

Chapter 6

Structured Robust Control for MIMO Systems Using Artificial Intelligent Techniques

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Abstract In this chapter, a new technique called fixed-structure robust control using artificial intelligent (AI) technique is proposed to enhance both performance and stability of controlled system. In this approach, the structure of controller is specified and the robust stabilization problem is solved by AI techniques. The advantages of simple structure, robustness and high performance can be achieved. In this paper, two multiple inputs multiple outputs (MIMO) controller design problems, i.e., robust control design for electro-hydraulic servo system and fixed-structure robust mixed-sensitivity approach for three phase inverter are illustrated. Simulation results show that the proposed controller has simpler structure than that of conventional robust controller, and the stability margin obtained indicates the robustness of the proposed controller.

Keywords Artificial intelligent techniques • H_∞ optimal control • Three phase inverter • Electro-hydraulic servo system

1 Introduction

Recently, many artificial intelligent (AI) techniques have been adopted to design robust controllers. In [1], the robust H_∞ optimal control problem with a structure specified controller was solved by genetic algorithm (GA). Mixed-sensitivity approach was adopted for indicating the performance of the designed controller. As

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results indicated, GA is a feasible method to design a structure specified H_∞ optimal controller. Chen et al. [2] proposed a PID design algorithm using mixed H_2/H_∞ control. In their chapter, H_2 is mixed with H_∞ to indicate both the performance and robustness of entire system. In addition, the controller parameters were tuned in the stability domain evaluated by Routh–Hurwitz stability criterion and sampling technique. Similar method was proposed by applying the intelligent GA to solve the robust H_2/H_∞ control problem [3]. Clearly, the results in their papers [1–3] clarified the robustness of the designed systems.

The above mentioned methods [1–3] were adopted to design the structure specified robust controllers. Their techniques are based on the concept of H infinity optimal control. Alternatively, McFarlane and Glover [4] proposed an alternative technique called H_∞ loop shaping control to design a robust controller. This technique is based on the concept of loop shaping which only two compensator weights need to be selected. In this control scheme, several researchers [5–7] proposed several fixed-structure methods to design robust controllers.

In this chapter, the fixed-structure robust control techniques are adopted to design the robust controllers for multiple inputs multiple outputs (MIMO) systems, i.e., a MIMO electro-hydraulic servo system and a three phase inverter system. The remainder of this chapter is organized as follows. Section 2 illustrates the modeling and control design of electro-hydraulic servo system. Particle swarm optimization (PSO) and robust loop shaping techniques are adopted to design the robust controller. Section 3 describes the robust control design for a three phase inverter system. GA and robust mixed-sensitivity method are adopted to design the robust controller. Finally, Sect. 4 summarizes the paper.

2 Fixed-structure Robust Loop Shaping Control for Electro-hydraulic Servo System

Electro-hydraulic servo system is an attractive choice for being used in both industrial and non-industrial applications. The advantages of this actuator are fast dynamic response, high power to inertia ratio, etc. Many approaches have been proposed to control this system to achieve good performance and robustness. One among them is robust control which the controlled system can perform well even under the conditions of disturbance and uncertainties. Normally, in the robust control design problem, several linear mathematic equations need to be solved to find the optimal robust controller. Unfortunately, resulting controllers determined by the conventional techniques are normally complicated with high order.

Typical electro-hydraulic servo system is shown in Fig. 6.1 which consists of a position control system and a force control system [8]. The position control system is adopted to control the actuator movement and the force control system is applied to supply a required force to the system load. The main objective of the servo system is to satisfy the specified requirements; for example, zero steady state errors

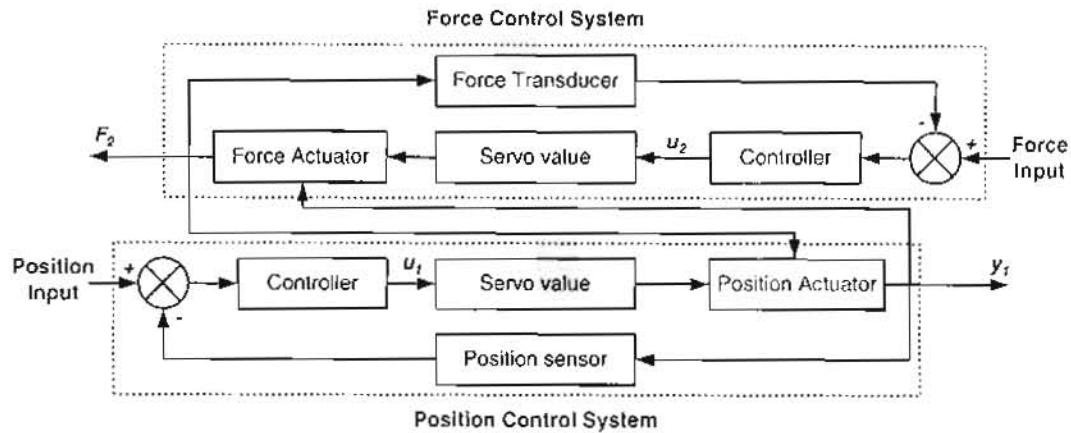


Fig. 6.1 Electro-hydraulic servo system

in motion of the actuator and force output. The state-space model of the electro-hydraulic servo system can be shown in the following equation [8]:

