Modeling Protection Systems in Time-Domain Simulations: A New Method to Detect Mis-Operating Relays for Unstable Power Swings

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***Abstract*—Large power system disturbances can cause stable or unstable power swings. Unstable power swings result in generator pole slipping. A generator or group of generators may accelerate or decelerate, leading to voltage depression at the electrical center along with generator tripping. This voltage depression may cause protective relay mis-operation and unintentional separation of the system. In order to avoid unintentional islanding, the potentially mis-operating relays should be blocked from tripping. This paper proposes a novel method to determine the location of the mis-operating relays at the planning phase. Blocking these mis-operating relays, combined with an appropriate islanding scheme, help avoid a system-wide collapse. The proposed method is tested on data from the Western Electricity Coordinating Council. A triple line outage of the California-Oregon Intertie is studied. The electrical center is determined and appropriate out-of-step blocking schemes are identified. The results show that the correct design of out-of-step protective relays improves the dynamic performance of the power system and causes less fluctuations in voltage and frequency throughout the system.**

***Index Terms*—Distance relays, electrical center, out-of-step condition, power system dynamics, power system protection, power system stability, relay mis-operation, transient stability study, unstable power swing.**

I. Introduction

MAJOR blackouts are usually the result of a single initiating event, followed by an inappropriate action or inaction of essential protective equipment. The North American Electric Reliability Corporation (NERC) mandates that the *N*-1 reliability requirement be maintained during power system operations and it must be accounted for during planning [1]. However, ensuring that the system is *N*-1 reliable is a complex task as the actual operating state of the system cannot be predicted a priori. Various corrective actions and technologies, such as remedial action scheme (RAS), under voltage and under frequency load shedding, capacitor and reactor bank, transmission switching, and flexible ac transmission systems (FACTS) can be implemented to remedy the post contingency violations.

Data from many blackouts in North America confirm that distance relay mis-operation is one key factor that may initiate a series of outages, which can cause a blackout. A power swing, triggered by initiating events, can cause protection system mis-operation. During an unstable power swing, the voltage magnitude at the electrical center will be depressed, resulting in protective relays detecting what appears to be a fault and, thus, the protective relays will trip additional transmission lines [2]. Power swings are classified to have a local mode or an inter-area mode. A local mode power swing represents a swing of a generator or a local plant with respect to the rest of the system. Inter-area power swings are the oscillations of a group of generators against other groups. The relay mis-operations during an inter-area power swing could result in the creation of uncontrolled islands in the system. During unstable power swings, controlled islanding should be initiated with the goal of minimizing the loss of load and ensuring synchronism within each generator group.

Controlled islanding can be achieved by implementing an appropriate out-of-step (OOS) protection scheme. The OOS protection scheme must block protective relays that would mis-operate. Modern relays are usually equipped with blocking capabilities to prevent unintentional distance relay operations during stable or unstable power swings [3]. Of course, identifying the proper locations where the tripping needs to occur is key to achieving the intended controlled islanding scheme. Each controlled island must achieve a supply-demand balance based on a proper load-generation shedding plan [3]. Failure to take the appropriate actions quickly may create unintentional islands, which can occur in the order of a few seconds, and can lead to a cascading outage [2].

The first step in implementing an OOS protection scheme is OOS detection. A well-designed protection scheme should differentiate between faults and power swings and block the relay tripping operation during power swings. In addition, a proper transfer trip signal should be sent to the OOS tripping locations. The rate of change of the swing impedance is usually used as a

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metric to differentiate between faults and power swings. During a fault, the voltage and current change from their normal value to the value capable of triggering the relay instantly. However, for a power swing, these values change slowly from the normal value [4]. This lower rate of change of swing impedance trajectory is utilized in modern relays via blinder schemes to detect a power swing. In addition, there are several different approaches presented in literature with the purpose of distinguishing between a power swing and a fault condition [5]–[16].

Blocking and tripping are two main functions of OOS protection schemes. The proper locations for OOS tripping and blocking functions must be decided based on the results of stability studies [3]. OOS tripping protection schemes are usually initiated after receiving transfer trip signals. Previous research efforts have proposed several innovative methods to design and allocate OOS tripping schemes [17]–[18]. The transmission lines, along the electrical center, may need to be blocked from tripping during an unstable power swing using an OOS blocking function. These transmission lines should be determined during the planning study and distance relays should be designed for these lines and equipped with OOS blocking functions. Failure to locate appropriate relays on these transmission lines and failure to correctly set these relays can result in system-wide outages [3].

This paper proposes a new approach to identify transmission lines along the electrical center. First, Section II presents the state of the art techniques for detecting the electrical center of the system for an unstable power swing. Section II also introduces the proposed approach and identifies its distinct advantages over prior approaches. Section III then details the proposed method. The dataset and the contingencies under study are described in Section IV. Section V presents the results and analysis of the study conducted on the Western Electricity Coordinating Council (WECC) system. The conclusions are given in Section VI.

