Testbed Study of Electromechanical Wave Propagation Impacts on Protective Devices

Ahad Esmaeilian, Mladen Kezunovic

***Abstract*--Electromechanical wave propagation may affcet power system protective device operation. This paper discusses the testbed development to study the electromechanical wave propagation impacts on power system dynamic behavior, and consequently impacts on protective devices including overcurrent, distance, and out-of step relays. To have a better insight, a test bed to simulate electromechanical oscillations of generator rotors has been implemented. The test cases are developed in Alternative Transients Program (ATP) considering continuum model which includes transmission capacity and uniformly distributed machine inertia in modeling the power network.**

***Keywords*: Electromechanical wave propagation, power swing, out-of-step, protective device, testbed.**

I. Introduction

Transmission line faults, load shedding or generator rejection can cause a mismatch between the mechanical power inputs and the electrical power outputs of the generators [1]. As a consequence, generator rotors start to move with respect to their synchronous reference frame. These oscillations may result in loss of synchronism in several generators and finally a wide spread blackouts may occur as reported in some historical events [2-4].

The electromechanical travelling wave follows the relations established by the swing equation of synchronous generators [5]. The difference between the mechanical and the electrical torque of generator will cause the deviation of the rotor speed from its nominal value. To compensate for this change, an increase or a decrease in the rotational speed of the rotor is demanded. As the generator's rotor angle changes, the neighboring busses with connected generators also experience changes in their generator angles which again cause a mismatch in the electrical torque on the neighboring generators. In this way the disturbance is propagated from one generator to the next, which is known as the electromechanical wave propagation.

Electromechanical traveling waves were directly observed on July, 1993 when during a load rejection test in Texas a propagating disturbance in frequency has been reported [6]. In the recent decades, several researchers studied different effects of electromechanical wave propagation in power system. Up to the present, the two-dimensional continuum model is considered as the most popular and accurate modeling of power networks to study electromechanical wave propagation [6-9]. The continuum model is based on partial differential equation which offers a travelling wave viewpoint toward power system dynamics and power system wide-area properties [6].

In 1974, continuum modeling approach was applied to large systems with concentrated parameters [7]. In 1998, with the limits of zero generator spacing, a nonlinear partial differential equation of rotor angle with respect to time and two dimensional coordinates was derived [8]. In 2004, to represent the distribution of parameters in continuum model, Gaussian smoothing method was utilized to deal with the spatially concentrated parameters of power system [9].

Several studies have been done utilizing a non-uniform media [10-12] to characterize wave propagation. In [13], authors combined partial separation of variables technique and finite difference method to obtain the numerical solution of wave equation in the non-uniform media.

In [14], authors perform a study to observe the effect of electromechanical wave propagation on the operation of protective device using simulations in MATLAB. The results indicate that under certain cases, the protective devices mis-operate due to the effect of electromechanical wave propagation.

This paper discusses the required testbed development and the effects of electromechanical wave propagation on protective devices including overcurrent, distance and out-of step relays. To have a better insight in the effect of electromechanical wave propagation on protective device, a simulation testbed aimed at evaluation of relay operation under electromechanical oscillations of generator rotors is presented in this paper. The test cases are developed in Alternative Transients Program (ATP) considering transmission capacity and uniformly distributed generator. The generated waveforms from ATP simulations are used to test operation of actual relays under different scenarios by creating hardware-in-the-loop testbed. The relay operation evaluation has been performed using a commercial relay and relay testing simulator [15, 16]. For the reason of simplicity, the simulations have been performed based on the well-established power system model known as 64-generator ring system, taken from [14].

The paper is organized as follows: Section II describes the electromechanical wave propagation phenomena and uses the continuum model for power system simulation; section III describes the testbed software and hardware development; section IV discusses the protective devices tests under the electromechanical waveform propagation; the conclusion are discussed in sections V.

