DEVELOPMENT OF DIFFERENTIAL PROTECTION SCHEME USING POSITIVE SEQUENCE CURRENT FOR A MICROGRID

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To my beloved family, thank you

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ABSTRACT

The microgrid (MG) is a developed form of the distribution network integrated with different distributed generation (DG) types to supply local demand. MG protection is a challenge typically due to the growing penetration of DG. Therefore, traditional protection schemes are not appropriate for the MG system. Therefore, an appropriate protection scheme should be designed to protect the MG against all types of faults for both grid-connected and islanded modes for loop and radial configuration. This research presents a comprehensive protection scheme for an inverter-based MG. This scheme proposed an index based on positive sequence current to differentiate between fault on the protected line and fault at other lines. This index was applied as a means of the differential protection scheme for MG with multi-sources. Also, the scheme proposed a new *R*-ratio method to provide self-backup protection when the main protection fails. This method could overcome the low fault current problem of DG in the islanded mode. In order to evaluate the confirmation of the proposed scheme, a complete fault analysis for all selected locations in the MG test system has been carried out by using PSCAD/EMTDC software. The case studies considered in this study include single line-to-ground fault (SLGF), line-to-line fault (LLF), double-line-to ground fault (DLGF), and three-line to ground fault (LLLGF) for both operation modes, grid-connected and islanded, for radial and loop configuration. Also, an unbalanced load was tested. The results show that the maximum fault clearing time for the main protection in grid-connected mode and islanded mode of 31.5 ms and 34 ms respectively. In contrast, the maximum fault clearing time for backup protection in grid-connected and islanded modes is 115.5 ms and 130 ms, respectively. Compared with other schemes, adaptive, signal processing, overcurrent, fault current limiter and traditional differential in terms of the operation speed of protection scheme and the existing backup protection, the proposed scheme has a faster clearing time.

ABSTRAK

Mikrogrid (MG) ialah bentuk rangkaian pengedaran yang dibangunkan yang disepadukan dengan jenis penjanaan teragih (DG) yang berbeza untuk membekalkan permintaan tempatan. Perlindungan MG merupakan satu cabaran lazimnya disebabkan penembusan DG yang semakin meningkat. Oleh itu, skim perlindungan tradisional tidak sesuai untuk sistem MG. Oleh itu, skim perlindungan yang sesuai harus direka bentuk untuk melindungi MG daripada semua jenis kerosakan untuk kedua-dua mod bersambung grid dan pulau untuk konfigurasi gelung dan jejari. Penyelidikan ini membentangkan skim perlindungan komprehensif untuk MG berasaskan penyongsang. Skim ini mencadangkan indeks berdasarkan arus jujukan positif untuk membezakan antara kerosakan pada talian dilindungi dan kerosakan pada talian lain. Indeks ini digunakan sebagai satu cara skim perlindungan pembezaan untuk MG dengan pelbagai sumber. Juga, skim ini mencadangkan kaedah nisbah R baharu untuk menyediakan perlindungan sandaran diri apabila perlindungan utama gagal. Kaedah ini boleh mengatasi masalah arus kerosakan rendah DG dalam mod pulau. Bagi menilai pengesahan skim yang dicadangkan, analisis kerosakan lengkap untuk semua lokasi terpilih dalam sistem ujian MG telah dijalankan dengan menggunakan perisian PSCAD/EMTDC. Kajian kes yang dipertimbangkan dalam kajian ini termasuk sesar satu talian ke tanah (SLGF), sesar talian ke talian (LLF), sesar dua talian ke tanah (DLGF), dan sesar tiga talian ke tanah (LLLGF) untuk kedua-dua mod operasi, bersambung grid dan berpulau, untuk konfigurasi jejari dan gelung. Juga, beban yang tidak seimbang telah diuji. Keputusan menunjukkan bahawa masa pembersihan kerosakan maksimum untuk perlindungan utama dalam mod bersambung grid dan mod pulau masing-masing 31.5 ms dan 34 ms. Sebaliknya, masa pembersihan kerosakan maksimum untuk perlindungan sandaran dalam mod bersambung grid dan pulau ialah 115.5 ms dan 130 ms, masing-masing. Berbanding dengan skim lain, penyesuaian, pemprosesan isyarat, arus lebih, pengehad arus kerosakan dan pembezaan tradisional dari segi kelajuan operasi skim perlindungan dan perlindungan

sandaran sedia ada, skim yang dicadangkan mempunyai masa pembersihan yang lebih cepat.

CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS AND ABBREVIATIONS

ADC	–	Analogue to digital converter
AC	–	Alternative current
CB	–	Circuit breaker
CT	–	Current transformer
CTR	–	Current transformer ratio
DC	–	Direct current
DG	–	Distributed generation
d–q	–	Direct quadrature
DSP	–	Digital Signal Processing
EHV	–	Extra High Voltage
FCL	–	Fault current limiter
FT	–	Fourier Transform
HHT	–	Hilbert–Huang Transform
HIF	–	High impedance faults
HV	–	High voltage
IBDG	–	Inverter based DG
LL	–	Line to line
LLG	–	Line to line to ground
LV	–	Low voltage
MM	–	Mathematical Morphology
OC	–	Overcurrent
PCC	–	Point of common coupling
R	–	Relay
RMS	–	Root mean square
SFCC	–	Superconducting fault current controller
SFCL	–	Superconducting fault current limiters

SG	–	Synchronous generator
SLGF	–	Single line to ground fault
OT	–	Operating time
THD	–	Total harmonic distortion
UFCL	–	Unidirectional fault current limiter
V	–	Voltage
VT	–	Voltage transformer
WT	–	Wavelet Transform
I_p	–	Pick up current
I_r	–	Restraining current
sec	–	Second
V_{a0}	–	Zero voltage sequence in phase 'a'
V_{a1}	–	Positive voltage sequence in phase 'a'
V_{a2}	–	Negative voltage sequence in phase 'a'
$V_{\max}$	–	Maximum voltage limit
V_{min}	–	Minimum voltage limit
V_{ph}	–	Phase voltage
Z_l	–	The impedance of the fault current limiter
Z_u	–	The impedance of the circuit under fault condition
α and β	–	The slope of the relay characteristics
δ	–	Phase angle

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Background

In a conventional power system (PS), power is generated centrally and then transmitted to the customer using long transmission lines and distribution networks (DN). In this case, power flows are unidirectional in the DN. Nowadays, with the increase in load demand, developments in renewable energy sources (RES) technology and increasing concerns about global warming have led to a new trend of electricity production at the distribution level. These technologies are usually referred to as distributed generation (DG). The introduction of DGs causes significant changes in the network topology and its properties from the perspective of PS operation [1]–[3]. With DG integration, microgrid (MG) appears as another structure in PS.