II. Review of Out-Of-Step and Electrical Center Detection Methods

Previous research efforts have proposed several methods to identify transmission lines along the electrical center [3] and [19]–[21]. Reference [19] specifies that modeling the protection system during transient stability studies is the most precise approach for identifying power swings and the related electrical center. However, relay characteristics must then be modeled and maintained, which is cumbersome and computationally challenging for planning studies [19].

Most approaches study whether the swing trajectory traverses a transmission line impedance to detect if the transmission line is along the electrical center. Due to system complexity, such studies commonly reduce the system to two equivalent sources (Thévenin equivalent models) and the transmission line of interest. Various techniques, such as short circuit analysis tools, are used to find these equivalent models [3]. However, if any machine loses synchronism with their own group, this approach cannot be used and a network-analyzer study is required [22]. The two-machine equivalent approach requires a priori knowledge of the electrical center location since the two asynchronous groups of generators cannot be modeled as a single equivalent machine, i.e., the rotor oscillations are not in phase. Also, [19] refers to [23] with regards to this two-machine equivalent method, "*When more than a line or two are to be analyzed, it is virtually impossible to use the method,*" [23]. Electrical center locations vary and need to be studied for various operational conditions, fault types, and fault locations. The challenge to complete multiple complex studies and the inaccuracy of the equivalent models are the primary causes of relay mis-operation. While this problem is well understood, the issue persists.

With present-day advanced transient study programs, the intersection of the relay impedance trajectories and the line impedance of transmission lines can be studied to determine the transmission lines along the electrical center [20]. However, this approach is not practical for large-scale test cases. An auxiliary method needs to be applied to find the intersection of the impedance locus and line impedance. Reference [21] provides a new approach, which is a more practical approach for the method in [20]. The technique suggested in [21] is innovative and advantageous in locating the electrical center for an unstable power swing. In this method, two sequential points on the relay impedance trajectory (corresponding to two sequential time intervals of transient studies) are projected to a perpendicular line of the transmission line impedance. If these projected values are of opposite algebraic signs, it is concluded that the relay impedance trajectory has intersected the line impedance characteristic between these two time intervals; therefore, the transmission line under study lies along the electrical center. Throughout the rest of this paper, the term "*projected relay trajectory method*" will refer to the electrical center detection algorithm in [21]. Although this method is innovative and fast, it has some inaccuracies and problems. The projected relay trajectory method [21] is implemented and compared with the method proposed in this paper. Section V provides examples where the projected relay trajectory method fails.

In [19], the system protection and control subcommittee of NERC suggests a voltage dip screening method in order to identify power swings and locate the system electrical center of a power swing. The voltage dip screening method in [19] can be used in transient planning studies. Such planning studies evaluate the power system operating condition, including voltages, for many contingencies in order to study the compliance of the system with various standards. The approach from [19] examines voltage drops during oscillations of the coherent groups of generators, i.e., inter-area oscillations. The transmission lines between these coherent groups of generators (at the electrical center) experience a condition similar to a three-phase short circuit, i.e., the line-to-line voltages become zero [24]–[25]. Using this attribute, the voltage dip screening method in [19] suggests that monitoring the voltage magnitude throughout the system (at buses) can be considered as a flag for a power swing and can detect the electrical center. Empirical evidence shows that voltage magnitudes at buses, particularly at those buses connected to lines along the electrical center, drop to at least the range of 0.5 and 0.6 pu [19]. Moreover, an analysis is performed in [19] in order to show the correlation between the voltage dip and presence of the relay impedance trajectory in distance relay zones. This reference indicates that additional studies need to be conducted in order to establish voltage dip thresholds. Although the suggested method in [19] is based on empirical results and is intuitive, it sheds light on the application of voltage evaluation techniques for power swing conditions and system electrical center detection.

This paper proposes a method that provides a screening tool for OOS and electrical center detection during transient stability planning studies, which can be considered an extension of the voltage dip screening method [19]. While the method of [19] relies on a voltage drop only at buses, the proposed analytical approach can evaluate voltage magnitudes anywhere along all transmission assets. The proposed extension is critical since a voltage dip screening approach relying only on bus voltage magnitudes can be highly inaccurate since the electrical center can occur at a bus or along a transmission line. Terminal buses of the transmission lines along the electrical center may not experience extreme voltage drops. Note that [19] examines only stable power swings while the proposed approach also applies to unstable power swings.

The proposed technique (referred to as the *minimum voltage evaluation* method in the remainder of this paper) calculates and evaluates the minimum voltage magnitude along the transmission lines using the results of a transient stability study. A low minimum voltage (without an actual fault) can be considered as a flag for an out-of-step condition as well as a potential reason for relay mis-operation of the related transmission line. These transmission lines should be equipped with OOS blocking protective relays.

