Underground Power Cable Detection and Inspection Technology Based on Magnetic Field Sensing at Ground Surface Level

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In this paper, a novel technique based on magnetic field sensing is proposed for underground power cable detection and inspection. In this technique, the current sources of the underground power cables are reconstructed based on a set of measured magnetic field values at the ground surface level emanated by the electric currents carried by the underground power cables. The stochastic optimization technique developed with an artificial immune system algorithm is applied to realize the reconstruction. The principle of this method was proved and verified experimentally by our laboratory setup. Application of this method was demonstrated on the simulation models of 11- and 132-kV underground power cables. The reconstruction results of the electrical and spatial parameters of the cables match accurately with the actual source parameters of the cables in the models. This paper shows that the proposed method is able to remotely detect the horizontal locations and vertical depths of underground power cables with high accuracy at the ground surface level requiring no prior knowledge about the exact locations of the cables. Thus, it can be potentially used to develop a portable locator for providing a map of the underground electrical cables by simultaneous detection of multiple power lines. This method can also enable engineers to correctly inspect the operation states of the target cables during onsite maintenance. This technique is applicable to various laying conditions and cable configurations (three core or single core) of the underground power cables. In addition, this is an entirely passive method and does not need any signal injection into the cables.

Index Terms— **Current source reconstruction, detection and inspection, magnetic field sensing, underground power cable.**

I. Introduction

ELECTRICITY power cables are used to deliver electricity to consumers. In metropolitan areas, most power cables are buried underground [1]. Without the prior knowledge of underground power cables, risk can be posed to the excavation workers or other construction workers. Therefore, underground power cables must be detected before any excavation works to check if there are any buried power cables underground [2], [3]. On the other hand, if the operation states of the underground power cables can be inspected, engineers could have better situational awareness and have more information about the potential problems of the underground power cables before digging up the cables for maintenance works [4]–[6]. This could make the underground power distribution network more reliable and avoid unnecessary power interruption.

Nowadays, cable avoidance tools [7] are used to detect the underground power cables. This kind of device works in different modes. In passive mode (50/60 Hz), it provides the approximate horizontal location of the target cable. In active mode, it measures the depth of an underground cable with the aid of a signal generator that typically injects 33 kHz signal into the cable. However, these tools can only detect spatial parameters of the underground cables. They cannot provide any electrical information in most cases. In addition, it heavily relies on the expertise, experience, and judgment of the operator to properly locate the underground cables. These tools are in principle just a magnetometer and they do not provide much analysis about the measured data. A certified personnel is typically needed (it is required by law in many countries) to use this kind of tool to carry out underground cable detection. These cable avoidance tools are expensive; particularly, the signal generators needed in active mode are costly. Therefore, it is of great application value to develop a novel detection and inspection technology for underground power cables [8].

According to Biot–Savart Law, a conductor carrying electric current generates magnetic field. The source current and the spatial location of the cable determine the distribution of the emanated magnetic field. Generally, a buried 11-kV 540 A underground power cable emanates magnetic field in the order of microTesla at the ground level. When the phase current varies, the ground-level magnetic field changes in magnitude and distribution correspondingly. Currently, commercially available magnetoresistive (MR) magnetic sensors can provide sensitivity down to around 10^{-9} T and spatial resolution of 0.9 mm [9]. Thus, the MR sensors installed on the ground level can accurately measure the emanated magnetic field distribution from the buried power cables. When a group of magnetic field values are measured, it is possible to reconstruct the spatial and electrical information of the underground power cables by solving inverse problem [10]. Previously, we developed a technique for monitoring operate state and identify energization status for underground power cables based on magnetic field sensing [11]. However, it has the limitation that the sensor array must be mounted around the cable surface which requires the cable to be dug out and exposed.