$$\begin{aligned}\dot{x} &= Ax + Bu \\ y &= Cx\end{aligned}\quad (6.1)$$

As seen in the above mentioned dynamic, the system is MIMO system which has two outputs, F_2 —force of the system and y_1 —position of the actuator, and two inputs (u). u_1 —input servo valve of the position control system, and u_2 —input servo valve of the force control system.

2.1 PSO Based Robust Loop Shaping Control

Based on the concept of PSO technique, in this problem, a set of controller parameters p is formulated as a particle and the fitness can be written as:

$$\varepsilon = \|T_{zw}\|_{\infty}^{-1} = \left\| \begin{bmatrix} I \\ W_1^{-1} K(p) \end{bmatrix} (I + G_s W_1^{-1} K(p))^{-1} M_s^{-1} \right\|_{\infty}^{-1} \quad (6.2)$$

Fitness value is specified as a very small value if the controlled system is unstable. The flow chart diagram of the proposed technique is shown in Fig. 6.2.

For the design, the controller $K(p)$ will be designed to minimize the infinity norm from disturbance to state or maximize the stability margin (ε) by using the PSO. The PSO is based on the concept of swarm's movement. When applying the PSO, PSO parameters, i.e. the population of swam(n), lower and upper boundaries ($p_{\min}$, $p_{\max}$) of problem space, minimum and maximum velocities of particles ($v_{\min}$, $v_{\max}$), maximum iteration($i_{\max}$), minimum and maximum inertia weights, need to be specified. In an iteration of the PSO, the value of fitness or objective

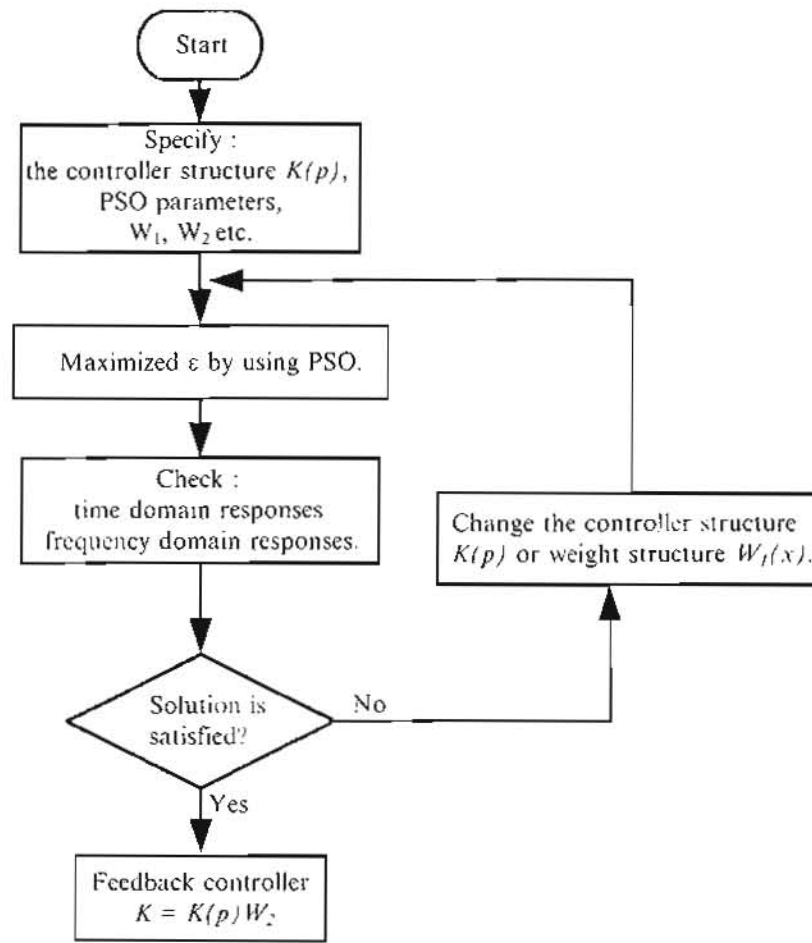


Fig. 6.2 The design of uncertainty weight of DC motor speed control plant

function (f_s) of each particle is evaluated. The particle which gives the highest fitness value is kept as the answer of current iteration. The inertia weight (Q), value of velocity (v) and position (p) of each particle in the current iteration (i) are updated by using equations (6.3)–(6.5).

$$Q = Q_{\max} - \left(\frac{Q_{\max} - Q_{\min}}{i_{\max}} \right) i \quad (6.3)$$

$$v_{i+1} = Q v_i + \alpha_1 [\gamma_{1i} (P_b - p_i)] + \alpha_2 [\gamma_{2i} (U_b - p_i)] \quad (6.4)$$

$$p_{i+1} = p_i + v_{i+1} \quad (6.5)$$

where α_1 , α_2 are acceleration coefficients.

