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Ultra-low frequency oscillation analysis and robust fixed order control design

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ABSTRACT

Yunnan Grid, a hydro-dominated system, has experienced many times ultra-low frequency oscillations (ULFO) since the grid is connected to the China Southern Grid via DC ties in 2016. The root cause of the oscillation phenomena is investigated in this work. The vector margin (VM) method, which has a closed-form stability margin expression, is utilized to analyze the phenomena, the analysis reveals that the large phase lags of hydro-power turbines at the oscillation frequency are the culprit. It is proved analytically that a hydro-dominated system model always includes a right-half-plane zero, and this zero introduces the large phase lag afore-mentioned and places a fundamental conflict between the stability and tracking performance. A frequency-domain robust fixed-order controller design method is proposed to maximize the tracking performance with specified stability margin in multiple operating points. Case studies of the four-machine two-area system and Yunnan Grid validate the introduced results.

1. Introduction

The problem of ultra-low frequency oscillation (ULFO) was observed in several hydro-power dominant systems [1,2], a characteristics of the oscillations is that all generators of the system oscillate at a common frequency below 0.1 Hz. Some studies refer to it as the "common mode" as opposed to the "local mode" and "inter-area mode" of low-frequency oscillations [3]. In 2016, Yunnan Grid in South China was asynchronously interconnected to the external grid, which turns Yunnan Grid into a hydro-power dominant system, and since then the system has experienced ULFO many times.

ULFO does not seem to be uncommon in the early 1960s and 1970s in North America where hydro units were operating in relatively isolated control area [4]. As the interconnection develops, the problem eventually disappeared, see [3,5] and references cited therein. ULFO is still a major concern in small hydro-dominated power systems that are remote and isolated.

Several studies have investigated the problem of ULFO. The ULFO was found to have a strong connection with hydro units based on the time-domain and eigenvalue techniques [2,5]. In Ref. [3] a closed-form formula was proposed to tune governor parameters based on Routh-Hurwitz criterion, a classic stability criterion that is favorited by many (see [6] for a most recent application). The damping of the ULFO is found to be mainly influenced by the parameters of the governors [7]. The higher order terms of the hydro-power turbine model were considered in [1,8,9], which helps make the simulation of the ULFO more accurate. The recent study [10] has found a linear relationship between the real part of ULFO mode and the damping coefficient of the hydro-power generator. The stability is found to be improved by installing PSSs [11], quitting primary frequency regulation (PFR) [12], optimizing governor parameters [6,10,13–15] or avoiding feed-forward control in governing system [16]. Despite several contributions on the subject, a quantitative analysis pinpointing why hydro-dominance introduces UFLO is still lacking. Also absent in the literature is a rigorous treatment on the stability-tracking conflict introduced by hydro-dominance.

The second theme of interest in this work is the control design of governors. Numerous results are available in the literature, see [17] for an up-to-date list of publications. Broadly speaking, we distinguish among two basic categories, namely, time-domain optimization methods and frequency-domain methods. In this work the frequency-domain methods are preferred because they offer additional insights. It is well-known that modern hydro units are often equipped with PID governors. This dictates that only fixed-order control design conceptions [18] are applicable to the parameter tuning. As a result, very few results are documented, among which representative Refs. [13,14] address the control design of governor of single unit.

This work intends to study the cause of the ULFO problem and

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propose a multi-machine fixed-order control design to improve the frequency regulation performance in a hydro-dominated system. First, the classic vector margin (VM) method is adopted to analyze the units' influence on ULFO stability. The result reveals that the inherent large phase lag of hydro-power generator governor and turbine at the oscillation frequency is the main reason for the ULFO. Second, the existence of a small real right half plane zero in the loop transfer function of the hydro-power dominant system is proved, the conflict between the stability and the tracking performance introduced by the zero is demonstrated. Third, a frequency-domain fixed-order control design for hydro-turbine governor is proposed, with a goal to maximize the tracking performance under the stability constraints. Case studies of the four-machine two-area system and China Yunnan Grid are presented to show the efficacy of the proposed methods.

2. The single-frequency system model

To analyze the ULFO problem, a complete system model is difficult to use and unnecessary. This section first introduces the single-frequency system model that is widely applied for the analysis of the ULFO problem [2,10], then the frequency-domain characteristics of hydro and thermal units will be briefly discussed.

The ultra-low frequency oscillation is characterized by a low oscillation frequency and a long oscillation period. Therefore, fast phenomena, such as voltages and rotor angles, can be represented by their equilibrium conditions instead of full dynamics under such time-scale. By neglecting fast dynamics that have reached equilibrium during the ULFO, the order of the system model is greatly reduced. Based on this assumption, the single-frequency system model [19–21] is adopted in the study, as shown in Fig. 1, where $G_1(s)$, $G_2(s)$, …, $G_N(s)$ are the governor transfer functions, $T_1(s)$, $T_2(s)$, …, $T_N(s)$ are the turbine transfer functions, $\Sigma\Delta P_m$ is the total incremental mechanical power, $\Sigma\Delta P_e$ is the total load change, $\Delta\omega$ is the system frequency change, D is the load-damping constant, M_Σ is the equivalent inertia constant. Under per unit system

$$M_\Sigma = \sum_{i=1}^{N} M_i, \tag{1}$$

where M_i is the inertia constant of generator i. Define governor-turbine transfer function $GT(s)$ as

$$GT(s) = G(s)T(s), \tag{2}$$

then the loop transfer function of the single-frequency model is

$$L(s) = \frac{1}{M_\Sigma s + D}\sum_{i=1}^{N} GT_i(s). \tag{3}$$

It can be seen from Fig. 1 that the governor and turbine models play a vital role in the ULFO. When the effects of water compressibility and pipe elasticity are neglected, the transfer function of the hydro-power turbine $T_h(s)$ is [22]

