Robust STATCOM Controller Design Using Genetic Algorithms

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***Abstract*—Static synchronous compensator (STATCOM) controls are known to enhance damping of a power system. The graphical loop-shaping procedure used in designing a robust STATCOM controller can be significantly improved by embedding some optimization procedure in it. In this article a Genetic Algorithms (GA) technique has been employed to find the fixed parameter robust controller parameters. GA based robust control design greatly reduces the computational effort compared to the manual graphical techniques. Simulation studies on a simple power system indicate that the designed controller provides very good damping properties.**

I. Introduction

It is well established that flexible ac transmission system (FACTS) devices can improve both transient as well as dynamic performances of a power system. These devices dynamically control the power flow through a variable reactive admittance to the transmission network and, therefore, generally change the system admittance. Controllable synchronous voltage sources, known as static synchronous compensator (STATCOM) are a recent introduction in power systems for dynamic compensation and for real time control of power flow. The STATCOM provides shunt compensation in a similar way to the static var compensators but utilizes a voltage source converter rather than shunt capacitors and reactors [1, 2].

It has been reported that STATCOM can offer a number of performance advantages for reactive power control applications over the conventional approaches because of its greater reactive current output capability at depressed voltage, faster response, better control stability, lower harmonics and smaller size, etc. [3,4].

Auxiliary signals in the STATCOM control circuit is known to improve the dynamic performance of a power system [3-5]. Such control strategies, which are robust in nature, have also been investigated [7-9]. A simple loop-shaping method, which yields a fixed parameter robust controller, has been investigated recently [7, 8]. The controller has been shown to provide very good damping characteristics. The graphical loop-shaping method involves a trial and error procedure. The success of the design depends, to a large extent, on the experience of the designer. For uncertain, unstable, and non-minimum phase plants, it is difficult to design a controller manually to satisfy all stability specifications. Also, designing a controller manually by loop-shaping technique for higher order systems like multi-machine power system can be quite a complicated task.

The convergence of the graphical loop-shaping method can be accelerated by embedding some optimization procedure in it. In this article, a Genetic Algorithm (GA) technique has been used for the design automation. Simulation studies carried out on a simple power system indicate that the GA embedded optimum robust control design provides very good damping to the power system.

II. The Power System Model

A single machine infinite bus system with a STATCOM installed at the mid-point of the transmission line is shown in Fig. 1. The dynamics of the generator is expressed in terms of the second order electromechanical swing equation and the internal voltage equation. The IEEE type-ST is used for the voltage-regulator excitation system. These are,

$$\begin{aligned}
\dot{\delta} &= \omega - \omega_o \\
\dot{\omega} &= -\frac{1}{M}[P_m - P_e - D(\omega - \omega_o)] \\
\dot{e}_q^{'} &= \frac{1}{T_{do}^{'}}[E_{fd} - e_q] \\
\dot{E}_{fd} &= -\frac{1}{T_A}(E_{fd} - E_{fdo}) + \frac{K_A}{T_A}(V_{to} - V_t)
\end{aligned} \quad (1)$$

Here, ω and δ are the generator speed and rotor angle while $e_q^{'}$ and E_{fd} represent the generator internal voltage and field voltages, respectively.

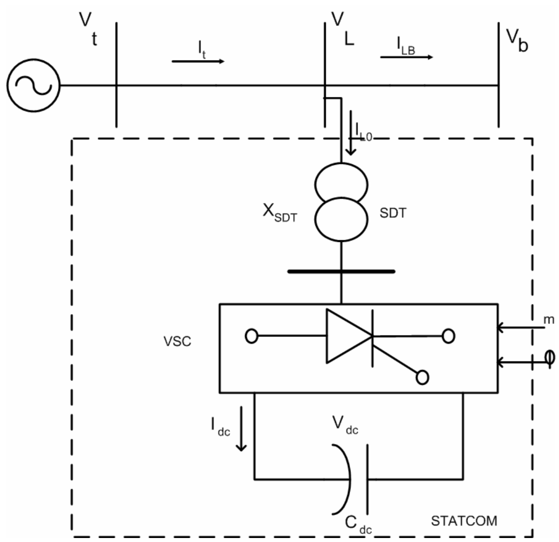

Fig. 1. Single machine infinite bus power system with STATCOM

The STATCOM system consists of a step down transformer (SDT) with a leakage reactance X_{SDT}, a three phase GTO-based voltage source converter, and a D.C. capacitor. The dynamic relation between the capacitor voltage (V_{dc}) and current (I_{dc}) in the STATCOM circuit are expressed as [3, 6],

$$\frac{dV_{dc}}{dt} = \frac{I_{dc}}{C_{dc}} = \frac{m}{C_{dc}}\left(I_{Lod}\cos\psi + I_{Loq}\sin\psi\right) \quad (2)$$

