Online emergency control to suppress frequency oscillations based on damping evaluation using dissipation energy flow

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ABSTRACT

When a frequency oscillation occurs, effective control measures should be taken to suppress the oscillation as soon as possible to avoid subsequent failures caused by the oscillation. Prime movers, including governors and turbines, with negative damping are the major cause of frequency oscillations, and quitting the primary frequency regulations of these units can increase the damping ratio of the system mode and make the oscillation decay. The dissipation energy flow method is further developed to evaluate the damping of prime movers for emergency control. The dissipation energy flow into the prime movers is computed online using phasor measurement data of 2–3 oscillation periods and is then used to evaluate the damping of the prime movers. The primary frequency regulations of the units with the lowest damping are quit to suppress the oscillation. The procedure of online emergency control is presented. Test results verify the validity of the proposed approach.

1. Introduction

Frequency oscillations with very low oscillation frequencies, typically in the range of 0.01–0.1 Hz, have occurred in several power systems [1–5]. Periodic oscillations with a frequency deviation of 0.05 Hz and period of 20–30 s were observed in the Turkish power grid [1], and frequency oscillations of considerable amplitudes and very low oscillation frequencies were observed in the Colombian power grid [2–3]. Some oscillations had deviations of up to 1 Hz from the nominal 60 Hz with 12–20 s periods and lasted for tens of minutes. One recent example occurred on March 28, 2016, in the Yunnan power grid, which is a provincial grid in China [5]. The Yunnan grid was asynchronously interconnected to other grids with only high voltage DC (HVDC) transmissions when the incident occurred. An oscillation arose, and the frequency oscillated between 49.9 and 50.1 Hz with the period of 20 s. The oscillation lasted for 25 min and greatly threatened the security of the system.

Conventional oscillation studies focus on low-frequency oscillations, which are oscillations between groups of generators and belong to small-disturbance rotor-angle stability [6]. However, after careful investigation, the abovementioned oscillations are not rotor-angle oscillations. They are strongly related with governors and turbines of generators and are the result of small-disturbance instability of the primary frequency regulation (PFR) process of the system. The corresponding oscillation mode is called the frequency mode [7–8] or common swing mode [9].

Several measures have been proposed to increase the damping and prevent frequency oscillations. Prime movers of generation units, including turbines and governors, play an important role in frequency oscillations. The negative damping of prime movers, especially hydro units, is a major cause of frequency oscillations [2,4–5]. Several methods are proposed to optimize the governor parameters to increase the damping of the prime mover and prevent frequency oscillations [10–11]. Adequately designed and tuned power system stabilizers (PSSs) can also be used to improve the damping of the frequency oscillation mode [9,12–13]. Other devices, such as static synchronous compensator, are also used to increase system damping [14]. However, these measures are preventive measures used to increase the system damping and prevent oscillations. When a frequency oscillation has already begun due to some issues, there is no time for these measures,

Nomenclature

$G_m(s)$, $G_{mi}(s)$ the transfer function of prime mover including governor and turbine, and that of unit i

$G_{gov}(s)$ the transfer function of governor

$G_t(s)$, $G_{ht}(s)$, $G_{st}(s)$ the transfer functions of turbine, hydro turbine and steam turbine respectively

P_m, ΔP_m the mechanical power and its deviation

ω, $\Delta\omega$ the generator speed and its deviation

f_0, ω_0 the synchronous frequency, and the synchronous angular frequency

ω_d the angular oscillation frequency

K_{mD}, K_{mDi} the damping torque coefficient, and that of unit i

K_{mS} the synchronizing torque coefficient

T_J, T_{Ji}, T_J^{eq} the mechanical starting time, that of unit i, and that of equivalent unit

W_{TEFL}, W_{IN} the transient energy flow, and that into generator

W_g, W_e the transient energy flow into generator related to the active power–frequency control loop, and to the reactive power–voltage control loop

W_D, W_{pm}^D the dissipation energy flow, and that into prime mover

$I_{ij,x}$, $I_{ij,y}$, I_x, I_y the current in xy frame

$U_{i,x}$, $U_{i,y}$, U_x, U_y the voltage in xy frame

U_i the voltage magnitude

θ_i, $\Delta\theta_i$ the voltage phase angle and its deviation

I_d, I_q the current in dq frame

U_d, U_q the voltage in dq frame

P_{ij}, ΔP_{ij} the active power and its deviation

Q_{ij}, ΔQ_{ij} the reactive power and its deviation

f, Δf_i the frequency, and the frequency deviation

δ the rotor angle of generator

P_e the electromagnetic power of generator

D the damping coefficient of generator

A, α the amplitude and phase angle of $G_m(j\omega_d)$

M_ω, φ the amplitude and initial phase angle of $\Delta\omega$

k_{pm} the average slope of $W_{pm}^D(t)$

K_A, T_A the gain and time constant of automatic voltage regulation

K_{STAB}, T_{WA}, T_1, T_2 the gain and time constants of power system stabilizer

