Distance Protection Zone 3 Misoperation During System Wide Cascading Events: The Problem and a Survey of Solutions

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Abstract

Distance relay zone 3 misoperation has been responsible for major blackouts around the world. Zone 3 misoperation generally occurs under system wide cascading events such as the 2003 Northeastern US-Canada blackout or under stressed system conditions such as the 2015 Turkish blackout. This paper summarizes the problem and provides a survey on the research efforts made to increase distance relay security to prevent distance protection misoperation.

Keywords: Distance protection zone 3, blackouts, cascading events, misoperation, security

1. Introduction

With the deregulated market structure in the United States and Europe, grid operators are under more pressure to reap more profits of existing infrastructure due to increased competition. The grid is thus increasingly operated near the threshold of stability. Failure of the grid, better known as blackouts, carries catastrophic economic and societal sequences. Large blackouts tend to be due to either extreme natural events such as hurricanes or a series of events called cascading failures [31]. In this paper, we only focus on cascading events. Those events can be any of the following: line tripping, overloading of other lines, malfunctions of protection systems, power oscillations and voltage instability [101]. The reason that is considered in this paper is distance protection misoperation which is a contributing factor in seventy percent of all cascading events [10]. If not discovered and mitigated in an early stage, cascading events generally lead to a complete blackout. With today's society much dependence on electricity as a form of energy, preventing such damage is detrimental.

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Cascading failures are defined as “a sequence of dependent failures of individual components that successively weaken the power system” [4]. Since the 2003 US-Canada blackout, cascading events have drawn much attention in the industrial and academic community. Even though, the world has witnessed many blackouts prior to the 2003 blackout [31, 30, 48], the dramatic causes and consequences of the 2003 blackout have left industrial and academic community with the burden of exploring this phenomenon in more detail. To understand the severity of the 2003 blackout [48], it sufficient to say it had caused the loss of 62 GW which caused the lights to turn off in the houses of more than 51 million people in the eastern interconnection. Considering the many components and the bits and pieces involved, a domino effect of events evolved slowly (hours) or fast (seconds) according to the region causing a degradation of the integrity of the system leading ultimately to a complete blackout. Daunting efforts had to be exerted to gain more knowledge and understanding of the underlying phenomenon.

Relays by design act quickly to remove the fault from the system by disconnecting faulted lines. However, sometimes relays fail to perform such function which is considered a protection system misoperation. Of all protection system misoperations that lead to cascading events, this paper focuses exclusively on distance protection misoperation. A protection system misoperation is defined as “a failure to operate as intended for protection purposes” [64]. Various categories are given for misoperation in [64]. However, in this proposal the word misoperation will be used exclusively to mean only one of them, namely, an operation in which a protection system trips a healthy line when no fault exists. Notable cascading events [101, 69] begin with lines that were tripped due to actual faults. The tripping of those faulty line causes the current flowing in those lines to be redistributed to adjacent lines. Those lines may be overloaded and thus tripped incorrectly -protection misoperation- which will trigger a sequence of cascading events that might ultimately lead to a blackout. It should be noted that regardless of the initial triggering events- whether a fault or not- that cause cascading events, historically those cascading events were triggered under stressful system conditions [48, 40].

As mentioned in [101], one of the effective ways to prevent cascading events is to specify potential undesirable relay operations ahead of time. In this paper, we show that even though distance protection misoperation can be anticipated ahead of time, prevention of this misoperation is not possible with distance protection principle only because the distance protection principle is not able to be selective in some regions of its operation.

The paper is organized as follows: Section (2) provides a sample distance relay that is set according to NERC standards. Once this relay is set according to NERC directives, it will be explained in the same section that the relay may still misoperate. The remaining sections survey literature for possible solutions for the problem of distance protection zone 3 misoperation.

2. The Distance Protection Misoperation Problem

As can be seen from the examples in [20, 48] in which distance protection misoperation have been the main cause of the blackouts or in [1] in which distance protection misoperation have been created in the IEEE 118 bus system , a distance protection misoperation is characterized by a distance protection system seeing a heavy load on a line as a fault. This confusion arises from the fact that the impedance measured by the impedance protection system coincides with that of a fault. The reason for the heavy load can be due to load shifting after a fault as in the 2003 US-Canada blackout [48] or due to lines out of service for maintenance causing one line to carry substantial system power transfer as in the 2015 Turkish blackout Entoso-E [20] or due to any unforeseen reasons.

To illustrate that this confusion is not tied up with a certain system condition but rather inherent insecurity in the distance protection principle, the single line diagram shown in Figure 1 on page 4 is used to formulate the problem in general terms. It will be shown below that this insecurity always exists and the degraded system conditions only excite it; that is, for some regions in the impedance protection zone the protection system is not able to be selective between a fault and non-fault condition. Without the degraded system conditions, it is highly unlikely that a distance protection misoperates. Even though, degraded system conditions can be anticipated in the planning stage, the system operator will have nothing in hand to prevent a distance protection misoperation if distance protection is used alone. It is important to keep in mind that distance protection systems are set locally with the help of the impedance of adjacent lines without any information about the system load until the coordination study phase. In the coordination study phase, the transmission line owner checks all settings against applicable standards. This is explained in detail in [98]. In the following paragraphs, we will set up the relay settings first then discuss what happens in system wide cascading events.

In Figure 1 on page 4, the distance protection relay that will be studied is the relay at point A of line A-C. Line A-C is connected to three (3) lines, namely C-M, C-N and C-P. The number of lines connected to line A-C will not affect zone1 or zone 2 settings but will affect zone 3 settings. As will be seen below, the more lines connected to line A-C, tripping in Zone 3 becomes more insecure. To simplify the analysis, all lines are assumed to have the same impedance as well as the short circuit level. However, as will be explained below, this simplification does not affect the generality of the problem formulation. The impedance and the rating of the lines are taken from [79]. The setting of zone 1 is assumed to be 0.85 of the line impedance. Zone 2 is assumed to be 1.2 of the line impedance. However, some consideration is needed to set up the third zone. The third zone has to be set such that it can protect the longest adjacent line (assumed to be line C-P in this case) and to protect 20% beyond that line to provide backup to the remote circuit breakers . In case of a bolted three phase fault on line C-P and assuming that the short circuit contributions of all buses is given in Figure 1 on page 4 by I_{index} where *index* is the bus name (being M , N, A or P), the voltage at distance protection system at A can be written as given in equation (1).

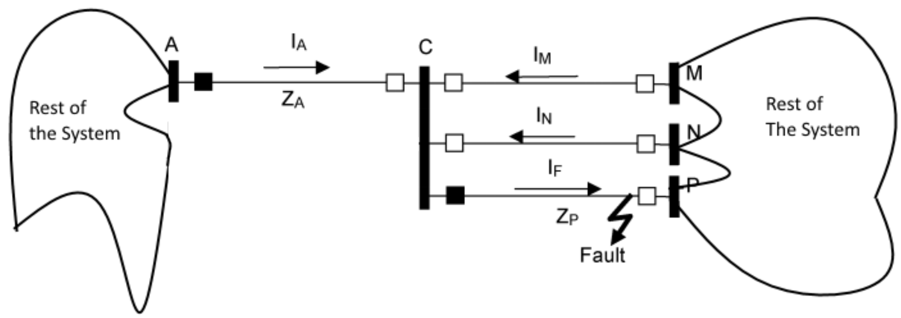

Figure 1: System Configuration for formulating the problem

$$V_A = I_A \times Z_A + Z_P \times (I_M + I_A + I_N) \tag{1}$$

The impedance that is seen by the relay A can then be written as in (2)

$$Z_R = \frac{V_A}{I_A} = Z_A + Z_P \left(1 + \frac{I_M + I_N}{I_A}\right) \tag{2}$$

(2) will only be applicable to faults on line C-P, if we need to include 20% for the line that is beyond bus P, then the impedance Z_P in (2) has be replaced by $1.2 \times Z_P$. Using the data in [79] and assuming all lines are identical as well as their short circuit contribution, then the setting of zone 3 will be $Z_A + 3.6 \times Z_P = 4.6 \times Z_A$. The three zones are plotted in Figure 2 on page 5. This ends setting up the relay locally.

