Exploring the Role of Fuzzy Logic in Fault Detection: Benefits and Limitations

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Abstract: *Ensuring uninterrupted electricity supply is a critical task for power system operators, necessitating accurate fault detection methodologies. This paper delves into the challenges surrounding fault detection and investigates the utility of fuzzy logic in overcoming these hurdles. Fuzzy logic has emerged as a potent tool due to its adeptness in managing uncertainty and modeling intricate relationships within fault detection systems. Highlighting its strengths, the paper emphasizes fuzzy logic's capacity to handle ambiguous data, adapt to dynamic conditions, and provide resilient detection amidst noisy environments. Moreover, it addresses inherent limitations of fuzzy logic and suggests potential strategies for mitigation, along with avenues for future research.*

Keywords: *Fault detection, power systems, fuzzy logic, uncertainty management, intricate relationships, resilient detection, limitations.*

I. INTRODUCTION

It is a challenging task for power system operators (PSO) to supply uninterrupted electric power to end-users. Although fault intrusion is beyond human control, it is essentially important to accurately detect, classify and locate the fault location [1-3]. Fault detection, classification and location finding methods in power transmission systems have been extensively studied. Efforts are under way develop an intelligent protection system that is able to detect, classify and locate faults accurately.

Advancements in signal processing techniques, artificial intelligence (AI) and machine learning (ML) have aided researchers in adopting a more comprehensive and dedicated approach in studies associated with conventional fault protection strategies [4]. Moreover, two established limitations of online fault detection mechanisms are being dealt with. The first limitation is the difficulty in obtaining the needed data. In order to gain information at different nodes/buses in the grids, intelligent electronic devices (IED) are installed.

Short circuit faults are more likely to appear in power systems (PS) than the series faults, break in the path of current [5]. Shunt faults result in catastrophes and leave hazardous effects on PS. Short circuit faults can be divided into symmetrical and asymmetrical faults and further classification is presented.

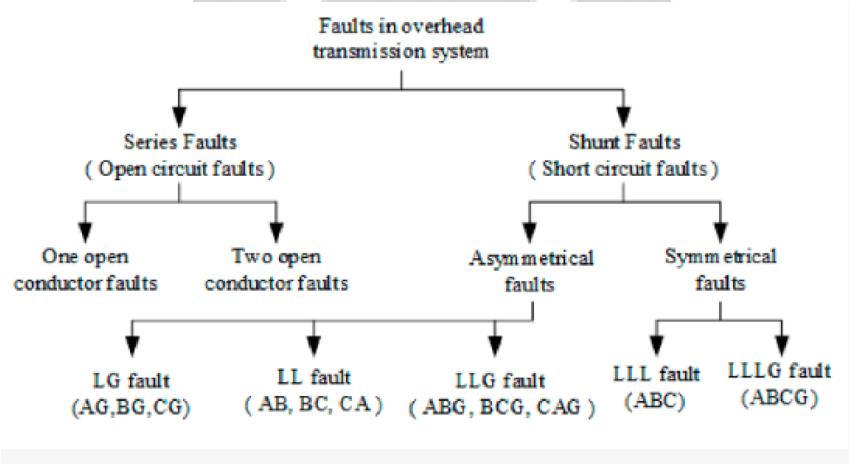

Fig. 1 Various types of faults that can occur within three-phase power transmission systems

Various types of faults can occur within three-phase power transmission systems, posing significant risks to the stability and reliability of the electrical grid. These faults include short circuits, where an unintended connection is created between conductors, potentially causing excessive current flow and equipment damage; open circuits, where one or more phases lose continuity, leading to voltage imbalances and operational disruptions; ground faults, involving unintended connections between a conductor and ground, which can result in insulation breakdown and pose safety hazards; and phase-to-phase faults, where two or more phases come into direct contact, causing overcurrent conditions and potential damage to transformers and other equipment. Efficient detection and mitigation strategies are essential to maintain system integrity and prevent cascading failures.

Fault diagnosis in power systems includes the detection of the time origin of failures with the identification and location of the event that occurred in these systems [6]. The proliferation of monitoring systems together with the exponential increase in computers processing data has stimulated the development of technologies dedicated to diagnosing electrical power system failures. These systems aim to assist decision-making both in real-time operation and in planning environments. Regulatory agencies in Brazil establish severe monetary penalties for agents in cases of transmission equipment unavailability and system restoration delays.

