Pertanika J. Sci. & Technol. 31 (6): 2887 - 2913 (2023)

SCIENCE & TECHNOLOGY

Journal homepage: http://www.pertanika.upm.edu.my/

Review Article

Renewable Energy Impact on Distance Relay Power Swing Blocking and Fault Discrimination: A Review

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ABSTRACT

The annual increase of the global load demand has led to higher penetration of inverter-based renewable energy resources like wind farms and solar PV into the modern grid system. Distance relay may mal-operate by incorrectly estimating line impedance as fault during swing scenarios considering the infeed contributions impact from renewable sources. The negative impact of these integrated power electronics-based devices on the power swing blocking (PSB) and out-of-steps tripping (OST) functions of the distance relay characteristics has not been extensively discussed in previous studies. This study divulges a comprehensive review of the various PSB and OST schemes studies conducted to prevent relay mal-operation during power swing (PS) and symmetrical faults. Also, the large-scale renewable resources penetrations impact the PS characteristic and trip decision operation of the distance relay divulged. The mining of distance relay event records for hidden useful knowledge deployment for intelligent PSB and OST functions is the future research direction. Using the distance relay divulged knowledge will assist in reducing the failure rate level of PSB and OST function distance relaying

ARTICLE INFO

Article history:
Received: 25 October 2022
Accepted: 06 March 2023
Published: 03 October 2023

DOI: https://doi.org/10.47836/pjst.31.6.14

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ISSN: 0128-7680
e-ISSN: 2231-8526

schemes, hence improving the degree of reliability/dependability of the power system under different operating conditions.

Keywords: Distance relay, faults; photovoltaic, power swing, renewable resources, windfarm

INTRODUCTION

In a modern interconnected power system, all generators run in synchronism under steady-state conditions, which leads to a balanced operating condition between generated power, connected loads demand and constant rotor angle (Khadka et al., 2020). However, when the steady-state balance condition between the generator and the load impedance characteristic is disrupted with the emergence of network disturbances (like line switching, faults, large load addition and large load disconnection), then power system instability emerges (Višić et al., 2020). This network's unbalanced state causes a sudden change in the power system operating fundamental parameters like the current, voltage, frequency and power flow resulting from changes in the generator's rotor angle (Mooney & Fischer, 2006). The rotor angle oscillations of the synchronous generator result in a change in power flow, voltage and current signals of the power system. A power swing (PS) is a variation of power system fundamental parameters that oscillates power flow in the electrical networks (Hashemi & Sanaye-Pasand, 2018; Shair et al., 2021). The PS phenomenon affects the smooth operation of the distance relay, resulting in the relay mal-operation. Power system swings can be categorised as stable and unstable swings—the stable swing scenarios enable the recovery of the generators from the transient instability during power system disturbances (Yellajosula et al., 2019). An unstable or out-of-step power swing (OST) causes continuous oscillation in power flow due to continuous changes in the generator rotor angle, which leads to serious power flow oscillation (Mohapatra et al., 2017) and power system breakdown or equipment damage if not addressed (Nasab & Yaghobi, 2020).

Generally, distance relay operates by estimating the line impedance using phasor measurement of voltage, current and phase angle difference between the signals from the relay location under SteadyState (normal) and transient (fault) conditions for informed trip decision (Paladhi et al., 2022; Rao & Pradhan, 2017). The power flow oscillation during PS and fault disturbances are similar in features and function of variations in voltage and current signals, which impacts the estimated impedance at the distance relay location on the high voltage transmission line (Arumuga & Reddy, 2022). The estimated impedance under transient disturbances (like PS and faults) is compared with the earlier preset SteadyState threshold value used for informed trip decision protection characteristic settings (Taheri et al., 2020). The distance relay is expected to initiate a power swing blocking (PSB) function during stable PS to prevent unnecessary tripping of the healthy section of the line even when the estimated impedance is lower than the preset threshold value, forcing the impedance locus trajectory into the preset protection zones (O'Donovan et al., 2020). However, initiate a trip command to the associated breaker during faults with similar impedance trajectory movement to prevent damage to equipment installation (Alsyoufi & Hajjar, 2019). The PS occurrences may interrupt the protection relay operation when the impedance locus intrudes into the operating zones of the relay characteristics, thereby causing mal-operation of the relay tripping as if it is a fault condition occurrence. For a short circuit fault, the estimated impedance seen by the relay reduces suddenly during short circuit fault interruption and compels sudden movement of the impedance trajectory into the trip operating zones of the relay to initiate tripping of the faulty line section (Kang & Gokaraju, 2016). The distance relay false tripping during stable PS is not expected because it may result in the blackout isolation of healthy sections of the line, compromising the reliability of the power system due to unexpected power outages resulting from protection system compromise (Sorrentino et al., 2018).

The distance relay is not expected to initiate a trip command under stable PS conditions by activating the PSB function of the distance relay. Under unstable swing and symmetrical fault conditions, the distance relay is expected to initiate a coordinated trip command using the out-of-step trip (OST) function of the relay to prevent a serious negative impact on the power system total blackout (Arumuga & Reddy, 2022; Sorrentino et al., 2018). When there is a power system blackout resulting from the relay mal-operation, it takes a longer time to restore the system to its normal operating conditions and creates a huge financial burden on utility companies if not prevented (Elliott et al., 2021). Several studies on power swing blocking (PSB) and OST functions have been conducted and integrated into the relay to detect and prevent unwanted tripping operations of the relaying schemes to address these challenges (Desai & Makwana, 2022).

