A Dynamic-SUGPDS Model for Faults Detection and Isolation of Underground Power Cable Based on Detection and Isolation Algorithm and Smart Sensors

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Abstract
This paper proposes a SUGPDS model based on Detection and Isolation algorithm and smart sensors, namely micro phasor measurement unit, smart sensing and switching device, phasor data concentrator, and ZigBee technology, etc. for the identification, classification, and isolation of the various fault occurs in the underground power cable in the distribution system. The proposed SUGPDS is a quick and smart tool in supervising, managing, and controlling various faults and issues and maintaining the reliability, stability, and uninterrupted flow of electricity. First, the SUGPDS model is analyzed using a distributed parameter approach. Then, the proper arrangement of the system required for the implantation of SUGPDS is demonstrated using figures. The Phasor data concentrator plays an essential role in developing the detection and classification report for identification and classification. Finally, smart sensing and switching device installed at a different location isolated the faulty phase from a healthy network. This approach helps to decrease power consumption. Hence, SUGPDS has super abilities compared to the underground power distribution system. The effectiveness of the proposed method and model is demonstrated via figures and tables.

Keywords Fault detection and isolation · Micro phasor measurement unit (µPMU) · Underground power cable · Phasor data concentrator (PDC) · Smart sensing and switching device (SSSD) · Smart underground power distribution system (SUGPDS) · Short-circuit fault · Open-circuit fault · Ground fault

1 Introduction
In the present scenario, electricity has become the backbone of our day to day life, not only in the technological field but also in every field such as domestic, industrial, commercial, medical, etc. In modern society, underground power distribution plays a crucial role [1]. However, fast and proper restorations are vital in the power distribution needed to improve the customers’ service quality [2]. In the power system [3, 4] structure, the electricity is distributed either over headline or underground cable [5, 6]. The over headline is commonly adopted in the transmission and distribution of electricity. The over headline becomes hazardous, arduous, or absurd in some areas; then, the most preferred solution is the underground power cable. Many places where the UG cables are used are urban areas, industries, and densely populated areas. Mainly there are three types of faults in the underground line. These faults have offbeat in nature and characteristics. Due to this distinct in nature and characteristics, will help a lot in fault diagnosis. The various types of UG faults and their cause [7] are shown in Table 1.

Incipient faults can greatly affect distribution system efficiency and reliability in the underground power cable. A fault portion detection approach based on the Murray loop method and Ohm’s law method is proposed to identify underground cable fault locations Hans et al. [8]. In the proposed method, the whetstone bridge supports detecting the accurate location of fault location, while the Ohm’s law method helps observe the voltage drop and current variation. Based on Fault Sensing Circuit and Wi-Fi Module Asif et al. [9] had proposed fault tacking system to supervise and sense the fault point in the underground power cable. The power flow can be controlled with the help microcontroller
and relay circuit. The proposed hardware model could be able to supervise and recognize the fault in the underground power cable. Based on IoT Goswami et al. [10], an approach was recommended to identify the underground power cable’s fault location. The author had also suggested the Node MCU Module with the integration of Wi-Fi and the Arduino sensor to observe the transformer’s condition. The author had investigated the average accuracy of fault exposure for LG fault 94.53% and LL fault 98.63%. Image processing Li et al. [11] had proposed an anomaly identification technique in the faulty section of the underground. The author also recommended the H–S color histogram to supervise the abnormal section and support oil leakage detection by comparing the sample images and supervised images. The proposed method can sense the abnormality rapidly and precisely by monitoring image and notify the potential hazard.

Bretas et al. [12] had proposed a methodology to support a parameter estimation approach based on a non-negative weighted least square estimator. And high accuracy was obtained as a result of the easy implementation of the method. For the four-circuit series- compensated transmission lines, Saber [13] proposed a framework based on the theory of the transmission lines and Taylor series expansion of distributed parameters. In a non-solidly earthed distribution network, classification and recognition architecture was suggested by Liang et al. [14] for Single-phase-to-ground faults (SFs). The study was carried out and tested through field data and artificial test data. Results were quite promising and able to recognize various types of SFs. Reddy et al. [15] had proposed self-parametric measurements to detect the fault and estimate its location for the LVDC micro-grid with OPAL-RT real-time simulator support. The results have been validated in a real-time environment. For estimating the fault location, Khoramabadi et al. [16] had presented a methodology including UPFC with the support of FDOST transform and one-ended voltage for compensating transmission line. The study was evaluated on a 500 kV transmission line with a length of 300 km and UPFC at various transmission line positions.