The MG has become a common term for DN that contains conventional DGs, RES, or both. The DGs include photovoltaic, wind power, hydro, gas turbine, diesel generator, microturbine, fuel cells, and battery storage [4]. From [5]–[9], it can be observed that the number of MG is increasing with the trend of DGs based on RES. Furthermore, MG is also one of the possible solutions in improving the resiliency of DN against extreme weather [10]. This shows the importance of MG in the current PS operations in maintaining PS reliability in various sections.

MG is connected to the main grid by the point of common coupling (PCC), as shown in Figure 1.1. The ability of MG is to operate in both modes, islanded and grid-connected, making it more reliable compared to conventional PS. In addition, MG helps to reduce power losses in a power network, increase the stability of the network, and enhance the power quality (PQ) [11]–[13].

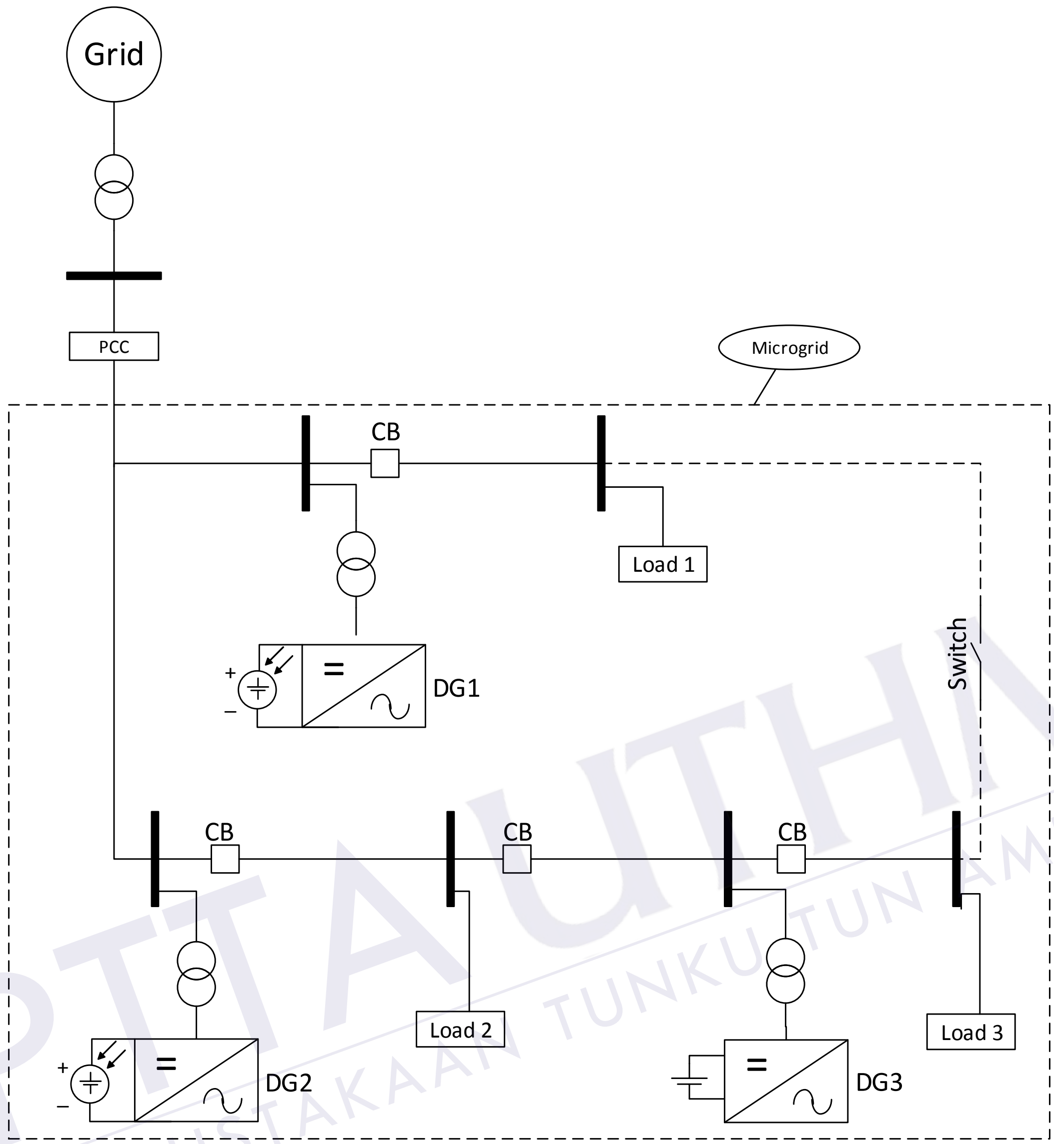

Figure 1.1: Single line diagram of MG

For grid-connected mode, the load in the MG was supplied by the utility and MG sources. While during islanded mode, only MG sources will be responsible for power generation. The concept of the MG is becoming popular where MG is expected to provide many advantages over traditional systems as follows [10], [14]:

- **Increase reliability:** MG provide a good solution to supply the islanded network during the disturbance in the main grid.
- **Improve energy efficiency:** the generation efficiency of a large power plant generally is low can reach 30 – 47% with transmission loss. While the efficiency of the MG system can reach above 80% without any transmission loss.

- **Reduce the overall operational burden:** MG reduces the burden on the grid by participating in various auxiliary services.
- **Mitigate overload problems:** a region of the PS is relieved by permitting a section of the PS to be islanded and eliminating load from the remainder of the PS.
- **Main grid maintenance:** allow for maintenance on the PS while allowing purposely islanded customers to stay supplied.
- **Environmental benefits:** using of RES contribute to reducing carbon emission.
- **Economic benefits:** Increasing the demand requires the installation of additional transmission lines to transfer the power to the customers, while the cost is lower than with DGs, which are often built immediately close to the load.