A. Detection and Determination of Faults

Overall, such detailed review is graded based on the current following three main components:

- Detection of fault.
- Determination of fault location (in case of faulty signal only)

Detection of fault: It's well recognized whenever at time of fault happens, the electrical signals such as (current, voltage, and power) produce important knowledge, that is also extracted which is used in algorithms for detection of faults. Appropriately, feature extraction method of the function was commonly used to obtain identifiable features of faulty signals as well as to decrease the dimension of input vector of data. Current techniques for detection the faults can also be classified according to the extraction methods used. While the key issue for many research scientists is to establish an effectiveness technique of extracting valuable features for issues in fault detection. Feature extraction methods can be categorized as follows in various domains:

- Time domain
- Frequency domain
- Time and frequency domain

Detection of fault built on Time domain strategies

Time domain strategies for the Empirical Mode Decomposition (EMD) techniques focused on fault detection have been provided as in [30-35]. This approach was commonly used for the study of nonlinear and non-stationary signals in power system studies. Reference [30] interacted with a research analysis of the general theory of the EMD methodology. Essentially, it is a sifting process where different oscillation modes are extracted from the initial signal. Hence these modes obtained are mono-component signal like limited frequency band. So the EMD is a technique that can be represented as intrinsic mode functions (IMF) to decompose the specific signal into the set of orthogonal elements. The IMF is characterized as just an oscillating function, reflecting the dynamics on various time-scale characteristics. This will also fulfill two conditions as follows:
The average value of the higher and lower envelopes is null at every point. It only has about one maximum in between zero crossing¬ points for a data set
Study of the time series estimated by the algorithm in [31] combined wavelet transform and empirical mode dependent on decomposition. With wavelet transform, the original time signal and IMF are decomposed. The results obtained from this study showed that this approach would decompose strongly non-stationary and non-linear signals into physical representative IMFs.
A new technique for detecting faults in power grids depending on the Intrinsic Time Decomposition (ITD) approach was introduced in the algorithm discussed in reference [35]. The ITD is a rapid time-domain signal processing method that doesn't require sensible tuning variables. And after that, the Singular Value Decomposition (SVD) methods used to decompose the Proper Rotation Components (PRCs) based ITD matrix of the currents obtained from the single-terminal of the secured phase.

Detection of fault built on frequency domain strategies

The frequency domain techniques may be commonly used to study transient signal, offering actual precise data on the frequency quality of the transient signals. it is common knowledge that, when a fault occurs, the frequency properties of current and voltage will change dramatically across varying frequency ranges [36]. Therefore, a variety of methods used to analyze frequency properties of time-domain signals. The commonly mathematical technique used is Discrete Fourier Transform (DFT) for digital systems that allows one to find the spectrum of time-domain signals. In addition, rapid execution of DFT could be completed utilizing Fast Fourier Transform (FFT) mechanism. FFT technique is used to convert discrete-time data sets into a discrete frequency representation [37]. At reference [38], the authors noticed that the efficiency of full-cycle (FCDFT) and half-cycle (HCDFT) techniques can be considered relatively similar towards each other. At reference [39] addressed with two techniques of removing harmonics and weakening DC elements using DFT strategies of full and half-cycle. In comparison, HCDFT velocity is faster than FCDFT. Hence, people uses HCDFT during fault occurrence to measure the symmetric component. Similarly, the necessity for HCDFT for fault determination was presented in [40, 41]. The detecting of fault for transmission line in [42] was indicated by evaluating phase voltage range using FFT method. References [43, 44] implemented FCDFT based approaches for purposes of data protection. The authors in [45] used the FFT method to convert the faulty signal from time to frequency domain. Reference [46] stated that DWT 's output for a single phase to ground fault case was higher than DFT, whereas DFT has strong results for certain kinds of fault. Instead, from the transient frequency band, traveling wave frequencies have been obtained to identify and locate various forms of faults. At reference [47] built DFT to obtain the severity of essential fault currents as features for process identification of failures. Reference [48] presented an improved DFT technique for real-time, time-domain interpolation-based applications.

Since the faults are a non-stationary transient phenomena, details about different spectral components which occurs at the moment of the happening of the fault seems to be very important. Seeing as FT just provides time-domain spectrum for signals and no data as to where these spectral components looks in duration, it is therefore not an appropriate method for identifying non-stationary signals [49].

