Optimal PI Controller Design and Simulation of a Static Var Compensator Using MATLAB's SIMULINK

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Abstract: - This paper presents graphic-based simulation and optimal PI controller design of a static var compensator (SVC) using MATLAB's SIMULINK. Utilization of MATLAB software simplifies problem solving complexity and also reduces working time. In this paper, an optimal PI controller design using genetic algorithms for the SVC was demonstrated. From which satisfactory controller design results, tests against power and three-phase fault disturbances were carried out. Also, comparisons between those results obtained by i) SVC with the PI controller and by ii) using power system stabilizer were examined to evaluate its effectiveness.

Key-Words: - PI Controller, Genetic Algorithms, Static Var Compensator, Power System Stabilizer

1 Introduction

To date under modern deregulated power market environment electric utility has become increasingly much more complex than the past. Apart from economic view point, stability problems are equally important to operate electric power system in real time [1]. The impedance of an electric power transmission system and a large amount of reactive power drawn by loads cause imperfection of power system operation, e.g. voltage drop, power losses, voltage/frequency swing, etc. Static var compensator (SVC) is one of FACTS (flexible AC transmission system) devices. It was first invented in the early 1970s [2]. The main function of the SVC is to regulate bus voltage across a protected load due to reactive power loading. When load voltage variation is detected, an SVC controller will perform the compensation by changing its susceptance in order to diminish this oscillation. To handle any stability-related problems accurate parameter estimation of the SVC is concerned and also parameters of the SVC controller, for example PI or PID type [3]. Although, from literature [3-8], there exist several research works describing procedure of designing such a controller, those are based on numerical computing coded in some programming language such as FORTRAN or C/C++, in which user-friendly GUI (graphic user interface) is rarely found.

As the long history of numerical techniques for solving engineering design problems, it has become widely-used GUI software, named MATLAB™ [9]. MATLAB originated in the late 1970s as a "matrix laboratory" for use in matrix algebra and numerical computation. Today, MATLAB consists of several software features in order to enhance its computing ability. MATLAB's SIMULINK is a tool for modeling, simulating, analyzing and designing multi-domain dynamic systems [10]. It provides several interactive graphical block diagramming tools. With its capabilities, controller design of a dynamic system based on any modern intelligent techniques such as genetic algorithms (GAs) is available. Engineers can observe and evaluate their designed parameters by simulating its associated SIMULINK block diagram. Together with MATLAB's GADS (genetic algorithms and direct search) TOOLBOX [11], the intelligent parameter design can be implemented in GUI environment.

This paper illustrates the way to apply the GAs to solve an optimal PI controller design problem of the SVC in order to regulate voltage variation caused by power loading and fault conditions. The basic concept and structure of the SVC and its linearized controller are explained in detail in section 2. Section 3 gives a brief of the step-by-step intelligent parameter estimation based on the GAs. Section 4 demonstrates an SVC model by using SIMULINK. This section also presents simulation results of various test case scenarios. Comparisons against those results obtained by SVC with a PI controller and by power system stabilizer (PSS) [1,12,13] are also included in this section. Discussion and conclusion are in section 5.

2 Linearized Control of Static Var Compensators

SVC is a typical shunt-connected reactive power compensator, consisting of thyristor-switched capacitors (TSCs) and thyristors-controlled reactors (TCRs) as shown in Fig. 1. For simplification, power system oscillation stability and control can be studied by using linearized power system models. Fig. 2 shows a single machine connected to an infinite bus power system (SMIB system). It can be described according to the non-linear differential equations from which the traditional Phillips-Heffron linear model [2,6] as shown in (1) – (4) for the system without the SVC.