I_{Lod} and I_{Loq} are the direct and quadrature axes components of STATCOM current I_{Lo}. The output voltage phasor is

$$\overline{V}_o = mV_{dc}\angle\psi \quad (3)$$

Here, m is the modulation index and ψ is the phase angle.

For a choice of the state and control vectors as $\left[\Delta\delta\ \Delta\omega\ \Delta e'_q\ \Delta E_{fd}\ \Delta V_{dc}\right]^T$ and $\left[\Delta m\ \Delta\psi\right]^T$ the nonlinear state equations (1-2) for the system can be expressed as,

$$\dot{x} = f(x,u) \quad (4)$$

III. THE ROBUST CONTROLLER DESIGN USING LOOP-SHAPING

The robust control design for the generator-STATCOM system starts by linearizing the nonlinear set of equations (5) around a nominal operating point as,

$$\begin{aligned}\dot{x} &= Ax + Bu \\ y &= Hx\end{aligned} \quad (5)$$

Here, control u is the modulation index m which is a measure of the STATCOM voltage magnitude. The nominal plant transfer function is,

$$P=H[sI-A]^{-1}B \quad (6)$$

Variations in the plant operating condition is included by a structured uncertainty model as,

$$\tilde{P} = (1 + DW_2)P \quad (7)$$

Here, W_2 is a fixed stable transfer function, the weight, and D is a variable transfer function satisfying $\|D\|_\infty < 1$. In the multiplicative uncertainty model (7), DW_2 is the normalized plant perturbation away from 1. If $\|D\|_\infty < 1$ then

$$\left|\frac{\tilde{P}(j\omega)}{P(j\omega)} - 1\right| \le \left|W_2(j\omega)\right|, \forall\omega \quad (8)$$

So, $|W_2(j\omega)|$ provides the uncertainty profile and in the frequency plane is the upper boundary of all the normalized plant transfer functions away from 1. For a control function C in cascade with the plant P, the robustness measures are,

a) The nominal performance measure is $\|W_1S\|_\infty < 1$

b) C provides robust stability iff $\|W_2T\|_\infty < 1$ (9)

c) Necessary and sufficient condition for robust nominal and robust performance is $\left\| |W_1S| + |W_2T| \right\|_\infty < 1$

In the above, W_1 is a real, rational, stable and minimum phase function. T is the input-output transfer function, complement of the sensitivity function S, and is given as

$$T = 1 - S = \frac{1}{1+L} = \frac{1}{1+PC} \quad (10)$$

Loop shaping is a graphical procedure to design a proper controller C satisfying robust stability and performance criteria given in (9). The basic idea of the method is to construct the loop transfer function, L = PC to satisfy the robust performance criterion approximately, and then to obtain the controller from the relationship C = L/P. Internal stability of the plants and properness of C constitute the constraints of the method. Condition on L is such that PC should not have any pole zero cancellation. A necessary condition for robustness is that either or both $|W_1|$, $|W_2|$ must be less than 1 [8]. For a monotonically decreasing function W_1, it can be shown that at low frequency the open-loop transfer function L should satisfy

$$|L| > \frac{|W_1|}{1 - |W_2|} \quad (11)$$

while, for high frequency,

$$|L| < \frac{1 - |W_1|}{|W_2|} \approx \frac{1}{|W_2|} \quad (12)$$

At high frequency |L| should roll off at least as quickly as |P| does. This ensures properness of C. The general features of open loop transfer function are that the gain at low frequency should be large enough, and |L| should not drop-off too quickly near the crossover frequency to avoid internal instability.

