ELECTROMAGNETIC FIELD APPLICATION TO UNDERGROUND POWER CABLE DETECTION

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Abstract: Before commencing excavation or other work where power or other cables may be buried, it is important to determine the location of cables to ensure that they are not damaged. This paper describes a method of power-cable detection and location that uses measurements of the magnetic field produced by the currents in the cable, and presents the results of tests performed to evaluate the method. The cable detection and location program works by comparing the measured magnetic field signal with values predicted using a simple numerical model of the cable. Search coils are used as magnetic field sensors, and a measurement system is setup to measure the magnetic field of an underground power cable at a number of points above the ground so that it can detect the presence of an underground power cable and estimate its position. Experimental investigations were carried out using a model and under real site test conditions. The results show that the measurement system and cable location method give a reasonable prediction for the position of the target cable.

1 INTRODUCTION

The location of buried utility service infrastructure is becoming a major engineering and social issue worldwide for their successful operation and maintenance. The lack of accurate positioning records of existing services such as water, sewer, power and telecommunications can create engineering and construction challengers and safety hazards when new construction, repairs, or upgrades are necessary. Two main reasons can cause the lack of records. One is that these infrastructures can exist underground for many years, largely forgotten; other one is that records almost always refer to positions relative to ground level physical features that may no longer exist or that may have been moved or altered. It is estimated that up to 4 million holes dug by utility companies annually in order to repair, or replace, or install buried assets in the street across the UK. Every time a hole is dug, there is a risk of hitting and damaging buried pipelines and cables, with the consequent risk of service disruption and threat to safety. In fact, over the past 10 years there have been over 1000 recorded injuries in the UK as a result of contact with underground electricity cables. Hence, before commencing excavation or other work where power or other cables may be buried, it is important to determine the location of the cables to ensure that they are not damaged during the work.

To address these issues, a consortium of UK universities and industrial partners are undertaking a large research project, entitled Mapping the Underworld (MTU) [1]. MTU aims to assess the feasibility of potential techniques that can be used in a combined manner to determine the accurate location of underground utilities, as well as to assess the condition of buried assets without breaking the ground's surface. The second phase of MTU focuses on creating and developing a prototype multi-sensor device, a platform that will use four different kinds of sensors to locate and map buried utility service infrastructure without excavation. The latest progress and outcome of this project can be found in [2, 3]. Here, we only consider the passive magnetic field technologies part of this project, in which the magnetic field produced by the working currents in the power cables is used to locate underground cables and metal pipes.

2 CABLE DETECTION AND LOCATION METHOD

Generally, cable detection using magnetic field technology is based on two basic principles: firstly, that an electric current can produce a magnetic field (electromagnetism) and secondly that a changing magnetic field within a coil of wire induces a voltage across the ends of the coil (electromagnetic induction). There are a variety of types of magnetic field sensors that can be used to detect the presence of magnetic fields or to measure their strength and direction. Induction coils (also called search coils), which are based on Faraday's induction law, are chosen. It is easy to design and manufacture such coils with suitable parameters. Our cable location method works by comparing the measured flux-density data with values predicted using a simple numerical model of one or more cables. In the simple version used to produce the presented results, it is assumed that the cable configuration that minimizes the total square error in fitting the measured field data is the most likely to represent the true configuration.

It should be noted that this approach is vulnerable to problems with over-fitting. To control this problem, it is important that the number of unknown currents being considered is significantly lower than the number of simultaneous magnetic field measurements. The latter number is limited by how closely we can place the sensors while still obtaining independent measurements, and by the number of sensors that we can reasonably consider using. Consequently, this requirement places a fundamental limit on the complexity of the cable configurations that can be considered.

To simplify the task of optimizing the parameters of the model, they are divided into two categories: unknown currents (and possibly other similar parameters) that are related to the field by linear equations, but can change between one measurement and the next; and geometric parameters that are assumed to be constant, but are related to the field by non-linear equations.

The set of unknown current values that minimizes the total square error can be found by matrix division; however, as the coefficients of the matrix equations are non-linear functions of the geometric parameters, these calculations must be repeated each time the geometric parameters are changed. Consequently, the matrix division must be included in the objective function used by the non-linear optimization program used to find the geometric parameters.

