J. Electrical Systems 20-2s (2024): 323-331

[1]Rashmi S. Phasate

[2]Asha D. Shendge

[3]Jagdish G. Chaudhari

[4]Bhupendra Kumar

Empirical Evaluation of Microgrid Fault Identification Models from a Statistical Perspective

Abstract: - Microgrid fault identification models are developed via integration of extensive data collection, pre-processing of collected data, current & voltage segmentation, feature representation, identification of variant feature sets, their classification & post-processing operations. Existing models that perform microgrid fault identification are either highly complex, or cannot be applied for heterogeneous fault types. Moreover, these models also showcase large variance in terms of their qualitative & quantitative performance levels. Due to these issues, it is difficult for researchers to identify optimum models for their performance-specific deployment use cases. To overcome these issues, a detailed review of different microgrid fault detection & mitigation models in needed, which can evaluate their performance in terms of qualitative & quantitative parameters. Thus, this text initially discusses characteristics of some of the recently proposed microgrid fault detection models in terms of their functional nuances, application specific advantages, deployment specific limitations, and context-specific future research scopes. After referring this discussion, it was observed that linear models that incorporate pattern recognition are highly useful for fault pre-emption and mitigation purposes. This text also compares these models in terms of their accuracy of detection, delay needed for fault identification, computational complexity, deployment cost, and scalability metrics.

Keywords: Microgrid, Faults, Q-Learning, Bioinspired, Line, Ground, Bus

I. INTRODUCTION

Design of microgrid fault identification models is a multidomain task that involves collection of large-scale voltage-and-current datasets taken from different circuit points, their filtering & pre-processing for noise removal & signal enhancement, segmentation of context-specific signals, their feature representation, classification & post-processing operations. A typical fault detection model [1] that combines disturbance analysis, with actuation for identification of inner faults, bus faults, line faults & their respective zones is shown, wherein buses are opened based on different fault types. The model also incorporates fault mitigation techniques that assist in removal of these faults for real-time use cases. The datasets generated by the model are processed via pattern analysis layers, which assists in improving their fault mitigation and identification capabilities. This is done via deep learning models.

Similar models [2, 3, 4] are discussed in the next section of this text, where they are evaluated in terms of their functional nuances, application specific advantages, deployment specific limitations, and context-specific future research scopes. Based on this discussion, section 3 compares these models in terms of their accuracy of detection, delay needed for fault identification, computational complexity, deployment cost, and scalability metrics. Finally, this text is concluded with various performance specific observations about the discussed models, and also recommends methods that can be used to further optimize their real-time performance under multiple use cases.

---

[1]Research Scholar, EE, G H Raisoni University Amravati, India

rashmiphasate@gmail.com

[2]Asso. Prof. EE, G H Raisoni Institute of Engg. & Tech. Pune, India

asha.shendge@raisoni.net

[3]Asst. Prof. EE, Nagpur Institute of Technology, Nagpur, India

jagdishchaudhari260878@gmail.com

[4]Asst. Prof. EE, G H Raisoni Institute of Engg. & Tech. Nagpur, India

bhupendra.kumar@raisoni.net

II. LITERATURE REVIEW OF DIFFERENT MICROGRID FAULT DETECTION TECHNIQUES

A wide variety of models are proposed for identification of microgrid faults, and each of them have their own characteristics. Unbalanced situations and interference from overcurrent components are taken into consideration in [1] by a microgrid-based inverter failure detection technique. Observed signals are first converted into data triangles via sliding triangularization, which may then be utilized to extract multiscale trend characteristics and data jitter components from the data. The suggested Jitter Signature Processing (JSP) technique may simplify logical and mixed operations and minimize amplitude. The signed information may be used to pinpoint the fault's degree and location, decreases the turbulence and quantity of fault data. When classifying information intelligently, the echo state network is employed. According to [2], the failure characteristics of distributed generators using inverters are greatly influenced by the inverter control techniques. Due to their small contributions to fault current, isolated microgrids are difficult to secure. In this paper, the protection mechanism design for islanded MG faults is covered. Researchers investigate the phase inconsistencies between PSC-FCs at both ends of the fault line in the first stage, using various network topologies and fault severity levels. It compares the phases of a defect that develops both within and outside. To create the protection criteria, initial peak sign and time data from PSC-FCs between the two lines are employed. In simulations utilizing a 10-kV islanded MG model with shifting fault resistances and measurement noise, the recommended method may be used to accurately identify internal faults in looping and radial islanded MGs.