Steps in the controller design include: determination of dB-magnitude plots for P and $\tilde{P}$, finding W_2 from (8), choosing L subject to (11-12), check for the robustness criteria, constructing C from L/P and checking internal stability. The process is repeated until satisfactory L and C are obtained.

IV. GENETIC ALGORITHMS

A. Introduction to GA

Genetic algorithms are stochastic search scheme based on natural population genetics to develop global optimal in complex multidimensional search spaces. GA was first proposed by Holland [10] and have been applied successfully to many engineering and optimization problems. GA use different genetic operators to manipulate individuals in a population of solutions over several generations to improve their fitness gradually. Normally, the parameters to be optimized are represented in a binary string or chromosomes. To start the optimization, GA use randomly produced initial solutions created by random number generator. This method is preferred when a priori knowledge about the problem is not available.

The search for the global optimal solution and the selection of a new improved population using GA relies on three genetic operators. These operators are selection, crossover, and mutation. After randomly generating the initial population of say *n* solutions, the GAS use the three genetic operators to yield N new solutions at each iteration. In the selection operation, each solution of the current population is evaluated by its fitness normally represented by the value of some objective function, and individuals with higher fitness value are selected. Different selection methods such as stochastic selection or ranking-based selection can be used.

The *Crossover* operator is applied to pairs of selected solutions with certain crossover rate. The crossover rate is defined as the probability of applying crossover to a pair of selected solutions. There are many ways of defining this operator. The most common way is called the one-point crossover which can be described as follows. Given two binary coded solutions of certain bit length, a point is determined randomly in the two strings and corresponding bits are swapped to generate two new solutions.

Mutation is an inversion of a gene in the genotype of a new member of the population. Mutation makes it possible to try a completely different solution and prevents GA from being trapped in a local minimum.. The probability of mutation should be small in order to let the population improve itself by crossover. This way of seeking different solutions does not imply any control on the direction, as in gradient-based or other techniques. The fitness evaluation unit in the GA algorithm acts as an interface between the GA and the optimization problem. Information generated by this unit about the quality of different solutions are used by the selection operation in the GA. The algorithm is repeated until a predefined number of generations have been produced.

B. GA Algorithm

The GA algorithm used in this paper can be briefly discussed by the following steps.

1: Initialize a population of n individuals randomly within the lower and upper bound of the problem space.
2: Apply Selection: Evaluate the optimization fitness functions J for the initial population and select the best individuals.
3: Apply Crossover operator to the selected population of solutions.
4: Apply Mutation .
5: Evaluate the optimization fitness functions J for the new population.
6: Stop if convergence criteria are met, otherwise go to step 5. The stopping criteria are, good fitness value, reaching maximum number of iterations, or no further improvement in fitness.

C. The Robust Design Using GA

In the proposed approach the controller structure is pre-selected and is given by,

$$C(s) = \frac{b_m s^m + \cdots\cdots + b_1 s + b_o}{a_n s^n + \cdots\cdots + a_1 s + a_o} \tag{13}$$

The open loop function L is then constructed from (13) as,

$$L(s) = P(s)C(s) \tag{14}$$

The performance index J in steps 2 and 5 of the GA algorithm for the STATCOM controller design is chosen to include the robust performance and stability criterion (9), the constraints on L given in (11-12), etc. The performance index is expressed as,

$$J = \sum_{i=1}^{N} r_i J_{Bi} + r_o J_S \tag{15}$$

where, J_{Bi} are the robust stability indices and J_S is the stability index. r_i and r_o are the penalties associated with the respective indices and N are the number of frequency points in Bode plot of L(jω).

In general, the robust stability bounds are very complicated and are non convex. It is difficult to give analytical expressions of the robust stability bounds. In this paper robust stability bounds are obtained from graphical method using Bode plots. At each frequency ω_i, the magnitude of open-loop transmission $L(j\omega_i)$ is calculated and then checked to see whether or not the robust stability bound is satisfied at that frequency. A robust stability index is defined by,

$$J_{Bi} = \begin{cases} 0 & \text{if bound at } \omega_i \text{ is satisfied} \\ 1 & \text{otherwise} \end{cases} \tag{16}$$

$$i = 1,2,3,\ldots\ldots N$$

The stability of the closed loop nominal system is simply tested by solving the roots of characteristic polynomial and then checking whether all the roots lie in the left side of the complex plane. The stability index J_S is defined as,

$$J_s = \begin{cases} 0 \text{ if stable} \\ 1 \text{ otherwise} \end{cases} \quad (17)$$

The coefficients b_m, ...b_1 and a_n, ...,a_1 are searched by the GA algorithm to satisfy the constraint equations. a_n can be set to 1.