3 MEASUREMENT SYSTEM AND SEARCH PROCEDURE

A measurement system consists of an array of search coils, a NI compact DAQ chassis with two NI data acquisition modules powered by a battery, and a laptop, as shown in Figure 1. Seven search coils are mounted on a support frame to measure the magnetic field driven by an underground power cable. Figure 2 is a schematic diagram of the coil array, while the coil position parameters are given in Table 1. All the coils have the same geometric parameters (2000 turns and 100 mm internal diameter), which were chosen to give appropriate sensitivity and spatial resolution. More information on coil parameters and laboratory tests have been reported in [4]. The detailed description about

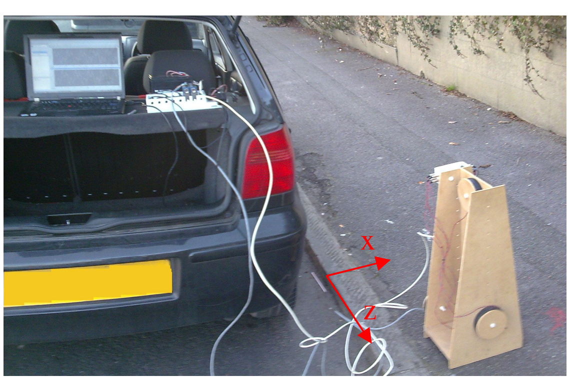


Figure 1: A measurement system on a footpath

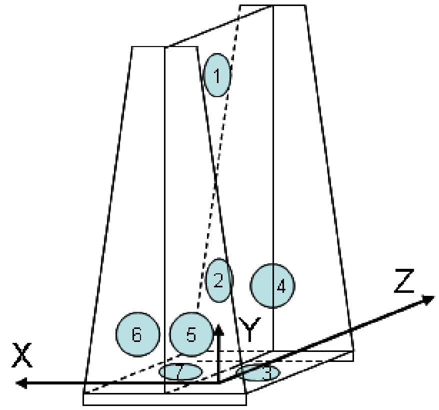


Figure 2: Schematic diagram (3D view) of the coil array

Table 1: Coil position parameters

Coil No.	X	Y	Z	Nx	Ny	Nz
1	0	620	0	1	0	0
2	0	220	0	1	0	0
3	-75	27	0	0	-1	0
4	0	170	113	0	0	-1
5	-75	120	-113	0	0	-1
6	75	120	-113	0	0	-1
7	75	27	0	0	-1	0

(X, Y and Z define the centre of each coil (in mm), while Nx, Ny and Nz define the component of the field measured by each coil. The coordinate system is shown in Figure 2.)

experimental setup also can be found in our other paper [5].

The cable search program mainly consists of measurement and signal processing and analysis. First of all, the support frame with its seven search coils is placed at a number of positions above the search area, and its position is recorded. The voltages induced in the coils are measured, and then Fourier analysis is used to extract the 50 Hz and harmonic signal components. Next, a least square error algorithm is applied to the resulting data in order to estimate the cable currents and residual errors for various assumed cable positions. Finally, the rms amplitude of the residual errors is plotted against the assumed cable position to give an indication of the likely locations of a buried cable.

4 EXPERIMENTAL RESULTS AND DISCUSSIONS

Experimental tests were carried out in a street with real operational power cable and also using a simulation cable, respectively.

4.1 Street testing

This test was carried out on a footpath (shown in Figure 1) close to a power transformer. We guess there is an underground power cable nearby. In fact, very strong magnetic field signals were previously traced from the transformer compound to the test area using a handheld magnetic field meter. Using the cable search program mentioned in section 3, this test was realized for a 2.2 × 3.5 m test area as shown in Figure 3.

Figure 4a shows the waveform of the voltage signal obtained from one of the coils. It is clear that it is a 50 Hz signal with lots of odd harmonics. This also can be confirmed by the frequency analysis of the signal shown in Figure 4b. By comparing the obtained voltage signals with the values obtained by modelling a long straight horizontal cable at various positions, a fitting error map can be plotted for any Z-coordinate value (as defined in Figure 1). Using the existing matlab programs, which were used in our previous test [5], maps of the minimum (rms) fitting error were plotted for a single cable as a function of its position in a specified vertical plane. Figure 5 shows a typical fitting error for this testing at z=0.5 m when we fixed the cable twist rate = -1.5 rad/m. This indicates that the possible cable position is 1.8 m in horizontal distance and 0.6 m in depth. Similar results are obtained for twist rates of -1.8 and -1.2 rad/m. This test result is believed to be reasonable for the following three reasons. First, a switch label in the substation indicates that an underground power cable goes in this general direction. Secondly, a handheld meter shows a maximum signal strength of 3.94 μT at X=1.8 m position. Thirdly, the minimum fitting error of 2% to 3% is much lower than that for other locations.