Integrating renewable energy generation sources into the modern power system grid, like wind farms and solar photovoltaic (PV), is conducted in line with the stipulated grid codes (Cabrera-Tobar et al., 2019; Zheng et al., 2017). These source integrations are facilitated by factors associated with the low global warming impact benefit due to the reduction in the emission levels of greenhouse gases (GHG) and sustainability of renewable natural sources with the ability to self-replenish. The higher penetrations of renewable sources into the conventional grid reduce the grid inertia (Dreidy et al., 2017; Ying et al., 2017) with the shutdown of more fossil-fired generation plants. However, this paradigm shift introduced some power system stability challenges affecting the smooth operation of power flow from the generating sources to the diverse connected load (Choudhury, 2020; Mararakanye & Bekker, 2019). Secondly, huge harmonic contents are introduced, affecting the power quality of the generated electrical power (Benjamin & Jain, 2018). The large harmonic contents injection from the integrated converters and cyclo-converters integration with the renewable sources (like windfarm and PV) negatively impacted the voltage and current signal waveforms used by the protective device for smooth operation (Choudhury, 2020; Mondal et al., 2020; Shafiullah et al., 2013). This integration impacted large disturbances like short circuit faults, generator disconnections, line switching, and addition and disconnection of large loads, which may compromise the power system stability (Bakar et al., 2010; Gunasegaran et al., 2015).

The increase in the renewable penetration in modern grid networks causes an increase in the swing frequency, voltage and current signal oscillations that adversely impact the time-based discrimination of faults from power swing (Buraimoh & Davidson, 2020). The distance relay's smooth operation is affected by the renewable power sources integration and PS scenarios, which are challenging in the accurate estimations of the line impedance by the distance relay (Ahmed et al., 2020; Mathe & Folly, 2017; Sorrentino et al., 2018). The wrong impedance estimation compromises the accurate trip decision-making that may result in the total system collapse or cascaded tripping of healthy sections of the networks if not addressed. The annual increase in the global load demand has led to higher penetration of inverter-based renewable energy resources into the modern grid system, as demonstrated in recent research (Sinsel et al., 2020). The negative impact of these integrated power electronics devices on the PS characteristics has not been extensively discussed. The higher renewable resource penetrations may adversely impact the trip decision operation of the distance relay if carefully investigated. The deployment of the distance relay assists in reducing the failure rate level and improving the degree of reliability/dependability of the power system. Distance relay may mal-operate by incorrectly estimating line impedance as fault during swing scenarios considering infeed contributions from renewable sources. The unwanted distance relay trip is not expected under stable swing conditions since the network can recover stability.

Given these challenges, this current study divulges a comprehensive review of the various power swing blocking (PSB) and OST schemes studies conducted to prevent relay mal-operation during swings and faults. Also, divulging the impact of high-scale penetration of the renewable energy sources on PS and faults characteristics impact the distance relay accurate trip decision. It is the motivation of this study as no earlier study was conducted in this direction. This review manuscript presents an up-to-date approach to addressing the impact of renewable integrated sources on PS generation and distance relay mal-operation under transient disturbance.

POWER SWING SCENARIOS AND CLASSIFICATION

Power swing is defined as the variation of power flow due to loss in synchronism of generators, which leads to a change in its SG rotor angle (Desai & Makwana, 2022). The large oscillations of the fundamental power system parameters between the sending and receiving ends affect the measured apparent impedance seen by the relay in a power system

(Arumuga & Reddy, 2022). The PS is classified based on the level of disturbances as stable and unstable power swings and also sub-classified based on the swing frequency as slow frequency (1–3 Hz) and fast frequency (4–7 Hz) (Brahma, 2007).

Power Swing Impact on Different Relays Operation

During PS, the load impedance locus oscillates between the initial position and the protection relay operating characteristic (zones) at the power oscillation frequency speed (Figure 1). The system impedance trajectory during the swing scenario may enter the protection trip zones of the relay characteristic (Rao & Ahmad, 2017). If the impedance locus stays in the protection zone beyond the preset operation time (T), a tripping operation is initiated even though no actual short-circuit fault occurred in the system (Torres et al., 2016). Such tripping operation is undesirable because no actual short circuit fault occurred, and tripping may lead to the isolation of healthy line sections and system instability. In this case, the protective relay should block tripping operation during the stable power swing since the oscillation from the rotor angle achieves a new stable operation point under a stable PS, as displayed with the new stable swing impedance locus.

In contrast, an unstable power swing scenario is a balanced three-phase symmetrical disturbance that causes undesired relay operation in a power system network (Camarillo-Peñaranda et al., 2020). It is due to a loss of synchronism as the rotor angle of the generator could not achieve a new equilibrium point, as displayed in Figure 1. Hence, it results in uncontrolled tripping of the protective relay, leading to cascade outages. The impact of a pole slipping from an unstable swing may damage the generator and associated turbines if not addressed. An unstable power swing is associated with low voltage, which may result in motor stalling, generator tripping and damage to connected voltage-sensitive loads. The protection remedy is to isolate the group of generators operating asynchronously to prevent

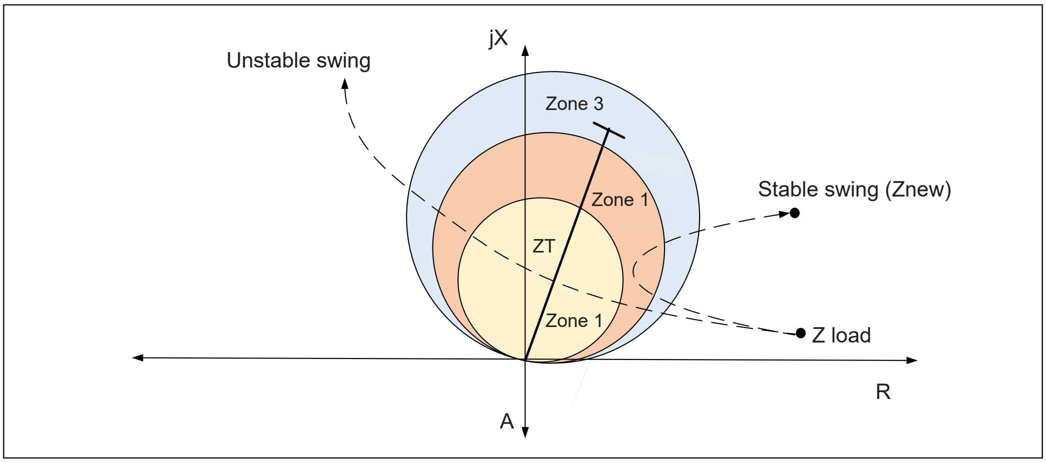


Figure 1. Stable and unstable swing locus trajectory movement

system equipment damage, power system shutdown and stability compromise (Sorrentino et al., 2018). Additional provision of reliable power system protection schemes that constantly monitor the changes in power flow, voltage, current and rotor angle to prevent cascaded outages is also required. The deployment of an OST protective relay function to discriminate between stable and unstable PS conditions is recommended (Gonzalez-Longatt et al., 2021).

