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Effects of large dynamic loads on power system stability

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ABSTRACT

This paper investigates the critical parameters of power systems which affect the stability of the system. The analysis is conducted on both a single machine infinite bus (SMIB) system and a large multimachine system with dynamic loads. To further investigate the effects of dynamic loads on power system stability, the effectiveness of conventional as well as modern linear controllers is tested and compared with the variation of loads. The effectiveness is assessed based on the damping of the dominant mode and the analysis in this paper highlights the fact that the dynamic load has substantial effect on the damping of the system.

1. Introduction

Electric loads play an important role in the analysis of angle and voltage stability of power systems. Due to the large diverse load components, the changing load composition with time, weather, and uncertain load characteristics; it is difficult to accurately model the loads for stability studies. The stability of electromechanical oscillations and voltage oscillations between interconnected synchronous generators and loads is necessary for secure system operation because an unsecured system can undergo non-periodic major cascading disturbances, or blackouts, which have serious consequences. Power grids all over the world are experiencing many blackouts in recent years [1] which can be attributed to special causes such as equipment failure, overload, lightning strokes, or unusual operating conditions.

The secure operation of power systems with the variation of loads has been a challenge for power system engineers since the 1920s [2,3]. The fundamental phenomenon of the secure power system operation is investigated in [4] which has explored a variety of machine loading, machine inertia, and system external impedances with a determination of the oscillation and damping characteristics of voltage or speed following a small disturbance in mechanical torque. Based on this phenomenon, many techniques to assess the stability of the power system have been proposed. In [5], there is an extensive description of power system stabilizers (PSSs) which are now widely used in power industries. Some improved methodologies of the PSS design are proposed in [6–9] which has large disturbance rejection capacity. A Fourier-based sliding method is considered in [10] for the secure operation of a power system with large disturbances. Recently, a coordinated PSS design approach is proposed in [11]. In these papers [4–11], the power system is mainly considered as a single machine infinite bus (SMIB) system or a multimachine system and linear control techniques are used to ensure the secure operation of the power system. Some nonlinear control techniques are also proposed in [12–14] for single machine infinite bus (SMIB) system or a multimachine system to obtain a better performance as compared to the traditional linear controllers.

Most of the work as mentioned in the literature [4–14], provides an overview of power system stability where the loads are considered as constant impedance loads. Recently, much attention has been paid to the research on the influence of dynamic or static characteristics of loads on power system stability analysis [15,16] and the reasonable representation of loads for different study purpose which is elaborately described in [17,18].

The induction motor loads which are considered as dynamic loads, account for a large portion of electric loads, especially in large industries and air-conditioning in the commercial and residential areas. The induction motors used in system studies are aggregates of a large number of different motors for which detailed data are not directly available; therefore it is important to identify the critical parameters for stability studies. The effects of induction machines on power system stability are focused in [19] where a Hellenic power system is considered for the analysis and attention is given to electromechanical oscillations and the critical parameter investigation. In [19] induction motors and synchronous generators are considered separately but practically most of the

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nonlinearities occur due to the interconnections between them. Moreover, in [19] some parameters are investigated which affect the stability of the system by neglecting the damping of the system, which is not practical, and finally power system stabilizers are implemented to make the system stable. The critical parameters for a SMIB system as well as large system are also investigated in our previous work [20] by considering all the limitations as presented in [19].

The dynamic stability analysis of power system networks with induction generators has been described in [21] where the induction generators are integrated with wind turbines, i.e., they are not considered as loads. The stability of induction motor networks is nicely described in [22] where the induction motors are considered as loads and bifurcation method is used to analyze the stability. In [22], only the slip of the induction motors is considered as dynamic which does not represent all behaviors of the motors clearly. To analyze the stability of power systems with induction motor loads, a conventional PSS which is also called a power oscillation damping controller (PODC) is used in [19] and a minimax LQG controller is used in [15,23]. The minimax LQG controller provides better performance as compared to the PODC [15,23]. In these papers [17–22], the performances of the controllers are tested by applying different types of faults within a certain range of operating points. But in all of these papers, there is no indication about the effectiveness of the controllers with the variation of dynamic loads.

The aim of this paper is to investigate the effects of dynamic loads on the stability of power systems. Here, the stability of the system with dynamic loads is analyzed by using the concept of the critical parameter investigation as described from our previous work [20]. In this paper, a PODC is designed for power systems with dynamic loads and the effectiveness of the PODC is evaluated with the variation of dynamic loads. Also, the effectiveness of the minimax LQG controller, which is referred to as robust PODC (RPODC), is determined with the changes in induction motor loads within the systems. The effectiveness is mainly considered based on the damping of the dominant mode with the controller. This paper also addresses the question whether dynamic loads influence the effectiveness of the PODC and RPODC with an SMIB system and to what extent as well as what is a suitable way of representing induction motor loads for this purpose.