The state-space model of nominal plant of electro-hydraulic servo system can be seen in the reference [8]. The state vector of this plant consists of four variables which are the supply pressure in force control system, the supply pressure in position control system, the position and the velocity of the actuator. Based on the reference [4], the pre- and post-compensator weights can be chosen as

Table 6.1 PSO parameters and controller parameter ranges

Parameters	Values
Minimum velocity	0
Maximum velocity	0.2
Acceleration coefficient	2.1
Minimum inertia weight	0.6
Maximum inertia weight	0.9
Maximum iteration	100
Population size	500
p_{1-8}	$[-60, 60]$

$$W_1 = \begin{bmatrix} \frac{0.53s + 62}{s + 0.001} & 0 \\ 0 & \frac{0.53s + 62}{s + 0.001} \end{bmatrix}, \quad W_2 = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \quad (6.6)$$

In this chapter, the structure of controller is selected as a MIMO PI control. By using the conventional robust loop shaping technique, the optimal stability margin of the shaped plant is found to be 0.5522. To design the conventional H_∞ loop shaping controller, stability margin 0.5217 is selected. The final controller (full order H_∞ loop shaping controller) is eighth order.

In this chapter, the structure of controller is selected as:

$$K(p) = \begin{bmatrix} \frac{p_1s + p_2}{s + 0.001} & \frac{p_3s + p_4}{s + 0.001} \\ \frac{p_5s + p_6}{s + 0.001} & \frac{p_7s + p_8}{s + 0.001} \end{bmatrix} \quad (6.7)$$

Next, the proposed technique is adopted to design the robust PI controller. In the optimization problem, the upper and lower bounds of control parameters and the PSO parameters are given in Table 6.1. After running the PSO for 56 iterations, the optimal solution is obtained as:

$$K(p) = \begin{bmatrix} \frac{-0.5284s - 36.683}{s + 0.001} & \frac{-0.0717s - 8.0878}{s + 0.001} \\ \frac{-0.0322s - 3.2293}{s + 0.001} & \frac{-0.8966s - 38.441}{s + 0.001} \end{bmatrix} \quad (6.8)$$

Figure 6.3 shows the fitness or stability margin (ϵ) of the best controller obtained in each iteration. As seen in this figure, the best controller evolved by the PSO has a stability margin of 0.3905.

Figure 6.4 shows the responses of the outputs of the system in two channels (position and force outputs) when the unit step command input is fed into the position command. As seen in this figure, the response from the proposed controller is similar to that of the conventional full order robust controller.

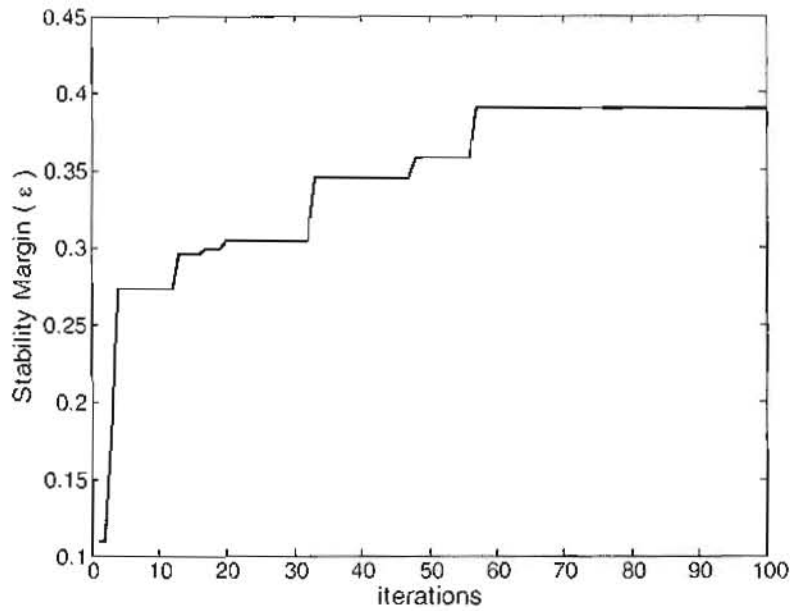


Fig. 6.3 Stability margin (ε) versus iterations

3 Fixed-Structure Robust Control for Three-phase Power Inverter

In this example, a design of grid connected three-phase current control inverters is illustrated. Fixed structured H_∞ optimal control design is applied to design the controller for the inverter. Controllers with robust stability (RS) and nominal performance (NP) are the main concerns of the design. GA is employed to solve for the optimal parameters of controllers. Structure of the controller is a proportional integral (PI) controller with MIMO. A fixed-structure current controller is designed for a grid connected 300 kW three-phase inverter as depicted in Fig. 6.5. Note that the parameters in Fig. 6.5 is represented in abc reference frame. The specifications of the inverter are shown in Table 6.2.

3.1 Model of Grid Connected Three-phase Power Inverter

By applying the Odq - abc transformation matrix defined by

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} \cos \omega t & \sin \omega t \\ \frac{1}{\sqrt{2}} \cos \left(\omega t - \frac{2\pi}{3} \right) & \sin \left(\omega t - \frac{2\pi}{3} \right) \\ \frac{1}{\sqrt{2}} \cos \left(\omega t + \frac{2\pi}{3} \right) & \sin \left(\omega t + \frac{2\pi}{3} \right) \end{bmatrix} \begin{bmatrix} i_0 \\ i_d \\ i_q \end{bmatrix}$$

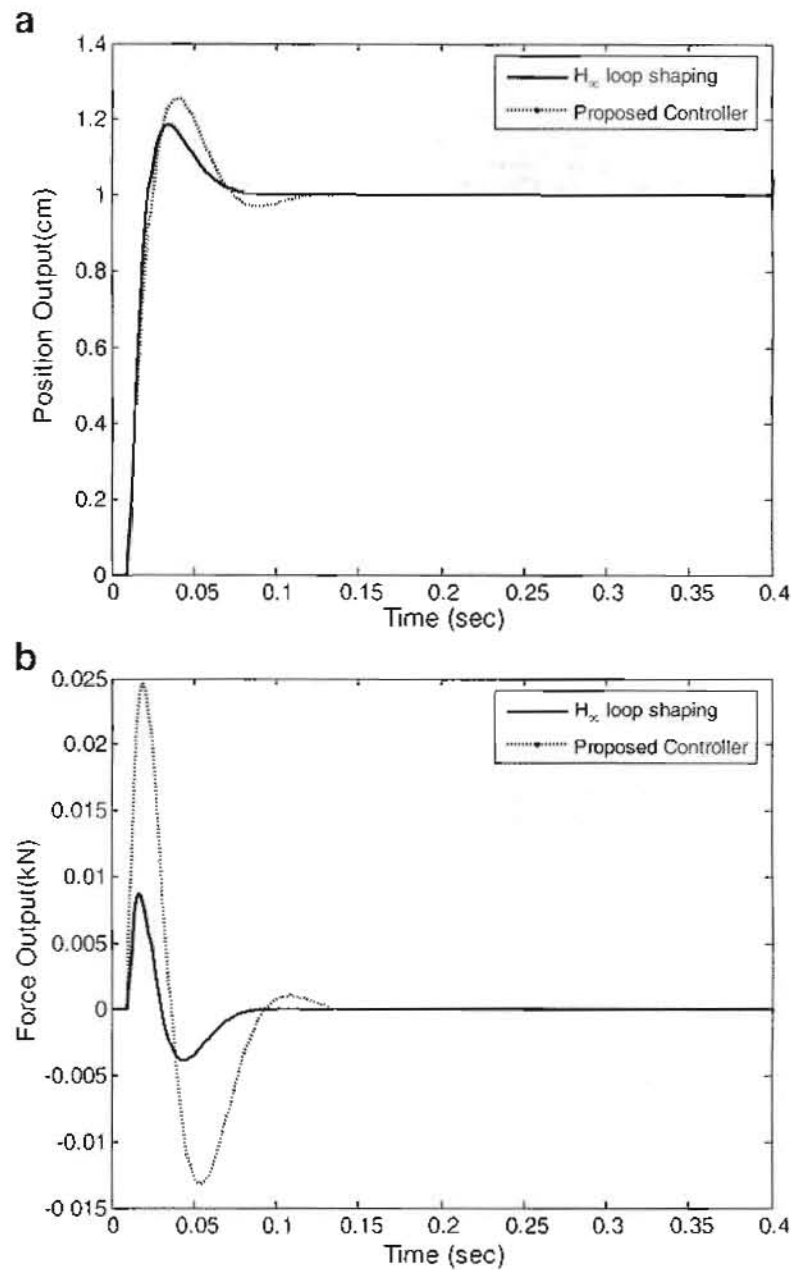


Fig. 6.4 Output responses of the system when the unit step is entered to position command

