Smart Meter-based Outage Detection and Fault Location in a Microgrid in Gaidouromantra, Greece

Sanjeev Bangali1, Vasilakis Athanasios2,Lagos Dimitrios2, Prasoon Arya1, Jigyasa Singhai1, Sarasij Das1*
1Dept. of Electrical Engineering, Indian Institute of Science, Bengaluru, India 2Dept. of Electrical and Computer Engineering, National Technical University of Athens, Athens, Greece sarasij@iisc.ac.in

Abstract

In the existing literature, Digital relay-based protection schemes are proposed for microgrids (MGs). Digital relays are expensive and uneconomical for practical microgrids. However, in most MGs, smart meters (SMs) with communication facilities are available at the consumer end for energy measurements. These SMs can measure the electrical quantities and communicate the measurements to the local server. This paper demonstrates that SMs can also be used for outage detection and fault location in practical MGs. Gaidouromantra MG is one such MG in Kythnos island, Greece, with SMs and communication facilities. This paper proposes two algorithms to detect outages and fault locations. The first algorithm is a voltage-based algorithm which assumes that SM communication is intact. The second algorithm extends the first. It uses current measurements along with voltage measurements to tackle the problem of SM communication disconnection after the fault. The algorithms use measurements from the SMs to detect the outage in the feeder and locate the fault with the guidance of the MG's topology. Additionally, the extended algorithm can be used to indicate SM communication failure and no-load/disconnection status of houses on the island, if any occur. The algorithms are validated using the Gaidouromantra MG model on Simulink and hardware-in-loop simulations of the Gaidouromantra MG. The proposed algorithms can generally be applied to MGs with radial structures consisting of a single grid-forming inverter and multiple grid-following inverters, as in Gaidouromantra.

1 Introduction

The advent of distributed energy resources (DERs) has led to the widespread emergence of microgrids (MGs). Such MGs often become a boon to residents by providing adequate electric power for various purposes. Fault location and outage detection in MGs is crucial for ensuring its safe and efficient operation. MGs are classified under the distribution network. Conventional fuse-based distribution system protection schemes are not suitable for MGs. So, digital relay-based solutions have been proposed for MG protection [1]. Unlike traditional power grids, MGs present unique challenges for fault location and detection due to limited and bi-directional fault currents. Implementation of traditional protection strategies in MGs poses challenges due to their varied architecture and operation [2].

Many alternate protection strategies and techniques have been proposed for MG protection. Various methods, such as impedance-based, phasor measurement unit (PMU)-based, smart feeder meter-based, and artificial intelligence (AI)-based methods, are mentioned in the literature. These schemes also include the use of smart meters (SMs). SMs record voltage and current values and have the ability to communicate with a local server. Reference [3] discusses using SMs and proposes protection functionalities to detect various faults in distribution system protection. References [4] and [5] describe the use of SMs for the detection of high-impedance faults (HIF). Reference [5] discusses HIF detection in the presence of power electronic loads and distributed generation (DG). Reference [6] proposes an algorithm that uses an iterative approach to construct the network matrix using SM data, thereby predicting the topology of distribution networks and detecting faults in the network. Reference [7] mentions using SMs for enhanced protection and monitoring in DG systems. Reference [8] proposes a modification of SMs to use a data-driven approach for predicting faults in DG systems. Reference [9] proposes the creation of low-voltage zones in combination with an impedance-based method combined with SM data to pinpoint the faulted zone. Reference [10] explores using micro-PMU (μ-PMU) and SM data to locate faults on active distribution networks. Reference [11] proposes upgrading SMs at the distribution substation to the ones with synchrophasor capability, enabling time-synchronised measurements to detect faults in the network.

References [12] and [13] propose the use of a generative adversarial network (GAN). Reference [12] suggests decomposing the network into multiple regions and using GAN to predict the fault location. However, reference

Table 1: Equipment Specification

Equipment	Specifications
Batteries	96kWh, 48V
Feeder Relay	SEL-751
Smart meters	Advanced smart meters and load controller (SLAMs)
Real-Time Automation Controller	SEL-3505, Real-Time Control and Logic Processing Unit

[13] proposes using SMs data distribution and GAN to detect outages. Reference [14] explores the use of a combination of fuzzy logic and neural network-based methods for detecting, characterising and locating faults based on the data from SMs and sensors. References [15] and [16] discuss using SMs in distribution lines to predict faulted lines. The power flow in the network is also predicted using SMs. Reference [17] uses state estimation-based methods for fault location in the distribution network. Along with this, the changeable weighting matrix method for bad data identification is also mentioned. Reference [18] proposes a novel method of using SM data and geographical information system to map and pinpoint the fault location. The SMs are fixed with a global system for mobile communication (GSM) module to communicate with the server during power failure.

