Identification and Location for Phase-to-Ground Fault with Magnetic Sensing in Power Distribution Network: Principle and Practical Implementation

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***Abstract*— Power distribution cables are the core of a power distribution network in the power system. Phase-to-ground faults account for around 70% of all faults in a power distribution network, and thus their identification and location are essential for the reliability and efficiency of a power system. In this paper, a current-measurement technique with magnetic sensing and computational intelligence for a power distribution cable is proposed, which can reconstruct the fault current while retaining its DC offset. From the DC component, the phase-to-ground fault and faulty phase can be identified accordingly. The technique also enables the double-ended current method to locate the fault since current measurement can then be implemented with magnetic sensors at both ends of the cable at a much lower cost than using current transformers. The implementing procedure of this method is presented for guiding its application in practical scenarios. The technique is envisioned to enhance the situational awareness of the smart grid.**

***Index Terms* — power distribution cable, phase-to-ground fault, location, power distribution network, smart grid**

I. Introduction

Power cables are critical in power distribution networks of a power system for delivering electricity to consumers in the city [1]. In the process of constructing smart grid in the 21st century, power distribution networks must be ensured with maximum reliability, longest service life and lowest maintenance cost for transferring energy more efficiently and affordably. Unfortunately, power distribution cables can suffer internal (e.g., moisture corrosion) or external damages (e.g., road construction) resulting in the termination of normal power delivery. As such, a fault occurs on a power distribution network should be rescued within the shortest time to reduce negative effects.

A short-circuit fault occurred on a power distribution network can be classified as following for a three-phase system: (a) phase-to-ground fault, (b) phase-to-phase fault, (c) phase-phase-to-ground fault, and (d) three-phase fault. First of all, the fault category needs to be identified since a proper protection scheme should be activated after a fault occurs. The faulty phase should also be recognized for triggering a corresponding relay to extinguish the arcs for preventing the situation from aggravating. Secondly, the inspection workload of repairman can be significantly reduced if the fault can be preliminarily located because power distribution cables are paved underground and thus the line-inspection work is not easy. Therefore, fault classification and location for power distribution networks is essential to improve the reliability of the system and reduce economic loss.

This paper focuses on the identification and location of a phase-to-ground fault as it accounts for around 70% of all faults in the distribution network according to the surveys [2, 3]. Traditional fault classification methods depend on setting a threshold for overcurrent (e.g., overcurrent method [4]) or recognizing the existence of high-frequency components in the faulty phase (e.g., high-frequency energy method [5]). However, these methods are not satisfactory due to the following reasons. Firstly, the workload of setting a threshold for each individual power distribution cable is substantial as the rated current of each power distribution cable is different. This problem is getting more severe as power distribution networks are expanding to meet the increasing electricity demand in the city. Secondly, a high-frequency energy component may arise in the unfaulty phase either due to the electromagnetic coupling between the healthy and unhealthy phase or from the electromagnetic interference (EMI). All in all, a robust and reliable method for identifying the phase-to-ground fault needs to be developed for the future power systems.

Meanwhile, there indeed exists a series of fault location methods for power distribution networks such as impedance method, traveling wave method, and signal injection method [6]. The impedance method is the simplest as it operates by just recording the voltage and current by transformers during fault without involving other external instruments. The distance between the measurement and fault point can be determined since the conductor length is proportional to its impedance. In terms of the impedance method, the double-ended current method which measures the current at both ends of the cable is most popular as it is free from the effect of fault resistance. However, this method has not been applied widely in power distribution networks due to the following reasons: firstly, the fault current cannot be accurately measured by current transformers (CTs) since the DC component in fault current can inversely result in a measurement bias in CTs. Secondly, to install the CTs at both ends of a power distribution cable is not economical. As such, for practical applications, this method needs a more convenient and economical current measurement technique that can measure current with DC component.

In this paper, a current-measurement technique with magnetic sensing and computational intelligence is developed. This method can measure the fault current successfully even with DC offset. The retained DC component is deployed for identifying the phase-to-ground fault and faulty phase. Meanwhile, the technique makes the double-ended current method capable for fault location since current measurement can then be implemented with magnetic sensors such as magnetoresistive sensors at a much lower cost (i.e., from several to tens of USD) than using CTs (i.e., hundreds of USD) [7, 8]. The rest of the paper is presented as follows: the working principle of this technique is introduced in Section II, and the practical implementation of this technique is described in Section III. Section IV draws the conclusion.

