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# Fixed-order loop shaping robust controller design for parametric models to damp inter-area oscillations

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ABSTRACT

The inter-area oscillations are common in power systems and can occur due to the changes in the load or generating power especially in long transmission lines. This paper presents the design of a robust fixed-order loop shaping controller to damp out the inter-area oscillations and to enhance the stability of the power system. The proposed loop shaping method is based on the shaping of the open-loop transfer function in the Nyquist diagram through minimizing the quadratic error between the actual and the desired open loop transfer functions in the frequency domain. The proposed method is robust with respect to multi-model uncertainty. Despite other robust controller design methods, the proposed approach deals with the entire system i.e. there is no need to reduce the system and still leads to a lower order controller. In addition, most of the robust methods are heavily dependent on selecting some weight filters which is not required in the proposed approach. This method is applied to the two-area four-machine system and 68 bus system and the effectiveness and robustness of the proposed method in damping inter-area oscillations are validated using case studies.



## 1. Introduction

### 1.1. Motivation

Damping of inter-area oscillations is one of the main challenges for maximizing the tie-line power transfer in power systems. These oscillations are the outcome of weakly interconnected power systems [1–10]. The inter-area oscillations become worse as the power system becomes more stressed. Recently, Flexible AC Transmission System (FACTS) devices have been used in power systems to control the bus voltages and tie-line power. They can also damp power system oscillations and improve the system stability by providing a supplementary control signal to the reference value of these devices [2–8]. Large scale integration of renewable resources in a modern power system has added extra uncertainty to the power system. As a result of this variability, it becomes necessary for the damping controllers to be robust.

Different types of robust control methods including $H_2$, $H_\infty$ and $H_\infty$ loop shaping are introduced and employed to design a robust controller that are able to cope with system uncertainty [11–20]. These different methods of the controller design are based on some optimization techniques. There are two drawbacks to these approaches:

1. They deal with a reduced order system which means there is no guarantee of the stability and performance. One of the main reasons for using a reduced order model in the other methods particularly $H_\infty$ technique is that, the conventional $H_\infty$ technique results in a controller that is the same size as the order of the system. Thus, using a full order system is computationally infeasible. Therefore, it is necessary to reduce the system to obtain a feasible controller.
2. Their performance is heavily dependent on weights selection which is not a trivial task.

This paper presents a design method that directly deals with the system without reducing it and does not depend on selecting some weight filters.

### 1.2. Literature review

Damping of inter-area oscillations in power system using $H_2$, $H_\infty$ and $H_\infty$ loop shaping methods has been previously studied

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[11–20]. The results show that these methods of designing the controller have the ability to damp out inter-area oscillations and enhance the stability of the power system. The solution to $H_\infty$ control design problem is based on the Riccati equation approach. Recently, linear matrix inequalities (LMIs) method is used to solve $H_\infty$ control design problem [10]. The main challenges with $H_2$ and $H_\infty$ approaches are that they depend heavily on the proper selection of some weight filters and the plant model needs to be reduced. Most of these designs are based on nominal operating point, i.e. the control objectives from $H_2$ and $H_\infty$ formulations are guaranteed around an operating point. On some occasions, the system might not be operating close to a nominal operating point and the controller might not work as expected.

The main concept of the $H_\infty$ loop-shaping method is to augment the open-loop model by pre and post compensators to get the desired shape [13]. Then the controller is designed by solving the $H_\infty$ optimization problem. There are two drawbacks on the standard $H_\infty$ loop shaping method; the first drawback is the challenge of selecting the proper loop shaping weights. Selecting the proper weights in this method is based on trial and error which is considerably time consuming. In particular, it is difficult to design proper reduced-order loop-shaping weights which meet the requirements of the multiple controls. The second drawback is the order of the designed controller. The order of the controller is considered as a key factor since the controller is implemented in computers and devices that have limited memory and computing power. Implementing a high order controller both in hardware and software is a challenging task and leads to numerical problems. Even though there are some methods to reduce the order of the controller, they do not guarantee that the reduced controller will achieve the requirements of stability and performance.

Recently, new techniques are presented in [17,18] to design a robust controller for multi-modal uncertainty using $H_2$ and $H_\infty$ under pole placement, however, these techniques require reducing the order of the plant model. Also, the designed controller based on these techniques lead to high-order controller compare it with the proposed approach.