Detection of fault built on Time and frequency domain strategies:

There are two techniques based on the Time and Frequency domain techniques: S-Transform and Discrete Wavelet Transform (DWT), which are regularly included in time and frequency domain analysis of the signal. Wavelet Transform is the supreme effective research tool used to evaluate faults of transmission line. Evaluated signals are being extracted from power systems that depend on frequency and time, that are defined as "chirp" signal (non-stationary signal). Wavelet Transform (WT) has been considered as an alternate to a Short Time Fourier Transform (STFT). The signal in STFT is subdivided into smaller sufficient parts, whereby sections of the signal could be considered to be stationary. Contrariwise, Wavelet MultiResolution Analysis (WMRA) remains a good choice of DWT toolkit, it splits signal into small and wide segments at high and low frequencies respectively. The WMRA methodology disintegrate original signal into components of low frequency (coefficients of approximation) as well as components of high frequency (coefficients of detail). DWT may extract those indexes from faulty signals, which have been used as discriminant feature for identifying faults. Therefore, many scientists need to select which basis wavelet (that selects the filter bank characteristics) when applying the WMRA strategy. To measure fault conditions, the high frequency components of currents are utilized to calculate fault criteria. Instead, such fault parameters are compared with threshold values for identifying faults in transmission line. A DWT-based method of detecting faults was introduced in [50]. Db4 was used as the mother wavelet to obtain their detail coefficients in the detection mode, using the fault detection technique. Through reference [51], the WMRA was described on a 220 KV transmission line for detection of faults. Reference [52] used db8 also as mother wavelet for identification of faults and for distinction between switching, shunt-faults, and lightning. Such a research also determined that the 3rd decomposed degree was the best appropriate degree of decomposition for identification and classification of faults. At reference [53], the DWT technique based on WMRA signal decomposition was utilized. Within that study, many mother wavelets have been assessed, and it has been promised that the db4 mother wavelet was chosen to that study.

Determination of fault location (in case of faulty signal only)

Single phase tripping, line to ground faults and auto-reclosure were widely used in long-line processes containing tripping the faulty phase. Classical phase selectors may endure certain areas of weakness owing to various operating systems and abnormal situations. Furthermore, an invention of wavelet transformation methods and the capability to concentrate on transients offers an efficient and consistent tool for precise and quick identification of phases. Even so, at reference [54], just the type including its fault (if LLG or LG) was defined as well as the trust component, although there was no specific determination of the faulted phase. In reference [55] the researcher introduced an innovative idea relying ANN and approach with in detection of faulty phases in smart grids. In reference [56], the faulty phase classification is done utilizing sharp transitions produced upon this faulty phase relying on WT. In reference [57], the researcher proposed a new faulty phases selection method dependent upon traveling wave as well as wavelet transformation.

II. LITERATURE REVIEW

(Pillai et al., 2019) [23] Despite the increasing global capacity of photovoltaic (PV) systems, the need for fault detection remains inadequately addressed, leaving systems vulnerable to potential hazards. This paper aims to fill this gap by reviewing and analyzing advanced fault detection techniques in PV systems, categorizing them based on detection approach and evaluating their effectiveness in detecting various types of faults. The study provides valuable insights for researchers seeking to enhance fault detection capabilities in PV systems.

(Chen et al., 2018) [24] Traditional current differential protection methods face challenges in accurately detecting faults in high-voltage transmission lines connected with large-scale inverter-interfaced generators (IIGs). This study proposes a sequence-component-based current differential protection scheme to address these challenges. The proposed scheme demonstrates improved sensitivity and reliability in discriminating between internal faults, external faults, and normal operating conditions, validated through simulation results.

(Santiago & Tavares, 2019) [25] This article delves into the phenomenon of severe temporary overvoltage (TOV) in very long transmission lines with half-wavelength properties, which are gaining popularity for bulk power transmission over extended distances. The study provides a detailed analysis of fault-resonance conditions and TOV, considering factors such as fault location, type, system parameters, and environmental variables. It offers insights into mitigating TOV risks in such transmission lines.

(Visacro et al., 2021) [26] Addressing the issue of high backflashover rates in transmission lines, this work proposes a methodology combining underbuilt wires, tower-footing resistance reduction, and partial phase protection with surge arresters to enhance lightning performance. The study evaluates the effectiveness of these measures through quantitative analysis, providing valuable guidance for improving the lightning resilience of transmission lines.

(Gusev & Dolin, 2018) [27] With the observed increase in short-circuit currents within electric power systems in Russia, particularly in regions with high power plant density, ensuring the thermal stability of overhead power transmission lines (OPTL) becomes crucial. This paper analyzes the thermal stability of OPTL and provides recommendations to address challenges associated with increased short-circuit currents.

(Mishra & Rout, 2017) [28] Introducing a novel micro-grid protection scheme based on Hilbert–Huang transform (HHT) and machine learning techniques, this study offers an innovative approach to fault classification in micro-grid systems. Through extensive simulations, the proposed scheme demonstrates effectiveness and reliability across various fault scenarios and micro-grid configurations.