Methods like [10] and [11] require additional equipment to be installed in the network. The methods also require a high data acquisition rate(HDAR) and granularity in addition to the add-on components to the network. With limited grid monitoring devices like in Gaidouromantra MG, the techniques described will fail. The methods mentioned in [4] and [5] focus solely on tackling HIF. Additional advanced grid monitoring and protection devices with HDAR are required to implement the methods as suggested in [12]-[18]. Also, a computer with higher processing capability is needed to run GAN and AI-based techniques. Techniques in [6] and [8] both propose the modification of SMs for fault detection. Even though there are multiple literature on the application of SMs in outage detection and fault location in MGs, there is a lack of practical demonstration of the concept. This paper fills the gap.

This article presents two new algorithms that use the measurements of SMs and the MG topology for outage detection and fault location. The proposed algorithms are simple compared to the existing algorithms yet effective for MGs that have a radial structure consisting of a single grid-forming inverter and multiple grid-following inverters, like Gaidouromantra. The first algorithm assumes the SM communication is intact and detects the outages and fault location using voltages measured from the SMs. The second algorithm, which is an extension of the first, additionally uses currents measured by SMs to detect outages and fault locations and tackles the problem of SM communication disconnection after faults. The extended algorithm also indicates communication failure and no-load/disconnection of SMs, if any occur. The algorithms are first tested in the Simulink environment by modelling the MG and later tested in a hardware-in-the-loop (HIL) simulation of the Gaidouromantra island in Greece.

2 Location description - Gaidouromantra microgrid, Kythnos, Greece

The MG in Gaidouromantra is located on Kythnos Island, Greece (marked in red at the bottom of Fig. 1). It is a standalone MG commissioned in 2001 [19]. The MG facility operates on 100% renewable energy and is primarily self-sufficient in electricity generation. The MG consists of six distributed photovoltaic (PV) arrays with a total capacity of 20kWp. This is supported by a 22kVA diesel generator. In addition to this, a 96kWh/15kW battery energy storage system (BESS) is also installed. The power system of the MG is managed by three single-phase inverters that provide a three-phase power supply. Three low-voltage feeders equipped with industrial relays constitute the distribution network. Fiber optic cable is run parallel to the overhead power lines. This acts as a channel for communication and control. MG consists of 14 vacation homes. Each vacation home is equipped with smart meters that monitor energy use and serve as load controllers. These meters support remote monitoring and load management. An industrial real-time automation controller is installed. This acts as a central communication hub. The specific details of the equipment used in Gaidouromantra MG are presented in table 1.

Figure 1: Kythnos MG

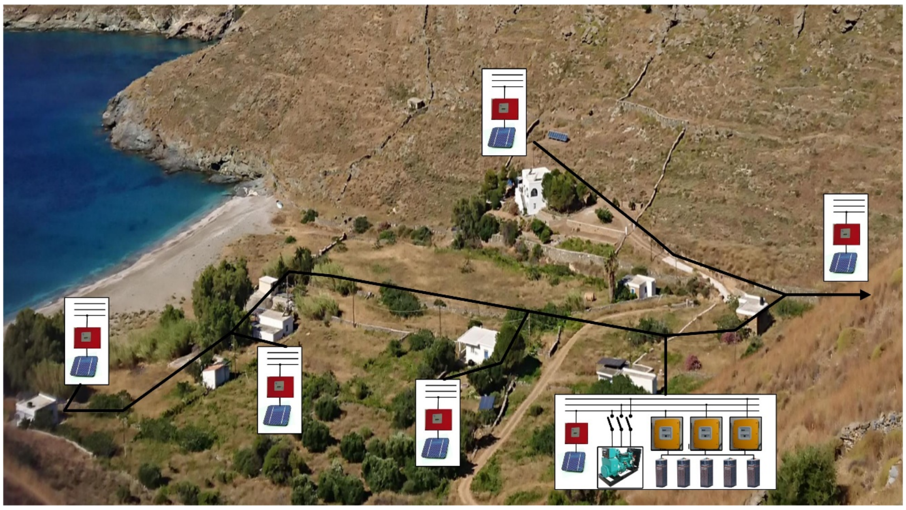

Figure 2: MG at Gaidouromantra

3 Methodology

The algorithm works on the following assumptions:

- The MG consists of only one grid-forming inverter, and all other inverters in the system are grid-following.
- The fuses/MCBs operate during the fault, and the voltage seen by smart meters downstream from the point of disconnection is zero.
- The topology of the system is strictly radial in nature.

3.1 Implementation of algorithm

A voltage-based algorithm (Algorithm 1) is developed to detect outages and locate fault locations. This algorithm assumes that the SM communication is intact even when there is a disconnect on the line. Algorithm 2 is an extension of Algorithm 1. It is developed to address the issue of SM communication disconnection. It uses both voltage and current measurements from SMs. The implementation of both are as follows:

3.1.1 Algorithm 1: Voltage-based outage detection and fault location

This algorithm uses root mean square (RMS) measurement values of voltage communicated by SMs. The algorithm considers pre-fault and post-fault values of voltage to analyse the location of the faults.