B_P the permanent droop of governor

K_P, K_I, K_D the gains of PID controller

T_G the main servo time constant

T_W the water starting time

F_{HP} the fraction of total turbine power generated by high pressure section in steam turbine

T_{CH}, T_{RH} the time constants of steam chest and reheater, respectively

P_L, P_{L0} the active load and its nominal value

K_L the load frequency sensitivity

T_{JM} the inertia constant of motor

s_m the slip of motor

T_m, T_e the mechanical torque and the electromagnetic torque of motor

and emergency control measures are required to suppress the oscillation as soon as possible.

There is hardly any study on the emergency control of frequency oscillations, while the emergency control of low-frequency rotor-angle oscillation has been studied [14–21]. The key is to locate the oscillation source [17], which is the device causing the oscillation and could be a generator with negative damping in free oscillation or the device where the external periodic disturbance is in forced oscillation. Online damping torque estimation methods can be used to find the generators with negative damping [18–19]. An energy flow method [20–21] is proposed for oscillation source location. The device producing dissipation energy, which is consistent with transient energy, is the source and can be located from the dissipation energy flow (DEF) in the network. The emergency control measures on the oscillation source, such as tripping the source or decreasing its output power, should then be undertaken to suppress the oscillation. However, the causes of frequency oscillations are different from rotor-angle oscillations. The emergency control measures of rotor-angle oscillations are not applicable to frequency oscillations.

The paper focuses on emergency control of frequency oscillations. The most efficient way to mitigate sustained frequency oscillations is to find the unit whose prime mover has negative damping and undertake countermeasures. Moreover, the approach should be online applicable, and a measurement-based and model-free approach is preferred because it can avoid the influence of wrong parameters, which are sometimes the causes of the negative damping of prime movers.

In the paper, the energy flow method is further developed to evaluate the damping of prime movers in frequency oscillations, and then an online emergency control based on phasor measurement unit (PMU) and wide-area measurement system (WAMS) is studied. The paper is organized as follows. Section 2 studies the damping of prime movers in frequency oscillations. Section 3 derives the DEF into prime movers and studies the damping evaluation based on WAMS. Section 4 proposes the online emergency control approach. Section 5 presents the test results, and Section 6 concludes the paper.

2. Damping torque of prime mover

Frequency oscillations are the result of small-disturbance instability of the frequency regulation process of power systems. Most of the recorded frequency oscillation incidents are associated with the PFR process, and the stability of the frequency oscillation mode is greatly affected by the characteristics of the prime movers.

The prime mover includes the governor and the turbine. The transfer function is $G_m(s) = \frac{\Delta P_m(s)}{-\Delta\omega(s)} = G_{gov}(s)G_t(s)$, where $G_{gov}(s)$ and $G_t(s)$ are the transfer functions of the governor and the turbine, respectively. Damping of a prime mover can be analyzed using the damping torque analysis (DTA) method. When the angular oscillation frequency is ω_d, the mechanical power can be represented as

$$\Delta P_m = G_m(j\omega_d)(-\Delta\omega) = (K_{mD} + jK_{mS})(-\Delta\omega) \quad K_{mD} = \mathrm{Re}(G_m(j\omega_d)) \quad K_{mS}$$
$$= \mathrm{Im}(G_m(j\omega_d)), \tag{1}$$

where K_{mD} is the damping torque coefficient.

The damping ratio of the frequency oscillation mode is greatly affected by the prime movers. A positive K_{mD} increases the damping ratio of the mode, and a negative K_{mD} decreases the damping ratio [11].

In frequency oscillations of multi-machine systems, the speeds of all generation units vary with the same phase and amplitude, and the frequencies in the synchronous grid oscillate together [1,5]. It is proposed in [7–8] that, using a single frequency assumption, all the units in the system can be aggregated into a single entity with an equivalent mechanical starting time, $T_J^{eq} = \sum_i T_{Ji}$, and the prime movers of all units are added together to form the prime mover of the equivalent unit, i.e., $G_m(s) = \sum_i G_{mi}(s)$. The effects of prime movers of different units are thus decoupled [11], and K_{mDi} of the ith unit affects the damping ratio of the system independently. When K_{mDi} is positive, the prime mover provides positive damping, increases the damping ratio of the mode, and is beneficial to the decay of the oscillation. A negative K_{mDi} decreases the damping ratio and contributes to a sustained frequency oscillation.

An emergency control approach can be inspired. When the system is oscillating due to a small or even negative damping ratio of the