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Multi-objective attuned design of damping controllers using frequency-based functions in smart grids

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ABSTRACT

Increasing expansion of power systems is accompanied by innovations in smart grid solutions to maintain system stability. This paper formulates the dual-dimensional supplementary damping controller (SDC) and accelerating power system stabilizer (PSS2B) design as a multi-objective optimization procedure including both performance and robustness criteria. In wide-area operation, PSS2B is used for damping low-frequency swings and maintaining the robustness of controller in a wide range of swing frequencies. A dual-dimensional controller model is employed for the SDC. The robustness requirement is procured by using the idea of pseudospectra to handle the changes of power system parameters and the time delay introduced by wide-area damping controller (WADC). The multi-objective optimization problem is solved using an improved non-dominated sorting genetic algorithm-II (INSGA-II) based on fuzzy decision making (FDM) method. Different simulations are carried out on a 4-machine 2-area test system in order to validate the effectiveness and robustness of the designed controllers.

1. Introduction

1.1. Motivation and approach

The existence of phasor measurement units (PMUs) with modern communication tools in expansion of smart grids creates new opportunities in power systems. The wide-area control technologies offer a great potential to overcome the shortcomings of conventional local controllers [1]. With the technology of global positioning system (GPS) based on PMU, dynamic data of power system such as voltage, current, angle and frequency can be accurately measured, synchronized and transferred across entire power system by wide-area measurement systems (WAMS) [3]. This makes it possible to construct the wide-area damping control (WADC) systems [2]. One of the concerns is the adverse effect of data communication problems like latency and low feedback data rate on the closed-loop performance, and hence on the secure operation of power system [4]. This in fact, has inhibited practical deployment of WADC until today, except for a few prototype or pilot schemes. Feedback data rate is often limited by the available bandwidth of communication channels and could be critical for satisfactory closed-loop performance due to latency created by confined communications [5]. Especially, for networked control systems relying on communication of feedback signals from distant sensors, bandwidth limitation is a matter of serious concern.

The secure operation of smart grids to maintain a high level of system stability is an important issue that it is required to be surveyed. Thus, the need for a systematic design procedure and a comprehensive study on suitable control strategies is gaining more and more attention. From viewpoint of stability analysis and control design, it is necessary to consider latency in the design procedure in order to retain a WADC-equipped power system stable. During the design of mentioned controllers, the robust control methods, as effective and premier solutions, can be used to handle the time delay as part of system uncertainties. For designing a robust controller it is important to consider the operating conditions and dynamic events occurring in the system. In other words, the controller has to be robust under various operating conditions due to stochastic nature of power system operation and configuration.

Both damping factor and damping ratio are often used as an objective function in the design procedure of damping controllers. Such objective functions may produce eigenvalues near an imaginary axis, or may lead to high-frequency swings [6,7]. Many damping controller design methods ensure good dynamic performance of the closed-loop system by driving all poles to a so-called