II. Principle

A. *Fault classification*

When a fault occurs, the normal current becomes asymmetrical and then returns to symmetrical in a few cycles (Fig. 1). The asymmetrical response in the fault is called DC decaying component and it is a naturally occurring phenomenon of the electrical system since the current cannot change abruptly in an inductive network (e.g., generators and transformers). The decaying time of DC component depends on the X/R of the power system, and the first peak can be several times as large as the steady-state level. This feature makes the fault current distinguishable from the normal current and thus can be used for identifying the faulty phase.

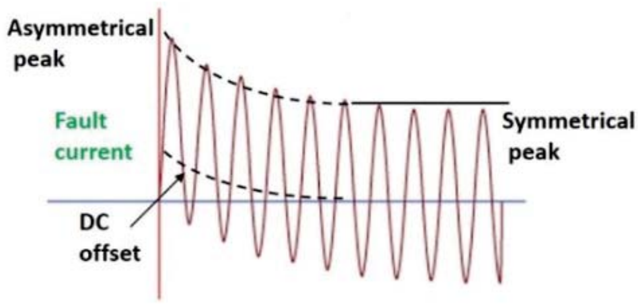

Figure 1. DC component arises in the fault current.

The phase-to-ground fault and corresponding faulty phase can be identified based on the existence of the DC component. Namely, only one phase has the DC component and the other two do not. Accordingly, the phase containing the DC component is the faulty phase. This method can overcome the disadvantages of traditional fault-identification methods. Firstly, this method does not need to set a threshold which changes with different power networks. Secondly, the DC component is not affected by high-frequency signals as their frequency spectrum is far away from each other. As such, identifying the phase-to-ground fault by recognizing the DC component is promising.

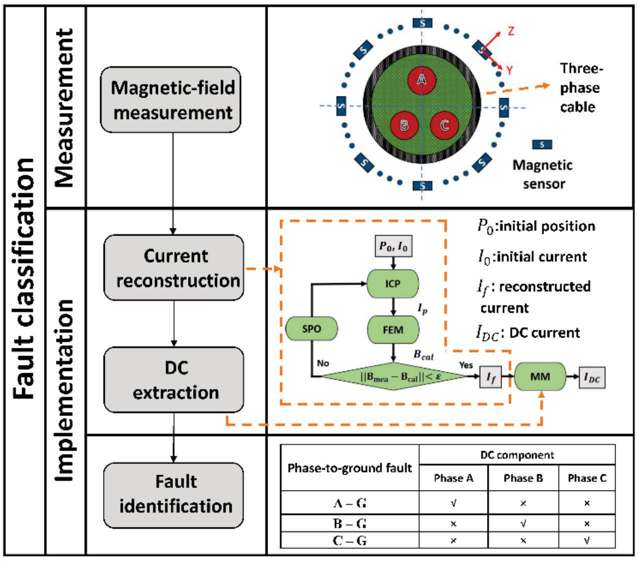

Figure 2. Identification of phase-to-ground fault based on the DC component, and the algorithm to extract the DC component.

Based on the above analysis, the DC component of each phase must be extracted accurately. However, the DC component cannot be measured precisely by the CTs as a decaying DC offset can affect the performance of CTs by changing their working point in the magnetization curve. As such, a computationally stochastic algorithm for reconstructing the three-phase currents and DC component based on the magnetic sensing is developed (Fig. 2). The program commences with the pre-set position of conductors (P_0) and currents (I_0). Based on the Biot-Savart law, the currents flowing in the phase conductors of the cable emanate magnetic fields which can be measured by the magnetic sensors installed around the cylindrical surface of the cable. With the measured magnetic fields (B_{mea}), the current is determined by the least square method via

