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Static VAR Compensator using Fixed Structure Static Output Feedback Robust Loop Shaping Control

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Abstract— **This paper proposes a new technique for designing a fixed-structure static output feedback robust loop shaping controller for a power system with VAR compensator. The proposed technique uses Particle Swarm Optimization (PSO) to evaluate the final solution. Infinity norm from disturbances to states is formulated as the cost function in our optimization. The performance of the designed system is investigated in comparison with the conventional H infinity loop shaping controller, the robust controller designed by LMI method and the reduced order robust controller by Hankel norm model reduction method. As results indicated, stability margin of our proposed controller is better than that of the others. In addition, the order of the proposed controller is much lower than that of the conventional robust loop shaping controller.**

Index Terms— **Fixed-structure robust loop shaping control, Particle Swarm Optimization, H infinity loop shaping control.**

I. INTRODUCTION

Presently, stability analysis is one of the most important issues for designing of power system stabilizer. Normally, in a power system, uncertainties can be occurred by various sources such as disturbances, switching, load changing, faults, etc. The analysis of stability and dynamic performance in a power system is not easy; however, it can be carried out by control system theory. To design an effective controller, many techniques such as fuzzy logic control in [1], hybrid method in [2], Real-Coded Genetic Algorithm in [3] and static Var compensator power swing damping controller in [4], etc. have been proposed and designed. In [1], a fuzzy logic was adopted to design a controller for static VAR compensator to improve the transient stability of the power system. As shown in their results, fuzzy logic can efficiently control the system at any load changing conditions. However, the uncertainty criterion is not considered in their design. Zhijun, et. al. [2] proposed a new hybrid method to simulate the power system with static VAR compensator dynamic phasor model. Their proposed simulator can show the voltage and current waveforms when a three phases fault is occurred. Panda, et. al. proposed a new design technique for power system stabilizer and a static VAR compensator controller. The optimal controller parameters were searched by real-coded Genetic Algorithm. Chang and Xu [4] proposed a static VAR compensator with power swing damping controller for different operating conditions. Their proposed controller can improve the damping of power system oscillation.

All techniques mentioned above do not include the system uncertainty or robust criterion into their designs. Robust control is a well-known technique to design a high performance controller for a system under uncertainty and disturbance conditions. In this technique, uncertainty can be modeled by many kinds of models such as, multiplicative uncertainty model (in mixed-sensitivity approach), co-prime factors uncertainty model (in H infinity loop shaping approach [5]), etc. Many robust control techniques have been investigated in power system control such as LMI based H infinity loop shaping in [6], loop shaping control in [7], inverse additive perturbation in [8], etc. As shown in previous research works, robust H infinity control is one of the most popular techniques for designing an effective controller under uncertainty and disturbance conditions. One of the most popular techniques of H infinity control is H infinity loop shaping which is a sensible and simple method. In addition, classical loop shaping which is an intuitive scheme is incorporated in the design. However, the resulting controller obtained from this approach has high order, making it difficult to implement in practical works. To overcome this problem, this paper focuses on the design of structure-specified controller which can guarantee the robust performance by maximizing the stability margin of the controlled system. In the proposed technique, infinity norm from disturbances to states is formulated as the objective function, and PSO is adopted to find the optimal controller. As shown in the results, our proposed technique gains better stability margin compared to the static H infinity loop shaping controller [6] and the reduced order controller. In addition, order of the proposed controller is much lower than that of full order robust loop shaping controller.

The remainder of this paper is shown as follows. Section 2 illustrates the conventional robust loop shaping. Sections 3 and 4 describe the proposed technique. Simulations and results are shown in Section 5. Finally, Section 6 concludes the paper.

