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Impact of electromechanical wave oscillations propagation on protection schemes



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A R T I C L E I N F O

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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.

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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



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

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.

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:

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

$$P = \frac{R}{\left|Z\right|^{2}} \left(\frac{\partial \delta(x_{0})}{\partial x}\right)^{2} \Delta x - \frac{X}{\left|Z\right|^{2}} \frac{\partial^{2} \delta(x_{0})}{\partial x^{2}} \Delta x$$
(2)

The real power produced at the generator terminal is:

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

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

$$P_{G}(x_{0}) = \Delta x G_{int} \left[\cos \left(\delta(x_{0}) - \varphi(x_{0}) \right) - 1 \right]$$
$$-\Delta x B_{int} \sin \left(\delta(x_{0}) - \varphi(x_{0}) \right)$$
(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:

$$P = P_{\rm G} - P_{\rm S} \tag{5}$$

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.

Plugging Eqs. (2)-(4) into Eq. (5), we obtain:

$$G\left(\frac{\partial\delta(x_0)}{\partial x}\right)^2 - B\frac{\partial^2\delta(x_0)}{\partial x^2} = G_{\text{int}}\left[\cos\left(\delta(x_0) - \varphi(x_0)\right) - 1\right] - B_{\text{int}}\sin\left(\delta(x_0) - \varphi(x_0)\right) - G_{\text{S}}$$
(6)

where, G_S is the load conductance. The obtained expression in Eq. (6) is known as continuum equivalent of load flow equations. However, the internal generator phase angle dynamics are modeled using:

$$m(x_0)\frac{\partial^2 \varphi(x_0, t)}{\partial t^2} + d(x_0)\frac{\partial \varphi(x_0, t)}{\partial t} = P_{\rm m}(x_0) - \frac{P_{\rm G@G}(x_0)}{\Delta x}$$
(7)

where, $m(x_0)$ and $d(x_0)$ are the generator inertia and damping constant and $P_m(x_0)$ is the mechanical power of a generator. Plugging Eq. (3) into Eq. (7), we obtain:

$$m(x_0) \frac{\partial^2 \varphi(x_0, t)}{\partial t^2} + d(x_0) \frac{\partial \varphi(x_0, t)}{\partial t}$$

= $P_m(x_0) + B_{int} \sin \left(\delta(x_0) - \varphi(x_0) \right)$
 $-G_{int} \left[1 - \cos \left(\delta(x_0) - \varphi(x_0) \right) \right]$ (8)

which is known as continuum equivalent of swing equations. Simulation studies of this paper were carried out using continuum PDE Eqs. (6) and (8).

To illustrate the concept of propagation of electromechanical wave oscillations, as shown in Fig. 2a, a simple power-system model is used which comprises of 64 identical serially connected generators through identical transmission lines, forming a ring [15]. The initial bus angles are evenly distributed from 0° to 360° by steps equal to $360/64 = 5.625^{\circ}$. Due to homogeneity and ring shape of the 64-bus system, it is well-suited to study basic aspects of electromechanical wave propagation phenomena. Fig. 2b shows the phasor angle of 64-buses (in radian) with respect to time of a given disturbance occurring at bus 16 at t = 0. Following the change in the angle of bus 16th shown (thicker line) in Fig. 2b, the other generators operate in a similar manner with a certain time delay. Plotting all the bus angles together, this time delay can be depicted as a wave modulated on buses' phasor angles, which travels away from the source of disturbance into the network at a finite speed. As can be seen in Fig. 2b, the speed of wave propagation is in order of a second, which is much slower than electromagnetic travelling waves (speed of light).

3. Testbed development

In this paper, two test systems are deployed as part of testbed to study effects of electromechanical disturbances propagating through terminals of protective devices. The first one called 64generator ring system [16] which has been already introduced in Section 2 (see Fig. 2a). Due to the radial nature of this test system, it is used to perform testing of overcurrent relays. The second one is the IEEE 118-bus test system [17] which is used to test performance of distance and OST relays. The simulation is done by developing MATLAB script based on solving PDE equations obtained from continuum approach in Section 2.

