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Deregulated AGC of multi-area system incorporating dish-Stirling solar thermal and geothermal power plants using fractional order cascade controller

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ABSTRACT

The present study highlights the attempt of incorporating geothermal power plant (GTPP), dish-Stirling solar thermal system (DSTS) and high voltage direct current transmission (HVDC) link, with the conventional thermal system, in automatic generation control of an interconnected power system under deregulated environment. Appropriate generation rate constraints are provided in thermal systems. A new fractional order (FO) cascade controller named as FO proportional-integral-FO proportional-integral-derivative (FOPI-FOPID) is proposed as secondary controller and its performance is compared with the commonly used classical controllers. A stochastic algorithm, Sine Cosine Algorithm (SCA) is used to optimize the controller gains and other parameters. Analyses of the dynamic responses reveal the superiority of FOPI-FOPID over the others in terms of settling time, peak deviation and magnitude of oscillation. Performance index comparison is carried out and integral squared error is selected. The effect of GTPP, DSTS and HVDC link have been examined separately and the responses disclose that integration of HVDC link to the combined system having both GTPP and DSTS along with thermal leads to better dynamics. Sensitivity analysis of SCA optimized FOPI-FOPID controller parameters obtained at nominal Disco Participation Matrix (DPM) validate that they are healthy enough and need not be optimized for change in DPMs.

1. Introduction

Automatic generation Control (AGC) of an interconnected system balances the load demand and losses with the total generated power. If this balance is hampered, the frequency and tie line powers of the power system automatically get deviated from their schedule values [1,2]. The structure of electric utilities has changed drastically since the Federal Energy Regulatory Commission (FERC) issued its Notice Proposed Rulemaking (NOPR) to encourage competitive electric market. The traditional structure of the power industry, where monopoly prevails in generation, transmission and distribution by a single utility company is called a “vertically integrated utility” (VIU). In the present scenario, power system is adopting the deregulated market operation which consist of generating companies (GENCOs), transmission companies (TRANSCOs), distribution companies (DISCOs), and an independent contract administrator (ICA). Thus, transforming the vertically integrated utilities to horizontally ones and thereby introducing competition among the players. In restructured environment, all GENCOs are not bound to take part in load frequency control (LFC) and DISCOs are independent of choosing any GENCO from either its own control area or others, to maintain the load demand. The ICA responsibly supervises the power transactions among the players to provide reliable operation of the power system. Several type of transactions are present in the market namely the bilateral contracts, poolco based transactions, and area regulation contracts [3–5].

The incremental power output of an area depends on its area control error (ACE) and the generation of each GENCO is based on its ACE participation factor (apf) [6]. The concepts of DISCO participation matrix (DPM), which is formed from the contract participation factors (cpfs); and apf on the dynamic responses of the system under deregulation are clearly described in [7] and its effects are very well highlighted in [5].

Donde et al. [8], Debbarma et al. [9] analyzed thermal generating open market environment. Later, AGC of multi-source power system incorporating different sources like hydro, gas and nuclear along with thermal became prominent and are presented by Mohanty et al. [4], Hota et al. [10] which gives a view of a more realistic system. Thus, it is evident that investigation on the reconstructed power system is restricted only to non renewable sources, and integration of renewable energy sources may lead to several prospects of further research.

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Though integration of dish-Stirling solar thermal system (DSTS) with LFC is studied by Rahman et al. [11] but it is limited to the conventional environment. Another renewable energy source which is a potential candidate throughout the globe for medium and large scale generation of electricity and space heating is the geothermal energy [12]. Geothermal energy belongs to the category of thermal energy which the earth stores inside itself automatically and thus it is derived from the earth crust directly [13]. Setel et al. [14] discusses the prospects of using geothermal energy for electricity production at average temperatures. Although geothermal power is a distinct source for harnessing electricity, but it is not yet implemented in AGC studies. Thus, including geothermal power plant (GTPP) with earlier existing renewable sources can add new dimension to AGC under deregulated environment.

Recently, power electronics devices have been applied in power system which leads to an innovative technology and also provide prominent changes in the economy. High voltage direct current transmission (HVDC) link interconnecting control areas has evolved in power system as several advantages like long distance bulk power transmission and adjustable DC power flow on the line are associated with it. Power flow oscillations in AC system, which results due to system disturbances, can be damped effectively by controlling the DC power. Most of the literatures deal with DC line connected in parallel with AC tie line [15]. However, a very limited literature includes HVDC link connected in the power system of any control area [4,16,17]. Hence, HVDC link is used to enhance the dynamic performances of power system.

