WIDE AREA PROTECTION AND FAULT LOCATION: REVIEW AND EVALUATION OF PMU-BASED METHODS

S.M. Blair*, G.M. Burt*, N. Gordon†, P. Orr†

*University of Strathclyde, UK, steven.m.blair@strath.ac.uk
†Synaptec Ltd, UK, philip.orr@synapt.ec

Keywords: Fault location, phasor measurement units (PMUs), photonic sensing, and wide area protection.

Abstract

Wide area protection (WAP) systems use multiple sources of information to improve trip times and reduce the complexity of protection settings. Therefore, such communications-enhanced schemes have the potential to replace conventional transmission system backup protection. Through review and assessment of the present state-of-the-art relating to WAP systems, this paper demonstrates how multiple synchrophasor data sources, and the associated communications systems, can be leveraged to enable new forms of supervisory protection. Two case studies are presented: a scalable WAP architecture for future decentralised power systems, and the validation a prototype WAP system, using the principle of distributed photonic sensing, highlighting how new tools can provide cost-effective solutions to emerging protection challenges.

1 Introduction

Enabling a fast-acting response to power system events is becoming critical to stable grid operation. Large-scale Phasor Measurement Unit (PMU) monitoring schemes are being utilised to enable new system functions such as fast-acting frequency control in low- and variable-inertia systems [1], and distributed control paradigms [2]. The use of data from PMUs will therefore underpin the real-time operation of future power systems.

Wide Area Monitoring, Protection, and Control (WAMPAC) systems, which typically involve the use of PMU data for diverse power system applications, have gathered significant interest, including recent investigations by CIGRE [3] and the IEEE Power System Relaying and Control (PSRC) committee [4]. WAMPAC applications include: state estimation, coordinated frequency response, real-time transfer capability, phase angle monitoring, real-time oscillation damping, system restoration, and coordinated protection. This paper focuses on the area of coordinated protection, in the context of emerging power system challenges. This work highlights what could be achieved in terms of protection, assuming a very high level of observability in future power systems.

This paper provides a comprehensive review of modern fault detection and fault location approaches, which typically employ synchrophasor data. These approaches include: wide area differential protection, superimposed components, centralised protection concepts, and pattern-matching systems. Furthermore, the paper describes a scalable, distributed architecture for wide area protection systems, and demonstrates the importance of measurement validation in the application of novel distributed photonic sensing systems.

2 Background

2.1 Overview

The term “wide area protection” (WAP) often refers to special provisions to respond to large disturbances during severe or multiple contingencies [5]. However, in the context of this paper, the term is used to refer to methods which are alternatives (or backups) to conventional protection schemes (e.g. differential, distance, and overcurrent protection), and which exploit information from multiple, coordinated locations. In most cases, the WAP scheme is intended to be implemented as a fast-acting backup scheme (relative to conventional backup systems) due to the communications latency which must be accommodated, rather than replacing primary protection [6]. It is assumed that PMU measurements are available at multiple nodes in the system, as illustrated in Figure 1.

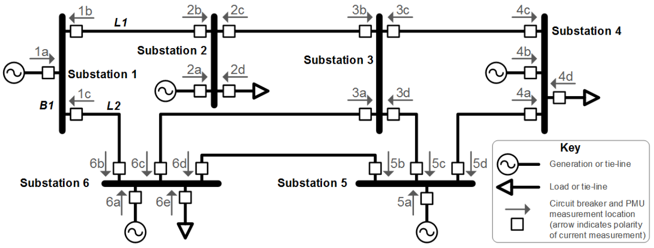

Figure 1: Representative transmission system WAP scheme with multiple PMUs

2.2 PMU Validation Requirements

Synchrophasor data must be robust to be trusted for use in real-time control and protection applications [7]. Therefore, the quality of Synchrophasor measurements from PMUs, including timing accuracy, has also been a key topic of research, particularly in the EU [8] and the USA [9], [10]. Research work has highlighted the challenges associated with: measurement quality, which is very important for distribution system applications of PMUs [10][1], PMU "data quality" [9], PMU timing accuracy [11], real-time supervisory assessment of multiple PMU data streams [12], and latency [13]. The importance of rigorous testing of PMU-based systems is strongly emphasised in [14].