Fig. 3a shows overview of the developed hardware-in-the-loop testbed. First, each test case is simulated using MATLAB and the voltage and current at all buses are captured as Common format for Transient Data Exchange (COMTRADE) files. Second, a simulator for open-loop transient testing of protective relays is used to transfer scaled voltage and current signals to protective devices. By using simulator and its designated software, users can utilize a portable universal relay test sets with transient testing capabilities of modern power system simulators [18]. This simulator is capable of sending signals in COMTRADE format to any relay connected to the I/O interface, which does the necessary analog to digital conversion. Different signals captured from MATLAB simulations are independently applied to the relays. For instance, Fig. 3b shows normalized voltage and currents in the test software which are captured and imported from MATLAB simulations. Third, scaled signals are applied to the terminals of the protective devices under test and those simulations performed in MATLAB will be repeated with protective device in the loop. Finally, event files are collected from relays and reported. Relay operation evaluation has been performed using two commercial relays [19,20]. The testbed set up brings the electromechanical wave propagation study to a new level which is more realistic and close to actual power system events.

4. Test results and discussion

Electromechanical wave propagation may cause different problems associated with security or dependability of protective device operation [21-27]. For instance, the security of an overcurrent relay with pick up setting selected to be twice as the maximum load will be affected due to instant increase of current level caused by electromechanical wave propagation. In the case of distance relay, as the transient passes through its terminal, the apparent impedance seen by the distance relay may fall inside one of the zones of the relay and cause security issue leading to relay mis-operation. In the case of OST relays, both security and dependability aspects might be at risk [21,22]. When the disturbance propagates through OST relays, the relay may operate and send the trip command. Since the propagation of electromechanical waves is a transient phenomenon, the OST relays must block tripping signal to maintain the security. To block relays following electromechanical wave propagation, a detection scheme is need to be developed to guide the blocking procedure. This can be done by applying wavelet or ANN based methods which can recognize the transient type and make the correct decision to avoid relay mis-operation (which will be considered as future work of current study). Meanwhile, if a fault occurs on the protective zone of the relay, to maintain the dependability, the relay must operate and trip the faulty line. Following subsections discusses the probable impact of electromechanical oscillations on overcurrent, distance and OST relays operation. The limitation of space allowed us to depict performance of relays at few buses. However, the behavior of all relays has been studied at the time of simulation. Selection of buses is done in a way that we could observe different behavior of relays (correct, incorrect and marginal operations), when electromechanical wave oscillations propagated through their terminals. To see the "propagation" nature of electromechanical oscillations, we also selected buses which are not adjacent to fault.

4.1. Impact on overcurrent relay

The pickup setting of the overcurrent relays can be calculated using different methods, however, as a rule of thumb one may consider it to be twice as the maximum load current. Setting up overcurrent relays in such a way may end up in a trip signal when the electromechanical waves pass through their locations. Overcurrent relays are widely used in distribution system (which is not highly affected by electromechanical wave propagation). However, they might be installed as back up protection in transmission and sub-transmission systems. As a result, study of the impact of electromechanical wave propagation on overcurrent relays might be necessary.



Fig. 2. Understanding of electromechanical wave propagation. (a) 64-generator ring system and (b) bus angle modulation following a fault at bus 16 at t=0.



Fig. 3. (a) Testbed for testing impact of electromechanical wave oscillation on protective device and (b) low voltage simulator sample output.



Fig. 4. Outputs of overcurrent relays installed at buses 20, 25 and 30 during electromechanical transient propagation.