$$I_p = (A^T A)^{-1} A^T B_{mea} \quad (1)$$

where A is a coefficient matrix calculated based on the relative position between the phase conductor and sensing currents. Then the magnetic-field distribution at the sensing points (B_{cal}) can be estimated by the finite element method (FEM) with the optimized currents. The Euclidean distance between the measured and calculated magnetic fields is compared. If it is larger than a pre-set threshold (ε), the positions of conductors are optimized by the source position optimization (SPO) which is embedded with genetic algorithm. The iteration continues until the final three currents (I_f) are attained when the Euclidean distance is smaller than the threshold. Afterwards the three-phase currents are processed by the mathematical morphology (MM) to extract the DC components. The opening ($\circ$) of MM algorithm is performed during the peak half cycle of phase currents, and the closing ($\bullet$) is performed during the trough half cycle as

$$D = \begin{cases} I \circ B & \text{for peak half cycle} \\ I \bullet B & \text{for trough half cycle} \end{cases} \quad (2)$$

where D is the extracted component. Finally, the existence of the DC component (i.e., the value of D) can be used to determine the phase-to-ground fault and faulty phase.

This measurement technique based on magnetic sensing for measuring the current and DC component of a power distribution cable has the following advantages: firstly, it can measure the fault current without the distortion from the DC offset. The traditional CTs cannot measure DC component because the DC current offsets the magnetic flux and increases their errors. Secondly, to install a magnetic sensor array around a cable is much cheaper than CTs. In addition, it can measure the three-phase currents simultaneously without the need to remove the cable insulation layer to make contact with each phase conductor.

B. Fault location

The double-ended current method measures the fault current at both ends of a cable. These fault currents can be measured by magnetic sensor arrays (Fig. 3(a)) following the algorithm in Fig. 2. When a fault occurs, the equivalent circuit for the phase-to-ground short-circuit fault is depicted in Fig. 3(b). The distance of fault point (x) can be calculated as

$$x = \frac{U - I_2(Z_0 l + Z_l)}{Z_0(I_1 - I_2)} \quad (3)$$

where Z_0 is the unit impedance of the cable, Z_l is the resistance of the load, l is the cable length, U is the voltage at sending end, and I_1, I_2 are the fault current at both ends of the cable, respectively. This method provides a good accuracy as the measurement is not affected by the fault resistance (Z_f) which is not measurable during a fault. The voltage at the sending end is measured by the potential transformers connecting with the bus.

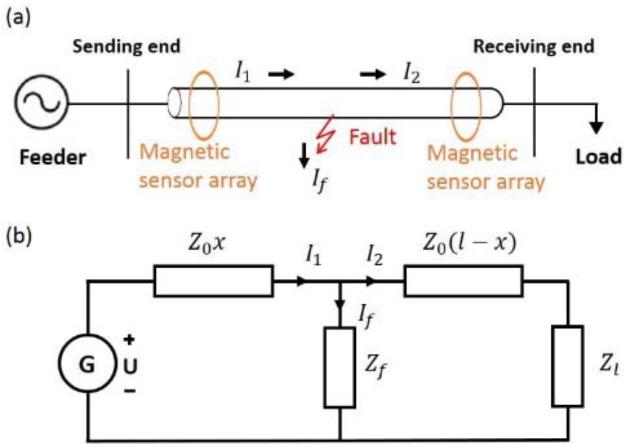

Figure 3. The double-ended current method for fault location. (a) Installation of magnetic sensors at both ends of a power distribution cable to measure the phase current from the magnetic field. (b) The equivalent circuit for the phase-to-ground short-circuit fault.

III. PRACTICAL IMPLEMENTATION

A. Platform hardware

The laboratory setup for demonstrating the implementation of this technique is presented in Fig. 4. It emulates a practical scenario that the electricity is delivered to customers through a three-phase three-core power distribution cable. In this setup, a programmable power source connects with a 3-phase 3-core power distribution cable (BS6622) and resistive loadings to form a closed circuit. The programmable power source (61704, Chroma) is able to generate different voltage and frequency to simulate various phase-to-ground faults. The magnetic-sensing platform is comprised of a magnetic sensor array and magnetic shielding. The electrical safety of the platform is ensured by installing a miniature circuit breaker (MCB) and a residual-current device (RCD). The MCB protects the circuit from overloading or short circuit, and RCD protects users from the electric shock caused by electricity leakage. The MCB and RCD are routinely checked for ensuring the safety of the experiment. In order to make sure that the output is consistent as programmed, the three-phase currents of the cable are measured by current clamps.

