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Impact of electromechanical wave oscillations propagation on protection schemes

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ABSTRACT

Major disturbances in power system can take place after power system elements such as generators, loads, or transmission lines are suddenly disconnected. Such disturbances can create so called "electromechanical wave oscillations" waves which propagate through transmission lines at much lower speed than speed of light. They can cause adverse effect on power system protective relays. In this paper, electromechanical wave oscillation propagation is modeled, and its impact on different power system protective relays, such as overcurrent, distance, and out-of-step relays is studied. Modified protection schemes are presented for each protective device to avoid their malfunction under effects of electromechanical wave oscillations. The electromechanical model adopted in this study considers the dynamics of generator mechanical shaft as well as conversion of mechanical power to electrical. Simulations used for testing of the improved protection solutions are carried out in MATLAB considering 64-bus generator ring system and IEEE 118-bus system.

1. Introduction

In the last two decades, Wide Area Measurement System (WAMS) made synchronized measurements available from various points across the power system. By analyzing such data, one can noticed the disturbances which propagate through the entire network at the speed much lower than the speed of light. They are called the "electromechanical wave oscillation" propagations.

Transmission line faults, load shedding or generator rejection can result in mismatch between the mechanical and electrical power at the terminal of the generators [1]. As a consequence, generator rotors start to move with respect to their synchronous reference frame. Due to the rotor inertia, re-synchronization of generator with the rest of system (if it happens) occurs with certain delay. This re-synchronization delay can be seen as a disturbance in the voltage phase angle, which propagates through power system with limited speed. Such oscillations can trigger a series of cascade outages and finally a wide spread blackouts may occur as reported for some historical events [2–4].

For the first time, electromechanical wave oscillations were observed and reported in July 1993 during a load rejection test in Texas [6]. In recent decades, substantial research was devoted to modeling the electromechanical disturbance propagation and understanding the dynamic behavior of power system [5–9]. Continuum approach is the most recognized method to model the propagation of electromechanical wave oscillations in power system. The continuum model is based on partial differential equation which offers a travelling wave description of power system dynamics and power system wide-area disturbances [6]. In [7], a continuum power system model is proposed to analyze the propagation of electromechanical disturbances in large power system with concentrated parameters. In this approach, power system is considered as a homogeneous system where transmission lines are represented by a reactance, and generators by a voltage source behind constant reactance. In [6], a more advanced continuum approach is proposed where the effect of loses is also included. Authors derived a nonlinear partial differential equation of the rotor angle with respect to time and two dimensional coordinates were introduced to model electromechanical disturbances propagation. In [9], the proposed continuum model is modified to take the geographical location of the elements of power system into the account. Gaussian smoothing method to deal with the spatially concentrated parameters of power system to represent the distribution of parameters in continuum model was deployed.

Several studies have been done utilizing a non-uniform media [10–13] to characterize wave propagation. In [12], a general method for the solution of the linearized equations for both homogeneous and inhomogeneous media is developed. This method yields solutions which describe propagating waves such as pulses, rapidly

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changing wave forms, or periodic waves. In [13], authors integrated partial variable separation and finite difference methods to attain the numerical solution of wave equation in the non-uniform environment.

So far, most of the studies were devoted to modelling of propagation of electromechanical wave oscillations in power system. Only a few studies considered effects of such disturbances on power system protection, monitoring and control schemes. In this paper, the required testbed development to evaluate the effects of propagation of electromechanical wave oscillations through protective devices including overcurrent, distance and out-of-step tripping (OST) relays is implemented. To have a better insight in the effect of electromechanical wave propagation on protective device, a simulation testbed evaluation of relay operation under electromechanical oscillations of generator rotors is presented. Test cases were developed in MATLAB considering partial differential equations obtained from continuum modeling. Then, the generated voltage and current waveforms were replayed as an input to an actual protective device to test its performance under different scenarios.

The paper is organized as follows: Section 2 describes the electromechanical disturbance propagation phenomena and gives an overview to the continuum modeling approach; Section 3 describes the testbed software and hardware development; Section 4 discusses testing of protective devices when electromechanical disturbances propagate through their terminals; and the conclusions are discussed in Section 5.