Results were highly accurate and promising efficient. For fault location indexing in the distribution power system, Fiaschetti et al. [17] used voltage sags and random nodes as measurement points. The experiment was analyzed using IEEE 34 node test feeder and produced a highly efficient output for fault detection. A Smart sensor [18, 19] network is most demanding for localization of the electric grid. Smart elements are the key to change UGPDS into SUGPDS, which includes the Micro phasor measurement unit (μPMU), Phasor data concentrator (PDC), ZigBee. These will improve the stability and reliability of the UGPDS. The PMU [20] fast time-stamped device measures the power grid’s synchro phasors for synchronous supervision and control management. The PMUs [21] are mostly used in the transmission system. Still, in recent scenarios, due to encroachment in the distribution system, it can also be installed for real-time observation, accurate estimation and improvement insecurity. For enhancing the quality of resolution in the distribution grid, μPMU is a superior option than PMU, which may install. The author discusses the fundamental concept of μPMU; also, it’s applications in distribution systems. And for the optimal placement of PMU, Xie et al. proposed [22] model considering power system controlled islanding. The main objective was to minimize the number of PMU and reduce the computational time of the issue. The reliability band stability of the distribution system can be improved with the help of ZigBee [23]. ZigBee technology uses in Smart Grid [24] HAN, UHV transmission lines monitoring, and fault identifying. For fast and effective wireless communication, ZigBee technology must be integrated with Smart Grid.

In the last decade, a vast number of research work have been reported on different aspects related to various faults in the area of underground power distribution system likely analysis of faults [25–30], adaptive fault [31–33], SC, OC and ground faults [34–37], detection [38, 39], classification [40] and fault location [41–46], sustainable protection [47, 48], noise monitoring [49], and for thermal test [50].

And one of the foremost drawbacks of the existing underground power distribution system (UGPDS) is distribution faults [7] that cause unwanted power loss in the power distribution systems. Such an increase in electricity demand put a burden on UGPDS due to which reliability and stability of it degraded. Drastically change in reliability and stability of UGPDS can affect the performance or damage the modern appliances due to which we will suffer from various complexities. It is clear from the literature surveys that previous researchers concentrated only on a few forms of fault detection. They have not aimed at shortening the problem of isolating the faulty section from the healthy section of the UGPDS. The previously suggested methods are inadequate, and the tracking and control systems’ communication was not so efficient and reliable. In Synchronous supervisor & decentralized control over the whole UGPDS

| Types of UG fault | Series or open circuit fault | Parallel or short circuit fault | Grounded or earth fault |
|-------------------|-----------------------------|--------------------------------|------------------------|
| Cause             | Sudden pressure on cable, breakdown of underground cable | Insulation failure of underground cable | Breakdown or insulation failure of underground cable |
section, the previous work was less accurate and effective. With this background, we proposed a dynamic-SUGPDS model for faults detection and isolation of underground power cable based on detection and isolation algorithm and smart sensors.

The remaining of this article is organized as follows. Section 2 proposed methodology, i.e., the SUGPDS model is discussed and the DI algorithm for PDC to generate DC report. However, we also suggests Process followed by SUGPDS for Identification and isolation of various faults and faulty UG power cables. The Result is discussed in the article in Sect. 3. Section 4 is allocated for Discussion and finally, Sect. 5 concludes the paper by discussing the future scopes.

2 Proposed Methodology

2.1 SUGPDS Model

We proposed the SUGPDS model based on smart elements like µPMU, PDC, ZigBee technology and switching device, etc. by the support of which we could be able in the identification and classification of the various fault occurs in the UG cable and its isolation from a healthy section of the UGPDS. The SUGPDS model is shown in Fig. 1.

The underground power cable ratings suitable for the proposed method should follow some standard parameters, as shown in Table 2.

2.1.1 Components Used in SUGPDS Model

The SSSD plays a vital role in identifying, classifying various types of UG power cable faults, and isolate it from the healthy section of SUGPDS. It is the backbone of the proposed SUGPDS. It coordinates with PDC to supervise & manage the SUGPDS. It consists of integrating smart sensors such as µPMU, ZigBee technology, and switching device, as shown in Fig. 2.