Utilities are already using PMU data as tools for visualisation and stability monitoring [15], but closed-loop control, i.e. where PMU data automatically and directly influence power system operation, is presently undergoing validation [1]. Furthermore, the North American SynchoPhasor Initiative (NASPI) presently recommends avoiding the use of PMU data for system-critical operations – unless timing accuracy and resiliency have been fully validated [11].

3 Summary of Approaches to Wide Area Protection using PMUs

There are several techniques which can use PMU data to perform fault detection and fault location. "Fault location" in this context refers to identifying the faulted circuit to trip, rather than estimating the distance to the fault (as can be achieved with, for example, travelling wave protection). The relevant methods in the literature can be categorised and summarised as follows:

Extensions of the principle of current differential protection. The method in [6] collects multiple PMU measurements and performs differential protection for each applicable zone, per phase. Expanded zones are established which can operate due to loss of inner zone PMU data or other issues. As described in [16], expanded zones can also block operation of an inner zone due to issues such as transformer saturation; this provides resilience to erroneous or lost measurements. The main benefits of the scheme are 1) faster-acting backup operation, and 2) avoiding the need to perform extensive, challenging validation of distance protection schemes. A similar method is presented in [17] based on the sum of the zero- and/or positive-sequence currents entering a protection zone (which is bounded by PMU measurements).

Superimposed components [18]–[20], which typically involves the difference between measurements during a fault and the pre-fault measurements. A similar approach involving autocorrelation of a current waveform for use in directional relays is described in [21]. Similarly, [22] proposes using the difference between steady-state voltage and the minimum voltage during a disturbance to identify the bus closest to a fault. The fault detection algorithm in [23] is based on the difference between measured voltage and frequency values and the nominal values, and fault location is based on the circuit with the largest normalised current magnitude. In general, the superimposed components technique is very promising in terms of providing a fast-acting response during dynamic system conditions, particularly due to the prevalence of converter-interfaced generation which may fundamentally change the voltage and current waveforms measured during disturbances such as faults; therefore conventional assumptions used for protection settings and coordination may no longer apply.

Centralised protection concepts, which are typically designed for application within a substation [24], could be applied over a wide area [25]. In summary, this approach involves the integration of multiple protection and control functions within a single system, typically using multiple synchronised measurements, in order to better detect fault conditions, improve protection reliability, and improve efficiency. However, this approach may not be scalable to very large systems, and there is a perceived lack of resilience compared to a paradigm using distributed protection devices (although, centralised protection systems can be designed with redundancy provisions). Centralised protection can also include the concept of the "virtualisation" of IEDs i.e. the functionality of multiple IEDs provided by a single hardware device.

Voltage magnitude-based protection, such as [26] and [27]. Reference [28] uses positive sequence voltage magnitude values to locate the bus closest to the fault, and positive sequence current angle differences to locate the faulted line; a similar method is presented in [29] where fault detection is based on negative- or zero-sequence voltage or current criteria, and which is enhanced by a method to improve the confidence of trips by combining information from conventional protection systems. A similar method of fault detection, using the angle difference for a two-terminal system, is described in [30], and a further related method is given in [31] (along with a fault detection method based on the ratio of symmetrical components). Another method of fault location using the change in voltage measurements is given in [32].

Fault passage indicators in distribution systems can be used to locate a faulted circuit section [33] based on a simple indication of current flow. Reference [34] presents a method for MV and LV systems using directional fault indicators which communicate with a control centre. Reference [35] presents an efficient method for fault location in distribution systems.

Pattern-matching, neural networks, expert systems, and other machine learning or rule-based methods to detect and locate grid disturbances [36]–[38]. The use of a bespoke real-time database of large-scale PMU data for event detection and fault location is described in [10]. Expert systems using, for example, "action factors" to combat uncertainty in order to identify the fault location [39]. In general, it is not clear if these systems could be used for protection applications where low latency is required.

---

[1] As noted in [50], fault location in distribution systems may require voltage angle measurements which are approximately two orders of magnitude more accurate than for transmission systems i.e. with a maximum phase error in the range 0.01-0.1°.

Model-based techniques, such as the use of a genetic algorithm to match multiple measurements to a simulated fault location and impedance [40]. Similar methods, for transmission and distribution systems, are described in [41]. Another approach is given in [42] using a real-time state estimation process. A further method is presented in [43], but with an impractical computational time approaching 100 ms. Reference [36] discusses a "physics-based" method to identify dynamic events from transmission system PMUs. These approaches all require power system impedances and other data.