Despite the various advantages of MG, integrating a large number of DG sources will provide new problems to the DN protection system. As a result, the influence of DG on the DN must be carefully studied in order to provide proper protection design, allowing it to function successfully. The differential protection scheme is developed in this thesis based on a positive sequence index to protect the inverter-based MG system in both grid-connected and islanded operation modes.

1.2 Problem Statement

The MG represents one of the most important solutions to the problems of traditional generation-based fossil fuels. However, there are many technical challenges to ensure it operates effectively. MG protection and its entities are a significant impediment. The design of an appropriate protection scheme for MG is a major challenge for MG operation. The installation of DGs to the DN leads to multi-sources of the current, altering the current flow during a fault in a different section of the feeder circuit.

Furthermore, there is a large difference in fault current level between the islanded and grid-connected modes. When the MG works independently of the main grid, the fault currents are small due to the limited current-carrying capacity of power electronics devices. The fault current is merely 1.2–3 times of rated current in the case of inverter-based DGs (IBDGs) [15]–[17], while synchronous generators, in grid-connected mode, can generate a fault current that is 4–10 times greater than IBDGs [18]. Thus, the coordination of traditional overcurrent (OC) protection is difficult for these two operation modes.

The differential protection scheme considers as one of the potential solutions for MG protection because it has a high sensitivity, more reliability, sufficient selectivity and high-speed tripping. However, the main disadvantage in this scheme is the need for an independent backup protection scheme, as there is a possibility that the communication system may fail. In addition to current transformer (CT) errors, CT matching and tap transformer. Adding backup protection means an additional cost due to installing other equipment (CT, VT, battery etc.) as well as to the complexity of coordination of the protective devices [17], [19], [20]. Therefore, a backup protection scheme that uses the same equipment as the main protection scheme is preferable from the operation point of view and the cost of the system. When PS is subjected to a fault and the main protection fail to clear this fault, the backup of the adjacent line must be energized and isolate the fault.

1.3 Objectives of the study

This study aims to protect the MG system having IBDGs in grid-connected and islanded modes of operation. The specific objectives of the work are:

(i) To propose an index-based positive sequence fault current as a means to detect the fault in the protected line.

(ii) To enhance the differential protection scheme for MG with multi-sources suitable for grid-connected and islanded modes of operations.

(iii) To develop a self-backup protection scheme to protect the adjacent lines in case of failure of the main protection scheme.

REFERENCES

[1] B. Julio and R. Agüero, "The Utility and Grid of the Future," vol. 14, no. 5, pp. 29–37, 2016.

[2] A. Hooshyar and R. Iravani, "Microgrid Protection," *Proc. IEEE,* vol. 105, no. 7, pp. 1332–1353, 2017, doi: 10.1109/JPROC.2017.2669342.

[3] P. T. Manditereza and R. C. Bansal, "Introducing A New Type of Protection Zone for the Smart Grid Incorporating Distributed Generation," *Int. Conf. Innov. Smart Grid Technol. ISGT Asia 2018*, pp. 86–90, 2018, doi: 10.1109/ISGT-Asia.2018.8467792.

[4] B. Han, H. Li, G. Wang, D. Zeng, and Y. Liang, "A Virtual Multi-Terminal Current Differential Protection Scheme for Distribution Networks with Inverter-Interfaced Distributed Generators," *IEEE Trans. Smart Grid*, vol. 9, no. 5, pp. 5418–5431, 2018, doi: 10.1109/TSG.2017.2749450.

[5] S. A. Hosseini, H. A. Abyaneh, S. H. H. Sadeghi, F. Razavi, and A. Nasiri, "An overview of microgrid protection methods and the factors involved," *Renew. Sustain. Energy Rev.*, vol. 64, pp. 174–186, Oct. 2016, doi: 10.1016/J.RSER.2016.05.089.

[6] B. J. Brearley and R. R. Prabu, "A review on issues and approaches for microgrid protection," *Renew. Sustain. Energy Rev.*, vol. 67, pp. 988–997, 2017, doi: 10.1016/j.rser.2016.09.047.

[7] S. Mirsaeidi, D. Mat Said, M. Wazir Mustafa, M. Hafiz Habibuddin, and K. Ghaffari, "Progress and problems in micro-grid protection schemes," *Renew. Sustain. Energy Rev.*, vol. 37, pp. 834–839, 2014, doi: 10.1016/j.rser.2014.05.044.

[8] A. A. Memon and K. Kauhaniemi, "A critical review of AC Microgrid

protection issues and available solutions," *Electr. Power Syst. Res.*, vol. 129, pp. 23–31, 2015, doi: 10.1016/j.epsr.2015.07.006.

[9] S. A. Gopalan, V. Sreeram, and H. H. C. Iu, "A review of coordination strategies and protection schemes for microgrids," *Renew. Sustain. Energy Rev.*, vol. 32, pp. 222–228, 2014, doi: 10.1016/j.rser.2014.01.037.

[10] E. Sortomme, S. S. Venkata, and J. Mitra, "Microgrid protection using communication-assisted digital relays," *IEEE Trans. Power Deliv.*, vol. 25, no. 4, pp. 2789–2796, 2010, doi: 10.1109/TPWRD.2009.2035810.

[11] D. P. Mishra, S. R. Samantaray, and G. Joos, "A combined wavelet and data-mining based intelligent protection scheme for microgrid," *IEEE Trans. Smart Grid*, vol. 7, no. 5, pp. 2295–2304, 2016, doi: 10.1109/TSG.2015.2487501.

[12] D. A. Gadanayak and R. K. Mallick, "Microgrid differential protection scheme using downsampling empirical mode decomposition and Teager energy operator," *Electr. Power Syst. Res.*, vol. 173, no. February, pp. 173–182, 2019, doi: 10.1016/j.epsr.2019.04.022.

