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Augmentation of transient stability margin based on rapid assessment of rate of change of kinetic energy

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ABSTRACT

A fast-load injection through a resistive dynamic brake with appropriate power dissipation capacity can absorb the excess transient energy caused by a large and sudden disturbance and thus improve the transient stability margin of a power system. However, fast assessment of the transient stability and the effective insertion/removal instants of the brake are longstanding challenges. This paper proposes a new criterion based on the rate of change of kinetic energy to rapidly evaluate system transient stability and identify conditions of effective insertion/removal instants of a dynamic brake. Unlike reported studies where the superiority of this criterion was only demonstrated through off-line simulation, both the theoretical modeling and practical implementation of this criterion is presented here using the one machine infinite bus system. A microprocessor controller based on a single-variable measurement, i.e. generator deviation speed, is proposed and implemented to control the dynamic brake during the disturbance periods. The observed behavior of the power system under sudden disturbances and the effect of timely insertion/removal of the dynamic brake on the transient stability of the power system under study are presented and evaluated. The proposed method has been successfully validated, demonstrating its suitability for practical and rapid assessment of transient stability.

1. Introduction

The increased dependence of modern society on electric energy has led to the need for effective methods of assessing and improving power system reliability when subjected to large and sudden disturbances. In order to achieve this, power system designers, planners, and scientists have directed their effort toward achieving the maximum possible system reliability at an affordable cost [1]. Various events can cause interconnected electric power system to move from a normal operating state into a transient emergency state [2–4]. Depending upon the nature and order of magnitude of the disturbance, stability studies are broadly classified into steady state, dynamic and transient stability. The transient stability, which is of particular interest in this paper, is associated with the operation of synchronous machines in parallel, and becomes important with long distance heavy power transmissions.

Unlike the step-by-step methods that are explicitly based on solving the system of differential equations, direct methods determine the transient stability based on the energy balance in the system. Among these are the classical equal-area method that is widely accepted in transient stability studies of one machine infinite bus and two-machine power systems [5]. However, as the systems became larger, and the complexity of the systems grew, this method became far too simplistic for use in multi-machine applications and one important drawback of the equal area approach is that where the critical clearing angle may be calculated the critical clearing time remains unknown [6]. Therefore, it is not applicable for online application and instantaneous actions to maintain stability [7].

Fast online stability assessment has been of interest to many researchers. Most of the methods reported in the literature focus on the stability criterion based on the system dynamic response that can decide the transient stability without the need for results obtained from the time-domain simulation. These methods include energy function analysis [8], phase-plane trajectories [9,10], time-domain equal-area criterion [7,11] and Lyapunov's method [12]. However, in multi-machine power systems, the generator groups must be identified before the online stability assessment.

Recently, a method for the online transient instability detection that is based on a concept called adjoint power system was reported in [13]. This method virtualizes the original system and represents all generators as a unit mass ball rolling on a concave is

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claimed to be sufficiently rapid and the identification of the coherent generator groups is not a requirement. However, validation of this method was only based on computer simulation. In [14], a real-time assessment method of power system transient stability using rate of change of kinetic energy (RACKE) criterion was reported. Effectiveness of this method in transient stability assessment has also been previously investigated in [15–18], using computer simulation. When compared to other equivalent direct methods, RACKE requires less computation time since it does not need to evaluate the equilibrium point.

This paper continues the works of [14,15] by presenting new theoretical modeling and experimental verification for the RACKE criterion to enable rapid assessment and control of the power system transient stability. The proposed criterion does not impose limitations on the system modeling and network structure, and equally applicable for power systems incorporating a single or group of machines. More importantly, it allows for rapid transient stability assessment using a single-variable measurement, i.e., deviation speed of the generator under disturbance. A power system of one machine connected to the infinite bus is used in this study. A microprocessor controller, which is capable of timely inserting and removing a dynamic brake, is designed and utilized to clear the disturbance and thus improving the transient stability margin of the power system.

The remainder of this paper is organized as follows. Section 2 provides a mathematical model for the proposed RACKE criterion, and selection of the dynamic brake size and its insertion/removal strategy. Section 3 describes the power system under study and hardware aspects of the proposed controller. Design aspects of the proposed controller software are described in Section 4. The obtained simulation and experimental results are presented and discussed in Section 5. Finally; the work is concluded in Section 6.