The differential protective relay is unaffected by the PS condition and does not respond to unstable power swing conditions on power transmission lines. In contrast, the stability and unstable power swing conditions affect the distance relay, overcurrent relay, and directional relay operations characteristics, resulting in uncontrolled tripping of associated breakers (Moustakas et al., 2020). The current flowing through the transmission line is a function of the two-terminal voltage phase angle difference. The generator rotor angle is directly proportional to the voltage phase difference seen by the distance relay, which influences the line impedance estimated by the distance relay (Jedrzejczak et al., 2016). The distance relay is expected to detect and block its trip operation under stable swing scenarios to improve the power system's stability and reliability. The distance relay compared the estimated line impedance with the preset threshold value under stable conditions by measuring the instantaneous voltage, current and phase angle for fault impedance estimation (Dubey et al., 2016).

The literature has recorded several power system blackouts in a few countries due to protective relay mal-operations, as highlighted in Table 1.

Table 1
Distance relay maloperation causes a power system blackout

Ref	Country	Year	Impact
Corsi and Sabelli, 2004	Italy	2003	The Italian power grid was subjected to 3 hours of blackout that affected over 60 million residences with 180 GWh energy shortfalls.
Bakar et al., 2010	Malaysia	2003, 2005	Two undesirable distance relay mal-operation recorded by the Malaysia TNB power grid system blackout for five hours due to load encroachment.
Ratha, 2013	India	July 30 and 31, 2012	Two different large-scale blackouts affected 350 and 680 million Indians, involving 75% of the total states of India.
Bowen et al., 2018	Brazil	March 21, 2018	Large-scale national grid blackout in Brazil with 19760 MW load disconnected (25% of the country's total connected loads) and 85% of the states.

Power Swing Impact Analysis Impact on Distance Relay

Considering two sources, V is a high voltage powered transmission line with generated voltages V_A and V_B at both terminal and voltage drop measurement at the relay location (Figure 2). The system power flow equation in any transmission line is expressed in Equation 1.

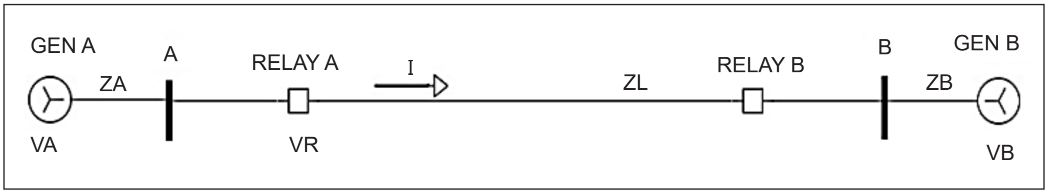


Figure 2. Two-source powered high voltage transmission line test system

$$P = \frac{V_s - V_r}{X} \text{Sin}\,\delta \quad (1)$$

Power swing is the variation of power flow as a result of synchronous generators' rotor angle changes, which may lead to loss of synchronism if it persists for too long. The current (I) flowing through the transmission line can be expressed mathematically in Equation 2.

$$I = \frac{V_A - V_B}{Z_A + Z_L + Z_B} \quad (2)$$

Where, P: power flow transfer on the transmission line; V_A: synchronous generator A source voltage; V_B: synchronous generator B source voltage; V_R: voltage drop measured at the relay location; X: reactance between the generator and the load; δ: rotor angle between the sending and receiving end voltage; Z_A: Impedance of generating source A; Z_B: Impedance of generating source B; Z_L: transmission line impedance; Z_T: total system impedance; and I: current flowing through the transmission line.

Substituting $Z_{T\,=}\ Z_A + Z_L + Z_B$ into Equation 2, simplified Equation 3

$$I = \frac{V_A - V_B}{Z_T} \quad (3)$$

Voltage drop at the relay location (V_R) is expressed in Equation 4.

$$V_R = V_A - I \times Z_A \quad (4)$$

The impedance seen by the relay is expressed in Equation 5 based on Ohms' law:

The impedance is seen by the distance relay, $Z_R = \dfrac{V_R}{I}$ (5)

Substituting Equation 3 and 4 in Equation 5 produced Equation 6.

$$Z_R = \frac{V_A - (I \times Z_A)}{I} = \frac{V_A}{I} - Z_A$$

$$Z_R = \left[\frac{V_A}{V_A - V_B} \times Z_T \right] - Z_A \tag{6}$$

If the voltage V_A at terminal A leads to the source voltage V_B at terminal B by angle δ, the ratio $V_A/V_B = n$. Substituting these parameters in Equation 6

$$Z_R = \left[\frac{\left[\frac{V_A}{V_B}\right]}{\left[\frac{V_A}{V_B}\right] - 1} \times Z_T \right] - Z_A$$

$$Z_R = \left[\frac{ne^{i\delta}}{ne^{i\delta} - 1} \times Z_T \right] - Z_A \tag{7}$$

Equation 7 represents the locus of the family of circles seen by the distance relay at the location with n as the parameter and δ as a variable. Where $n=V_A/V_B$

When n = 1, the power swing locust is a straight line perpendicular to the total line impedance Z_T at angle 90^0 with the locus illustrated in Figure 3.

For n > 1, the centre of the power swing locust lies on the expansion of the total line impedance. The distance of the terminal end B to the centre of the locus and the radius of the circle are in Equations 8 and 9, respectively, as displayed in Figure 3.

Distance of B to the centre of the circle, $D_{BC} = \dfrac{Z_T}{(n^2 - 1)}$ (8)

The radius of the circle, $r_{BC} = \dfrac{nZ_T}{n^2 - 1}$ (9)

For n < 1, a distance of A to the centre of the circle and the radius of the circle in Equations 10 and 11, respectively, are displayed in the locus of Figure 3.