[13] O. Núñez-Mata, R. Palma-Behnke, F. Valencia, P. Mendoza-Araya, and G. Jiménez-Estévez, "Adaptive protection system for microgrids based on a robust optimization strategy," *Energies*, vol. 11, no. 2, 2018, doi: 10.3390/en11020308.

[14] C. 21 IEEE Standards Coordinating, *IEEE Guide for Design, Operation, and Integration of Distributed Resource Island Systems with Electric Power Systems*, no. July. 2011.

[15] Z. Liang, L. Mu, F. Zhang, H. Zhou, and X. Zhang, "The fault detection method of islanded microgrid with the V/f controlled distributed generation," *Int. J. Electr. Power Energy Syst.*, vol. 112, no. December 2018, pp. 28–35, 2019, doi: 10.1016/j.ijepes.2019.04.030.

[16] S. Yang and X. Tong, "Integrated power flow and short circuit calculation method for distribution network with inverter based distributed generation," *Math. Probl. Eng.*, vol. 2016, 2016, doi: 10.1155/2016/9404951.

[17] S. Mirsaeidi, D. Mat Said, M. Wazir Mustafa, M. Hafiz Habibuddin, and K. Ghaffari, "An analytical literature review of the available techniques for the protection of micro-grids," *Int. J. Electr. Power Energy Syst.*, vol. 58, pp. 300–306, 2014, doi: 10.1016/j.ijepes.2014.01.032.

[18] E. Casagrande, W. L. Woon, H. H. Zeineldin, and D. Svetinovic, "A differential sequence component protection scheme for microgrids with inverter-based distributed generators," *IEEE Trans. Smart Grid*, vol. 5, no. 1, pp. 29–37, 2014, doi: 10.1109/TSG.2013.2251017.

[19] M. Norshahrani, H. Mokhlis, A. H. A. Bakar, J. J. Jamian, and S. Sukumar, "Progress on protection strategies to mitigate the impact of renewable distributed generation on distribution systems," *Energies*, vol. 10, no. 11. pp. 1–30, 2017, doi: 10.3390/en10111864.

[20] X. Kang, C. E. K. Nuworklo, B. S. Tekpeti, and M. Kheshti, "Protection of micro-grid systems : a comprehensive survey," no. October, pp. 19–20, 2017, doi: 10.1049/joe.2017.0584.

[21] X. Qin, B. Li, Q. Guo, S. Hong, Q. Zhou, and T. Bi, "Study on power system disturbance identification and location based on WAMS," *IEEE Power Energy Soc. Gen. Meet.*, pp. 0–5, 2012, doi: 10.1109/PESGM.2012.6345756.

[22] R. S. Tiwari and O. H. Gupta, "Study of Combined Time & Current Grading Protection Scheme for Distribution System," *2020 Int. Conf. Power Electron. IoT Appl. Renew. Energy its Control. PARC 2020*, pp. 443–448, 2020, doi: 10.1109/PARC49193.2020.236651.

[23] T. Loix, T. Wijnhoven, and G. Deconinck, "Protection of microgrids with a high penetration of inverter-coupled energy sources," *2009 CIGRE / EEE PES Jt. Symp. Integr. Wide-Scale Renew. Resour. into Power Deliv. Syst.*, pp. 1–6, 2009.

[24] L. Chen and S. Mei, "An integrated control and protection system for photovoltaic microgrids," *CSEE J. Power Energy Syst.*, vol. 1, no. 1, pp. 36–42, 2015, doi: 10.17775/cseejpes.2015.00005.

[25] H. Margossian, J. Sachau, and G. Deconinck, "Short circuit calculation in

networks with a high share of inverter based distributed generation," *2014 IEEE 5th Int. Symp. Power Electron. Distrib. Gener. Syst. PEDG 2014*, no. September, 2014, doi: 10.1109/PEDG.2014.6878629.

[26] I. Seol, B. Ha, M. Jung, and Y. Jung, "The development of optimal protection coordination program for distribution automation system among the protective devices," *Proc. IEEE Power Eng. Soc. Transm. Distrib. Conf.*, vol. 2005, pp. 1–5, 2005, doi: 10.1109/tdc.2005.1546986.

[27] W. Rebizant, J. Szafran, and A. Wiszniewski, "Hardware and Functional Development of Protection Devices and Systems," 2011, pp. 13–27.

[28] J. Gers, *Protection of Electricity Distribution Networks*, 2nd ed. IEE Power and Energy Series.

[29] J. T. Blackburn, J. Lewis; Domin, *Protective Relaying Principles and Applicaitons*, 4th ed. Taylor & Francis Group, 2014.

[30] S. H. Horowitz, A. G. Phadke, and J. K. Niemira, *Power System Relaying*, 4th ed. John Wiley and Sons Ltd, 2013.

[31] G. (SIEMENS) Ziegler, *Numerical Distance Protection Principles and applications*, 4th ed. Publicis Publishing, 2008.

[32] H. Cheung, A. Hamlyn, L. Wang, C. Yang, and R. Cheung, "Investigations of impacts of distributed generations on feeder protections," *2009 IEEE Power Energy Soc. Gen. Meet. PES '09*, 2009, doi: 10.1109/PES.2009.5275220.

[33] S. Conti, "Analysis of distribution network protection issues in presence of dispersed generation," *Electr. Power Syst. Res.*, vol. 79, no. 1, pp. 49–56, 2009, doi: 10.1016/j.epsr.2008.05.002.

[34] E. J. Coster, J. M. A. Myrzik, B. Kruimer, and W. L. Kling, "Integration Issues of Distributed Generation in Distribution Grids," *Proc. IEEE*, vol. 99, no. 1, pp. 28–39, 2011, doi: 10.1109/JPROC.2010.2052776.

[35] A. R. Haron, A. Mohamed, H. Shareef, and H. Zayandehroodi, "Analysis and solutions of overcurrent protection issues in a microgrid," *PECon 2012 - 2012 IEEE Int. Conf. Power Energy*, no. December, pp. 644–649, 2012, doi:

10.1109/PECon.2012.6450293.

[36] B. Hussain, S. M. Sharkh, and S. Hussain, "Impact studies of distributed generation on power quality and protection setup of an existing distribution network," *Power Electron. Electr. Drives Autom. Motion (SPEEDAM), 2010 Int. Symp.*, pp. 1243–1246, 2010, doi: 10.1109/SPEEDAM.2010.5545061.