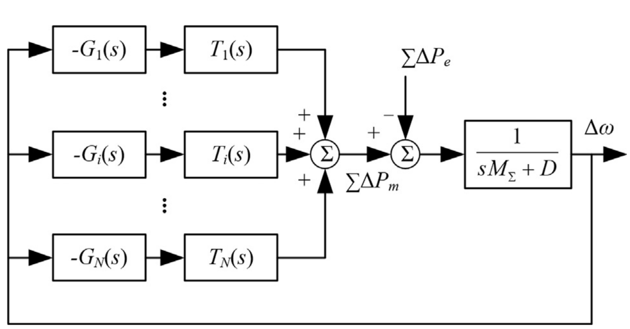

Fig. 1. *N*-machine single-frequency model.

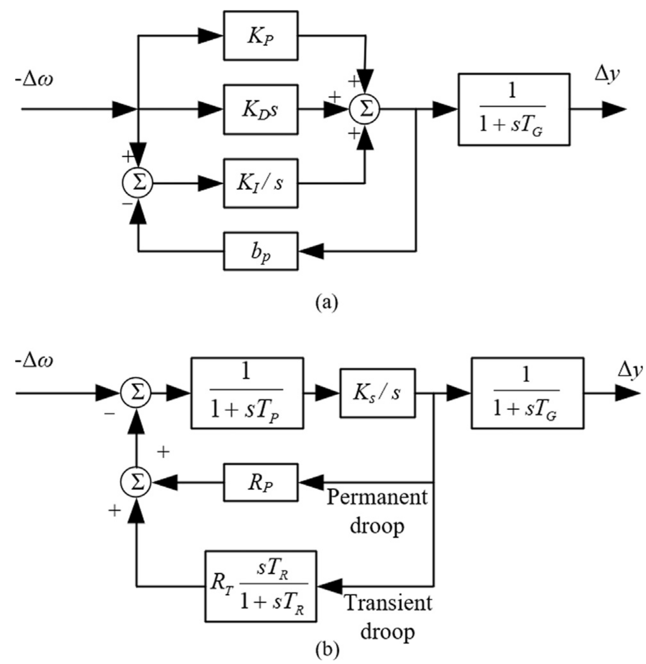

Fig. 2. Models for hydro-turbine governors: (a) PID governor; (b) mechanical governor.

$$T_h(s) = \frac{\Delta P_m}{\Delta y} = a_{23}\frac{1-(a_{13}a_{21}/a_{23}-a_{11})T_W\cdot s}{1 + a_{11}T_W\cdot s}, \tag{4}$$

where P_m is the mechanical power, y is the guide vane position, coefficients a_{11}, a_{13}, a_{21}, a_{23} are partial derivatives that depend on the turbine characteristics and vary with respect to operating conditions, T_W is the water inertia time constant given by

$$T_W = \frac{Q_r L}{gH_r A}, \tag{5}$$

in which Q_r and H_r are the water flow base and the pressure head base, g is the gravity acceleration, L and A are the length and cross section area of the pipe in the water passage. The value of a_{23} is positive, and the value of $(a_{13}a_{21}/a_{23}$-$a_{11})$ is positive and around 1.

In modern power systems, most of hydro-power generators are equipped with PID governors (Fig. 2(a)), while some of the rest use mechanical governors (Fig. 2(b)). The transfer function of the PID governor is

$$G_{h,PID}(s) = \frac{\Delta y}{-\Delta\omega} = \frac{K_P\cdot s + K_I + K_D\cdot s^2}{b_p K_I + s}\cdot\frac{1}{1 + T_G\cdot s}, \tag{6}$$

where K_P, K_I, K_D are the coefficients for the proportional, integral and derivative terms, b_p is the permanent droop, T_G is the servo time constant.

For steam-power generators, the common reheat steam-power generator model is used in the study. The transfer function of a reheat steam turbine is as follows [3]

$$T_s(s) = \frac{\Delta P_m}{\Delta y} = \frac{1 + F_{HP}T_{RH}\cdot s}{(1 + T_{CH}\cdot s)(1 + T_{RH}\cdot s)}, \tag{7}$$

where T_{CH} is the main inlet volumes and steam chest time constant, T_{RH} is the reheater time constant, F_{HP} is the fraction of total turbine power generated by high pressure section.

The transfer function of the steam-turbine governor is

$$G_s(s) = \frac{\Delta y}{-\Delta\omega} = \frac{1}{R}\cdot\frac{1}{1 + T_G\cdot s}, \tag{8}$$

where R is the speed droop, T_G is the servo time constant.