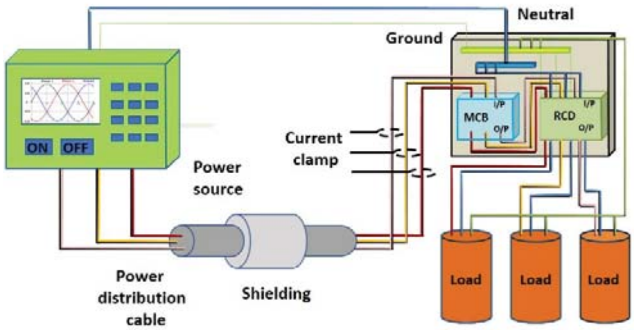

Figure 4. Platform to emulates a practical scenario. It comprises of a programmable power source, power distribution cable, and loadings. The magnetic sensors are installed around the cable and they are protected by a triple-layered magnetic shielding.

TABLE I. IMPLEMENTATION PROCEDURE

Procedure		
Step	**Item**	**Issues to consider**
i	Sensor installation	a. Sensor performance b. Sensor quantity c. Mounting
ii	Shielding installation	Size and cost
iii	Magnetic measurement	Hysteresis and saturation
iv	Data acquisition and processing	Noise filter
v	Current reconstruction	Parameter setting
vi	DC extraction	Threshold setting

B. Identification

The procedure for implementing this method is summarized in Table I. The details are as follows:

(i) Sensor installation: the magnetic sensors should be chosen carefully for operating within its linear range to achieve accurate measurement. Besides, the sensor should be able to measure small magnetic-field variation with high resolution. In practice, the magnitude of magnetic fields around a cable can be evaluated by finite element method

(FEM) under different current conditions. For example, the strength of the magnetic field around a power cable (No. BS6622 [9, 10]) is around 10 mGauss per ampere. In terms of commercial 3-axis magnetoresistive sensors, for example, HMC2003 by Honeywell, they are able to detect a current change from 4 mA to 200 A based on its measurement range from 40 μGauss to 2 Gauss [11]. In fact, magnetoresistive sensors are recommended for the onsite work where the environment might be harsh because their power consumption is relatively low and they are robust in terms of operation temperature and susceptibility to dust and dirt [12]. There is a tradeoff between the accuracy of the current reconstruction and sensor quantity. More magnetic sensors can provide more information to reconstruct the current for achieving higher accuracy. However, adding more sensors leads to an increase in hardware cost. As such, a simulation is needed before hardware design to study how many sensors are needed for achieving the expected accuracy within the acceptable cost. Besides, the positions of magnetic sensors need to be stably fixed because the relative positions between sensors and cable conductors are critical for the accuracy of current reconstruction. The mounting can be fabricated by 3D printing which provides a high level of precision.

(ii) Shielding installation: a shielding is needed to protect the magnetic measurement around the target power distribution cable from the background noise. A multi-layer magnetic shielding can enhance shielding effectiveness [13]. There is a tradeoff between the shielding effectiveness and shielding size and cost. More layers of shielding can increase the shielding effectiveness but it increases the size and cost. In addition, there should be some redundant space between the cable and internal surface of shielding as the shielding itself can also affect the magnetic field distribution of the power cable.

(iii) Magnetic measurement: the magnetic field emanated from the power distribution cable is measured by the sensor array around the cable surface. For some MR sensors such as the HMC2003, Honeywell, they possess on-chip current strap for re-magnetization process in case of saturation, and thus a reset circuit is needed. For example, in this reset circuit (Fig. 5(a) and (b)) designed for HMC2003 in our lab, a 3-4 amps pulse is generated from the P and N channel of drivers in the MOSFET (NDS9952, FAIRCHILD) which are controlled by SET and RESET signals from the microprocessor to set the magnetization of the permalloy film.