Robust secondary controllers are essential to maintain a smooth frequency profile. Performance of Integral (I) [9], integral derivative (ID) [5], proportional-integral-derivative (PID) [6] controllers are explored in AGC. Integral-double derivative (IDD) and proportional-integral-double derivative (PIDD) are compared by Banaja et al. [4] with the classical controllers. Sahu et al. [18] have worked on the concept of two-degree-of-freedom proportional integral derivative (2DOF-PID) controller. Fractional order controllers like fractional order proportional-integral-derivative ($PI^{\lambda}D^{\mu}$) controller are discussed in [19]. Arya has implemented fractional-order fuzzy PID controller in [20] and [21]. Dash et al. [22,23] though have demonstrated cascaded controllers like proportional integral-proportional derivative (PI-PD) and proportional derivative-proportional integral derivative (PD-PID), but it was not in deregulated market. Recently, Raju et al. [24] presented the integral-proportional derivative (I-PD) controller under competitive market conditions. Even though works related to both fractional order controller and cascaded controller are being analyzed separately, combination of both the concepts is still unaddressed. Hence, application of fractional order cascade controller (FOCC) in AGC studies and specifically in deregulation is needed to be demonstrated.

In order to set the controllers gains at the optimum values, suitable optimisation techniques are necessary. Several heuristic techniques such as bacterial foraging optimisation [9], differential evolution [10], genetic algorithm [10], have been applied to LFC problem. Optimization techniques like fruit fly algorithm [4], biogeography based optimisation [5], firefly algorithm [25] and flower pollination algorithm (FPA) [22] have shown evident results. Raju et al. [24] discussed a nature inspired, moth-flame optimization. Another recent technique proposed by Mirjalili [26] named as Sine Cosine Algorithm (SCA) is present whose performance is yet to be analyzed in AGC.

To optimize the controller gains and other parameters using any optimization technique, a performance index or cost function is required. Some commonly used performance indices are integral squared error (ISE), integral absolute error (IAE), integral time absolute error (ITAE), and integral time squared error (ITSE) which are available in various literatures [16,22,27–29]. Generally, ITAE and ISE are mostly used in AGC studies for their better performance as compared to ITSE and IAE [16]. However, ITSE has grown its importance as many recent literatures [27–29] have selected it as an appropriate performance index. Authors in [22] have selected ISE as cost function for FPA in four area thermal system. On the other hand, Barisal [16] chose ITAE as performance index for teaching learning based optimization in multi-source system. ITSE was preferred by Morsali et al. in [27–29]. However, which performance index is suitable for SCA technique used for optimization in multi-area multisource deregulated system comprising of GTPP and DSTS yet to be evaluated. Considering the above cases, the main objectives of the present work are

(a) To develop a two area, multi source deregulated power system with GTPP, thermal and DSTS GENCOs in each area.
(b) Optimization of different controller gains like I, proportional integral (PI), PID, cascade combination of fractional order PI and fractional order PID controller (FOPI-FOPID) and other parameters using SCA technique in order to find the best.
(c) Performance comparison of the different performance indices like ISE, IAE, ITAE, and ITSE using SCA for the best controller to identify the suitable one.
(d) To study the effect of GTPP, DSTS and HVDC link when incorporated along with the AC tie line.
(e) Sensitivity analysis for variation in Disco Participation Matrix (DPM).

2. System investigated

A two area deregulated system is considered for investigation with area capacity ratio of 1:4. Based on the types of GENCOs used, there are five systems. They are system with (i) only thermal GENCOs (ii) DSTS & thermal GENCOs (iii) GTPP & thermal GENCOs (iv) GTPP, DSTS & thermal GENCOs (v) same system as (iv) along with HVDC link. Fig. 1(a) shows the schematic diagram of the proposed system. The different GENCOs participating for the different DISCOs as per the cpfs are shown in upper and lower section of Fig. 1(a). The apf for each GENCO are chosen based on their generation schedule [7]. GRC of 3%/min along with single reheat turbine is equipped in thermal unit. The nominal parameters for the thermal systems and DSTS are taken from [9] and [11] respectively and given in Appendix A. The controller gains, governor and turbine time constants of GTPP are optimized using SCA technique. Various controllers such as I, PI, PID, FOPI-FOPID are used one at time as secondary controllers. Performance indices for ISE, IAE, ITSE, and ITAE, given by (1)–(4) respectively are taken for comparison, for selecting the best, to design the controller using SCA. MATLAB software is used for Simulink Model and execution of programmable codes.

$$J_{ISE} = \int_0^T \{(\Delta f_i)^2 + (\Delta P_{tiei-j})^2\} dt; \quad (1)$$

$$J_{IAE} = \int_0^T \{|\Delta f_i| + |\Delta P_{tiei-j}|\} dt; \quad (2)$$

$$J_{ITSE} = \int_0^T \{(\Delta f_i)^2 + (\Delta P_{tiei-j})^2\} t dt; \quad (3)$$

$$J_{ITAE} = \int_0^T \{|\Delta f_i| + |\Delta P_{tiei-j}|\} t dt; \quad (4)$$

where i = area number (1, 2), j = area number (1, 2) (i ≠ j).

3. System components, controller and optimization technique

3.1. Geothermal power plant

Geothermal power is a potential and reliable source of energy, in terms of electricity generation. The International Geothermal Association estimated that about 10,715 MW of geothermal power is online in 24 countries, which is expected to generate 67,246 GWh of electricity in 2010. This was expected to grow to 18,500 MW by 2015 [30]. The largest installed capacities are in United States having