The proposed minimum voltage evaluation method contributes to the challenge to detect mis-operating relays during unstable power swings and identifies essential locations for OOS blocking functions. The proposed minimum voltage threshold method extends the empirical based approach of [19] with an analytical approach to determine the worst voltage dip along transmission lines. This approach is not only effective but it is straightforward, easy to implement, and computationally fast making it suitable for large-scale power systems. Furthermore, the results demonstrate that the proposed approach is able to detect all transmission lines along the electrical center. Prior methods, such as the projected relay trajectory method in [21], do not detect all transmission lines along the electrical center, which can lead to further relay mis-operation and, thus, a cascading outage. Finally, this paper provides realistic results and confirmation of the proposed method and its achievements by studying the projected relay trajectory method and the proposed method on actual data of the WECC system.

III. Minimum Voltage Evaluation Method

This paper proposes an analytical voltage evaluation method in order to detect unstable power swings and essential locations of OOS blocking functions for an unstable power swing. During OOS conditions, the voltage at the electrical center is depressed; this property is utilized by the proposed OOS condition and electrical center detection method. The proposed method evaluates the voltage magnitude throughout the system using the outputs of the transient stability planning study. The voltage along each transmission line can be calculated based on the network solution, i.e., the value of bus voltages and transmission lines flows,

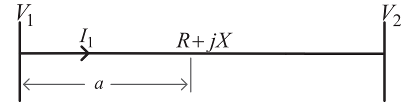


Fig. 1. Voltage evaluation along a transmission line.

at each time interval of the transient stability study. Therefore, the proposed model does not require any modification to existing transient stability study practices.

If the magnitude of the voltage along transmission lines (or at the terminal buses) reduces significantly, while no fault is present on the transmission line, it can be concluded that the system is experiencing an unstable power swing. In addition, the distance relays of the transmission lines with the depressed voltage are prone to operate. Therefore, these relays should be equipped with OOS blocking functions.

Using a simple optimization model, the minimum voltage magnitude through each transmission line can be calculated, which indicates the worst voltage dip along a transmission line. The minimum voltage evaluation method determines the worst voltage dip along transmission lines to detect unstable power swings and the essential locations of OOS blocking functions.

The proposed method includes the following assumptions: 1) the shunt admittance of transmission lines are considered to be negligible. Thus, the current through the line is the same as the current at the end of the line. 2) The line impedance is assumed to be uniform throughout the length of the line.

First, a transient stability study for the critical contingency needs to be performed. Using bus voltages and transmission lines flows, which are known for each time interval from the results of the transient stability study, the value of voltage along each transmission line can be evaluated using (1). Note that a represents the fraction of the length of the transmission line under study. This is shown in Fig. 1.

$$\begin{aligned} V_a &= V_1 - a \times (R + jX) I_1 \\ &= (V_{1x} - aRI_{1x} + aXI_{1y}) + j\,(V_{1y} - aXI_{1x} - aRI_{1y}) \end{aligned} \tag{1}$$

In this equation, V_{1x}, V_{1y}, I_{1x}, and I_{1y} are the real part of V_1, the imaginary part of V_1, the real part of I_1, and the imaginary part of I_1 respectively. Moreover, R and X are resistance and reactance of the transmission line respectively. Therefore, the magnitude of V_a can be expressed as (2).

$$|V_a| = \sqrt{(V_{1x} - aRI_{1x} + aXI_{1y})^2 + (V_{1y} - aXI_{1x} - aRI_{1y})^2} \tag{2}$$

All variables on the right hand side of (2) are known based on the transient stability study. The voltage magnitude through the transmission line can be calculated at each time interval. Furthermore, the minimum voltage magnitude, which shows the worst voltage dip, through a transmission line is calculated at each time interval using the minimization problem presented in (3) and (4).

$$\text{Objective:} \quad \text{Minimize}$$

$$|V_a| = \left(\sqrt{(V_{1x} - aRI_{1x} + aXI_{1y})^2 + (V_{1y} - aXI_{1x} - aRI_{1y})^2}\right) \tag{3}$$

$$\text{Subject to:} \quad 0 \le a \le 1 \tag{4}$$

This minimization problem is a single variable optimization model, i.e., a is the only unknown. For each time interval and for each transmission line, this optimization problem is solved to provide the fraction of the length of the transmission line (a), that experiences the lowest voltage magnitude, and the minimum voltage. This nonlinear problem can have local optimal solutions at: 1) points where $d_{|V_a|}/d_a = 0$ for $0 \le a \le 1$; 2) end points, i.e., $a = 0$, or $a = 1$; 3) points where $d_{|V_a|}/d_a$ does not exists. The smallest value of $|V_a|$ among the local minima is considered as the global minimum for (3)–(4). Note that $d_{|V_a|}/d_a$ represents the first derivative of voltage magnitude (equation (3)) with respect to the fraction of length of transmission line (a, which is shown in Fig. 1).