After setting up the relay locally, engineers need to apply applicable standards and directives to their settings for compliance purposes. This step involves running worst case power flow in the summer peak case. The most notable directive is the load encroachment. The load encroachment zone is an area of the protection zone in which the load impedance " encroaches" –intrudes- upon the fault impedance. Load encroachment will obviously cause misoperation and should be removed from the zone of protection. To plot the load encroachment zone according to NERC directives [80, 79, 64], the load zone should include the point which corresponds to 150% line loading and 0.85 per unit voltage. Thus the load encroachment locus of the distance relay at A will consist of two parts. The first part will be an arc of circle of radius given in (3) which is given as arc **RIT** in Figure 1 on page 4. This arc **RIT** corresponds to the least impedance that the relay should not issue a trip command for. The load lines will be two lines making an angle of $\pm 30°$ with the x-axis ($\pm 30°$ represents the power factor of the line under worst case loading condition)

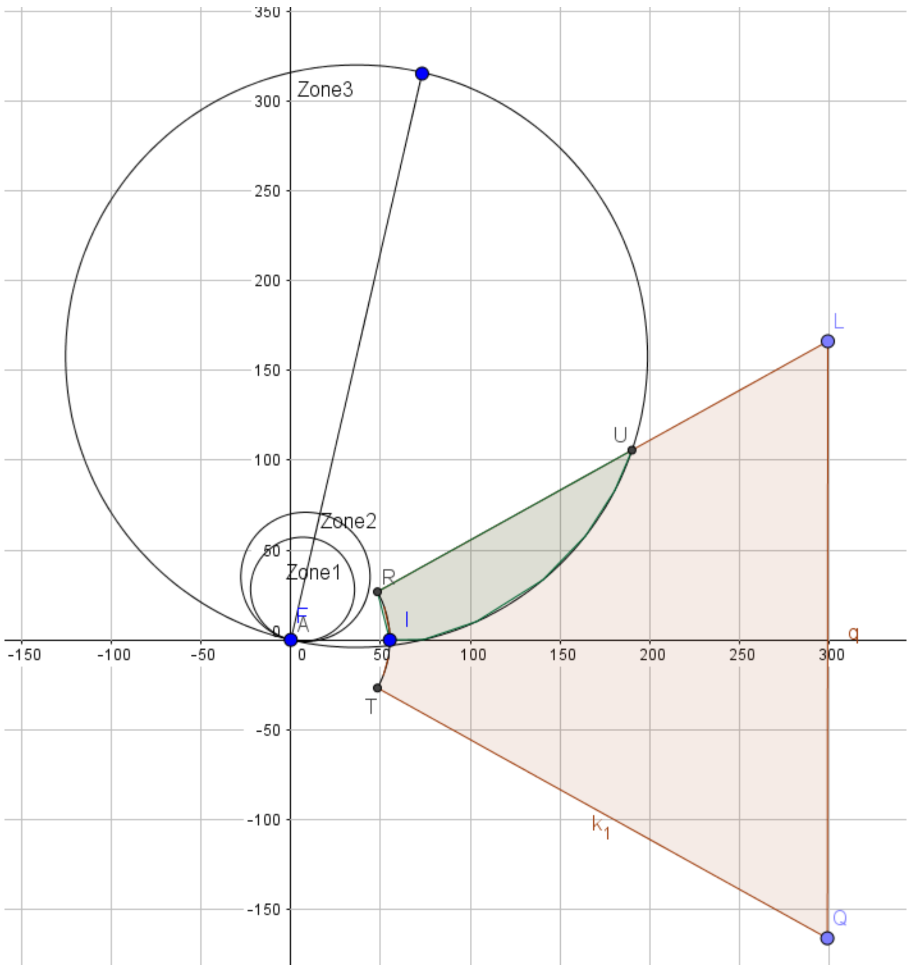

Figure 2: Distance protection characteristic

$$Z_{load} = \frac{V_A}{I_A} = \frac{\frac{345kV}{\sqrt{3}} \times 0.85}{1.5 \times 3000} = 57\Omega \tag{3}$$

The orange area **RLQT** is the load encroachment area. NERC directives [80, 79, 64] states that this load encroachment zone has to be removed from the relay operating zone. It can be seen at once that if the impedance seen by the relay lies within the green area **URI** then a relay may confuse this operating point for a fault since the point lies already in zone 3. This confusion arises if the fault resistance is high enough to cause the fault point to lie within the green area **URI**. In Figure 2 on page 5, this fault resistance ranges from 30Ω to 90Ω. The fault resistance can be obtained by measuring the distance between the diameter **AB** of zone 3 circle to point **R** and **U** of the green zone. If it is known in advance that the fault resistance calculated cannot be attained along the route of the transmission line, then the risk of misoperation is nonexistence and the green area can be removed from zone 3 without affecting the security or reliability of the distance protection system. However, fault resistance along the route of the transmission line is not known in advance. Also, one should note that solid state and electromagnetical relays can not be programmed, only microprocessor relays can. This really means that older relays will have to comply with NERC standards by disabling zone 3 altogether. It is shown in [32] that disabling zone 3 in some cases will force protection engineers to provide back up protection solutions to remote circuit breakers. This might involve a considerable cost. Additionally, not all countries around the world have standards as strict as NERC, so the green area **URI** exist in the zone of protection without regard from the settings engineer. Lastly, even if the relay complies with NERC directives, an impedance can still fall anywhere in zone 3, not only the green area **URI,** under stressed system conditions as Phadke and Horowitz pointed out in their paper [32]. This shows clearly the impedance protection is inherently insecure under stresses system conditions.

Attention is now given to the assumptions stated in the beginning. It was assumed that all lines have the same impedance and all of them are contributing equal currents to the fault. It can be seen at once from Figure 2 on page 5 that this assumption is not restricting the generality of the problem formulation. Because in any case the green area **URI** will exist due to the load profile under stressed conditions. Additionally, the fault contribution of the transmission lines will only affect the diameter **BA** of zone 3 which will only affect point **U**. Point **U** correspond to the max fault resistance. Stated differently, there will be always an overlap between the dynamic rating of the line and zone 3 and the short circuit levels from nearby lines will only affect the size of the overlap (area **URI)** not the overlap itself. Another variation of Figure 2 on page 5 is given explicitly in [68], however the one given here is more general. Lastly, to derive (1) and (2), a three phase fault has been assumed. Nevertheless, if a single line to ground fault occurs then the positive sequence impedance seen by the distance protection system will still be given by (2).

It should be apparent from the description above that the major issue that is faced by traditional impedance protection system is that the steady state impedance corresponding to a heavy load is coincident to the impedance under a fault on a remote line to which the distance protection system provides backup protection. It could be argued that impedance protection should be supervised by other steady state protection principles to enhance its selectivity, i.e, the ability to differentiate between a load and a fault current. However, other protection principles -such as over current protection- that can make the distinction between a load and a fault depend on the anticipated power flow for operation while the problem in hand is different. The confusion that is seen by the distance protection is because the power flow under system wide cascading failures changes considerably from the planned power flow. In other words, the load encroachment zone has to be set for system wide cascading scenarios that is not known in advance, which is close to impossible undertaking. One of the authors [32] states this fact as:

"The overwhelming thrust of the NERC rules and other instructions regarding the application of zone 3 elements has been to prevent its operation during emergency conditions. Although this is a desirable goal, it should be recognized that even with all the intelligence available to modern computer relays, the problem of distinguishing a fault from a heavy load in a relatively short time and using only the current and voltage signals available to the relay can not be solved in every single imaginable (and some unimaginable) power system scenarios".

The next few sections survey the literature for possible solutions for this type of distance relay misoperation.

3. Survey of Solutions

As shown above in the general formulation of the problem, a distance protection system may not be able to differentiate between a heavy line load and a fault if system is stressed enough to cause such confusion. Several approaches have been devised to solve the problem. The solutions proposed can be divided into two major categories:

- Detection and mitigation of zone 3 misoperation in the planning stage
- Detection and mitigation of cascading events in real time operations

In the planning stage, the power system operator has access to all relay settings and system anticipated conditions ahead of time. Using the forecasted load conditions and system settings, distance protection misoperation can be anticipated and thus blocked before occurrence.

In real time operations research path, new relaying principles as well as and changes to the local function of the distance relay have been proposed in literature which can be classified into two major categories:

- Communication assisted schemes
- Modifications to local distance protection

The following subsections details each of these research paths and categories.