2.1.2 The Various Functions of SSSD are as Follows

2.1.2.1 µPMU (Micro Phasor Measurement Unit) µPMU is a smart electronic sensor that measures the deferent electrical parameters like voltage, current, phase angle and frequency with a high degree of accuracy at each SSSD of SUGPDS. The micro-phasor measurement unit (µPMU) is being rapidly developed and is becoming increasingly relevant for future distribution network applications. Due to the high costs, it is impractical and unaffordable to position all buses with µPMUs, contributing to the need to assess the optimum location in the distribution system with small numbers of

![Fig. 1 SUGPDS model](image-url)
μPMUs. To reduce the number of μPMUs and SSSD, we have used the improved IENS model [51], which improves the observability of the distributed network, as shown in Fig. 3, by utilizing the measurements smart meters and pseudo measurements of the load powers in the distribution systems. The number of phasor measuring instruments is considerably shortened by using an inadequate observability analysis to achieve the entire perceptibility. The suggested full and incomplete observability study for Phasor measuring units is used to measure IEEE 14, 24, 30, 57, and both SR and sub-systems 1, 2 for 270, and 444 bus capacity. Similarly, the Phasor measurement units and double-usage relays positioning are considered as IEEE 14, 30, and 57 bus Systems. A complete observability analysis is also used to consider single SSSD and μPMUs loss condition.

2.1.2.2 ZigBee ZigBee is wireless communication media, particularly design for sensing and controlling networks; it assists in data transfer from various SSSD, located at remote places of SUGPDS to Phasor data concentrator (PDC).

2.1.2.3 Switching Device A smart relay and circuit breaker can be used as switching and isolating elements. As it receives a control signal from the control unit, it switches or isolates a particular faulty phase cable.

2.1.2.4 Control Unit It receives an action report regarding the faulty phase, faulty section & type of faults from the PDC and implements the action against fault by sending the control signal to the switching unit of the SSSD. It can improve electricity management and isolation of the faulty section from the healthy section of the SUGPDS.

2.1.2.5 PDC (Phasor Data Concentrator) PDC is the foremost building block of the SUGPDS. It collects the data (electrical parameters) measure by the μPMU installed at different specific remote points of SSSD via wireless communication systems like ZigBee. It compares and classifies the various types of fault and faulty phases based on the algorithm proposed. Based on the fault detection, an action report will be generated automatically and transferred to the control unit further to implement the action report against the faulty section.

2.1.3 The DI Algorithms for the PDC to Classify the Various Faults are as Follows

For detection and classification of various faults and faulty phases, the electrical parameter is measured by SSSD, especially μPMU, such as current, voltage, frequency and phase angle, etc. These parameter data are transfer to the PDC through ZigBee Cloud. The PDC compares and checks the characteristics parameter of two consecutive SSSDs based
on the DI algorithm table, as shown in Table 3. Based on the parameter characteristics, generates a DC (Detection and Classification) report. The DC report has two types of reports, i.e., fault report, which contains information about the type of fault and faulty phase, and action report, which is about the action to be taken against the fault and faulty phase shown in Fig. 4.

The action report is transmitted to the control unit that decodes the action report and takes action against the faults and faulty phase via SSSDs, i.e., Switching Device. In the DI algorithm table, we use the or & and operators to combine the parameter characteristics as well as cases and then have been used to make a comparison B/W the different conditions/cases of faults so that the DC report can be generated easily as possible. Here, first of all, it checks the different cases for line currents (I_R or I_Y or I_B), phase Voltage (V_R or V_Y or V_B), and line voltage (V_{RY} or V_{YB} or V_{BR}). If all these three characteristics parameters are satisfied with a single case that combines all of these electrical parameters, the DC Report is getting generated. The DC report tells about the fault types, faulty phase, and the action report against the fault and faulty phase.

2.1.4 A Process Followed by SUGPDS for Identification of Various Faults and Faulty Phase of UG Power Cable

The multi-core underground cable consists of three phases (R, Y & B) and four wires (R, Y B & N). In our proposed method, SSSD is installed at specific places or nodes of SUGPDS. SSSD is a quick and smart Device, as mentioned above. All the wires of the UG cable are connected to SSSD, as shown in figure. The μPMUs element of SSSD measures all the electrical parameters such as voltage, current, frequency, and phase angles from every phase. The measured parameter data are sent to the PDC through ZigBee Technology (a wireless communication media). PDC block compares and classify the various types of fault, and faulty phases based on the algorithm proposed that generate DC report. DC report consists of two types of reports, i.e., fault report and action report. An action report will be automatically transferred to the Control Device to perform a particular action. The Control Device implements the action against the fault by sending the control signal to the Switching Unit of the SSSD that can provide electricity management and
### Table 3: DI algorithm table for generation of DC report

| Characteristics parameter between two SSSD | DC report |
|---------------------------------------------|-----------|
| Cases | Line current (IR or IY or IB) | Phase voltage (VR or VY or VB) | Line voltage (VRY or VYB or VBR) | Fault type | Faulty phase |
| Case 1 (I_R = I_C or I_Y = I_C or I_B = I_C) | (V_R ≠ 0 or V_Y ≠ 0 or V_B ≠ 0) | (V_{R_Y} ≠ 0 or V_{Y_B} ≠ 0 or V_{B_R} ≠ 0) | Open circuit fault | RYB cable O/C |
| Case 2 (I_R = I_C or I_Y ≠ 0 or I_B ≠ 0) | (V_R ≠ 0 or V_Y ≠ 0 or V_B ≠ 0) | (V_{R_Y} ≠ 0 or V_{Y_B} ≠ 0 or V_{B_R} ≠ 0) | R Phase | |
| Case 3 (I_R ≠ 0 or I_Y = I_C or I_B ≠ 0) | (V_R ≠ 0 or V_Y ≠ 0 or V_B ≠ 0) | (V_{R_Y} ≠ 0 or V_{Y_B} ≠ 0 or V_{B_R} ≠ 0) | Y Phase | |
| Case 4 (I_R ≠ 0 or I_Y ≠ 0 or I_B = I_C) | (V_R ≠ 0 or V_Y ≠ 0 or V_B ≠ 0) | (V_{R_Y} ≠ 0 or V_{Y_B} ≠ 0 or V_{B_R} ≠ 0) | B Phase | |

Multi-core underground cable consists of three phases (R, Y and B) and four wires (R, Y, B and N); O/C open circuit; S/C short circuit
isolation of the faulty section from the healthy section of the SUGPDS, as illustrated in Fig. 5.

2.1.5 An Actions Report to be Followed by the Control Unit and SSSD (Switching Element) for Various Faults are as Follows

2.1.5.1 No Load Condition If no load condition is found in any section of the distribution network, then the nearest SSSD has the capability to effectively detect such a variation in electrical parameter, i.e., variation in current–voltage or frequency of line as shown in Fig. 6 and Table 4. In this way, it can easily and effectively distinguish between the no-load and open circuit fault situations.

2.1.5.2 Open Circuit Fault As O/C faults detected between SSSD1 and SSSD2 based on the DI algorithm conditions by the support of PDC and an action report is feed to the control unit, as shown in Fig. 7. All other healthy phases will continue with supply to the load as O/C’s isolation process is done as shown in Table 5, which describes a Comparative analysis of electrical parameters for O/C fault between two SSSDs.

2.1.5.3 Short Circuit Fault If S/C faults are detected between SSSD1 and SSSD2 based on the DI algorithm conditions by the support of PDC and an action report is feed to the control unit. The control unit decodes the action report and generates the control signal, which is transfer to the switching device of SSSD 1, as shown in Fig. 8. Comparative analysis of electrical parameters for S/C fault between two SSSDs, as shown in Table 6.

2.1.5.4 Ground Fault As ground faults detected between SSSD1 and SSSD2 based on the DI algorithm conditions by the support of PDC and an action report is feed to the control unit. The control unit decodes the action report and generates the control signal, which is transfer to the switching device of SSSD1, as shown in Fig. 9. Comparative analysis of electrical parameters for ground fault between two SSSDs, as shown in Table 7.

3 Results

By the adopting the SUGPDS model, we can detect and isolate the UG power cable faults with very ease and rapidly effective technique that enhance the accuracy, stability, and reliability of the underground power cable distribution management. The effectiveness of the proposed method and model is demonstrated via figures and tables.
3.1 Results for Open Circuit Fault

Based on control signal, the switching device isolate the particular o/c phases as shown in Table 8.

3.2 Results for Short Circuit Fault

Based on the control signal, the switching device (smart relay and circuit breaker) isolate the particular short-circuited phases as shown in Table 9. All other healthy phases will continue with supply to the load as the isolation process of S/C is done.

3.3 Results for Ground Fault

Based on the control signal, the switching device (smart relay and circuit breaker) isolate the particular grounded phases as shown in Table 10. All other healthy phases will continue with supply to the load as the isolation process of grounded phases is done.

4 Discussion

By adopting the proposed method, we can lifetime monitor the realistic of underground power cable. After implementing the proposed methodology and model, we can control voltage instability and improve the power quality of the distribution system. The major contribution of the article is as follows:

- A new dynamic-SUGPDS model is proposed.
- The SUGPDS model for choosing the most effective controls for voltage instability prevention.
- The SUGPDS presents superior abilities compared to the existing UGPDS.
- SUGPDS is appropriate not only small but also for large systems or areas with better performances.
- Remote monitoring and effective decentralized control.
- Effective coordination and secured communication among the monitoring and controlling devices.
- Boost the durability and overall performance of distribution system.
- The proposed model also helps in effective power utilization and load management and can decrease power consumption.
• Robustness of the proposed method during stable and unstable voltage conditions.
• The effectiveness of the proposed methodology and model is demonstrated via figures and tables.
• This paper presents a method for realistic lifetime monitoring of underground power cable.

The comparison analysis among various state-of-the-art for the Underground Power Cable Distribution System concerning different parameters is illustrated in Table 11. And, from Table 11, it is clear that the SUGPDS helps to decrease power consumption. Hence, the reliability, stability, proper supervision, power efficiency, electricity management, detection and control of underground power cable can be achieved with the support of SUGPDS.
### Table 4 Comparative analysis of electrical parameters for no load condition between two SSSDs

| Case no | Condition                                                                 | Reading of DC report | Switching implantation SSSD |
|---------|---------------------------------------------------------------------------|----------------------|-----------------------------|
| 1       | No load ($I_R = I_C$ or $I_Y = I_C$ or $I_B = I_C$) and ($I_{NL} = \text{no vary}$) | ($V_R \neq 0$ or $V_Y \neq 0$ or $V_B \neq 0$) | RYB cable Not loaded        |
|         |                                                                            | ($V_{RY} \neq 0$ or $V_{YA} \neq 0$ or $V_{RB} \neq 0$) | SSSD 1                      |
| 2       | ($I_R = I_C$ or $I_Y = 0$ or $I_B = 0$) and ($I_{NL} = \text{no vary}$)    | ($V_R \neq 0$ or $V_Y \neq 0$ or $V_B \neq 0$) | R Phase Not loaded          |
|         |                                                                            | ($V_{RY} \neq 0$ or $V_{YA} \neq 0$ or $V_{RB} \neq 0$) | SSSD 1                      |
| 3       | ($I_R = 0$ or $I_Y = I_C$ or $I_B = 0$) and ($I_Y = \text{no vary}$)       | ($V_R \neq 0$ or $V_Y \neq 0$ or $V_B \neq 0$) | Y Phase Not loaded          |
|         |                                                                            | ($V_{RY} \neq 0$ or $V_{YA} \neq 0$ or $V_{RB} \neq 0$) | SSSD 1                      |
| 4       | ($I_R = 0$ or $I_Y = 0$ or $I_B = I_C$) and ($I_{NL} = \text{no vary}$)    | ($V_R \neq 0$ or $V_Y \neq 0$ or $V_B \neq 0$) | B Phase Not loaded          |
|         |                                                                            | ($V_{RY} \neq 0$ or $V_{YA} \neq 0$ or $V_{RB} \neq 0$) | SSSD 1                      |
Fig. 7 O/C faults detection and their isolation from the healthy section between SSSD1 and SSSD2
### Table 5  Comparative analysis of electrical parameters for O/C fault between two SSSDs