[37] K. Kauhaniemi and L. Kumpulainen, "Impact of distributed generation on the protection of distribution networks," in *IEE Conference Publication*, 2004, vol. 1, no. Mv, pp. 315–318, doi: 10.1049/cp:20040126.

[38] L. Kumpulainen and K. Kauhaniemi, "Analysis of the impact of distributed generation on automatic reclosing," *Power Syst. Conf. …*, pp. 1–6, 2004, doi: 10.1109/PSCE.2004.1397623.

[39] M. R. Miveh, M. Gandomkar, S. Mirsaeidi, and M. R. Gharibdoost, "A review on protection challenges in microgrids," *2012 Proc. 17th Conf. Electr. Power Distrib. EPDC 2012*, 2012.

[40] J. Morren and S. W. H. D. Haan, "Impact of distributed generation units with power electronic converters on distribution network protection," *Dev. Power Syst. Prot. 2008. DPSP 2008. IET 9th Int. Conf.*, pp. 664–669, 2008, doi: 10.1049/cp:20080118.

[41] K. Tuitemwong and S. Premrudeepreechacharn, "Expert system for protection coordination of distribution system with distributed generators," *Int. J. Electr. Power Energy Syst.*, vol. 33, no. 3, pp. 466–471, 2011, doi: 10.1016/j.ijepes.2010.10.009.

[42] A. Zamani, T. Sidhu, and A. Yazdani, "A strategy for protection coordination in radial distribution networks with distributed generators," in *IEEE PES General Meeting, PES 2010*, 2010, pp. 1–8, doi: 10.1109/PES.2010.5589655.

[43] N. Zhou, X. Lei, X. Jing, X. He, and Z. Jiao, "Study on the Influence of Distribution Generation on Over Current Relays in Distribution Networks," 2015, no. Icaees, pp. 989–994, doi: 10.2991/icaees-15.2015.182.

[44] A. Girgis and S. Brahma, "Effect of distributed generation on protective device

coordination in distribution system," *LESCOPE 2001 - 2001 Large Eng. Syst. Conf. Power Eng. Powering Beyond 2001, Conf. Proc.*, pp. 115–119, 2001, doi: 10.1109/LESCPE.2001.941636.

[45] T. S. Ustun, C. Ozansoy, and A. Zayegh, "Fault Current Coef fi cient and Time Delay Assignment for Microgrid Protection System," *Power Syst. IEEE …*, vol. 28, no. 2, pp. 598–606, 2013, [Online]. Available: http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=6308748.

[46] P. N. Vovos, A. E. Kiprakis, A. R. Wallace, and G. P. Harrison, "Centralized and distributed voltage control: Impact on distributed generation penetration," *IEEE Trans. Power Syst.*, vol. 22, no. 1, pp. 476–483, 2007, doi: 10.1109/TPWRS.2006.888982.

[47] P. H. A. Barra, D. V. Coury, and R. A. S. Fernandes, "A survey on adaptive protection of microgrids and distribution systems with distributed generators," *Renew. Sustain. Energy Rev.*, vol. 118, no. October 2019, pp. 1–16, 2020, doi: 10.1016/j.rser.2019.109524.

[48] G. D. Rockefeller, C. L. Wagner, J. R. Linders, K. L. Hicks, and D. T. Rizy, "Adaptive transmission relaying concepts for improved performance," *IEEE Trans. Power Deliv.*, vol. 3, no. 4, pp. 1446–1458, 1988, doi: 10.1109/61.193943.

[49] L. Che, M. E. Khodayar, and M. Shahidehpour, "Adaptive protection system for microgrids: Protection practices of a functional microgrid system," *IEEE Electrif. Mag.*, vol. 2, no. 1, pp. 66–80, 2014, doi: 10.1109/MELE.2013.2297031.

[50] Z. Alhadrawi, M. N. Abdullah, and H. Mokhlis, "An adjustable differential protection scheme for microgrids with inverter-based distributed generation," *Int. J. Adv. Trends Comput. Sci. Eng.*, vol. 9, no. 1 Special Issue 4, pp. 664–672, 2020, doi: 10.30534/ijatcse/2020/9391.42020.

[51] R. Sitharthan, M. Geethanjali, and T. Karpaga Senthil Pandy, "Adaptive protection scheme for smart microgrid with electronically coupled distributed generations," *Alexandria Eng. J.*, vol. 55, no. 3, pp. 2539–2550, 2016, doi:

10.1016/j.aej.2016.06.025.

[52] E. C. Piesciorovsky and N. N. Schulz, “Comparison of Programmable Logic and Setting Group Methods for adaptive overcurrent protection in microgrids,” *Electr. Power Syst. Res.*, vol. 151, pp. 273–282, 2017, doi: 10.1016/j.epsr.2017.05.035.

[53] P. Mahat, Z. Chen, B. Bak-Jensen, and C. L. Bak, “A Simple Adaptive Overcurrent Protection of Distribution Systems With Distributed Generation,” *Smart Grid, IEEE Trans.*, vol. 2, no. 3, pp. 428–437, 2011, doi: 10.1109/TSG.2011.2149550.

[54] E. C. Piesciorovsky and N. N. Schulz, “Fuse relay adaptive overcurrent protection scheme for microgrid with distributed generators,” *IET Gener. Transm. Distrib.*, vol. 11, no. 2, pp. 540–549, 2017, doi: 10.1049/iet-gtd.2016.1144.

[55] T. S. Ustun and R. H. Khan, “Multiterminal Hybrid Protection of Microgrids over Wireless Communications Network,” *IEEE Trans. Smart Grid*, vol. 6, no. 5, pp. 2493–2500, 2015, doi: 10.1109/TSG.2015.2406886.

[56] O. V. Gnana Swathika and S. Hemamalini, “Prims-Aided Dijkstra Algorithm for Adaptive Protection in Microgrids,” *IEEE J. Emerg. Sel. Top. Power Electron.*, vol. 4, no. 4, pp. 1279–1286, 2016, doi: 10.1109/JESTPE.2016.2581986.

