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Coordinated design of STATCOM and excitation system controllers for multi-machine power systems using zero dynamics method

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ABSTRACT

FACTs devices are being used in transmission networks for increasing the power transfer limit and stability improvement. They also help damp out both local and inter-area low frequency oscillations. However, uncoordinated design of these devices with excitation systems may deteriorate the power system performance. Moreover, power system is a large, complex and nonlinear system, and the controllers that are designed based on linear control theories may have a detrimental effect on the system performance, especially when there are large disturbances occurring in the system. The design method of a nonlinear control technique, named zero dynamics is given in this paper to design the controllers of STATCOM and excitation systems coordinately for multi-machine power systems. This technique is able to provide the stability of both external and internal dynamic performances of the system. Simulations results clearly verify that the proposed method improves the power system stability.

1. Introduction

Due to the interactions between generators through the weak tie-lines and the existence of high gain automatic voltage regulators (AVRs), low frequency oscillations normally exist in power systems. As a result of this phenomenon there will be limit on the maximum power to be transmitted on tie-lines. Two types of oscillations are usually known. One is referred to inter-area modes resulted from swinging one generation area with respect to other areas. The second one is associated with swinging of generators existed in one area against each other and is known as local mode [1].

Power system stabilizers (PSSs) have been widely utilized to add a signal into the AVR to boost the power system stability. In this regard, different methods have been developed to design multiple stabilizers installed in different generators coordinately in order to damp out both inter-area and local modes [2]. With respect to the variations of system operating points, although many design methodologies have been provided to improve the PSS performance, there are still many researches to overcome the tuning problem for damping both kinds of oscillations in a robust way [2].

Moreover, when there are large disturbances taking place in the system, the system operating point varies significantly and nonlinearities may have a considerable effect on the system performance. In this situation, the controllers designed based on linear models may not retain stability. Therefore, it is necessary to use control design methodology in which the nonlinearities of the power system model can be considered. Besides, although the excitation control is able to improve the transient stability, it will fail to keep the system stability if a large fault happens near to the generator terminal [3].

Recently because of the world economic growth, the need for expanding modern power system rises. However, due to environmental problems and urbanization it is hard to build up new transmission lines. Therefore, the use of the new equipment such as FACTS devices is greatly taken into account. These devices can increase the transfer power limits and also improve the steady-state and transient stability [4]. However, as shown in [4] the interactions between the excitation systems and FACTs controllers may cause the dynamic instability if they are designed based on uncoordinated control strategies.

As shown in [4–7] the coordinated design of the excitation system without PSS and the supplementary controllers of FACTs devices could be one of the best solution to damp out both inter-area and local modes as well as boosting the transient stability. In [7], a coordinated design of UPFC controller and excitation system by using the feedback linearization technique is studied on a single machine infinite bus (SMIB) system. This technique is also used for designing TCPS [6,8], SVC [9,10] and STATCOM [4] controllers with excitation system simultaneously. In [11] back-stepping method is also used to design excitation system and TCSC controllers coordinately. It is shown that the controllers improve the transient stability, the voltage regulation and the system damping. Hamiltonian and adaptive Hamiltonian methods [12,13] have been used to design the controllers of STATCOM and excitation system coordinately. In [14], H_∞ theory is also applied to design STATCOM

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Nomenclature

T_s	the time constant of STATCOM
I_{qs}	STATCOM current
δ_i	rotor angle of ith generator
ω_i and ω_0	rotor speed and rotor synchronous speed of ith generator
H_i	moment of inertia of ith generator
P_{mi} and P_{ei}	mechanical power and electrical power of ith generator
D_i	damping coefficient of ith generator
E'_{qi}	q-axis component of transient internal electro-motive force of ith generator
x'_{di}	d-axis component of transient synchronous reactance of ith generator
E_{fdi}	d-axis component of field voltage of ith generator
T'_{doi}	transient time constant of ith generator
G_{ij}, B_{ij}	real and imaginary parts of the (i, j)th element of the system admittance matrix
G_{is}, B_{is}	conductance and susceptance of the line between ith generator and STATCOM
$X(t)$	state vector of nonlinear system
y_{nl}	output vector of nonlinear system
r_i	relative degree of nonlinear system of the ith subsystem
Q_{ij}	$L_{g_j}L_f^{r_t-1}h_t(X)$ of the (i, j)th element of the Q matrix
b_i	$L_f^{r_t}h_t(X)$ of the (i, j)th element of the b matrix
$z(t)$	state vector of linear system
$\upsilon(t)$	inputs of the linear system
$y_l(t)$	the output of the linear system
$u_{feedback}$	input of the nonlinear system
η_k	state variable of the nonlinear model
$y_{nl,d}$	desirable nonlinear output
v	virtual inputs of the linear system
Z	transform which converts the nonlinear system to a linear one
E_{fdi}	input voltage of the excitation system of ith generator
$u_s = I_{qs}^{ref}$	STATCOM reference current
K_δ, K_ω, K_p	the coefficients of the desirable feedback control law of generator which connect to STATCOM directly
K_s	the coefficient of desirable feedback control law of STATCOM
α and β	constant coefficient to normalize the speed deviation $(\Delta\omega)$ and STATCOM bus voltage deviation