| Case no | Fault type                  | Reading of DC report | Switching implantation SSSD |
|---------|-----------------------------|-----------------------|-----------------------------|
|         |                             | SSSD 1                | SSSD 2                      |                             |
|         |                             | Line current          | Phase voltage               | Line voltage                | DC report |                             |
|         |                             |                        |                            |                            |           |                             |
| 1       | Open circuit fault detected | (I_R ≠ 0 or I_Y ≠ 0 or I_B ≠ 0) and (I_L fall up-to I_C) | (I_R ≠ 0 or I_Y ≠ 0 or I_B ≠ 0) and (Slightly rise in V_Ry for a short interval and then attains steady state) | (I_R ≠ 0 or I_Y ≠ 0 or I_B ≠ 0) and (V_R ≠ 0 or V_Y ≠ 0 or V_B ≠ 0) | RYB Cable O/C | SSSD 1 |
| 2       |                             | (I_R ≠ 0 or I_Y ≠ 0 or I_B ≠ 0) and (I_R fall up-to I_C) | (V_R ≠ 0 or V_Y ≠ 0 or V_B ≠ 0) and (Slightly rise in V_R for a short interval and then attains steady state) | (I_R = I_C or I_Y ≠ 0 or I_B ≠ 0) | R Phase | SSSD 1 |
| 3       |                             | (I_R ≠ 0 or I_Y ≠ 0 or I_B ≠ 0) and (I_Y fall up-to I_C) | (V_R ≠ 0 or V_Y ≠ 0 or V_B ≠ 0) and (Slightly rise in V_Y for a short interval and then attains steady state) | (I_R ≠ 0 or I_Y ≠ 0 or I_B ≠ 0) | Y Phase | SSSD 1 |
| 4       |                             | (I_R ≠ 0 or I_Y ≠ 0 or I_B ≠ 0) and (I_B fall up-to I_C) | (V_R ≠ 0 or V_Y ≠ 0 or V_B ≠ 0) and (Slightly rise in V_B for a short interval and then attains steady state) | (I_R ≠ 0 or I_Y ≠ 0 or I_B ≠ 0) | B Phase | SSSD 1 |
Fig. 8 SC faults detection and their isolation from the healthy section between SSSD1 and SSSD2

### Table 6 Comparative analysis of electrical parameters for S/C fault between two SSSDs

| Case no | Fault type | DC report | Switching implantation SSSD |
|---------|------------|-----------|-----------------------------|
| SSSD 1  |            | R and Y S/C | SSSD 1                      |
| SSSD 2  |            | Y and B S/C | SSSD 1                      |
| SSSD 1  | RYB Cable  | R and Y S/C | SSSD 1                      |

| Reading of | Line current | Phase voltage | Line voltage | Line current | Phase voltage | Line voltage |
|------------|--------------|---------------|-------------|--------------|---------------|-------------|
| SSSD 1     | (I_R = -I_Y and I_B ≠ 0) | (V_R = V_Y and V_B ≠ 0) | (V_RY = 0 and V_YB ≠ 0 and V_RB ≠ 0) | (I_R = I_C, I_Y = -I_C, I_B ≠ 0) | (V_R = V_Y = 0 and V_B ≠ 0) | (V_RY = 0 and V_YB = -VB and V_BR = VB) |
| SSSD 2     | (I_R = I_C, I_Y = -I_C, I_B ≠ 0) | (V_R = V_Y = 0 and V_B ≠ 0) | (V_RY = 0 and V_YB = 0 and V_BR = 0) | (V_R = V_Y = 0 and V_B ≠ 0) | (V_RY = V_Y = 0) | (V_YB = 0 and V_BR = 0) |

**Diagnosis algorithm for short circuit faults**

1. **Case 1**
   - Short circuit fault detected
   - \(I_R = -I_Y\) and \(I_B ≠ 0\)
   - \(V_R = V_Y\) and \(V_B ≠ 0\)
   - \(V_{RY} = 0\) and \(V_{YB} ≠ 0\) and \(V_{RB} ≠ 0\)

2. **Case 2**
   - \(I_Y = -I_R\) and \(I_B ≠ 0\)
   - \(V_Y = V_B\) and \(V_R ≠ 0\)
   - \(V_{YB} = 0\) and \(V_{BR} ≠ 0\) and \(V_{RY} ≠ 0\)

3. **Case 3**
   - \(I_B = -I_R\) and \(I_Y ≠ 0\)
   - \(V_B = V_R\) and \(V_Y ≠ 0\)
   - \(V_{BR} = 0\) and \(V_{YR} ≠ 0\) and \(V_{YB} ≠ 0\)

4. **Case 4**
   - \(I_R + I_Y + I_B = 0\)
   - \(V_R = V_Y = V_B\)
   - \(V_{RY} = 0\) and \(V_{YB} = 0\) and \(V_{RB} = 0\)
5 Conclusion