A three-phase inverter as shown in Fig. 6.5 can be represented by a linearized state space model around “a normal operating point” in rotational reference frame as [9–12]

$$\Delta \dot{x}_{Lr} = A_{Lr} \Delta x_{Lr} + B_{Lr} \Delta u_{Lr} \quad (6.9)$$

where

$$\Delta x_{Lr} = [\Delta I_d \ \Delta I_q \ \Delta I_s \ \Delta V_d \ \Delta v_{cfd} \ \Delta v_{cfq} \ \Delta I_{LD} \ \Delta I_{LQ}]^T$$

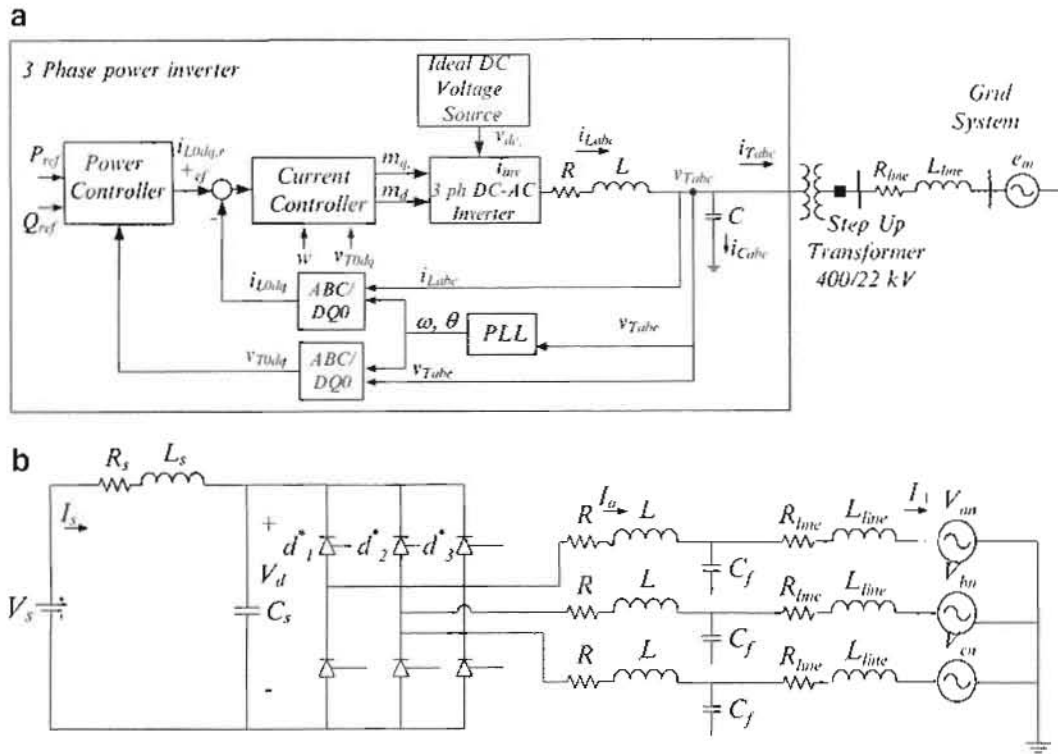


Fig. 6.5 Model of three-phase inverter grid connected inverter in *abc* reference frame: (a) System diagram. (b) Circuit diagram of the three-phase inverter [9]

Table 6.2 Parameters of the grid connected three-phase power converter

Control parameters	Values
Switching frequency, f	10 kHz
DC voltage source (V_d)	1,100 V (with 20 percent uncertainty)
Rated output voltage (V_T)	380 Vrms, $f = 50$ Hz
Nominal output power (P_L)	300 kW
Grid connection	$R_{line} = 50$ m Ω , $L_{line} = 4$ μ H, $C_f = 850$ μ F
DC-AC inverter	$R = 200$ m Ω , $L = 300$ μ H, $R_s = 3$ m Ω , $L_s = 3$ μ H, $C_s = 5,000$ μ F (with 5.0 percent uncertainty)

and

$$\Delta u_{Lr} = [\Delta m_d \quad \Delta m_q]^T$$

$$A_{Lr} = \begin{bmatrix} -\frac{R}{L} & -\omega & 0 & \frac{\sqrt{6}}{4L}m_d & -\frac{1}{L} & 0 & 0 & 0 \\ \omega & -\frac{R}{L} & 0 & \frac{\sqrt{6}}{4L}m_q & 0 & -\frac{1}{L} & 0 & 0 \\ 0 & 0 & -\frac{R_s}{L_s} & -\frac{1}{L_s} & 0 & 0 & 0 & 0 \\ -\frac{\sqrt{6}}{4C_s}m_d & \frac{\sqrt{6}}{4C_s}m_q & \frac{1}{C_s} & 0 & 0 & 0 & 0 & 0 \\ \frac{1}{C} & 0 & 0 & 0 & 0 & -\omega & -\frac{1}{C} & 0 \\ 0 & \frac{1}{C} & 0 & 0 & 0 & \omega & 0 & -\frac{1}{C} \\ 0 & 0 & 0 & 0 & \frac{1}{L_{line}} & 0 & -\frac{R_{line}}{L_{line}} & -\omega \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{L_{line}} & \omega & -\frac{R_{line}}{L_{line}} \end{bmatrix}$$

