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Profit enhancement by a set of performance and robustness indices based design of dual-dimensional PODC and PSS2B in smart grids

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ABSTRACT

Expansion of power systems is accompanied by innovations in smart grid solutions to power system operation and control. Profit enhancement by power oscillation damping controllers (PODC) and acceleration based power system stabilizer (PSS), model PSS2B, designed by the idea of pseudo-spectra based on multi-objective optimization is presented. The contribution of multi-objective functions in respect of performance and robustness criteria in stability enhancement is evaluated by considering the control actions of PODC and PSS2B as an ancillary service (AS). The robustness requirement is achieved by using the idea of pseudo-spectra to handle the changes of power system parameters and time delay introduced by processing of remote signals in the wide-area supplementary damping controller (WASDC). The weighted sum of six objective functions as performance and robustness criteria is selected as low-frequency oscillation damping index (LFODI). Two scenarios for the evaluation of small signal stability as an AS provided by PODC and PSS2B are considered. A multi-objective optimization approach based on LFODI, generation costs is formulated and improved non-dominated sorting genetic algorithm-II (INSGA-II) is employed to solve this problem. Fuzzy decision making (FDM) is used to find the best compromise solution from the set of Pareto-solution obtained by INSGA-II. Comparative analysis of the results of the conventional method and the proposed design method is presented by case study on a modified 2-area 4-machine power system.

1. Introduction

Application of phasor measurement units (PMUs) with modern communication tools in expansion of smart grids creates new opportunities. The presence of such technologies enables advanced smart grid applications, such as the real-time tracking of system dynamics [1], that were not feasible before. Secure operation of smart grids to maintain high level of system stability is an important issue. Hence, the need for a systematic study and design of a comprehensive system control strategy is gaining greater attention. From the deregulated electricity market perspective, independent system operators (ISOs) are in charge of guaranteeing stable, secure and reliable operation of the power grid [2]. It includes tuning of the controllers to enhance system security [3]. Thus, there is a need for tuning methods that guarantee system stability within the context of a market operating environment.

In a system with several generators, parameters of the PSSs would be optimally tuned in a coordinated manner by the ISO, or a similar entity. These PSSs perform a service for system by providing stabilization action in response to disturbances that occur in the system. In the absence of this service, the system will in some cases become unstable due to sustained low-frequency oscillations [4]. Evidentially, this directly affects the transmission system security and reliability, and hence the service provided by such PSS control action can be classified within the AS definition as a service for bulk transmission system security.

The wide-area control technologies offer a great potential to overcome the shortcomings of conventional local controllers such as PSSs [5]. One promising application of wide-area control system (WACS) using global measurements obtained by wide-area measurement systems (WAMS) is WSADC [6]. WASDC implementation, such as control of PSS using synchronized phasor measurements have been discussed in [7]. One of the concerns is the adverse effect of data communication problems, like latency and low data of feedback rate, on the closed-loop performance and hence secure operation of power system [8]. This has inhibited practical deployment of WSADC 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 [9]. Especially, for networked control

