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Effects of PLL and frequency measurements on LFC problem in multi-area HVDC interconnected systems

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ABSTRACT

Recent advancements in power electronics have made HVDC links and renewable based generation more popular in power systems application with better grid support functionalities like frequency control and inertia emulation tasks. Conventional operation and control strategies are undergoing of different changes and all the infrastructure of future modern power system should efficiently support the delivery of ancillary services in complex scenarios of AC/DC multi-area interconnected system. The AGC system of tomorrow must be able to handle complex interactions between control areas with HVDC links and distributed generation equipment. In such scenario, the effects of wide-area interconnections, PLL (Phase Locked Loop) and frequency measurements cannot be ignored. The dynamics effects of PLL and frequency measurements are very important for HVDC operation. For obtaining an acceptable performance of AC/DC system, the dynamic models of PLL and measurements need to be taken into account. This paper focused on the effects of PLL and frequency measurements in frequency supports of HVDC interconnected system. A novel approach for analyzing the dynamic effects of HVDC links considering PLL effects during coordination with AC system is presented and discussed. The effects of PLL are considered by introducing a second-order function. A Pade approximation method is also introduced for adding the effects of communication delays on AGC operation and the state space models are presented. The proposed model is analyzed for different multi-area test systems which contains parallel AC/DC transmission links.

Introduction

In the recent years, the number of bulk power exchanges over long distances between control areas are significantly increasing. This increase is mainly due to the deregulation of power industry with the high implementation of power electronic based components in the power grid [1].

Recent developments of renewable energy integration and super-grid interconnections in modern power systems attract a lot of attentions to HVDC transmission which is known as a proven tool for dealing with new challenges of the future power system. The capability of DC systems to transmit higher power over longer distances, the possibility of interconnecting asynchronous networks, and their high efficiency have maintained the interest of both industry and academia [2,3]. Expansions of interconnected systems with wide area HVDC control application are leading to a complex scenario which bring more challenges in terms of communications, coordination and frequency control of interconnected multi-area systems.

Interconnected power system consists of several control areas. Any mismatch between generated power and demand can cause the system frequency or tie-line power flow to deviate from their scheduled values. To eliminate these deviations, the AGC is applied to manipulate the set-points of different power generation units in each area [4]. Accordingly, the objective of AGC is to regulate the generated power from various sources in each area in a way that the frequency of power system and tie-line powers are kept within prescribed limits. The recent trends of research are through the adoption of previous concepts and conventional models considering new AC/DC complex scenarios with more application of DC interconnections and RES (Renewable Energy Systems) penetrations [5,6].

The traditional LFC models have been modified and revised to add different functionalities in the reformulation of conventional power systems. Most of those modifications are related to the AGC in a deregulated market scenario [7], different types of power plants like renewable generation [8] and recently the demand side dynamic models [9]. Therefore, the general model of multi-area

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AGC system is adapting to meet the necessary changes in modern scenarios of the power systems. It should be noted that AGC facilities could potentially be used not only to realize emergency control for frequency stability, also to coordinate with modern HVDC transmission and FACTS devices for long-term dynamics control [10,11]. As it was explained, the power grid is experiencing the increased needs for important issues, e.g. enhancing the bulk power transmission for a very long distance, reliable integration of large-scale renewables with multi-area interconnected systems and more flexibility and controllability in power flow at the transmission system. Renewable energy sources, which are located far away from consumption centres, are now driving forces for the development of new transmission concepts. Challenging projects usually include integration of large-scale offshore wind farm which are located far from shore, or the integration of solar energy from the Middle East and North Africa [12]. In those projects, it is claimed that DC transmission systems are more technically and economically convenient than AC [12]. Moreover, another driving force for the development of new transmission concepts is power market integration, which means trading of power over long distances.

One major challenge for the power system under deregulation is to implement communication and controllers into suitable levels of system operation and control [13]. The widespread application of communication systems in the power system control causes unavoidable time delays. Considering the characteristic of the communication channel, LFC scheme is a typical time delay system. From stability analysis and controller design point of view, it is very important to identify the maximum range of delay which allows a power system equipped with an LFC scheme to remain stable. Recently, time delay has been considered in the design of load frequency controller in different case studies [13,14]. But there is not a lot of work considering a scenario with complex AC/DC interconnection and communication delays of LFC loop at the same time.

As it was mentioned, in order to enhance the controllability, one important application of HVDC transmission line is its operation in parallel with an existing AC transmission line. Thus, they can act as AC/DC parallel links interconnecting any two control areas. In literature, AGC of a two-area power system interconnected via AC/DC parallel link, is carried out with different control approaches for better dynamic responses [14–21]. But in none of them a complete model of DC link for AGC application is considered. In all the presented research work, the part related to PLL dynamics and frequency measurements of HVDC stations is also missed.

