<table>
<thead>
<tr>
<th>Title</th>
<th>Novel application of magnetoresistive sensors for high-voltage transmission-line monitoring</th>
</tr>
</thead>
<tbody>
<tr>
<td>Author(s)</td>
<td>Sun, X; Lui, KS; Wong, KKY; Lee, WK; Hou, Y; Huang, Q; Pong, PWT</td>
</tr>
<tr>
<td>Issued Date</td>
<td>2011</td>
</tr>
<tr>
<td>URL</td>
<td><a href="http://hdl.handle.net/10722/137294">http://hdl.handle.net/10722/137294</a></td>
</tr>
<tr>
<td>Rights</td>
<td>This work is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License.; ©2011 IEEE. Personal use of this material is permitted. However, permission to reprint/republish this material for advertising or promotional purposes or for creating new collective works for resale or redistribution to servers or lists, or to reuse any copyrighted component of this work in other works must be obtained from the IEEE.</td>
</tr>
</tbody>
</table>
Novel Application of Magnetoresistive Sensors for High-Voltage Transmission-Line Monitoring

X. Sun\(^1\), K. S. Lui\(^1\), K. K. Y. Wong\(^1\), W. K. Lee\(^1\), Y. Hou\(^1\), Q. Huang\(^2\), and P. W. T. Pong\(^1\)

\(^1\)Department of Electrical and Electronic Engineering, The University of Hong Kong, Hong Kong
\(^2\)School of Automation Engineering, University of Electronic Science and Technology of China, Chengdu 61173, China

High-voltage transmission lines are responsible for transmission of electric power. Their sag and electric current are important parameters for transmission-line monitoring. In this paper, a simple and promising method based on magnetoresistive sensors is proposed for transmission-line monitoring. This is a noncontact method and its installation is simple without the need for power cut. The method involves measuring emanated magnetic field from a line conductor at the ground level and, then, calculating the source position and current inversely. A proof-of-concept laboratory setup was constructed and a series of experiments were carried out for demonstration. This method can handle complicated transmission-line configuration by integrating the stochastic optimization approach into the inverse electromagnetic calculation. It was tested with the computational simulation of a 500 kV transmission-line configuration. The result shows the feasibility of using this transmission-line monitoring method in reality.

Index Terms—Galloping, magnetoresistive (MR) sensors, overhead transmission lines, sagging, smart grid.

I. INTRODUCTION

LON-G-DISTANCE high-voltage power transmission is vital in electricity power delivery because power loads are usually far away from power generation sites. Overhead transmission lines are reliable carrier wires, which provide the competent ability for the present power grids to transfer electricity from sources to distribution networks and, then, to the consumers. In view of its instantaneous nature, electricity is generated and used and cannot be stored in large scale at present. During the transmission process of electricity, balance must be constantly maintained to match the power supply and demand. Especially when an on-peak demand is coming, power companies have to supply excessive amount of electricity within the rating limits of transmission lines. Thus, transmission-line monitoring is a very important issue to ensure effective and reliable transmission of electricity.

Electric current and line positions are two important parameters to measure for transmission lines. The electric current flowing in the lines should be measured to avoid/reduce overload, phase unbalance, fluctuation, etc. Line positions should be monitored to keep track of the sagging and galloping situations. Conductors between two transmission towers often suffer sagging and galloping. Sagging is the length extension of a line conductor caused by overheating due to excessive current loading. Sagging can lower a conductor to an unsafe height above the earth. Galloping is the low-frequency, large-amplitude, wind-induced oscillation of overhead transmission lines [1]. The oscillations can cause serious transmission problems, such as flashover due to infringed line-to-line clearances, risk of mechanical failure of transmission tower, and excessive loading stress. Finally, if a power utility can accurately measure both electric current and line positions in real time, the resulting knowledge will enable the dynamic rating of the power networks. Hence, transmission-line monitoring is critical for the efficient usage of power line capacity and reliable operation of power transmission networks. Advanced sensor technology is needed to fulfill these requirements for transmission-line monitoring in the smart grid, which will modernize our present power grids and enable the wide-scale utilization of renewable energy [2].

At present, there are several techniques and devices for transmission-line monitoring. Current transformers (CTs) are typically used for current measurement. However, they are expensive and limited by their magnetic core characteristic and narrow bandwidth [3], [4]. There are some existing devices that can directly or indirectly measure sag of transmission lines. “Power donut” is a temperature sensor platform installed on live wires [5]. However, this device measures the conductor surface temperature rather than the core temperature for calculating sag. In addition, it is an expensive platform and its installation requires working with live wires. Another device is a tension sensor that calculates the sag from the measured tension on a transmission line [6]. However, it requires expensive equipment and complicated installation. A promising technology using the global positioning system (GPS) is under development [7]. This technology is still in its infancy. Problems such as installation, shielding, and electromagnetic interference (EMI) from phase conductors have to be confronted. In another technique, camera and image-processing technology are used to measure conductor sag [8]. It is a costly technique and its installation requires contact with phase conductors for placing the targets. A method based on electromagnetic coupling was reported for transmission-line monitoring [9]. However, for different line configurations, the grounded wire position and the sag calculation need to be modified. Also, EMI from nearby transmission lines cannot be neglected.

The new method proposed here makes innovative use of magnetoresistive (MR) sensors, and it is competent for transmission-line monitoring and addresses the problems and limitations of the other techniques and devices [10]. The MR sensors can be installed on the ground level so that power outage is avoided and there is no need to work with live wires. It calculates the current
flow and line positions from the magnetic field emanated from the phase conductors.

II. METHOD AND TECHNOLOGY

The magnetic field generated by a single-phase conductor element can be described by using the Biot–Savart law

$$\mathbf{B} = \int \frac{I d\mathbf{w} \times \mathbf{r}}{4\pi |r|^3}$$

(1)

where

- $I$ source current;
- $d\mathbf{w}$ vector whose magnitude is the length of the differential element of source at the direction of the current;
- $\mathbf{r}$ displacement vector from the source element to the point where magnetic field is being computed;
- $\mu_0$ permeability of free space;
- $\mathbf{B}$ net magnetic field.

In case of multiple-phase conductors, the resulting magnetic field can be determined by applying the superposition principle. It should be observed that in (1), the resulting magnetic flux density at the field point carries the electric and spatial information of the current source. If magnetic field data are collected at some points within span, electric current flow and line positions can be calculated by solving an inverse problem of electromagnetism (EM) [11]. Overhead line conductors suspended between towers take on the appearance of catenary due to their own weights. The conductor catenary that is symmetric with the $y$-axis and placed in the $y$–$z$ plane can be described by

$$y = a \cosh \left( \frac{z}{a} \right) + y_0,$$

(2)

The parameters $a$ and $y_0$ are determined by the origin of the catenary coordinate system as discussed in [12]. The differential element of conductor catenary can be written as

$$d\mathbf{w} = \sinh \left( \frac{z}{a} \right) d\mathbf{a}_y + d\mathbf{a}_z.$$

(3)

By applying the Biot–Savart law, the magnetic field generated by phase current flowing in the line conductor can be determined at any point in vicinity [10]. In order to illustrate how the emanated magnetic field provides detailed information of line conductors, a practical 500 kV transmission-line configuration was simulated with increasing current load and various sags. The line configuration shown in Fig. 2 has a span of 400 m and the current per phase is 1000 A. Fig. 3(a) shows the magnetic field generated at the midspan along the $x$-axis at the height of 1 m from the ground. The lateral profile of the magnetic field was simulated with different phase currents of 1000 A and 1050 A with the same sag of $s = 5$ m. Fig. 3(b) shows the same simulation but using different sag values ($s = 5$ m and $s = 10$ m) with the same phase current of 1000 A. The simulation results show that the changes in electric current or sag are reflected by the magnetic field emanated from the lines. Similarly, this technology is also applicable for galloping. Provided the sensitivity of the magnetic sensors is sufficient, the electric and spatial information of the overhead line can be found by inverse calculation from the magnetic field measured at the ground level. According to the simulation results in Fig. 3, the strength of the magnetic field emanated from an overhead line is typically on the order of $10^{-7}$ T. Currently, commercially available anisotropic magnetoresistance (AMR), giant magnetoresistance (GMR), and tunneling magnetoresistance (TMR) sensors can provide sensitivity of around $10^{-7}$, $10^{-8}$, and $10^{-9}$ T, respectively. Therefore, the sensitivities of MR sensors are two to four orders of magnitude larger than necessary to carry out the monitoring in this novel application.

III. EXPERIMENT

In order to verify this transmission-line monitoring technology, a scaled laboratory setup including a set of sensors and an electric power line was established in the Smart Grid and High Power System Laboratory, the University of Hong Kong, Hong Kong, to act as the test bed for transmission-line monitoring. The setup is shown in Fig. 4. It consists of two MR sensors, an infrared (IR) sensor, an electric power cable, and two suspension towers. The MR sensors act as core components, which are used to measure magnetic-field vectors with high
sensitivity. The vectors data are important inputs for calculating electric current and spatial information of the line conductor. Honeywell HMC2003 three-axis AMR sensor hybrid was selected. It can handle the measurements of magnetic-field vectors in three orthogonal coordinate axes simultaneously. The IR sensor is a fast-response and high-accuracy temperature sensor. It is used to monitor the cable from overheating. The heights of the suspension towers can be adjusted to control the altitude of the cable. Fig. 5 shows the schematic diagram of this laboratory setup. The height of the suspension towers is 0.38 m. The distance between the towers is 3 m. The two MR sensors are placed symmetrically at the midspan along the x-axis at the height of 5 cm. The distance between them is 0.6 m. The lowest point along the power cable was moved to different positions in order to simulate various sagging and galloping situations. The magnitude of the electric current was 150 A (rms) and its frequency was 50 Hz. The electric current was monitored with a Fluke 434 power quality analyzer. The measurement results of the magnetic flux density vectors are displayed in Table I.

<table>
<thead>
<tr>
<th>Sag (x,y)</th>
<th>Sensor 1</th>
<th>Sensor 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>B_x (10^3 T)</td>
<td>B_z (10^3 T)</td>
</tr>
<tr>
<td>1</td>
<td>2.816</td>
<td>-3.852</td>
</tr>
<tr>
<td>2</td>
<td>2.968</td>
<td>-4.227</td>
</tr>
<tr>
<td>3</td>
<td>2.408</td>
<td>-4.688</td>
</tr>
<tr>
<td>4</td>
<td>4.812</td>
<td>-3.211</td>
</tr>
</tbody>
</table>

Given a current source element, construct a line perpendicular to the generated magnetic flux density vector at the field point and therewith the line must pass through the source element. By the same token, with the magnetic flux density vectors measured at two field points, the position of their common source can be determined. The cross points of the two constructed perpendicular lines are determined to be the position of the common source. Fig. 6 shows the locations of the calculated and the actual source positions for the cases of Table I.

As demonstrated with this proof-of-concept laboratory setup, the proposed method can realize simple power line monitoring on both electric current and line position. There are differences between laboratory condition and actual operating environment. In real situations, we need to consider more factors, such as image current due to a conducting ground, multiple power cables, double circuits, and bundled phase conductors. Further development and optimization of the method are needed to cope...
It just takes a few minutes to solve the inverse problems. The was coded in MATLAB and run on a normal desktop computer.

The calculation in the computational simulation of the three-phase magnetic field at a series of field points stochastically and minimizing the Euclidean distance between the calculated and the measured magnetic fields. The method is put into practice for calculation in the computational simulation of the three-phase transmission-line configuration shown in Fig. 2. The effect of image current is considered in both the computational simulation and the stochastic optimization process. Fig. 8 shows the identification of conductor positions with this stochastic approach. The calculated line positions are very close to the actual positions with an average error of only 6 cm or 0.246% in terms of percentage. It is evident that this technique can provide an accurate identification for transmission-line positions. Furthermore, this AIS technique can also handle conductor line sagging and galloping. As such, the proposed transmission-line monitoring method with MR sensors can be extended to more complicated line configurations by integrating the AIS technique into the inverse calculation problem. This inverse calculation algorithm was coded in MATLAB and run on a normal desktop computer. It just takes a few minutes to solve the inverse problems. The computational time can be further suppressed by coding in C language and optimizing the code. This greatly facilitates real-time monitoring on sagging and galloping.

V. CONCLUSION

A widely applicable, low-cost, noncontact, and accurate method for transmission-line monitoring was proposed and demonstrated in this paper. This method measures the emanated magnetic field from the transmission line to determine the phase conductor current and line position. The proof-of-concept experiments on a single power cable showed that this technique is feasible and practical. An inverse calculation method based on stochastic optimization (AIS) was applied for solving more complicated scenarios with multiple transmission lines. The AIS optimization can enable this transmission-line monitoring technique to handle various line configurations. As such, this monitoring technology has great potential to enhance situational awareness, enable dynamic line rating, optimize asset utilization, and realize advanced system measurement of the future smart grid.

ACKNOWLEDGMENT

This work was supported by the Seed Funding Program for Applied Research and the Initiative on Clean Energy and Environment of The University of Hong Kong.

REFERENCES