3.1. Detection and mitigation of zone 3 misoperation in the planning stage

Most Independent System Operators (ISOs) today use N-1 criterion to judge whether the system is secure after the removal of one line in planning stage. However, given that distance protection system misoperation is not triggered until two or three lines go out of service [48, 40, 99], the distribution of power flow is hard to be taken into account in the planning stage as it would mean performing N-2 and N-3 contingency analysis which is expensive computationally. Thus, it is increasingly hard to assess protection system capability under the most stressful system conditions. However, the authors in [44, 43] provided an efficient method to study the sensitivity of zone 3 under various operating conditions.

Even though blackouts have hit North American and Europe and most of the world in the last century, the blackout of 2003 was determinantal in directing the scientific community into investigating the subject in detail, partly because the consequences its events had and how its events unfold. In the same year of 2003, [7] was published to pinpoint which lines can cause the system to drift to a blackout. The idea in [7] is that a probability function is defined that can be used in the planning stage to measure the failure probability of the system after certain number of lines are taken out of service sequentially. The system operator can issue a warning message in real time operations in case the scenarios identified in the planning stage occur during operations. The authors also showed that the probability is heavily dependent on the system dynamics and the operating point. The authors noted that the system behavior resemble the one with self-organized criticality, a concept that the authors explored in more detail in [8, 63]. The model along with its own parameters has been developed in [6, 16].

Since line heavy loading has been the reason for major blackouts Pourbeik et al. [77], many authors have devoted considerable effort to studying these types of blackouts. In [5], the authors define an entropy quantity that can be shown by simulations that the system is about the brink of collapse when a threshold is attained. A drawback of this approach is that it depends on the DC power flow whence the AC power flow should be used when the system is under stressed system conditions. Running an AC power flow in the planning stage requires more computational power. Mitigation of cascading events that lead to distance protection zone 3 misoperation in the planning stage is further explored in [95], where the emphasis is on early detection of cascading events. The authors in [95] proposed certain indices that can accurately gauge the severity of system conditions and the likelihood of cascades. An index that is used to monitor distance relays is also proposed. However, in practice only N-1 contingencies are studied and thus the severity index is chosen based on that case. However, if the system enters N-2 or N-3 contingency conditions, tuning of the "severity" threshold will be a difficult task computationally.

The authors in [72] proposes three solutions in the situation when the operator finds in the planning stage that it will be necessary to relieve a load from an overloaded line. The authors in [15] proposed that controlled islanding to be made to prevent overall system collapse. The authors in [15] train a decision tree with certain operating conditions to obtain the best islanding scheme possible. This process needs to be done under N-1 contingency analysis. A drawback of this method is the fact that the tree highly depends on the operating system conditions and the load pattern. A similar approach has been provided in [84] where a neural network is used instead of a decision tree.

Lastly, distance protection co-ordination has been done explored in [82, 83, 26, 70]. Due to the fact that distance protection co-ordination requires large amount of offline simulations and performing many contingency conditions, the authors in [97] introduced the idea of "distance of impact" to automate the distance protection co-ordination. However, the authors uses the super computer to perform their computations at the first stage. Once the distance of impact of each relay has been calculated, co-ordination of the distance relays becomes straight forward.

In summary, prevention of distance protection misoperation is the planning stage is a hard task. To be able to fully prevent distance protection misoperation, an N-x , where x is greater than 1, contingency analysis need to be done. Even though this could be done for small benchmark systems, the contingency analysis, under uncertain load and generation, is computationally impossible for large system consisting of thousands of buses.

3.2. Communication Assisted Schemes

Zone 3 misoperation can be completely eliminated by using distance protection with communication capabilities. Blocking and unblocking schemes have been known for a while and they have good performance Anderson [3]. From a theoretical perspective, if the local relay can communicate with other distance relays within its reach, then a very secure zone 3 scheme can be devised.