$$B_{Lr} = \begin{bmatrix} \frac{\sqrt{6}}{4L} V_d & 0 \\ 0 & \frac{\sqrt{6}}{4L} V_d \\ 0 & 0 \\ -\frac{\sqrt{6}}{4C_s} I_d & \frac{\sqrt{6}}{4C_s} I_q \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}, \quad \Delta x_r = \begin{bmatrix} \Delta I_d \\ \Delta I_q \\ \Delta I_s \\ \Delta V_d \\ \Delta v_{cfd} \\ \Delta v_{cfq} \\ \Delta I_{LD} \\ \Delta I_{LQ} \end{bmatrix}, \quad \Delta u_r = \begin{bmatrix} \Delta m_d \\ \Delta m_q \end{bmatrix}$$

From the definition of rotational reference frame, real power and reactive power outputs (P^{ref} and Q^{ref}) of inverter based DGs with balanced three-phase loads can be calculated as

$$I_{LD} = \frac{V_{Td} P^{\text{ref}} - V_{Tq} Q^{\text{ref}}}{V_{Td}^2 + V_{Tq}^2} \quad \text{and} \quad I_{LQ} = \frac{v_q P^{\text{ref}} + v_d Q^{\text{ref}}}{v_d^2 + v_q^2}$$

In this application, time domain performance (e.g., speed, overshoot) of the controller is evaluated by applying integral squared error (ISE) or the “cheap” linear quadratic regulator (LQR) cost function as [13]

$$J = \sqrt{\int_0^\infty \|e(\tau)\|^2 d\tau}$$

Where $e(t)$ is a vector of error signals.

The objective function of the robust control optimization problem is

$$\underset{\Theta}{\text{minimize}} J(\Theta)$$

subject to

$$\left\| \frac{W_m T}{W_s S} \right\|_\infty = \max_\omega \sqrt{|W_m T|^2 + |W_s S|^2} < 1$$

Where γ is a pre-specified upper bound which defines the rigorousness of control specifications, W_m is a multiplicative weight function of a plant, W_s is weighted sensitivity function. For the illustrative plant, the multiplicative weight function (W_m) requires a steep bound in the form [14]

$$W_m = \left(\frac{1}{k_m \sqrt{\varepsilon}} \left[\frac{s + \frac{\omega_{hc}}{k_m \sqrt{M_u}}}{s + \frac{\omega_{hc}}{k_m \sqrt{\varepsilon}}} \right] \right)^{k_m} I_{2 \times 2} \quad (6.10)$$

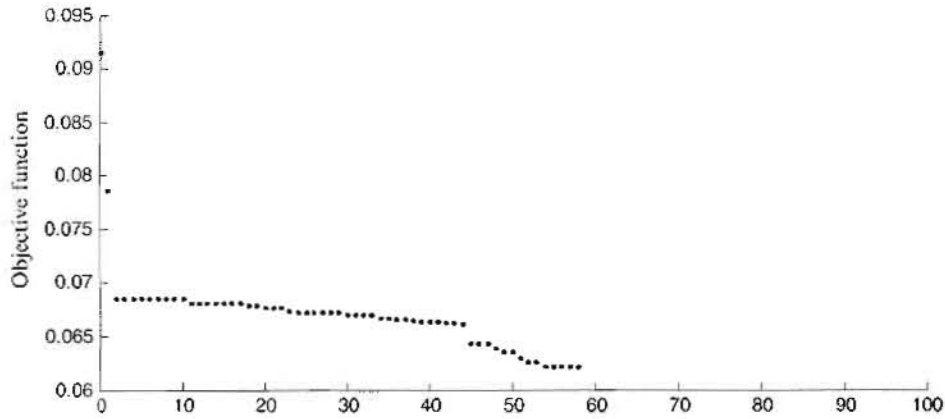


Fig. 6.6 Objective function of the illustrative case

parameters in (6.10) are chosen as follow: $\varepsilon = 0.01$, $k_m = 3$, $M_y = 4.5$, $\omega_{bc} = 2.5$ kHz. The weighted sensitivity function (W_S) is chosen as

$$W_S = \left(\frac{1}{k_s \sqrt{M_S}} \left[\frac{s + k_s \sqrt{M_S} \omega_{hc}}{s + k_s \sqrt{\varepsilon} \omega_{hc}} \right] \right)^{k_s} I_{2 \times 2}; \quad (6.11)$$

parameters in (6.11) are chosen as follow: $\varepsilon = 0.01$, $k_s = 1$, $M_S = 10$, $\omega_b = 10$ Hz. To avoid difficulty in implementation (i.e., controller with higher order), a PI controller is pre-specified as the configuration of $K(s)$ [1].