and excitation system controllers coordinately to improve the transient stability of the power system.

The promising solution of designing the controllers of FACTS and excitation systems together and considering the fact that power systems are large, nonlinear and time variant, the aim in this paper is to use a nonlinear control method to achieve the improvement in both dynamic and transient stability performances.

In recent years, the research results of different nonlinear control system theories show that using nonlinear state feedback and suitable coordinate transformation can exactly linearize an affine nonlinear system satisfying certain conditions [15]. The state feedback calculated by the exact linearization method compensates nonlinear characteristics of the original system and transforms it into a controllable linear system with good dynamic performance and ensures the system stability [15,16]. However, it is known that the control law designed by this method is quite complicated [16]. Therefore, to solve this drawback another method, called zero dynamics, has been proposed to design the controllers. This method does not need to exactly linearize all system state equations, but just a part of them. This approach of the feedback linearization algebraically transforms nonlinear system dynamics into a partly linear one which is a reduced-order linear system and an autonomous nonlinear system. A controller can be then designed for the reduced-order system. The autonomous system is also known as zero dynamics of the system which should be stable [17].

External and internal dynamics are also two main parts of the dynamic performance of any system. For internal dynamics having the stability is the only requirement. However, for the external dynamics of the system in addition to the stability, a good performance must be achieved. In this regard, zero dynamics method is also able to provide both those objectives [17–20]. In [17] this technique has been applied to control the grid current and dc-link voltage for maximum power point tracking and to improve the dynamic response of a three-phase grid-connected photovoltaic system. In [18,19] zero dynamics method has been used to design the excitation system controller for a single machine infinite bus (SMIB) power system. This method is also employed in [20] to design STATCOM and excitation system controllers coordinately for a SMIB power system. However, the simple methodology given in [20] cannot be practical and it is impossible to be used for the real multi-machine power systems. It is evident that the dynamics of other machines affect the system performance. Therefore, it is necessary to give a rigorous method applicable for such a system. In this paper, first a complete formulation of zero dynamics is expressed for a MIMO system. Then, this technique is used to design the controllers of STATCOM and excitation systems coordinately in the n-machine power system. For this purpose, in order to determine the unknown parameters of the zero dynamics controller, the design problem is converted to an optimization problem, and is solved by using hybrid Bacteria Foraging Nelder–Mead (BF–NM) algorithm [21,22]. The performance of the proposed design is investigated on a multi-machine power system and simulation results confirm the effectiveness of this method for power system stability enhancement.

2. Power system and STATCOM model

2.1. Synchronous static compensator (STATCOM)

A static synchronous compensator (STATCOM) is a regulating device used in AC transmission networks. It is based on a power electronics voltage-source converter and can act as either a capacitor or a reactor to deliver or absorb the reactive power. Usually a STATCOM is installed to support electricity networks that have a poor power factor and often a poor voltage regulation [23]. It also improves the system damping and the transient stability of the first swing of rotor angular velocity for severe fault conditions [23].

2.1.1. STATCOM modeling

In this study, STATCOM is modeled by a shunt current source as shown in Fig. 1. In this model, STATCOM current is in quadrate with its terminal voltage.

A first order differential equation is used to describe the transient performance of the STATCOM, as follows [20]:

$$\frac{dI_s}{dt} = \frac{1}{T_s}\left(I_{qs}^{ref} - I_{qs}\right) \tag{1}$$

The bus voltage of STATCOM as can be seen from Fig. 1 may be written as follows [20,24]: