Table of Contents

A Methodology for Fault Detection and Classification using PMU Measurements.2

An adaptive PMU based fault detection/location technique for transmission lines. I. Theory and algorithms2

Graph Algorithms for Topology Identification Using Power Grid Probing3

Real-Time Identifiability of Power Distribution Network Topologies With Limited Monitoring3

Elements of Networked Protection Systems for Distribution Networks and Microgrids: A Cyber-Security Perspective4

Unsupervised Impedance and Topology Estimation of Distribution Networks—Limitations and Tools4

A Supervised Learning Approach to Transient Analysis for Microgrid Protection Systems5

Event Detection and Localization in Distribution Grids with Phasor Measurement Units5

A Dependency Graph Approach for Fault Detection and Localization Towards Secure Smart Grid6

Voltage Sag Data Utilization for Distribution Fault Location6

A Systematic Approach for Ranking Distribution Systems Fault Location Algorithms and Eliminating False Estimates7

Low-Resolution Fault Localization Using Phasor Measurement Units with Community Detection7

High impedance fault detection of distribution network by phasor measurement units8

Fault Detection and Faulted Line Identification in Active Distribution Networks Using Synchrophasors-Based Real-Time State Estimation8

A Simple High Impedance Fault Detection Method based on Phase Displacement and Zero Sequence Current for Grounded Distribution Systems9

Accurate Fault Detection of Distribution Network with Optimal Placement of Phasor Measurement Unit9

Amit Jain, TC Archana and MBK Sahoo, “**A Methodology for Fault Detection and Classification using PMU Measurements.**” Proceedings of the National Power Systems Conference (NPSC) - 2018, December 14-16, NIT Tiruchirappalli, India.

<http://www.iitk.ac.in/npsc/Papers/NPSC2018/1570476979.pdf>

Abstract: Phasor Measurement Units (PMU) has become integral part of advanced measurement technologies for power transmission and distribution systems. The PMU measurement gives a clear picture of sequence of phenomenon happening in power system. In power system, faults, load change etc. happens frequently. Since faults are severe cases it is required to detect them at the earliest. Here a two-stage fault detection method is proposed which can clearly distinguish between disturbances and faults in power system. The positive and zero sequence voltages obtained from PMUs are utilized in the detection algorithm. Once the fault is detected, it is required to recognize the kind of fault that has occurred. A Support Vector Machine is proposed for categorizing the fault type. The 14 bus IEEE transmission test system is modelled in PSS/E and MATLAB/Simulink for testing and validating the proposed detection and classification methods.

Joe-Air Jiang, Jun-Zhe Yang, Ying-Hong Lin, Chih-Wen Liu and Jih-Chen Ma, **"An adaptive PMU based fault detection/location technique for transmission lines. I. Theory and algorithms**," in *IEEE Transactions on Power Delivery*, vol. 15, no. 2, pp. 486-493, April 2000.
doi: 10.1109/61.852973

<http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=852973&isnumber=18531>

Abstract: An adaptive fault detection/location technique based on a phasor measurement unit (PMU) for an EHV/UHV transmission line is presented. A fault detection/location index in terms of Clarke components of the synchronized voltage and current phasors is derived. The line parameter estimation algorithm is also developed to solve the uncertainty of parameters caused by aging of transmission lines. This paper also proposes a new discrete Fourier transform (DFT) based algorithm (termed the smart discrete Fourier transform, SDFT) to eliminate system noise and measurement errors such that extremely accurate fundamental frequency components can be extracted for calculation of fault detection/location index. The EMTP was used to simulate a high voltage transmission line with faults at various locations. To simulate errors involved in measurements, Gaussian-type noise has been added to the raw output data generated by EMTP. Results have shown that the new DFT based method can extract exact phasors in the presence of frequency deviation and harmonics. The parameter estimation algorithm can also trace exact parameters very well. The accuracy of both new DFT based method and parameter estimation algorithm can achieve even up to 99.999% and 99.99% respectively, and is presented in Part II. The accuracy of fault location estimation by the proposed technique can achieve even up to 99.9% in the performance evaluation, which is also presented in Part II.