In this subsection, 64-generator ring system is used to perform simulation studies. Fig. 4a–c shows the magnitude of the currents captured by overcurrent relays located at three different buses (20, 25 and 30) following a solid three phase fault inserted at bus 16. The dotted lines show the pick-up setting of the time-delayed overcurrent relay, while the magnitude of instantaneous overcurrent relay is set at 5 pu. It can be seen from Fig. 4a that the disturbance reaches the bus 20 in less than 1 s. The measured current exceeds the pick-up setting level at 2.12 s and the event file retrieved from the overcurrent relay shows that the trip signal is initiated at 2.73 s.

Fig. 4b shows that the disturbance reaches at bus 25 after around 3 s. While the measured current exceeds the pick-up setting level at

Table 1	
Modifying time dial setting (TDS) of overcurrent r	elays.

Bus no.	Primary TDS (pu)	Trip signal time (s)	Updated TDS (pu)	Trip signal time (s)
20	1	2.73	1.1	No trip
25	1	No trip	1	No trip
30	1	No trip	1	No trip

3.89 s, no trip signal has been initiated, since the current magnitude falls below the pick-up setting before the time delay overcurrent module operates and sends the trip signal.

Fig. 4c depicts the longer delay of the disturbance reaching the bus 30. This increasing delay of disturbance propagation from bus to bus illustrates the propagation speed of electromechanical waveforms which is much slower than electromagnetic one. It should be noted that unlike the electromagnetic wave propagation which is in the order of microseconds, this phenomenon occurs in the order

Table 2

Performance of distance relays with power swing blocking (PSB) module.

Bus no.	Without PSB module	With PSB module
17	Trip at Zone-1	No trip
15	Trip at Zone-2	No trip
27	No trip	No trip
42	No trip	No trip

of seconds. In this case, the current disturbance is not big enough to exceed the pick-up level. Therefore, no trip will be initiated.

By observing the results of the above mentioned case at the three different buses of the ring system, following may be noted:

- The electromechanical propagation speed is in order of seconds.
- The magnitude of transients die down as it propagates further from initiation location due to damping factor of generators.







Fig. 6. Distance relays outputs installed at buses 17, 15, 27 and 42 during electromechanical wave propagation.



Fig. 7. OST relays outputs installed at buses 26, 28 and 38 during electromechanical wave propagation.

• Since the speed of transient oscillation itself is in order of seconds, the best solution to avoid false trip signal is to increase time delay of overcurrent relay.

In Table 1, results of the same disturbances before and after increasing of time dial setting (TDS) of overcurrent relays are compared. It can be seen that with increasing TDS of overcurrent relay at bus 20 from 1 to 1.1 pu, false trip could be avoided.

Increasing the TDS might seem an easy way to avoid unwanted tripping of overcurrent relays under propagation of electromechanical wave oscillations, but one should verify the coordination of overcurrent relays after increasing of TDS. For instance, if we increase the TDS of relay at bus 20 more than 24%, the relay will no longer be coordinated with the other relays.

4.2. Impact on distance relay

Traditionally, zone-1 of a distance relay is set between 85% and 90% of the line length and operates instantaneously. Zone-2 is generally set at 120–150% of the line length with coordination delay around 0.3 s. Zone-3 covers 120–180% of the next line with time delay of 1 s. When the electromechanical transient wave passes through the terminal of a transmission line where the distance relay is located, the apparent impedance seen by the distance relay may fall inside one of the zones of the relays and relay mis-operation occurs.

In this subsection, IEEE 118-bus test system is used to perform simulation studies (see Fig. 5). Fig. 6a–d shows the *R*–*X* plans of distance relays installed at four different buses (15, 17, 27 and 42) following a solid three phase fault inserted at bus 30. It can be seen from Fig. 6a that the impedance characteristic falls inside zone-1 of relay installed at bus 17 and false trip signal is initiated.

In Fig. 6b, the electromechanical transient causes the measured impedance of the relay installed at bus 15 to enter Zone-2. Since the impedance locus stays in the second zone for more than 0.3 s (zone-2 time delay setting), another false trip signal is initiated.

