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Enhancing Power System Oscillation Damping Using Coordinated PSS and SVC Controller

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ABSTRACT: *In this paper, power system stability enhancement via coordinated design of a power system stabilizer and a static VAR compensator-based stabilizer is investigated. Genetic algorithm is used for optimization and finding optimal control parameters. This paper considers both with SVC and without SVC conditions for adjustment of optimal control parameters. The coordinated design problem of excitation and SVC-based controllers is formulated as an optimization problem with an Eigen value-based objective function. The objective function has been calculated according to system Eigen values. The results are intended to stabilize the system by transferring the real part of the Eigen values from right hand of s-plane to left hand and hence improving the overall system stability. In this work, genetic algorithm is used for optimization and finding optimal control parameters.*

KEYWORDS: *Power System Oscillation Damping, PSS-SVC Controller, Genetic Algorithm*

I. INTRODUCTION

Low frequency oscillations have been observed when large power systems are interconnected by relatively weak tie lines. These oscillations may sustain and grow to cause system separation if no adequate damping is available [1, 2]. Nowadays, the conventional power system stabilizer (CPSS) is widely used by power system utilities. Voltage stability, load-angle stability, power oscillations and Frequency stability are the major criterion in the planning of power system dynamics. Voltages profile of power system is a good indication of the of power system security. Load angle stability of power systems mainly depend on the stability of power system generators. When the generation does not match load, the power system will face frequency deviation. These oscillations may sustain and grow to cause system separation if no adequate damping is available. The conventional power system stabilizer (CPSS) is widely used by power system utilities.

In [3] a detailed account of analytical work carried out to determine the parameters of power system stabilizers (CPSS) for a large generating station. Kundur et al. [3] have presented a comprehensive analysis of the effects of the different CPSS parameters on the overall dynamic performance of the power system. It is shown that the appropriate selection of CPSS parameters results in satisfactory performance during system upsets. In addition, Gibbard [4] demonstrated that the CPSS provide satisfactory damping performance over a wide range of system loading conditions. Robust design of CPSSs in multi-machine power systems using genetic algorithm is presented in Ref. [5], where several loading conditions are considered in the design process. Although PSSs provide supplementary feedback stabilizing signals, they suffer a drawback of being liable to cause great variations in the voltage profile and they may even result in leading power factor operation under severe disturbances [6]. The recent advances in power electronics have led to the development of the flexible AC transmission systems (FACTS).Generally, a potential motivation for the accelerated use of FACTS devices is the deregulation environment in contemporary utility business. Along with primary function of the FACTS devices, the real power flow can be regulated to mitigate the low frequency oscillations and enhance power system stability. This suggests that FACTS will find new applications as electric utilities merge and as the sale of bulk power between distant and ill interconnected partners become more wide spread.

In this paper, an approach for enhancing of power system stability in low frequency oscillations via coordinated design of power system stabilizers (PSSs) and static VAR compensator (SVC)-based damping stabilizers is thoroughly investigated. For optimal adjustment of control parameters, genetic algorithm is used.

II. POWER SYSTEM MODEL

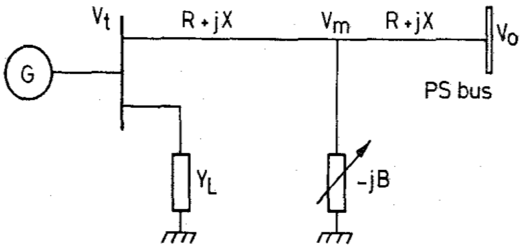


Figure 1 : Single Machine Infinite Bus System with PSS and SVC

Table – 1
SYSTEM DATA

Line and Load	Generator
X_1 = 0.4985	X_q = 0.55
R_2 = -0.017	X_d' = 0.190
R_1 = -0.017	T_{do}' = 7.76
b = 0.262	X_d= 0.973
g = 0.249	D = 0
X_2 = 0.4985	M = 9.26

A. SYNCHRONOUS GENERATOR

In this paper, a single machine infinite bus system is considered. The generator is equipped with a PSS and the system has a SVC installed at midpoint of the transmission line as shown in Fig. 1. The generator has local load of admittance $Y_L = g + jb$ and the transmission line has impedances of $Z_1 = R_1 + jX_1$ and $Z_2 = R_2 + jX_2$for the first and the second sections respectively. Systems data is shown in table I. The generator is represented by the 3rdorder model comprising of the electromechanical swing equation and the generator internal voltage equation.

