depends upon both the initial operating conditions of the system and the severity of the disturbance. The voltage stability, and steady state and transient stabilities of a complex power system can be effectively improved by the use of FACTS devices [3].

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SVC is a first generation FACTS device, can control voltage at the required bus thereby improving the voltage profile of the system. The primary task of an SVC is to maintain the voltage at a particular bus by means of reactive power compensation (obtained by varying the firing angle of the thyristors) [4, 5].
SVCs have been used for high performance steady state and transient voltage control compared with classical shunt compensation. SVCs are also used to dampen power swings, improve transient stability, and reduce system losses by optimized reactive power control [6]. In this paper dynamics of the system is compared with and without SVC. SVC is carried out and the system stability is analyzed using the above FACTS devices. To achieve the optimum performance of FACTS controllers' proper placement of these devices in the system is as important as an effective control strategy

II. STATIC VAR COMPENSATOR (SVC)

Static Var systems are applied by utilities in transmission applications for several purposes. The primary purpose is usually for rapid control of voltage at weak points in a net work. Installations may be at the midpoint of transmission interconnections or at the line ends. Static Var Compensators are shunt connected static generators and or absorbers whose outputs are varied so as to control voltage of the electric power systems. In its simple form SVC is connected of FC-TCR configuration as shown in Figure.1.1 The SVC is connected to a coupling transformer that is connected directly to the ac bus whose voltage is to be regulated. The effective reactance of the FC-TCR is varied by firing angle control of the anti parallel thyristors. The firing angle can be controlled through a PI controller in such a way that the voltage bus where the SVC is connected is maintained at the reference value.

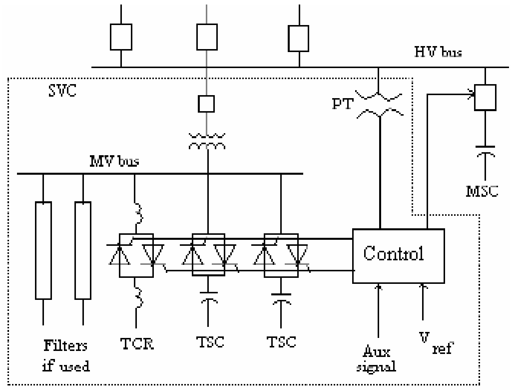

Figure.1.1 Typical SVC System

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III. DEVELOPMENT OF TRANSIENT STABILITY SOLUTION

Transient stability analysis is used to investigate the stability of power system under sudden and large disturbances, and plays an important role in planning and operation of the power system. The transient stability analysis is performed by combining a solution of the algebraic equations describing the network with numerical solution of the differential equations. Although significant improvements have been made in the application of numerical and computational methods to the transient stability calculation, the computational demands are rising rapidly at the same time. Therefore there is a continual search for faster and accurate solutions to the transient stability problem

IV. CASE 1st OR METHOD 1st

An SVC significantly enhances the ability to maintain synchronism of a power system, even when the system is subjected to large, sudden disturbances.

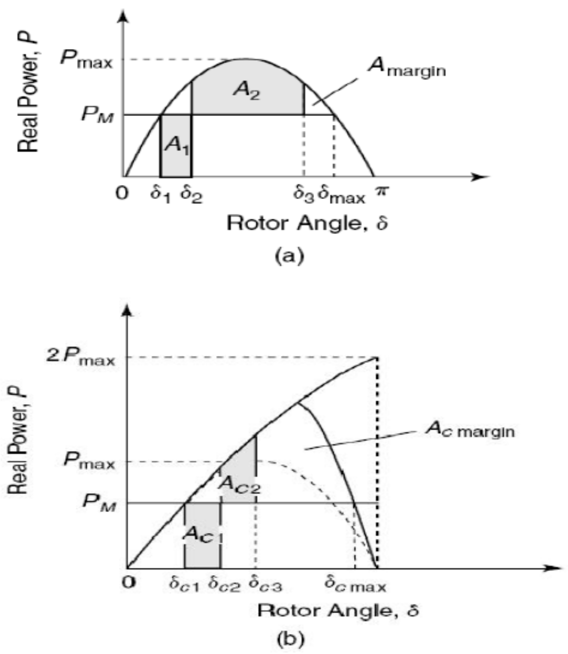

Figure:1.2 Power-angle curves depicting transient-stability margins in the SMIB system: (a) the uncompensated system and (b) the SVC-compensated system.