[57] F. Coffele, C. Booth, and A. Dysko, “An Adaptive Overcurrent Protection Scheme for Distribution Networks,” *IEEE Trans. Power Deliv.*, vol. 30, no. 2, pp. 561–568, 2015, doi: 10.1109/TPWRD.2013.2294879.

[58] H. Muda and P. Jena, “Superimposed Adaptive Sequence Current Based Microgrid Protection: A New Technique,” *IEEE Trans. Power Deliv.*, vol. 32, no. 2, pp. 757–767, 2017, doi: 10.1109/TPWRD.2016.2601921.

[59] J. Ma, X. Wang, Y. Zhang, Q. Yang, and A. G. Phadke, “A novel adaptive current protection scheme for distribution systems with distributed generation,” *Int. J. Electr. Power Energy Syst.*, vol. 43, no. 1, pp. 1460–1466, 2012, doi: 10.1016/j.ijepes.2012.07.024.

[60] B. Hussain, S. M. Sharkh, S. Hussain, and M. A. Abusara, “An adaptive relaying scheme for fuse saving in distribution networks with distributed generation,” *IEEE Trans. Power Deliv.*, vol. 28, no. 2, pp. 669–677, 2013, doi: 10.1109/TPWRD.2012.2224675.

[61] P. H. Shah and B. R. Bhalja, “New adaptive digital relaying scheme to tackle recloser–fuse miscoordination during distributed generation interconnections,” *IET Gener. Transm. Distrib.*, vol. 8, no. 4, pp. 682–688, 2014, doi: 10.1049/iet-gtd.2013.0222.

[62] M. H. Cintuglu, T. Ma, and O. A. Mohammed, “Protection of Autonomous Microgrids Using Agent-Based Distributed Communication,” *IEEE Trans. Power Deliv.*, vol. 32, no. 1, pp. 351–360, 2017, doi: 10.1109/TPWRD.2016.2551368.

[63] H. F. Habib, A. A. S. Mohamed, M. El Hariri, and O. A. Mohammed, “Utilizing supercapacitors for resiliency enhancements and adaptive microgrid protection against communication failures,” *Electr. Power Syst. Res.*, vol. 145, pp. 223–233, 2017, doi: 10.1016/j.epsr.2016.12.027.

[64] S. B. A. Bukhari, R. Haider, M. Saeed Uz Zaman, Y. S. Oh, G. J. Cho, and C. H. Kim, “An interval type-2 fuzzy logic based strategy for microgrid protection,” *Int. J. Electr. Power Energy Syst.*, vol. 98, no. December 2017, pp. 209–218, 2018, doi: 10.1016/j.ijepes.2017.11.045.

[65] D. S. Kumar, D. Srinivasan, and T. Reindl, “A Fast and Scalable Protection Scheme for Distribution Networks with Distributed Generation,” *IEEE Trans. Power Deliv.*, vol. 31, no. 1, pp. 67–75, 2016, doi: 10.1109/TPWRD.2015.2464107.

[66] S. Kar, S. R. Samantaray, and M. D. Zadeh, “Data-Mining Model Based Intelligent Differential Microgrid Protection Scheme,” *IEEE Syst. J.*, vol. 11, no. 2, pp. 1161–1169, 2017, doi: 10.1109/JSYST.2014.2380432.

[67] M. Manohar, E. Koley, and S. Ghosh, “Reliable protection scheme for PV integrated microgrid using an ensemble classifier approach with real-time validation,” *IET Sci. Meas. Technol.*, vol. 12, no. 2, pp. 200–208, 2018, doi:

10.1049/iet-smt.2017.0270.

[68] S. A. Saleh, R. Ahshan, M. S. Abu-Khaizaran, B. Alsayid, and M. A. Rahman, “Implementing and testing d-q WPT-based digital protection for microgrid systems,” *IEEE Trans. Ind. Appl.*, vol. 50, no. 3, pp. 2173–2185, 2014, doi: 10.1109/TIA.2013.2290814.

[69] S. A. Saleh, “Signature-coordinated digital multirelay protection for microgrid systems,” *IEEE Trans. Power Electron.*, vol. 29, no. 9, pp. 4614–4623, 2014, doi: 10.1109/TPEL.2013.2285978.

[70] J. J. Q. Yu, Y. Hou, A. Y. S. Lam, and V. O. K. Li, “Intelligent Fault Detection Scheme for Microgrids with Wavelet-based Deep Neural Networks,” *IEEE Trans. Smart Grid*, vol. 3053, no. c, pp. 1–10, 2017, doi: 10.1109/TSG.2017.2776310.

[71] M. A. Farhan and S. S. K, “Mathematical morphology-based islanding detection for distributed generation,” *IET Gener. Transm. Distrib.*, vol. 11, no. 14, pp. 3449–3457, 2017, doi: 10.1049/iet-gtd.2016.1163.

[72] X. Li, A. Dysko, and G. M. Burt, “Traveling wave-based protection scheme for inverter-dominated microgrid using mathematical morphology,” *IEEE Trans. Smart Grid*, vol. 5, no. 5, pp. 2211–2218, 2014, doi: 10.1109/TSG.2014.2320365.

[73] A. Gururani, S. R. Mohanty, and J. C. Mohanta, “Microgrid protection using Hilbert–Huang transform based-differential scheme,” *IET Gener. Transm. Distrib.*, vol. 10, no. 15, pp. 3707–3716, 2016, doi: 10.1049/iet-gtd.2015.1563.

[74] M. Mishra and P. K. Rout, “Detection and classification of micro-grid faults based on HHT and machine learning techniques,” *IET Gener. Transm. Distrib.*, vol. 12, no. 2, pp. 388–397, 2018, doi: 10.1049/iet-gtd.2017.0502.

[75] S. B. A. Bukhari, M. Saeed Uz Zaman, R. Haider, Y. S. Oh, and C. H. Kim, “A protection scheme for microgrid with multiple distributed generations using superimposed reactive energy,” *Int. J. Electr. Power Energy Syst.*, vol. 92, pp. 156–166, 2017, doi: 10.1016/j.ijepes.2017.05.003.