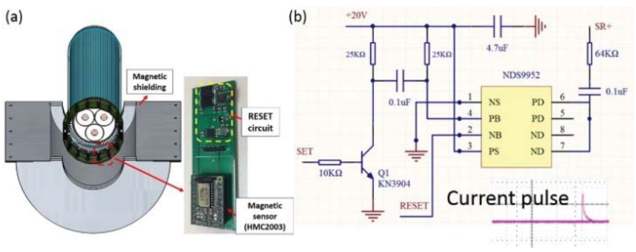

Figure 5. Magnetic sensor array with RESET circuit installed around the cable surface within the magnetic shielding. (a) Magnetoresistive sensors (Honeywell, HMC2003) with a RESET circuit. (b) RESET circuit for re-magnetization.

(iv) Data acquisition and processing: the magnetic sensor data are collected by a data acquisition hardware (e.g., data acquisition card developed by National Instrument) in order to be inputted to a computer for further process. The interferences from electrical contact and electrostatic coupling in a cabling system [14] may contaminate the signal quality. These noises can be removed by Fourier or wavelet denoising.

(v) Current reconstruction: the current reconstruction can start after the magnetic data is collected with the noise removed. The initial populations and genetic-algorithm parameters (i.e., crossover and mutation probability) in the stochastic program can affect the current reconstruction results. The phase differences are pre-set with 120-degree differences, and the cable positions are pre-set at the middle between the cable centre and cable surface. The currents are pre-set with the rated values of the power distribution cable. In the genetic algorithm, the crossover rate is set large (e.g., between 0.65 and 0.85) to expedite the search. The mutation rate is set low (e.g., < 0.05) so that the search does not turn into a primitive random search.

(vi) DC extraction: the mathematical morphology runs in half of a cycle to extract the DC component according to Eq. (2) from the reconstructed currents. A small threshold is set to compare with the extracted DC component for determining the existence of DC component because the positive and the negative cycle of the phase current might not be perfectly symmetrical in operation (e.g., effect of motor starting).

The experimental result implemented with the above procedure and platform is presented in Fig. 6. A phase-to-ground fault (phase A) was generated. The cable current was measured by the current clamp (Fig. 4) and the current waveform is shown in Fig. 6(a). The reconstructed current and extracted DC components are shown in Fig. 6(b). A large DC offset can be found in phase A (~ +2.2A) while the DC offset of other phases did not reach the threshold (e.g., 0.5A) because the DC offsets in phase B and phase C were only around +0.003A and +0.027A respectively. Therefore, it can be determined to be a phase-to-ground fault in phase A.

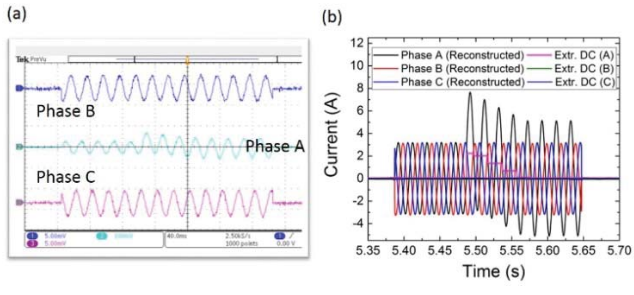

Figure 6. Practical implementation of a phase-to-gound fault. (a) Three-phase currents measurement by current clamps. (b) Reconstructed phase currents and extracted DC components.

C. Location

The above current-measurement platform with magnetic sensing can be further extended for the fault location using double-ended current method. The initial steps of fault location are the same as procedure (i) – (v) in Section III.(B), while some differences are discussed as follow:

(i) Platform installation: the current-measurement platforms with magnetic sensing need to be installed at both ends of a cable (Fig. 3(a)). When a short-circuit fault occurs on the cable, the current at the front end (near voltage source) becomes very large (i.e., several times as the rated values) while the one at the back end (near loading) reduces to a low value due to the short-circuit path. Therefore, the magnetic sensors at the front are recommended with a large measurement range while the ones at the back with a smaller measurement range for higher resolution.

(ii) Data processing: the double-ended current method requires the current signals measured at both ends of the cable at the same time. In our platform, a clock synchronization is necessary in the operation which provides a common time frame to different devices. The data communication and integration can be operated via a supervisory control and data acquisition (SCADA) system (Fig. 7).