In the existing underground power distribution system (UGPDS), fault detection and isolation are tedious tasks. Proper supervision is not possible in underground power cables. Its adverse effect affects electricity management and control, but many valuable appliances are damaging at a high rate. The reliability and stability of electrical appliances decrease rapidly, which is one of the main reasons for getting electricity limited. In this article, we proposed a (Smart Underground Power Distribution System) SUGPDS Model which can solve and make the detection and isolation technique quite simple and easy with the supports of Smart Sensing and Switching Device (SSSD) and different smart sensors like micro phasor measurement unit, smart sensing and switching device, phasor data concentrator, and ZigBee technology, etc. The Detection and Isolation (DI) algorithm also has been proposed for the Phasor Data Concentrator (PDC) for the classification of various kinds of faults with the capability of isolation of the faulty phase. Hence, the reliability, stability, proper supervision, power efficiency, electricity management, Detection and control of underground power cable can be achieved with the support of SUGPDS. Further machine learning and deep learning concepts can be deployed for differentiating low and high impedance faults.

Fig. 9 Ground faults detection and their isolation from the healthy section between SSSD1 and SSSD2
Table 7  Comparative analysis of electrical parameters for ground fault between two SSSDs

| Case no | Fault type | Reading of DC report | Switching implantation SSSD |
|---------|------------|-----------------------|-----------------------------|
| SSSD 1  | SSSD 2     | Line current | Phase voltage | Line voltage | Line current | Phase voltage | Line voltage |                |
| Case 1  | Ground Fault Detected | (I_R + I_Y + I_B = I_f) | (V_R = V_Y = V_B) | (I_R = I_C and I_Y = I_C and I_B = I_C) | (V_R = V_Y = V_B = 0) | (V_R = V_Y = V_B = 0) | All cables are grounded |
|         |            | (I_R = I_B or I_Y ≠ 0 or I_B ≠ 0) | (V_R = 0 or V_Y ≠ 0 or V_B ≠ 0) | (I_R = I_C or I_Y ≠ 0 or I_B ≠ 0) | (V_R = -V_Y or V_B ≠ 0 or V_B ≠ 0) | (V_R = -V_Y or V_B ≠ 0 or V_B ≠ 0) | R grounded |
| Case 2  |            | (I_R ≠ 0 or I_Y = I_B or I_B ≠ 0) | (V_R ≠ V_Y or V_B ≠ 0) | (I_R ≠ 0 or I_Y = I_B or I_B ≠ 0) | (V_R ≠ V_Y or V_B ≠ 0) | (V_R ≠ V_Y or V_B ≠ 0) | Y grounded |
| Case 3  |            | (I_R ≠ 0 or I_Y ≠ 0 or I_B = I_Y or I_B ≠ 0) | (V_R ≠ V_Y or V_B ≠ 0) | (I_R ≠ 0 or I_Y ≠ 0 or I_B = I_Y or I_B ≠ 0) | (V_R ≠ V_Y or V_B ≠ 0) | (V_R ≠ V_Y or V_B ≠ 0) | B grounded |
| Case 4  |            | (I_R ≠ 0 or I_Y ≠ 0 or I_B = I_Y or I_B ≠ 0) | (V_R ≠ V_Y or V_B ≠ 0) | (I_R ≠ 0 or I_Y ≠ 0 or I_B = I_Y or I_B ≠ 0) | (V_R ≠ V_Y or V_B ≠ 0) | (V_R ≠ V_Y or V_B ≠ 0) | B and R grounded together |
| Case 5  |            | (I_R + I_Y = I_f and I_B ≠ 0) | (V_R = V_Y = V_B = 0 and V_B ≠ 0) | (I_R = I_Y = I_C and I_B ≠ 0) | (V_R = V_Y = V_B = 0 and V_B ≠ 0) | (V_R = V_Y = V_B = 0 and V_B ≠ 0) | R and Y grounded together |
| Case 6  |            | (I_R + I_B = I_f and I_Y ≠ 0) | (V_Y = V_B = 0 and V_R ≠ 0) | (I_Y = I_B = I_C and I_R ≠ 0) | (V_Y = V_B = 0 and V_R ≠ 0) | (V_Y = V_B = 0 and V_R ≠ 0) | Y and B grounded together |
| Case 7  |            | (I_B + I_Y = I_f and I_Y ≠ 0) | (V_R = V_B = 0 and V_Y ≠ 0) | (I_B = I_R = I_C and I_Y ≠ 0) | (V_R = V_B = 0 and V_Y ≠ 0) | (V_R = V_B = 0 and V_Y ≠ 0) | B and R grounded together |
### Table 8 Healthy phases and phases through uninterrupted flow of electricity in O/C faults