In Fig. 6c and d, the impedance measurements of relays do not fall inside any of relay's Zones located at buses 27 and 42. As a result, no false trip signal due to relay mis-operation occurred.

By observing the results of the above mentioned case at the four different buses, the following could be concluded:

- Depends on the location of distance relays, they might be affected by electromechanical wave oscillations. If the relay is closer to the source of electromechanical wave propagation the chances for mis-operation are greater.
- Since the propagation speed of electromechanical waves is in the order of seconds, by using same methodology as power swing blocking scheme one can avoid distance relay mis-operations.

Table 2 compares the results under the same disturbance by adding power swing blocking module to distance relays at four

locations. As expected, in all four locations, unwanted trip signal is avoided considering the PSB module in distance relays. It should be noted that almost all of the modern digital distance relays are equipped with the PSB module. Therefore, with proper setting of PSB module, performance of distance relays in actual field might not be affected due to the propagation of electromechanical wave oscillations through their terminals.

4.3. Impact on out of step relay

OST relays are triggered after one or more generators in power system are about to lose their synchronization with the rest of system. In such cases, if the swing is unstable, the OST relay should trip those generators to safeguard the rest of power system from cascade event outages and ultimately a major blackout [28]. However, in the case of stable swings, the OST relay should block tripping signal even though the impedance characteristic enters relays' backup zones.

An OST relay is usually comprised of two sets of double blinders as shown in Fig. 7. When an impedance characteristic penetrates into outer blinders, a timer starts counting. In the case of a fault, the impedance characteristic encroaches the inner blinder before the timer ends. Therefore, OST relay should not block the distance relay's trip signal [29]. In the case of unstable swing, the inner blinder encroached after the timer ends. Consequently, OST should operate and separate it from the rest of system. Finally, if a stable swing occurs, only outer blinder might be entered. It should be noted that OST relay settings are based upon enormous transient and stability studies of the entire power system and cannot be simply modified or [30,31].

When electromechanical disturbances propagate through the terminal of OST relays, the same condition as mentioned in previous subsection may occur. In such cases, the inner and outer blinders of OST relays are entered, and since electromechanical wave is a transient phenomenon, it is desirable to block the tripping signal of the OST relays for the duration of the wave propagation.

In this subsection, IEEE 118-bus test system is used to perform simulation studies. Fig. 7a–c shows the R-X plane of the OST relays installed at three different buses following a solid three phase fault inserted at bus 23. It can be seen from Fig. 7a that the impedance characteristic enters both outer and inner blinder of OST relay installed at bus 26, which means the OST relay detects the condition as unstable swing. As a result a false trip signal will be generated by the relay.

In Fig. 7b, the electromechanical wave propagation causes the measured impedance to enter the impedance characteristics' outer blinder of OST relay installed at bus 28, while the inner zone is never entered. As it has already been mentioned, it means the OST relay detects the condition as a stable swing. Therefore, no false trip will be initiated.

In Fig. 7c, none of the OST relay zones are entered. As a result, the OST relay detects the condition as normal and no trip signal will be initiated. By observing the results of the above mentioned

case at the three different buses, the following conclusions may be reached:

- Depends on the location of OST relays, they might be affected by electromechanical wave propagation. If the relays are closer to the source of electromechanical wave disturbances, the chance of mis-operation is greater.
- The OST relays may only fail to operate correctly when both inner and outer blinders are entered.

5. Conclusion

This study could have an important role in improving the wide area protection and reducing the risk of major blackouts. The authors achieved the following contributions:

- Specification of the theoretical framework for study of electromechanical wave propagation.
- Development of comprehensive testbed to study the phenomena associated with electromechanical wave propagation.
- Discovery of problems associated with protective device operation under the impact of electromechanical wave oscillations propagating through their terminals.
- Suggested solutions to avoid protective device mis-operation under this condition.

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