### 1.3. Contributions

The contribution of the paper is introducing a new approach to design a fixed-order linearly parameterized controller using the loop-shaping approach that doesn't suffer from other methods' drawbacks. First, the controller design technique presented in the paper can use the full order system for designing a robust loop shaping controller since the order of the controller is fixed without sacrificing the computational time required (which is taken care by convexifying the problem). This eliminates the need for using an approximate reduced order model rather than the actual model. The proposed approach can also use reduced order system. Second, the proposed approach doesn't require the weight filters selection. Third, multi-model uncertainty is considered. The proposed approach is based on the shaping of the open-loop transfer function in the Nyquist diagram [21–23]. The control objective is to reduce the distance between the designed open-loop transfer function and the desired one by minimizing their quadratic error in the frequency. The desired transfer function needs to be specified in order to carry out the optimization and design the controller. The proposed approach can handle both stable and unstable plant models. In this work, however, only stable plant models are considered. Frequency Domain Robust Control (FDRC) Toolbox which is introduced in [23] is used in this paper to design loop shaping fixed-order robust controller.

The rest of this paper is organized as follows: the background on the design of the robust loop-shaping controllers in the Nyquist diagram is discussed in Section 2. Section 3 introduces the test power systems (two-area four-machine system and 68 bus system) including the models of the Static VAR Compensator (SVC) and the Doubly Fed Induction Generator (DFIG). The controller design procedure is introduced in Section 4. The time domain simulations, eigenvalues analysis and results are presented in Section 5. Section 6 provides concluding remarks.

## 2. Loop shaping controller

The primary purpose of this paper is to introduce and design a linearly parameterized robust controller. To demonstrate the capability of the proposed method and controller, it is used to damp out the inter-area oscillations. Consider a linearly parameterized controller of the form given in (1) [21–25]:

$$K(s) = \rho^T \varphi(s) \tag{1}$$

where

$$\rho = [\rho_1 \; \rho_2 \ldots \rho_n]$$

$$\varphi(s) = [\varphi_0(s)\varphi_1(s)\ldots\varphi_{n-1}(s)]^T$$

where $n$ is the number of controller parameters, $\rho_i$ is the controller parameters and $\varphi_i(s)$ is a basis function. The Laguerre function is a commonly used basis function and is given in (2) [22].

$$\varphi_0(s) = 1, \varphi_i(s) = \frac{\sqrt{2\zeta}(s-\zeta)^{i-1}}{(s+\zeta)^i} i \geqslant 1, \quad \zeta > 0 \tag{2}$$

where $\zeta > 0$ is the Laguerre parameter. It can be shown that for any finite order transfer function $F(s)$, arbitrary Laguerre parameter $\zeta > 0$ and an arbitrary constant $\varepsilon > 0$, there exists a finite $n$ such that

$$\|F(s) - \rho^T\varphi(s)\|_p < \varepsilon \text{ for } 0 < p < \mathit{infinity} \tag{3}$$

The controller parameterization presented in (1) allows us to get a good approximation of any finite order stable transfer function with a desired level of accuracy by varying the parameter $n$. The result of the optimization problem given in (3) is dependent on the difference between the poles of $F(s)$ and $\zeta$. A better approximation of any finite order stable transfer function can be obtained for a given controller order if the choice of $\zeta$ is proper. More details for optimal selection of the basis function can be found in [21].

The reason behind using the linearly parameterized controller is because all points on the Nyquist diagram of the open loop transfer function $L(j\omega,\rho)$ can be written as a linear function of the controller parameters ρ as given in (4). This property helps in obtaining a convex parameterization of the loop shaping fixed order controller.

$$\begin{aligned} L(j\omega,\rho) &= K(j\omega,\rho)G(j\omega) = \rho^T\varphi(j\omega)G(j\omega) \\ &= \rho^T\mathcal{R}(\omega) + j\rho^T\mathcal{I}(\omega) \end{aligned} \tag{4}$$

where $\mathcal{R}(\omega)$ and $\mathcal{I}(\omega)$ are respectively the real and imaginary parts of $\varphi(j\omega)G(j\omega)$.

In case of a single model, $G$ is a scalar function whereas for a multi-model controller design $\mathcal{G} = \{G_i(j\omega), i = 1,\ldots,m\}$ is defined where $G_i(j\omega)$ represents the i-th model in the multi-model uncertainty set. In this case, $L_i(j\omega)$ is the open-loop transfer function for the i-th model.

### 2.1. Robust performance constraints

The main idea of this method is based on minimizing the difference between the desired open loop transfer function $L_d(j\omega_k)$ and the open loop transfer function $L_i(j\omega_k,\rho)$ shown in Fig. 1 [22]. As it is well known, $(-1+j0)$ is the critical point on the Nyquist plot for analyzing the stability of the closed-loop system. Therefore, the