In this paper, we developed a novel underground power cable detection and inspection technology based on magnetic field sensing at ground surface level without the need of excavating the cable. It operates in passive mode with no need for any signal injection and it can perform multicable detection. Using this technology, the horizontal locations and the vertical depths of the underground cables can both be remotely and accurately measured requiring no prior knowledge about the exact locations of the cables. In addition, it can inspect the operation states of underground power cables

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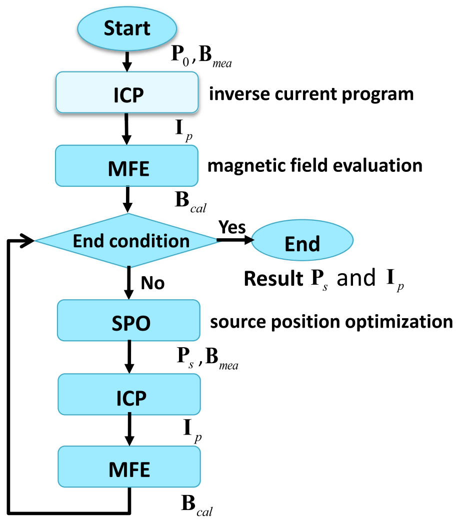

Fig. 1. Flowchart of current source reconstruction based on magnetic field sensing.

and provide more detailed information than the existing cable avoidance tools. Besides spatial parameters, it can provide detailed electrical parameters of the underground power lines, which are important for analyzing the power systems. For examples, when phase current imbalances are detected, the operator can diagnose the system operating in an unstable state. This technology can also provide the information of system frequency, which is the only parameter that can indicate the balance of the power system and reflect if supply–demand mismatch occurs.

II. Current Source Reconstruction Methodology for Underground Power Cable

Stochastic optimization technique is used to solve the inverse problem and reconstruct the horizontal locations, the vertical depths, and the electrical parameters of the target cable conductors from the magnetic field measured remotely at the ground surface level [10]. Two nested algorithms including least square approximation (LSA) and artificial immune system (AIS) are used in the optimization process [12], [13]. The whole process is described in the flowchart (Fig. 1). It starts with the default position parameters $\mathbf{P}_0$ of the underground cable conductors. Phase current $\mathbf{I}_p$ in each conductor is calculated by inverse current program (ICP) based on the LSA algorithm, with position parameters and measured magnetic field $\mathbf{B}_{\text{mea}}$ as variables by

$$\mathbf{I}_p = (\mathbf{A}^T\mathbf{A})^{-1}\mathbf{A}^T\mathbf{B}_{\text{mea}} \tag{1}$$

where $\mathbf{A}$ is the coefficient matrix which depends on the cable conductor positions. Then, the magnetic field $\mathbf{B}_{\text{cal}}$ is calculated using $\mathbf{I}_p$ and $\mathbf{A}$ in magnetic field evaluation (MFE) module based on finite element analysis (FEA) as [14], [15]

$$\mathbf{B}_{\text{cal}} = \mathbf{A}\mathbf{I}_p. \tag{2}$$

There is a predetermined minimum threshold value of the Euclidean distance $\|\mathbf{B}_{\text{cal}} - \mathbf{B}_{\text{mea}}\|$ as the end condition for terminating the optimization. If the end condition is not satisfied, the algorithm randomly generates a group of new position parameters $\mathbf{P}_s$ using AIS algorithm in source position optimization module. With the $\mathbf{B}_{\text{mea}}$ and the new $\mathbf{P}_s$, the $\mathbf{I}_p$ is computed again in the ICP module. The new $\mathbf{P}_s$ and $\mathbf{I}_p$ are then used to simulate new $\mathbf{B}_{\text{cal}}$ in the MFE. When the Euclidean distance between the calculated $\mathbf{B}_{\text{cal}}$ and $\mathbf{B}_{\text{mea}}$ is smaller than the minimum threshold value, the optimization process is finished, and then the resulting $\mathbf{P}_s$, and $\mathbf{I}_p$ are saved as the optimum current source parameters; otherwise, the iteration continues to loop. This optimization process is repeated multiple times (N) to obtain the final $\mathbf{P}_s$ which are the ensemble averages of these N optimum values. Accordingly, the final $\mathbf{I}_p$ is obtained from the final $\mathbf{P}_s$ and the measured magnetic field.