The swing equation is divided into the following equations

$$\dot{\delta} = \omega_b\ (\omega - 1)$$

$$\dot{\omega} = \frac{P_m - P_e - D(\omega - 1)}{M}$$

Where,

P_m = Mechanical input power of the generator

P_e = Electrical Output power of the generator

D = Damping cooeficient

M = Inertia costant

ω_b = Base frequency

The output power of the generator can be expressed in terms of d-axis and q-axis components of the armature current *I* and terminal voltage *v*as:

$$P_e = v_d i_d + v_q i_q$$

The internal voltage behind the transient reactance is as:

$$\dot{E_q}' = \frac{E_{fd} - (x_d - x_d{}')i_d - E_q{}'}{T_{do}{}'}$$

Where,

$\dot{E_q}'$ = Field Voltage

$\dot{T_{do}}'$ = Open Circuit Field Tie constant

$x_d \& x_d{}'$ = d − axis reactance and the d − axis transient reactance

B. EXCITER

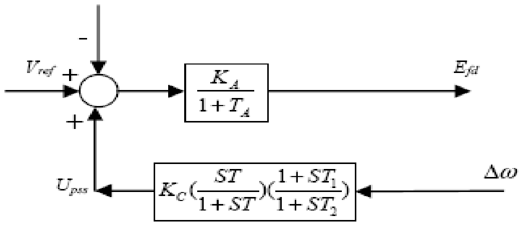


Figure 2 : IEEE-ST1 Excitation System with PSS

The IEEE Type-ST1 excitation system shown in Fig. 2 is considered. It can be described as

$$\dot{E}_{fq} = \frac{K_A(V^{ref} - V) - E_{fd}}{T_A}$$

Where,

K_A = Gain of the excitation system

T_A = Time constant of the excitation system

V^{ref} = Reference Voltage

The terminal voltage can be expressed as:

$$V = (v_d^{\,2} + v_q^{\,2})^{1/2}$$

$$v_d = x_q i_q$$

$$v_q = E_q{}' - x_d{}' i_d$$

Where,

x_q = q − axis reactance

The PSS is installed in the feedback loop to generate a stabilizing signal U_{pss}.

C. SVC-BASED STABILIZERS

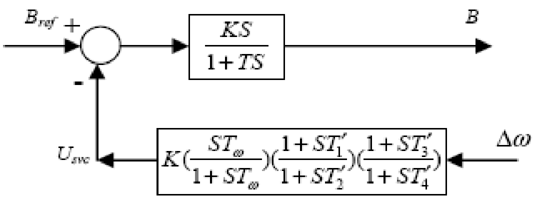


Figure 3 : SVC with a lead lag Controller

Equations that can describe SVC models are:

$$I_s = Y_s V_M$$

$$I_{sd} = -V_{Mq} B$$

$$I_{sq} = -V_{Md} B$$

As shown in Fig. 1, the SVC is installed at a point of the transmission line. Fig. 3 illustrates the block diagram of an SVC with a lead-lag compensator.

The susceptance of the SVC, B, can be expressed as:

$$\dot{B} = \frac{K_s(B^{ref} - U_{SVC}) - B}{T_s}$$

Where,

B^{ref} = Reference Susceptance of SVC which is taken as 0.6 in this paper

K & T = *Gain and Time constant of SVC*

D. SYSTEM LINEARIZED MODEL

In the design of electromechanical mode damping controllers, the linearized incremental model around a nominal operating point is usually employed. For this purpose, first the equation of i_d and i_q must be linearized, and then substituted in different equations to get

$$\Delta P_e = K_1\Delta\delta + K_2\Delta E_q{}' + K_3\Delta B$$
$$\left(\frac{1 + sK_3T_{do}}{K_4}\right)\Delta E_q{}' = \Delta E_{fd} + K_5\Delta\delta + K_6\Delta B$$
$$\Delta V_t = K_7\Delta\delta + K_8\Delta E_q{}' + K_9\Delta B$$