[76] S. Kar and S. R. Samantaray, “Time-frequency transform-based differential scheme for microgrid protection,” *IET Gener. Transm. Distrib.*, vol. 8, no. 2, pp. 310–320, 2014, doi: 10.1049/iet-gtd.2013.0180.

[77] S. Kar and S. R. Samantaray, “Combined S-transform and data-mining based intelligent micro-grid protection scheme,” *SCES 2014 Inspiring Eng. Syst. Glob. Sustain.*, pp. 1–5, 2014, doi: 10.1109/SCES.2014.6880053.

[78] K. Lai, M. Illindala, and M. Haj-ahmed, “Comprehensive Protection Strategy for an Islanded Microgrid Using Intelligent Relays,” *Ind. Appl. Soc. Annu. Meet.*, vol. 53, no. 1, pp. 1–11, 2015, doi: 10.1109/IAS.2015.7356952.

[79] K. O. Oureilidis and C. S. Demoulias, “A Fault Clearing Method in Converter-Dominated Microgrids with Conventional Protection Means,” *IEEE Trans. Power Electron.*, vol. 31, no. 6, pp. 4628–4640, 2016, doi: 10.1109/TPEL.2015.2476702.

[80] A. H. A. Bakar, B. Ooi, P. Govindasamy, C. Tan, H. A. Illias, and H. Mokhlis, “Directional overcurrent and earth-fault protections for a biomass microgrid system in Malaysia,” *Int. J. Electr. Power Energy Syst.*, vol. 55, pp. 581–591, 2014, doi: 10.1016/j.ijepes.2013.10.004.

[81] A. Hooshyar and R. Iravani, “A New Directional Element for Microgrid Protection,” *IEEE Trans. Smart Grid*, vol. 9, no. 6, pp. 6862–6876, Nov. 2018, doi: 10.1109/TSG.2017.2727400.

[82] M. A. Zamani, A. Yazdani, and T. S. Sidhu, “Investigations Into the Control and Protection of an Existing Distribution Network to Operate as a Microgrid: A Case Study,” *IET Conf. Renew. Power Gener. (RPG 2011)*, no. c, pp. 42–42, 2011, doi: 10.1049/cp.2011.0115.

[83] A. H. Etemadi and R. Iravani, “Overcurrent and overload protection of directly voltage-controlled distributed resources in a microgrid,” *IEEE Trans. Ind. Electron.*, vol. 60, no. 12, pp. 5629–5638, 2013, doi: 10.1109/TIE.2012.2229680.

[84] D. M. Bui, K.-Y. Lien, S.-L. Chen, Y.-C. Lu, C.-M. Chan, and Y.-R. Chang, “Investigate dynamic and transient characteristics of microgrid operation and

develop a fast-scalable-adaptable algorithm for fault protection system," *Electr. Power Syst. Res.*, vol. 120, pp. 214–233, Mar. 2015, doi: 10.1016/j.epsr.2014.04.003.

[85] E. Sortomme, S. S. Venkata, and J. Mitra, "Microgrid protection using communication-assisted digital relays," *IEEE Trans. Power Deliv.*, vol. 25, no. 4, pp. 2789–2796, 2010, doi: 10.1109/TPWRD.2009.2035810.

[86] K. Y. Lien *et al.*, "A novel fault protection system using communication-assisted digital relays for AC microgrids having a multiple grounding system," *Int. J. Electr. Power Energy Syst.*, vol. 78, pp. 600–625, 2016, doi: 10.1016/j.ijepes.2015.12.019.

[87] A. Hussain, M. Aslam, and S. M. Arif, "N-version programming-based protection scheme for microgrids: A multi-agent system based approach," *Sustain. Energy, Grids Networks*, vol. 6, pp. 35–45, 2016, doi: 10.1016/j.segan.2016.02.001.

[88] Z. Akhtar and M. A. Saqib, "Microgrids formed by renewable energy integration into power grids pose electrical protection challenges," *Renew. Energy*, vol. 99, pp. 148–157, 2016, doi: 10.1016/j.renene.2016.06.053.

[89] A. Khademlahashy, L. Li, J. Every, and J. Zhu, "A review on protection issues in micro-grids embedded with distribution generations," *Proc. 2017 12th IEEE Conf. Ind. Electron. Appl. ICIEA 2017*, vol. 2018-Febru, pp. 913–918, 2018, doi: 10.1109/ICIEA.2017.8282969.

[90] M. Alam, M. Abido, and I. El-Amin, "Fault Current Limiters in Power Systems: A Comprehensive Review," *Energies*, vol. 11, no. 5, pp. 1–24, Apr. 2018, doi: 10.3390/en11051025.

[91] W. K. A. Najy, H. H. Zeineldin, and W. L. Woon, "Optimal protection coordination for microgrids with grid-connected and islanded capability," *IEEE Trans. Ind. Electron.*, vol. 60, no. 4, pp. 1668–1677, 2013, doi: 10.1109/TIE.2012.2192893.

[92] L. Huchel, H. H. Zeineldin, and E. F. El-Saadany, "Protection Coordination Index Enhancement Considering Multiple DG Locations Using FCL," *IEEE*

Trans. Power Deliv., vol. 32, no. 1, pp. 344–350, 2017, doi: 10.1109/TPWRD.2016.2533565.

[93] A. Elmitwally, E. Gouda, and S. Eladawy, “Optimal allocation of fault current limiters for sustaining overcurrent relays coordination in a power system with distributed generation,” *Alexandria Eng. J.*, vol. 54, no. 4, pp. 1077–1089, 2015, doi: 10.1016/j.aej.2015.06.009.

[94] T. Ghanbari and E. Farjah, “Unidirectional fault current limiter: An efficient interface between the microgrid and main network,” *IEEE Trans. Power Syst.*, vol. 28, no. 2, pp. 1591–1598, 2013, doi: 10.1109/TPWRS.2012.2212728.

[95] K. Wheeler, M. Elsamahy, and S. Faried, “Use of superconducting fault current limiters for mitigation of distributed generation influences in radial distribution network fuse–recloser protection systems,” *IET Gener. Transm. Distrib.*, vol. 11, no. 7, pp. 1605–1612, 2017, doi: 10.1049/iet-gtd.2015.1156.

