

Simultaneous Amplification of Generator Power and Damping of Oscillations using the Static VAR Compensator (SVC)

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Abstract: In this paper, to provide the required grid reactive power the Static VAR Compensator (SVC) is used instead of the reactive power capacity produced by generator. Besides, a PID controller is used in order to control the SVC performance. Despite the fact that the SVC instead of the generator supplies the grid reactive power, however by optimal determination of the controller coefficients, the generator oscillation power which is due to the fluctuations in the grid load can be also preferably controlled. Therefore, the SVC can be applied for reactive power supply in addition to simultaneous damping of oscillations. There are various methods to determine the PID controller coefficients according to the optimization problem. Among all the optimization methods, the Genetic Algorithm is used to determine the controller coefficients due to its simplicity and accuracy. The minimization of the real part of the eigenvalue associated with the generator speed oscillations ($\Delta\omega$) is considered as the target function of optimization problem and this optimization is performed by Genetic Algorithm. As a final point, this idea is implemented on an experimental Single-Machine Infinite Bus (SMIB) system.

Key words: Static VAR Compensator (SVC), Genetic Algorithm, PID Controller.

1. Introduction

In recent years, the increased demands for electricity consumption have resulted in the essential intensification in the power production and transmission; on the other hand the developments of power production as well as the transmission lines emerge to be impractical due to the limited resources. Therefore, the producers of power and transmission lines should effort with their nominal capacities close to the permitted temperature range. The performance of equipments with the nominal capacity makes the system lose its balance due to any external perturbation and consequently creates significant damages in the

systems. To overcome this problem, the Flexible Alternating Current Transmission Systems (FACTS) are designed. These systems by producing oscillations damper signals make the system attenuate the imposed fluctuations and regain the balance after being exposed to an external perturbation. Some instances of FACTS devices include Static VAR Compensator (SVC), Thyristor Controlled Phase Shifter (TCPS), Thyristor Controlled Series Capacitor (TCSC) and Unified Power Flow Controller (UPFC) [1-3]. The main task of such devices is to control the voltage or power distribution in addition to manage system fluctuations by producing damping signals. The Static VAR Compensator (SVC) is one of the many FACTS devices invented in the early 1970s. The main task of SVC is to configure the bus voltage according to the reactive power injection. The presence of controller and its domination over the performance of the SVC attenuate the fluctuations caused by the perturbations and accordingly the system remains stable. Therefore, accurate determination of controller parameters which are generally of PID types is a very significant issue. Prior to the invention of FACTS devices, the Power System Stabilizer (PSS) was used in order to attenuate the generator fluctuations, in the internal structure of which a Low Pass Filter (LPF) and PID controller existed [4]. The process of determining the PSS controller coefficients was performed according to traditional trial and error methods and therefore was very difficult and imprecise. With the advent of smart computational algorithms and their accuracy in the calculations, a greater tendency was created towards these types of algorithms for determining the controller coefficients. Currently, taking into consideration the invention of FACTS devices and smart computational algorithms, the attenuation of fluctuations has become precise and within the numerous articles published in

recent years, the focus is more on the coordinated adjustment of PSS and FACTS devices for further attenuation of oscillations [5-10]. According to the type of power system and the desired target, a variety of FACTS devices can be used and the optimal controller coefficients can be determined. In [5] the authors have used TCSC and PSS simultaneously to increase the damping of power system oscillations and have calculated the controller coefficients by means of the Genetic Algorithm. In [6] the authors have performed the best improvement of reactive power compensation using SVC.

In [7-10] the authors have targeted the correction coefficient of asynchronous motors power using SVC and TCSC. In general, there are several methods for optimal determination of the controllers coefficients. Some of the computational algorithms are: Particle Swarm Optimization Algorithm, Ant Colony Algorithm, Bees Algorithm, and Leap Frog Algorithm. Our objective in this paper is to utilize a SVC in capacitive mode instead of using the generator capacity to produce the required grid reactive power. The SVC can also be shifted to capacitive mode by adjusting the angle of its Thyristor fire. Then, we adjust the coefficients of installed PID controller by Genetic Algorithm in such a way that in case of any perturbation on the system, the controller can extremely attenuate such fluctuations and the system returns to initial state. At the end, we implement this idea on a Single-Machine Infinite Bus (SMIB) system. In order to perform the Genetic Algorithm program we use MATLAB TOOLBOX, the application of which is very simple instead of using FORTRAN.