Distance of A to the centre of the circle,

$$D_{AC} = \frac{Z_T}{\left(\frac{1}{n^2} - 1\right)} \tag{10}$$

The radius of the circle,

$$r_{AC} = \frac{\frac{1}{n} Z_T}{\left(\frac{1}{n^2} - 1\right)} \tag{11}$$

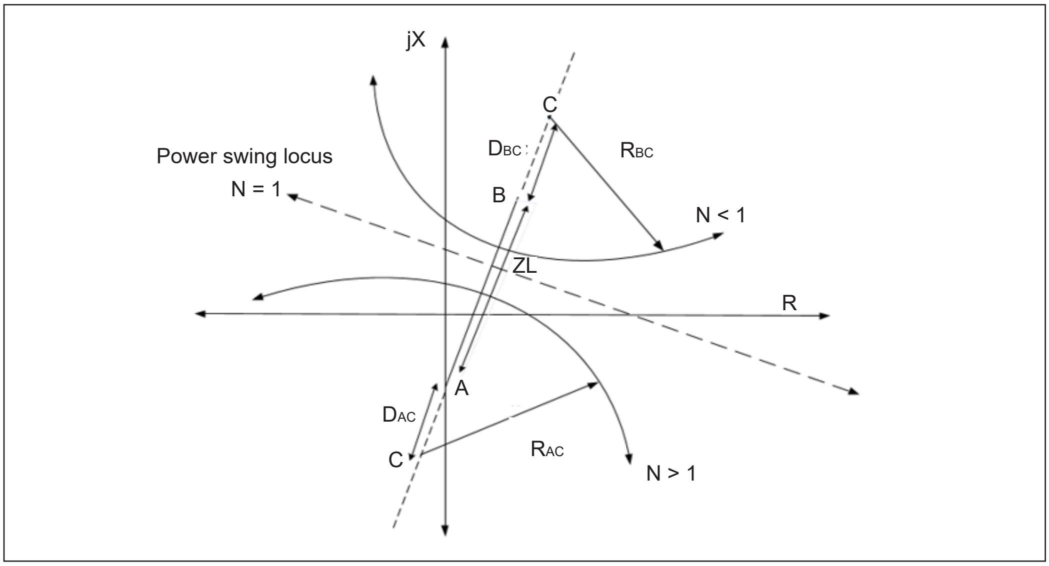


Figure 3. Power swing characteristic locus trajectory

Distance Relay Characteristic Under Power Swings

Power swing is typically a phase symmetrical event similar to a three-phase symmetrical fault but with longer oscillation time as compared to a short circuit fault with a fast movement response (Mahamedi, 2010). If the locust of the impedance seen by the distance relay during the PS scenario entered and stays in the trip zones of the distance relay R-X characteristics, the relay sees low estimated impedance as a fault and thereby initiates a tripping command. The time the PS locus travels through the relay characteristic and the trip zones determines whether the relay will trip the associated breakers. The current flowing through the transmission line depends on the phase difference between the two sources' terminal voltages. The system voltage phase difference is directly proportional to the generator's rotor angle, influencing the current flow through the relay on the transmission line (Bakar et al., 2010). The electrical current magnitude directly impacts the estimated impedance seen by the distance relay. Furthermore, the PS scenarios influence the performance and operation of the distance relay in a power system since the estimated impedance depends on the source and line impedance magnitudes for an informed decision.

A power swing scenario appears like a short circuit fault that changes its distance from the relay location. The greater the area occupied by the distance relay characteristic on the R-X diagram, the more vulnerable the relay mal-operation impact from the PS. The mho relay characteristic displayed the lowest impact of PS false tripping of the distance relay considering the smallest area coverage of PS impact locus on the relay characteristic plot on the R-X diagram of Figure 4. The impedance characteristics plot with a larger swing impedance locus coverage on the same R-X plot follows it. On the contrary, the reactance characteristic has the largest PS impact on the distance relay mal-operation, considering the largest area coverage of the swing locus on Figure 4 R-X diagram.