[96] H. He *et al.*, “Application of a SFCL for Fault Ride-Through Capability Enhancement of DG in a Microgrid System and Relay Protection Coordination,” *IEEE Trans. Appl. Supercond.*, vol. 26, no. 7, pp. 1–8, Oct. 2016, doi: 10.1109/TASC.2016.2599898.

[97] M. Ebrahimpour, B. Vahidi, and S. H. Hosseinian, “A Hybrid Superconducting Fault Current Controller for DG Networks and Microgrids,” *IEEE Trans. Appl. Supercond.*, vol. 23, no. 5, pp. 1–6, Oct. 2013, doi: 10.1109/TASC.2013.2267776.

[98] S. F. Zarei and M. Parniani, “A Comprehensive Digital Protection Scheme for Low-Voltage Microgrids with Inverter-Based and Conventional Distributed Generations,” *IEEE Trans. Power Deliv.*, vol. 32, no. 1, pp. 441–452, 2017, doi: 10.1109/TPWRD.2016.2566264.

[99] H. Zeineldin, E. El-saadany, and M. A. Salama, “Distributed Generation Micro-Grid Operation: Control and Protection,” in *2006 Power Systems Conference: Advanced Metering, Protection, Control, Communication, and Distributed Resources*, 2006, pp. 105–111, doi: 10.1109/PSAMP.2006.285379.

[100] S. Conti, L. Raffa, and U. Vagliasindi, “Innovative solutions for protection

schemes in autonomous MV micro-grids," *2009 Int. Conf. Clean Electr. Power, ICCEP 2009*, pp. 647–654, 2009, doi: 10.1109/ICCEP.2009.5211985.

[101] M. Dewadasa, A. Ghosh, and G. Ledwich, "Protection of microgrids using differential relays," in *2011 21st Australasian Universities Power Engineering Conference, AUPEC 2011*, 2011, pp. 1–6.

[102] A. Soleimanisardoo, H. K. Karegar, and H. H. Zeineldin, "Differential frequency protection scheme based on off-nominal frequency injections for inverter-based islanded microgrids," *IEEE Trans. Smart Grid*, vol. 10, no. 2, pp. 2107–2114, 2019, doi: 10.1109/TSG.2017.2788851.

[103] A. H. Abdulwahid and S. Wang, "A new differential protection scheme for microgrid using Hilbert space based power setting and fuzzy decision processes," *Proc. 2016 IEEE 11th Conf. Ind. Electron. Appl. ICIEA 2016*, pp. 6–11, 2016, doi: 10.1109/ICIEA.2016.7603542.

[104] H. Gao, J. Li, and B. Xu, "Principle and implementation of current differential protection in distribution networks with high penetration of DGs," *IEEE Trans. Power Deliv.*, vol. 32, no. 1, pp. 565–574, 2017, doi: 10.1109/TPWRD.2016.2628777.

[105] A. Pathirana, A. Rajapakse, and N. Perera, "Development of a hybrid protection scheme for active distribution systems using polarities of current transients," *Electr. Power Syst. Res.*, vol. 152, pp. 377–389, 2017, doi: 10.1016/j.epsr.2017.07.022.

[106] M. A. Zamani, T. S. Sidhu, and A. Yazdani, "A communication-based strategy for protection of microgrids with looped configuration," *Electr. Power Syst. Res.*, vol. 104, pp. 52–61, 2013, doi: 10.1016/j.epsr.2013.06.006.

[107] I. M. Microgrids and T. S. Sidhu, "A Communication-Assisted Protection Strategy for," vol. 3, no. 4, pp. 2088–2099, 2012.

[108] S. Mirsaeidi, D. M. Said, M. W. Mustafa, M. H. Habibuddin, and K. Ghaffari, "A Protection Strategy for Micro-Grids Based on Positive-Sequence Impedance," *Distrib. Gener. Altern. Energy J.*, vol. 31, no. 3, pp. 7–32, 2016, doi: 10.1080/21563306.2016.11744002.

[109] S. Mirsaeidi, D. M. Said, M. W. Mustafa, and M. H. Habibuddin, "A protection strategy for micro-grids based on positive-sequence component," *IET Renew. Power Gener.*, vol. 9, no. 6, pp. 600–609, 2015, doi: 10.1049/iet-rpg.2014.0255.

[110] B. Ram and D. N. Vishwakarma, *Power System Protection and Switchgear*, 2nd ed. Tata McGraw Hill Education Private Limited, 2011.

[111] C. R. Mason, *The Art and Science of Protective Relaying*, 2nd ed. UMI, 1997.

[112] *Protective Relays Their Theory and Practice*, 2nd ed. Springer.

[113] "NPTEL :: Electrical Engineering - Power System Protection." https://nptel.ac.in/courses/108/101/108101039/.

[114] M. R. D. Zadeh, T. S. Sidhu, and A. Klimek, "Suitability analysis of practical directional algorithms for use in directional comparison bus protection based on IEC61850 process bus," *IET Gener. Transm. Distrib.*, vol. 5, no. 2, pp. 199–208, 2011, doi: 10.1049/iet-gtd.2010.0229.

[115] M. M. Eissa and M. M. A. Mahfouz, "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, 2012, doi: 10.1049/iet-gtd.2012.0319.

[116] K. Zimmerman and D. Costello, "Fundamentals and improvements for directional relays," *2010 63rd Annu. Conf. Prot. Relay Eng.*, 2010, doi: 10.1109/CPRE.2010.5469483.

[117] B. Brusilowicz and N. N. Schulz, "Polarizing Voltage Generating Method for Distance and Directional Protection Elements," *IEEE Trans. Power Deliv.*, vol. 36, no. 1, pp. 74–83, Feb. 2021, doi: 10.1109/TPWRD.2020.2974737.

[118] Y. V. V. S. Murty and W. J. Smolinski, "Design and implementation of a versatile digital directional overcurrent relay," *Electr. Power Syst. Res.*, vol. 18, no. 1, pp. 47–55, 1990, doi: 10.1016/0378-7796(90)90045-5.

[119] P. System Relaying Committee of the IEEE Power Engineering Society, *IEEE Std C37.230^{TM}-2007, IEEE Guide for Protective Relay Applications to Distribution Lines*, vol. 2020. 2008.