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An efficient methodology for the analysis of primary frequency control of electric power systems

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Abstract

The paper presents an efficient methodology for the analysis of primary frequency control of electric power systems. This methodology continuously monitors the electromechanical transient processes with durations that last up to 30 s, occurring after the characteristic disturbances. It covers the period of short-term dynamic processes, appearing immediately after the disturbance, in which the dynamics of the individual synchronous machines is dominant, as well as the period with the uniform movement of all generators and restoration of their voltages. The characteristics of the developed methodology were determined based on the example of real electric power interconnection formed by the electric power systems of Yugoslavia, a part of Republic of Srpska, Romania, Bulgaria, former Yugoslav Republic of Macedonia, Greece and Albania (the second UCPTE synchronous zone).

Keywords: Methodology; Primary frequency control; Real interconnection

1. Introduction

In existing primary frequency control of electric power systems (EPSs) analysis, the dominant approach uses simplified methods, which have resulted in corresponding analytical expressions for monitoring the dynamics of the unique frequency change in power systems [1–4]. These simplified approaches have their practical value in the context of global studies of these phenomena, especially if sufficiently accurate estimates of the equivalent parameters are made based on assumptions introduced for obtaining simplified expressions.

However, if more accurate analyses are needed to monitor the state of certain (or all) elements of the power system during the transient process, which the above-mentioned simplified methods evidently are not able to do, stricter approaches are necessary. They model the complete power system network and all the relevant components, including control and protection devices [5–8].

This paper presents a way to form an efficient methodology for the stricter analysis of primary frequency control of EPSs.

The main characteristics of the developed methodology are, firstly, the physical nature and the evolution of the analyzed electromechanical transient processes is strictly respected. In other words, the short-term dynamic processes, occurring directly after the disturbance and in which the dynamics of individual synchronous machines is dominant, is consistently modeled. The same attention to the process is paid during the modeling of the following transient period, when the unique power system frequency is re-established. The transition from one type of dynamics to another, which differ in duration and character, is performed automatically when certain predefined criteria are met (the practical established uniform movements of the individual rotors of synchronous generators and the end of the transient processes in the voltage control loop).

Next, the corresponding balance equations, e.g. the load-flow models are formed using the injected active and reactive power, respecting the nature and main characteristics of the dynamics considered. Starting with application of the Newton–Rhapson method [9] on the balance equations formed this way, and introducing justified simplifications and assumptions in the formation of the corresponding Jacobian matrices, the special fast decoupled procedures with fast and reliable convergence characteristics are developed [10,11].

The next main characteristic of the developed methodology is the unified numerical solution technique of the corresponding nonlinear differential equations (which describe the dynamics of relevant EPS's components) when the necessary speed and economy of simulation are

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Nomenclature

B_{ij} susceptance of branch “i,j”
E'_d EMF caused by the flux linkage in the *d*-axis
E'_q EMF caused by the resultant flux linkage in the *q*-axis of the synchronous machine corresponding to the transient period
f, f_n actual and rated value of power system frequency
$F_i = M_i/M_s$
G_{ij} conductance of branch “i,j”
k,l,m subiteration indices
$M = T_J S_n$ constant of synchronous machine; T_J: inertia time constant; S_n: rated apparent power
$M_s = \sum_{i=1}^{N_G} M_i$
N number, i.e. designation of the set of all nodes of power system
N_G number, i.e. designation of the set of generator nodes
N_L number, i.e. designation of the set of load nodes
P,*Q* injected active and reactive power
P_G, Q_G generator active and reactive power
P_L, Q_L load active and reactive power as a complex function of the frequency and voltage
P_m generator mechanical power
P_{as} system acceleration power
T_G hydroturbine gate servomotor time constant
T_R hydroturbine dashpot time constant
T_W hydroturbine water starting time
V magnitude of the voltage phasor
x'_d, x'_q *d*-axis and *q*-axis transient reactance of synchronous machine
Y_{ij} magnitude of the admittance $Y_{ij} = G_{ij} + 1B_{ij}$

Greeks

δ hydroturbine permanent speed droop coefficient
δ electrical angle of the synchronous machine *q*-axis with respect to the arbitrary chosen synchronous axis of rotation
η hydroturbine transient speed droop coefficient
θ phase of the voltage phasor
μ_{ij} comlementary phase angle of the impedance $Z_{ij} = 1/Y_{ij}$

secured. The corresponding systems of differential equations are solved using quasi-linearization, decomposition and diagonalization, for an adequately chosen time step, and using Caushy’s formula for the subsequent transition from differential to difference equations, which have an elementary form [12,13]. Thus, the integration is performed without numerical instability, quickly and effectively, with the desired simulation accuracy and with very low memory requirements.

The above improvements have permitted a more detailed and precise monitoring of the transient process in the power systems during the primary frequency control. These approaches are very important in practice, inter alia, for verifying the effects of the existing, automatic underfrequency load-shedding systems and the effects of automatic generator frequency protection. They are especially important in the development of new concepts for the significant protection functions of power systems.

It should also be noted, that the proposed methodology, primarily intended for more accurate analysis of primary frequency control, can be of great practical use in the more accurate determination of the causes and the effects of voltage instability, owing to the established flexibility of the load-flow solution for large variations in load characteristics.

The second part of paper gives the selected results of practical application of the developed methodology—the example of real electric power interconnection formed by the EPS’s of Yugoslavia, a part of Republic of Srpska, Romania, Bulgaria, former Yugoslav Republic of Macedonia, Greece and Albania (the present state of interconnection in the Balkans, which is operating as an “island” with respect to the interconnection UCPTE). The analysis of the sensitivity of results to changes in significant control parameters confirms the need of respecting, where necessary, the UCPTE criteria and requirements concerning primary frequency control. Furthermore, the sensitivity analysis indicates whether there is a real possibility of improving the quality of primary frequency control by adequate settings of the control parameters that are adjustable quantities.