$$K(s) = \begin{bmatrix} K_{PD} + \frac{K_{ID}}{s} & 0 \\ 0 & K_{PQ} + \frac{K_{IQ}}{s} \end{bmatrix}$$

To determine the optimal controller, the proposed technique employs GA to search for the optimal control parameters. The best objective function and the optimal solution from GA optimization are 0.073 with $K_{PD} = 2.22 \times 10^{-4}$, $K_{PQ} = 1.91 \times 10^{-4}$, $K_{ID} = 0.191$ and $K_{IQ} = 0.199$. The objective functions from each generation are shown in Fig. 6.6.

The effectiveness of the proposed controller is verified by the time domain responses under step changes of the ideal DC source voltage. The fluctuation of DC voltage imitates operating conditions of renewable resources (e.g., fuel cells, solar cells, wind turbines), which may results from variations of environmental conditions.

In this example, results of a simulation with a reference value of average real power output (P^{ref}) at 300 kW are shown in Fig. 6.7. To demonstrate the stability of the plant, by applying the model of a grid connected three-phase inverter as shown in Fig. 6.5, the ideal DC voltage source (V_{DC}) is perturbed: from 1,100 V (normal value) to 800 V at $t = 0.10$ ms and back to 1,100 V at $t = 0.15$ ms. Note from

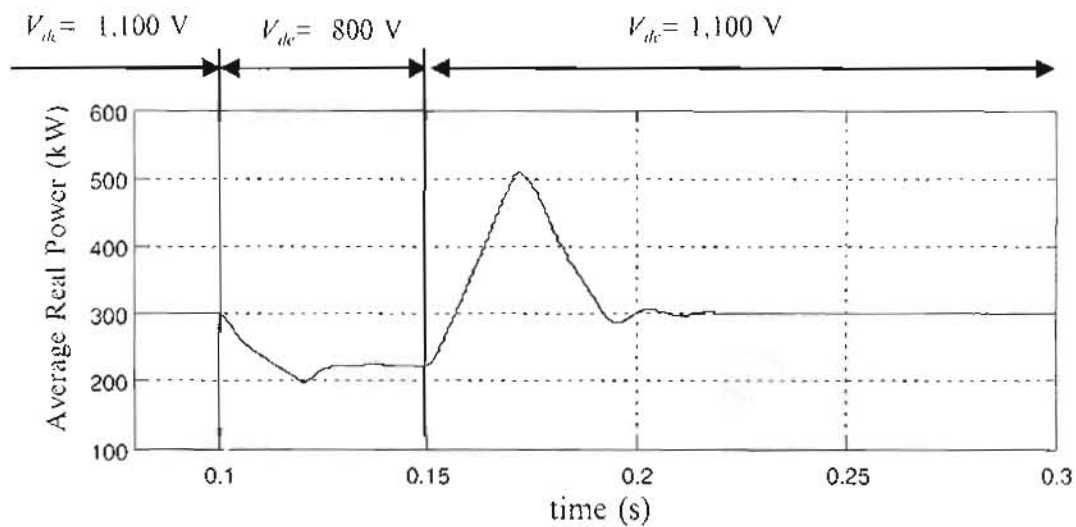


Fig. 6.7 A simulation result of a three phase inverter with $P_{\text{ref}} = 300 \text{ kW}$ and V_{DC} perturbations