2. Continuum modeling of electromechanical wave propagation

Electromechanical wave oscillations occur following exchange of energy between mechanical shaft of generators and the electrical network. The electromagnetic wave transients emerge in power system following energy interchange between electrical network and inductors/capacitors. Electromechanical disturbance mathematically follows the swing equation of synchronous generators. When a disturbance occurs on a transmission line, it leads to a mismatch between electrical and mechanical torque of generators located in the vicinity. The difference between mechanical and electrical torque of generators will cause deviation of the rotors' speed from their nominal values. To compensate for this change, an increase or a decrease in the rotor speed is demanded. Following the generators' rotor angles oscillation, the adjacent buses also encounter change in their generators' rotor angles which again cause a power mismatch. In this fashion, electromechanical wave oscillation oscillations are propagated through the entire network. Electromechanical waveforms are characterized by phase angle modulation of voltages and currents with much lower frequency (0.1–10.0 Hz) than electromagnetic transients (>100 kHz). These oscillations may also produce cyclic or ramped changes in system frequency [14].

A proper system modeling is required before studying the effect of electromechanical waveform propagation on the power system. Applying differential algebraic equations (DAEs) is the conventional way of modeling electromechanical wave propagation in power system. Due to complexity, this approach could be time consuming and the result would be hard to analyze for a large network. Therefore, researchers introduced a much simpler method which embeds the effect of electromechanical wave propagation into power system behavior [5–9].

The so called continuum model, considers power system with spatially distributed parameters not only for impedance of transmission lines, but also inertia of generators. The continuum model is based on applying partial differential equations (PDEs) describing the power systems to the infinitesimal element distributed along the power system. Due to generators rotor inertia, the timescale of electromechanical oscillations is large compared to the power system frequency. Therefore, the variables in continuum model can be considered as phasor parameters [9]. The continuum model mainly grasps a global view of complicated large-scale power systems rather than focusing on the microscopic view of the system. Using continuum approach, propagation of electromechanical wave oscillations can be formulated similar to electromagnetic travelling wave theory.

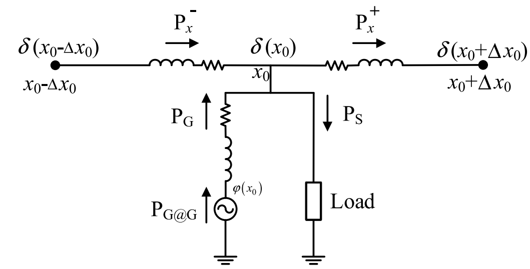

Fig. 1. Incremental system used for continuum modeling of system at x_0.

In the context of continuum modeling, any given point could be represented as shown in Fig. 1. This model allows for representation of lines with different per-unit impedances, shunt reactances, generators and loads. The flexibility of the incremental model allows any arbitrary network topology to be modeled with continuum approach. Following is a brief summary of continuum formulation. In Fig. 1, the net real electrical power flow at point x_0 can be written as:

$$P = \frac{R}{\Delta x|Z|^2}\left[1-\cos\left(\delta(x_0)-\delta(x_0\pm\Delta x)\right)\right] + \frac{X}{\Delta x|Z|^2}\left[\sin\left(\delta(x_0)-\delta(x_0\pm\Delta x)\right)\right] \quad (1)$$

where, $\delta(x)$ represents the phase angle of voltage at x. R, X and, Z represent resistance, reactance and impedance of the branch, respectively. Using Taylor series expansion about x_0, and disregarding higher order terms we get:

$$P = \frac{R}{|Z|^2}\left(\frac{\partial\delta(x_0)}{\partial x}\right)^2\Delta x - \frac{X}{|Z|^2}\frac{\partial^2\delta(x_0)}{\partial x^2}\Delta x \quad (2)$$

The real power produced at the generator terminal is:

$$P_{G@G}(x_0) = \Delta x G_{int}\left[1-\cos\left(\delta(x_0)-\varphi(x_0)\right)\right] - \Delta x B_{int}\sin\left(\delta(x_0)-\varphi(x_0)\right) \quad (3)$$

The real power delivered to the point x_0 by the generator is given by:

$$P_G(x_0) = \Delta x G_{int}\left[\cos\left(\delta(x_0)-\varphi(x_0)\right)-1\right] - \Delta x B_{int}\sin\left(\delta(x_0)-\varphi(x_0)\right) \quad (4)$$

where, G_{int} and B_{int} represent conductance and susceptance of a generator. By conservation of power, the summation of power at a region must be zero, which implies:

$$P = P_G - P_s \quad (5)$$

where, P is the net real power flow at x_0, P_G is real power delivered by generator and P_s is the real power consumed by the load.