The adoption of LVDC [3] microgrids in the electrical system has increased quickly due to their many advantages. It is difficult to locate faults in the LVDC microgrid because of high fault currents and excessive fault-level variability. This research offers a method for differential protection for LVDC microgrids with DG and storage. Differential currentand its first derivative defects are found and categorized using decision tree (DT) and K-nearest neighbor (KNN) methods. The suggested protection system is put through its paces and found to be resilient to a range of failures and operational circumstances. The real-time functionality of the proposed system is tested and verified using MATLAB/SIMULINK and Typhoon HIL. According to the findings, the recommended approach can identify and categorize faults for LVDC microgrid protection with high accuracy and short reaction time.

Techniques for DC microgrid fault isolation and detection (FDI) need to be improved, claims [4]. In this study, system-modelling-based FDI is created to react to a variety of component failures. First, a malfunctioning multiterminal dc microgrid's state space is built. The FDI function based on H/H is then constructed. In order to accomplish fault isolation selectivity, the observer uses LMI optimization. The FDI approach can isolate dc microgrid problems in less a millisecond. Research in [5] offers a revolutionary short-circuit fault detection method for dc microgrids (LV-DCMG). The most prevalent dc power system problem, SC faults, have the potential to be quite harmful. Since capacitors make up the majority of the DCMG, filter capacitor current dynamics are utilized. The average capacitance current is used as a detection criterion in the suggested technique. Researchers advise a zonal dispersed network to benefit from the isolation attained via iteration. Digital simulations and DSP-based experiments have shown the viability of the suggested strategy. Using this method, defects with low and high impedance may be discovered.

Hybrid AC/DC microgrids are becoming more and more popular, but their protection schemes still have many issues, such as inconsistent fault current supply from DGs, difficulty differentiating between internal and external faults[6]. It is advised to use a hybrid AC/DC Microgrid Fault Localization (HFL) technique. A range of failure situations, such as internal/external faults, single/double line faults, and fault sites with variable fault resistance, have been investigated using PSCAD/EMTDC on AC and DC circuits. The findings show that the recommended approach can identify internal faults from outside events and estimate the fault's location even in noisy environments.

IIDGs, which have minimal fault current contributions, make microgrid protection more challenging. In the case of a short-circuit problem, the third harmonic voltage of the IIDG controller is suggested in this article as a novel approach to overcurrent protection. Regardless of the limiting fundamental fault current, harmonic voltages are produced during failures to form a new current flow layer in the harmonic domain [7]. The Canadian 9-bus and IEEE 33-bus test systems are used. The harmonic time-current-voltage-directional relay that has been presented does not need any communication in order to maintain proper protection coordination. According to [8] there are protection problems due to the increasing penetration of distributed energy in microgrid. In the system presented, the microgrid is protected using the Hilbert transform and data mining. First, Hilbert transformations of faulty signals are used to extract the fault characteristics then AdaBoost classifier assigns a fault to a certain category. The suggested approach uses Python to train and assess the data mining model, and MATLAB to simulate feature extractions on an IEC medium voltage microgrid. Using logistic regression with AdaBoost is more accurate than decision trees, SVMs, and random forests.

Research in [9] discussed a sliding mode control-based secondary voltage and frequency restoration approach for island microgrids. (MGs). This work addresses the general issue of frequency and voltage restoration of MGs. Through the use of Lyapunov analysis, researchers improves the system's dependability while reducing its vulnerability to failure. The work in [10] discusses dispersed rapid fault detection in a DC microgrid with several linked DGUs. Each DGU contains a local fault detector that is dependent on the state it is in right now and measurements gathered nearby to construct a network of fault detection. By employing the Linear Matrix Inequality Technique (LMIT), to solve multiobjective optimization issues, fault detector settings and the ideal number of performance indices may be found. The proposed method improves the convergence rate of the fault detection observer and enables faster fault detection in DC microgrid systems.