2. Static VAR Compensator (SVC)

SVC is one of the FACTS devices used to produce reactive power and is installed in parallel. SVC can be obtained from the parallel setting of a Thyristor Controlled Reactor (TCR) with a capacitor. By controlling the angle of Thyristor fire, it can be used both in capacitive and inductive modes and our goal in this paper is the application of capacitive mode. The rate of the current passing through the TCR can be obtained via Equation (1).

$$I_{LF} = \frac{V}{L\omega} \left(1 - \frac{2}{\pi} \alpha - \frac{1}{\pi} \sin(2\alpha)\right) \quad (1)$$

in which α is the angle of Thyristor fire, V is both sides voltage of TCR, L is the inductive inductance and ω is the angular frequency of the grid connected to TCR. According to Equation (1) the admittance can be obtained through the following relationship.

$$Y_L(\alpha) = \frac{1}{L\omega} \left(1 - \frac{2}{\pi} \alpha - \frac{1}{\pi} \sin(2\alpha)\right) \quad (2)$$

Now if we set in parallel a capacitor with TCR, the total admittance will be equal to $Y_{SVC} = -jY_C + jY_L$. It is obvious that by adjusting the angle of α fire the SVC functional mode can be changed. The SVC structure described above is shown in Fig. 1.

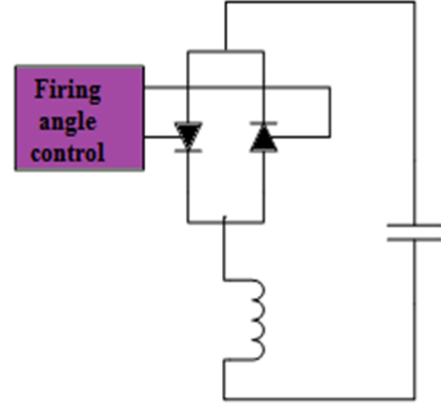


Fig. 1. Internal Structure of SVC

3. Lineated Power System Model

3.1. Generator

In this study a Single-Machine Infinite Bus (SMIB) system is considered as Fig. 2. The generator is equipped with a PSS along with a SVC which operates in the capacitive mode connected to the generator bus and generator includes pss circuit. the line impedance is equal to $R + jX$. The generator is shown by the third order model called Heffron-Phillips Model which includes electromechanical oscillations equations and generator internal voltage equations [4]. The equations of electromechanical oscillations include the following:

$$\dot{\Delta\delta} = \omega_0(\Delta\omega) \quad (3)$$

$$\dot{\Delta\omega} = \frac{1}{2H}(\Delta P_m - \Delta P_e - K_D \Delta\omega) \quad (4)$$

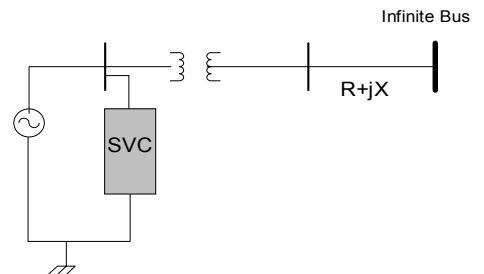


Fig. 2. The Experimental System

in which ΔP_m and ΔP_e are the changes in generator input and output power, $2H$ and D are respectively the inertia and damping coefficients, $\Delta\omega$

and $\Delta\delta$ are the speed and angle of the generator and ω_0 is the synchronous speed. The output electrical power of the generator can be written based on d and q axis components, armature current i and terminal voltage v as follows:

$$P_e = v_d i_d + v_q i_q \quad (5)$$

The E'_q internal voltage equation is as follows.

$$\dot{E}'_q = \frac{1}{T'_{d0}} (\Delta E_{fd} - (x_d - x'_d) \Delta i_d - \Delta E'_q) \quad (6)$$

In which ΔE_{fd} is the field voltage, T'_{d0} is the time constant of open circuit, x_d and x'_d are the reactance and transient reactance of d axis.

3.2. Power System Stabilizer (PSS)

The block diagram shown in Fig. 3 is considered as the power system stabilizer.