The phase-locked loop (PLL) is typically used for angle reference generation for the traditional line-commutated converter (LCC)-based HVDC and the newer voltage-sourced converter (VSC)-based HVDC transmission applications [22]. This angle reference is used for generating the firing pulses for the insulated-gate bipolar transistor (IGBT) switches of the VSC. Results from recent research works show that the gains of the PLL parameters can greatly affect the operation of the VSC-HVDC converter. The efficiency and maximum power limits of VSC system can be affected by PLL gains and damping [23,24].

In this paper, a novel approach for analyzing the impacts of PLL and frequency measurements of HVDC links on the stability of multi-area load frequency control (LFC) systems is proposed. The used PLL model is based on a second-order function describing the PLL dynamics and its control gains. This function is added in a DC link which is implemented by a Supplementary Power Modulation Controller (SPMC). This controller is presented in a coordinated manner for controlling the HVDC set-points during AGC operation.

Since the importance and application of HVDC links are increasing, it was necessary to introduce a more detailed model of HVDC station dynamics for LFC studies. In fact, the main objective of this paper is to introduce and analyze the dynamic effects of PLL as an important part of VSC stations. It should be noted that the effects of the time delay in the LFC loop are also considered and sensitivity analysis is performed. A complete state space model of multi-area AGC system with a parallel AC/DC line considering PLL and delay effects is presented. Stability regions of the system for different values of time delay in LFC loop are obtained and presented. The proposed model will be very essential and useful for further studies in frequency and active power regulation with HVDC links.

In the following sections, the dynamic model of multi-area AGC system with AC/DC connection will be explained in Section 'Multi-area AC/DC interconnected system'. Then the complete model of AGC with PLL model and communication delays of LF loop is presented in Section 'AC/DC interconnected control system with communication delay and PLL'. System analyses with the simulations in different test systems (two and four areas) are given in Sectio n 'Simulation results' and finally the paper is concluded by Section 'Conclusion'.

Multi-area AC/DC interconnected system

The load frequency control and AGC issue is well discussed in power system control literatures [1–4]. To understand the concept of LFC problem, the Area Control Error (ACE) is introduced. In a two-area power system model, the ACE for ith area is defined as follows:

$$ACE_i = \beta_i \Delta f_i + \Delta P_{ij} \tag{1}$$

where the ΔP_{ij} is the net tie-line power flow variation between two areas ($\Delta P_{ij} = -\Delta P_{ji}$), f is the system's frequency; β_i is referred as the frequency bias and is generally referred to the tie-line bias control. Therefore, in a normal two-area AC link we have:

$$\Delta P_{ij} = \Delta P_{tie,AC} \tag{2}$$

The state space presentation of ith area could be as follow:

$$\Delta\omega_i = \frac{K_{pi}}{1 + sT_{pi}}\left[\Delta P_{mi} - \Delta P_{Li} - \Delta P_{tie,AC}\right] \tag{3}$$

$$\Delta P_{mi} = \sum_{k=1}^{n} \Delta P_{m,ik} \tag{4}$$

where ΔP_{Li} $(i = 1, 2)$ is local load deviation, K_{pi} is the power system gain, T_{pi} is the power system time constant, $\Delta P_{m,ik}$ $(k = 1, 2)$ is the output of generation units and:

$$K_{pi} = \frac{1}{D_{sys-i}}, \quad T_{pi} = \frac{M_{sys-i}}{D_{sys-i}} = \frac{2H_{sys-i}/\omega_0}{D_{sys-i}} \tag{5}$$

Considering that H_{sys-i} and D_{sys-i} are inertia and damping. The rest of the variables could be defined as follows:

$$\Delta P_{m,ik} = \frac{1}{1 + sT_{tg,ik}}\left[\frac{\Delta\omega_i}{R_i \times 2\pi} - K_{li}\Delta P_{refi}\right] \tag{6}$$

where $R_k (k = 1:4)$ is considered as droop for each generation company (GENCO), T_{tg} is the overall time constants of turbine and governor in each GENCO and is equal to $(T_{tik} + T_{gik})$ [5]. The reference of generation units in ith area will be based on ACE and could be considered like this:

$$\Delta P_{refi} = \frac{ACE_i}{s} = \frac{1}{s}\left[\frac{\beta_i}{2\pi}\Delta\omega_i + \Delta P_{tie,AC}\right] \tag{7}$$

$$\Delta P_{tie,AC} = \frac{T_{ij}}{s}\left[\Delta\omega_i - \Delta\omega_j\right] \tag{8}$$

and T_{ij} is also the synchronization power coefficient [1].