The flow chart for the proposed automatic loop-shaping is shown in Fig. 2.

V. IMPLEMENTATION OF THE ROBUST CONTROLLERS

A. Graphical Procedure

The generator angular speed deviation $\Delta\omega$ is selected as the plant output, while the input is STATCOM voltage modulation index m. The nominal plant transfer function for selected operating point is,

$$P=\frac{0.2104s^2(s+100.827)(s-0.234)}{(s+99.17)(s+1.10)(s+0.05)(s^2+0.68s+21.63)} \quad (18)$$

Off-nominal power outputs between 0.4 and 1.4 pu and power factor form 0.8 lagging to 0.8 leading were considered. The quantity, $\left|\tilde{P}(j\omega)/P(j\omega)-1\right|$ for each perturbed plant is constructed and the uncertainty profile is fitted to the following function,

$$W_2(s)=\frac{0.9s^2+15s+27}{s^2+5s+31} \quad (19)$$

A Butterworth filter satisfies all the properties for $W_1(s)$ and is written as

$$W_1(s)=\frac{K_d f_c^2}{s^3+2s^2 f_c+2sf_c^2+f_c^3} \quad (20)$$

For K_d = 0.01 and f_c = 0.1, and for a choice of open-loop transfer function L as,

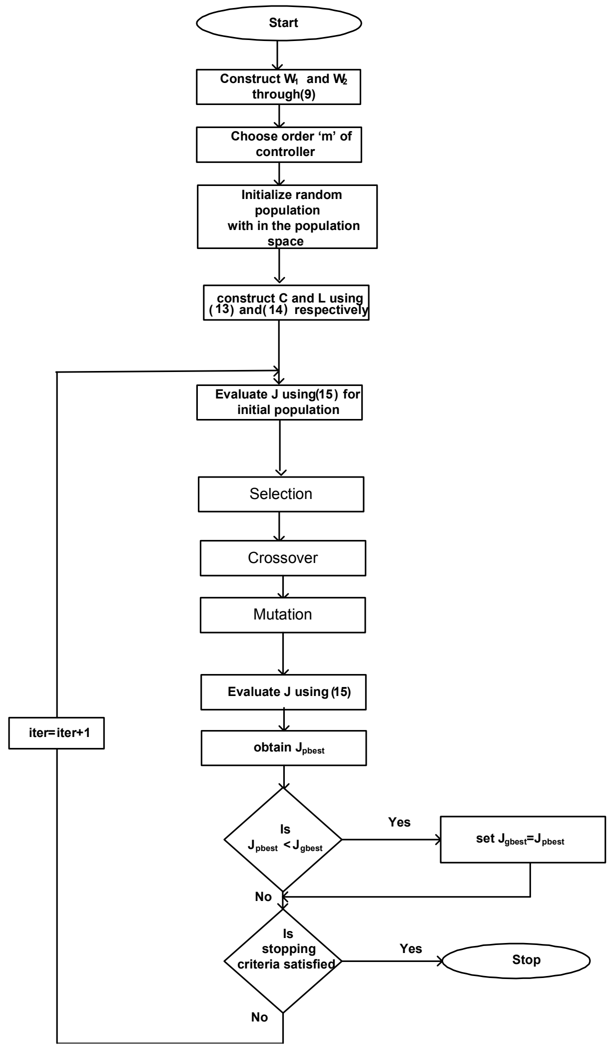

Fig. 2. Flow chart for the proposed automatic loop-shaping.