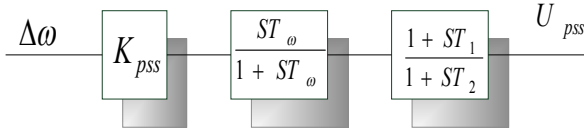


Fig. 3. Block Diagram of PSS

The structure shown in this diagram includes a gain block K_{pss} , a washout block with time constant T_ω , and a phase compensating block with time constants T_1 and T_2 . The input signal of $\Delta\omega$ is the speed deviation and the output signal of U_{PSS} is the stabilizer signal. This system will be added to Heffron-Philips Model in continuation.

3.3. SVC Controller

The SVC controller block diagram is shown in Fig. 4. As it can be seen, it is a PID controller in which K_{svc} is the controller gain and T_4 , T_5 are time constants. The controller input signal $\Delta\omega$ and output signal Δx_{svc} provide the SVC capacity deviation to stabilize the oscillations.

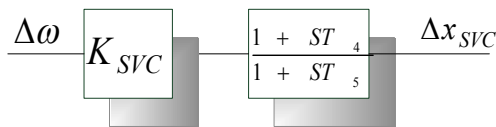


Fig. 4. SVC Block Diagram

3.4. Lineared Model

In order to design a controller which can attenuate swiftly the system oscillations, generally the non-linear

system equations will be lineated around one point of the operation [4]. In general, the lineated system can be stated as follows:

$$\dot{X} = AX + BU \quad (7)$$

in which the state vector is $[\Delta\delta, \Delta\omega, \Delta E'_q, \Delta E_{fd}]^T$ and the inputs vector is $[\Delta P_m, V_{ref}]$. V_{ref} is a reference voltage at which the generator voltage should always be remained. The block diagram model of the lineared power system is displayed in Fig. 5, and $K_1 - K_6$, K_p , K_q , K_v are defined as Equation (8).

$$K_1 = \frac{\Delta P_e}{\Delta\delta} \quad K_2 = \frac{\Delta P_e}{\Delta E'_q} \quad K_p = \frac{\Delta P_e}{\Delta X_{svc}} \quad (8)$$

$$K_3 = \frac{\Delta E_q}{\Delta E'_q} \quad K_4 = \frac{\Delta E_q}{\Delta\delta} \quad K_q = \frac{\Delta E_q}{\Delta X_{svc}}$$

$$K_5 = \frac{\Delta V}{\Delta\delta} \quad K_6 = \frac{\Delta V}{\Delta E'_q} \quad K_v = \frac{\Delta V}{\Delta X_{svc}}$$

4. Formulation of the Problem

In this article, the cleaner block is disregarded and the determination of PID, PSS, (K_{pss}, K_{svc}) controller gains and the time constants T_1, T_2, T_4, T_5 are considered. It is necessary to mention that the two output signals $U_{PSS}, \Delta X_{svc}$ are zero when the system works in steady states. But once there is a perturbation in the system, the signals according to the generator speed variations attenuate together the fluctuations. In this problem, the determination of the presented SVC and PSS coefficients are conducted via Genetic Algorithm. In order to shift the system oscillations toward damping, the real part of electromechanical mode associated with the generator speed should be drawn as much as possible to the left side of the imaginary axis in the complex space. Therefore, the objective function considered in this problem for the minimization is simply the real part of generator speed electromechanical mode. The famous modal analysis method is used to obtain this mode. The calculations are done using the MATLAB software version 2009a[11]. First, using the eig command we specify the system eigenvalue and then we multiply the obtained vectors to the vector in which only the first determinant is one and the rest are zero, so that the eigenvalue of generator speed will be obtained.

$$[1 \ 0 \ 0 \ \dots] * \text{eig}(A) \quad (9)$$

It is clear that eig is a perpendicular vector and the number of its columns is equal to the number of rows in the multiplied row matrix. If the optimization is not

limited in this problem, the obtained values may be large and thus the system response will be slow or even negative values may be obtained for time constants and this is also unacceptable. Thus, we have to limit these values as follows:

$$0 < T_1, T_2, T_4, T_5 < 2 \quad (10)$$

But we do not limit the gain values so that the Genetic Algorithm will have a broader space to search.

5. Review of Genetic Algorithm

The Genetic Algorithm is a search tool and useful method for optimization. One of the best features of the Genetic Algorithm is that it needs the minimum amount of information about the problem for optimization and also needs no auxiliary conditions such as the existence of derivatives and boundary conditions and the only desired criterion is the objective function. This Algorithm in each computational replicate (generation) works out on the population of chromosomes (possible answers) and using the genetic operators; Mutation, Cross-over and Perturbation performs random variations on the set of chromosomes. Then among the obtained answers based on the proximity to the desired criteria, it is used to produce the next generations.