4 Evaluation of Two Schemes

4.1 WAP Architecture for Multi-Area Power Systems

A radical new power system control architecture has been designed within the ELECTRA IRP research project [44] to directly address the challenges associated with the real-time operation of grids with highly-distributed resources. This architecture decentralises critical system functions – such as the provision of inertia, frequency containment, and balancing – into zones or "cells" which may be smaller than conventional Load Frequency Control (LFC) areas. Each cell is responsible for the provision and activation of reserves, communicating with neighbouring cells where necessary; this process will be automated rather than depending on manual input. This "divide and conquer" approach, which has been named the Web of Cells (WoC), is designed to allow the grid to efficiently scale to a very large number of measurable and controllable devices – without excessive computational requirements or communications delays.

Under such a radical new control paradigm, protection and automation strategies are required to detect emergent issues in real time and instruct a fast-acting response utilising flexible grid resources.

This section illustrates a proposed WAP architecture for the WoC structure. It may be tempting to utilise the well-known concept of a hierarchical or multi-layer Phasor Data Concentrator (PDC) architectures [5] within each of the cells that compose the power system. However, for protection applications, a hierarchical structure is not desirable because fault location requires granular measurements (rather than aggregated data) to be most effective, and these measurements should be delivered with as low latency as possible (i.e. avoiding multiple aggregation stages). Therefore, the proposed WAP architecture is "flat", where individual PMU measurements are communicated to a single WAP PDC. Separate WAP systems should also be applied at transmission and distribution levels; at distribution voltage levels, it is assumed that each cell would be protected by one or more separate instances of the wide protection scheme due to the less stringent requirements for protection operation, compared with transmission systems.

Two variants of the proposed architecture are presented:

1. **Separation of cells**, with a special case for tie-lines (Figure 2). Tie-lines may be protected using conventional methods such as current differential protection. This variant reduces the area over which the WAP system operates (potentially reducing the impact of communications delays), but the tie-lines do not benefit from the enhancements offered by wide protection (i.e. faster acting backup). This approach also may be appropriate for DC tie-lines which may not fit with the WAP operating principle, which may be designed for AC networks.
2. **"Overlapping" of cell boundaries** to include tie-lines within the WAP system (Figure 3). This requires slightly more measurements to be communicated to the cell PDCs, but ensures that the tie-lines are included within the wide area protection scheme. Note that Figure 3 shows each tie-line being included in the wide area protection scheme for both neighbouring cells; alternatively, a single cell could manage the WAP for a tie-line.

Further simulation-based evaluation of protection systems within the WoC architecture is given in [45], and will be further analysed in a upcoming publicly-available deliverable.

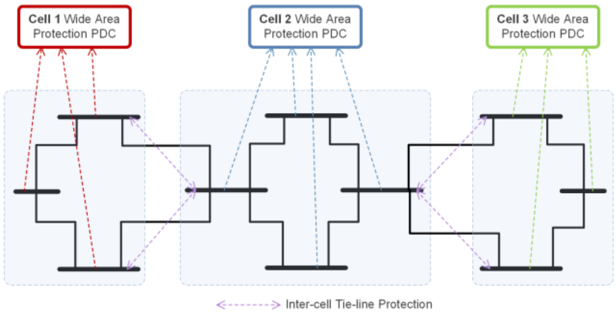

Figure 2: WAP architecture – without cell overlap

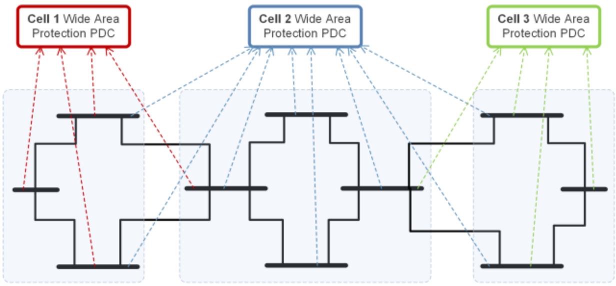

Figure 3: WAP architecture – with cell overlap

4.2 Validation of Distributed Photonic Sensing

Distributed photonic sensor systems offer a novel approach to integrate multiple voltage and current sensors over a wide area within a single optical fibre [46]. A central interrogator unit is able to process all measurements and deliver waveform data or synchrophasor data from each monitoring location. The sensors are passive, i.e. a power supply and a time synchronisation method are not required at any measurement location. Other parameters, such as temperature, can also be monitored. The main benefit of this approach is that synchronised, distributed measurements are available at the interrogator, enabling an unprecedented level of power system observability.