III. Experimental Proof of Concept

To verify this current source reconstruction methodology based on magnetic field sensing for detecting and inspecting underground power cables, a laboratory setup including a MR three-axis sensor (Honeywell HMC2003) array and three-phase straight power lines (50 Hz) with flat formation was established to act as the experimental proof-of-concept setup. Fig. 2(a) and (b) show the actual setup and its schematic diagram, respectively. The eleven MR sensors are equally separated and placed as an array. We define the height of sensor array as $y = 0$ cm and the height of power lines as -50.0 cm. The positions of power lines are $(-16, -50)$, $(0, -50)$, and $(16, -50)$. A three-phase mains power supply was connected with the three power lines. The phase current amplitudes were 16.3, 16.2, and 16.5 A in phase A, B, and C, respectively (Experiment 1). Their emanated magnetic field was measured by the sensor array, as shown in Fig. 3(a). The measured magnetic field values are very close to the values calculated analytically. Based on the measured magnetic field, the current source reconstruction was carried out to find out the spatial and electrical parameters of these three-phase power lines. The reconstructed power line positions are $(-15.52, -50.3)$, $(-0.25, -49.31)$, and $(15.71, -50.28)$ with average error of 3.7% to the line-to-line distance. As shown in Fig. 3(b), the reconstructed phase current amplitudes are found to be 16.0, 15.8, and 16.3 A in phase A, B, and C, respectively. The average error to actual value is 2%. From the reconstructed phase current curves in Fig. 3(b), the current cycle is determined to be 20.1 ms, corresponding to a system frequency of 49.8 Hz with an error of 0.4% to the actual mains frequency. In general, the error between the reconstructed results and the actual values is less than 4% for this experiment. When we decrease the phase current amplitudes to 8.2, 8.1, and 8.2 A in phase A, B, and C, respectively (Experiment 2), the emanated magnetic field changes correspondingly as measured by the MR sensors [Fig. 3(c)]. The measured magnetic field values match well with the analytically calculated values. Based on the measured magnetic field, the spatial, and electrical parameters are reconstructed. The power line positions are reconstructed to be $(-15.39, -50.4)$, $(0.43, -50.73)$, and $(16.4, -50.36)$ with average error of 4.3% to the line-to-line distance. The reconstructed phase current curves are shown in Fig. 3(d). The reconstructed phase current amplitudes are 8.5, 8.3, and 8.0 A in phase A, B, and C, respectively. The average error to the actual value is 3%. The reconstructed current cycle is found to be 19.83 ms, corresponding to a system frequency of 50.4 Hz with an error of 0.8% to the mains frequency. In general, the error between the reconstructed results and the actual values is less than 5% for this experiment. We can see that the spatial and electrical parameters determined