The SM location is already known from the topology information. A threshold value of voltage for SMs is calculated and stored in the database beforehand. Every SM model has a minimum measurement voltage below which it will not work. A common threshold voltage is selected to be greater than the minimum measurement voltage of SM but less than the nominal voltage of the grid. The voltage values from SMs are obtained using an existing data acquisition system.

Working logic: The SM data are received and arranged upstream to downstream, feeder-wise, in the database. These are labelled and time-stamped. For outage detection, the algorithm checks the voltage difference between adjacent nodes iteratively for the entire feeder. For a healthy system, the voltage difference between adjacent nodes should be close to zero under normal operating conditions. If they are intact, then the system is healthy. In contrast, if there are voltage violations, i.e. if the voltage difference across adjacent nodes, when calculated, is above the set threshold voltage, the algorithm will flag it as an outage. The particular node at which the voltage violation is found is then mapped to the topology of the system to indicate the location of the fault. The flowchart of outage detection is shown in Fig. 3. The higher the number of SMs in the network, the higher the accuracy of fault location.

3.1.2 Algorithm 2: Extended outage detection and fault location algorithm

The algorithm uses current measurements along with voltage measurements from SMs. This is an extension of algorithm 1. Furthermore, this algorithm enables the operator to identify the no-load/disconnection status

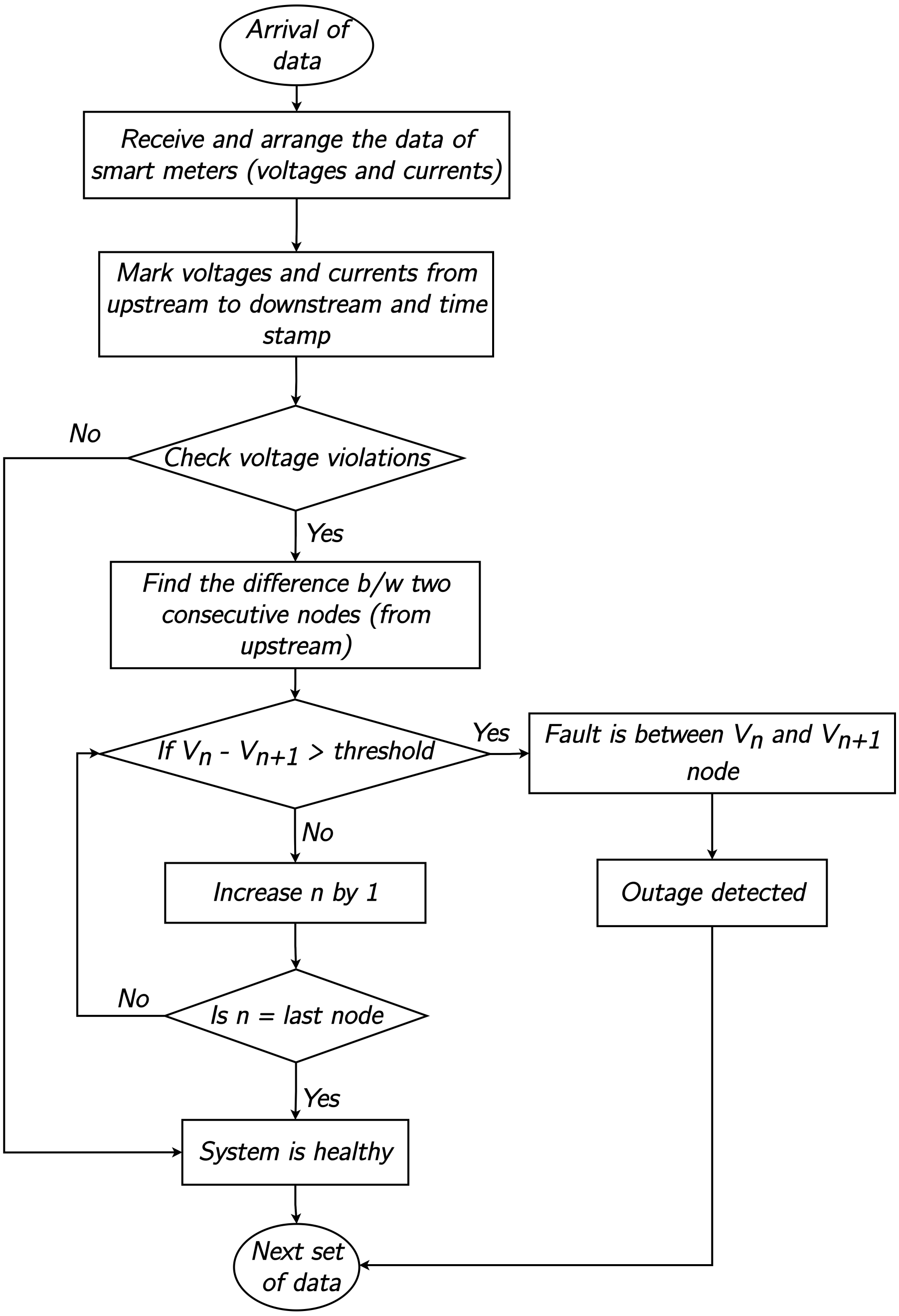

Figure 3: Algorithm 1: Voltage-based outage detection and fault location

of the house on a feeder basis. This algorithm will work even when the SM communication is disconnected after the fault. A threshold voltage for SMs is calculated in a similar way as in algorithm 1 and stored in the database.