5.1. Cross-over

The cross-over is an operation which works out on the two chromosomes of the existing population and will change their characteristics randomly. The chromosomes resulting from this action are new answers which are considered the children of previous chromosomes because they hold many characteristics of the previous chromosomes.

5.2. Mutation

Mutation is an action which works out on one of the chromosomes and will change its properties randomly in the mutation point. This stands for the gene change in the selected chromosome. The speed of mutation is determined by the user. If the mutation speed is high, the children inherit fewer characteristics from parents. In the moments which the question is close to answer, the impact of the mutation operator is more than cross-over operator. In fact, this operator prevents the desired function moving towards the optimum local points (local minimums).

5.3. Perturbation

This operator along with very small changes in the chromosomes can well create new chromosomes similar to the mutation operator which can help the convergence of the problem. The children of this operator are added to the next generation.

5.4. Selection

The selection is an operation in which the chromosomes of the next generation are determined from the current population based on the Survival of the Fittest Idea. This factor is the most important stage in the Genetic Algorithm and plays an important role in this Algorithm. There are several methods for this operation and there is a section available in MATLAB TOOLBOX with the same title so the user can select one of them according to his/her preference. Among these methods the Roulette Wheel and Tournament can be stated.

6. The Experimental System

The experimental system is shown in Fig. 2. This system consists of the following components.

- 1) A generator with the task to supply the required grid power.
- 2) SVC installed to provide the required grid reactive power and causes the generator to quit the sub-stimulatory mode and to decrease the pressure in load peak hours.
- 3) The transformer installed to raise the transmission power voltage and to reduce the loss.
- 4) Transmission line
- 5) Infinite bus which is a status display of the extensive grid connected to the transmission line.

In the Appendix section, the parameters of the desired system are presented.

7. Application of the Genetic Algorithm in Optimization Problem

In this section, by means of the Genetic Algorithm we seek to investigate whether the SVC can attenuate severe fluctuations all alone and whether the coordination between PSS and SVC can affect the oscillations damping in the system. To solve this problem we refer first to the third order generator model, i.e. Heffron- Philips Model (Fig. 5). First, we obtain the model parameters with analyzing the power, and then using the obtained model we note down the state equations of the system. After the entries of state equations and obtaining the Matrix A (in which the coefficients of controllers are listed as parameter) by making use of the modal analysis and eig command in MATLAB software we can define the desired function in the Genetic Algorithm. The Flowchart in Fig. 6 demonstrates properly the performance of these stages. The parameters values related to the Heffron-Phillips Model are specified in Table 1. The above stages were performed first on a system in which only the SVC was used and the Genetic Algorithm calculated the SVC optimized parameters as presented in Table 2.

Table 1
The Parameters Values of Heffron Phillips Model

| | | | | | |
|-------|-------|-------|-------|-------|-------|
| K_1 | K_2 | K_3 | K_4 | K_5 | K_6 |
| 1.14 | 1.41 | .34 | 2.044 | -.098 | .3216 |
| K_p | K_q | K_v | K_A | T_A | T_3 |
| -.008 | -.041 | -.027 | 100 | .25 | 2.725 |

Table 2
Optimal Values of SVC Parameters

| | | |
|-----------|-------|-------|
| K_{SVC} | T_4 | T_5 |
| 6.856 | 2 | .012 |

It is necessary to mention that the form of the waves related to $\Delta\omega$ and $\Delta\delta$ when there is no control is presented in Fig. 7. As it is clear, the system is highly oscillatory and the amplitude increases over time. Fig. 8 is associated with the waveforms when the SVC is used all alone to attenuate the fluctuations and Fig. 9 shows the convergence of Genetic Algorithm. As it can be seen, the fluctuations are decreasing over time, but its weak decreasing trend is not acceptable. In the next

stage, the SVC and PSS are used simultaneously. The optimum values are given in Table 3.

Table 3
Values of PSS and SVC Coordinated Adjustment using Genetic Algorithms

| | | |
|-----------|-------|-------|
| K_{PSS} | T_1 | T_2 |
| 33.511 | 1.974 | 0 |
| K_{SVC} | T_4 | T_5 |
| -5.969 | 1.837 | 0.015 |

In Fig. 10 the waveforms related to PSS and SVC coordinated adjustment are presented and Fig. 11 shows the convergence of related Genetic Algorithms. As Fig. 10 indicates, the PSS and SVC coordinated adjustment could very well attenuate the oscillations. It is necessary to mention that all of these fluctuations are with the assumption of short circuit occurrence in the system causing the passage of a circuit from the generator terminal which is ten times bigger than the rated current.