So that K1-K9 are the linearization constants after considering the effect of SVC and PSS. As a result the linearized model of equations is shown in below:

$$\Delta\dot{\omega} = a_1\Delta\omega + a_2\Delta\delta + a_3\Delta E_q{}' + a_4\Delta B$$
$$\Delta\dot{\delta} = a_5\Delta\omega$$
$$\Delta\dot{E}_q{}' = b_1\Delta\delta + b_2\Delta E_q{}' + b_3\Delta E_{fd} + b_4\Delta B$$
$$\Delta\dot{E}_{fd} = c_1\Delta\omega + c_2\Delta E_q{}' + c_3\Delta E_{fd} + c_4U_{pss} + c_5\Delta B$$
$$\dot{e} = d_1\Delta\omega + d_2\Delta\delta + d_3\Delta E_q{}' + d_4e + d_5\Delta B$$
$$\dot{U}_{pss} = f_1\Delta\omega + f_2\Delta\delta + f_3\Delta E_q{}' + f_4e + f_5U_{pss}$$
$$\dot{X}_1 = h_1\Delta\omega + h_2\Delta\delta + h_3\Delta E_q{}' + h_4X_1 + h_5\Delta B$$
$$\dot{X}_2 = m_1\Delta\omega + m_2\Delta\delta + m_3\Delta E_q{}' + m_4X_1 + m_5X_2 + m_6\Delta B$$
$$\dot{U}_{svc} = n_1\Delta\omega + n_2\Delta\delta + n_3\Delta E_q{}' + n_4X_1 + n_5X_2 + n_6U_{svc} + n_7\Delta B$$
$$\Delta\dot{B} = l_1U_{svc} + l_2\Delta B$$

The above linearized model of the single machine infinite bus system can be represented in a closed loop for as:

$$\dot{X} = AX$$

$$\begin{bmatrix} \Delta\dot{\omega} \\ \Delta\dot{\delta} \\ \Delta\dot{E}_q{}' \\ \Delta\dot{E}_{fd} \\ \dot{e} \\ \dot{U}_{pss} \\ \dot{X}_1 \\ \dot{X}_2 \\ \dot{U}_{svc} \\ \Delta\dot{B} \end{bmatrix} = \begin{bmatrix} a_1 & a_2 & a_3 & 0 & 0 & 0 & 0 & 0 & 0 & a_4 \\ a_5 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & b_1 & b_2 & b_3 & 0 & 0 & 0 & 0 & 0 & b_4 \\ c_1 & 0 & c_2 & c_3 & 0 & c_4 & 0 & 0 & 0 & c_5 \\ d_1 & d_2 & d_3 & 0 & d_4 & 0 & 0 & 0 & 0 & d_5 \\ f_1 & f_2 & f_3 & 0 & f_4 & f_5 & 0 & 0 & 0 & 0 \\ h_1 & h_2 & h_3 & 0 & 0 & 0 & h_4 & 0 & 0 & h_5 \\ m_1 & m_2 & m_3 & 0 & 0 & 0 & m_4 & m_5 & 0 & m_6 \\ n_1 & n_2 & n_3 & 0 & 0 & 0 & n_4 & n_5 & n_6 & n_7 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & l_1 & l_2 \end{bmatrix} \begin{bmatrix} \Delta\omega \\ \Delta\delta \\ \Delta E_q{}' \\ \Delta E_{fd} \\ e \\ U_{pss} \\ X_1 \\ X_2 \\ U_{svc} \\ \Delta B \end{bmatrix}$$

III. PROPOSED METHOD FOR OPTIMAL ADJUSTMENT OF PSS AND SVC

Using system state matrix calculated above, Eigen values of systems will be calculated. According to the dimension of dynamic system, there are ten Eigen values. For identifying Eigen values corresponding to electro mechanical mode, sensitivity analysis of Eigen values with respect to machine inertia could be used. The structure of PSS and SVC are shown in Fig. 2 and Fig. 3respectively.
Control parameters of PSS are as follows:
K_c:Gain
T_1,T_2,T: Time Constants of stabilizer
In this paper, the values of T_2 and T have already been selected which are 0.1 and 3 respectively, and search must be applied for finding optimal values of K_c and T_1.
Control Parameters of SVC are as follows:
T_1',T_2',T_3',T_4',T_ω, K: Time Constants of stabilizer
K: Gain
T_ω: Time of resetting stabilizer
In this paper, the values of T_ω is considered as constant which is 3 and T_1',T_2',T_3',T_4',K as control parameters to be sought.
The other parameters that are considered as constant are:

K_A = 50; T_A = 0.05 (Exciter Parameters)
K_s = 50; T_s = 0.05 (SVC Parameters)

