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Design of wide-area robust damping controller based on the non-convex stable region for inter-area oscillations

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ABSTRACT

In view of the low frequency, low damping ratio and long duration characteristics of the inter-area oscillation mode, the stable region is firstly extended by the eigenvalue shifted factor in this paper. Furthermore, a non-convex stable region is designed which can stabilize the system rapidly. Then a mixed H_2/H_∞ multi-objective robust control strategy based on the non-convex stable region is proposed considering the perturbation and system uncertainty. Finally, time-domain and frequency-domain simulations are carried out in the 4-machine and 16-machine test systems respectively, and simulation results verify that the proposed strategy is more effective and robust than the traditional H_2/H_∞ control strategy.

1. Introduction

Inter-area oscillation usually exists in weakly interconnected power systems [1]. With its wide-spread influence, long duration time, and being difficult to be damped using local information [2], it has become one of the most prominent threats to system safety and stability. Conventional control methods are mostly based on traditional control theories [3], including phase compensation method, pole assignment method and sensitivity analysis method, etc. As the modern control theory becomes more sophisticated, many new control methods have been introduced into the design of system damping control, such as linear optimal control [4], adaptive control [5,6], and robust control [7,8]. The linear optimal control adopts the sum of the squares of state variables and control variables as the performance indicator and obtains the optimum control by solving the Riccati equation. Adaptive control works by adjusting the control principle continuously with the changing operating condition to guarantee that the control performance stays close to that of the reference model. These two methods both have sufficient damping when the system and perturbation models are accurately built. But when uncertainty occurs in these models, the damping effect can hardly be guaranteed with these methods.

In comparison, robust control methods have unique superiority in dealing with the uncertainty in system parameters and the external perturbation [9,10]. Ref. [11] presents a polytope based damping controller designed to accommodate multiple cases with different operating conditions. Ref. [12] presents an optimization-based tuning scheme used for coordination of structurally constrained PSSs and SDCs to damp interarea oscillations and to optimize their control efforts under multiple operating conditions. Furthermore, the mixed H_2/H_∞ control theory is favored by many specialists and scholars due to its comprehensive consideration of factors such as the system stability and robustness [13–16]. In the design of the mixed H_2/H_∞ controller, the system oscillation mode needs to be shifted to the left half-plane or a pre-designed stable region in order to guarantee the dynamic and steady-state performance of the closed-loop system. The shifting is conducted according to the Gutman theorem [17] in traditional methods, but it is limited to the convex region.

In view of the low frequency, low damping ratio and long duration characteristics of the inter-area oscillation mode, the stable region is firstly extended by the eigenvalue shifted factor in this paper. Furthermore, a non-convex stable region is designed which can stabilize the system rapidly. Then a mixed H_2/H_∞ multi-objective robust control strategy based on the non-convex stable region is proposed considering the perturbation and system uncertainty. Finally, time domain and frequency domain simulations are conducted in the 4-machine and 16-machine test systems respectively, and simulation results verify that the proposed strategy is more effective and robust than the traditional H_2/H_∞ control strategy.

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Nomenclature

$\boldsymbol{x}$	system state vector
$\boldsymbol{u}$	control input vector
$\boldsymbol{y}$	output vector
$\boldsymbol{A}$	system state matrix
$\boldsymbol{B}$	control input matrix
$\boldsymbol{C}$	output matrix
$\boldsymbol{D}$	feed forward matrix
z	any point on the complex plane
c_{kl}	kth row ith column element of matrix **M**
$\boldsymbol{C}_1$	the weight matrix of state variables
$\boldsymbol{D}_{12}$	the weight matrix of control input related to the performance indicator of H_∞
D_{11}	the weight matrix of perturbation input related to the performance indicator of H_2
$(c_0, 0)$	the coordinates of the center
$\boldsymbol{M}_{R_1}$	the corresponding set
$\boldsymbol{U}(\boldsymbol{F})$	coefficient matrix expressed in terms of variable $\boldsymbol{F}$
γ	the given upper bound γ for H_∞ performance
$\boldsymbol{w}$	external perturbation input vector
$\boldsymbol{z}_\infty$	controlled vectors related to the performance indexes of H_∞
$\boldsymbol{z}_2$	controlled vectors related to the performance indexes of H_2
$\boldsymbol{B}_1$	gain matrix of input $\boldsymbol{w}$
$\boldsymbol{B}$	control input matrix
$\boldsymbol{F}$	eigenvalue shifted factor matrix
α	the weights of the H_2 performance index
β	the weights of the H_∞ performance index.
m	the order of **M** matrix
D_{11}	the weight matrix of perturbation input related to the performance indicator of H_∞
$\boldsymbol{C}_2$	the weight matrix of state variables
$\boldsymbol{D}_{12}$	the weight matrix of control input related to the performance indicator of H_2
d	the intersection point of the non-convex region and imaginary axis
$\mathbf{X}$	positive definite symmetric matrix
$\boldsymbol{V}(\boldsymbol{F})$	coefficient matrix expressed in terms of variable $\boldsymbol{F}$
η	the given upper bound for H_2 performance