G. Cavraro and V. Kekatos, "**Graph Algorithms for Topology Identification Using Power Grid Probing,"** in *IEEE Control Systems Letters*, vol. 2, no. 4, pp. 689-694, Oct. 2018.
doi: 10.1109/LCSYS.2018.2846801

<https://ieeexplore.ieee.org/document/8383953>
Abstract: To perform any meaningful optimization task, power distribution operators need to know the topology and line impedances of their electric networks. Nevertheless, distribution grids currently lack a comprehensive metering infrastructure. Although smart inverters are widely used for control purposes, they have been recently advocated as the means for an active data acquisition paradigm: reading the voltage deviations induced by intentionally perturbing inverter injections, the system operator can potentially recover the electric grid topology. Adopting inverter probing for feeder processing, a suite of graph-based topology identification algorithms is developed here. If the grid is probed at all leaf nodes but voltage data are metered at all nodes, the entire feeder topology can be successfully recovered. When voltage data are collected only at probing buses, the operator can find a reduced feeder featuring key properties and similarities to the actual feeder. To handle modeling inaccuracies and load nonstationarity, noisy probing data need to be preprocessed. If the suggested guidelines on the magnitude and duration of probing are followed, the recoverability guarantees carry over from the noiseless to the noisy setup with high probability.

G. Cavraro, A. Bernstein, V. Kekatos and Y. Zhang, "Real-Time Identifiability of Power Distribution Network Topologies With Limited Monitoring," in IEEE Control Systems Letters, vol. 4, no. 2, pp. 325-330, April 2020. doi: 10.1109/LCSYS.2019.2926101

<https://ieeexplore.ieee.org/document/8754743>
Abstract: Recovering the distribution grid topology in real time is essential to perform several distribution system operator (DSO) functions. DSOs often do not have any direct monitoring of switch statuses to track reconfiguration. At the same time, installing real-time meters at a large number of buses is challenging due to the cost of endowing every metered bus with a real-time communication channel. The goal of this letter is to develop a meter placement strategy allowing DSOs to deploy only few real-time meters. After casting the topology recovery task as an optimization problem, a meter placement strategy ensuring unique recovery of the true topology is devised. A graph-theoretical approach is pursued to partition the grid into connected portions called observable islands. The proposed strategy then simply requires installing a meter in the path between every pair of boundary nodes, i.e., ends of edges connecting two different islands. Under some ideal assumptions, this placement strategy ensures unique recovery of the topology. The approach is also validated through numerical simulations under realistic scenarios using a standard IEEE benchmark feeder.
<https://ieeexplore.ieee.org/document/8754743>

Seyedi, Younes & Karimi, Houshang & Grijalva, Santiago & Sanso, Brunilde. (2020). **Elements of Networked Protection Systems for Distribution Networks and Microgrids: A Cyber-Security Perspective**. Accepted for presentation in IEEE CANADIAN CONFERENCE ON ELECTRICAL AND COMPUTER ENGINEERING, Apr. 2020

 [https://www.researchgate.net/publication/339079430\_Elements\_of\_Networked\_Protection\_Systems\_for\_Distribution\_Networks\_and\_Microgrids\_A\_Cyber-Security\_Perspective](https://www.researchgate.net/publication/338900677_Elements_of_Networked_Protection_Systems_for_Distribution_Networks_and_Microgrids_A_Cyber-Security_Perspective)

Abstract: Networked protection systems use information, communication and computation technologies to collect and process sensor data from spatially distributed sensors, and launch protective and control actions by sending commands to local devices. Such protection systems are also capable of supporting specialized tasks including asset control and backup protection in case of traditional relaying failures. This paper explains the structure and the fundamental elements of the networked protection systems in distribution systems and microgrids. The overall system is divided into three subsystems which are interconnected by communication systems. Different types of cyber-attacks on the subsystems and their impacts are discussed from the vantage point of protection. False and delayed tripping, non-detection, cascading failures, and unstable operation of distributed energy resources (DERs) are discussed as the critical issues that can be related to cyber-attacks.