If the minimum voltage along a transmission line (in the absence of a fault) is zero, the contingency would lead to an OOS condition and the associated line is along the electrical center. However, the transient stability study monitors the system behavior in discrete time intervals. The voltage magnitude through the line may traverse to zero in between two discrete time intervals. In such, cases it is insufficient to search for a voltage magnitude of zero. Since power swings traverse slowly, a small threshold can be considered for this technique. Therefore, if (5) holds, the contingency would lead to an unstable power swing and the transmission line is located along the electrical center.

$$|V_{a^{\min}}| \le \varepsilon \tag{5}$$

In (5), $|V_{a^{\min}}|$ is the minimum voltage magnitude through the transmission line, which occurs at $a^{\min}$ fraction of the length of the line, and ε represents the established threshold. Note that the minimization problem, (3)–(4), and the evaluation of (5) should be performed for all time intervals of the transient stability study in order to detect all of the mis-operating relays.

The accuracy of the proposed method is tested and shown in Section V. The results show that the minimum voltage evaluation method successfully recognizes all the relays, which may mis-operate during an unstable power swing.

IV. Test Case and Contingency Description

The WECC system data, representing the 2009 summer peak load case, is used to perform the analysis. The system includes 16,032 buses, 3,217 generators, 13,994 transmission lines, and 6,331 transformers. The overall generation capacity is about 238 GW and the load is about 167 GW.

The California-Oregon Intertie (COI) includes three 500 kV transmission lines transferring about 3800 MW from north to south during this hour and they are very critical tie lines.

First, an outage on two of the three COI ties is studied, which causes a stable power swing. The minimum voltage during this stable power swing is evaluated and the application of the minimum voltage evaluation method is shown in Section V-A. Second, a fault on bus MALIN, located in the Northwest area, is modeled. It is considered that this fault leads to the outage of all three COI tie lines, which results in an unstable power swing; see Sections V-B-V-D for a discussion of this case. Both these contingencies fall under category D of the NERC standard [26].

In the dataset provided, no distance relays are modeled. Throughout the remainder of this paper, the term "base case" will be used in reference to the results pertaining to the original dataset. Transient stability analysis is first performed on the base case dataset considering the described contingencies (double and triple outages of the COI).

Additional studies are conducted where the triple line outage of the COI is studied with the modeling of distance relays for all lines at or above 100 kV. These distance relays are modeled using a model from the Positive Sequence Load Flow (PSLF) library [27]. This model just considers two zones for each distance relay. Please note that there exist other distance relay models in PSLF, which are able to model three zones of distance relays. However, implementation of these distance relay models are avoided due to the large scale test case and software limitation. The zone 1 and zone 2 of the modeled distance relays are considered to be 0.85 and 1.25 times the transmission line reactance respectively. The zone 2 of the distance relays operate with a time delay of 0.25 seconds. Zone 1 initiates tripping without any time delay. However, the breaker operation time is modeled to be 0.03 seconds. While the relay settings for various transmission lines will vary across a system, these settings are considered to be similar for all transmission lines in this paper due to the lack of available data for protection systems across the entire WECC.

A controlled islanding scheme is tested using the designed OOS protection. The OOS tripping is based on the well-known (northeast/southeast) NE/SE separation scheme for the WECC [28]–[29]. This separation would be initiated after receiving a transfer trip signal from Bonneville Power Administration (BPA) and Pacific Gas and Electric (PG&E) [30]. An OOS blocking scheme is performed based on the minimum voltage evaluation method. In order to compare the proposed method with previous research, the OOS blocking function, based on the projected relay trajectory method [21], is also tested.

In order to test both the minimum voltage evaluation and the method in [21], a series of steps are carried out to replicate existing industry practices. Existing practices for conducting transient stability studies do not contain the modeling of protection systems. Therefore, transient stability studies are conducted using the base case dataset, which does not include the distance relays. The transient stability results are used by these two approaches, the minimum voltage evaluation method and the method from [21], to determine appropriate OOS blocking schemes; Sections V-C-V-D present these results. Next, the protection systems and associated OOS blocking schemes are then modeled in transient stability analysis to determine if there are any relay mis-operations using these two approaches, the minimum voltage evaluation method and the projected relay trajectory method [21]. Note that the corresponding RAS of the described contingency (outage of COI interties) are modeled in all simulations, which includes the tripping of generators in the northwest, brake insertion at Chief Joseph, generator and pump load tripping in northern California, series capacitor bypassing in northern California, shunt reactor or capacitor insertion where needed, and the NE\SE Separation Scheme [31]. The NE\SE Separation Scheme initiates after the trip signal is received at Four Corners. In addition, all other RAS schemes in [31], which may be initiated as a result of relay mis-operation based on the system conditions, are modeled. More details are provided in Section V-C.