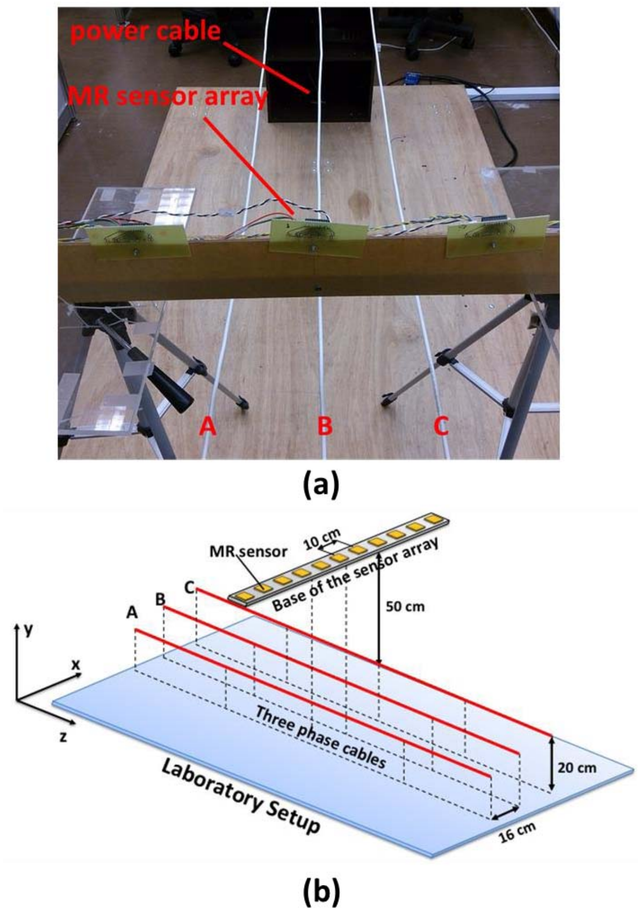

Fig. 2. Testbed including MR magnetic sensors and three-phase power cables for testing and verifying the detection and inspection technology. (a) Laboratory setup. (b) Schematic diagram of the laboratory setup.

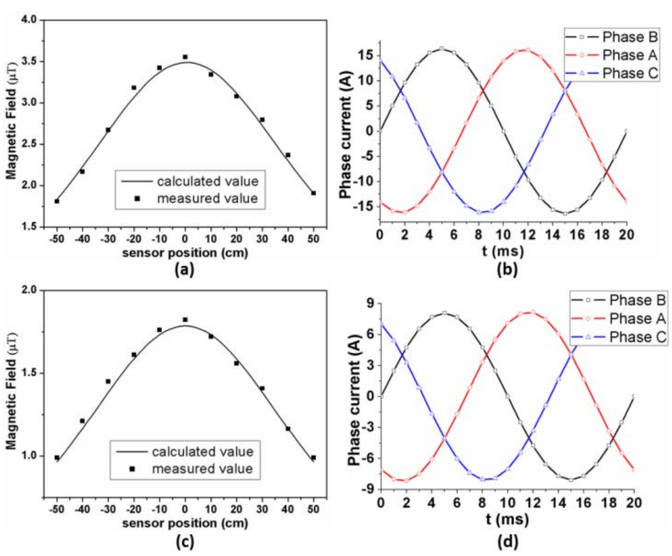

Fig. 3. Experimental and reconstruction results obtained from the laboratory setup for (a) and (b) Experiment 1 and (c) and (d) Experiment 2. Figures on the left: the measured magnetic field values (black squares) by MR sensors and analytically calculated (curve) magnetic field values. Figures on the right: the reconstructed phase current curves based on the measured magnetic field values obtained from experiment.

by measuring the emanated magnetic field and using the current source reconstruction methodology match well with the actual values of the power lines in these experiments (errors less than 5%). The principle of this detection and inspection technology is physically sound and feasible.

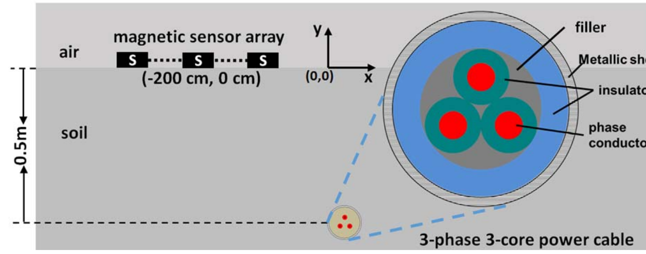

Fig. 4. Model of 11-kV three-phase three-core underground power cable. S denotes the magnetic sensor. The coordinate of the center of the magnetic sensor array is indicated. The internal structure of the power cable is illustrated.