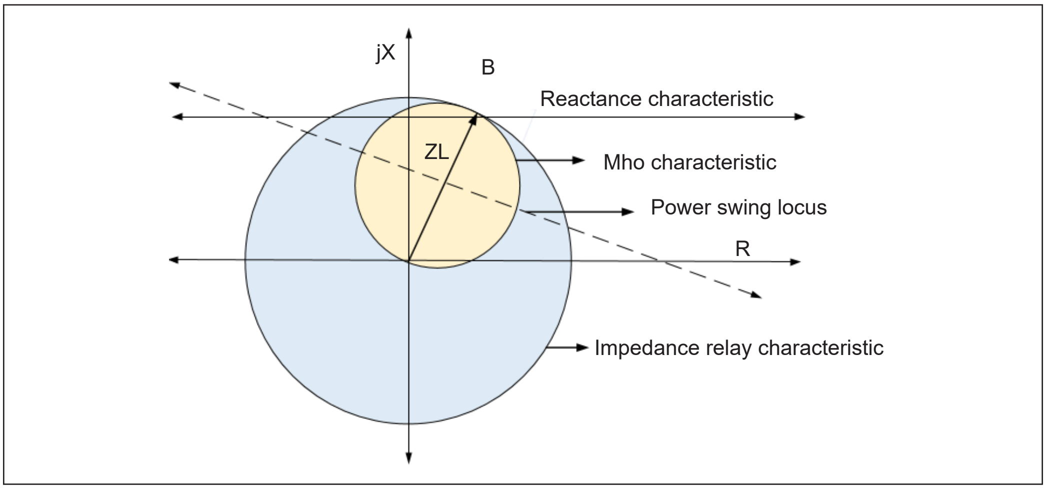


Figure 4. Power swing impact on distance relay characteristics

POWER SWING BLOCKING (PSB) AND OUT-STEP-TRIPPING (OST) TECHNIQUES

The distance relay has two operating functions, known as power swing blocking (PSB) and out-of-step tripping (OST), that mitigate the impact of PS on the power system (Desai & Makwana, 2021). The PSB discriminate the PS from short-circuit faults by blocking the relay from operation during the PS scenarios and unblocking the relay operation during fault. The PS appears like a fault but changes its location with respect to the relay location because the distance relay measures the impedance to the fault section of the line. The estimated impedance during PS is similar to that of a three-phase symmetrical short circuit fault in characteristics, which initiates the relay mal-operation trip command. The estimated impedance seen by the relay during PS is constantly changing based on the change in the distance of the PS impedance locus from the relay location. One of the primary functions of the distance relay is to discriminate between PS and short circuit faults effectively. The relay PSB function device prevents unwanted tripping of the system for enhanced reliability/dependability and unblocks the scheme during short circuit faults to prevent system damage. Several PSB scheme research studies have been conducted to address this limitation, as seen in the algorithm comparison performance study conducted in this direction (Khoradshadi-Zadeh, 2005). Mooney and Fischer (2006) presented a practical relay setting guideline for the conventional PSB functions in their study to aid smooth PSB implementation, and Nayak et al. (2010) divulged a comparative analysis between existing PSB scheme merits and limitations.

In contrast, the out-of-step tripping (OST) function of distance relay discriminates between stable and unstable PS (types) scenarios based on the swing impedance locus and initiates system partitioning in case of unstable swing occurrences (Holbach, 2006). The OST function prevents the tripping of the distance relay during stable swings. A stable swing is determined if the impedance locus does not enter the OST zone and the relay blocks from the trip operation (Tziouvaras & Hou, 2004). The function initiates a trip operation during an unstable swing if the impedance trajectory enters the OST operating zone.

This section highlights updates on the different PSB and OST protection schemes from literature deployed in preventing the distance relay mal-operation during the PS condition. Numerical relay manufacturers adopt some of these methods in the modern power system network protection scheme.

Rate of Change in Impedance Methods

It is a conventional approach mostly deployed by relay manufacturers that consider the rate of changes in the impedance estimation by the distance relay. The discrimination is based on the rate of change of the positive sequence component of the impedance locust ($\Delta Z_{app}/\Delta t$) during PS and fault scenarios, as illustrated in Rao et al. (2017). Gao and Wang (1991) established that the rate of change of impedance is gradual and slow in the case of PS compared to an instantaneous change in impedance under fault conditions. Under the normal operating conditions of the system, the load impedance Z_{load} is located outside the distance relay operation characteristic zones without tripping, as displayed in Figure 5.

On the contrary, the emergence of stable PS conditions generates a slow-moving impedance locus gradually into the relay operation characteristic trip zones, as illustrated

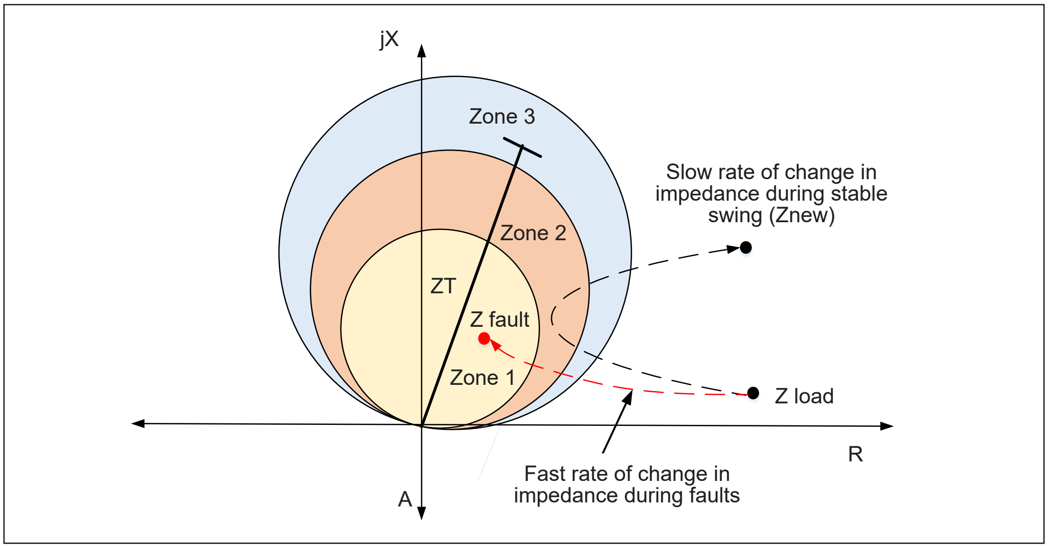
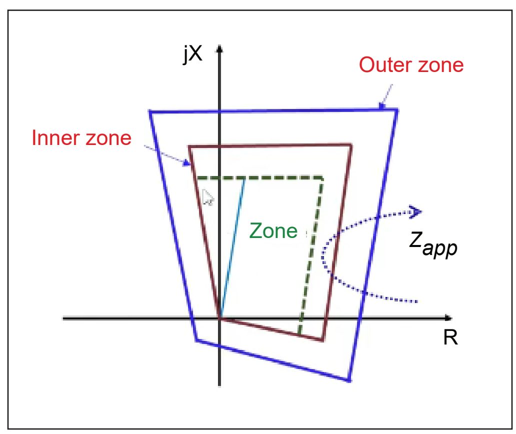


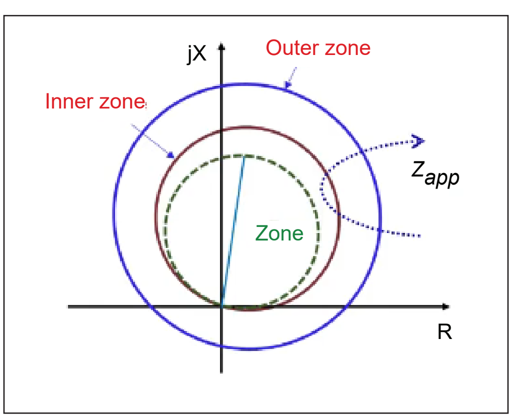
Figure 5. Rate of change in impedance locus in the distance relay

in Figure 5. Hence, the relay mal-operates due to a reduction in the estimated impedance seen by the relay inside the preset trip zones. Under a fault condition, the rate of change in impedance ($\Delta Z_{app}/\Delta t$) seen by the relay is also lower than the preset value but forces the impedance trajectory to transit instantaneously from the load point into the relay operating zones. The operating principle of such a scheme is based on identifying the difference between the time taken for the rate of change in impedance during PS and the fault condition for PSB or fault trip decision (Arumuga & Reddy, 2022).