V. Numerical Results and Analysis

All transient stability studies are performed using PSLF. The minimum voltage evaluation method and the projected relay trajectory method [21] are programmed using MATLAB to locate the potential mis-operating relays. First, the application of the proposed method for OOS detection is described in Section V-A. Then, the impacts of the simultaneous outage of three COI ties are studied using the base case data in Section V-B. A transient stability study for the triple line outage of the COI is performed while modeling distance relays and OOS protection schemes in Sections V-C-V-D. In Section V-C, the OOS blocking is implemented based on the projected relay trajectory method [21]. The proposed minimum voltage evaluation method is tested in Section V-D.

A. Out-Of-Step Detection

The minimum voltage evaluation method determines whether a specific contingency would cause an unstable power swing. After conducting a transient stability study, the minimum voltage of each transmission line can be calculated using the proposed method. This minimum voltage magnitude can be used as an indicator of stability of the power swing. In this section, the outage of two COI ties is studied. This contingency causes a stable power swing, i.e., all generators swing together. The proposed method estimates the minimum voltage magnitude through all transmission lines in the system to be 0.43 pu. Performing a similar study for an unstable power swing, i.e., initiated by triple outages of the COI tie lines, the minimum voltage magnitude is observed to be 0 pu. Therefore, a voltage magnitude of 0 (or near to 0) in the power system (in the absence of a fault) indicates an unstable power swing.

B. System Behavior During COI Tie Lines Contingency

A transient stability study for the base case dataset considering the simultaneous outage of all three COI ties has been performed. The generators' rotor angles are shown in Fig. 2. As observed in Fig. 2, the generators are split into two separate groups. Some of the generators lose synchronism within their own group and continue to slip poles. For this operating condition and in response to the described contingency, the generators located in the northern part of the system accelerate in comparison to the generators located in the southern part of the system. Fig. 3 shows the accelerating and decelerating areas within the WECC system for this power swing.

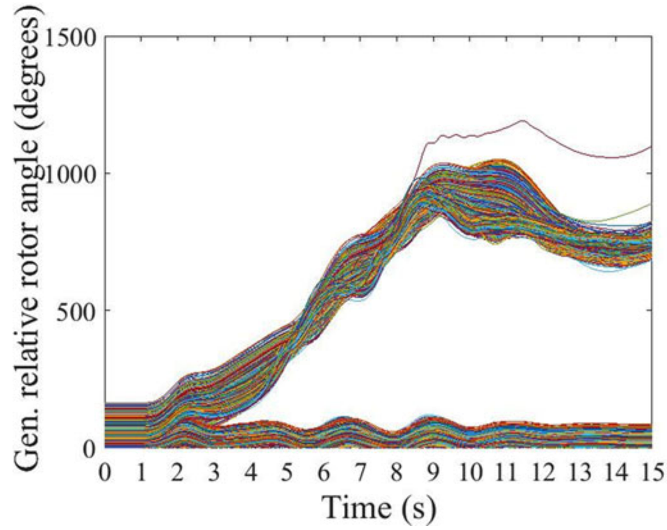


Fig. 2. Generator relative rotor angles for the base case.

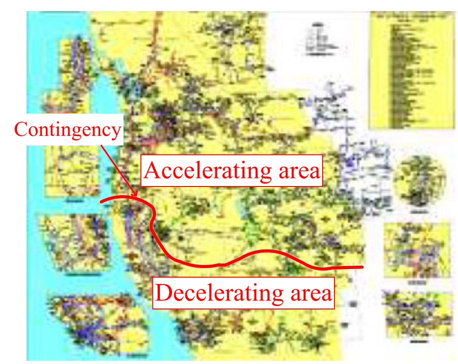


Fig. 3. Acceleration and deceleration areas for the WECC system.

C. Out-Of-Step Blocking Using the Projected Relay Trajectory Method [21]

In this section, the simultaneous outage of all three COI ties, which results in an OOS condition, is studied. An OOS protection scheme is designed and modeled for the WECC system. The OOS blocking scheme is located on the transmission lines along the electrical center found by the projected relay trajectory method [21]. A separation scheme based on the slow coherency controlled islanding scheme is implemented [25]. This separation scheme is compatible with the NE/SE separation and splits the system into two islands. This split is implemented by tripping 15 transmission lines of the desired cutset during the OOS condition, which is initiated by the outage on the COI tie lines. In order to observe the impact of relay mis-operation, a delayed separation scheme is implemented. The time sequence of the actions is shown in Fig. 4. Moreover, as mentioned in Section IV, the distance relays for all transmission lines at or above 100 kV are modeled.

