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Optimal AGC of a multi-area power system with parallel AC/DC tie lines using output vector feedback control strategy

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ABSTRACT

This article presents the design of optimal automatic generation control (AGC) regulators using output feedback control strategy for a multi-area interconnected power system. The power system consists of unidentical areas having diverse type turbines. The parallel AC/DC tie-lines are considered as area interconnection between the areas. Efforts have been made to propose optimal AGC regulators based on feedback of output state variables, which are easily accessible and available for measurement. In addition, a modified area control error incorporating DC tie-line power deviation is used in the design of optimal AGC regulators. The designed optimal AGC regulators are implemented and the system dynamic responses for various system states are obtained considering 1% load perturbation in one of the areas. The system dynamic performance is compared with that obtained with optimal AGC regulators designed using full state vector feedback control strategy. The pattern of closed-loop eigenvalues is also determined to test the system stability.

Introduction

The demand of electrical power is increasing enormously throughout the world due to continuously developing trends. The large capacity generating stations and higher rating generating units have become essential to meet the several economic and technical objectives set up by the various utilities. The economic considerations are the main reasons to install these generating stations at a remote location from the load centers. Every electrical utility is under obligation to provide a continuous power supply within a reasonable offset in frequency and voltage of the system to its consumers. Further, power supply to the consumers should be economical and profitable to the utilities. Moreover, realizing the benefits of variability in generation mixes and load patterns, utilities have switched over to operate in interconnected fashion utilizing over which the power is being exchanged among the control areas. This ensures the power engineers to enhance overall reliability of the systems along with other technical and economic benefits. However, the complexity of the system increases.

The selection of transmission line to assign the duties of an area interconnection plays an important role in the modern power systems. These lines should be capable of transmitting the electrical power among widely spread power pools in an efficient and effective manner without affecting the system dynamic behavior so much. In India, till the 1970s, the power is being exchanged by AC transmission lines operating at higher voltage levels, *i.e.*, extra high voltage AC (EHVAC) lines. However, these transmission lines were associated with the presence of severe inter-area oscillations, transmission of disturbances from one area to another and higher fault levels. All these problems were alleviated with the emergence of DC transmission system to a great extent. One of the most promising applications of HVDC transmission is its operation with AC link in parallel as an area interconnection. It has been demonstrated very effective in stabilizing the power system dynamics also [1,2].

The power systems operate at constant frequency and voltage most of the time with certain specified index of system reliability for its dedicated applications. However, an allowable deviation of these is permitted without affecting the operating output of the connected consumer equipments. There is a mismatch between power demand and generation. For any mismatch between real

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Nomenclature

a_{12}	area size ratio coefficient
a_{23}	area size ratio coefficient
a_{31}	area size ratio coefficient
ACE_i	area control error
B_i	frequency bias constant
H_i	per unit inertia constant
D_i	load frequency constant
i	subscript referring to area i ($i = 1, 2$)
K_{pi}	power system gain
M_i	effective rotary inertia
P_{ri}	rated area power output
R_i	speed regulation parameter
T_{12}	synchronizing coefficient of EHVAC link
T_{Gi}	speed governor time constant of area i (s)
T_{pi}	power system time constant (s)
T_{ti}	non reheat turbine time constant (s)
ΔF_i	incremental change in frequency
ΔP_{Ci}	incremental change in speed-changer position
ΔP_{Di}	incremental change in load demand
ΔP_{tiei}	incremental change in tie-line power through EHVAC link
Δx_{Ei}	incremental change in governor valve position
ΔP_{Mi}	incremental change in power generation
ΔP_{dci}	incremental change in tie-line power through HVDC link
ΔP_{xi}	incremental fraction generated power in tandem compound, single reheat turbine
T_{ij}	transmission constant (considered equal for all interconnections)
T_w	hydro turbine time constant
T_1	tandem compound, single reheat turbine time constant
T_2	tandem compound, single reheat turbine time constant
T_3	tandem compound, single reheat turbine time constant
K_1	tandem compound, single reheat cylinder fraction
K_2	tandem compound, single reheat cylinder fraction
K_3	tandem compound, single reheat cylinder fraction

power demand and real power generation the frequency and voltage deviates from their nominal values. Generally, the power systems are frequently subjected to varying load demands. For an efficient and successful operation of the power system these mismatches between generations and demands are to be corrected via a control scheme popularly known as automatic generation control (AGC) scheme. The overall objective of the AGC is to control the electrical output of the generating units in order to supply the continuously changing customer power demand. AGC regulates the output power of electric generators within a area in response to changes in system frequency, tie-line loading and a linear combination of these is called area control error (ACE). This maintains the scheduled system frequency and power exchange with other areas within predetermined limits.

In literature, for designing AGC schemes many research articles are reported concerning AGC of interconnected power systems [3–6]. The studies in [3,4] were based on classical control concept. The regulator designs based on classical technique are limited to single-input–single-output type systems. The interconnected power system is a multi-input/multi-output system and for effective AGC, it can be executed by designing AGC regulators using modern control techniques. Following the pioneering work of O.I. Elgerd and C.E. Fosha in 1970 [7], many optimal AGC schemes have been proposed in literature over more than 40 years period of time [8–13]. It has been established that the system's dynamic performance with greater stability margins can be achieved with regulators designed using optimal control strategies as compared to that obtained with conventional/classical control techniques. Therefore the application of modern control theory is the most promising tool to handle the AGC problem of large interconnected power systems. The application of modern control theory for the design of optimal AGC regulators requires availability of all the system states directly or through state reconstruction procedures. However, in real time power system operation and control it is very difficult or sometimes impossible to have all the system states accessible and measurable. Often state reconstruction techniques are employed to cope such difficulties situations/problems but costly and add complexity to the systems. Therefore, controller designs based on the feedback of system states are easily accessible and available for measurements have been preferred for AGC of power system applications. The research articles dealing with the design of AGC regulators based on output vector feedback control concept are proposed in [14–16]. However, the most of the studies of AGC regulators based on full state and output vector feedback were limited to identical two-area power system models having reheat, non-reheat or hydro turbines and very few efforts have been made to AGC of a multi-area power system with power generation through plants of diverse types in different areas with different capacities. Similarly no attention has been made in AGC studies to design optimal AGC regulators based on output vector feedback for a multi-area power system interconnected via parallel EHVAC/HVDC tie-lines. In the view of the above discussion, the following contributions are set to meet in the present article;

- To design optimal AGC regulators for a 3-area interconnected power system with hydro turbines generating 2000 MW power in area-1, non-reheat turbines in area-2 having 4000 MW capacity and tandem compound non-reheat turbines in area-3 generating 6000 MW power respectively. The design of AGC regulators is based on (i) full state vector and (ii) output vector feedback control strategy.
- Two types of area interconnections; (i) EHVAC transmission link and (ii) parallel EHVAC/HVDC transmission links are considered for the investigations.
- The optimal AGC regulators designed are implemented considering 1% load disturbance in either of the areas to investigate the system dynamic performance and compared with that obtained using full state vector feedback control through performance index minimization and feedback gains to show the effectiveness and feasibility of the proposed control strategy.
- The pattern of closed-loop system eigenvalues is also computed to investigate the dynamic stability of the system with the designed optimal AGC regulators.

The rest of the article is organized as follows: Firstly, the power system models identified for the investigations are described. It is followed by the optimal AGC regulator design using output vector feedback. Secondly, the dynamical models of the system are developed and presented. In the third part, the simulation results are tabled. Finally, the investigations of the results are discussed and finally, the conclusions drawn from the study are listed.

Power system model under investigation

For the present study, the following two power system models are considered.