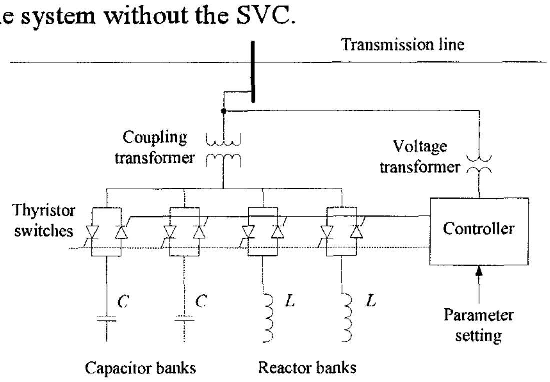

Fig. 1. Structure of the SVC

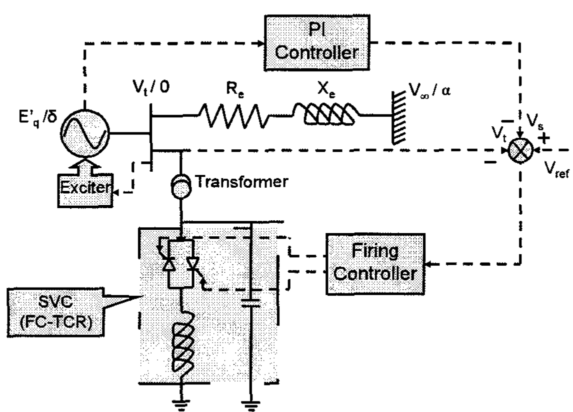

Fig. 2. SMIB system with SVC

$$\dot{\delta} = \omega_0 \Delta\omega \tag{1}$$

$$\Delta\dot{\omega} = \frac{(P_m - P_e - D\Delta\omega)}{2H} \tag{2}$$

$$\dot{E}_q' = \frac{(-E_q + E_{qe})}{T_{do}'} \tag{3}$$

$$\dot{E}_{qe} = K_A \frac{(V_{to} - V_t)}{1 + sT_A} \tag{4}$$

..., where

$$P_e = \frac{E_q' V_b \sin\delta}{X_{d\Sigma}'} - \frac{V_b^2 (X_q - X_d') \sin 2\delta}{2X_{d\Sigma}' X_{q\Sigma}} \tag{5}$$

$$E_q = \frac{X_{d\Sigma} E_q'}{X_{d\Sigma}'} - \frac{(X_d - X_d') V_b \cos\delta}{X_{d\Sigma}'} \tag{6}$$

$$V_{td} = \frac{X_q V_b \sin\delta}{X_{q\Sigma}} \tag{7}$$

$$V_{tq} = \frac{X_L E_q'}{X_{d\Sigma}'} + \frac{V_b X_d' \cos\delta}{X_{d\Sigma}'} \tag{8}$$

$$X_{d\Sigma}' = X_d' + X_L \tag{9}$$

$$X_{q\Sigma} = X_q + X_L \tag{10}$$

$$X_{d\Sigma} = X_d + X_L \tag{11}$$

X_L reactance of the transmission line
X_d d-axis reactance of the machine
X_d' d-axis transient reactance of the machine
X_q q-axis reactance of the machine
X_q' q-axis transient reactance of the machine

When an SVC is installed in the system, (5) – (8) must be modified to include the effect of the installed SVC with a reactance of X_{SVC} on the overall system performance. Define C and X_{TL} in (12) and (13). Therefore, derived equations for reactive power compensation by using the SVC in the SMIB system can be expressed as follows.

$$C = 1 - \frac{X_L}{X_{SVC}} \tag{12}$$

$$X_{TL} = \frac{X_L}{C} = \frac{X_L}{1 - \frac{X_L}{X_{SVC}}} \tag{13}$$

$$P_e = \frac{E_q' V_b \sin\delta}{C X_{d\Sigma}'} - \frac{V_b^2 (X_q - X_d') \sin 2\delta}{2C^2 X_{d\Sigma}' X_{q\Sigma}} \tag{14}$$

$$E_q = \frac{X_{d\Sigma} E_q'}{X_{d\Sigma}'} - \frac{(X_d - X_d')V_b \cos\delta}{C X_{d\Sigma}'} \quad (15)$$

$$V_{td} = \frac{X_q V_b \sin\delta}{C X_{q\Sigma}} \quad (16)$$

$$V_{tq} = \frac{X_L E_q'}{X_{d\Sigma}'} + \frac{V_b X_d' \cos\delta}{C X_{d\Sigma}'} \quad (17)$$

By linearizing (14) – (17) at a given operating condition, the Phillips-Heffron linearized model for the SMIB with the SVC [2,6] can be obtained as shown in Fig. 3.

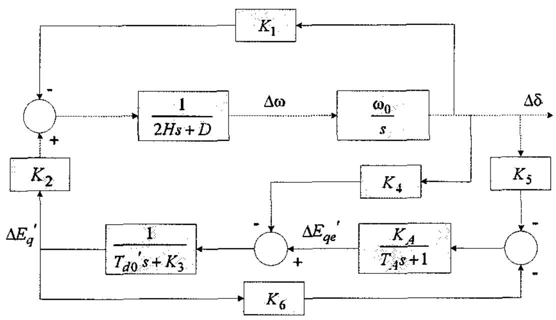

Fig. 3. Simplified control block diagram of the SMIB system without SVC

The control block diagram of the SMIB system without the SVC can be depicted in Fig. 3. It defines an uncompensated system for this paper. When the SVC is connected to the SMIB system, it depends on selection of its controller. Although there exist many efficient control schemes to perform this compensation, only a PI controller is chosen for study. With the PI control structure as shown in Fig. 4, two parameters, K_P and K_I, must be tuned in order to minimize voltage oscillation in both magnitude and frequency swings. Combined with the PI controller to control the SVC operation, the control block diagram of the SMIB system with the SVC is illustrated as shown in Fig. 5.

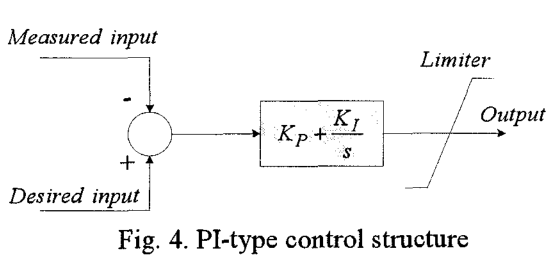

Fig. 4. PI-type control structure

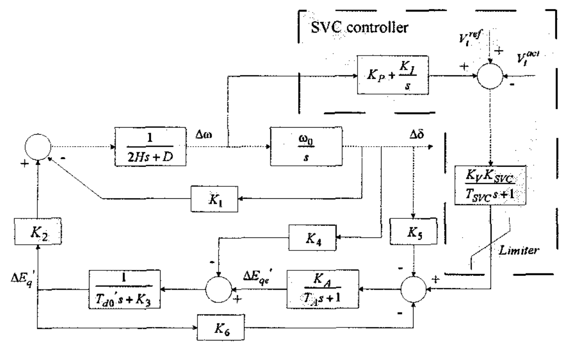

Fig. 5. SMIB system with the SVC-PI controller

3 Intelligent Parameter Tuning Based on Genetic Algorithms

There exist many different approaches to tune controller parameters. The GAs is well-known [11,13-15] there exist a hundred of works employing the GAs technique to design the controller in various forms. The GAs is a stochastic search technique that leads a set of population in solution space evolved using the principles of genetic evolution and natural selection, called genetic operators e.g. crossover, mutation, etc. With successive updating new generation, a set of updated solutions gradually converges to the real solution. Because the GAs is very popular and widely used in most research areas [6,14-15] where an intelligent search technique is applied, it can be summarized briefly as shown in the flowchart of Fig. 6 [15].

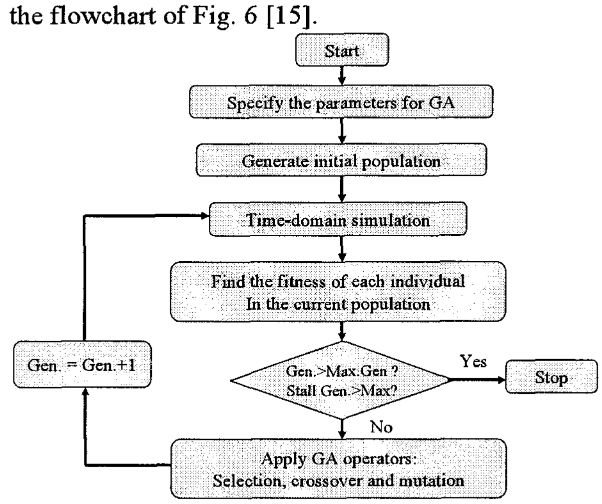

Fig. 6. Flowchart of the GAs procedure

In this paper, the GAs is selected to build up an algorithm to tune K_P and K_I parameters. The procedure to perform the proposed parameter tuning is described as follows. First, time-domain results of magnitude and frequency swing obtained by simulating the SMIB system in SIMULINK are obtained. Second, the Genetic Algorithms (GADS

TOOLBOX) is employed to generate a set of initial random parameters. With the searching process, the parameters are adjusted to give response best fitting close to the desired response. To perform the searching properly, its objective function is the key. In this paper, the objective function is defined in (18).

$$\int_{0}^{t_{sim}} t\left|\Delta\omega(t)\right|dt \qquad (18)$$

..., where

$y_{desired}$ is the desired response

$y_{simulated}$ is the simulated response

4 Results and Discussion

The SMIB system as shown in Fig. 2 was employed. According to those described in Section 2, system parameters characterizing the SMIB system are presented in Table 1 in both cases (with SVC-PI controller and with PSS).

Table 1. System parameters

K_1	K_2	K_3	K_4	K_5
0.5995	0.9263	0.5294	0.4319	-0.0878
K_6	$K_V K_{SVC}$	H	D	T_{d0}'
0.6004	10.00	4.00	0.00	5.044
X_d	X_q	X_d'	K_A	T_A
1.00	0.60	0.30	50.00	0.05

By using MATLAB's SIMULINK, the control block diagram of each test case can be formed graphically. Although this model can be written in other programming codes such as C/C++, FROTRAN, or even MATLAB programming codes, these programs are usually complex and difficult to debug. In addition, it takes very long editing time to modify the programming codes in order to perform a different task. In this paper, a control model for each case is presented in Figs. 7 and 8 for the SMIB without and with the SVC, respectively.

In this paper, the PI parameter tuning was performed by using the GAs. The success of the tuning is associated with the GA's parameter setting. The following is a set of parameters used in this research.

GA's parameter setting

Population size	20
Crossover probability	80%
Mutation probability	1.0%
Maximum generation counted	1000
Maximum generation stalled	50

Variable ranges $0.1 \leq K_P, K_I, \leq 150$

Objective function (discretized version):

$$\text{Minimize} \qquad \sum_{i=1}^{N} t_i \left|\Delta\omega(i)\right|$$

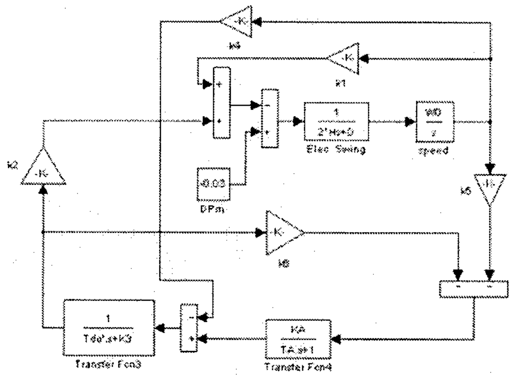

Fig. 7. Control block diagram of a simplified SMIB formulated by using MATLAB' SIMULINK

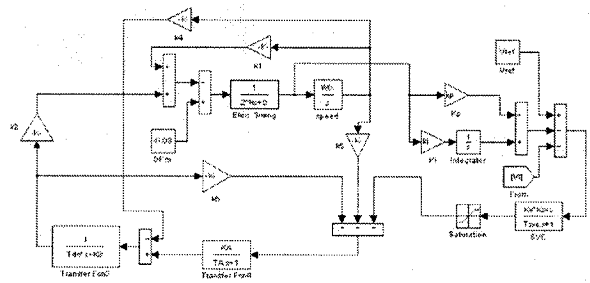

Fig. 8. Control block diagram of the SMIB with SVC-PI controller formulated by using MATLAB's SIMULINK

By using MATLAB's SIMULINK, the simulation can be done easily. However, due to its simplification, several adjustments during its numerical computing procedure cannot be changed by users. One of frequent errors found by using the SIMULINK is the mismatch of time stepping. To guarantee accuracy and stability of simulated results, variable time stepping is applied to most of SIMULINK numerical computation block, for example the ODE solver. Different value of K_P and K_I leads to a different number of sampling after the simulation. For example, given that the simulation time span is set to 0.0 – 1.0 second. If the K_P and K_I are 1.0 and 10.0 respectively, the simulation produces a 1000×1 array for variable x. By adjusting the value of the K_P and K_I to 2.5 and 5.0 respectively, the variable x becomes a 1150×1 array for this case. This results in computational inaccuracy of the objective function. To play with this inaccuracy, linear interpolation [19] of every simulated output is required. If a 1000×1 array of variable x is selected, all x obtained by the simulation must be interpolated to give a corresponding value at fixed 1000 positions of the simulated time span. Fig. 9 describes this interpolation. The circles on the graph indicate fixed positions of the interpolation, while the triangles present points obtained by simulating the SIMULINK model. Using the linear interpolation, the squares estimating the simulated outputs at given positions can be calculated.

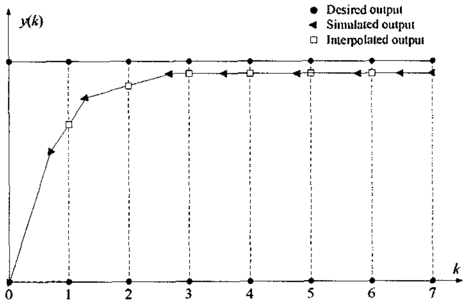

Fig. 9. Linear interpolation to estimate simulated output obtained by using SIMULINK

With 30 computational trials in case of the parameter tuning based on the GAs, one trial is selected to present the convergence characteristic of the PI tuning algorithm as shown in Fig. 10. In addition, the best parameters obtained from each case are put in Table 2.