(Tehrani & Levorato, 2020) [29] Focusing on fault detection in electric transmission lines within smart grid systems, this paper presents a data-driven approach leveraging deep learning techniques. By utilizing advanced metering devices and a combination of Long-Short Term Memory and Convolutional Neural Network architectures, the proposed method outperforms existing solutions in fault detection accuracy and interpretability.

III. ROLE OF FUZZY LOGIC IN FAULT DETECTION: ADVANTAGES AND LIMITATIONS

Fuzzy logic has emerged as a valuable tool in fault detection within modern power systems, offering a flexible and adaptive approach to handling uncertain and imprecise information. This section provides an overview of how fuzzy logic is applied in fault detection systems, highlighting its ability to model complex, nonlinear relationships and its suitability for capturing the inherent uncertainties present in power system operations.

A. Advantages of Fuzzy Logic in Fault Detection

Fuzzy logic offers several advantages when employed in fault detection systems within power grids. This subsection explores these advantages, including its ability to handle vague and ambiguous information effectively, its capacity to incorporate expert knowledge and linguistic variables into decision-making processes, and its flexibility in adapting to changing operating conditions and system dynamics. Additionally, the ability of fuzzy logic to provide robust fault detection even in the presence of noise and measurement inaccuracies is discussed.

- **Handling Uncertainty:** Fuzzy logic excels in handling uncertainty inherent in fault detection systems, as it can accommodate imprecise and incomplete information effectively.
- **Incorporating Expert Knowledge:** Fuzzy logic allows for the integration of expert knowledge and linguistic variables into fault detection processes, enabling the system to emulate human decision-making capabilities.
- **Flexibility and Adaptability:** Fuzzy logic-based fault detection systems are flexible and adaptive, capable of adjusting to changes in operating conditions and system dynamics without requiring extensive reprogramming.
- **Robustness to Noise:** Fuzzy logic exhibits robustness to noise and measurement inaccuracies, making it suitable for fault detection in real-world power systems where data may be corrupted or noisy.
- **Interpretability:** Fuzzy logic models are inherently interpretable, allowing operators and engineers to understand the reasoning behind fault detection decisions, which can aid in system diagnosis and troubleshooting.
- **Nonlinear Relationship Modeling:** Fuzzy logic can effectively model complex, nonlinear relationships between system variables, enabling more accurate fault detection in scenarios where traditional linear methods may be inadequate.
- **Adaptive Threshold Setting:** Fuzzy logic systems can dynamically adjust threshold values based on current system conditions, improving the reliability and accuracy of fault detection without manual intervention.
- **Integration with Other Techniques:** Fuzzy logic can be seamlessly integrated with other fault detection techniques, such as neural networks or genetic algorithms, to enhance overall system performance and reliability.
- **Suitability for Complex Systems:** Fuzzy logic is well-suited for fault detection in complex power systems with multiple interconnected components, where traditional rule-based approaches may struggle to capture the system's intricacies.
- **Reduced Engineering Effort:** Implementing fuzzy logic-based fault detection systems often requires less engineering effort compared to developing complex mathematical models or rule-based systems, leading to faster deployment and lower development costs.

B. Limitations of Fuzzy Logic in Fault Detection

While fuzzy logic offers numerous benefits, it also presents certain limitations that should be considered in the design and implementation of fault detection systems. This part of the review discusses these limitations, such as the complexity of fuzzy logic systems and the challenges associated with tuning membership functions and rulesets. Furthermore, the potential for computational overhead and increased processing time in large-scale power systems is addressed.

Understanding these limitations is crucial for effectively leveraging fuzzy logic in fault detection applications and mitigating its drawbacks.

C. Mitigation Strategies and Future Directions

To address the limitations of fuzzy logic in fault detection, this section explores potential mitigation strategies and areas for future research. This may include advancements in optimization techniques for fuzzy logic systems, integration with machine learning algorithms for improved performance, and development of hybrid approaches that combine fuzzy logic with other fault detection methodologies. By addressing these challenges and exploring new avenues for research, the role of fuzzy logic in fault detection within modern power systems can be further enhanced.

V. CONCLUSION

Fuzzy logic stands as a promising approach for fault detection in power systems, offering versatility and robustness. While it excels in managing uncertainty and modeling complex systems, challenges such as complexity and computational overhead persist. By addressing these challenges through strategic approaches and fostering further research, the efficacy of fuzzy logic in fault detection can be maximized, ensuring the reliability and efficiency of power system operations.

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