A. Esmaeilian and M. Kezunovic are with Texas A&M University, Dept. of Electrical and Computer Eng., College Station, TX, USA (e-mail: ahadesmaeilian@tamu.edu, kezunov@ece.tamu.edu)

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II. Electromechanical Wave Propagation Continuum Modeling

Electromechanical waveform propagation arises from exchanges between the electrical and mechanical energy stored in the rotating mass of machines while the electromagnetic transients arise due to changes in energy conversions between electrical energy and the energy stored in inductors and capacitors. 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) [17]. These oscillations may produce cyclic or ramped changes in system frequency.

A proper system modeling is required before studying the effect of electromechanical waveform propagation on the power system. Applying conventional algebraic and nonlinear differential equations to the large detailed model of the entire power system considering electromechanical wave propagation is not a feasible approach. Therefore, researchers introduced a theoretical method to create a balance between accuracy and simplicity, which allows them to closely observe the effect of electromechanical wave propagation on power system behavior.

This theoretical method which has been called continuum modeling considers power system with spatially distributed parameters. This means that all power system parameters such as generator inertia, generator reactance and loads are distributed along the line length similar to the line impedance z. The continuum system derivation is based on applying differential equations describing the power systems to the infinitesimal element. Any point in the power system can be modeled by the incremental system as shown in Fig. 1. The magnitudes of the voltage in the entire system are supposed to be fixed, then using Taylor series expansion about δ(x,y), the following two equations can be derived.

$$u_x\left(\frac{\partial\delta}{\partial x}\right)^2+u_y\left(\frac{\partial\delta}{\partial y}\right)^2+t\frac{\partial\delta}{\partial x}\frac{\partial\delta}{\partial y}-v_x\frac{\partial^2\delta}{\partial x^2}-v_y\frac{\partial^2\delta}{\partial y^2}-w\frac{\partial^2\delta}{\partial x\partial y}$$
$$=a[\cos(\delta(x,y)-\varphi(x,y))-1]-b[\sin(\delta(x,y)-\varphi(x,y))]-g \qquad (1)$$

$$m\frac{\partial^2\varphi}{\partial t^2}+d\frac{\partial\varphi}{\partial t}=p-a[1-\cos(\varphi(x,y)-\delta(x,y))]-b[\sin(\varphi(x,y)-\delta(x,y))] \qquad (2)$$

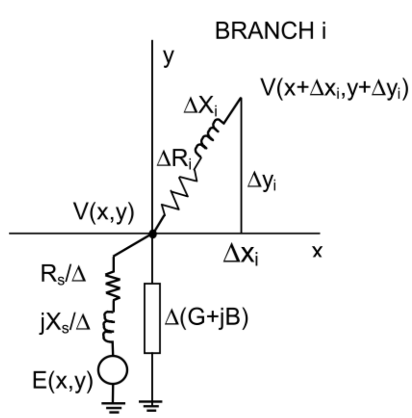


Fig. 1. Incremental system used for continuum modeling of system

where the generator's internal and external phase angles are φ(x,y) and δ(x,y) respectively. These two equations are called continuum equivalent of the load flow equations and the continuum equivalent of the coupled set of swing equations, respectively.

Details of the derivation, solution of the equations, and the definitions of the parameters (u_x, u_y, v_x, v_y, w, t, a, b, m, d, p, and g) are omitted from this paper for the sake of brevity, and can be found in reference [6].

III. Testbed Development

Building Experimental test set-up to study effects of electromechanical waveform propagation on protective relays has been done in two major steps. Following subsections describe the procedure of each step.

A. Testbed Software Development

In this study, for the reason of simplicity, the simulations will be performed based on the well-established system model known as 64-generator ring system, taken from [14]. The test cases are developed in Alternative Transients Program (ATP) considering continuum model, which includes transmission capacity and uniformly distributed machine inertial in modeling of power network (See Fig. 2).