It is important that such a new approach maintains interoperability with other substation equipment and standards. In particular, a commercial prototype of the technology developed by Synaptec Ltd will be trialled in two operational high voltage substations in the UK in 2018 as part of the Future Intelligent Transmission Substation (FITNESS) project [47]. This section describes the implementation and testing of the Synaptec distributed optical sensing technology to perform as a wide-area Merging Unit (MU) and support the IEC 61850-9-2 Sampled Value (SV) protocol.

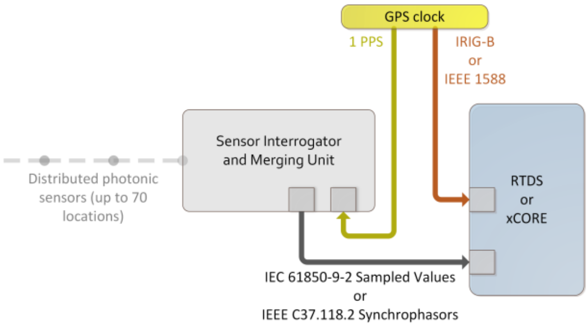

Figure 4: Interrogator SV validation

Figure 5: Hardware in the loop laboratory testbed

The method described in [48] has been used to develop the SV protocol implementation for the Synaptec MU. Two real-time platforms have been used to automatically validate the performance of the MU by monitoring SV Ethernet frames produced by the MU under test and enable the performance to be quantified. Figure 4 illustrates how a Real Time Digital Simulator (RTDS) has been used to capture the SV output from the MU and compare this with reference clock data (which is generated internally by the RTDS). The Synaptec MU and the RTDS are synchronised to the same Global Positioning System (GPS) clock source. The accuracy of the measurements made by the RTDS is limited by the simulation time-step of 50 µs. The hardware in the loop (HIL) laboratory testing arrangement is shown in Figure 5.

Figure 6 compares the behaviour of the SV data received from the MU under test with the reference MU generated internally by the RTDS. Figure 7 provides further detail of the "zero-crossing" to illustrate the difference between the two sample count plots. These plots confirm that the MU correctly produces SV data at the required 4 kHz sampling rate, with the sample count value ranging from 0 to 3999, and maintains synchronism over time. It can be observed that the MU lags the reference MU by approximately 1 ms, due to internal processing and communications requirements, which is within the transfer time requirement of 2 ms. Furthermore, using the xCORE platform and the accurate method and software available at [49], the SV data output has been monitored over a longer period to validate that the sample count attribute has been updated consistently; no inconsistencies have been observed.

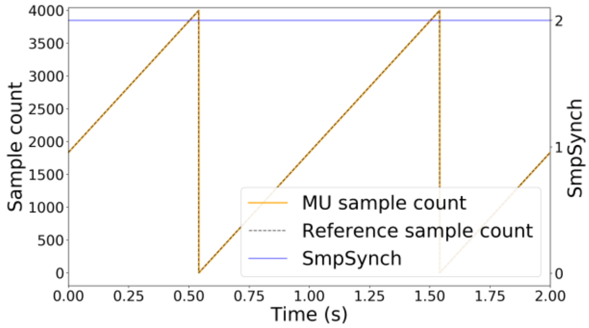

Figure 6: Validating SV latency measurement

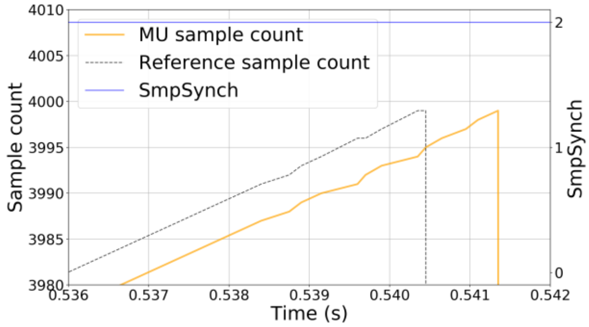

Figure 7: Validating SV latency measurement (zoomed)

5 Conclusions

This paper has captured and categorised the main methods for performing wide area protection using PMU data. A scalable, distributed architecture for wide area protection – assuming a high presence of PMUs – has been proposed. The importance of validating measurement data quality has also been highlighted, and this has been demonstrated for the IEC 61850-9-2 Sampled Value output from a novel wide-area Merging Unit; this also illustrates the importance of HIL testing of novel grid solutions. Further work will analyse the use of multiple different fault location methods, including realistic communications delays for PMU data. The authors will also validate the use of distributed photonic sensing systems to rapidly locate and isolate faults in hybrid circuits (i.e. circuits composed of cables and overhead lines), which are challenging and costly to protect using conventional protection methods.