IV. Applications in Underground Power Cables

Eleven-kilovolt three-phase three-core underground power cable with rating current 540 A at 50 Hz in trefoil formation [16] is modeled as an example to demonstrate this technology. It is buried with depth of 0.5 m [positioned at (0 cm, -50 cm)] (Fig. 4). In the simulation model, FEA is used to compute the magnetic field generated by the underground power cable. The material parameters used in FEA are displayed in Table I. Based on the simulation result of the ground-level magnetic field, it is found that the peak value of magnetic flux density (4.5 μT) at the ground level is obtained at $x = 0$ (vertically above the power cable) and decreases rapidly as the field point is further away from the central point. A magnetic sensor array is used to measure the ground-level magnetic field. In reality, this magnetic sensor array can be implemented with a MR sensor array just like the one used in our laboratory setup. The magnetic sensor array can be placed arbitrarily [for example centered at (-200 cm, 0 cm) here] on the ground. Here, it is composed of 11 magnetic sensors with 10 cm spacing among each other (same as the sensor array layout in our laboratory setup in Fig. 2). A group of magnetic field values can thus be measured for reconstructing the current sources in the target cables. With the magnetic field data [inset of Fig. 5(a)], the current sources in the underground cable can be reconstructed using our method described in Section II. Fig. 5(a) shows that the center of the sensor array is placed at (-200 cm, 0) and the actual cable location at (0 cm, -50 cm). The reconstructed cable location result is (0.74 cm, -50.7 cm). The horizontal error of location is less than 1 cm. The 0.7 cm error in its vertical position is 1.4% of the actual depth of the cable. Based on the results of the reconstructed cable position, each phase current is reconstructed at every 1 ms, as shown in Fig. 5(b), where the amplitude and phase of each conductor current are reconstructed. The reconstructed current amplitudes in phase A, B, and C are 532, 533, and 547 A, respectively. They are only slightly deviated from the actual value of 540 A by less than 1.5%. The reconstructed phase angles in phase A, B, and C are $-120.6°$, $-0.4°$, and $121.1°$, respectively. These values are merely deviated from the actual angles by less than 1%. The current cycle is found to be 20.19 ms, corresponding to a system frequency of 49.53 Hz with only a small error of 0.9%. In general, the application of this underground power cable detection and inspection technology in 11-kV three-phase three-core cables provides accurate

TABLE I
ELECTROMAGNETIC PROPERTIES OF THE MATERIALS IN FEA MODELS OF 11- AND 132-kV UNDERGROUND CABLE

	relative permittivity ε_r	Conductivity σ_r (s/m)	relative permeability μ_r
Phase conductor (Copper)	1.0	5.8×10^7	1.0
Conductor insulator (XLPE)	2.3	0.0	1.0
Filler (PVC)	2.3	0.0	1.0
Metallic sheath (Copper)	1.0	5.8×10^7	1.0
Soil (Loamy, Dry)	3.06	0.0	1.0
Air	1.0	0.0	1.0

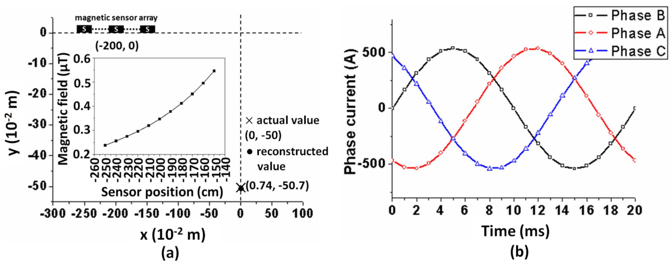

Fig. 5. Results of current source reconstruction of 11-kV underground power cable. (a) Magnetic sensor array positions, actual, and reconstructed position of the cable. (b) Reconstructed phase current curve of each phase conductor.

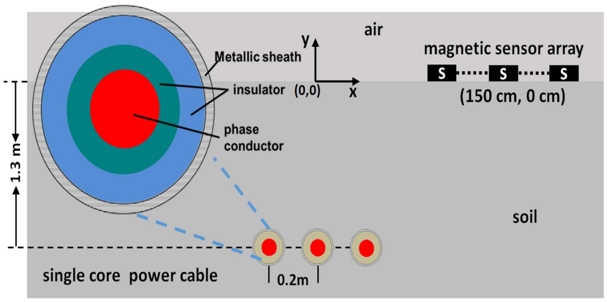

Fig. 6. Model of 132-kV underground power cables with three individual conductors. S denotes the magnetic sensor. The coordinate of the center of the magnetic sensor array is indicated. The internal structure of the power cable is illustrated.