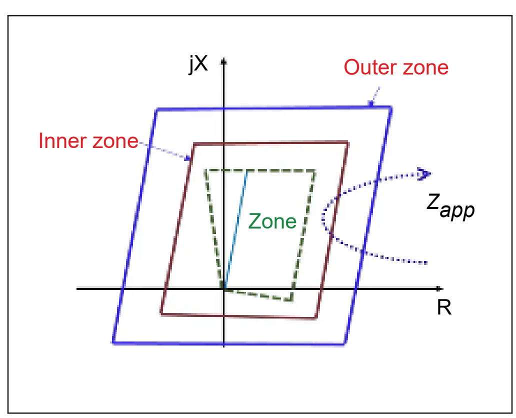
Concentric Characteristics Approach. In this approach, two sets of similar concentric characteristics are drawn with reference to the protection characteristic zone of interest displayed for polygon, mho and trapezoidal protection characteristics of distance relay on the R-X characteristics plots of Figure 6. The relay timer estimates the time taken for the estimated impedance locus to cross through the outer and inner concentric characteristics of the relay during PS and faults. The estimated time is then compared with the preset threshold time (T) of the relay (Rao et al., 2017). If the recorded duration for crossing the outer and inner concentric characteristic is greater than the preset time (T), then the relay classifies such disturbance as PS and then blocks the relay from the trip operation (PSB). In contrast, if the estimated time is shorter than the preset time (T), such a scenario is classified as a fault; the relay then unblocks to enable the tripping operation to the associated breaker (Zhu et al., 2004).



(a)



(b)



(c)

Figure 6. Distance relay concentric characteristic plots: (a) polygon; (b) mho; and (c) trapezoidal

Double Blinder Characteristics Approach. This approach addresses the existing operating limitations of the rate of change in the impedance and the concentric cycle approaches. The scheme draws two sets of inner and outer blinders parallel to the system line impedance after determining the protection zone of interest (mostly demonstrated for zone 3 of the distance relay) (Kang & Gokaraju, 2016). The double blinder scheme is mostly targeted at detecting out-of-step occurrences during PS to prevent relay mal-operation as the impedance locus of the PS is projected perpendicular at an angle of 90° to the total system impedance displayed in Figure 7.

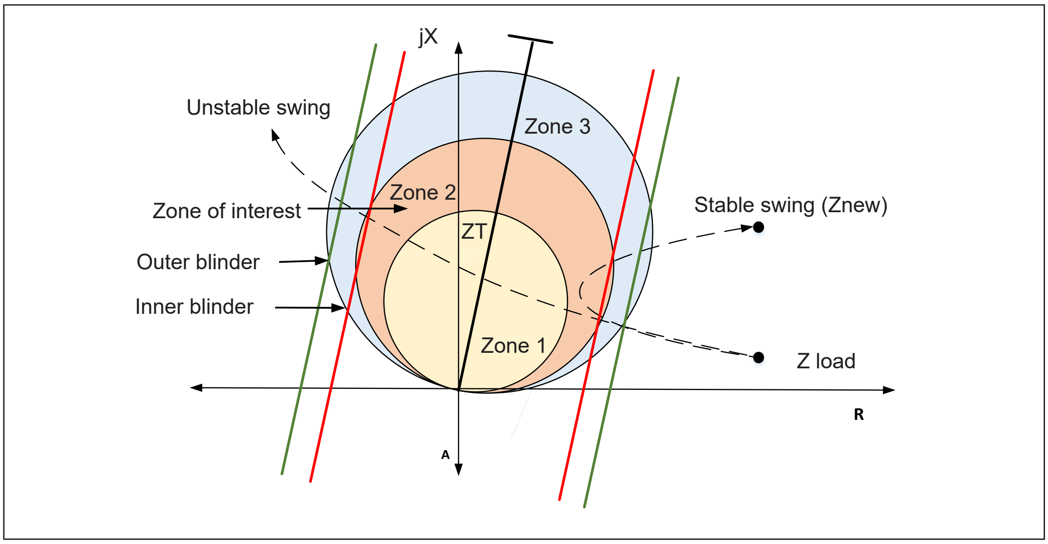


Figure 7. Double blinder scheme for distance relay

Change in Resistance Monitoring Method. A resistance monitoring approach is an alternative method introduced to address the challenges in complex grid analysis studies to prevent distance relay mal-operation during a PS scenario. Generally, the relay's resistance component of the measured impedance changes continuously during the PS scenario but changes instantaneously and remains at the new value during fault inception duration (Nayak et al., 2010).

Rate of Change in System Parameters Methods

These are alternative approaches associated with the rate of changes in three-phase power, voltage variation, frequency and current, as illustrated in this discussion. These PSB and OST schemes are developed using other power system network oscillating parameters associated with PS and fault disturbances. In a study conducted by Taheri et al. (2020), outside the rate of change in impedance deployed, the rate of change of the instantaneous frequency parameter for detection and discrimination of PSB and fault. Taheri and Razavi

(2018) adopted the RMS value of the current signal measurement for detecting PS and fault discrimination as executed. Other adopted similar schemes are the following:

(i) Power Variation Scheme
(ii) Power Swing Centre Voltage (Vcosθ) Based Scheme
(iii) Incremental Current Estimation Scheme
(iv) Rate of Change in Instantaneous Frequency

Signal Analysis Schemes

The spectrum analysis of parameter variation during power system disturbance can be observed through the extracted signal parameters for comprehensive analysis. Adopting analogue and digital signal analysis methods on the extracted power system parameters' signal or waveform is to hide knowledge in the analysed signal to detect power system feature responses under PS and fault disturbances. With the advent of digital signal analysis tools, which has encouraged various types of research on PS and fault detection, discrimination to address the impending negative impacts on the distance relay mal-operations (Khodaparast & Khederzadeh, 2014; Lazaro et al., 2018; Morais et al., 2015). The list of a few signal analyses approached adopted the time domain, frequency domain, and multiresolution analysis of power system signals from monitored system parameters based on literature are the following:

(i) Fourier transform Signal Analysis Scheme
(ii) Wavelet Transform Signal Analysis Scheme
(iii) S-Transformation Based Scheme

Artificial Intelligent-based Schemes

It is a pattern recognition approach for classifying PS and fault as adopted in modern protection relaying trip function development. The AI methods are deployed for PS and fault detection across conducted studies on the PSB and OST functions development. These have eliminated the rigour of complex impedance estimations and the adoption of operation parameter variation during PS disturbances studies. A few of the conducted research methods are highlighted as follows:

(i) Neural Network (ANN) Based Scheme
(ii) Support Vector Machine (SVM)
(iii) Adaptive neuro-fuzzy inference system (ANFIS)

RENEWABLE IMPACT ON DISTANCE RELAY PSB AND OST FUNCTIONS

The high penetration of renewable energy sources, mostly from PV and wind farms on the transmission network, is due to the high cost, rapid depletion and supply sustainability challenges of fossil fuel energy resources in the power generation system (Moustakas et al., 2020). These reasons have increased investment in these two renewable energy generation sources with a dramatic increase in the emergence of improved wind turbines, PV panels, batteries and converters development (Lawan et al., 2017). These renewable source penetrations significantly impact the power system disturbance and transient instability resulting from the power swing and faults. The large-scale penetration demands are due to the annual increase in load demand, which has also produced a new set of protection relay operation challenges (Shair et al., 2021). Inverter-based renewable sources from both windfarm and PV affect the PS characteristic, which may result in the mal-operation of the PSB and OST tripping function of the distance relay as reported (Haddadi et al., 2021; Haddadi et al., 2019).

Large-scale grid-connected PV system on the existing traditional power system is due to low maintenance and operation costs compared to the conventional fossil fuels power generation methods (Yang et al., 2010). The solar PV system is made up of solar panels and control power inverters for integration into distributed and transmission grid networks in compliance with the stipulated grid code (Buraimoh & Davidson, 2020; Zheng et al., 2017). In a comparative study on the impact of large-scale penetration of PV on PS generation, the result demonstrated fluctuation in voltage rise on the IEEE 9 bus system. The oscillation impacted the PS characteristic locus, and noticeable oscillations in active and reactive power were recorded before and during the PV penetrations (Yusoff & Abidin, 2013). The study does not account for the impact of the PV integration on the PSB function of the relay as the drawback. Another detailed study by Jia et al. (2017) considered the PV inverter penetrated grid performance impact on the PSB function of a relay under PS and fault conditions investigated to enhance trip characteristics. Furthermore, an adaptive protection scheme is presented to adjust the distance relay settings on a large-scale integrated PV. The voltage and current signal data from the PV source at the relay location are deployed for the impedance boundary setting of the relay to discriminate faults from swing (Mishra et al., 2020). The deployment of variation in the PS phase angle of the fault current for the adaptive relay impedance setting is presented (Liang et al., 2020).

Similarly, the large-scale penetration of wind farms in the modern electrical system has impacted the power system stability (Rampokanyo & Kamera, 2018). The wind farm is made up of several wind turbines that analyse the impact of the wind farm on the PS and distance relay mal-operation. Windfarms, unlike synchronous generators, are mostly designed from an asynchronous generator having the power angle (P-δ) replaced with the torque-speed (T–ω) curve (Samuelsson & Lindahl, 2005). Hence, having the rotor speed and rotating flux at the same speed (equal), the rotor angle is constant and easily obtained under stable conditions.

There is a need to divulge some factors that affect the PS generation level and their impact on the operation of the distance relay PSB and OST functions as divulged in this current study. Some of these factors are the types of generators, Power Grid Code [Fault-Ride-Through (FRT)], the control scheme used, and harmonic contents.

Types of Wind-turbine Generator

The wind turbine is classified into variable and fixed speeds based on the rotor design, which impacts differently on the PS and distance relay operations (Mathe & Folly, 2017). The fixed-speed wind turbine demonstrated fixed speed during operation, as observed in the Squirrel cage induction generator (SCIG) wind turbine (Sravanthi & Rani, 2014). The impact of the SCIG on the PS has been divulged in (Zare & Azad 2020); the Induction generator (IG) damped PS in the power system network and does not contribute to PS fluctuation resulting from the synchronous generator (SG) due to rotor angle stability (Abbasi & Yaghobi, 2017). The induction-based generator wind turbine performed better than a synchronous generator (Folly & Sheetekela, 2009; Slootweg & Kling, 2003). The comparative study conducted between SCIG and SG illustrates more oscillation from SG than the IG impact on the PSB and OST function of the distance relay. It is because the PS equation for the SG is defined by P–δ parameters, while that from IG is represented by T–ω in Muljadi et al. (2007).

On the contrary, the variable speed generator design is found in the double-feed induction generator (DFIG) wind turbine with rotor and stator windings connected to the power grid through an electronics converter (Ontiveros et al., 2010). This type of turbine increases the obtained energy from the wind and improves the power quality and mechanical stress reduction (Abdin & Xu, 2000). The study demonstrated low participation of the DFIG wind turbine in the PS generation in any integrated power system (Gautam et al., 2009). In a conducted study by Chowdhury et al. (2013), variable speed wind generators (DFIG) have demonstrated better performance with low swing frequency than the fixed speed (SCIG and synchronous generator-based turbine) under PS conditions. The DFIG windfarm integration separates the mechanical oscillation of the rotor from the electrical oscillation of the power system (Ying et al., 2017). Furthermore, the oscillation in the rotor speed of a fixed-speed wind turbine affects the variation in the active power delivery in the power system. Contrarily, the variable-speed wind turbine delivers the same magnitude of active power at different speeds by controlling the rotor voltage (Chung, 2013). Increasing wind farm penetration decreases the synchronous generator contributions and PS frequency reduction on the existing grid, enhancing system stability (Khoradshadi-Zadeh, 2005).