V. POWER-ANGLE CURVES:

An enhancement in transient stability is achieved primarily through voltage control exercised by the SVC at the interconnected bus. A simple understanding of this aspect can be obtained from the power-angle curves of the uncompensated and midpoint SVC–compensated SMIB system. The power-angle curves for both systems are depicted in Fig.1.2. The initial operating point in the uncompensated and compensated systems are indicated by rotor angles δ_1 and δc_1. These points correspond to the intersection between the respective power-angle curves with the mechanicalinput line P_M, which is same for both the cases. In the event of a 3-phase-to-ground fault at the generator terminals, even though the short-circuit current increases enormously, the active-power output from the generator reduces to zero. Because the mechanical input remains unchanged, the generator accelerates until fault clearing, by which time the rotor angle has reached values δ_2 and δc_2 and the accelerating energy, A_1 and Ac_1, has been accumulated in the uncompensated and compensated system, respectively. When the fault is isolated, the electrical power exceeds the mechanical input power, and the generator starts decelerating. The rotor angle, however, continues to increase until δ_3 and δc_3 from the stored kinetic energy in the rotor. The decline in the rotor angle commences only when the decelerating energies represented by A_2 and Ac_2 in the two cases, respectively, become equal to the accelerating energies A_1 and Ac_1.

The power system in each case returns to stable operation if the post-fault angular swing, denoted by δ_3 and δc_3, dnot exceed the maximum limit of dmax and d*c* max, respectively. Should these limits be exceeded, the rotor will not decelerate. The farther the angular over swing from its maximum limit, the more transient stability in the system. An index of the transient stability is the available decelerating energy, termed the *transient-stability margin*, and is denoted by areas *A* margin and *Ac* margin in the two cases, respectively. Clearly, as *Ac* margin significantly exceeds *A* margin, the system-transient stability is greatly enhanced by the installation of an SVC.

The increase in transient stability is thus obtained by the enhancement of the steady-state power-transfer limit provided by the voltage-control operation of the midline SVC.

VI. SYNCHRONIZING TORQUE

A mathematical insight into the increase in transient stability can be obtained through the analysis presented in the text that follows. The synchronous generator is assumed to be driven with a mechanical-power input, P_M. The transmission line is further assumed to be lossless; hence the electrical power output of the generator, P_E, and the power received by the infinite bus are same. The swing equation of the system can be written as:

$$M\frac{d^2\delta}{dt^2} = P_M - P_E \qquad (1.1)$$

Where

M = the angular momentum of the synchronous generator

δ = the generator-rotor angle

For small-signal analysis, the Eq. (1.1) is linearized as

$$M\frac{d^2\Delta\delta}{dt^2} = \Delta P_M - \Delta P_E \qquad (1.2)$$

The mechanical-input power is assumed to be constant during the time of analysis; hence $\Delta P_M = 0$. The linearized-swing equation then becomes

$$M\frac{d^2\Delta\delta}{dt^2} = -\Delta P_E \qquad (1.3)$$

or

$$\frac{d^2\Delta\delta}{dt^2} = -\frac{1}{M}\left(\frac{\partial PE}{\partial d}\right)\Delta\delta = -\frac{K_S}{M}\Delta\delta \qquad (1.4)$$