Working logic: Feeder-wise, the current and voltage readings are fetched and stored in the database. The algorithm determines whether the voltage and current readings from all SMs are available in the database. If both are available for all SMs as per the topology, the system is healthy, and no additional steps are required until the next initiation. However, if the voltage measurement of a particular SM is available but the current reading is zero or not available, it could mean that the SM under consideration is disconnected or has no load connected to it. If the voltage reading of the SM under consideration and the multiple other SMs in the feeder are unavailable, a probable outage has occurred. Outage detection and fault location logic is initiated (section 3.1.1). However, if the voltage reading of the SM under consideration alone is not available, it implies a communication failure. The flowchart in Fig. 4 shows the flow of this algorithm.

Algorithms 1 and 2 do not indicate the instant of the fault, so continuous monitoring is unnecessary. However,

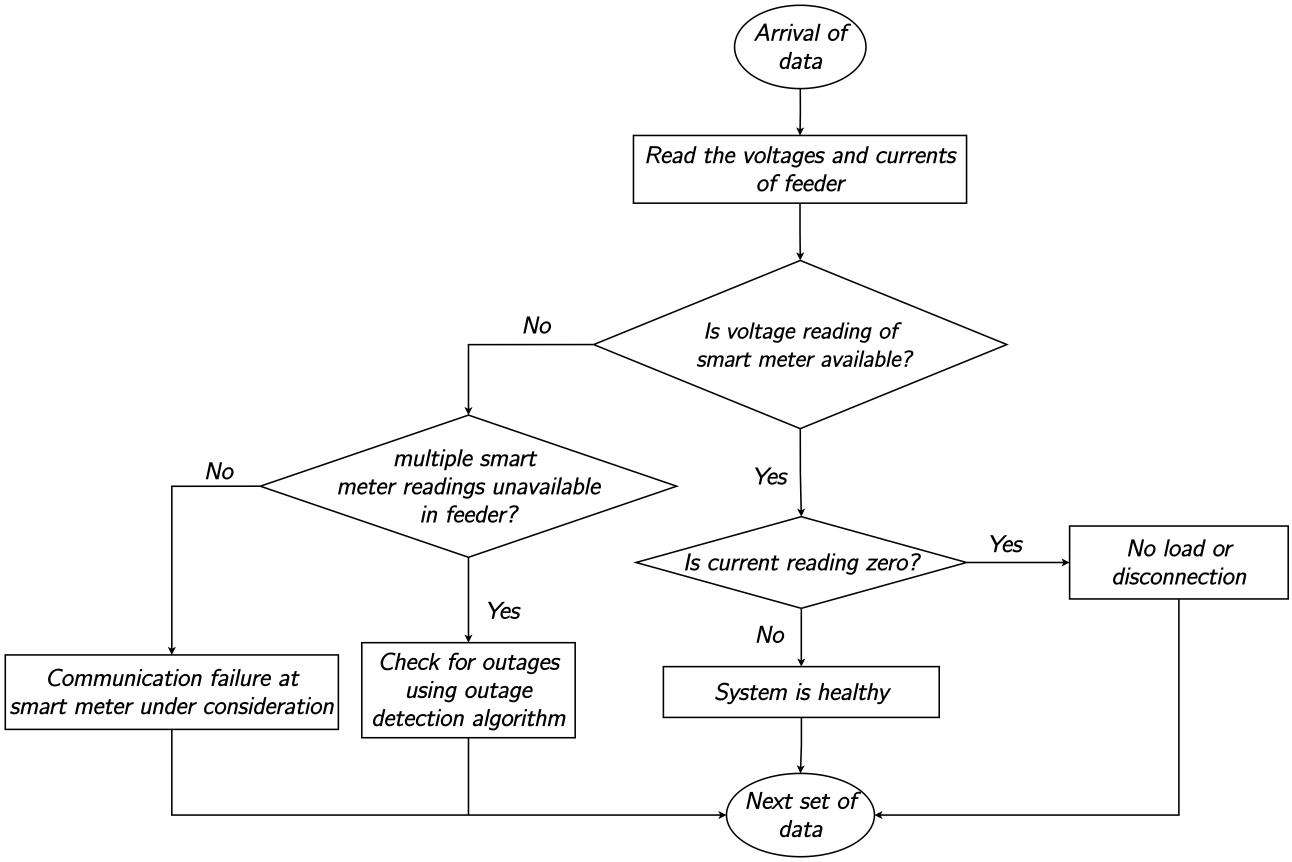

Figure 4: Algorithm 2: Extended outage detection and fault location algorithm

a steady number of measurements at regular intervals can accurately predict the outage and fault location. Special care must be taken to segregate new incoming data from existing data; hence, time stamping is necessary to ensure reliability. In both algorithms, as the voltage values of SMs are compared with a pre-decided threshold, a wide range of data granularity can be supported.