II. CONVENTIONAL H_∞ LOOP SHAPING CONTROL

H infinity loop shaping control was first introduced by McFarlane [9]. In this design, desired open loop shape in frequency domain is specified by shaping the open loop of the system, G, with the weighting functions, pre-

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compensator (W_1) and post-compensator (W_2). The shaped plant can be written as:

$$G_s = W_1 G W_2 \quad (1)$$

$$G_\Delta = (N_s + \Delta_{Ns})(M_s + \Delta_{Ms})^{-1} \quad (2)$$

where Δ_{Ns} and Δ_{Ms} are the uncertainty transfer functions in the nominator and denominator factors, respectively. G_Δ is the shaped plant with uncertainty. $\|\Delta_{Ns}, \Delta_{Ms}\|_\infty \le \varepsilon$, where ε is the stability margin. The design steps of H infinity loop shaping can be briefly described as follows:

Step 1 Specify pre- and post-compensator weights for achieving the desired open loop shape.

Step 2 Find the optimal stability margin (ε_{opt}) by solving the following equation.

$$\gamma_{opt} = \varepsilon_{opt}^{-1} = \inf_{stab\,K} \left\| \begin{bmatrix} I \\ K \end{bmatrix} (I - G_s K)^{-1} M_s^{-1} \right\|_\infty \quad (3)$$

If (ε_{opt}) is too low, then go to Step 1 to select the new weights.

Step 3 Select the stability margin $(\varepsilon < \varepsilon_{opt})$ and then synthesize the controller, K_∞, by solving the following inequality.

$$\|T_{zw}\|_\infty = \left\| \begin{bmatrix} I \\ K_\infty \end{bmatrix} (I - G_s K_\infty)^{-1} M_s^{-1} \right\|_\infty = \left\| \begin{bmatrix} I \\ K_\infty \end{bmatrix} (I - G_s K_\infty)^{-1} \begin{bmatrix} I & G_s \end{bmatrix} \right\|_\infty \le \varepsilon^{-1} \quad (4)$$

Step 4 Final controller (K) is

$$K = W_1 K_\infty W_2 \quad (5)$$

III. FIXED-STRUCTURE OUTPUT FEEDBACK ROBUST LOOP SHAPING CONTROL

Although robust loop shaping technique is an efficient technique to design a robust controller for MIMO system; however, the final controller designed by this approach is usually high order and complicated controller. To overcome this problem, many techniques such as Hankel norm model reduction [5], LMI based static output feedback robust loop shaping control [6], etc. have been proposed to reduce the order of controller. However, in many cases, stability margin obtained from above mentioned techniques is not good enough. Thus, to enhance the design, we propose a PSO based fixed-structure output feedback robust loop shaping control to design a fixed-structure robust controller. The proposed technique can be summarized as follows:

Step 1 Specify the structures of weight and controller. In the proposed technique, structure of weights and controller must be the same structure. Select the post-compensator weight as I.

Step 2 The structure of the final controller is $K(p)$, thus, based on (5),

$$K_\infty = W(x)^{-1} K(p) \quad (6)$$

By substituting (6) into (4), the infinity norm of transfer function from disturbances to states, subjected to be minimized, can be written as:

$$J_{cost} = \frac{1}{\varepsilon} = \gamma = \|T_{zw}\|_\infty = \left\| \begin{bmatrix} I \\ W(x)^{-1} K(p) \end{bmatrix} (I - G_s W(x)^{-1} K(p))^{-1} \begin{bmatrix} I & G_s \end{bmatrix} \right\|_\infty \quad (7)$$

Consequently, it is reasonable to set the fitness function of PSO as:

$$fitness(fs) = \left\| \begin{matrix} \begin{bmatrix} I \\ W(x)^{-1} K(p) \end{bmatrix} (I - G_s W(x)^{-1} K(p))^{-1} \begin{bmatrix} I & G_s \end{bmatrix} \\ 0.0001 \end{matrix} \right\|_\infty^{-1} \quad (8)$$

Step 3 Use PSO to find the optimal parameter, p^* and x^*. The following section describes the steps of PSO adopted in the proposed design.

IV. PARTICLE SWARM OPTIMIZATION ALGORITHM

PSO was first proposed in [12]. In our work, this technique is used for solving the fixed structure robust loop shaping control problem. The particle in this problem is a set of parameters x and p of weight W(x) and final controller $K(p)$, respectively. Following steps are the PSO procedure.