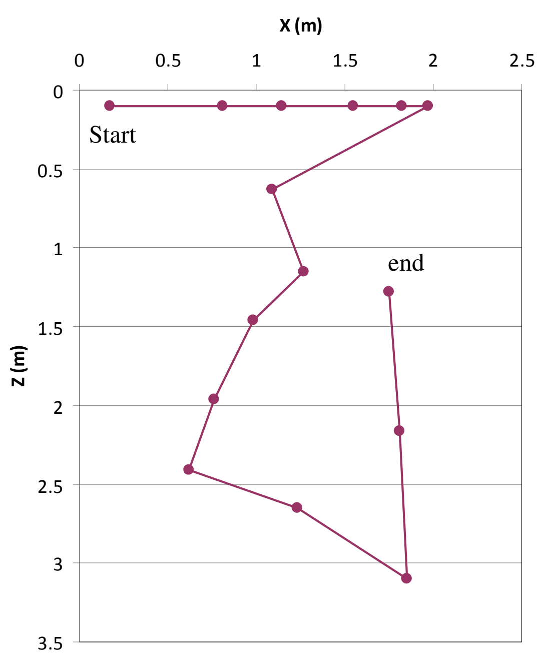
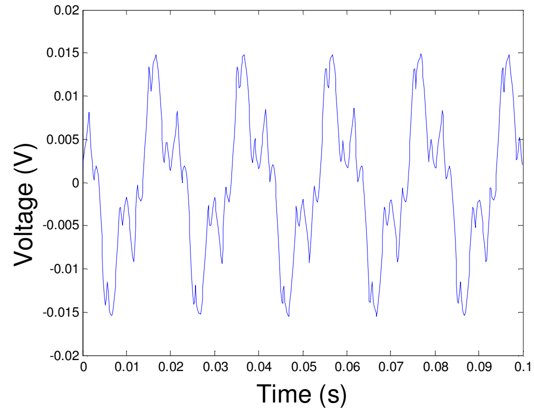
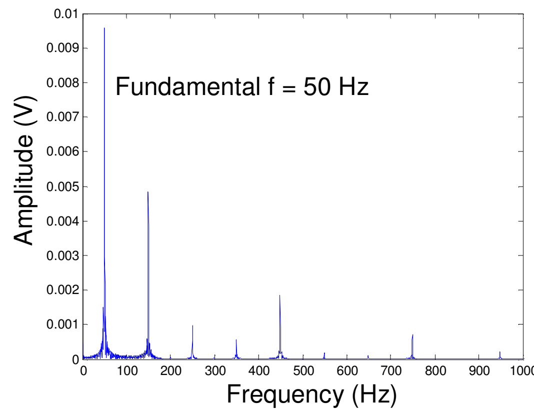


Figure 3: Test points and route (here z and x-coordinate value as defined in Figure 1)



(a)



(b)

Figure 4: Measured 50 Hz signal for a street test, showing large 3rd and 9th harmonic components. (a) time domain, (b) frequency domain

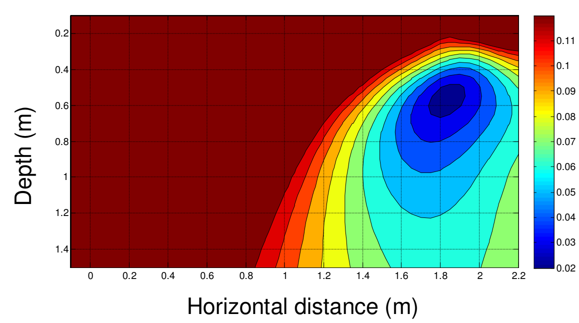
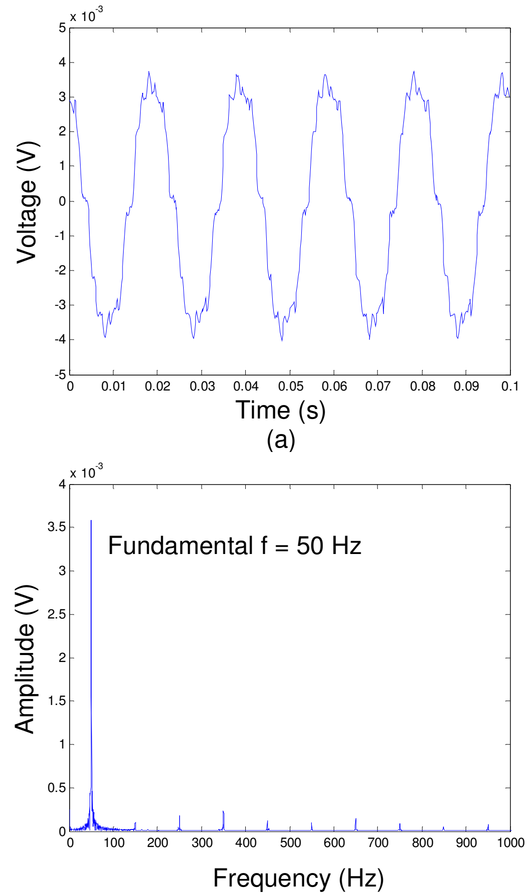