| S. no | O/C phase | Healthy phase | An uninterrupted flow of electricity |
|-------|-----------|---------------|-------------------------------------|
| 1     | R, Y, and B | None          | Not possible through phases         |
| 2     | R          | Y and B       | Possible through Y and B phase      |
| 3     | Y          | B and R       | Possible through B and R phase      |
| 4     | B          | R and Y       | Possible through R and Y phase      |

### Table 9 Healthy and isolated phases in S/C faults

| S/C phase | Healthy phase | Isolated phase | An uninterrupted flow of electricity |
|-----------|---------------|----------------|-------------------------------------|
| R and Y   | B             | R and Y        | Possible only through B phase       |
| Y and B   | R             | Y and B        | Possible only through R phase       |
| B and R   | Y             | B and R        | Possible only through Y phase       |

### Table 10 Healthy and isolated phases in-ground faults

| S. no | Grounded phase | Healthy phase | Isolated phase |
|-------|----------------|---------------|----------------|
| 1     | R              | Y and B       | R              |
| 2     | Y              | B and R       | Y              |
| 3     | B              | R and Y       | B              |
| Author/Reference          | Faults finding                | Methods                                           | Remarks                                                                                                                                 |
|---------------------------|-------------------------------|--------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------|
| Prabhavathi et al. [41]   | Ground faults                 | Discrete Wavelet Transform (DWT)                  | • Applicable for high voltage power link of 11 kV  
• Communication—Unidirectional  
• Monitoring—Asynchronous Monitoring  
• Isolation of faults or faulty phase—Not possible |
| Lee et al. [36]           | Pole to ground faults         | Discrete Wavelet Transform (DWT) + PSCAD         | • Applicable for Underground LVDC  
• Communication—Unidirectional  
• Monitoring—Synchronous Monitoring  
• Response—Unhurried & unreliable response  
• Not able to detect Short circuit and Open circuit fault |
| Somani et al. [29]        | Short circuit fault           | IEEE 14 Bus System + Matlab Simulink             | • Communication—Unidirectional  
• Monitoring—Asynchronous Monitoring  
• Response—Unhurried & unreliable response  
• Not able to detect Ground and Open circuit fault  
• Controllability and Observability—Poor |
| Goswami et al. [10]       | Line-to-line (LL) and line-to-ground (LG) | IoT + MCU Module | • Accuracy: LG fault (94.53%) and LL fault (98.63%)  
• Communication—Bidirectional  
• Monitoring—Synchronous Monitoring  
• Load Management—Inadequate  
• Isolation of faults or faulty phase—Not possible |
| Asif et al. [9]           | Short circuit fault and open circuit fault | PROTEUS + LCD display + fault sensing circuit module and Microcontroller | • Applicable for high voltage power link of 11 kV  
• Communication—Unidirectional  
• Monitoring—Asynchronous Monitoring  
• Controllability and Observability—Poor  
• Chance of error—High |
| Hans et al. [8]           | LG, LL, AND LLL faults        | Murray loop and Ohm’s Law Method                  | • Applicable for high voltage power link of 11 kV  
• Communication—Bidirectional  
• Monitoring—Synchronous Monitoring  
• Isolation of faults or faulty phase—Not possible |
Table 11 (continued)

| Author/Reference | Faults finding | Methods | Remarks |
|------------------|----------------|---------|---------|
| Proposed model- SUGPDS model | Short circuit fault, open circuit fault, ground fault and no load condition | Integration of sensor i.e. µPMU + PDC + ZigBee + Smart Relay + Circuit Breaker and DI Algorithm | • Communication—Bidirectional<br>• Nature of system—Digital system<br>• Response—Quick & reliable response<br>• Controllability and Observability—Superior<br>• Power interruption and cable insulation failures—Less<br>• Monitoring—Synchronous monitoring<br>• µPMU (Present)—Measures: voltage, current, phase angle & frequency<br>• PDC(Present)—Power consumption analysis become better, and load management become superior<br>• Control and Switching Unit (Present)—Isolation of faults or faulty phase—Not possible<br>• Overall highly accurate and reliable |

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