4 Microgrid model

The algorithm is tested on the Gaidouromantra MG model. The system topology of the MG is shown in Fig. 5.

4.1 Simulink model

The Gaidouromantra MG model is developed in a Simulink environment. The model incorporated the feeders as transmission lines, houses as RLC loads and the grid-forming inverter at the system house as a constant three-phase voltage source. Individual inverters connected to PVs are not incorporated in the model as they are assumed to stop operating as soon as there is a fault. The single-line diagram of the Simulink model is shown in Fig. 6. The faults are generated using the built-in three-phase fault block. The test cases and results are shown in section 5.

4.2 Digital twin model

A digital twin model of Gaidouromantra is developed in the real-time digital simulator (RTDS). The model specifically replicated the characteristics of Gaidouromantra MG. The model is shown in Fig. 7.

The RTDS model has a feeder relay unit with a breaker at the system house. The only sectionalising equipment to clear the fault apart from the main breaker is the MCBs at the individual houses. It is located in the electric boards of the houses after the SMs. The breakers at the beginning of each feeder are located at the system house and are controlled by the feeder relays. The simulation updated its database with measurements every few seconds, making it likely to lack any voltage measurements that would indicate a faulted condition.

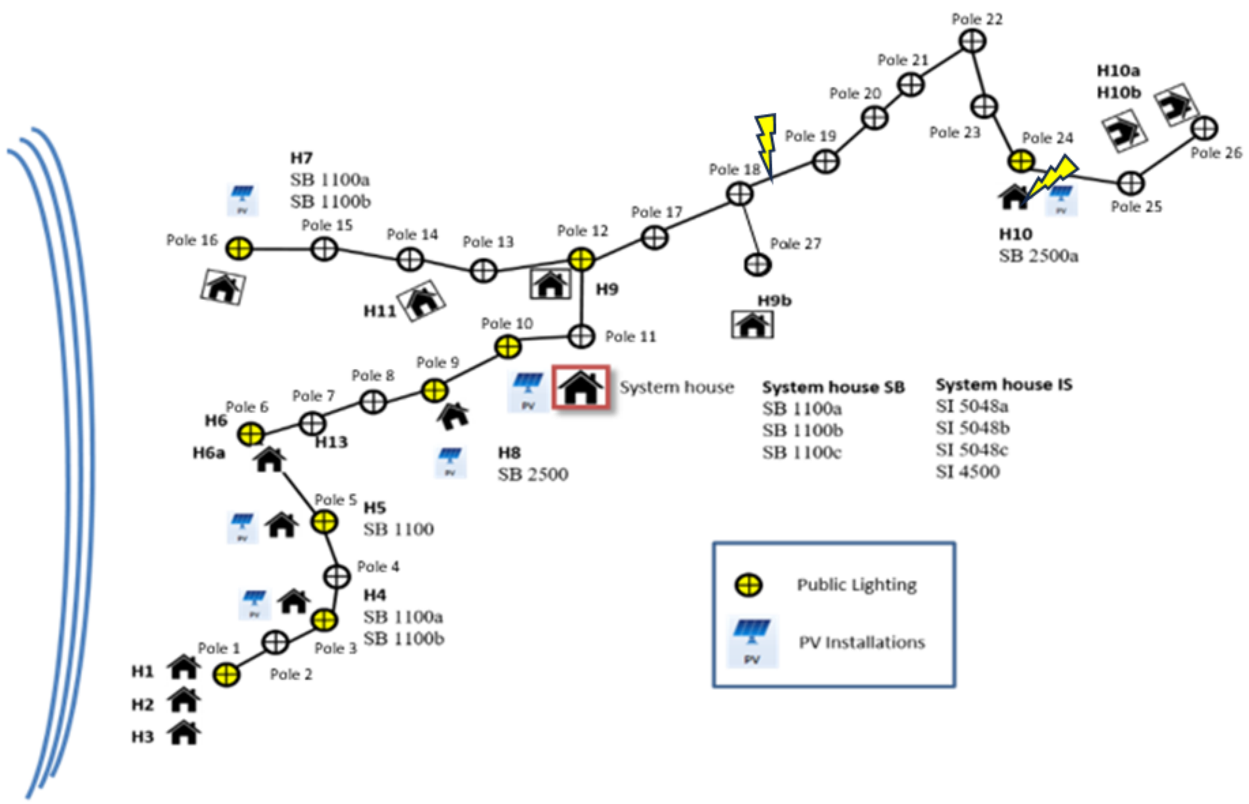

Figure 5: Topology of Gaidouromantra MG

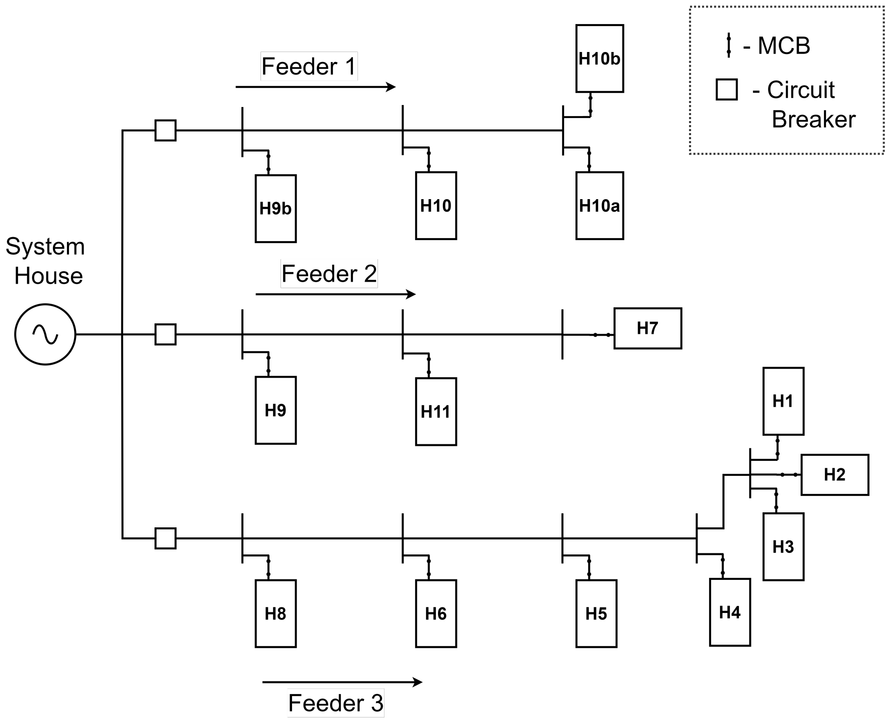

Figure 6: Simulation model of the Gaidouromantra MG

Consequently, in the event of a house fault, the voltage measurements before and after fault clearance would likely show normal operating conditions, making outage detection based on current measurements more reliable.

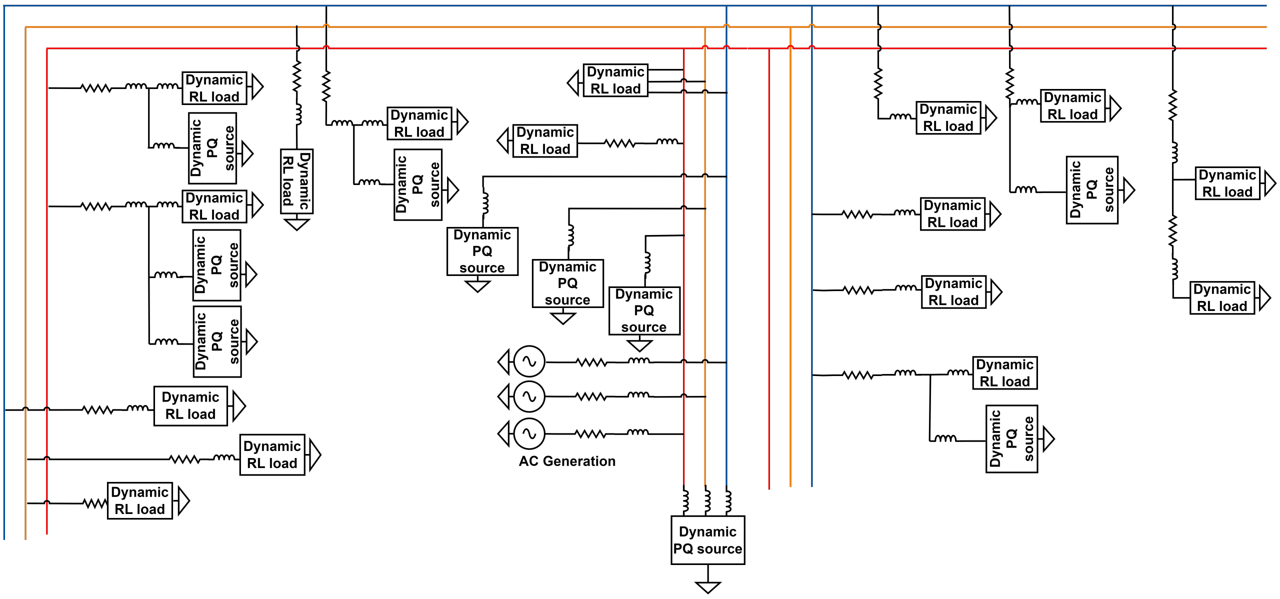

Figure 7: Gaidoromantra digital twin model

5 Results

5.1 Simulink simulation results

The test cases for the Algorithm 1 simulation are shown below.