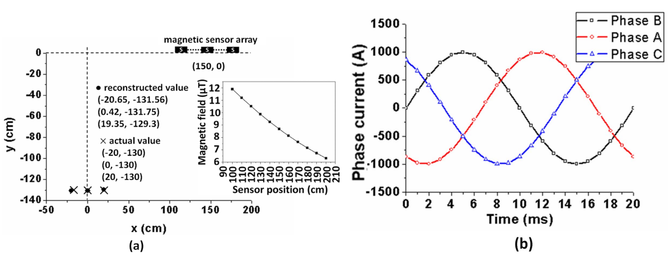

Fig. 7. Results of current source reconstruction of 132-kV underground power cables. (a) Magnetic sensor array positions, actual, and reconstructed positions of the cables. (b) Reconstructed phase current curve of each phase conductor.

reconstructed spatial and electrical parameters with errors less than 2%.

To test this method in different laying conditions of underground power cable, we create a model of 50 Hz 132-kV underground power cables with flat formation, as shown in Fig. 6 [16]. The material parameters used in FEA are also displayed in Table I. In this case, there are three target cables. They are buried at depth of 1.3 m and separated with 0.2 m among each other. The rating ampere of each single conductor cable is 1020 A. In Fig. 7(a), the center of the magnetic sensor array is arbitrarily placed at (150 cm, 0 cm). With a group of magnetic field values measured [inset of Fig. 7(a)], the locations and depths of the three power cables are reconstructed. It is found that the cable locations are (−20.65 cm, −131.56 cm), (0.42 cm, −131.75 cm), and (19.35 cm, −129.3 cm). The average error of the reconstructed cable horizontal locations is 0.47 cm, which is 2.3% of the distance between them. The average error for the reconstructed vertical depth is 1.3 cm, which is 1% of the cable depth. The phase current curve of each cable is reconstructed in Fig. 7(b). The reconstructed current amplitudes in phase A, B, and C are 1029, 1029, and 1015 A, respectively. These are only slightly deviated from the actual value of 1020 A by less than 0.9%. The reconstructed phase angles in phase A, B, and C are −121.1°, 0.6°, and 120.9°, respectively. These values are merely deviated from the actual angles by less than 0.9%. The system frequency of 50.79 Hz is obtained with an error of 1.58% to the 50 Hz mains frequency. In general, the application of this underground power cable detection and inspection technology in 132-kV three-phase cables provides accurate reconstructed spatial and electrical parameters with errors less than 3%. The error is greater than the 11-kV scenario due to the spatial separation among the conductor positions of 132-kV cables is much wider than the 11-kV cable.

It is worth noting that the placement of the magnetic sensor array is flexible and it does not need to be exactly above the cables to be detected as demonstrated by these two application examples. A horizontal offset of over a meter between the center of the sensor array and the cables can be tolerated, and accurate reconstructed results can still be obtained. It is highly advantageous to the practical application of this technique on site because in reality only rough locations of the power cables are provided by the underground cable route maps from the power companies.

V. CONCLUSION

In this paper, we developed a novel underground power cable detection and inspection technology based on magnetic field sensing and current source reconstruction. When a group of magnetic field values are measured by a magnetic sensor array at ground surface level, current source reconstruction can be applied to solve the inverse problem and obtain the spatial and electrical parameters of the cables including horizontal location, vertical depth, and current information requiring no prior knowledge of the exact cable locations. Since the complete process is only based on the remote magnetic field sensing and current source reconstruction, it is a passive detection and inspection method with no need of any signal injection. In addition, it is able to detect multiple targets simultaneously. The principle of this technology was proved experimentally with our laboratory setup. We successfully applied and demonstrated it in the simulation models of 11-kV trefoil-formation and 132-kV flat-formation underground power cables. Thus, it is universally applicable for various laying conditions and configurations of underground power cables. This technology is feasible for detecting the positions and inspecting the operation states of underground power cables. It can help locating underground power cables before excavation works. It can be potentially used to develop a portable locator for providing a map of the underground electrical cables by simultaneous detection of multiple power lines. In addition, engineers can apply this technology to inspect the operation states of the underground power cables remotely without digging up the cables.

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