K. Moffat, M. Bariya and A. Von Meier, "**Unsupervised Impedance and Topology Estimation of Distribution Networks—Limitations and Tools**," in *IEEE Transactions on Smart Grid*, vol. 11, no. 1, pp. 846-856, Jan. 2020.
doi: 10.1109/TSG.2019.2956706

<https://ieeexplore.ieee.org/document/8918302>

Abstract: Distribution network models are often inaccurate or nonexistent. This work considers the problem of estimating the impedance and topology of distribution networks from noisy synchronized phasor measurements of nodal voltages and current injections, without any prior network information. We prove fundamental limits for unsupervised estimation of electrical networks, establishing effective impedance between active nodes as the core, generally-attainable network information. We propose a noise-robust technique for estimating effective impedances via the reduced Laplacian form of the Kron reduced admittance matrix, termed the “subKron” form. We present the Complex Recursive Grouping algorithm to reconstruct radial networks from effective impedances. Simulation results on noisy data demonstrate the efficacy of the proposed methods for small networks, and the challenges of applying them to large networks. Evaluations of estimation and reconstruction accuracy with decreasing signal to noise ratio highlight fundamental tradeoffs in unsupervised network estimation performance from noisy measurements.

Seyedi, Younes & Mahseredjian, Jean & Sanso, Brunilde & Karimi, Houshang & Grijalva, Santiago. (2020). **A Supervised Learning Approach to Transient Analysis for Microgrid Protection Systems.** Submitted to IEEE Transactions on Smart Grid

https://www.researchgate.net/publication/339079423\_A\_Supervised\_Learning\_Approach\_to\_Transient\_Analysis\_for\_Microgrid\_Protection\_Systems

Abstract: This paper presents a new transient analysis approach for automatic detection and spatio-temporal analysis of microgrid faults based on supervised learning and phasor data analytics. The key concept is to identify faults and their subsequent disturbances by efficient supervised learning and inference algorithms that analyze the features of transients. This approach requires only one sensor which measures the phasors of voltages and currents at the microgrid point of common coupling (PCC). Two algorithms are developed that determine fault indices and transient features for simulation-based training, online classification and backup protection purposes. Moreover, non-stationarity and variance tests are proposed for detection of post-fault disturbances and monitoring of fault isolation by local protective devices. The performance and accuracy of the developed methods are verified through extensive simulations of different low-voltage microgrids with high penetration of solar photovoltaic (PV) systems.

[Omid Ardakanian](https://arxiv.org/search/cs?searchtype=author&query=Ardakanian%2C+O), [Ye Yuan](https://arxiv.org/search/cs?searchtype=author&query=Yuan%2C+Y), [Roel Dobbe](https://arxiv.org/search/cs?searchtype=author&query=Dobbe%2C+R), [Alexandra von Meier](https://arxiv.org/search/cs?searchtype=author&query=von+Meier%2C+A), [Steven Low](https://arxiv.org/search/cs?searchtype=author&query=Low%2C+S), [Claire Tomlin](https://arxiv.org/search/cs?searchtype=author&query=Tomlin%2C+C), **“Event Detection and Localization in Distribution Grids with Phasor Measurement Units”**

<https://arxiv.org/pdf/1611.04653.pdf>

Abstract: The recent introduction of synchrophasor technology into power distribution systems has given impetus to various monitoring, diagnostic, and control applications, such as system identification and event detection, which are crucial for restoring service, preventing outages, and managing equipment health. Drawing on the existing framework for inferring topology and admittances of a power network from voltage and current phasor measurements, this paper proposes an online algorithm for event detection and localization in unbalanced three-phase distribution systems. Using a convex relaxation and a matrix partitioning technique, the proposed algorithm is capable of identifying topology changes and attributing them to specific categories of events. The performance of this algorithm is evaluated on a standard test distribution feeder with synthesized loads, and it is shown that a tripped line can be detected and localized in an accurate and timely fashion, highlighting its potential for real-world applications.

M. He and J. Zhang, "**A Dependency Graph Approach for Fault Detection and Localization Towards Secure Smart Grid,"** in IEEE Transactions on Smart Grid, vol. 2, no. 2, pp. 342-351, June 2011.

doi: 10.1109/TSG.2011.2129544

<https://ieeexplore.ieee.org/abstract/document/5767534>

Abstract: Fault diagnosis in power grids is known to be challenging, due to the massive scale and spatial coupling therein. In this study, we explore multiscale network inference for fault detection and localization. Specifically, we model the phasor angles across the buses as a Markov random field (MRF), where the conditional correlation coefficients of the MRF are quantified in terms of the physical parameters of power systems. Based on the MRF model, we then study decentralized network inference for fault diagnosis, through change detection and localization in the conditional correlation matrix of the MRF. Particularly, based on the hierarchical topology of practical power systems, we devise a multiscale network inference algorithm that carries out fault detection and localization in a decentralized manner. Simulation results are used to demonstrate the effectiveness of the proposed approach.