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Nomenclature

SDC	supplementary damping controller
PSS	power system stabilizer
PSS2B	accelerating power PSS model
WADC	wide-area damping controller
INSGA-II	improved non-dominated sorting genetic algorithm-II
FDM	fuzzy decision making
GPS	global positioning system
PMU	phasor measurement unit
WAMS	wide-area measurement systems
WACS	wide-area control system
LMI	linear matrix inequalities
BMI	bilinear matrix inequalities
FACTS	flexible alternating current transmission system
MADM	multi-attribute decision making
UPFC	unified power flow controller
SBX	simulated binary crossover
DCD	dynamic crowding distance
DM	cecision makers
LFS	low-frequency swing
E'_q, E_{fd}	generator internal and field voltage
η_m	polynomial mutation index
η_c	crossover index
Γ	feasibility space
m_E, m_B	excitation and boosting amplitude modulation ratio
δ_E, δ_B	excitation and boosting phase angle
n_0	number of objectives
V_{Et}, I_E	excitation voltage and current
A_s, B_s, C_s, D_s	state matrixes for a linearized power system excluding the controllers
δ, ω	rotor angle and speed
K_s, T_s	FACTS gain and time constant
T'_{do}	time constant of excitation circuit
T_E, T_M	electrical and mechanical torque
T_A, K_A	regulator time constant and gain
D, M	machine damping and inertia coefficient
H	inertia constant
V_{Bt}, I_B	boosting voltage and current
x_E, x_B	excitation and boosting transformer reactance
C_{dc}, V_{DC}	DC link capacitance and voltage
u_{pss}	PSS control signal
P_m	mechanical input power
P_e	active power
T_1, T_2	lead and lag time constant of controller
T_3, T_4	lead and lag time constant of controller
μ	time delay
T_ω	washout time constant
G	proportional gain of the controller
R	residue magnitude
t, v	right and left eigenvector
x_d, x'_d	direct axis reactance of synchronous generator under steady state and transient state situations
J	objective function
ζ, σ	real part and damping ratio of the eigenvalue
σ_{min}	minimum singular value
σ_{max}	maximum singular value
E'_q, E_{fd}	generator internal and field voltage
A_e, B_eC_e, D_e	state matrixes for a closed-loop power system
A_c, B_cC_c, D_c	state matrixes for linear damping controller

linear matrix inequalities (LMI) or bilinear matrix inequalities (BMI) region [8]. The drawback of matrix inequality approach is that it usually yields controllers with a complex structure and of high order. The simplicity of the controllers structure is always preferred because it is easy to adapt them in the existing controllers through either hardware or software modifications. The industry is more comfortable to implement simple PID or lead-lag type controllers. Therefore, there is research tendency for designing low-order robust control algorithms. The difficulty to deal with the robustness by matrix inequalities has recently led to solve the problem of robust design by non-convex non-smooth numerical optimization by using suitable robustness criteria [9]. Low order and large system dimension, which limit the applicability of design methods based on matrix inequalities, can be effectively dealt with by non-smooth optimization.

The innovation of this paper is organized around three important matters:

- Design of robust WADC based on non-convex non-smoth numerical optimization to deal with some uncertainties in smart grids.
- WADC and PSS2B coordination for improvement of dynamic performance of smart grids by multi-objective optimization.
- Design of low-order damping controllers, WADC and PSS2B, with better efficiency in comparison with previous controllers.

1.2. Literature review

The stability analysis of WADC systems (including PSS) using synchronized phasor measurements have been discussed in [10]. Using conventional control approaches, researchers in [11] focused on desirable properties of communication networks to guarantee a minimum performance level of system. The robust design of damping controllers based on damping factor and damping ratio indices has been developed in [6,7]. Also, The optimization-based design of low-order PSS and FACTS devices that allow the handling of robustness have been discussed in [12,13].

1.3. Contributions

Based on the idea of pseudospectra, an attempt has been made in this paper to robust attuned design of dual-dimensional SDC and PSS2B. Pseudospectra notion is an effective method for analyzing the robust controller in the theory of matrices. Focusing on inter-area modes, a dual-dimensional SDC is utilized, where the first dimension of control is derived by local signals and the second dimension is supplied from global signals. In this paper, the latency caused by transmission of remote signals is considered as part of system uncertainties, and will be taken care of by robust design of controllers. The existing approaches to robust design of WADC to deal with latency is based on matrix inequalities [10,14,15]. Application of matrix inequality methods is restricted by some matters: (a) large-order controllers to ensure the convexity of the matrix inequalities, (b) numerical problems related to structural constraints of controllers or dimension of the solution space, (c) frequently fail to converge or stop due to nonfeasibility, and (d) heavy computational burden. The style applied in this paper can handle structural constraints of wide-area controllers, large dimensions of the system model and problems related to matrix inequality-based methods. A multi-objective optimization approach including both performance and robustness criteria is utilized, and INSGA-II is then applied in searching to find the