Acknowledgements

The work in this paper has been in part supported by the European Commission, under the FP7 project ELECTRA (grant no: 609687). Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect those of the European Commission. The work has also been supported by the Energy Technology Partnership.

References

[1] P. Wall, N. Shams, V. Terzija, V. Hamidi, C. Grant, D. Wilson, S. Norris, K. Maleka, C. Booth, Q. Hong, and A. Roscoe, "Smart frequency control for the future GB power system," in *IEEE PES ISGT Europe*, 2016.

[2] E. G. Sansano, M. H. Syed, A. Roscoe, G. Burt, M. Stanovich, and K. Schoder, "Controller HIL testing of real-time distributed frequency control for future power systems," in *IEEE PES Innovative Smart Grid Technologies, Europe*, 2016.

[3] CIGRE Working Group B5.14, "Wide area protection & Control technologies," 2016.

[4] IEEE Power System Relaying Committee (PSRC) Working Group C-14, "Use of Synchrophasor Measurements in Protective Relaying Applications," 2013. [Online]. Available: http://www.pes-psrc.org/Reports/Use of Synchrophasor Measurements in Protective Relaying Applications_final.pdf.

[5] M. Begovic, D. Novosel, D. Karlsson, C. Henville, and G. Michel, "Wide-Area Protection and Emergency Control," *Proc. IEEE*, vol. 93, no. 5, pp. 876–891, May 2005.

[6] E. Udren, "Principles for Practical Wide-Area Backup Protection with Synchrophasor Communications," in *CIGRE Paris Session B5*, 2014.

[7] NERC, "Real-Time Application of Synchrophasors for Improving Reliability," 2010. [Online]. Available: http://www.nerc.com/docs/oc/rapirtf/RAPIR final 101710.pdf.

[8] EURAMET, "EURAMET Smart Grids II," 2017. [Online]. Available: http://www.smartgrids2.eu/.

[9] NASPI PMU Applications Requirements Task Force, "PMU Data Quality: A Framework for the Attributes of PMU Data Quality and a Methodology for Examining Data Quality Impacts to Synchrophasor Applications," 2017.

[10] A. von Meier, E. Stewart, A. McEachern, M. Andersen, and L. Mehrmanesh, "Precision Micro-Synchrophasors for Distribution Systems: A Summary of Applications," *IEEE Trans. Smart Grid*, pp. 1–1, 2017.

[11] NASPI Time Synchronization Task Force, "Time Synchronization in the Electric Power System," 2017.

[12] M. Biswal, S. M. Brahma, and H. Cao, "Supervisory Protection and Automated Event Diagnosis Using PMU Data," *IEEE Trans. Power Deliv.*, vol. 31, no. 4, pp. 1855–1863, Aug. 2016.

[13] V. Terzija, G. Valverde, Deyu Cai, P. Regulski, V. Madani, J. Fitch, S. Skok, M. M. Begovic, and A. Phadke, "Wide-Area Monitoring, Protection, and Control of Future Electric Power Networks," *Proc. IEEE*, vol. 99, no. 1, pp. 80–93, Jan. 2011.

[14] M. Kezunovic, A. Esmaeilian, T. Becejac, P. Dehghanian, and C. Qian, "Life Cycle Management Tools for Synchrophasor Systems: Why We Need Them and What They Should Entail," *IFAC-PapersOnLine*, vol. 49, no. 27, pp. 73–78, 2016.

[15] A.-J. Nikkilä, M. Kuivaniemi, and J. Seppänen, "Using wide area measurements to improve situational awareness and power system analytics in Finnish power system," *NASPI International Synchrophasor Symposium*, 2016. [Online]. Available: https://www.naspi.org/sites/default/files/2016-10/fingrid_nikkila_wide_area_measurements__20160322.pdf.