IV. OBJECTIVE FUNCTION

The proposed method has improved system stability by shifting Eigen values to the left side of the s-plane so that mechanical modes of system along with other modes have been at least a minimum stability. In this paper, for the optimal adjustment of control parameters, single operating point approach is used.

$$F = -\sum_{i=1}^{10} (\alpha_i^3 + 10\beta_i^3)$$

Where,
$\alpha_i = \sigma_i$ if ($\sigma_i < 0$)
$\beta_i = \sigma_i$ if ($\sigma_i >= 0$)
σ_i = Real part of i^{th} Eigen value

In the one point based approach, the objective function is composed according to function of system dynamic in one operating point. In both approaches, maximization of the objective function has been performed under following constraints.

$$K_c^{min} \le K_c \le K_c^{max}$$
$$T_1^{min} \le T_1 \le T_1^{max}$$
$$K^{min} \le K \le K^{max}$$
$$T_1'^{min} \le T_1' \le T_1'^{max}$$
$$T_2'^{min} \le T_2' \le T_2'^{max}$$
$$T_3'^{min} \le T_3' \le T_3'^{max}$$
$$T_4'^{min} \le T_4' \le T_4'^{max}$$

In this paper, genetic algorithm is used as search engine for optimization and finding optimal control parameters. To indicate capability of controllers, three scenarios have been chosen. In the first scenario only SVC has been implemented for adjusting control parameters. The second scenario has been applied PSS solely in the system. Third scenario considers both SVC and PSS for finding optimal control parameters. Then the result will be compared.

V. GENETIC ALGORITHM

Real-coded genetic algorithm

Genetic algorithms (GA) are search algorithms based on the mechanics of natural selection and survival-of-the fittest. One of the most important features of the GA as a method of control system design is the fact that minimal knowledge of the plant under investigation is required. Since the GA optimize, a performance index based on input/output relationships only, far less information than other design techniques is needed. Further, as the GA search is directed towards increasing a specified performance, the net result is a controller, which ultimately meets the performance criteria. In addition, because the Gad not need an explicit mathematical relationship between the performance of the system and the search update, the GA offer a more general optimization methodology than conventional analytical techniques.

Due to difficulties of binary representation when dealing with continuous search space with large dimension, the proposed approach has been implemented using RCGA. The following are the main steps involved in the Genetic Algorithm:

1. Selection

Selection is the process of choosing two parents from the population for crossing over. In the proposed GA, method of stochastic tournament is used for selection based on their objective function. The commonly used reproduction operator is the proportionate reproductive operator where a string is selected from the mating pool with a probability proportional to the fitness.

2. Cross Over

Crossover is the process of taking two parent solutions and producing new children. After the selection process, the population is enriched with better individuals. Reproduction makes clones of good strings but does not create new ones. Crossover operator is applied to the mating pool with the hope that it creates a better offspring. There are various crossover techniques. In this paper BLX-0.5 crossover technique has been implemented.

3. Mutation

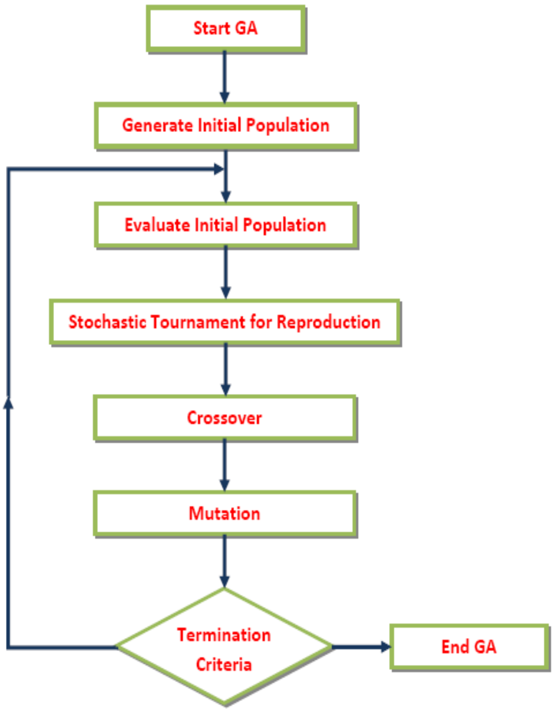
After crossover, the strings are subjected to mutation. Mutation prevents the algorithm to be trapped in a local minimum. Mutation plays the role of recovering the lost genetic materials as well as for random distributing genetic information. It is an insurance policy against their reversible loss of genetic material. In this paper probabilistic mutation is 0.1