Power Grid Code

The grid codes that require PV and wind turbines to be permanently connected to the grid during fault and power system disturbances are based on the fault-ride-through (FRT) ability to impact the network stability (Cabrera-Tobar et al., 2019; He et al., 2016). The

FRT is achieved by investigating the PV and wind turbine inverter-based control system to determine the allowable current value that is permitted through the system to ensure system stability under low SG inertial in earlier conducted studies (Liu et al., 2017; Saleh et al., 2015; Tu et al., 2014; Yoosefian & Chabanloo, 2020).

Electrical Center Movement

An electrical centre is a point in a power system where the system voltage becomes zero during PS occurrences. Large-scale penetration of the wind farm changes the PS impedance directory seen by the relay due to the reduced grid inertia from the reduction in the number of SGs. Also, the solar PV penetration impacts the system voltage rise and the relay operation, as presented in Yan et al. (2011), but the impact on the system active power variation is not reported. The changes in the system parameters result in the estimation of the system impedance, leading to mal-operation of the PSB and OST function of the relay with only connected SGs. Hence, it leads to unexpected tripping of a healthy section of the line during a stable swing and may further affect the movement of the system's electrical centre deployed for optimal location setting of the PSB and OST function implementation (Verzosa, 2013). The large-scale wind farm penetration directly influences the movement of the electrical centre of the power system (Haddadi et al., 2019).

Control System/Harmonic Content

The renewable energy system operates with the installations of large-scale inverter-based control systems, which produce harmonic injection into the system's fundamental frequency. Harmonic content in a system can be determined by load characteristic study influenced by the harmonic contents in the sampled current signal waveform. Injected inter-harmonic frequencies from non-linear loads or power inverter systems create a harmonic distortion effect on the measured voltage and current waveforms seen at the relay location for impedance estimation in the trip decision (Tin et al., 2011; Wannous & Toman, 2018). The harmonic content in the current and voltage waveform seen by the relay adversely impacts the relay operation characteristic and also causes the thermoelectric effect of the system (Wannous & Toman, 2018). A simulation study considered harmonic analysis of the power electronics load on the distance relay characteristics to prevent mal-operation of the distance relay PSB and OST function in Saha et al. (2014). Given this adverse impact, a reliability study is conducted to analyse the harmonic contributions from non-linear connected load and their impact on the relay operation characteristic encroachment leading to mal-operation (Jedrzejczak et al., 2016). Wrong impedance estimation due to harmonic frequency contents causes the distance relay to overreach or underreach its operation characteristic within the protection zone coverage (Taheri & Sedighizadeh, 2020).

FUTURE RESEARCH PROSPECT

Modern digital numerical relays are microprocessor-based with the capability to monitor and record operation events data. An automated distance relay performance analysis has been carried out by manipulating the event report domiciled inside the numerical relay in building an Expert system (Othman et al., 2009; Othman et al., 2010; Othman et al., 2016). Event reporting is a standard feature in most microprocessor-based protective relays used as a framework for knowledge discovery in huge database (KDD) records to discover the relay's decision algorithm (prediction rules) and the association rule under different operating conditions and network topological changes. These huge databases contained useful hidden information that can be used in building expert system decision rules as deployed in Othman et al. (2011).

Data mining strategies have assisted in utilising the intelligent electronic devices (IEDs) recorded dataset and divulging the hidden knowledge in the recorded event report at a relay device level in Othman and Aris (2012). The data and useful information saved in these reports are valuable records for testing, measuring performance, analysing problems, and identifying deficiencies before resulting in future relay mal-operation. All necessary relay fault data must be collected and analysed for complete retrospective verification that all elements of the protection relay system characteristics were set properly and operated as anticipated under different operating conditions (normal, PS and faults). A simulation study based on fault discrimination under integrated renewable energy sources using data mining classification model development for relay trip decision-making is presented in Emmanue et al. (2019) and Emmanuel et al. (2020). None of these studies considered relay event data mining under PS scenarios as the major drawback.

Few identified data mining methods for PS detection and fault discrimination only considered developing a model based on an adaptive decision algorithm for distance relay PSB function performance on compensated and uncompensated power transmission systems (Dubey et al., 2016). The renewable integrated network impact was not considered in the study. Machine learning adoption for ensemble model development in fault classification during PS on non-renewable integrated lines is presented in Patil et al. (2019) and Swetapadma and Yadav (2016). No study has been reported on the data mining application on PSB and OST function model development. The data mining and deep learning approach will handle all impeding mathematical complexity in the PSB and OST function modelling of distance relay operation characteristics using hidden information in the historical event records. These unattempted approaches are the future frontier for the novel PSB and OST function model designs for distance relays.

CONCLUSION

This review has presented additional updated information relevant to earlier studies from the existing body of literature on the impact of renewable integration on the PS generation and distance relay PSB and OST operation characteristic compromise. The system operation was performed under different system topologies with reference to different types of generators (SG, SCIG and DFIG) with different impacts on PS and fault characteristics divulged. Integrating large-scale inverter-based renewable sources from both windfarm and solar PV arrays with interharmonic and subharmonic frequencies could pollute the system voltage and current seen by the distance relay. These polluted signals compromise distance relay operation due to overreach or underreach of the relay operation characteristic zones. The intelligent-based PSB and OST function modelling have been comprehensively divulged, considering a reduction in the mal-operation compromise merits over the conventional methods. Continuous research on PSB and OST functions is important to improve the PS and fault discrimination functions in different distance relay operating characteristics.

Data mining and deep learning methods seem promising because they present a realistic model development based on extracted real-life scenarios and data information with reduced mathematical rigour in complex number handling. Mining hidden knowledge embedded in the relay event records under different network topology changes in the relay operation characteristic is the next discovered frontier added to the existing body of knowledge through this review study.

ACKNOWLEDGEMENTS

This work was supported by the Geran Putra Berimpak - Universiti Putra Malaysia (GPB-UPM) under Grant UPM/800-3/3/1/GPB/2019/9671700.

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