(iii) Fault location: the fault can be located by using Eq. (3) with the bus voltage (U), currents at the front end (I_1) and back end (I_2) of the faulty phase, and network parameters (Z_0, Z_l). The voltage signals can be obtained from the potential transformers installed at the bus, and the currents are measured by the magnetic-sensing platform located at both ends of the cable. The unit resistance of cable is provided on the datasheet. The loading resistance can be calculated from the voltage and current of the network before a fault occurs.

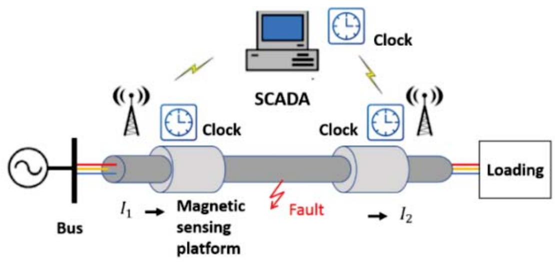

Figure 7. Fault location based on current-measuerment with magnetic sensing. The data communication and process is operated by a supervisory control and data acquisition (SCADA) system.

An implementation example is given as follows: a phase-to-ground fault occurs at the 3 km of a 20 km cable at 0.10 s. The three-phase voltage at the bus and the reconstructed current at both ends of the cable can be found by following the procedure in Section III, and they are exhibited in Fig. 8. The reconstructed currents from the magnetic fields match well with the actual currents of the cable. The DC component arose after the fault and phase A could be recognized as the faulty phase. The fault was determined to be located at 3.067 km by Eq. (3) with voltage and current measurement at 0.12 s in Fig. 8 (i.e., bus voltage was -765.26 V, and front and back currents were -85.41 and -3.13 A, respectively). The relative error is merely 2.23%. The test results in Table II indicated that the fault can be successfully located with a relative error within 3% for other fault location conditions.

IV. Conclusion

A current-measurement technique for power distribution cables with magnetic sensing and computational intelligence is proposed in this paper. This technique can successfully measure the DC offset in fault currents, which can then be used to identify the phase-to-ground fault and faulty phase. The deployment of DC component for fault identification is advantageous: firstly, the serviceman does not need to set a threshold for each individual power distribution cable. Secondly, the DC component is free from the effect of electromagnetic coupling or EMI. The current-measurement technique based on magnetic-field sensing also enables the double-ended current method to locate the fault since it can be implemented with magnetic sensors at a low cost to both ends of a cable. The implementing procedure of this technique to identify and locate faults is presented for guiding its usage in practical scenarios.

TABLE II. Fault Location Result by Double-Ended Current Method Based on Magnetic Sensing

Test No.	Fault distance (km)	Estimated distance (km)	Relative error (%)
1	3	3.067	2.23
2	6	6.068	1.13
3	9	9.07	0.77
4	15	15.072	0.48
5	18	18.073	0.40

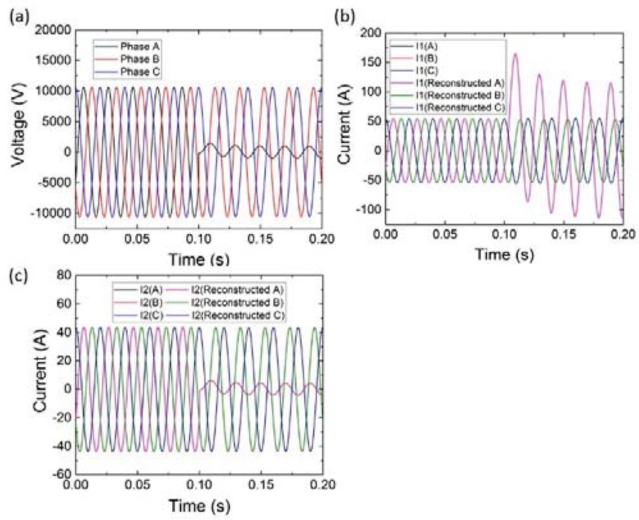

Figure 8. Voltage and current measurement for a power cable in phase-to-ground fault (the cable length is 20 km, the unit impedance of phase conductor is 0.024 Ω/km, and the load resistance is 242 Ω). (a) Voltage measured at the sending end. (b) Current reconstruction from the magnetic sensing at the sending end. (c) Current reconstruction from the magnetic sensing at the receiving end.

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