Switch fault and open-phase fault diagnostics for inverter failures may be complicated and lead to false warnings when sensor-generated single-phase or multiphase detection signals exhibit data loss and misleading fault characteristics. Virtual Mirrors (ViM) have been found to improve microgrid inverter fault diagnostics [11]. The first stage is to produce fake information in virtual mirrors. In order to get cross variables and related mirror cross variables from virtual mirrors and detected signals, which may be retrieved and normalized fault components from various angles, a cross comparison processing approach is employed. There is thus minimal data loss. Then, SCF and AF are computed. AF employs a steady-state fault degree expression to reduce false alarms. By examining fault detection data and mirror complementary location data, the fault is found. Results of experiments support the suggested approach. Work in [12] offers a sensor fault-resilient control technique for distributed energy resources (DERs) on isolated microgrids. The SMO and H output feedback controller provides robustness against false sensor readings for the DER components of an islanding microgrid. Sensor flaws might lead to incorrect measurements in this article. A fault-tolerant control approach is developed using the SMO's evaluation of sensor failures such that incorrect readings have no impact on the H output feedback control. To illustrate the value of this novel control strategy, test microgrid systems with distributed energy resources are employed. In [13], microgrid defects are recognized and categorized using an intelligence-based ensemble. This strategy is suggested due to the dynamic nature of microgrids and the reliance on traditional fault diagnosis and protection on fault current level or impedance. These techniques assist pupils in increasing accuracy by using group judgment. Data may be divided across classifiers to do this. It is called Brown boost. One of its key benefits is nonconvex optimization. Because of this, it may be used to noisy or incorrectly categorized real-world data sets and is resistant to overfitting. To lessen the susceptibility to noise, features from transient data were extracted using the Hilbert-Huang Transform (HHT). The findings of this research are supported by an IEC test microgrid that has different noise levels and synchronization delays. A suggested technique in [14] of fault location is offered for dc microgrid constant power loads (CPLs). A local CPL protection relay is developed based on the transient current and voltage of the main distribution line. In order to build a system that can locate both low and high-impedance issues, a fault resistance estimating process must be used. In Digilent Power Factory, offline digital time-domain simulations are used to assess and empirically show the efficacy of the suggested method. The results of modelling and actual testing, as well as comparisons with existing methods, demonstrate that the recommended technique can predict fault location and resistance with acceptable error margins.

If there are interruptions to the grid that are balanced or unbalanced, DA-AFM may be able to operate networked microgrids [15]. The DA-AFM project aims to: (1) enable NMs' quick fault ride-through capabilities; (2) reduce the overall contribution of faults by coordinating heterogeneous microgrids; and (3) leverage SDN for very robust AFM. In this instance, the issue is stated as an optimization issue that may include goals and restrictions for programmed fault management. It's crucial to use an SDN-enabled distributed and asynchronous surrogate Lagrangian relaxation in the DA-AFM system to reduce single points of failure, protect privacy, and end idle waiting (DA-SLR). The value of DA is shown through six case studies of NM microgrids. As per [16], DC microgrids are a promising future technology for electricity networks. An FDI approach for dc microgrids is presented in this article using second derivative current regularity (SDOC). In this study, the coherence between a single SDOC characteristic and a dc short-circuit failure is used for FDI. This method is more resistant to disruptions caused by sources. This FDI approach may benefit various microgrid topologies and converters.

Modern fault-resilient microgrids (MGs) need healthy phases during unbalanced short-circuits to increase system dependability. In this work, differential power-based selective phase tripping is used. Calculating differential power requires knowledge about the voltage and current at the line-end [17]. By identifying wrong phases, an MG may be made threshold-free using a power coefficient index (PCI). To evaluate the protection strategy, a grid-connected or islanding PSCAD/EMTDC simulated standard MG is employed. The effectiveness of the plan is also evaluated using the OPAL-RTDS RT platform. According to [18], Erroneous MG phases may be tripped fast and securely using the suggested approach. It is difficult to create inverter-based microgrid protection methods. Since inverters can only handle a small amount of fault current, standard overcurrent prevention is inappropriate for inverter-based microgrids. In this study, a new microgrid protection method based only on current polarity comparison is described. The suggested approach makes advantage of the pre- and post-fault current phase differences (PPFCPD). Using PSCAD/EMTDC, a microgrid with relay-based inverters might be modelled. The method shown here may be advantageous for microgrids that use inverter-based inverters.

Due to the characteristics of dc current, DCCBs are unable to immediately isolate and cut off fault current. The work in [19] presents a novel bidirectional DCCB with a microsecond reaction time based on Z-source topology. One connected inductor and a central tap configuration in the core component of the DCCB decrease bulk and cost. The suggested topology's switch-off procedure is examined using hardware circuit design approaches for line failure scenarios along with MATLAB simulations. According to [20], tiny electric power networks known as microgrids may be used for distributed generation and energy storage. In the case of a problem, static switch's duty is to open the circuit. This work employs a Taguchi-based ANN and multiresolution DWT analysis to recognize, categorize, and find errors (ANN). In order to train the ANN, three orthogonal Taguchi datasets—three-phase fault voltages, three-phase fault currents, and neutral fault currents—are compared. Incorrect phase and location are identified by ANN.