Where

K_S = the synchronizing power coefficient

= the slope of the power-angle curve

= $\partial P_E\, \partial\delta$

or

$$\frac{d^2\Delta\delta}{dt^2} + \frac{K_S}{M}\Delta\delta = 0 \qquad (1.5)$$

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The characteristic equation of the differential equation (1.5) provides two roots:

$$\lambda_1\lambda_2 = \pm\sqrt{\frac{Ks}{M}} \quad (1.6)$$

If the synchronizing torque *Ks* is positive, the resulting system is oscillatory with imaginary roots:

$$\lambda_1,\lambda_2 = \pm j\omega s \quad (1.7)$$

Where

$$\omega s = \sqrt{\frac{Ks}{M}} \quad (1.8)$$

On the other hand, if the synchronizing torque *Ks* is negative, the roots are real. A positive real root characterizes instability. The synchronizing-torque coefficient now determined for both the uncompensated and SVC-compensated systems.

VII. UNCOMPENSATED SYSTEM

The electrical power, *P*, transferred from the generator across the lossless uncompensated tie-line is given by Eq. (1.1). The corresponding synchronizing torque is expressed by:

$$K_{SU} = \frac{\partial P}{\partial d} = \frac{V_1V_2}{X}\cos\delta \quad (1.9)$$

VIII. SVC-COMPENSATED SYSTEM

The power transfer, *Pc*, from the generator across the lossless uncompensated tie-line is given by Eq. $Pc = \frac{V1\,V2}{X/2}$ sin $\delta/2$. It can be alternatively expressed in terms of an equivalent transfer reactance, X_T, between the generator bus and the infinite bus.

$$Pc = \frac{V_1V_2}{X}\sin\delta \quad (1.10)$$

Where

$$X_T = X - \frac{X^2}{4}B_S \quad (1.11)$$

The net SVC susceptance, *BS*, is given by

$$B_S = \frac{\alpha c}{Xc} - \frac{\alpha i}{Xi} \quad (1.12)$$

Where

Xi = V ²nomQir = the total inductive reactance of the SVC

Xc = V²nomQcr = the total capacitive reactance of the SVC

Vnom = the nominal voltage

QirQcr = the inductive- and capacitive-reactive-power rating of the SVC

αi = the conducting fraction of the TCR

αc = the conducting fraction of the TSC (= 1 for the fixed capacitor)

The SVC adjusts *ai* and *ac* to maintain a constant voltage, *Vm*, at the connecting bus.

The synchronizing-torque coefficient of the uncompensated system is expressed as

$$K_S = \frac{\partial PE}{\partial d} = \frac{V_1V_2\cos\delta}{\partial\delta} + \left(\frac{V_1V_2\,\text{sinsin}\,\delta}{VmXT}\right)^2\frac{X^2}{4XT} \quad (1.13)$$

Thus the pure-voltage control operation of the SVC increases the synchronizing torque coefficient by the following amount:

$$\Delta K_S = K_S - K_{SU} \quad (1.14)$$

Substituting from Eq. (1.9) in Eq. (1.13) gives

$$\Delta KS = \frac{V1V2\cos\delta}{XXT}(X - XT) + \left(\frac{P}{Vm}\right)^2\frac{X^2}{4XT} \quad (1.15)$$

The frequency of oscillation also increases by a factor

$$\sqrt{1 + \frac{\Delta Ks}{KS}} \quad (1.16)$$

An enhanced synchronizing torque implies an increase in the transient-stability margin of the power system. An SVC thus augments the transient stability of the power system.

IX. MODULATION OF THE SVC BUS VOLTAGE

We have seen from the previous section that an SVC can improve the transient stability of a power system by maintaining the midpoint voltage constant. Now, however, it is shown that if an appropriate modulation of the SVC bus voltage is permitted, the transient stability can be substantially augmented as compared to the constant-voltage control strategy of SVC.