When designing the OOS blocking functions based on the projected relay trajectory method [21], seven additional

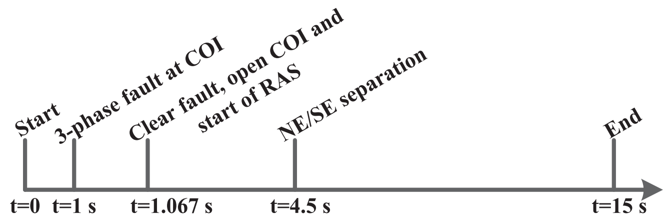


Fig. 4. Time sequence of the contingency under study.

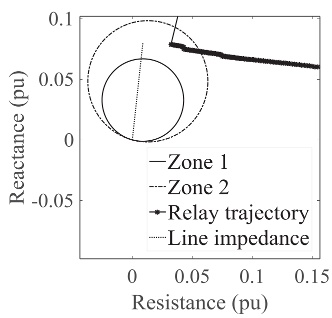


Fig. 5. Relay impedance trajectory for a mis-operating relay on a 345 kV transmission line.

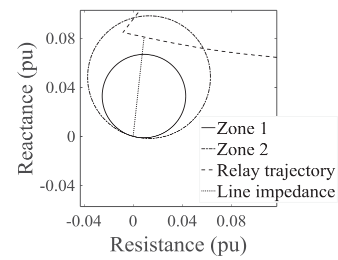


Fig. 6. Relay impedance trajectory for a mis-operating relay on a 345 kV transmission line without modeling any distance relay.

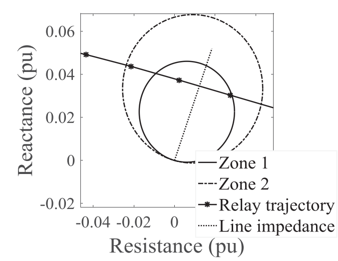


Fig. 7. Relay impedance trajectory for a mis-operating relay on a 115 kV transmission line.

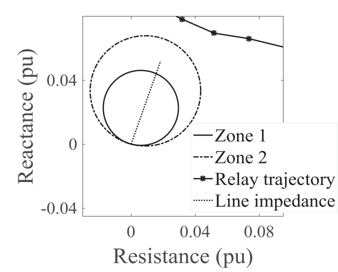


Fig. 8. Relay impedance trajectory for a mis-operating relay on a 115 kV transmission line without modeling any distance relay.

distance relays observe the relay impedance trajectory in their characteristic and mis-operate. These mis-operating relays protect three 345 kV, two 230 kV, and two 115 kV transmission lines. Mis-operation of one of the relays (namely Montrose-Hesperus 345 kV line) initiates a RAS action when the Nucla generators operate above 60 MW [31]: the Montrose-Nucla 115 kV line is automatically transfer tripped. This RAS action (TOT2A in [31]) is also modeled in this study. Please note that none of the other RAS actions, which are presented in [31], initiate during the performed study.

The relay impedance trajectory of one of the relays located on a 345 kV line is shown in Fig. 5. Zone 2 of this distance relay initiates tripping during this unstable power swing. The relay impedance trajectory enters and stays in the zone 2 characteristic of this relay for 0.316 s. This relay needs to be blocked from tripping. Blocking can be achieved using a dual blinder scheme. Unlike the projected relay trajectory method [21], the minimum voltage evaluation method is able to successfully detect this line as a necessary location to install OOS blocking function, such as a dual blinder scheme. All of the per unit (pu) values, which are specified in the Figures, are calculated using the corresponding system base values.

The relay trajectory in Fig. 5 is recorded while other distance relays have mis-operated and the network topology has been updated. As it was mentioned before, no distance relay is included while collecting the data input of the proposed method and the method of [21]. Therefore, the effects of mis-operation of relays are not captured in the initial study. In order to study the deficiency of the projected relay trajectory method [21], the relay trajectory should be studied without modeling the mis-operation of the other relays. Such a relay trajectory for the relay on the same 345 kV transmission line is shown in Fig. 6. While the relay impedance trajectory passed very close to the line impedance, it does not intersect the line impedance; therefore, the projected relay trajectory method [21] is not able to predict mis-operation of this distance relay. It can be concluded that simply blocking the relay on the lines where their relay impedance trajectory intersects the line impedance is not sufficient; the protective relays on the other transmission lines, which connect two oscillating groups of generators, may mis-operate. A more generic approach needs to be implemented in order to recognize all of the mis-operating relays. These mis-operating relays need to be equipped with OOS blocking functions to prevent a cascading blackout.