Figure 5: Fitting error for a street test at Z=0.5 m (possible cable position is X=1.8 m and Depth = 0.6 m)

4.2 Simulation cable testing

This experiment used a single-phase simulation cable, placed on the floor. Measurements were taken with the coil array at a number of positions, all the same height above the cable. This cable is not twisted and carried a 6A return 50 Hz current. Using our search program and cable location method mentioned above, some test results were obtained. Figure 6a shows the waveform of the measured voltage signal obtained from one of the coils. It is clearly a 50 Hz signal with quite small harmonic components. This is confirmed by the frequency analysis of the signal shown in Figure 6b. Figure 7 shows the map of the minimum fitting error for one such test; the red circle indicates the real position of the cable. It is clear that the predicted position is very close to the real position.



(b)

Figure 6: Measured 50 Hz signal for the simulation test, showing the low harmonic content. (a) time domain, (b) frequency domain.

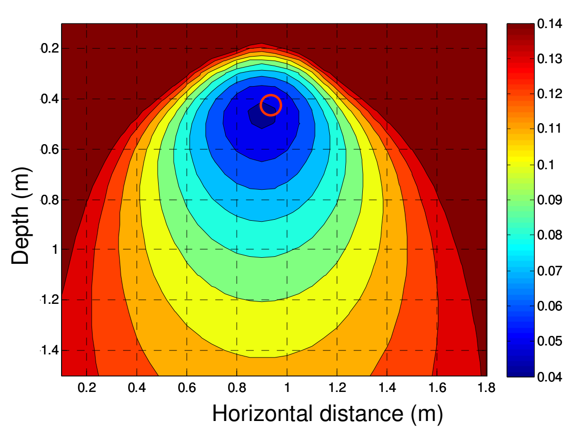


Figure 7: fitting error for the simulation test

4.3 Discussion

From two test results above, it can be seen that the measurement system and cable location method is suitable to complete such cable detection and location. Table 2 lists a brief summary on above two tests. It can be seen that the minimum fitting error for the street test is less than that for the simulation test. It is possible that this could indicate that the signal-to-noise ratio is better in the street test; we know that the signals from this street test are stronger than those from the simulation test, but we have no way to measure the noise levels in the street tests. However, in street tests, the cable location program searches for a twisted cable; hence, it has an additional parameter that can be used to reduce the fitting error.

Another difference for these two tests is that the signal propagation medium for magnetic fields is different. However, soils have no significant effect on low-frequency magnetic fields. Hence, magnetic field measurements will only yield information on metal structures, primarily electricity cables. In addition, there are some differences between the signal waveforms in these two tests, even though both have a fundamental frequency of 50 Hz. Significant 3rd and 9th harmonics appear in the street test, while all the harmonics are small in the simulation test.

Table 2: A brief summary on these two testing

Test site	Street test	Simulation test
Test target	three-phase real twisted cable, only know approximate position. don't know current	single-phase simulation no-twisted cable, know exact position and current
Signal strength (Maximum value)	3.94 μT	0.57 μT
Signal propagation medium	Soil	Air
Signal waveform and frequency	50 Hz signal with lots of harmonics	50 Hz signal with quite small harmonics
Minimum fitting error	2%	4%

5 CONCLUSIONS AND FUTURE WORK

A measurement system has been constructed, which uses an array of search coils to measure the distribution of power-frequency magnetic fields.

Using this system experimental investigations have been carried out in a street footpath and using a simulated cable. Results show that the measurement system and cable location method can give reasonably precise and believable estimates of the cable's location. However, these tests were restricted to areas that are each believed to contain only one power cable. This was necessary since, with only 7 search coils, the search programs should not be used to search for more than one cable at once. This restriction is required to avoid problems with over-fitting.

To allow the system to consider more than one cable in the search area and improve search range and precision, the measurement system has been expanded and a larger frame manufactured to support 27 coils. This will provide the search programs with the larger number of simultaneous independent flux-density measurements that are required to search for more than one cable. Further testing will be done with the revised system to evaluate its performance.

6 ACKONWLEDGEMENTS

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