Bias and overcurrent might obstruct the microgrid inverter's ability to identify faults. This might lead to erroneous protection unit activation and false alarms. The work in [21] suggests a novel approach to extract fault characteristics from Data Curve Fold Lines (DCFL). Its capacity to detect errors or malfunctions is unaffected by asymmetrical interference. Second, it is advised to use an easy-to-understand, simple-to-remember, and straightforward-to-calculate trend encoding technique. By applying logical connection procedures, diagnoses are produced. The suggested algorithm sets are validated using comparisons and outcomes from experiments. The goal of the research in [22] is to identify and isolate faults in DC microgrids without turning them off. This research suggests a tailored security strategy using Local Measures (LocM) for LVdc networks and calculated criteria for all of the present sophisticated electronic devices. The solution shown here does not compromise information about a terminal's directionality. Its high resistance to failure and broad variety of fault sites were evaluated on LVdc test-beds. This approach is effective at detecting faults quickly.

Research by [23] emphasizes the challenge of locating defects in DC systems due to the absence of phasor measurements. The study recommends communication-based defense but acknowledges the risk of failure if the network collapses. To address this, it proposes a backup mechanism based on locally observed current signals and Derivative and Integral Current Characteristics (LCS DCC). This backup system can effectively isolate faulty parts even without communication. Hardware-in-loop simulations in real-time digital scenarios demonstrate the effectiveness of the proposed approach in quickly and accurately identifying faults in 600 V TN-S grounded DC microgrids. According to [24], power electronics are being more and more integrated into transmission and distribution networks for renewable energy. When compared to synchronous generators, the power electronics have an impact on fault-feeding and control characteristics. This study provides a technique for differential line protection based on Local Fault Detection and Comparing Relay Outputs (LFD CRO) at both ends of the line using a low-bandwidth, adaptable communication system. The suggested method is examined in a hypothetical example system with a range of potential outcomes.

Research in [25] discussed the ability of islanded ac microgrids (MGs) to adaptively and resiliently control secondary voltage and frequency in the presence of failing sensors was investigated. Sensor failures or data breaches have a detrimental influence on the quality and stability of MG. Existing techniques presuppose that the data from DG sensing is in excellent or perfect shape. With the use of an Adaptive Fault-Tolerant Control Strategy (AFTCS), secondary voltage may be restored. The time-varying fault limitations are established to minimize voltage tracking errors. If the same control method is used, the frequency restoration and power sharing of the ac MG system could be stable. The issue of unidentified border sensor malfunctions is more challenging for secondary MG control than it was for earlier dispersed control systems.

A cooperative fault-tolerant control (CFTC) strategy may be used to resolve several actuator failures in autonomous AC microgrids [26]. The suggested approach addresses heterogeneous actuator flaws such loss of effectiveness (LOE) and unknown bias errors. Researchers also deploy distributed energy storage as a component of our island microgrid (DES). For exact active power-sharing, the state of charge of DESs must also be balanced (SoC). Performance evaluations of the proposed CFTC algorithm and comparisons with other previously-reported methods are performed using MATLAB/Simulink simulations of a test microgrid system. Through simulation and comparison with existing methods, it has been shown that this technique is accurate in managing microgrid voltage and frequency, balancing the SoC, and offering proportionate active power-sharing situations.

Research in [27] proposed a generalized OC and OL protection scheme to be used for the protection studies of ac-island (autonomous) microgrids and provide a management strategy during and after short circuits and overloading for droop-controlled and directly voltage-controlled inverter-interconnected distributed energy resources (IIDERs).A novel technique for identifying and categorizing flaws uses Artificial Neural Networks (ANNs) and transient monitoring (TMF). This model implements a current-limiting strategy (CLS) in many reference frames to improve microgrid fault ride-through (FRT). The effectiveness, authenticity, and applicability of the proposed OC/OL protection system and experimental verification using the OPAL-RT simulator shown .

The research in [28] presents a novel defect detection method for low- and high-impedance problems (HIFs). HIFs are challenging for ordinary overcurrent relays to detect because to their low fault current. The trip signal is produced using the differential negative-sequence impedance angle's cumulative sum (DNSIA). Computer simulation findings show that the suggested strategy effectively differentiates between LIFs and HIFs. An IEEE 13-bus test system is modelled and simulated using RTDS/RSCAD. By developing an experimental configuration for control hardware-in-the-loops, the method for real-time implementation is proven. As per [29], in inverter-interfaced islanded microgrids, the limited fault current presents challenges for conventional overcurrent protection systems. The problem is addressed in this study by feeder current MSTCT fault detection. The overlay element of MSTCT is used to generate a new directional element. This gadget is unaffected by nonlinear loads or measurement noise. The reliability of the proposed protection mechanism is evaluated using MATLAB/Simulink simulations of benchmark low-voltage microgrid network conditions from CIGRE.