Conceptually, detection of fault generated traveling waves can provide a precise answer on whether a fault has occurred within the distance relay reach. Traveling waves (TWs) based fault detection and location has been proposed [17]. The moment of arrival of the TWs at both ends of the line are transmitted to the relays at both ends of the line and a decision is made based on the time used by the TWs to reach both ends. A modern realization of this idea has been given in [89, 90]. Fault generated waveforms varies with time and frequency [91], so neither pure time nor pure frequency methods are suitable for analyzing such transient signals. Wavelet transform (WT) has been the tool used recently to analyze the high frequency components [85, 34, 22, 23, 87, 76, 58] that occur after a fault using deterministic and probabilistic approaches. The approach given in [55] transforms the signals from the a-b-c frame into the modal form then applies the WT to the resulting voltage and current signals to locate the fault. The same approach can be used to detect faults. However, the paper uses the energy of the transformed signals which is likely to be confused for faults on adjacent lines. Since there seems to be no relation between the energy contained in the wavelets and the associated transient phenomena, as the energy depends on the width of the window frame, various pattern recognition approaches have been devised to attack this problem. In [36], a high frequency transient based protection using support vector machines is given where appropriate line traps are installed at the terminals of the line and support vector machines are used to classify internal and external faults based on the frequency spectrum of the current signals. An adaptive wavelets based on Bayesian linear discrimination is given in [75]. Only current measurement is used and is applied to windows shorter than one fourth of a cycle. In [100], a single ended algorithm for fault detection and classification of faults on double circuit lines have been proposed. The algorithm uses both voltages and currents at a single end of the line to detect and classify faults. A critic of TW fault detection methods can be found at [93].

Due to the fact that zone 3 of distance relays may not be able differentiate between heavy line load and an actual fault on the system, the authors in [46] proposed that a tool is to be installed at the control center , also known as Independent System Operator (ISO), to continuously supervise the operation of zone 3 relays. Even though this solution might be able to prevent all zone-3 misoperations, but it needs considerable cost to construct the communication infrastructure that is needed to transmit the data from all distance relays in the system to the system operator.

The 2003 blackouts pointed out the importance of having events along with the time they occurred. Investigators spent much of their time trying to match up the waveforms to reconstruct the sequence of events that led to the blackout. It was then apparent that to facilitate the transfer and comparison of waveforms, all samples need to have a time stamp for this purpose. Phasor Measurement Unit (PMU) or synchrophasor technology were then developed to address this shortcoming. By the time of 2003 blackout, state estimation was a very mature field, but PMUs opened new areas for the application of state estimation by reducing the time needed to do state estimation due to the wide spread deployment in the transmission network. A PMU measures the positive sequence voltage and current (magnitude and angles), which opens new areas for adaptive relaying and wide area control and protection [73]. In conventional protection schemes, the relay is only applied to the transmission line protected much like distance relaying. However, in a wide area protection scheme, a complete area can be protected using selected PMU devices without the need to apply PMUs to each single bus in the system.

With the introduction of PMUs, several fault detection and locations methods have been proposed [2, 37, 103, 59, 65, 86, 106, 45, 81, 60, 42]. The essential feature of all PMU detection schemes is that using the communication links to transfer data between the two ends of the lines, several conclusions can be drawn regarding whether the line is undergoing abnormal conditions. A salient feature of the PMU algorithm is the ability to monitor the status of the line and compute the parameters of the lines online in a very accurate way. In [2], PMUs at both ends of the line are used to locate fault in any series compensation lines without the need to know the model of the series compensation devices. The method estimates the line parameters from the PMU measurements without the need to know any information regarding the line in advance.