2. H_2/H_∞ robust control strategy based on the non-convex stable region

2.1. Non-convex stable region

Lemma 1 [18]. *The Lyapunov 1st method. For the plant* $\sum : (\boldsymbol{A}, \boldsymbol{B}, \boldsymbol{C}, \boldsymbol{D})$, *there are:*

$$\begin{aligned} \dot{\boldsymbol{x}} &= \boldsymbol{A}\boldsymbol{x} + \boldsymbol{B}\boldsymbol{u} \\ \boldsymbol{y} &= \boldsymbol{C}\boldsymbol{x} + \boldsymbol{D}\boldsymbol{u} \end{aligned} \tag{1}$$

where x is the system state vector, u is the control input vector, y is the output vector, A is the system state matrix, B is the control input matrix, C is the output matrix, and D is the feed forward matrix.

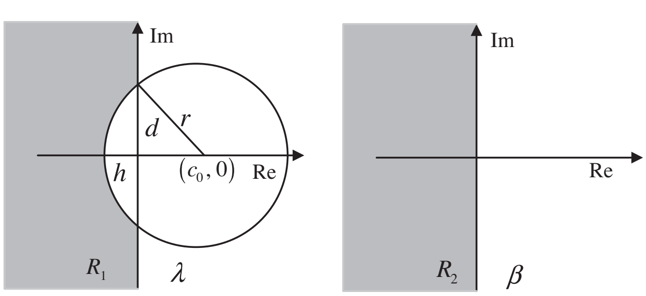
In the equilibrium state where $x_e = 0$, the necessary and sufficient condition for the system to be asymptotically stable is that all eigenvalues of matrix $\boldsymbol{A}$ have negative real parts.

Lemma 2 [19]. *The fact that all the eigenvalues of matrix $A \in R^{n\times n}$ have negative real parts equals to that there is a symmetric matrix $X > \mathbf{0}$ which satisfies $AX + XA^{\boldsymbol{T}} < \mathbf{0}$.*

The oscillation modes of the system can be shifted to the stable region in the left half-plane by Lemmas 1 and 2. However, this method cannot guarantee enough damping for all the oscillation modes. Thus, according to the Gutman theorem, as long as there is a positive definite symmetric matrix **X** that meets Eq. (2), all eigenvalues of matrix $\boldsymbol{A}$ should be in the stable region $\boldsymbol{M}$ described by Eq. (3).

$$\sum_{k,l} c_{kl}\boldsymbol{A}^k\boldsymbol{X}(\boldsymbol{A}^{\boldsymbol{T}})^{\boldsymbol{l}} < 0 \tag{2}$$

$$\boldsymbol{M} = \left\{ z \in \mathbf{C} : \sum_{0\leqslant k,l\leqslant m} c_{kl} z^{\boldsymbol{k}} \bar{z}^l < 0 \right\} \tag{3}$$



(a) non-convex region R1 in the plane λ (b) left half-plane R2 in the plane β

Fig. 1. The mapping of complex planes.

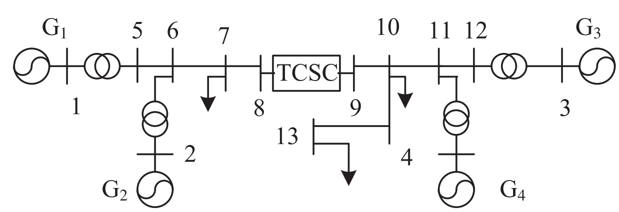


Fig. 2. Test system of 2-area 4-machine.

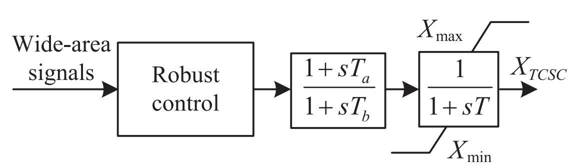


Fig. 3. Structure of TCSC supplementary controller.

Table 1
Dominant modes in 4-machine system without controllers.

Mode	Frequency (Hz)	Damping ratio	Mode type
1	0.4926	0.0086	Inter-area
2	1.0854	0.0773	Inner-area
3	1.0948	0.0724	Inner-area