This concept is illustrated through the set of power-angle curves depicted in Fig. 1.3 Curve (a) illustrates the power-angle curve of the system without SVC, whereas curve (b) illustrates the same for the system compensated by an ideal SVC of an unlimited reactive-power rating. When the real-power output of the synchronous generator gradually exceeds the surge impedance loading (SIL), the SVC tends to become increasingly capacitive. As long as the SVC remains within its capacitive-controllable range, the power-angle curve remains the same as curve (b) until point *A* is reached, when the capacitance limit of SVC is attained. Beyond point *A*, the power-angle curve switches to curve (c), or curve *ORAB*, which corresponds to the power-angle curve of a fixed capacitor having the full rating of the SVC capacitor. This curve relates to an effective transfer reactance X_T , with positive *Bs*, that is less than the transmission-line reactance *X* [see Eq. (1.11)].

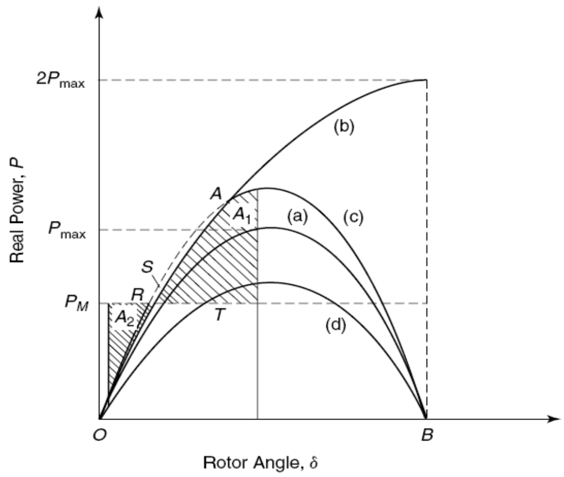

Figure:1.3 Power-angle curves of a SMIB system: curve (a) for an uncompensated case; curve (b) with an ideal midpoint-connected SVC; curve (c) with a midpoint-connected fixed capacitor; and curve (d) with a midpoint-connected fixed inductor.

However, when the power transfer is less than the SIL, the SVC is inductive, with continuously varying levels of inductive-reactive power. If the SVC reactance is fixed at some inductive value, the power-angle curve changes to curve (d), which is below curve (a).

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In this case, the transfer reactance X_T becomes more than X because of the negative B_S.

To begin, let us examine the case of first-swing stability, in which the rotor angle increases following a fault and goes through an over swing. The decelerating energy, which also represents the synchronizing coefficient, is indicated by the hatched area A_1. This behavior relates to a constant-voltage control strategy of the SVC. If a higher voltage is established momentarily by making the SVC more capacitive, additional decelerating energy, shown by area A_{RS}, would be made available. The full capacitor-swing curve is chosen only to illustrate this concept. Increasing the voltage temporarily thus restricts over swing and allows higher critical fault-clearing time.

Once the rotor angle reaches its maximum value, it tends to reverse, or backswing. It is important to minimize this backswing to ensure transient stability. For a constant-voltage control of the SVC, the developed accelerating power is indicated by A_2. However, if the SVC reactive power is rapidly changed to establish a slightly lower terminal voltage—momentarily—at the instant of maximum over swing, an additional accelerating torque, indicated by area O_{ST}, becomes available. This reduces the magnitude of backswing.