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Nomenclature

UPFC–PODC	unified power flow controller–power oscillation damping controller
PSS	power system stabilizer
WASDC	wide-area supplementary damping controller
AS	ancillary service
LFODI	low-frequency oscillation damping index
INSGA	improved non-dominated sorting genetic algorithm
ISO	independent system operators
PODC	power oscillation damping controller
FDM	fuzzy decision making
LMI	linear matrix inequalities
BMI	bilinear matrix inequalities
MADM	multi-attribute decision making
SBX	simulated binary crossover
DCD	dynamic crowding distance
PSS2B	accelerating power PSS model
SSC-OPF	small perturbation stability constrained OPF
GPS	global positioning system
PMU	phasor measurement unit
WAMS	wide-area measurement systems
WACS	wide-area control system
FACTS	flexible alternating current transmission system
TCSC	thyristor controlled series capacitor
VSC	voltage source converter
LFS	low-frequency swing
SVD	singular value decomposition
NERC	North American electric reliability council
AVR	automatic voltage regulation
LAE	least average error
m_E, m_B	excitation and boosting amplitude modulation ratio
δ_E, δ_B	excitation and boosting phase angle
F	output feedback matrix
ω	generator speed
A_r, B_r C_r, D_r	state matrixes for a closed-loop power system
λ	eigenvalue of A_r
k_s, T_s	FACTS gain and time constant
P_{Gen}	real power of ith generator
C_{Gen}	offer price of ith generator
ρ_i	weight factors for J_i
J	objective function
η_m	polynomial mutation index
η_c	crossover index
Γ	feasibility space
n_0	number of objectives
ζ, σ	real part and damping ratio of the eigenvalue
σ_{min}	minimum singular value
σ_{max}	maximum singular value
x_E, x_B	excitation and boosting transformer reactance
C_{dc}, V_{DC}	DC link capacitance and voltage
u_{pss}	PSS control signal
t, v	right and left eigenvector
R	residue magnitude
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
K	proportional gain of the controller
OS_i	overshoot of ith signal
US_i	undershoot of ith signal
$T_{s,i}$	settling time of ith signal
ρ_{set}	weightage set
$J_k^{\rho_{set,i}}$	J_k value at weightage set i
$J_k^{overall}$	overall J_k values
η_{LAE}	performance index
P_{tie}	tie-line active power
A_c, B_c, C_c, D_c	state matrixes for linear damping controller
A_s, B_s, C_s, D_s	state matrixes for a linearized power system excluding the controllers

systems relying on communication of feedback signals from distant sensors, bandwidth limitation is a matter of serious concern. In recent years, research has been focused on desirable properties of communication networks to guarantee a minimum performance level with conventional control approach [10]. Also, a lot of attention has been devoted to assessing the stability of standard communication networks [11]. From the viewpoint of stability analysis and controller design, it is necessary to consider latency in the design procedure in order to maintain a WASDC-equipped power system stable. In the design of said controllers, robust control methods can be used as effective and premier solutions to handle the time delay as part of system uncertainties.

Various methods of robust control design have been suggested in the literature. Many damping controller design methods ensure dynamic performance of the closed-loop system by driving all poles to a so-called linear matrix inequalities (LMI) or bilinear matrix inequalities (BMI) region specially defined in the complex plane [12]. Drawback of the matrix inequality approach is that it usually yields controllers with a complex structure and of high order. The simplicity of the controller structure is always preferred because it is easy to adapt in the existing controllers through either hardware or software modifications. Therefore, there is scope for low-order robust control design. The difficulty in dealing with the robustness by matrix inequalities has recently led to a new trend in control theory to solve the problem of robust design by non-convex, non-smooth numerical optimization using suited robustness criteria [13]. High order and large system dimension, that limit the applicability of design methods based on matrix inequalities, can be effectively dealt with non-smooth optimization.

With deregulation and the separation of generation and transmission, the ISO often has no direct control over individual power stations and has to purchase ASs from AS providers [14]. In such an environment, issues pertaining to payment mechanisms for such services are extremely important for the proper functioning of the system [15]. Price estimation of system security provided by PSS and WASDC has become one of the concerns in power system [16]. A survey from the economic perspective of service provided by dual-dimensional supplementary damping controller and PSS2B is given in [17]. Allocation of payoffs to generators for their PSS-control services and a possible payment scheme is considered in [18] based on cooperative game theory using the concept of shapely values [19]. Two scenarios for small signal stability service valuation have been presented in [20] with the economic value of this service determined by a multi-objective optimization process.

The role and performance of the dual-dimensional PODC and PSS2B, designed based on the idea of pseudo-spectra to deal with the fixed structure of controllers in the context of deregulated power markets, is examined in this paper. Pseudo-spectra opinion is an effective method for analyzing the robust controller in the theory of matrices. Focusing on inter-area modes, a dual-dimensional PODC is utilized. The latency caused by transmission of remote signals is considered as part of system uncertainties handled with robust controllers. It is proposed that the PODC and PSS2B efforts