The network model consists of 64 serially connected busses, forming a ring (two neighboring busses are connected with a transmission line with a reactance X, as well as the first and the last bus, a synchronous generator connected at each bus). All the transmission lines are unique with same length and impedances. All the generators have same internal reactance as well as inertia constant. Table I contains parameter values used to model the system in ATP.

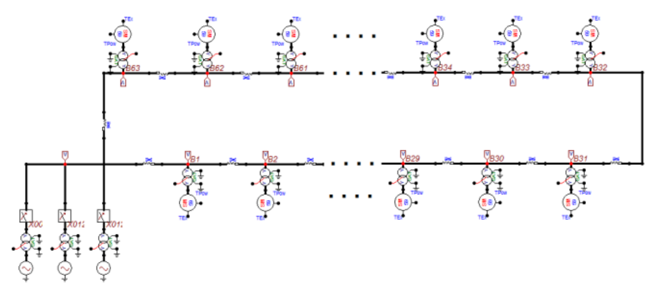


Fig. 2. 64-Generator ring system modeled in ATP

TABLE I: 64-Generator Ring System Model Parameters

Transmission line	Impedance	R=0.513 Ω/km L=5.99 H/km
	Line Length	L=100km
Transformer	Impedance	$R_1=R_2=0.001$ Ω $L_1=L_2=0.01$Ω
Generator	Inertia Constant	H=0.02
	Reactances	X_d=0.146 pu X_q=0.097 pu $X_{d'}$=0.061 pu $X_{q'}$=0.097 pu $X_{d''}$=0.04 pu $X_{q''}$=0.06 pu

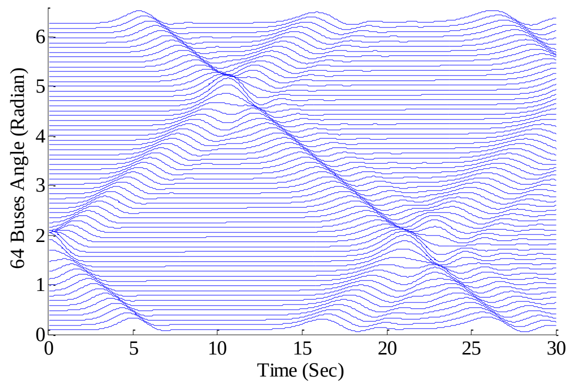


Fig. 3. Electromechanical wave propagation after a disturbance at bus 16

Fig. 3 shows an example of electromechanical waveform propagation through the network. In this simulation, a step change of 0.5 radian is applied to the 16th generator rotor angle at t=0. As depicted in Fig. 3, the rest of generator rotor angles follow the changes, but each one with a certain time delay after the 16th one. This can be represented as a wave when the angles of all the generators are plotted together. The propagation wave travels away from the disturbance source till it reaches the boundaries of the power system (where it reaches open circuit, tripped lines, etc.), then it bounces back, forming a reflected wave. The superposition of both, the initial and the reflected wave, causes power-system transients, which may affect power system in different ways, which in turn may affect operation of protective devices.

B. Testbed Hardware Development

The next step is the impact evaluation, which requires a testbed capable of applying generated waveforms obtained from ATP simulations to test operation of actual relays under different scenarios. The relay operation evaluation has been performed using two different types of relays: a) distance relay and overcurrent relay. The testbed comprises a simulator for open-loop transient testing of protective relays. The software is designed to complement and improve widely accepted methods and practices of the relay testing. By using this software users can utilize a portable universal relay test sets with transient testing capabilities of modern power system simulators [18]. This test set is capable of sending signals from file formats such as ATP PL4, and COMTRADE to any relay connected to the I/O interface which does the necessary analog to digital conversion.