X. RESULT AND DISCUSSION FOR CASE 1st

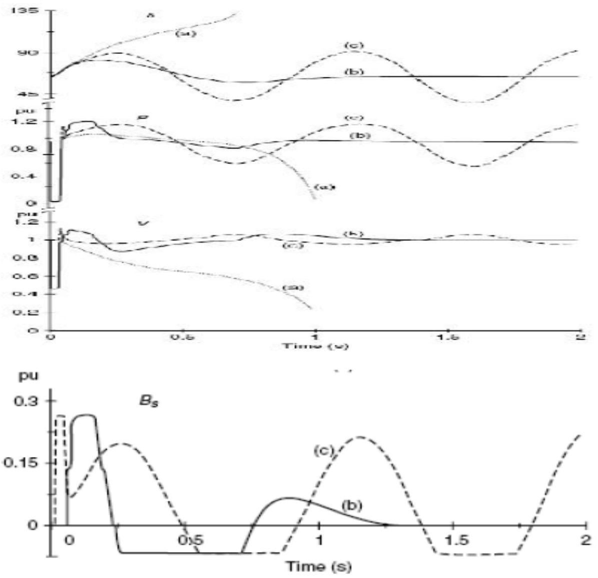

Figure 1.4 Shows the system response for severe disturbance, P_0 = 0.9 pu: curve (a) without SVC; curve (b) with SVC (0.27-pu capacitance 0.07-pu inductance) with the optimum control strategy; and curve (c) with SVC (0.27-pu capacitance 0.07-pu induction) with the constant-voltage control strategy.

A control strategy of modulating the SVC bus voltage instead of keeping it strictly constant thus aids in substantially improving the overall transient stability of the study system. An example of the advantage achieved by adopting the voltage-modulation control strategy, in comparison to constant-voltage regulation, Figure 1.4 depicts the performance of the SVC following a severe fault in a power system. The time variations in the generator rotor angle, real-power transfer, bus voltage, and SVC susceptance are depicted for the two SVC control strategies, and the behavior of the uncompensated system is also presented. In the absence of an SVC, the fault clearing results in severe voltage depression followed by system instability. A voltage-modulation control strategy rapidly stabilizes the oscillations in the rotor angle, power transfer, and terminal voltage, as compared to the constant-voltage control of SVC. Thus, higher power transfer becomes feasible with enhanced transient stability.

XI. CASE 2nd OR METHOD 2nd

Case studies are conducted, to evaluate the performance of the controller, on 10-Generator, 39-Bus, New England Test System:

For this system, generator #9 is severely disturbed, so swing curves of generator #9 are only observed. Both Classical and Detailed models are considered for this study. A three-phase fault at any bus with a clearing time of 60ms is considered to observe both transient stability and damping of power oscillations.

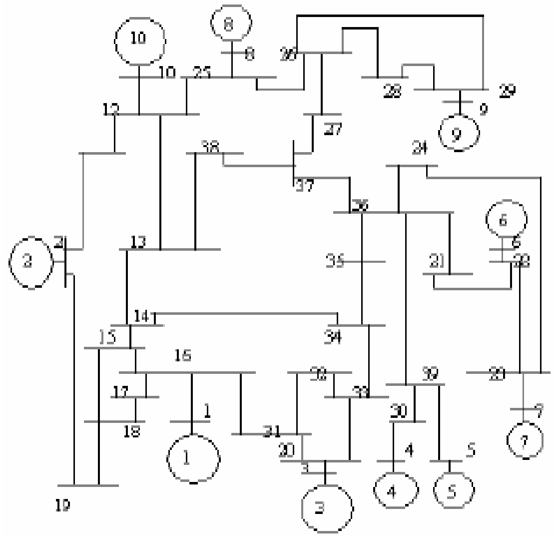

Figure 1.5(a)

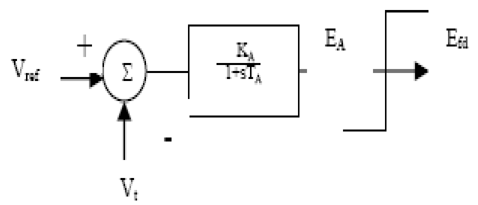

Figure 1.5(b)

Figure 1.5(a): 10-Generator, 39-Bus, New England Test System ***Figure 1.5(b):*** AVR model

The following cases are considered : Fault at bus #26, no line cleared SVC at 28 bus.