According to [30], LVdc microgrids simplify renewable energy integration but lack effective defense against faults, especially high-resistance ones. The article proposes a preventive approach using innovative electrical devices at each end of the protected zone to detect fault occurrence and direction. The suggested fault classification method benefits both islanded and grid-connected LVdc microgrids. The proposed protection methods are evaluated using a microgrid simulation model with TN-S grounding system settings across various application scenarios. As discussed in [31], Microgrids require sophisticated control techniques to address issues as noise, vibration, and device malfunctions. This research presents a fault-tolerant active control method for DC islanded microgrids. Voltage and current measurements may be done correctly with a distributed H observer. An observer-based status feedback controller is developed for the system to ensure stability. A Supplementary Consensus Control Layer (SCCL) allows for current sharing. Through simulations and testing on a DC microgrid system, fault tolerance is assessed. Here the proposed observer-based control strategy may increase the reliability and resilience of DC microgrids.

Research in [32] asserts that safeguarding microgrids at the POI (Point of Interconnection) is challenging. Because the microgrid provides very little fault current, it is challenging to detect single-line-to-ground (SLG) failures. Utilizing Direct Transfer Trip (DTT) and Over-Voltage Relay (OVR) are two microgrid SLG protection techniques. The major downsides of these systems are high installation and maintenance costs, relay sensitivity, and slow fault clearing times caused by selectivity requirements. This study suggests installing a distance relay on the associated transformer's microgrid/LV side to protect against utility/HV SLG failures. The recommended distance relay reliably locates, measures, and isolates the problem using residual voltage compensations. According to [33], research suggests a dc microgrid monitoring system that employs line admittances and series arc fault detection to pinpoint issues using a Kalman filter (KF)-based method. To calculate line admittances, the approach analyzes voltage and current samples from network nodes. When a high-impedance series arc fault occurs, the damaged line in a microgrid must be located using the KF algorithm. A simulation and findings demonstrate that implementation is feasible.

Research in [34] offers a fault detection, characterization, and fault current control strategy for solar-based dc microgrids. Faults in DC microgrids are identified using overcurrent and current directional/differential comparison protection techniques. Using the adaptive droop method described in this article, fault current and output voltage may be controlled. A simulation is used to test the suggested dc microgrid protection method. As claimed in [35], a DC fault is a significant barrier to a DC microgrid's stability. This research examines DC microgrids with various operating modes and fault locations. Then, a coordinated control technique for SFCL in ground faults and SMES-battery HESS is suggested. This technique lowers the fault current and modifies the DC side's DC bus voltage. Finally, a comparison analysis in PSCAD/EMTDC demonstrates the effectiveness of the approach in various settings.

III. EMPIRICAL EVALUATION & COMPARISON BETWEEN DIFFERENT MICROGRID FAULT DETECTION MODELS

To further evaluate the above discussed models, this section compares them in terms of accuracy of fault detection (A), delay needed for fault identification (D), computational complexity (CC), deployment cost (DC), and scalability (S) metrics. To equalize this evaluation, their performance levels were quantized into Low Quantized Range (LQR=1), Moderate Quantized Range (MQR=2), High Quantized Range (HQR=3), and Very High Quantized Range (VHQR=4), which will assist to compare their performance for identification of optimal fault detection models. This performance comparison can be observed from Table 1.