- Fault on feeder 1 between house 9b (H9b) and house 10 (H10).
- Fault on feeder 2 between house 11 (H11) and house 7 (H7).
- Fault on feeder 3 between house 8 (H8) and house 6 (H6).

The test cases for the Algorithm 2 simulation are shown below.

- Disconnection test on house 5 (H5) in feeder 3.
- Normal Operation (no fault in MG).

5.1.1 Fault on feeder 1

The fault on feeder 1 is created between H9b and H10. The algorithm indicated that there is a fault in feeder 1, and the location of the fault is between H9b and H10.

5.1.2 Fault on feeder 2

The fault on feeder 2 is created between H11 and H7. The algorithm indicated that there is a fault in feeder 2, and the location of the fault is between H11 and H7.

5.1.3 Fault on feeder 3

The fault on feeder 3 is created between H8 and H6. The algorithm indicated that there is a fault in feeder 3, and the location of the fault is between H8 and H6.

5.1.4 Disconnection at H5 in feeder 3

The connection for H5 is removed in the simulation. The algorithm indicated that H5 in feeder 3 had no load or the house was disconnected from the MG.

Table 2: Simulated test cases for Algorithm 1 and 2

Test Condition	Test between nodes	Message on console
Feeder 1	H9b - H10	Fault between H9b and H10 (Feeder1)
Feeder 2	H11 - H7	Fault between H11 and H7 (Feeder2)
Feeder 3	H8 - H6	Fault between H8 and H6 (Feeder3)
Disconnection	H5	No-Load/Disconnection at H5 (Feeder 3)
Normal Operation	No fault	System is healthy

Table 3: Outage detection output messages

Fault	**Message produced by ecoMicrogrid**
Feeder Fault	”Communication failure at Smart Meter: âH9b-SEMâ”
	”Communication failure at Smart Meter: âH10-SEMâ”
	”Disconnection at Feeder: âFeeder 1â”
H10 Fault	”Disconnection or no load at Smart Meter: âH10-SEMâ”

5.1.5 Normal operation

The algorithm indicated that the system was healthy.

Table 2 shows the messages displayed on the console.

5.2 HIL testing results

Algorithm 2 is incorporated into the ecoMicrogrid (ecoMG) tool, which is part of the ”RE-EMPOWERED” project [20] for HIL testing. Algorithm 2 consists of multiple modules, including the voltage-based logic of Algorithm 1. To test the algorithm, two faults are simulated in the digital twin of Gaidouromantra. The test cases are (a) Feeder fault and (b) House fault.

5.2.1 Feeder fault

For feeder fault, the simulated SMs located at H9b and H10 were forced to drop their communication with the ecoMG hardware.

5.2.2 House fault

House H10 is forced to drop communication with the ecoMG hardware.

Table 3 shows the messages produced by ecoMG for respective faults.

In both faults, the outage detection module responded with indicative messages. The detection of the feeder fault is based on the zero current measurements from the feeder relay. The simulated breaker operation at the system house resulted in communication drops from the H9b and H10 smart meters. For the H10 fault, the detection is based on the zero current measurements from the H10 simulated smart meter.

These results demonstrate the effectiveness of the outage detection algorithm in identifying and responding to faults within the MG, ensuring improved reliability and operational efficiency.

6 Conclusion

The paper presents two algorithms to detect outages and fault locations in radial MGs with a single grid-forming inverter and multiple grid-following inverters, like Gaidouromantra. The first algorithm is a voltage-based algorithm, which assumes the SM communication during faults is intact. The second algorithm, which is an extension of the first, additionally uses current measurements along with voltage measurements to tackle the issue of SM disconnection after faults. The algorithms are tested on the Simulink model of Gaidouromantra MG for various test cases. The algorithms display the feeder and the point of disconnection accurately. The extended algorithm also predicts no-load/disconnection and communication failure accurately. The algorithms are incorporated into the ecoMG tool as a part of the "RE-EMPOWERED" project and are tested in HIL simulations for two cases. In both these cases, the results matched the expected output.

7 Acknowledgements

This work was financially supported by the Department of Science and Technology (DST), India and the European Union's Horizon 2020 Research and Innovation Program through the RE-EMPOWERED Project under Grant Agreement No DST/TMD/INDIA/EU/ILES/2020/50(c) and 101018420 respectively.

References

[1] A. Hooshyar and R. Iravani, "Microgrid Protection," *Proceedings of the IEEE*, vol. 105, pp. 1332–1353, 7 2017.