Similarly, the relay impedance trajectories of another mis-operating relay, which is located on a 115 kV line, are shown in Fig. 7 and Fig. 8. Fig. 7 shows this relay impedance characteristic while including the modeling of distance relays and the OOS blocking function using [21], which results in other relays mis-operating as well. While in this figure the relay impedance trajectory intersects the line impedance, this transmission line is not detected by the method in [21] for a potential relay mis-operation. Fig. 8 shows the impedance trajectory of the same relay without considering the effects of other relay mis-operations. As it can be seen in Fig. 8, the relay impedance trajectory does not intersect the line impedance, which is why the projected relay trajectory method [21] is not able to

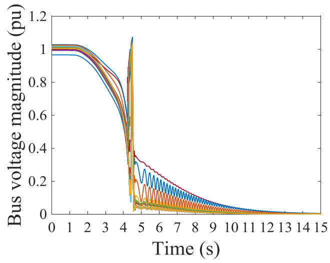


Fig. 9. Voltage magnitudes at 38 buses of an uncontrolled island.

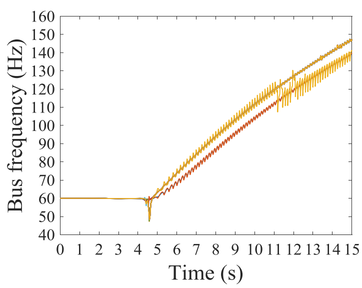


Fig. 10. Frequency at 38 buses of an uncontrolled island.

predict the mis-operation of this line. Therefore, the projected relay trajectory method [21] is sensitive to the network topology and is inaccurate without modeling protection systems when conducting the initial transient stability study. The relay impedance trajectory method [21] is dependent on measuring impedance, i.e., voltage and current. The current is highly dependent on the network topology. Unlike the method of [21], the minimum voltage evaluation method evaluates only voltage magnitude, which is less sensitive to the network topology. To this date, due to the complexity of integrating, maintaining, and updating protection system data with the transient stability data, these two different sets of data are usually handled separately. Therefore, a method with a high level of sensitivity to the protection system operation is less desirable. In addition, based on these results, it can be concluded that failing to detect relay mis-operation may cause additional relays to mis-operate.

As mentioned earlier in this Section, seven additional distance relays mis-operate if the OOS blocking scheme is designed based on the projected relay trajectory method [21]. While modeling TOT2A RAS and as a result of mis-operation of these seven relays, four additional uncontrolled islands are formed: a 38-bus island, an 11-bus island, a 9-bus island, and one individually isolated bus. The 38-bus uncontrolled island is formed due to the mis-operation of 4 distance relays along with tripping of 3 other transmission lines due to the NE/SE separation. The bus voltage magnitudes and frequencies of these 38 buses are shown in Fig. 9 and Fig. 10 respectively. Similarly, the bus voltage magnitudes and frequencies of the 11-bus island are shown in Fig. 11 and Fig. 12 respectively.

The frequency at these 11 buses does not show disruptive behavior. However, Fig. 9–Fig. 11 show the collapse of voltage and frequency in these uncontrolled islands. It can be concluded that improper design of OOS blocking functions may lead to

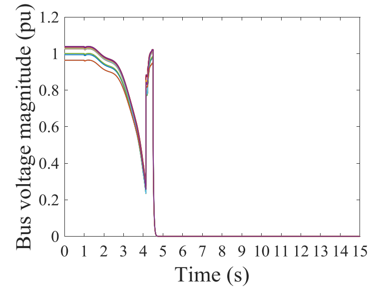


Fig. 11. Voltage magnitudes at 11 buses of an uncontrolled island.

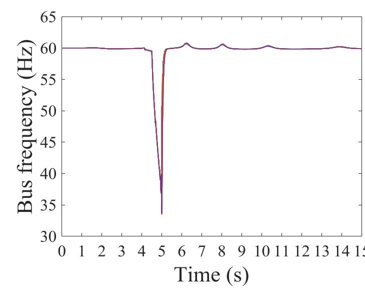


Fig. 12. Frequency at 11 buses of an uncontrolled island.

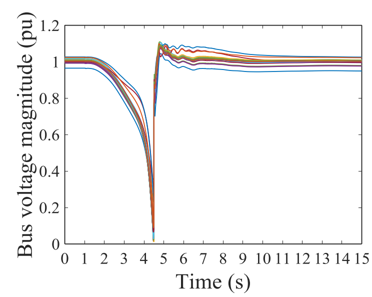
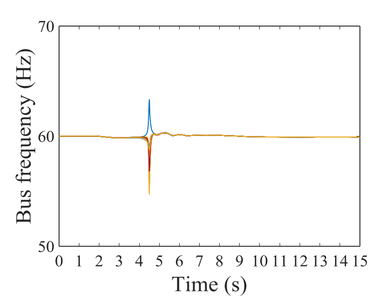


Fig. 13. Voltage magnitudes at 38 buses for controlled islanding case.



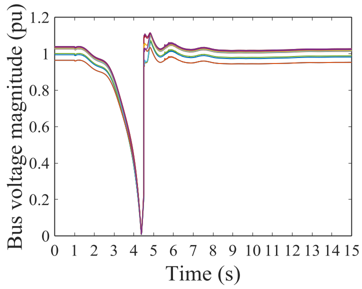


Fig. 15. Voltage magnitudes at 11 buses for controlled islanding case.