4. Fitness Function

As mentioned in section IV the goal of optimization algorithm is adjusting of control parameters and for this purpose, the objective function is described as below:

$$F = -\sum_{i=1}^{10} (\alpha_i^3 + 10\beta_i^3)$$

5. Genetic Algorithm Flowchart:



VI. SIMULATION RESULT

The proposed approach has been applied on the system shown in figure 1 on six different operating conditions (light, normal, heavy). The points are arranged in the following tables 2 and the Eigen values of corresponding to these points with different system configuration (without PSS+SVC, with PSS and with PSS+SVC) are analyzed in Table-5

Table – 2
Different Operating Points

Operating Point	Condition	P (pu)	Q (pu)
1	Normal	1.0	0.015
2	Normal	1.0	0.4
3	Heavy	1.1	-0.3
4	Heavy	1.4	0.4
5	Light	0.8	-0.3
6	Light	0.8	0.4

With considering the stability of Operating point 1, GA is used to find the optimized control parameters of PSS and SVC and improved the stability of the system using the objective function as defined above. The Control Parameters as found to be as shown in Table 3.

Table – 3
Optimized Control Parameters

Control Parameters	With PSS only	With PSS + SVC
Kc	9.4987	6.3407
T1	0.4212	0.9953
K	-	0.0825
T1'	-	0.0071
T2'	-	0.0582
T3'	-	0.0022
T4'	-	0.1224

Then using the Optimal Parameters that are achieved form the genetic algorithm code. System Eigen values are checked on different operating conditions (Light, Normal, Heavy). It is observed that the system stability is improved by using the optimized parameters of GA and the results are shown in Table-5. Some of the parameters of SVC and PSS have already been assigned as follows in Table-4:

Table – 4

PSS	T = 3	T2 = 0.1	-
SVC	**Ks = 50**	**Ts = 0.05**	**Tw = 3**

Table – 5
Eigen Values at Different Operating Points and Different Configuration

Operating Point	Without PSS+SVC	With PSS	With PSS+SVC
1	-10.3930 + 3.2837i -10.3930 - 3.2837i 0.2951 + 4.9596i 0.2951 - 4.9596i	-17.9572 -4.8908 + 6.3583i -4.8908 - 6.3583i -1.2256 + 4.9074i -1.2256 - 4.9074i -0.3391	-19.6784 -19.3371 +10.4474i -19.3371 -10.4474i -4.1356 + 8.6220i -4.1356 - 8.6220i -1.1218 + 3.8849i -1.1218 - 3.8849i 1.1585 -0.3363 -0.0001
2	-10.4805 + 3.7102i -10.4805 - 3.7102i 0.3827 + 3.7265i 0.3827 - 3.7265i	-17.6101 -5.7468 + 6.6226i -5.7468 - 6.6226i -0.5416 + 3.4907i -0.5416 - 3.4907i -0.3422	-19.3331 -19.3371 +10.4475i -19.3371 -10.4475i -4.9438 + 8.3722i -4.9438 - 8.3722i -0.4855 + 3.0713i -0.4855 - 3.0713i 1.1585 -0.3377 -0.0001
3	0.3209 + 5.6404i 0.3209 - 5.6404i -10.4188 + 2.4926i -10.4188 - 2.4926i	-18.5799 -3.7629 + 5.9295i -3.7629 - 5.9295i -2.0422 + 5.9290i -2.0422 - 5.9290i -0.3388	-20.3813 -19.3371 +10.4474i -19.3371 -10.4474i -3.3190 + 9.1902i -3.3190 - 9.1902i -1.5869 + 4.0328i -1.5869 - 4.0328i 1.1586 -0.3361 -0.0001