Table 2. Best PI parameters for each test case

Case	K_P	K_I	Cost
1. NI case	1.0167	11.9559	3.12×10^{-6}
2. IP case	0.3474	11.3270	3.23×10^{-6}

NI case denotes non-interpolation case
IP case denotes interpolation case

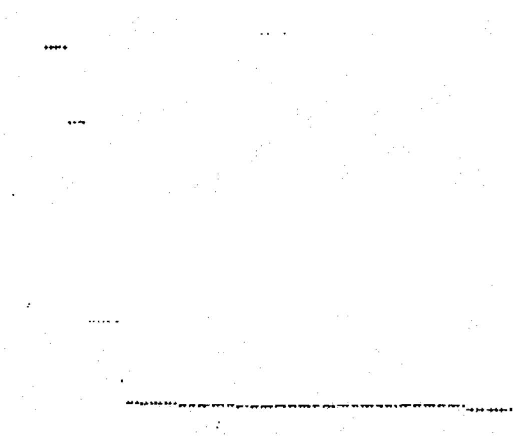

Fig. 10. Convergence of the PI parameter tuning using MATLAB's GADS TOOLBOX for the first 100 consecutive generation

To evaluate the effectiveness of the design algorithm, tests against i) power and ii) three-phase fault disturbances are situated. The obtained results of the power disturbance case are shown in Figs. 11 and 12 for the generator speed and the generator terminal voltage variations, respectively. In the same manner, Figs. 13 and 14 also present the simulated results of the three-phase fault disturbance case.

As a result, responses due to some disturbances given in this paper are stabilized and fast when the optimal PI parameter with linear interpolation in order to solve a problem of computational inaccuracy is taken into account. Furthermore, it gives the best response compared with the others.

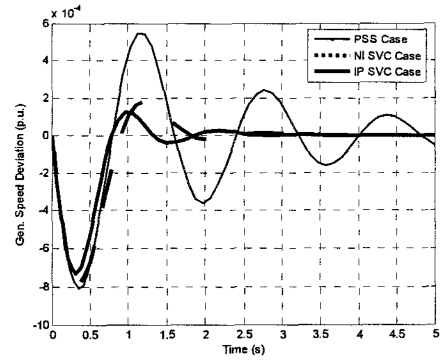

Fig. 11. Generator speed variation due to the power disturbance test case

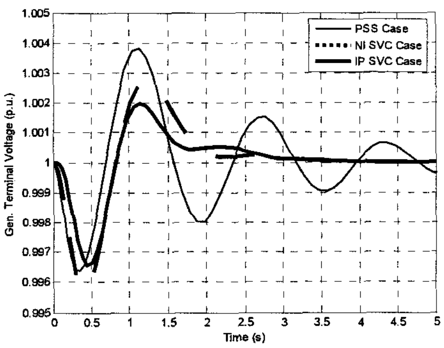

Fig. 12. Generator terminal voltage variation due to the power disturbance test case

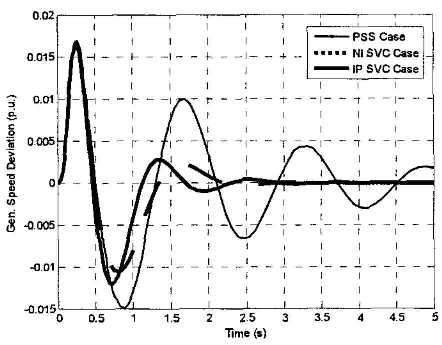

Fig. 13. Generator speed variation due to the three-phase fault disturbance test case

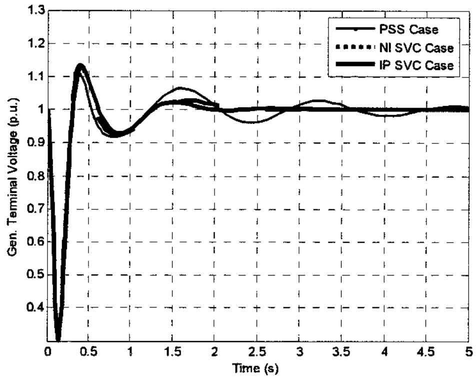

Fig. 14. Generator terminal voltage variation due to the three-phase fault disturbance test case

5 Conclusion

This paper illustrates the utilization of MATLAB's SIMULINK to optimal PI controller design for a static var compensator, which is connected to an infinite bus power system. The proposed design includes linear interpolation of every simulated output to distribute all state variables uniformly over all fixed points of calculation. The computational inaccuracy can be eliminated. In addition, the simulation results confirm that the optimal PI controller design using the GAs together with linear interpolation to enhance computational inaccuracy gives good performances due to both power and three-phase fault disturbances.

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