S. Lotfifard, M. Kezunovic and M. J. Mousavi, "**Voltage Sag Data Utilization for Distribution Fault Location**," in IEEE Transactions on Power Delivery, vol. 26, no. 2, pp. 1239-1246, April 2011.

doi: 10.1109/TPWRD.2010.2098891

<https://ieeexplore.ieee.org/abstract/document/5692876>

Abstract: Fault location in distribution systems is an important function for outage management and service restoration directly impacting feeder reliability. In this paper, a fault location method based on matching calculated voltage sag data and data gathered at some nodes in the network is proposed. A method for characterization of voltage sags is utilized to reduce amount of transferred data. The proposed method can pinpoint fault location precisely, and is applicable to any complex distribution systems with load taps, laterals, and sub-laterals, single-phase loads, as well as networks with heterogeneous lines. The performance of the proposed method is demonstrated on the IEEE 123-node distribution test system via computer simulations in Alternate Transients Program software.

S. Lotfifard, M. Kezunovic and M. J. Mousavi, "**A Systematic Approach for Ranking Distribution Systems Fault Location Algorithms and Eliminating False Estimates**," in IEEE Transactions on Power Delivery, vol. 28, no. 1, pp. 285-293, Jan. 2013.

doi: 10.1109/TPWRD.2012.2213616

<https://ieeexplore.ieee.org/document/6355982>

Abstract: The need for distribution reliability enhancement in the age of smart grids requires reliable methods for locating faults on distribution systems leading to a faster service restoration and maintenance cost optimization. Given the numerous fault location methods, one faces the challenge of objectively evaluating and selecting the most proper method. In this paper, a two-step approach is proposed and discussed for ranking available fault location methods that takes into account application requirements and modeling limitations and uncertainties. The ranking method formulated as uncertainty analysis utilizes 2 n + 1 point estimation to calculate the statistical moments of the fault location estimation error. These moments plugged into the Chebyshev's inequality provide a basis for ranking the fault location method. The selected method may still suffer from multiple fault location estimations. To address this caveat, voltage sag characteristics reported by few intelligent electronic devices (IEDs) along the feeder are utilized. The number and location of these IEDs are determined through an optimal approach specifically formulated for this problem. The proposed two-step ranking methodology and the IED placement optimization approach were implemented on a simulated distribution system and their effectiveness was demonstrated through a few select scenarios and case studies.

**M. Jamei, A. Scaglione and S. Peisert**, "Low-Resolution Fault Localization Using Phasor Measurement Units with Community Detection," 2018 IEEE International Conference on Communications, Control, and Computing Technologies for Smart Grids (SmartGridComm), Aalborg, 2018, pp. 1-6.
doi: 10.1109/SmartGridComm.2018.8587461

<https://ieeexplore.ieee.org/abstract/document/8587461>
Abstract: A significant portion of the literature on fault localization assumes (more or less explicitly) that there are sufficient reliable measurements to guarantee that the system is observable. While several heuristics exist to break the observability barrier, they mostly rely on recognizing spatio-temporal patterns, without giving insights on how the performance are tied with the system features and the sensor deployment. In this paper, we try to fill this gap and investigate the limitations and performance limits of fault localization using Phasor Measurement Units (PMUs), in the low measurements regime, i.e., when the system is unobservable with the measurements available. Our main contribution is to show how one can leverage the scarce measurements to localize different type of distribution line faults (three-phase, single-phase to ground, ...) at the level of sub-graph, rather than with the resolution of a line. We show that the resolution we obtain is strongly tied with the graph clustering notion in network science.

**M. G. M. Zanjani, H. K. Kargar and M. G. M. Zanjani**, "High impedance fault detection of distribution network by phasor measurement units," 2012 Proceedings of 17th Conference on Electrical Power Distribution, Tehran, 2012, pp. 1-5.

<https://ieeexplore.ieee.org/document/6254586>
Abstract: This paper proposed a new algorithm for High Impedance Fault (HIF) detection using Phasor Measurement Unit (PMU). This type of faults is difficult to detect by over current protection relays because of low fault current. In this paper a new method based on PMU is proposed which is sensitive to the change of current phasor. The phasors are measured PMU to obtain the square summation of errors. Two types of data are used for error calculation. The first one is sampled data and the second one is estimated data. The estimated data is obtained by phasors which explained in paper in detail. The verification of the proposed method is done by EMTP.