Step 1 Randomly initialize the several sets of x and p as particles in the 1st iteration of PSO. Define the PSO parameters such as population size, maximum and minimum velocities. Constrains in this problem are set as the frequency domain specifications as follows:

$$\begin{aligned} &\text{Crossover frequency} > CF \\ &\underline{\sigma}(G_S(\omega < \omega_{low\,freq})) > LG \\ &\overline{\sigma}(G_S(\omega > \omega_{high\,freq})) < HG \end{aligned} \quad (9)$$

where CF is the crossover frequency of the desired loop shape of the shaped plant, LG is the specified gain, $\underline{\sigma}(G_S(\omega < \omega_{low\,freq}))$ is the lower singular values shape in low frequency range $(\omega < \omega_{low\,freq})$ of the desired loop shape, HG is the specified gain, $\overline{\sigma}(G_S(\omega > \omega_{high\,freq}))$ is the upper singular values shape in high frequency range $(\omega > \omega_{high\,freq})$ of the desired loop shape.

Step 2 Find the fitness of each particle using (8).

Step 3 Update the inertia weight (Q), position and velocity of each particle using the following equations.

$$Q = Q_{\max} - \left(\frac{Q_{\max} - Q_{\max}}{i_{\max}} \right) i \quad (10)$$

$$v_{i+1} = Q v_i + \alpha_1 \left[\gamma_{1i} \left(P_b - p_i \right) \right] + \alpha_2 \left[\gamma_{2i} \left(U_b - p_i \right) \right] \quad (11)$$

$$p_{i+1} = p_i + v_{i+1} \quad (12)$$

where α_1, α_2 are acceleration coefficients.

γ_{1i}, γ_{2i} are any random number in $(0 \rightarrow 1)$ range.

Step 4 While the current iteration is less than the maximum iteration, go to step 2. If the current iteration is the maximum iteration, then stop. The particle which has maximum fitness is the answer of the optimization.

V. SIMULATIONS AND RESULTS

A power system with VAR compensator control was studied in this research work. The voltage source inverter causes lagging or leading reactive power. In the controlled system, there are a DC voltage loop and a reactive current loop to control the output reactive power. Thus, this system is a MIMO system, which has 2 inputs, ΔM – Modulation ratio of the inverter and Δφ – phase angle of the inverter voltage, and 2 outputs, Δid - reactive current, and ΔVc - DC voltage. In this paper, the nominal plant has a transfer function [6, 11] as:

$$G(s) = \frac{1}{(s+0.2124)(s^2+0.2492s+12.55)} \times \begin{bmatrix} 0.2307s(s+33.56) & -3.2226(s^2+0.0934s+7.944) \\ -27.556(s+0.2308) & 3.5807(s+1.723)(s-1.261) \end{bmatrix} \quad (13)$$

Pre-compensation (W_1) can be designed by PI pre-compensator as:

$$W = diag\left(\frac{a(s+0.2)}{s}, \frac{b(s+0.2)}{s}\right) \quad (14)$$

where a and b are parameters that can be adjusted to achieve the desired open loop shape. In this paper, these parameters are determined by PSO, and the post-compensator (W_2) is selected as I.

In [6], there are three cases of weight parameters selected by trial and error method. The detail of each case can be seen in Table 1. The design of the proposed controller is done by assigning the controller structure as:

$$K(p) = \begin{bmatrix} \frac{p_1 s + p_2}{s} & \frac{p_3 s + p_4}{s} \\ \frac{p_5 s + p_6}{s} & \frac{p_7 s + p_8}{s} \end{bmatrix} \quad (15)$$

Ranges of the weight parameters are chosen as a-$b \in [0, 5]$. The controller parameters ranges are chosen as $p_{1-8} \in [-1, 1]$.Parameters of PSO are selected as follows: population size = 200; minimum and maximum velocities are 0 and 2 respectively; acceleration coefficients = 2.1; minimum and maximum inertia weights are 0.6 and 0.9, respectively; maximum iteration = 25. The frequency domain constrains are selected as follows: $\omega_{low\ freq.} = 10^{-4}$ rad/sec, $\omega_{high\ freq.} = 10^3$ rad/sec, LG = 50 dB, HG = -40 dB and CF = 0.1 rad/sec. When running the PSO for 25 iterations, the optimal solution is obtained as (16) and (17). The stability margin obtained from the proposed controller is 0.5237.