Table 1. Empirical evaluation of different fault detection & mitigation models

Model	**A**	**CC**	**D**	**DC**	**S**
JSP [1]	*MQR*	*LQR*	*HQR*	*HQR*	*LQR*
IBDG [2]	*HQR*	*MQR*	*HQR*	*HQR*	*MQR*
DT kNN [3]	*LQR*	*HQR*	*HQR*	*VHQR*	*LQR*
FDI [4]	*HQR*	*MQR*	*HQR*	*HQR*	*MQR*
LV DCMG [5]	*HQR*	*HQR*	*MQR*	*HQR*	*HQR*
HFL [6]	*MQR*	*HQR*	*MQR*	*MQR*	*MQR*
IIDG [7]	*HQR*	*HQR*	*HQR*	*HQR*	*MQR*
Hilbert [8]	*HQR*	*MQR*	*LQR*	*HQR*	*HQR*
Lyapunov [9]	*HQR*	*HQR*	*MQR*	*MQR*	*MQR*
LMIT [10]	*HQR*	*HQR*	*HQR*	*HQR*	*LQR*
ViM [11]	*MQR*	*HQR*	*MQR*	*MQR*	*HQR*
SMO [12]	*HQR*	*HQR*	*MQR*	*HQR*	*HQR*
HHT [13]	*HQR*	*VHQR*	*HQR*	*HQR*	*MQR*
CPL [14]	*HQR*	*HQR*	*HQR*	*MQR*	*MQR*
DA AFM [15]	*VHQR*	*VHQR*	*MQR*	*MQR*	*HQR*
SDOC [16]	*HQR*	*HQR*	*HQR*	*HQR*	*HQR*
PCI [17]	*HQR*	*HQR*	*HQR*	*HQR*	*LQR*
PPFCPD [18]	*VHQR*	*HQR*	*MQR*	*HQR*	*HQR*
DCCB [19]	*HQR*	*MQR*	*HQR*	*VHQR*	*MQR*
DWT ANN [20]	*VHQR*	*MQR*	*MQR*	*VHQR*	*VHQR*
DCFL [21]	*HQR*	*HQR*	*MQR*	*HQR*	*HQR*
LocM [22]	*HQR*	*HQR*	*HQR*	*HQR*	*HQR*
LCS DCC [23]	*HQR*	*HQR*	*HQR*	*VHQR*	*HQR*
LFD CRO [24]	*HQR*	*HQR*	*MQR*	*VHQR*	*MQR*
AFTCS [25]	*HQR*	*HQR*	*HQR*	*HQR*	*MQR*
CFTC [26]	*MQR*	*MQR*	*HQR*	*VHQR*	*HQR*

ANN TMF [27]	*VHQR*	*MQR*	*MQR*	*HQR*	*VHQR*
DNSIA [28]	*HQR*	*HQR*	*VHQR*	*VHQR*	*LQR*
MSTCT [29]	*MQR*	*HQR*	*VHQR*	*HQR*	*HQR*
PFHO [30]	*HQR*	*MQR*	*HQR*	*HQR*	*HQR*
SCCL [31]	*VHQR*	*MQR*	*MQR*	*HQR*	*VHQR*
DTT OVR [32]	*HQR*	*HQR*	*HQR*	*HQR*	*HQR*
KF [33]	*HQR*	*MQR*	*HQR*	*HQR*	*HQR*
DCCB [34]	*MQR*	*HQR*	*HQR*	*VHQR*	*HQR*
RS FL [35]	*HQR*	*HQR*	*HQR*	*HQR*	*MQR*

Based on this evaluation, it can be observed that DA AFM [15], PPFCPD [18], DWT ANN [20], ANN TMF [27], SCCL [31] showcase higher accuracy, thus can be used for applications where high precision of fault detection & mitigation is needed with low errors. Similarly, it can also be observed that JSP [1], IBDG [2], FDI [4], Hilbert [8], DCCB [19], DWT ANN [20], CFTC [26], ANN TMF [27], PFHO[30], SCCL[31], KF[33] showcase lower complexity, thus can be used small to medium scaled circuits, where computational power is limited, with lower number of faults. Based on this calculation, it was observed that SCCL [31], ANN TMF [27], DWT ANN [20], Hilbert [8], DA AFM [15] and PPFCPD [18] showcased better overall performance, and can be used for high accuracy of fault detection, with low delay, low cost, low complexity and high scalability performance levels for a wide variety of fault scenarios.

IV. CONCLUSION & FUTURE WORK

This text compares & evaluates a wide variety of models for identification & mitigation of microgrid faults. These faults include line, ground, line-to-line, open circuit, short circuit, and component faults. For applications requiring high precision of fault identification and mitigation with minimal errors, the high-accuracy DA AFM, PPFCPDs, DWTANNs, ANN TMFs, SCCLs, may be employed. It is also possible to notice lesser complexity in the IBDG (FDI), Hilbert (Hilbert), DCCB (DCCB), DWTANN (CFTC), ANN TMF (PFHO), SCCL (SCCL) and KF (LK) algorithms. Hilbert also shown to have smaller delays, which may be applied in high-speed fault detection applications. Scalability was also found to be an important factor in the development of large-scale circuits such as the SCCL. SCCL, ANN TMF and Hilbert were found to have the best overall performance, and can be used to detect faults with high accuracy and low delay, as well as low cost, low complexity, and high scalability in various fault scenarios. In future, these models must be validated on larger density circuits. Their performance can also be improved via use of deep learning, Q-Learning, and other incremental learning methods, which will assist in fault pre-emption, thereby improving detection & mitigation performance under multiple use cases.

REFERENCES

[1] Z. Huang and Z. Wang, "A Multiswitch Open-Circuit Fault Diagnosis of Microgrid Inverter Based on Slidable Triangularization Processing," in IEEE Transactions on Power Electronics, vol. 36, no. 1, pp. 922-930, Jan. 2021.