2. Mathematical modeling

This section presents the mathematical modeling of RACKE, the selection of dynamic brake size and optimum time of brake insertion and removal for a single machine connected to the infinite bus.

2.1. RACKE criterion

Any difference that takes place between the input mechanical power (P_m) to a generator and the electrical power (P_e) it delivers must cause acceleration or deceleration of the machine, according to what is known as the swing equation, under the following assumptions; (i) constant voltage behind the transient reactance, (ii) no damping, (iii) constant mechanical power input, and (iv) losses neglected. The dynamic equation of a single machine connected to an infinite bus can be modeled in this form [18]:

$$M\frac{d^2\delta}{dt^2} = P_a = P_m - P_e \tag{1}$$

where P_a is the accelerating power that represents the difference between inputs and outputs power that cause system to accelerate. The kinetic energy of the rotating masses of a turbine generator can be written as

$$W_K = \frac{1}{2}I\omega^2 \tag{2}$$

where I is the moment of inertia (pu s) and ω is the angular velocity (rad/s). At steady state, the kinetic energy (W_{ko}) is given by

$$W_{ko} = \frac{1}{2}I\omega_s^2 \triangleq H \tag{3}$$

where H is the inertia constant. Rearranging (3) yields

$$I = \frac{2H}{\omega_s^2} \tag{4}$$

By analogy to the definition of momentum as $M' = mv$, i.e., mass times velocity, the angular momentum (M) is be given by

$$M = I\omega \tag{5}$$

The angular momentum M is not strictly constant because ω varies somewhat during the swing that follows a disturbance. However, the change in speed at steady state is considered small compared to the synchronous speed ω_s. Hence, M can be approximated by

$$M = I\omega_s \tag{6}$$

Now, RACKE is given by the derivative of (2), as follows:

$$\mathrm{RACKE} = \frac{dW_K}{dt} = \frac{1}{2}I\left(2\omega\frac{d\omega}{dt}\right) \triangleq P_K \tag{7}$$

where P_K is the amount of kinetic power transmitted by the generator rotor during a disturbance for a single machine connected to an infinite bus [14]. Simplifying (7) yields

$$\mathrm{RACKE} = I\omega\frac{d\omega}{dt} \tag{8}$$

Rearranging (6) for I and substituting in (8) yields

$$\mathrm{RACKE} = M\left(\frac{\omega}{\omega_s}\right)\frac{d\omega}{dt} \tag{9}$$

At any instant of time, the instantaneous value of RACKE (IRACKE) can be obtained from

$$\mathrm{IRACKE}(t) = M\left(\frac{\omega_{(t)}}{\omega_s}\right)\frac{d\omega}{dt} \tag{10}$$

where $\omega_{(t)}$ is the instantaneous angular velocity of the rotor.

Since solving the swing equation that corresponds to the value of M, at synchronous speed may introduce only a negligible error, M can be assumed constant in (10). As a result, RACKE is solely dependent on the measurement of the deviation speed. This simplifies practical implementation of RACKE criterion and significantly reduces the associated computation time.

2.2. Selection of brake size

A resistive dynamic brake with appropriate power dissipation capacity for short time periods is an effective means of improving the stability of a power system under large and sudden disturbances [19]. It acts as a fast load injection to absorb the excess transient energy caused by a disturbance. During the transient period, the brake is shunted between the terminals of the disturbed generator and earth to dissipate the excess energy gained by the generator [17]. As $\omega = d\delta/dt$, the dynamic equation (1) can be rewritten, after inclusion of the dynamic brake, as follows:

$$M\frac{d\omega}{dt} = P_a = P_m - (P_e + P_{r_b}) \tag{11}$$

where P_{r_b} is the power absorbed by the braking resistor. It is clear from (11) that dynamic braking increases the transient stability limit. Appropriate selection of the dynamic brake resistor provides efficient dissipation of energy.

The maximum power transfer theorem is used to find the best brake size that gives maximum power transfer which helps in increasing the stability margin of the system. Therefore, any system is reduced to its equivalent Thevenin impedance, looking at the system from the point where the brake is to be placed. The