[2] M. W. Altaf, M. T. Arif, S. N. Islam, and M. E. Haque, "Microgrid Protection Challenges and Mitigation Approaches-A Comprehensive Review," pp. 38 895–38 922, 2022.

[3] A. Radhakrishnan and S. Das, "Protection Functionalities in Smart Meters to Enhance Distribution System Protection," in *2018 IEEE Innovative Smart Grid Technologies - Asia (ISGT Asia)*, 2018, pp. 1038–1043.

[4] S. Chakraborty and S. Das, "Application of Smart Meters in High Impedance Fault Detection on Distribution Systems," *IEEE Transactions on Smart Grid*, vol. 10, no. 3, pp. 3465–3473, 2019.

[5] A. Radhakrishnan and S. Das, "Location of High Impedance Faults Using Smart Meters in Distribution Systems with DGs, Power Electronic Loads and Electric Arc Furnaces," in *2019 IEEE Milan PowerTech*, 2019, pp. 1–6.

[6] C. Flynn, A. B. Pengwah, R. Razzaghi, and L. L. H. Andrew, "An Improved Algorithm for Topology Identification of Distribution Networks Using Smart Meter Data and Its Application for Fault Detection," *IEEE Transactions on Smart Grid*, vol. 14, no. 5, pp. 3850–3861, 2023.

[7] S. Chakraborty, S. Das, T. Sidhu, and A. Siva, "Smart Meters for Enhancing Protection and Monitoring Functions in Emerging Distribution Systems," *International Journal of Electrical Power Energy Systems*, vol. 127, p. 106626, 2021.

[8] S. Dutta, S. K. Sahu, M. Roy, and S. Dutta, "A Data Driven Fault Detection Approach With an Ensemble Classifier Based Smart Meter in Modern Distribution System," *Sustainable Energy, Grids and Networks*, vol. 34, p. 101012, 2023.

[9] F. C. L. Trindade and W. Freitas, "Low Voltage Zones to Support Fault Location in Distribution Systems With Smart Meters," *IEEE Transactions on Smart Grid*, vol. 8, pp. 2765–2774, 11 2017.

[10] P. K. Ganivada and P. Jena, "A Fault Location Identification Technique for Active Distribution System," *IEEE Transactions on Industrial Informatics*, vol. 18, pp. 3000–3010, 5 2022.

[11] M. Khairalla and et al., *Fault Location Based on Smart Meters Time Synchronized Measurements.* 2015 First Workshop on Smart Grid and Renewable Energy (SGRE) : Doha, Qatar, 22-23 March 2015, IEEE, 2015.

[12] X. Wang, Z. Shi, B. Liu, W. Xiao, and C. Shuai, "Smart Meter-based Outage Detection Method for Power Distribution Systems," *EAI Endorsed Transactions on Energy Web*, vol. 11, pp. 1–10, 2024.

[13] Y. Yuan, K. Dehghanpour, F. Bu, and Z. Wang, “Outage Detection in Partially Observable Distribution Systems Using Smart Meters and Generative Adversarial Networks,” *IEEE Transactions on Smart Grid*, vol. 11, pp. 5418–5430, 11 2020.

[14] F. G. Y. Souhe, A. T. Boum, P. Ele, C. F. Mbey, and V. J. F. Kakeu, “Fault Detection, Classification and Location in Power Distribution Smart Grid Using Smart Meters Data,” *Journal of Applied Science and Engineering (Taiwan)*, vol. 26, pp. 23–34, 2022.

[15] M. Dashtdar, S. M. S. Hosseinimoghadam, and M. Dashtdar, “Fault Location in the Distribution Network Based on Power System Status Estimation With Smart Meters Data,” pp. 129–147, 4 2021.

[16] M. Dashtdar and M. Dashtdar, “Fault Location in the Distribution Network Based on Scattered Measurement in the Network,” pp. 539–562, 5 2022.

[17] S. Jamali, A. Bahmanyar, and E. Bompard, “Fault Location Method for Distribution Networks Using Smart Meters,” *Journal of the International Measurement Confederation*, vol. 102, pp. 150–157, 5 2017.

[18] F. A. Albasri, E. A. Nainoon, R. Ayyad, Z. A. Zaki, and H. Alawi, “A Fault Location System Using GIS and Smart Meters for the LV Distribution System.” 2019 International Conference on Innovation and Intelligence for Informatics, Computing, and Technologies (3ICT), 2019.

[19] N. Hatziargyriou, A. Dimeas, N. Vasilakis, D. Lagos, and A. Kontou, “The Kythnos Microgrid: A 20-Year History,” *IEEE Electrification Magazine*, vol. 8, pp. 46–54, 12 2020.

[20] (2024) Empowered: Renewable energy empowering european indian communities. [Online]. Available: https://reempowered-h2020.com/