M. Pignati, L. Zanni, P. Romano, R. Cherkaoui and M. Paolone, "Fault Detection and Faulted Line Identification in Active Distribution Networks Using Synchrophasors-Based Real-Time State Estimation," in IEEE Transactions on Power Delivery, vol. 32, no. 1, pp. 381-392, Feb. 2017.
doi: 10.1109/TPWRD.2016.2545923

<https://ieeexplore.ieee.org/document/7439849>
Abstract: We intend to prove that phasor-measurement-unit (PMU)-based state estimation processes for active distribution networks exhibit unique time determinism and a refresh rate that makes them suitable to satisfy the time-critical requirements of protections as well as the accuracy requirements dictated by faulted line identification. In this respect, we propose a real-time fault detection and faulted line identification functionality obtained by computing parallel synchrophasor-based state estimators. Each state estimator is characterized by a different and augmented topology in order to include a floating fault bus. The selection of the state estimator providing the correct solution is performed by a metric that computes the sum of the weighted measurement residuals. The proposed process scheme is validated by means of a real-time simulation platform where an existing active distribution network is simulated together with a PMU-based monitoring system. The proposed process is shown to be suitable for active and passive networks, with solid-earthed and unearthed neutral, for low- and high-impedance faults of any kind (symmetric and asymmetric) occurring at different locations.

S. Myint, W. Wichakool and P. Santiprapan, "A Simple High Impedance Fault Detection Method based on Phase Displacement and Zero Sequence Current for Grounded Distribution Systems," 2018 IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC), Kota Kinabalu, 2018, pp. 118-122.
doi: 10.1109/APPEEC.2018.8566323

<https://ieeexplore.ieee.org/document/8566323>
Abstract: A new simple algorithm to detect high impedance high impedance fault (HIF) in grounded distribution networks with the combination of a wavelet transform and phasor measurement unit (PMU) techniques is presented in this paper. The protection algorithm observes the changing conditions of phase displacement between phase voltage and current signals and high frequency component present in the detail coefficient of zero sequence current of the specified measured terminal. The proposed method consists in three simple steps. The first step is checking whether the system is normal or abnormal by using the total sum of mean absolute values of phase displacements between phase voltages and currents. Then, the second step is whether system unbalance is fault or other load switching will be checked by using the sum of mean values of phase displacement between voltage and current. Finally, the algorithm will observe the present of high frequency transient components in the residual current signal to ensure that the system is under fault condition. The proposed PMU and wavelet-based fault detector has been tested with MATLAB Simulink-generated signals, more simple than conventional algorithms and methods. The scheme proved to be robust against transients generated during normal events such as feeder energizing and de-energizing as well as capacitor bank switching.

P. Ray and S. Beura, "**Accurate Fault Detection of Distribution Network with Optimal Placement of Phasor Measurement Unit**," 2019 International Conference on Intelligent Sustainable Systems (ICISS), Palladam, Tamilnadu, India, 2019, pp. 76-81.
doi: 10.1109/ISS1.2019.8908029

<https://ieeexplore.ieee.org/document/8908029>
Abstract: With increasing power system complexities, fault becomes more common which makes the equipments and workers exposed to catastrophes. Previously supervisory control and data acquisition(SCADA) system were used to monitor and detect fault in power system, but it's lower sampling rate makes it inappropriate to use. This paper presents an improved approach for fault detection in distribution line. The proposed method uses Phasor Measurement Units (PMU)to detect fault quickly and operate the circuit breakers(CB) to ensure system stability and security. For this purpose 30 kW generating station feeding power to 10 km distribution line with a step up transformer (208/11 kV) and a 24 kW solar photovoltaic(PV)module is used here. PMU's are installed at synchronous generator, PV grid, and load buses respectively. The data from the PMU are aligned and planned to IEEE C37.118 format before transmitted to the Phasor data concentrator. Here, positive sequence phase locked loop (PLL) based PMU is used to measure the power system parameters like voltage, frequency, and phase respectively. The large deviation in any parameter can be used to trigger the CB. Quick and Accurate fault detection in the distribution network eliminates any big catastrophic effect and saves from monetary loss. The performance of the proposed model can be evaluated by calculating Total Vector Error of the PMU and then comparing it with IEEE C37.118 standards. Proposed scheme also provides optimal placement of PMU in the given system.