The block diagram of the setup is shown in Fig. 4. Different

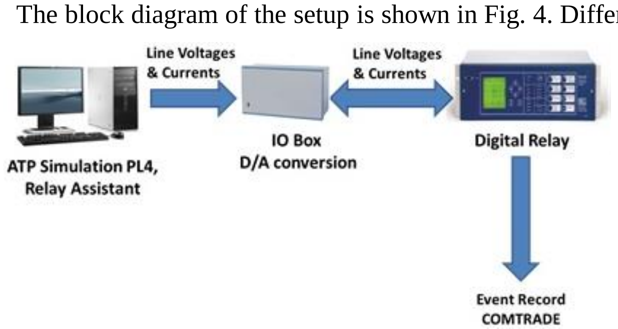


Fig. 4. Schematic of experimental testbed development.

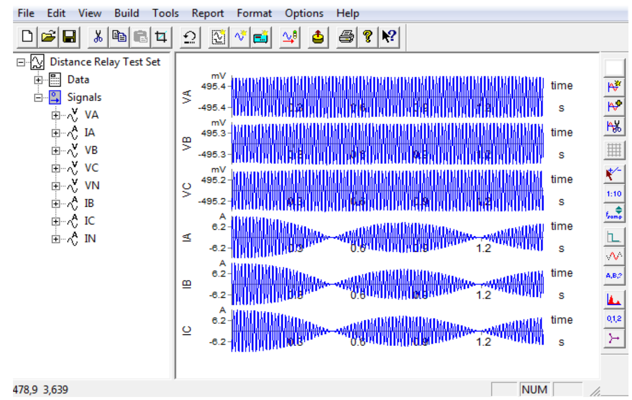


Fig. 5. Voltage and current waveforms in Relay Assistant Software

signals captured from ATP simulations are independently applied to the relays. For instance, Fig. 5 shows normalized voltage and currents in the test software which are captured and imported from ATP simulation. In the next step, the test software transfers the voltage and currents to the digital distance relay through a digital to analog converter. Finally, event files in COMTRADE format are collected from the relay and reported. 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.

IV. Test Results and Discussion

By now, readers should have a general knowledge about the electromechanical wave propagation phenomena, when it appears in the network, and how it propagates through the system. In this section, we narrow down the study to the understanding of effect of this phenomenon on the power system protection devices.

Electromechanical wave propagation may cause different problems associated with security or dependability of protective device operation [19-23]. For instance, the security of an overcurrent relay with pick up setting selected to be twice the maximum load will be affected due to instant increase of current level caused by electromechanical wave propagation. In the case of distance relays, as the transient passes through the terminal of a line where the distance relay is located, the apparent impedance seen by a 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 out-of-step (OST) relays, both security and dependability aspects might be at risk [19, 20]. When the disturbance propagates through OST relays, the relay may operate and send the trip command. Since the wave propagation is a transient phenomenon, it is desirable to block the out-of-step relays 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 the phenomena on overcurrent, distance and out-of-step relay operation.

A. 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 the maximum load current. Setting up the 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), but they might be installed as back up protection in transmission and sub-transmission system. As a result, study of the impact of electromechanical wave propagation might be necessary.

Fig. 6 (a-c) shows the magnitude of the currents captured by overcurrent relay at three different buses following a 0.5 radian step change 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 5pu.

It can be seen from Fig. 6-a that the disturbance reaches the bus 20 in less than 1 sec. The measured current exceeds the pick-up setting level at 2.12 sec and the trip signal is initiated at 2.73 sec.

Fig. 6-b shows that the disturbance reaches the bus 25 after around 3 sec. While the measured current exceeds the pick-up setting level at 3.89sec, 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.