$$W(x) = diag\left(\frac{0.1181(s+0.2)}{s}, \frac{0.3505(s+0.2)}{s}\right) \quad (16)$$

$$K(p) = \begin{bmatrix} \frac{-0.0197s-0.0174}{s} & \frac{0.0521s+0.0453}{s} \\ \frac{0.4207s+0.0517}{s} & \frac{-0.2478s-0.0026}{s} \end{bmatrix} \quad (17)$$

As seen in Fig.1, the stability margin obtained by the evolved weight in (16) and the optimal controller in (17) is 0.5237. Table 1 shows the stability margin obtained from the static output feedback robust loop shaping controller in [6]. The reduced order controller by Hankel norm model reduction is also shown in this Table. Clearly, the stability margin of the proposed controller is better than that of the controllers designed by LMI approach [6] and model reduction technique. In addition, these results point out that the proposed technique is effectively used to design the robust controller and gives a better performance than the other techniques.

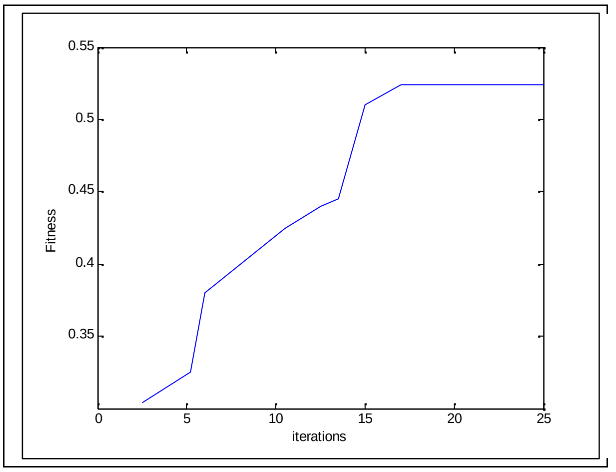
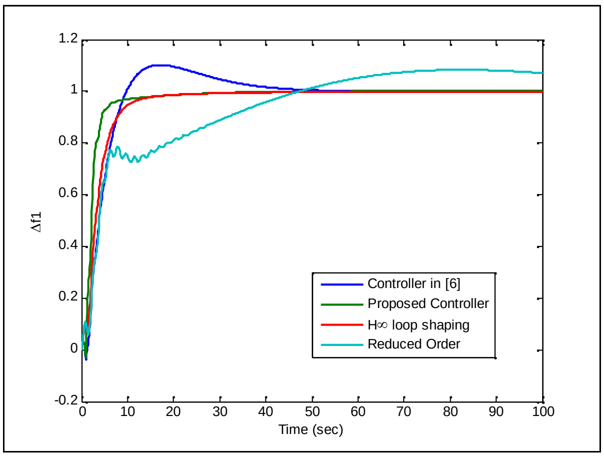


Fig.1 Stability margin (ε) versus iterations

Table 1. Results of stability margin obtained from the controller in [6], reduced order controller. (The stability margin of the proposed controller is 0.5237)

Parameters involved in pre compensator	Stability margin (ε)		
	Static H_∞ loop shaping [2nd order]	Reduced order	Full order [10th order]
Case I (a=0.1, b=0.2)	0.4242	0.1556 [4th order]	0.6487
Case II (a=0.1, b=0.3)	0.4474	0.2547 [5th order]	0.6201
Case III (a=0.3, b=0.5)	0.4260	4.9×10^{-6} [5th order]	0.5587



(a)