4	-12.5062 3.3085 -5.4990 + 3.5756i -5.4990 - 3.5756i	-18.9232 -4.9806 + 8.0279i -4.9806 - 8.0279i 2.7002 -4.0212 -0.3236	-19.6133 -19.3372 +10.4475i -19.3372 -10.4475i -4.8589 + 8.5007i -4.8589 - 8.5007i -0.4300 + 3.0435i -0.4300 - 3.0435i 1.1585 -0.3380 -0.0001
5	0.0730 + 5.5402i 0.0730 - 5.5402i -10.1709 + 3.0068i -10.1709 - 3.0068i	-17.6916 -4.5790 + 5.9018i -4.5790 - 5.9018i -1.6707 + 5.6308i -1.6707 - 5.6308i -0.3380	-19.4084 -19.3370 +10.4473i -19.3370 -10.4473i -3.7694 + 8.6016i -3.7694 - 8.6016i -1.6235 + 4.1854i -1.6235 - 4.1854i 1.1584 -0.3357 -0.0001
6	0.2172 + 3.7674i 0.2172 - 3.7674i -10.3150 + 3.7639i -10.3150 - 3.7639i	-17.0534 -5.9689 + 6.3867i -5.9689 - 6.3867i -0.5984 + 3.5386i -0.5984 - 3.5386i -0.3410	-18.7082 -19.3370 +10.4474i -19.3370 -10.4474i -5.1838 + 8.0255i -5.1838 - 8.0255i -0.5583 + 3.1535i -0.5583 - 3.1535i 1.1584 -0.3371 -0.0001

Comparison of Result for load angle (delta)

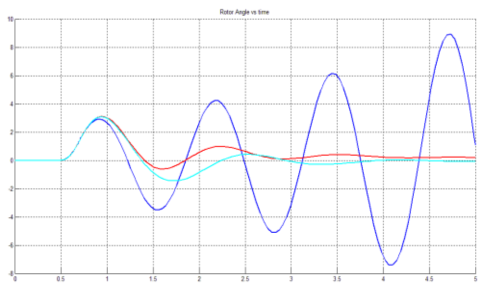


Figure 4: Operating Point 1

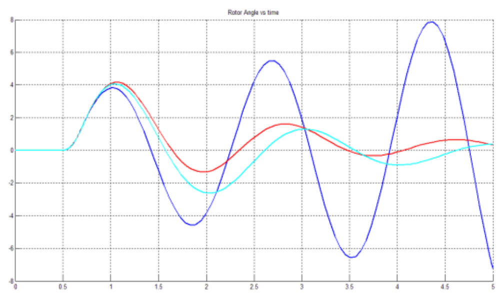


Figure 5 : Operating Point 5

Comparison of Result for Speed

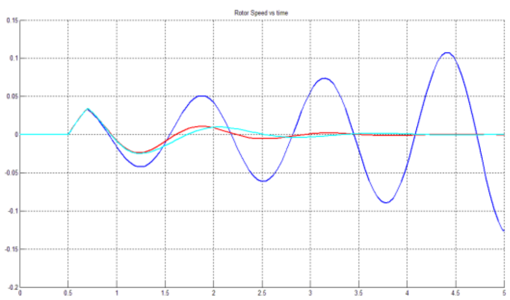


Figure 4 : Operating Point 1

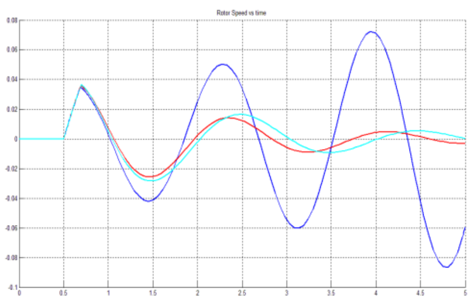


Figure 5 : Operating Point 5

In the end, simulation has been performed on the linear model to access the potential of the proposed algorithm. Figure 4 and 5 shows the system response with the specified disturbance at operating point 1 & 5. It can be seen that the coordinated design approach provides the best damping characteristics and enhances the stability of the system. In figures 6and 7 comparison of rotor speed at different operating points without PSS-SVC, with PSS and with PSS-SVC is shown. Combined scheme of PSS-SVC has better performance damping the oscillations.

VII. CONCLUSION

In this paper, a coordinated approach for enhancing the power system in low frequency oscillations via coordination of Power System Stabilizer (PSS) and Static Var Compensator (SVC) is investigated. For optimal adjustment of control parameters, genetic algorithm optimization technique has been utilized. For improving system stability, three scenarios have been implemented. Without PSS-SVC, with PSS and with PSS-SVC. The last scheme provides the most optimal results. Also, the system stability in different operating conditions (Light, Normal and Heavy) has been examined.

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