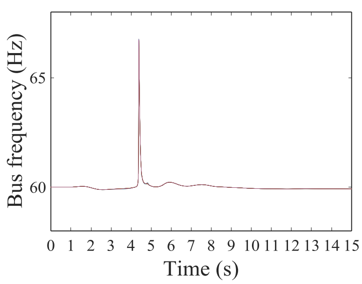


Fig. 16. Frequency at 11 buses for controlled islanding case.

islands, 3 uncontrolled islands are formed at roughly the same locations.

D. Controlled Islanding

The simulated contingency, implemented distance relays, OOS tripping and time sequence of the events are similar to Section V-C. However, the OOS blocking function is implemented based on the minimum voltage evaluation method. Using this proposed method, all of the potential mis-operating relays, including the seven relays that mis-operated using the projected relay trajectory method [21] in Section V-C, are successfully detected. By implementing the OOS blocking functions for these transmission lines along with the OOS tripping functions, the system is divided into two controlled islands (north and south islands). None of the distance relays will mis-operate; each of the two islands stay connected and synchronized. The voltage magnitudes and frequencies of the 38 buses and 11 buses, which constitute uncontrolled islands is Section V-C., are shown in Fig. 13–Fig. 16. These buses stay connected to the rest of the system and their voltage magnitudes and frequencies show non-oscillatory and stable behavior at the end of the time horizon of the study.

Reference [19] indicates that a voltage dip in the range of 0.5 to 0.6 pu can be used to identify a power swing. With a simple example, [19] explains that the buses that are close to the electrical center experience a voltage dip below 0.6 pu. The voltage profile for terminal buses of some of the transmission lines, which were recognized only by this proposed method (and not by the projected relay trajectory method [21]), are shown in Fig. 17. As shown in these figures, the voltage magnitudes at these buses are compatible to the explanation of [19]. Similarly, other transmission lines, which were detected to be along the

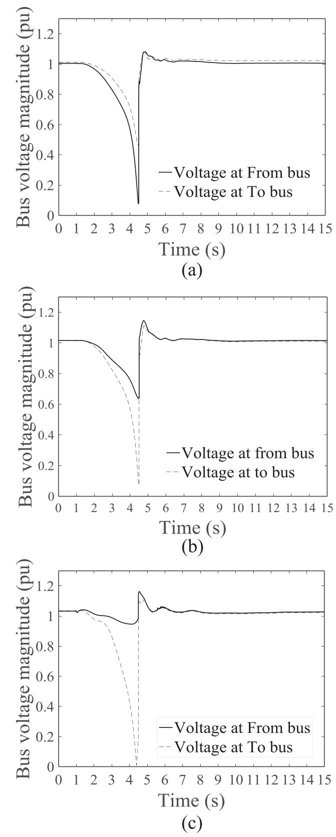


Fig. 17. Bus voltage magnitudes for buses connected to the potentially mis-operating relays with voltage level: (a) 115 kV, (b) 230 kV, and (c) 345 kV.

electrical center by the proposed method, satisfy this criterion. Note that there are cases where one bus voltage magnitude does not fall below 0.6 pu but still the line is along the electrical center. This confirms that the voltage dip screening method [19] requires more testing to be generalized.

VI. Conclusion

This paper proposes a method that is able to detect stable and unstable power swings within transient stability studies. Moreover, this method can be easily used in power system planning studies to identify the necessary locations for the OOS blocking function. The proposed method is based on evaluating the minimum voltage through each transmission line for each time interval of the transient stability study. The minimum voltage evaluation method is tested on data from the WECC. The proposed method is also compared to the projected relay trajectory method [21]. The results show that the proposed method is able to detect the potential mis-operating relays correctly. The proposed method augments and enhances the RAS associated with the COI outages. The OOS blocking scheme based on the proposed method, along with NE/SE separation scheme, provides a proper controlled islanding scheme. In addition, the results show that the proposed method is less sensitive to the network topology in comparison to prior approaches, e.g., [21]. It can be concluded that assessing voltage drop is a reliable method to detect electrical center. Blocking only the relays, which their relay impedance trajectories intersect the line impedance, is not sufficient and may result in uncontrolled islanding. Moreover, the voltage dip screening strategy, which is explained by NERC [19], confirms the accuracy of the proposed method. The conducted studies indicate that OOS relays have to be designed with great care. Failure in detecting all mis-operating relays may result in failure of the islanding scheme and may lead to a system-wide collapse. This paper identifies a solution for distance relay mis-operation during unstable power swings. This work can be expanded to identify mis-operation of various protection devices. Overall, a range of operating conditions and disturbances must be analyzed to design protection systems. Such cases require extensive testing via simulations to verify that the designed settings work effectively and protect the system following disturbances.

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