In [41] synchrophasors are proposed to supervise zone 3 operation which result in a very robust zone 3 distance protection system. However, to fully take advantage of the method, strategically located PMU have to exist in the system which add more complexity to the system. A multi agent system has been proposed in [49]. In Garlapati et al. [24], a non-intrusive agent to supervise zone 3 relay is proposed. In this scheme, agents installed at each relay are used to aid zone 3 relays. Since the agent in non-intrusive, it only aids the protection without enforcing a decision. Zone 3 is also adjusted adaptively in real time using agents disturbed across nearby substations as given in [27]. In [37], PMUs are used to detect and locate faults in symmetrical lines. Clarke transformation is used to estimate the line parameters in real time and fault detection is based on predefined metric. That calculated metric is the fault distance. If the fault distance is measured to be more than zero, then fault is declared and line is opened. In [103] the effect of arc on the method proposed has been examined. In [65] limited number of PMUs are used to determine the faulted line as well as the location of the fault. An optimization approach is used to locate a set of PMUs such that the observability is independent of the generator models. A backup protection zone is then constructed using the lines and buses between each PMU such that a line in not included in two regions. The sum of zero and positive sequence currents are used as discriminant for fault detection and location. In [19], a backup wide area protection scheme is proposed. In this scheme, the absolute difference of the bus angles and currents are used to detect the fault. The minimum voltage magnitude establishes the closest bus to the fault and the maximum current angle difference between the buses establishes the faulted lines. However, for the method to work, the minimum voltage threshold has to be established. It is shown in the paper that a voltage threshold less than 0.95 means that there is a fault on a system. This immediately points out that in case of voltage instability conditions, the method can operate erroneously. In [9], an adaptive method to protect parallel transmissions line is proposed. The method uses both current and voltages from both ends of the line to locate and detect faults. A fault distance index is first defined. This fault distance index uses samples of voltages and currents at both ends which are substituted in this fault index. If the fault index deviates from zero, then the fault is declared. In [29], another wide area protection scheme is proposed. The measured voltage and current of one terminal of the line are used to estimate the voltages at the other end. If an internal fault on the line being monitored exists, then the estimated value will be different form the measured value at that bus. This discrepancy causes the fault to be detected. In [61], a wide area fault detection method on series compensated lines are proposed. The closest bus to the fault is selected based on a predetermined magnitude threshold in the same way in [19]. Then the cosine of the angle between the sequence voltages and currents are then used to establish a criterion to detect and locate the faulted line. The authors in [47, 102] use PMUs, that are in place as part of a wide area protection scheme, to detect the power flow transfer due to the removal of faulted line from service. Based on that detection zone 3 is adaptively adjusted to prevent misoperation.

In summary, even though PMUs did not find wide acceptance in the industry for transmission line protection due to the high communication bandwidth [106] requirements of the communication links as well cybersecurity risks [13], PMU assisted wide area measurement and protection schemes have been proved to be very useful in the industry for implementing special protection schemes. A survey [54] in the industry show that all ISO and utilities use one type or another of WAMPs systems. Additionally, an optimization problem has to be set up to strategically locate PMUs. The optimization problem is generally formulated to include N-1 contingency conditions and when the system suffers from the loss of more than one element, the power system may not be observable anymore.

3.3. Modifications to Local Distance Protection

Augmenting zone 3 distance protection with more elaborate logic has been proposed in literature. Local measurements are used in [62] to assist zone-3 tripping. The DC decaying component and the load angle are used to determine whether a fault has occurred within the reach of local distance relay. The drawback of this method is that the fault must have significant decaying DC component which makes it challenging for certain fault incipient angles and transmission line lengths. Additionally, the paper assumes the angle between the current and the voltage at the relay to be more than 50 degrees as a fault indicator. However, it has been pointed out in [32] that under stressed system conditions the angle may indeed exceed that thresholds with no fault on the system. In [38] the rate of change of voltage is used as a trip restraint to prevent distance protection misoperation in the real time. However, for the trip command to be safe, large amount of offline simulations need to be carried out to know the worst case rate of change of voltage. Additionally, given that zone 3 are activated within 90 cycles, changes to zone 3 time delay may be needed to fully detect the zone 3 misoperation. This in turn means that checking coordination with nearby distance protection systems need to be done as well. Since it is hard to distinguish between evolving pre-blackout event and short circuit conditions using magnitude of voltage, the rate of change of current as well has been used along with the rate of voltage as trip restraint in [92]. The authors in [21] gives an algorithm for distance protection using wavelets. The algorithm is wavelet counterpart of the DFT (discrete Fourier transform) used in modern day distance relays. However, the paper does not point out how his algorithm will prevent distance protection misoperation since after all it still uses impedance as an indicator for fault detection.