[16] Y. Gong, Y. Huang, and N. N. Schulz, "Integrated Protection System Design for Shipboard Power System," *IEEE Trans. Ind. Appl.*, vol. 44, no. 6, pp. 1930–1936, 2008.

[17] M. K. Neyestanaki and A. M. Ranjbar, "An Adaptive PMU-Based Wide Area Backup Protection Scheme for Power Transmission Lines," *IEEE Trans. Smart Grid*, vol. 6, no. 3, pp. 1550–1559, May 2015.

[18] S. Pati, C. K. Panigrahi, and P. R. Pattanaik, "A Superimposed Components based Fault Detector for Power System Applications," *Indian J. Sci. Technol.*, vol. 9, no. 13, Apr. 2016.

[19] R. K. Aggarwal, Y. Aslan, and A. T. Johns, "New concept in fault location for overhead distribution systems using superimposed components," *IEE Proc. - Gener. Transm. Distrib.*, vol. 144, no. 3, p. 309, 1997.

[20] A. P. Apostolov, D. Tholomier, and S. H. Richards, "Superimposed components based sub-cycle protection of transmission lines," in *IEEE PES Power Systems Conference and Exposition, 2004.*, 2004, pp. 508–513.

[21] M. M. A. Mahfouz and M. M. Eissa, "New high-voltage directional and phase selection protection technique based on real power system data," *IET Gener. Transm. Distrib.*, vol. 6, no. 11, pp. 1075–1085, Nov. 2012.

[22] X. Liang, S. A. Wallace, and D. Nguyen, "Rule-Based Data-Driven Analytics for Wide-Area Fault Detection Using Synchrophasor Data," *IEEE Trans. Ind. Appl.*, vol. 53, no. 3, pp. 1789–1798, May 2017.

[23] Y. Seyedi and H. Karimi, "Coordinated Protection and Control Based on Synchrophasor Data Processing in Smart Distribution Networks," *IEEE Trans. Power Syst.*, 2017.

[24] S. Brahma, "Advancements in Centralized Protection and Control within a Substation," *IEEE Trans. Power Deliv.*, vol. PP, no. 99, pp. 1–1, 2016.

[25] M. Kezunovic, "Translational Knowledge: From Collecting Data to Making Decisions in a Smart Grid," *Proc. IEEE*, vol. 99, no. 6, pp. 977–997, Jun.

2011.

[26] F. Yu, C. Booth, and A. Dyśko, “Backup Protection Requirements in Future Low-Inertia Power Systems,” in *51st International Universities’ Power Engineering Conference*, 2016.

[27] Z. Galijasevic and A. Abur, “Fault location using voltage measurements,” *IEEE Trans. Power Deliv.*, vol. 17, no. 2, pp. 441–445, Apr. 2002.

[28] M. M. Eissa, M. E. Masoud, and M. M. M. Elanwar, “A Novel Back Up Wide Area Protection Technique for Power Transmission Grids Using Phasor Measurement Unit,” *IEEE Trans. Power Deliv.*, vol. 25, no. 1, pp. 270–278, Jan. 2010.

[29] Z. Zhang, X. Kong, X. Yin, Z. Yang, and L. Wang, “A novel wide-area backup protection based on fault component current distribution and improved evidence theory.,” *ScientificWorldJournal.*, vol. 2014, p. 493739, 2014.

[30] J.-A. Jiang, Ching-Shan Chen, and Chih-Wen Liu, “A new protection scheme for fault detection, direction discrimination, classification, and location in transmission lines,” *IEEE Trans. Power Deliv.*, vol. 18, no. 1, pp. 34–42, Jan. 2003.

[31] F. Zhang and L. Mu, “Wide-area protection scheme for active distribution networks based on phase comparison,” in *2015 5th International Conference on Electric Utility Deregulation and Restructuring and Power Technologies (DRPT)*, 2015, pp. 927–932.

[32] Q. Jiang, X. Li, B. Wang, and H. Wang, “PMU-Based Fault Location Using Voltage Measurements in Large Transmission Networks,” *IEEE Trans. Power Deliv.*, vol. 27, pp. 1–1, 2012.

[33] I. Abdulhadi, F. Coffele, and C. Booth, “Testing of Distribution Network Fault Passage Indicators to Facilitate Enhanced Network Automation,” in *PAC World Conference*, 2015.