[2] L. He, Z. Shuai, X. Chu, W. Huang, Y. Feng and Z. J. Shen, "Waveform Difference Feature-Based Protection Scheme for Islanded Microgrids," in IEEE Transactions on Smart Grid, vol. 12, no. 3, pp. 1939-1952, May 2021.

[3] A. Saxena, N. K. Sharma and S. R. Samantaray, "An Enhanced Differential Protection Scheme for LVDC Microgrid," in IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 10, no. 2, pp. 2114-2125, April 2022.

[4] T. Wang et al., "Model-Based Fault Detection and Isolation in DC Microgrids Using Optimal Observers," in IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 9, no. 5, pp. 5613-5630, Oct. 2021.

[5] N. Yadav and N. R. Tummuru, "Short-Circuit Fault Detection and Isolation Using Filter Capacitor Current Signature in Low-Voltage DC Microgrid Applications," in IEEE Transactions on Industrial Electronics, vol. 69, no. 8, pp. 8491-8500, Aug. 2022.

[6] R. Bhargav, C. P. Gupta and B. R. Bhalja, "Unified Impedance-Based Relaying Scheme for the Protection of Hybrid AC/DC Microgrid," in IEEE Transactions on Smart Grid, vol. 13, no. 2, pp. 913-927, March 2022.

[7] W. T. El-Sayed, M. A. Azzouz, H. H. Zeineldin and E. F. El-Saadany, "A Harmonic Time-Current-Voltage Directional Relay for Optimal Protection Coordination of Inverter-Based Islanded Microgrids," in IEEE Transactions on Smart Grid, vol. 12, no. 3, pp. 1904-1917, May 2021.

[8] S. Baloch and M. S. Muhammad, "An Intelligent Data Mining-Based Fault Detection and Classification Strategy for Microgrid," in IEEE Access, vol. 9, pp. 22470-22479, 2021.

[9] M. A. Shahab, B. Mozafari, S. Soleymani, N. M. Dehkordi, H. M. Shourkaei and J. M. Guerrero, "Distributed Consensus-Based Fault Tolerant Control of Islanded Microgrids," in IEEE Transactions on Smart Grid, vol. 11, no. 1, pp. 37-47, Jan. 2020.

[10] M. Mola, A. Afshar, N. Meskin and M. Karrari, "Distributed Fast Fault Detection in DC Microgrids," in IEEE Systems Journal, vol. 16, no. 1, pp. 440-451, March 2022.

[11] Z. Huang, Z. Wang and C. Song, "Complementary Virtual Mirror Fault Diagnosis Method for Microgrid Inverter," in IEEE Transactions on Industrial Informatics, vol. 17, no. 11, pp. 7279-7290, Nov. 2021.

[12] S. Saha, S. Gholami and M. K. Khan Prince, "Sensor Fault-Resilient Control of Electronically Coupled Distributed Energy Resources in Islanded Microgrids," in IEEE Transactions on Industry Applications, vol. 58, no. 1, pp. 914-929, Jan.-Feb. 2022.

[13] R. Azizi and S. Seker, "Microgrid Fault Detection and Classification Based on the Boosting Ensemble Method With the Hilbert-Huang Transform," in IEEE Transactions on Power Delivery, vol. 37, no. 3, pp. 2289-2300, June 2022.

[14] N. Bayati, H. R. Baghaee, A. Hajizadeh and M. Soltani, "Localized Protection of Radial DC Microgrids With High Penetration of Constant Power Loads," in IEEE Systems Journal, vol. 15, no. 3, pp. 4145-4156, Sept. 2021.

[15] W. Wan et al., "Distributed and Asynchronous Active Fault Management for Networked Microgrids," in IEEE Transactions on Power Systems, vol. 35, no. 5, pp. 3857-3868, Sept. 2020.

[16] T. Wang and A. Monti, "Fault Detection and Isolation in DC Microgrids Based on Singularity Detection in the Second Derivative of Local Current Measurement," in IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 9, no. 3, pp. 2574-2588, June 2021.

[17] B. Anudeep and P. K. Nayak, "Differential Power Based Selective Phase Tripping for Fault-resilient Microgrid," in Journal of Modern Power Systems and Clean Energy, vol. 10, no. 2, pp. 459-470, March 2022.

[18] B. Wang and L. Jing, "A Protection Method for Inverter-based Microgrid Using Current-only Polarity Comparison," in Journal of Modern Power Systems and Clean Energy, vol. 8, no. 3, pp. 446-453, May 2020.