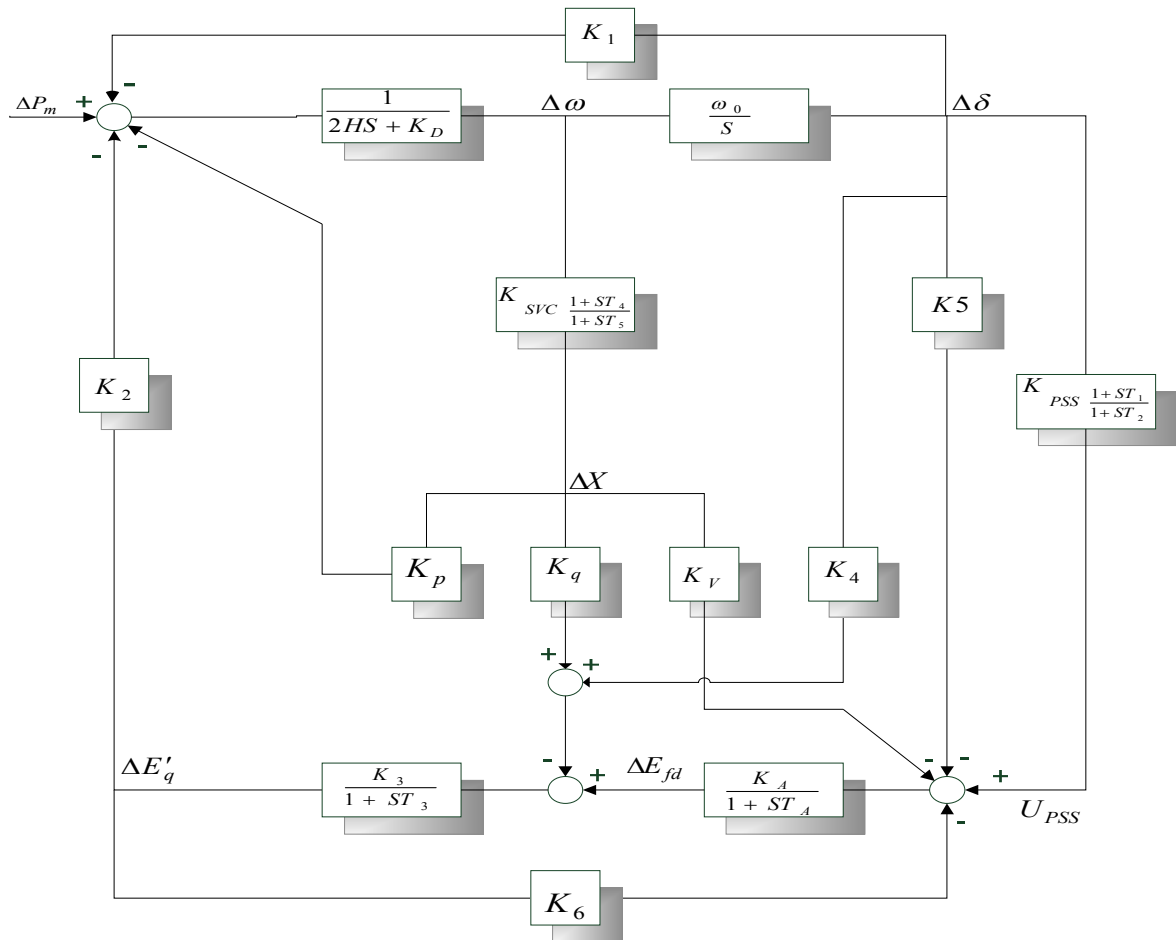


Fig. 5. Heffron-Phillips Model of Generator along with Extra Controllers

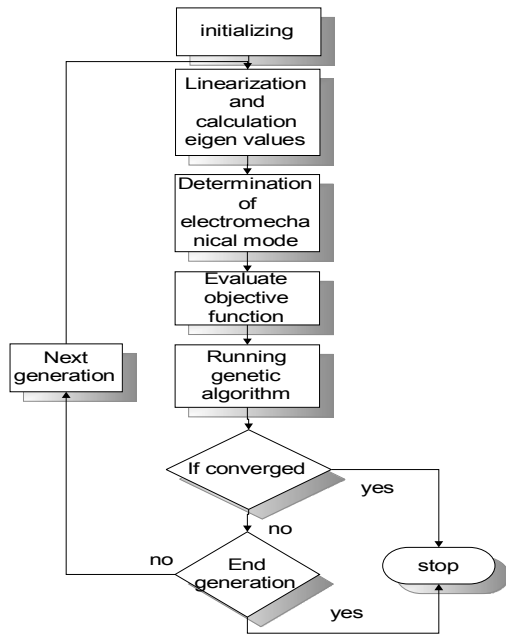


Fig. 6. Genetic Algorithm Flowchart

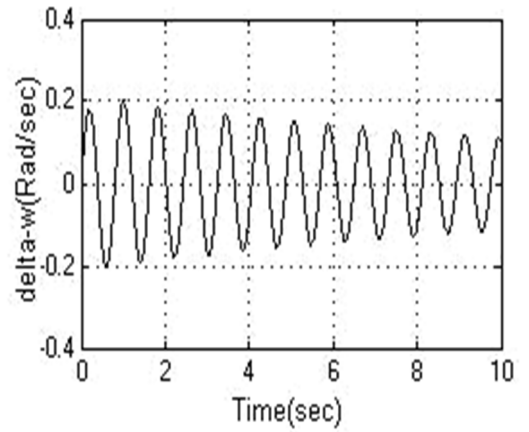


Fig. 8.a. $\Delta\omega$ Changes in the Absence of SVC

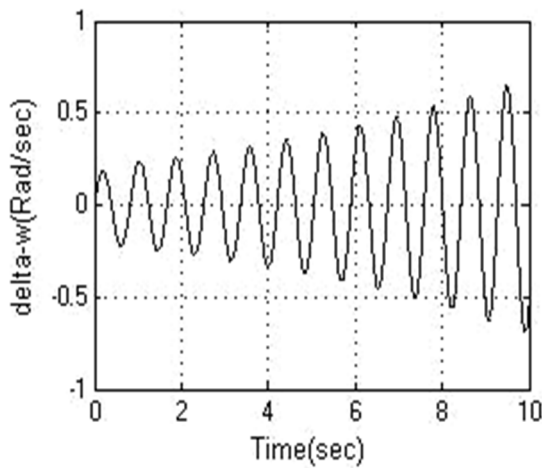


Fig. 7.a. $\Delta\omega$ Changes without Controller

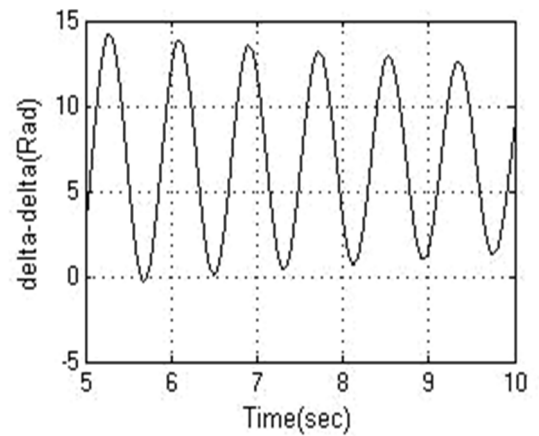


Fig. 8.b. $\Delta\delta$ Changes in the Presence of SVC

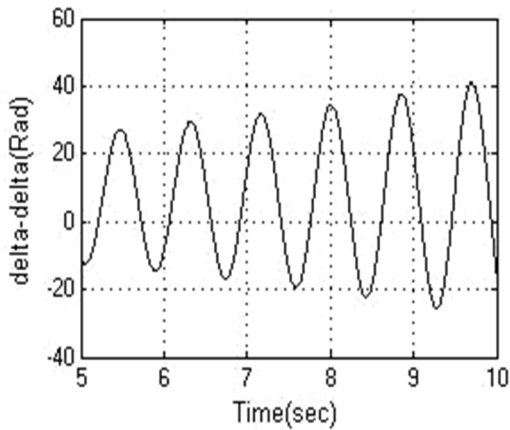


Fig. 7.b. $\Delta\delta$ Changes without Controller

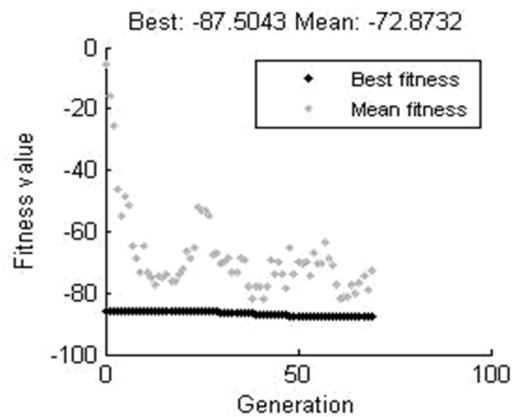


Fig. 9. The Convergence of Genetic Algorithm with SVC

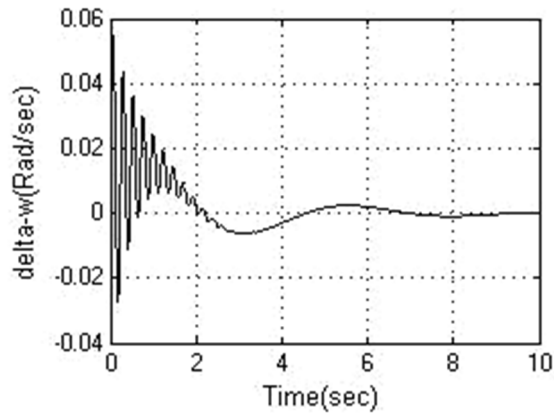