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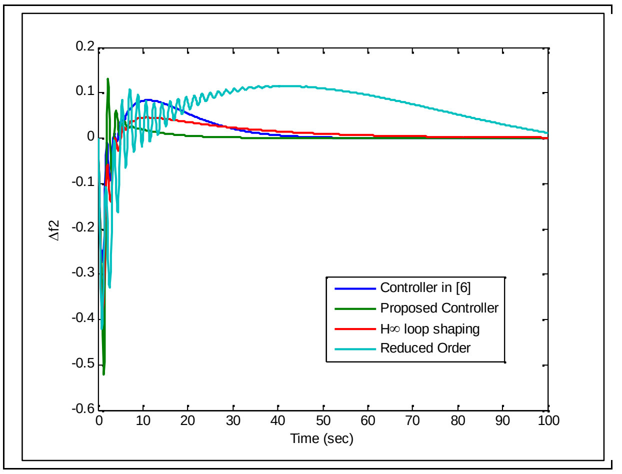
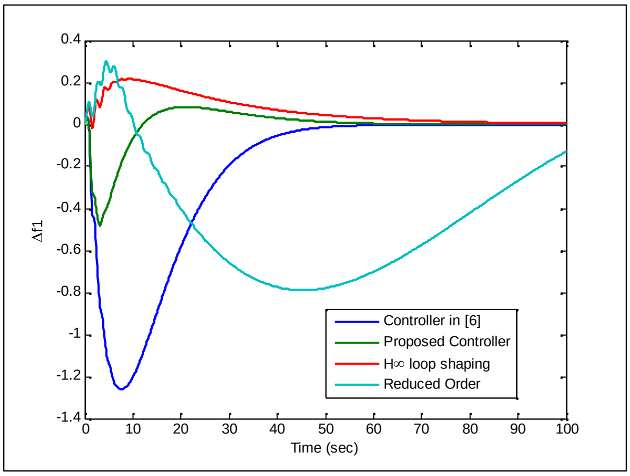
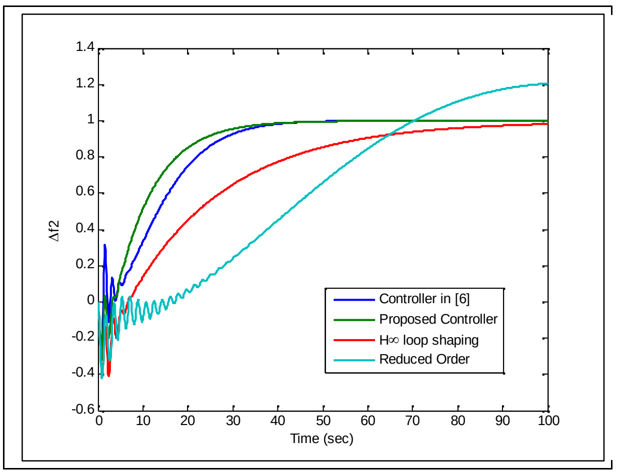


(b)

Fig.2 Output response of the system when the unit step and disturbance (0.3u(t)) are entered to reactive current command, (a) channel 1, (b) channel 2 of the system.



(a)



(b)

Fig.3 Output response of the system when unit step and disturbance (0.3u(t)) are entered to DC voltage command, (a) channel 1 (b) channel 2 of the system.

Fig. 2 shows the responses of the output of the system in 2 channels (DC voltage and Reactive Current) when the unit step command and disturbance are fed into the reactive current command. As seen in this figure, the proposed controller can perform well and its response is close to the full order robust loop shaping controller, with lower overshoot than the controller in [6]. In addition, the responses from the proposed controller have better setting time than that of the reduced order controller. Fig. 3 shows the responses of the system when unit step and disturbance are fed into DC Voltage command. The figure shows that the proposed controller is better able to maintain the output level when disturbance is entered than the other reduced order controllers.

VI. Conclusions

This paper proposes a new technique to design a fixed-structure robust controller for VAR compensator connected electric power system. The proposed technique uses Particle Swarm Optimization to find the final optimal controller. As seen in the results, our proposed controller gains better robust performance (measured by an index, stability margin) compared to the conventional static H infinity loop shaping [6], reduced order controller. In addition, the order of the proposed controller is much lower than that of the conventional H infinity loop shaping controller. The effectiveness of the proposed controller is also verified by the time domain responses under the conditions of input disturbances.

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