Generator:

X_d = 1.6, X_d'=0.32, T_{do}'=6.0, X_q =1.55,

X_q'=0.32, T_{qo}' = 0.44, H=5.0, f_B = 60 Hz

Network: X_{tr} =0.1, X_{L1} = X_{L2} = 0.2, X_b =0.1

AVR: K_A = 200, T_A = 0.05, E_{fdmin} = -6.0, E_{fdmax} = 6.0

Initial Operating Point: V_g = 1.05, P_g = 0.75, E_b=1.0

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XII. TRANSIENT STABILITY EVALUATION WITH AND WITHOUT SVC

The algorithm for the transient stability studies with FACTS devices involves the following steps:

1. Reads the line data. It includes the data for lines, transformers and shunt capacitors.
2. Form admittance matrix, Y_{BUS}
3. Reads generator data (R_a,X_d,X_q, X_d', X_q',H,D etc).
4. Reads steady state bus data from the load flow results. ([V], [δ], [P_{load}], [Q_{load}], [P_{gen}], [Q_{gen}]).
5. Calculates the number of steps for different conditions such as fault existing time, line outage time before auto-reclosing, simulation time etc
6. Modify Y_{BUS} by adding the generator and load admittances.

For generator bus 'i'

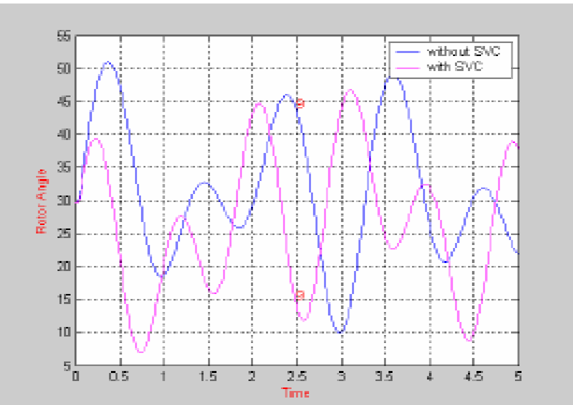
$Y_{ii} = Y_{li} + Y_{gi}$ $\qquad$ $Y_{gi} = \frac{1}{R_{gi} + jX_{di}}$

For load bus 'i'

$Y_{ii} = Y_{li} + Y_{Li}$ $\qquad$ Where $Y_{Li} = \frac{P_{Li} + jQ_{Li}}{|V|^2}$

7. Calculate fault impedance and modify the bus impedance matrix when there is any line outage following the fault.
8. Calculate the initial conditions and constants needed in solving the DAEs of generators, AVR etc.
9. Solves the network equation iteratively in each time step.
10. For X_d-X_q models calculates V_d-V_q using the obtained voltages and rotor angles.
11. Calculates the generator electric power outputs
12. The time step is advanced by the current time step.
13. Solves the generator swing equations using trapezoidal rule of integration keeping generator mechanical power output as constant.
14. Solves the AVR equations
15. Solves the UPFC and SVC. The bus current injection vector is modified with UPFC and SVC injection currents. Then network equation is again solved using [Y_{BUS}] [V]=[I_{inj}].
16. Checks for number of steps.
17. Steps from 7 to 12 are repeated up to the total number of steps.
18. Plots the swing curves for all the generators.

XIII. SIMULATION RESULT



Swing curves- Classical model: Fault at bus # 26, no line cleared, SVC at bus # 28.

XIV. RESULT AND DISCUSSION FOR CASE 2ND

The transient stability and damping of power oscillations are evaluated with SVC. Dynamics of the system is compared with and without presence of SVC in the system. It is clear from the results that there is considerable improvement in the system performance with the presence of SVC. SVC helps in improving transient stability by improving critical clearing time.

XV. CONCLUSION

Instabilities in power system are created due to long length of transmission lines, interconnected grid, changing system loads and line faults in the system. These instabilities results in reduced line flows or even line trip. SVC FACTS devices stabilize transmission systems with increased transfer capability and reduced risk of line trips.

Financial benefit from SVC FACTS devices comes from the additional sales due to increased transmission capability, additional wheeling charges due to increased transmission capability and due to delay in investment of high voltage transmission lines or even new power generation facilities. Also, in a deregulated market, the improved stability in a power system substantially reduces the risk for forced outages, thus reducing risks of lost revenue and penalties from power contracts.

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