Fig. 10.a. $\Delta\omega$ Changes with Coordinate Adjustment

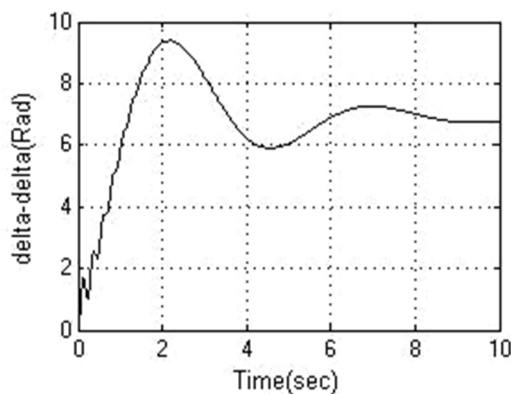


Fig. 10.b. $\Delta\delta$ Variations with the Coordinated Adjustment

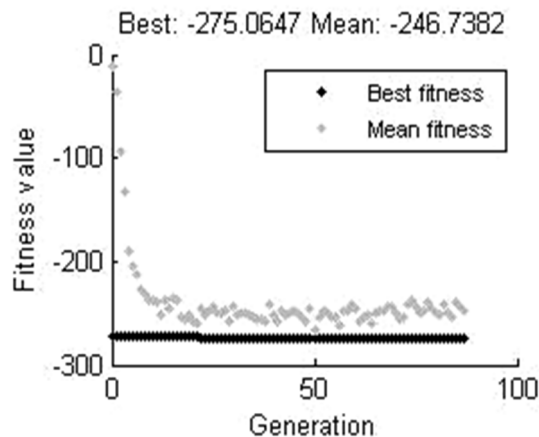


Fig. 11. Convergence of Genetic Algorithm with Coordinated Adjustment

8. Conclusion

The main objective of this paper was to apply the SVC reactive power capacity in capacitive mode instead of using the generator reactive power capacity. Then we decided to set the SVC controlling parameters by means of the Genetic

Algorithm in such a way that the damping of oscillations is maximized. By optimal adjustment we witnessed that damping was obtained but the damping process was slow and unacceptable. Then we carried out an optimum setting between PSS and SVC controllers and by applying these parameters in the MATLAB-SIMULINK software environment and obtaining the relevant waveforms, we observed that the oscillations were desirably attenuated and consequently our idea is performable. It is necessary to mention that the above stages are implemented on the experimental system shown in Fig. 2 and its parameters are given in the Appendix.

Appendix

The parameters of our experimental system are as follows.

| | | | | | | |
|-----|-------|-------|-----------|-------|-------|-----------|
| P | Q | U_t | x'_d | x_d | H | R_a |
| 0.9 | 0 | 1 | 0.3 | 1.81 | 3.5 | 0 |
| f | x_q | k_D | T'_{d0} | x_L | x_t | x_{svc} |
| 60 | 1.76 | 0 | 8 | 0.25 | 0.15 | 3.33 |

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