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Regional frequency response analysis under normal and emergency conditions

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ABSTRACT

This paper presents a frequency response analysis approach suitable for a power system control area in a wide range of operating conditions. The analytic approach uses the well-known system frequency response model for the turbine–governor and load units to obtain the mathematical representation of the basic concepts. Primary and supplementary frequency controls are properly considered and the effect of emergency control/protection schemes is included. Therefore, the proposed analysis/modeling approach could be gainfully used for the power system operation during the contingency and normal conditions. Time-domain nonlinear simulations with a power system example showed that the results agree with those predicted analytically.

1. Introduction

The recent power system events and blackouts show that improvement of overall power system emergency response requires better detection mechanisms, more effective analysis and modelling, and control strategies in order to obtain a new trade-off between system security, efficiency and dynamic robustness. Following a large disturbance, the power system frequency may drop quickly if the remaining generation no longer matches the load demand. System frequency changes of a large scale power system are a direct result of the imbalance between the electrical load and the power supplied by system connected generators [1]. Any short-term energy imbalance will result in an instantaneous change in system frequency as the disturbance is initially offset by the kinetic energy of rotating plant. Significant loss of generating plant, without adequate system response, can produce extreme frequency excursions outside the working range of plant.

Off-normal frequency can directly impact on power system operation and system reliability. A large frequency deviation can damage equipment, degrade load performance, cause the transmission lines to be overloaded and can interfere with system protection schemes, and ultimately lead to system collapse [2]. Fig. 1 shows that depending on the deviation range, supplementary control such as load-frequency control (LFC) and emergency control may be required in addition to the natural governor response.

The f_0 is nominal frequency, and Δf_1, Δf_2 and Δf_3 show frequency variation ranges corresponding to the different operating condition based on the accepted standards. Under normal operation, frequency is maintained near to nominal frequency by balancing generation and load. Small frequency deviation (Δf_1) can be attenuated by the governor natural autonomous response (primary control). To ensure that the control area is able to restore area frequency if it deviates more than Δf_1 Hz, LFC systems are deployed. LFC is required to maintain the system frequency and time deviation within the limits specified in the frequency operating standards. The frequency deviation Δf_2 is mainly determined by the available amount of operating reserved power [3]. For a larger frequency deviation and in a more complex condition, emergency control schemes are used to restore the system frequency.

Most published works on the power system frequency regulation have considered separate modeling and even analysis spaces for the normal, LFC and emergency conditions [4–9]. This paper presents an analytic approach to examine the frequency regulation and evaluate the frequency response under normal, LFC and emergency operating conditions. This work attempts to adapt the well-known conventional LFC model for use in contingency and emergency circumstances by including the effects of emergency protection and control dynamics. The paper first presents the mathematical representation of the frequency response and important related concepts for a control area using a low-order dynamic model. Following that, the presented analytical results are examined on a two control area power system.

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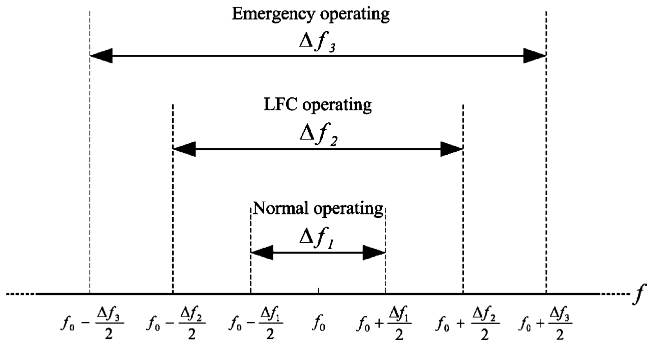

Fig. 1. Frequency range and different control actions.

2. Control area dynamic model

Usually, a simple low-order linear system is used for estimating the frequency behavior of a real power system. A large scale power system typically consists of a number of interconnected control areas. Consistent with standard practice, we use low-order transfer functions to model generator, turbine and power system (rotating mass and load) units. The mentioned low-order structure is well discussed in Refs. [7,8]. It was shown that the aggregate load-frequency dynamic response of a control area power system following a disturbance can be represented by a reduced model including an equivalent system inertia H, system load damping D, system regulation R and turbine–governor model $M(s)$.