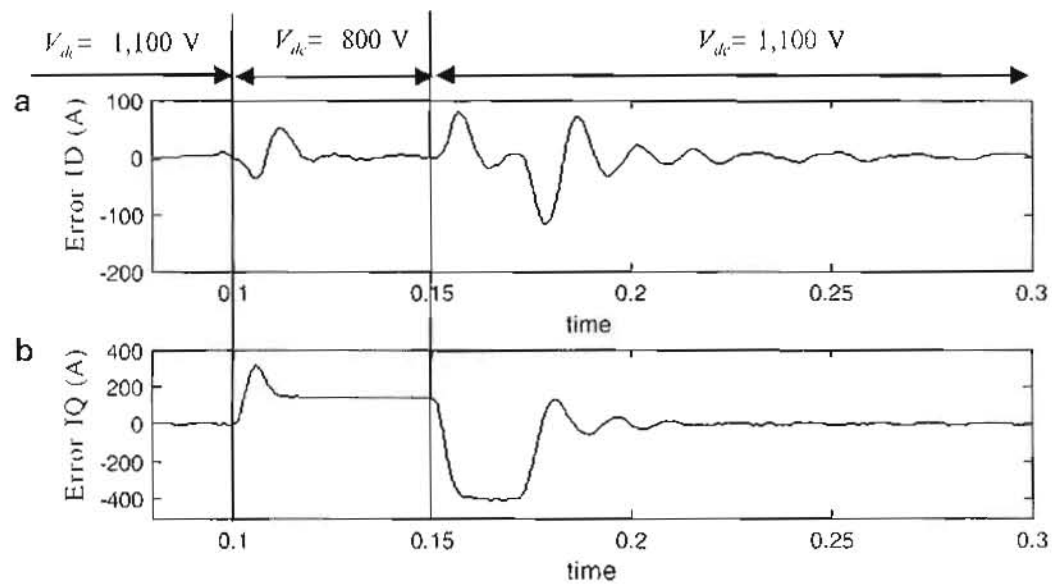


Fig. 6.8 Error of current (a) in direct axis (I_{LD}) and (b) in quadrature axis (I_{LQ})

Fig. 6.7 that the average output power has a capability to recover from DC voltage drop up to 27 percent within 2–3 cycles. Figure 6.8 shows the error of output current in direct and quadrature axis measure at the terminal of the inverter.

4 Conclusions

This paper proposes several new techniques for designing the fixed structure robust controllers. As shown in the results, the proposed technique can be applied to control the MIMO plants, i.e., the electro-hydraulic servo system and the three

phase inverter system. The stability margin (ε) obtained by the proposed technique indicates the robustness and performance of the proposed controller. Simulation results verify that the proposed technique is a feasible approach and reduces the gap between theoretical and practical schemes.

References

1. Chen BS, Cheng YM (1998) A structure-specified optimal control design for practical applications: a genetic approach. *IEEE Trans Control Syst Technol* 6(6):707–718
2. Chen BS, Cheng Y-M, Lee CH (1995) A genetic approach to mixed H_2/H_∞ optimal PID control. *IEEE Trans Control Syst* 15(5):51–60
3. Ho SJ, Ho SY, Hung MH, Shu LS, Huang HL (2005) Designing structure-specified mixed H_2/H_∞ optimal controllers using an intelligent genetic algorithm IGA. *IEEE Trans Control Syst* 13(6):119–124
4. McFarlane D, Glover K (1992) A loop shaping design procedure using H_∞ synthesis. *IEEE Trans Automatic Control* 37(6):759–769
5. Genc AU (2000) A state-space algorithm for designing H_∞ loop shaping PID controllers, technical report. Cambridge University Press, Cambridge
6. Patra S, Sen S, Ray G (2008) Design of static H_∞ loop shaping controller in four-block framework using LMI approach. *Automatica* 44:2214–2220
7. Kaitwanidvilai S, Parnichkun M (2004) Genetic algorithm based fixed-structure robust H infinity loop shaping control of a pneumatic servo system. *Int J Robot Mechatronics* 16(4):362–373
8. Olanthichachai P, Kaitwanidvilai S Structure specified robust H infinity loop shaping control of a MIMO electro-hydraulic servo system using particle swarm optimization, lecture notes in engineering and computer science. In: Proceedings of the international multicongress of engineers and computer scientists 2011, IMECS 2011, Hong Kong, 16–18 March 2011, pp. 879–883
9. Nimpitiwan N, Kaitwanidvilai S (2011) Robust control design for three-phase power inverters using genetic algorithm. In: Proceedings of international conference electrical engineering/electronics, computer, telecommunications and information technology (ECTI-CON), pp. 756–759
10. Kroutikova N, Hernandez-Aramburo CA, Green TC (2007) State-space model of grid-connected inverters under current control mode. *IET Electr Power Appl* 1(3):329–338
11. Abdel-Rahim N, Quaicoe JE (1996) Small-signal model and analysis of a multiple feedback control scheme for three-phase voltage-source UPS inverters. In: Proceedings power electronics specialist conference (PESC), vol. 1, Baveno, Italy, pp. 188–194
12. Wu R, Dewan SB, Slemon GR (1991) Analysis of an AC-to-DC voltage source converter using PWM with phase and amplitude control. *IEEE Ind Appl* 27(2):355–364
13. Jamshidi M, Krohling RA, Coelho LS, Fleming PJ (2002) Robust control systems with genetic algorithms. Taylor & Francis, New York
14. Rodriguez AA (2005) Analysis and design of multivariable feedback control systems. Control3D, Tempe, AZ: Control3D.