$$L=\frac{5.173s^2(s+100.827)(s-0.234)(s+1)(s+1.094)}{(s+99.17)(s+1.10)(s+0.05)(s^2+0.68s+21.63)}\times \frac{(s+0.0476)(s+0.001)(s+99.174)}{(s+10)(s+0.1)(s+0.01)^3} \quad (21)$$

the desired controller transfer function is given by

$$C=\frac{24.583(s+1)(s+1.094)(s+0.0476)(s+0.001)(s+99.174)}{(s+10)(s+0.1)(s+0.01)^3} \quad (22)$$

The dB-magnitude plots relating W_1, W_2 and L, which were employed to arrive at this controller, is shown in Fig. 3. The open-loop function L is selected to fit the bounds set by (11-12). The plots for the nominal and robust performance criteria are shown in Fig. 4. While the nominal performance measure W_1S is well-satisfied, the combined robust stability and performance measure peaks slightly.

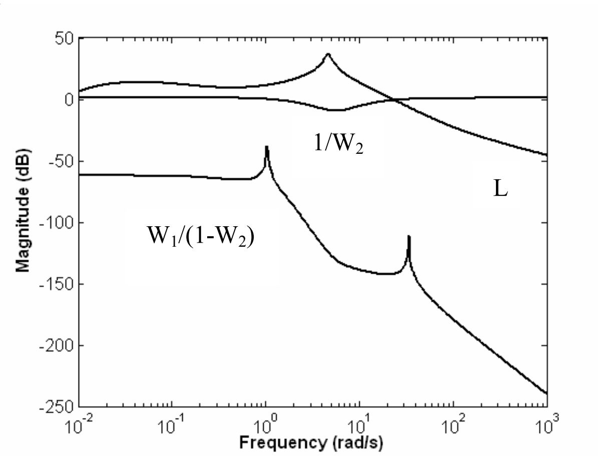

Fig. 3. Loop-shaping plots relating W_1, W_2 and L.

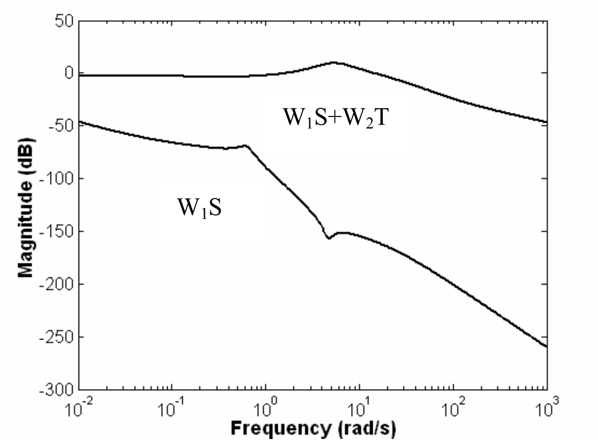

Fig. 4. The nominal and robust performance criteria.

B. Automatic Loop-shaping with GA

For the nominal plant transfer function (18), the GA starts with W_1 and W_2 arrived at through the graphical procedure given in section V-A. A fifth order controller function is chosen as,

$$C(s)=\frac{b_4s^4+b_3s^3+b_2s^2+b_1s^1+b_0}{a_4s^4+a_3s^3+a_2s^2+a_1s^1+a_0} \qquad (23)$$

where, the coefficients a's and b's are to be determined. The control parameters for the GA algorithm are chosen as,

TABLE I
GA parameters

Parameters	Values
Maximum generations	1000
Population size	300
Crossover probability	1
Mutation probability	0.001

The GA algorithm converged to give the following robust controller function,

$$C(s)=\frac{35s^4+2500s^3+0.001s^2+2038.4s^1+200}{1s^4+0.02071s^3+1.597s^2+0.025s^1+0.3285} \qquad (24)$$

The open-loop function L(s) obtained from L(s) = P(s) C(s) is,

$$L(s)=\frac{0.2104s^2(s+100.827)(s-0.234)}{(s+99.17)(s+1.10)(s+0.05)(s^2+0.68s)+21.63}\times \qquad (25)$$
$$\frac{35s^4+2500s^3+0.001s^2+2038.4s^1+200}{1s^4+0.02071s^3+1.597s^2+0.025s^1+0.3285}$$

The dB magnitude vs. frequency plot relating L(s), $W_1(s)$ and $W_2(s)$ obtained through the automatic procedure is shown in Fig. 5. It can be seen from the figure that the loop-shaping requirements on L(s) are satisfied at all frequencies. Fig.6. shows the convergence profiles for the automatic robust design.