[34] K. Sun, Q. Chen, and Z. Gao, “An Automatic Faulted Line Section Location Method for Electric Power Distribution Systems Based on Multisource Information,” *IEEE Trans. Power Deliv.*, vol. 31, no. 4, pp. 1542–1551, Aug. 2016.

[35] J.-H. Teng, W.-H. Huang, and S.-W. Luan, “Automatic and Fast Faulted Line-Section Location Method for Distribution Systems Based on Fault Indicators,” *IEEE Trans. Power Syst.*, vol. 29, no. 4, pp. 1–10, 2014.

[36] S. Brahma, R. Kavasseri, H. Cao, N. R. Chaudhuri, T. Alexopoulos, and Y. Cui, “Real-Time Identification of Dynamic Events in Power Systems Using PMU Data, and Potential Applications—Models, Promises, and Challenges,” *IEEE Trans. Power Deliv.*, vol. 32, no. 1, pp. 294–301, Feb. 2017.

[37] V. Miranda, “Excess of Data, Lack of Models,” *IEEE PowerTech Conference*, 20017. [Online]. Available: http://sites.ieee.org/pes-powertech/files/2017/07/PowerTech-2017-Vladimiro-Miranda.pdf.

[38] M. Khan, P. M. Ashton, M. Li, G. A. Taylor, I. Pisica, and J. Liu, “Parallel Detrended Fluctuation Analysis for Fast Event Detection on Massive PMU Data,” *IEEE Trans. Smart Grid*, vol. 6, no. 1, pp. 360–368, Jan. 2015.

[39] J. C. Tan, P. A. Crossley, P. G. McLaren, I. Hall, J. Farrell, and P. Gale, “Sequential tripping strategy for a transmission network back-up protection expert system,” *IEEE Trans. Power Deliv.*, vol. 17, no. 1, pp. 68–74, 2002.

[40] M. Kezunovic, “Fault location estimation based on matching the simulated and recorded waveforms using genetic algorithms,” in *7th International Conference on Developments in Power Systems Protection (DPSP 2001)*, 2001, vol. 2001, pp. 399–402.

[41] M. Kezunovic, “Smart Fault Location for Smart Grids,” *IEEE Trans. Smart Grid*, vol. 2, no. 1, pp. 11–22, Mar. 2011.

[42] 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,” *IEEE Trans. Power Deliv.*, vol. 32, no. 1, pp. 381–392, Feb. 2017.

[43] J. Zare, F. Aminifar, and M. Sanaye-Pasand, “Synchrophasor-Based Wide-Area Backup Protection Scheme with Data Requirement Analysis,” *IEEE Trans. Power Deliv.*, vol. 30, no. 3, pp. 1410–1419, Jun. 2015.

[44] ELECTRA IRP, “European Liaison on Electricity Committed Towards long-term Research Activity - Integrated Research Programme,” 2013. [Online]. Available: http://www.electrairp.eu/.

[45] S. M. Blair, G. Burt, A. Lof, S. Hänninen, B. Kedra, M. Kosmecki, J. Merino, F. R. Belloni, D. Pala, M. Valov, B. Lüers, and A. Temiz, “Minimising the impact of disturbances in future highly-distributed power systems,” in *CIGRE B5 Symposium*, 2017.

[46] P. Orr, G. Fusiek, P. Niewczas, C. D. Booth, A. Dysko, F. Kawano, T. Nishida, and P. Beaumont, “Distributed Photonic Instrumentation for Power System Protection and Control,” *IEEE Trans. Instrum. Meas.*, vol. 64, no. 1, pp. 19–26, Jan. 2015.

[47] Scottish Power Ltd, “FITNESS – Future Intelligent Transmission Network SubStation,” 2017. [Online]. Available: https://www.spenergynetworks.co.uk/pages/fitness.aspx.

[48] S. M. Blair, F. Coffele, C. D. Booth, and G. M. Burt, “An Open Platform for Rapid-Prototyping Protection and Control Schemes with IEC 61850,” *IEEE Trans. Power Deliv.*, vol. 28, no. 2, pp. 1103–1110, 2013.

[49] S. M. Blair, “Real-time measurement of PMU reporting latency,” 2017. [Online]. Available: https://doi.org/10.5281/zenodo.400934.

[50] A. von Meier and R. Arghandeh, “Chapter 34 – Every Moment Counts: Synchrophasors for Distribution Networks with Variable Resources,” in *Renewable Energy Integration*, L. E. Jones, Ed. 2014, pp. 429–438.