Single-ended traveling wave relaying principles were also proposed. Detection of fault traveling waves can provide an answer on whether the fault is within the reach of the distance protection or not. A traveling waves based protection technique using wavelets and principal component analysis is given in [35], where a principal component analysis is used to identify dominant patterns of the voltage and current signal which is preprocessed by wavelet transforms. The proposed algorithm uses the polarity, magnitude and time interval to propose discrimination criteria for protection. In [52, 51], Parks transformation is used to transform both traveling waves of voltages or currents at one end of the line. After that a rotation frame establishes whether the waveforms are due to a fault or not. The system is in steady state with no fault if the rotation frame measured is balanced and rotating with zero rotational speed to the predefined ABC frame. However, when a fault occurs, the measured rotation frame is different than the predefined ABC frame rotation causing the fault to be detected. In this method, it not quite possible to tell whether the fault is from the faulted line or due another line since the rotation is used a fault discriminant. A directional ultra-fast protection based on wavelets is given in [18]. The spectrum energy is introduced to represent the energy of the high frequency components of two defined quantities. These quantities are derived from the forward and traveling waves of the fault voltage and current.

The use of fault generated high frequency components has been also investigated in literature [78]. Such usage can give more a precise answer whether a fault has occurred within the distance protection reach thus making tripping in zone 3 more secure. In [88] three phase currents are used to detect and classify faults. A single stage DWT is performed with DB6 and the wavelets coefficients are then extracted for a windows of 0.25 seconds. The first coefficient to be extracted is then compared against a predetermined threshold which if exceeded a fault is declared. A draw back of this is the apparent confusion that will arise if the disturbance is not fault. In [28], time domain features as well as frequency domain features are both extracted for one quarter of a cycle to train a rough membership neural network. A drawback of this approach is the massive amount of preprocessing that is needed to detect and classify faults. In [50], Tsallis Entropy is used instead of the traditional Shannon entropy approach to detect and classify faults. It is shown in this paper that Tsallis Entropy gives better classification accuracy than traditionally entropy based methods. Additionally, it is shown that using Tsallis entropy makes it easier to select the threshold for fault detection.

Additionally, the use of artificial neural networks for fault classification and detection has been given in [11, 39, 71] where voltage and current samples are fed directly to the ANN for fault detection and classification on the protected line. In [39] samples of voltages and currents are used as a feature vector to train ANN. With the advent of wavelets, special wavelet transforms are applied to voltage and current waveforms before they are fed to the ANN for training [57, 107]. In [57] and [107], DWT is applied to voltage and current signals at a relay location resulting in series of details coefficients that are fed to the ANN for fault detection and type classification. In [94] and [56], DWT is applied to voltages and currents but instead of feeding the details coefficients to the ANN, the entropy of the signal is captured and fed instead to the ANN to make fault type classification between faults on the same transmission line. In [74], the energy of certain current levels and approximations is used to train a probabilistic classifier, and using this energy feature a decision is made whether a transient signal if due to a fault or non-fault condition on a line. An expert system based neural network is proposed in [12] where entropy database is used for fault detection and classification. Since the parameters of transmission lines in reality varies stochastically in a specific range, the authors in [14] studied the effect of this stochastic nature of line parameters in deep detail.

Various adaptive zone 3 settings are provided in [25, 96] where zone 3 reach is adjusted based on local information. In [104, 105], ANN has been used to predict the correct load blinder under various system conditions. The load blinder is then combined with the zone 3 settings to block any undesirable tripping. However, the effect of the system topology wasn't studied. It is foreseen that the inclusion for contingency analysis in ANN training will require large offline simulations. In [66, 67], the authors proposes a 4th protection zone for protection. The rate of change of the impedance once it enters that 4th zone and proceeds to zone 3 is calculated and a decision is made whether to issue a trip command based on that rate. Although, the approach is very promising, a fast evolving system instability could mislead the scheme. Lastly, the authors in [53] to identify power flow overload based on a complex phasor plane. The paper only differentiates between three phase faults and overloads. However, the method is not applicable in case an open phase fault occurs and causes asymmetrical power flow transfer. Additionally, the method is not applicable when three phase faults and system overload coexist.

In Summary, the use of high frequency fault generated transients seem to be the most promising area. However, in this class of solutions the following are observed:

- **All methods except the one in [74] uses voltages for classification. It is known that CVT attenuates all high frequencies beyond 200 Hz [33]effectively making the voltage signal unusable**
- **Transients on nearby lines are ignored which can mislead the schemes**
- **Transposition is a universal assumption even though it does not exist in real power systems**
- **Typical response time is 1/4th of a cycle which is the same as phasor estimation methods**
- **Reliability and security of the proposed schemes are rarely studied**

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