[19] Y. Yang, C. Huang, Z. Zhao, Q. Xu and Y. Jiang, "A New Bidirectional DC Circuit Breaker With Fault Decision-Making Capability for DC Microgrid," in IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 9, no. 3, pp. 2476-2488, June 2021.

[20] Y. Hong and M. T. A. M. Cabatac, "Fault Detection, Classification, and Location by Static Switch in Microgrids Using Wavelet Transform and Taguchi-Based Artificial Neural Network," in IEEE Systems Journal, vol. 14, no. 2, pp. 2725-2735, June 2020.

[21] Z. Huang and Z. Wang, "A Fault Diagnosis Algorithm for Microgrid Three-Phase Inverter Based on Trend Relationship of Adjacent Fold Lines," in IEEE Transactions on Industrial Informatics, vol. 16, no. 1, pp. 267-276, Jan. 2020.

[22] V. Nougain and B. K. Panigrahi, "Detection of DC System Faults Based on the Principle of Threshold Violation in i-r Plane," in IEEE Systems Journal, vol. 15, no. 1, pp. 856-864, March 2021.

[23] A. Meghwani, R. Gokaraju, S. C. Srivastava and S. Chakrabarti, "Local Measurements-Based Backup Protection for DC Microgrids Using Sequential Analyzing Technique," in IEEE Systems Journal, vol. 14, no. 1, pp. 1159-1170, March 2020.

[24] J. Nsengiyaremye, B. C. Pal and M. M. Begovic, "Microgrid Protection Using Low-Cost Communication Systems," in IEEE Transactions on Power Delivery, vol. 35, no. 4, pp. 2011-2020, Aug. 2020.

[25] X. Li, Q. Xu and F. Blaabjerg, "Adaptive Resilient Secondary Control for Islanded AC Microgrids With Sensor Faults," in IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 9, no. 5, pp. 5239-5248, Oct. 2021.

[26] A. Afshari, M. Karrari, H. R. Baghaee, G. B. Gharehpetian and S. Karrari, "Cooperative Fault-Tolerant Control of Microgrids Under Switching Communication Topology," in IEEE Transactions on Smart Grid, vol. 11, no. 3, pp. 1866-1879, May 2020.

[27] H. R. Baghaee, M. Mirsalim, G. B. Gharehpetian and H. A. Talebi, "OC/OL Protection of Droop-Controlled and Directly Voltage-Controlled Microgrids Using TMF/ANN-Based Fault Detection and Discrimination," in IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 9, no. 3, pp. 3254-3265, June 2021.

[28] K. Dubey and P. Jena, "Impedance Angle-Based Differential Protection Scheme for Microgrid Feeders," in IEEE Systems Journal, vol. 15, no. 3, pp. 3291-3300, Sept. 2021.

[29] K. Allahdadi, I. Sadeghkhani and B. Fani, "Protection of Converter-Interfaced Microgrids Using Modified Short-Time Correlation Transform," in IEEE Systems Journal, vol. 14, no. 4, pp. 5172-5175, Dec. 2020.

[30] S. Ahmadi, I. Sadeghkhani, G. Shahgholian, B. Fani and J. M. Guerrero, "Protection of LVDC Microgrids in Grid-Connected and Islanded Modes Using Bifurcation Theory," in IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 9, no. 3, pp. 2597-2604, June 2021.

[31] M. Huang, L. Ding, W. Li, C. -Y. Chen and Z. Liu, "Distributed Observer-Based H∞ Fault-Tolerant Control for DC Microgrids With Sensor Fault," in IEEE Transactions on Circuits and Systems I: Regular Papers, vol. 68, no. 4, pp. 1659-1670, April 2021.

[32] Y. Yin, Y. Fu, Z. Zhang and A. Zamani, "Protection of Microgrid Interconnection Lines Using Distance Relay With Residual Voltage Compensations," in IEEE Transactions on Power Delivery, vol. 37, no. 1, pp. 486-495, Feb. 2022.

[33] K. Gajula and L. Herrera, "Detection and Localization of Series Arc Faults in DC Microgrids Using Kalman Filter," in IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 9, no. 3, pp. 2589-2596, June 2021.

[34] S. Augustine, M. J. Reno, S. M. Brahma and O. Lavrova, "Fault Current Control and Protection in a Standalone DC Microgrid Using Adaptive Droop and Current Derivative," in IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 9, no. 3, pp. 2529-2539, June 2021.

[35] Y. Zhou, C. Ji, Z. Dong and S. Zhang, "Cooperative Control of SFCL and SMES-Battery HESS for Mitigating Effect of Ground Faults in DC Microgrids," in IEEE Transactions on Applied Superconductivity, vol. 31, no. 8, pp. 1-5, Nov. 2021