Here, to cover the variety of generation types in the control area, different values for turbine–governor parameters and the generator regulation parameters are considered. Fig. 2 shows the block diagram of typical control area with n generator units. The shown blocks and parameters are defined as follows:

Δf	Frequency deviation,
ΔP_m	Governor valve position,
ΔP_S	Supplementary control action,
ΔP_P	Primary control action,
ΔP_{tie}	Net tie-line power flow,
ΔP_L	Load deviation,
H	Equivalent inertia constant,
D	Equivalent damping coefficient,
T_{ij}	Tie-line synchronizing coefficient between areas i and j,
B	Frequency bias,
R_i	Drooping characteristic,
ACE	Area control error,
α_i	Participation factors,
$M_i(s)$	Low-order governor–turbine model,
PI	Proportional Integral controller.

As shown in Fig. 2, the frequency performance of a control area is represented approximately by a lumped load generation model using equivalent frequency, inertia and damping factors [10].

$$H = H_{sys} = \sum_{i=1}^{N} H_i, \qquad D = D_{sys} = \sum_{i=1}^{N} D_i \tag{1}$$

Following a load disturbance within the control area, the frequency of the area experiences a transient change and the feedback mechanism generates appropriate rise or lower signal to the participating generator units according to their participation factors α_i to make generation follow the load. In the steady state, the generation is matched with the load, driving the tie-line power and frequency deviations to zero. As there are many generators in each area, the control signal has to be distributed among them in proportion to their participation. Hence, the ACE participation factor shows the sharing rate of each participant generator unit in the LFC task. For a control area we can write

$$\sum_{i=1}^{n} \alpha_i = 1; \quad 0 \le \alpha_i \le 1 \tag{2}$$

The balance between connected control areas is achieved by detecting the frequency and tie line power deviations to generate the ACE signal which is then utilized in the control strategy as shown in Fig. 2. The ACE for each control area can be expressed as a linear combination of tie-line power change and frequency deviation.

$$ACE = B\Delta f + \Delta P_{tie} \tag{3}$$

In typical LFC implementations, the system frequency gradient and ACE signal must be filtered to remove noise effects before use. The ACE signal then is often applied to a proportional integral (PI) control block [11,19]. Control dead band and ramping rate are different for various systems [18]. The control can send higher/lower pulses to generating plants if its ACE signal exceeds a standard limits.

The signal w in Fig. 2 can be defined as follows:

$$w = \sum_{\substack{j=1 \\ j \neq i}}^{N} T_{ij} \Delta f_j \tag{4}$$

According to Fig. 2, the output signal of the mentioned system has the following form:

$$\Delta P_{S_i}(s) = \alpha_i \left(K_P + \frac{K_I}{s} \right) ACE(s) \tag{5}$$

3. Frequency response analysis

Considering the effect of primary and supplementary controls, the system frequency can be obtained as follows:

$$\Delta f(s) = \frac{1}{2Hs + D} \left[\sum_{i=1}^{n} \Delta P_{m_i}(s) - \Delta P_{tie}(s) - \Delta P_L(s) \right] \tag{6}$$

where

$$\Delta P_{m_i}(s) = M_i(s)[-\Delta P_{P_i}(s) + \Delta P_{S_i}(s)] \tag{7}$$

and

$$\Delta P_{P_i}(s) = \frac{\Delta f(s)}{R_i} \tag{8}$$

$$\Delta P_{S_i}(s) = \alpha_i \left(K_P + \frac{K_I}{s} \right) (\Delta P_{tie}(s) + \beta \Delta f(s)] \tag{9}$$

Practically, the integral coefficient K_I is enough small and can be ignored in the computation. The expressions (7)–(9) can be substituted into (6) with the result

$$\Delta f(s) = \frac{1}{2Hs + D} \left(\left[K_P \sum_{i=1}^{n} \alpha_i M_i(s) - 1 \right] \Delta P_{tie}(s) - \left[\sum_{i=1}^{n} M_i(s) \left(\frac{1}{R_i} - \alpha_i \beta K_P \right) \right] \Delta f(s) - \Delta P_L(s) \right) \tag{10}$$

For the sake of load disturbances analysis we are usually interested in $\Delta P_L(s)$ in the form of a step function, i.e.,

$$\Delta P_L(s) = \frac{\Delta P_d}{s} \tag{11}$$