The rest of the paper is organized as follows. In Section 2, the mathematical modeling of a SMIB system with dynamic load is given. Participation factors and eigenvalue analysis which are used to identify the critical parameters are given in Section 3. Section 4 shows the role of critical parameters on the stability of a large system. An overview of the PODC and RPODC design is presented in Sections 5 and 6, respectively. The effects of large dynamic loads with a PODC and RPODC are shown in Section 7. Finally, the paper is concluded with future trends and further recommendation in Section 8.

2. Power system model

Power systems can be modeled at several different levels of complexity, depending on the intended application of the model. Fig. 1 shows a SMIB system with induction motor loads [24] which is the main focus of this paper as the foundation of this work is built up from this model. Since a SMIB system qualitatively exhibits the important aspects of the behavior of a multimachine power system and is relatively simple to study, it is extremely useful in studying the general concepts of power system stability [13].

In this SMIB model, the power is supplied to the load (P_L = 1500 MW, Q_L = 150 Mvar) from the infinite bus and local generator (approximately, (P_G = 300 MW, Q_G = 225 Mvar). The load at bus-2 is made of three parts: (i) a constant impedance load, (ii) an equivalent large induction motor, and (iii) a shunt capacitor for compensation purposes. The major portion of these loads is the equivalent induction motor.

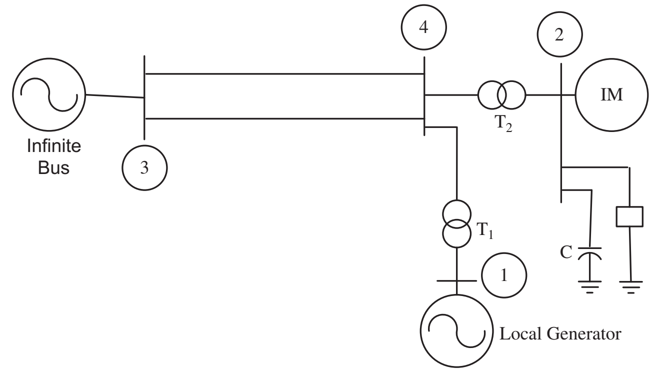

Fig. 1. Test system.

With some typical assumptions, the synchronous generator can be modeled by the following set of differential equations [5]:

$$\dot{\delta} = \omega \tag{1}$$

$$\dot{\omega} = -\frac{D}{2H}\omega + \frac{1}{2H}(P_m - E'_q I_{qg}) \tag{2}$$

$$\dot{E}'_q = \frac{1}{T'_{do}}[E_f - (X_d - X'_d)I_{dg}] \tag{3}$$

$$\dot{V}_0 = \frac{1}{T_r}(V_t - V_0) \tag{4}$$

where δ is the power angle of the generator, ω is the rotor speed with respect to the synchronous reference, H is the inertia constant of the generator, P_m is the mechanical input power to the generator which is assumed to be constant, D is the damping constant of the generator, E'_q is the quadrature-axis transient voltage, K_A is the gain of the exciter amplifier, T'_{do} is the direct-axis open-circuit transient time constant of the generator, X_d is the direct-axis synchronous reactance, X'_d is the direct axis transient reactance, $V_t = \sqrt{(E'_q - X'_d I_{dg})^2 + (X'_d I_{qg})^2}$ is the terminal voltage of the generator, V_0 is the output voltage of the transducer, T_r is the time constant of the transducer, I_{dg} and I_{qg} are direct and quadrature axis currents of the generator. The main source of significant nonlinear effects in this model is related to I_{dg} and I_{qg} for which the expressions will be provided at the end of this section.

A simplified transient model of a single cage induction machine is described by the following algebraic-differential equations written in a synchronously-rotating reference frame [23,25]:

$$(v_d + jv_q) = (R_s + jX')(i_{dm} + ji_{qm}) + j(e'_{qm} - je'_{dm})$$

$$\dot{s} = \frac{1}{2H_m}(T_e - T_m)$$

$$\dot{e}'_{qm} = -\frac{1}{T'_{dom}}e'_{qm} + \frac{1}{T'_{dom}}(X - X')i_{dm} - s\omega_s e'_{dm}$$

$$\dot{e}'_{dm} = -\frac{1}{T'_{dom}}e'_{dm} - \frac{1}{T'_{dom}}(X - X')i_{qm} + s\omega_s e'_{qm}$$

where $X' = X_s + \frac{X_m X_r}{X_m + X_r}$ is the transient reactance, R_s is the stator resistor which is assumed to be zero, X_s is the stator reactance, X_r is the rotor reactance, X_m is the magnetizing reactance, $X = X_s + X_m$ is the rotor open-circuit reactance, T'_{dom} is the transient open circuit