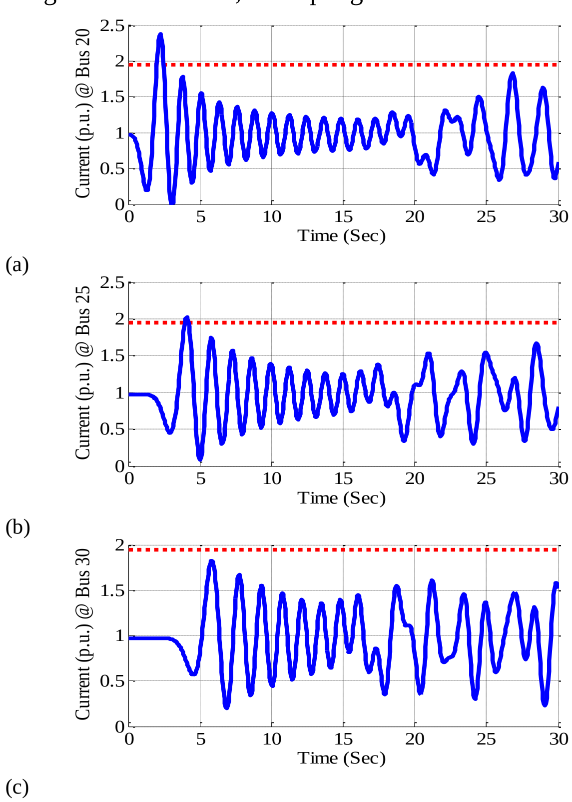


Fig. 6. Outputs of overcurrent relays installed at buses 20, 25 and 30 during electromechanical transient propagation

Fig. 6-c 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 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.
- 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.

B. 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% to 150% of the line length with coordination delay around 0.3 sec. Zone-3 covers 120% to 180% of the next line with time delay of 1 sec. 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.

Fig. 7 (a-d) shows the R-X plan of the distance relays

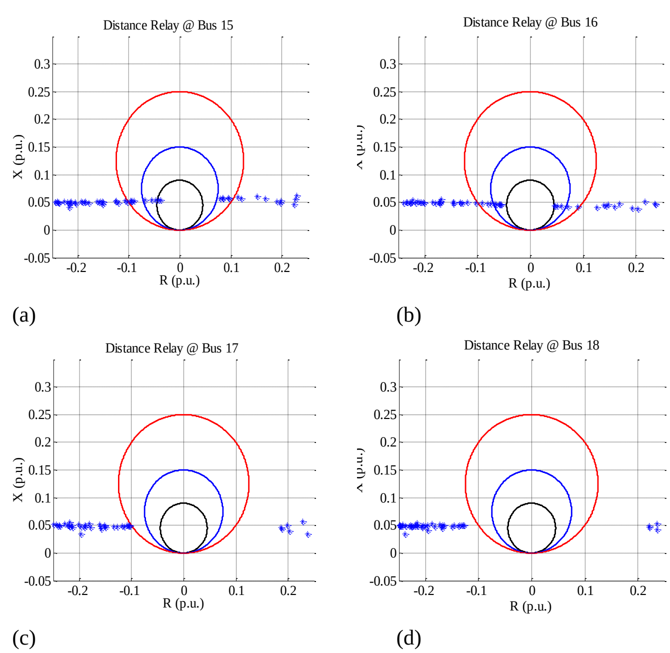


Fig. 7. Distance relays outputs installed at buses 15, 16, 17 and 18 during electromechanical wave propagation

installed at four different buses following a 0.5 radian step change inserted at bus 14. It can be seen from Fig. 7-a that the impedance characteristic falls inside zone-1 of relay installed at bus 15 and false trip signal is initiated.

In Fig. 7-b, the electromechanical transient causes the measured impedance of the relay installed at bus 16 to enter Zone-2. Since the impedance locus stays in the second zone for more than 0.3 sec, another false trip signal is initiated.

In Fig. 7-c and Fig. 7-d, the impedance measurements of relays do not fall inside any of relay's Zones. As a result, no false trip signal due to relay mis-operation will occur.