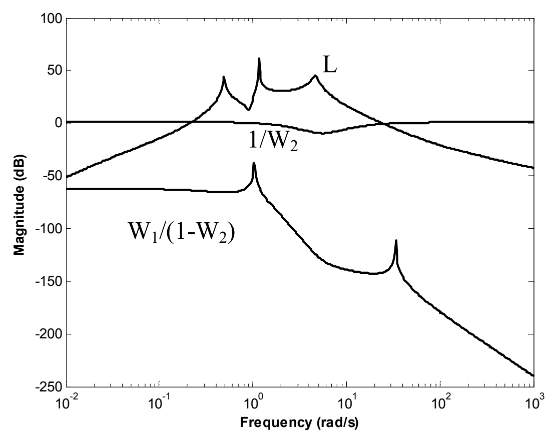

Fig. 5. Automatic loop-shaping plots relating W_1, W_2 and L

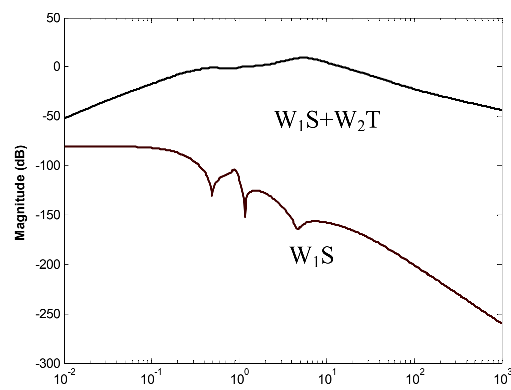

Fig. 6. Robust and nominal performance criteria with automatic loop-shaping

A comparison of the simulation results with the graphical and GA based automatic loop-shaping methods are given in Figure 7.

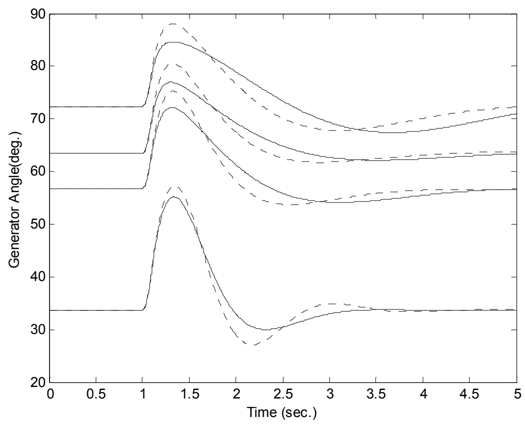

Fig. 7. Comparison of generator rotor angle variations following a 50% input torque pulse (solid line is for automatic loop-shaping and dotted line for graphical method).

Fig.7. shows the rotor angle variations following a 50% torque pulse on the generator shaft with the robust control for the following 4 loading conditions: (a) 1.2-pu generator power output, 0.98-pf lead, (b) 1-pu output, 0.95 pf lag, (c) 0.9-pu output, unity pf and (d) 0.5-pu output, 0.95-pf lag. It can be observed that both manual and GA based automatic techniques produce controller functions that give almost identically good transient control.

CONCLUSIONS

A Genetic Algorithms procedure has been employed to design a loop-shaping based robust STATCOM controller. The automatic loop-shaping using GA minimizes the trial and error procedure involved in the graphical loop-shaping construction procedure. The controller structure can also be pre-selected reducing the overall computational burden. Simulation studies indicate that the GA based robust loop-shaping design provides effective power system damping control.

LIST OF SYMBOLS

M,D	inertia and damping coefficients
V_t,V_{to}	generator terminal voltage and reference voltage
P_m, P_e	generator input and output power
C_{dc}	d.c. capacitance
ψ	phase angle of the mid-bus voltage
e_q	internal voltage behind synchronous reactance
E_{fd}	generator field voltage
δ	generator rotor angle
T'_{do}	open circuit field time constant
K_A,T_A	exciter gain and time constants
x_d,x_d'	direct axis synchronous and transient reactance
ω_o	base radian frequency
V_b, V_L	infinite bus and STATCOM bus voltages

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