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

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

C. Impact on Out of Step Relay

Out-of-step relays are designed to detect conditions when a group of machines or a portion of the power system is about to go out of synchronism with the rest of the network. If the condition is detected, the relay should separate the affected machines from the rest of the network to avoid a catastrophic failure of the entire network [24]. However, if the swings are stable, the out-of-step relay should block tripping even though the apparent impedance enters some relay zones. The inner blinder (see Fig. 8) is used to detect an unstable swing. The outer blinder is used to start a timer. For a fault condition, the impedance locus enters the inner blinder before the timer ends [25]. For an unstable swinging condition, the inner blinder is entered after the timer ends. If the inner blinder is never entered after the outer blinder is entered, a stable swing is recognized. No tripping is permitted for a stable swing. For an unstable swing, an appropriate blocking or tripping scheme must be provided. The zone settings and various timer settings are based upon numerous simulations of transient stability events performed for assumed system conditions [26, 27].

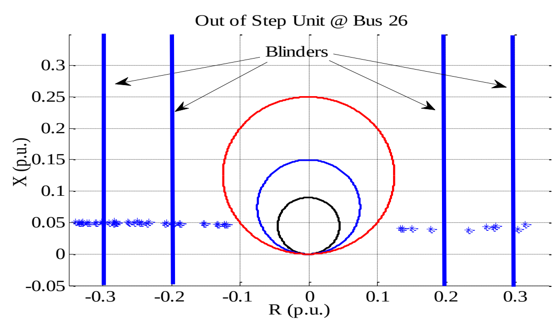
In the case of electromechanical wave propagation into the network, the same condition as mentioned in previous subsection may occur at terminal of a line where an out-of-step (OST) relay is installed. In such cases, the inner and outer blinders of out-of-step relays are entered, and since electromechanical wave is a transient phenomenon, it is desirable to block the tripping of the out-of-step relays for the duration of the wave propagation.

Fig. 8 (a-c) shows the R-X plane of the OST relays installed at three different buses following a 0.5 radian step change inserted at bus 20. It can be seen from Fig. 8-a 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.

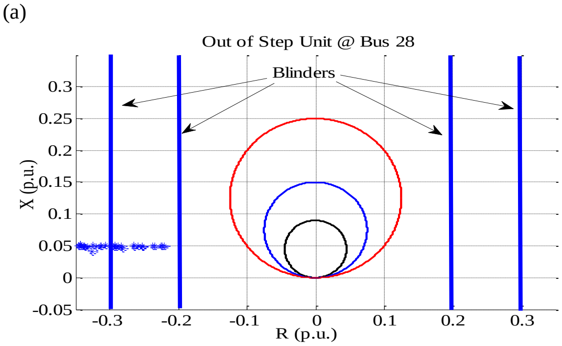
In Fig. 8-b, the electromechanical wave propagation causes the measured impedance to enter the impedance characteristics' outer blinder of OST relay installed at bus 28, while the inner zone is never entered. As it has already been mentioned, it means the OST relay detects the condition as a stable swing. Therefore, no false trip will be initiated.

In Fig. 8-c, 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:

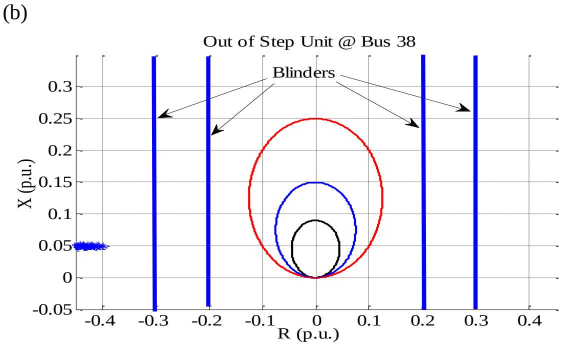
- Depends on the location of OST relays, they might be affected by electromechanical wave propagation. If the relays are closer to the source of electromechanical wave propagation, the chance of mis-operation is greater.
- The OST relays may only fail to operate correctly when both inner and outer blinders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



(a)



(b)



(c)

Fig. 8. Out-of-step relays outputs installed at buses 26, 28 and 38 during electromechanical wave propagation

V. 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 propagation
- Suggestion for solutions to avoid protective device mis-operation under this condition.

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