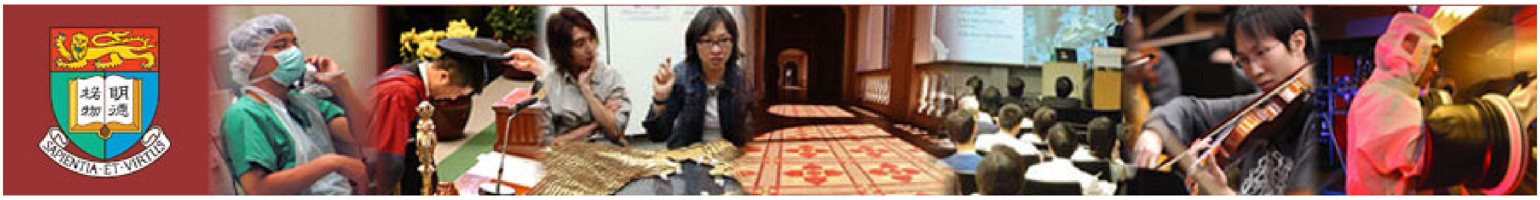

Title	Overhead High-Voltage Transmission-Line Current Monitoring by Magnetoresistive Sensors and Current Source Reconstruction at Transmission Tower
Author(s)	Sun, X; Huang, Q; Jiang, L; Pong, PWT
Citation	The 3rd International Symposium on Advanced Magnetic Materials and Applications (ISAMMA), Taiwan, 21-25 July 2013. In IEEE Transactions on Magnetics, 2014, v. 50 n. 1, p. article no. 2274747
Issued Date	2014
URL	http://hdl.handle.net/10722/186748
Rights	IEEE Transactions on Magnetics. Copyright © Institute of Electrical and Electronics Engineers.

Overhead High-Voltage Transmission-Line Current Monitoring by Magnetoresistive Sensors and Current Source Reconstruction at Transmission Tower

X. Sun[1], Q. Huang[2], L. J. Jiang[1], and P. W. T. Pong[1]

[1]Department of Electrical and Electronic Engineering, The University of Hong Kong, Hong Kong
[2]School of Energy Science and Engineering, University of Electronic Science and Technology of China, Chengdu, China

This paper proposes a novel current monitoring technology based on magnetic field sensing at a transmission tower for overhead high-voltage transmission lines (HVTLs), which can accurately measure phase current parameters in real time. This technology is based on the phenomenon that the magnetic field distribution at the top level of a transmission tower can reflect the operation states of the transmission lines including current amplitude and phase angle imbalances. A current source reconstruction method based on stochastic optimization strategy was developed to reconstruct the electrical parameters from the magnetic field emanated by the overhead transmission lines. This concept of current monitoring by magnetic field sensing and current source reconstruction was experimentally implemented and verified in our laboratory setup. A typical model of 500 kV three-phase transmission lines was simulated to further corroborate this technology. The reconstruction results for the 500 kV transmission lines verify the feasibility and practicality of this novel current monitoring technology based on magnetic field sensing at the top of a transmission tower for monitoring overhead transmission lines.

***Index Terms*—Current monitoring technology, current source reconstruction, high-voltage transmission line (HVTLs), magnetic field sensing, phase current imbalance.**

I. Introduction

IN a power grid, the typical delivery distance of overhead high-voltage transmission lines (HVTLs) is several hundreds to thousands of kilometers. Abnormal changes of electrical parameters in any part of the transmission network can lead to serious damage and failure of power delivery. A current monitoring technology is needed to provide accurate detection and location of phase current changes in real-time. Its large-scale deployment can avoid unstable electricity supply or even failure of power delivery. This technology, in order to be practical and applicable in real power line monitoring, must require that the monitoring device should be compact, easy for installation, and make no contact with the lines. With these features, the technology can monitor the phase current of transmission-line spans in order to enable engineers to quickly find and accurately locate abnormal changes. Moreover, it can maintain its stability and accuracy in detection when the phase currents and line configuration are significantly changed. However, at present, the phase currents of HVTLs are measured by current transformers (CTs) [1], [2]. CTs are massive, bulky, and require regular maintenance. They have to make contact with the live wires in order to make measurement. Moreover, CTs can only be installed in substations, limiting the large-scale monitoring of phase currents in the HVTL networks. In order to overcome the shortcomings of the existing method, a novel noncontact transmission-line current monitoring (TLCM) technology is needed.

For HVTLs, based on the Biot–Savart law, the emanated magnetic field from the phase currents in the phase conductors are correlated with the electrical parameters of the phase currents. Therefore, it is possible to work inversely to find out the electrical information of the conductors by measuring and analyzing the emanated magnetic field.

The magnetometer technology has been advancing very rapidly for the past decade. Due to its important application as the read heads in hard disk drives, magnetoresistive (MR) sensors have received an enormous amount of research effort and resources. The sensitivity of spintronic sensors has achieved gigantic progress. The low-field detection of MR sensors is advancing towards 1 picoTesla [3]. Thus, MR sensors are an ideal candidate as a magnetometer for sensing the magnetic field from the transmission line which is typically on the order of microTesla. Moreover, due to their mass manufacturability and CMOS compatibility, MR sensors can be produced at small dimensions with very low cost, which is conducive to their large-scale deployment in the form of a magnetometer array.

Inverse problems are frequently encountered in science and engineering, in which observed measurements are converted into information about the physical properties of interest. The solutions to these problems provide answers about the physical parameters that cannot be directly measured. Among the many different approaches to solving inverse problems, the stochastic optimization method is preferred because it is more likely to find out the global optimum.

In this work, we developed a novel noncontact TLCM technology based on measuring the magnetic field emanating from the transmission lines and solving the inverse problem by a current source reconstruction method. We experimentally tested and verified the accuracy of this TLCM technology with our laboratory setup which is a test bed with a MR sensor array and a three-phase three-cable system (50 Hz 16 A currents) established. Next, the magnetic field generated by the phase conductors of HVTL was studied with a typical 500 kV model. Finite element analysis (FEA) was conducted to investigate the influence of the steel structure of transmission tower on the magnetic field distribution in the sensing zone where the mag-

Manuscript received April 29, 2013; accepted July 16, 2013. Date of current version December 23, 2013. Corresponding author: P. W. T. Pong (e-mail: ppong@eee.hku.hk).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TMAG.2013.2274747

netic sensor array would be located. Current source reconstruction technology was applied and the reconstruction results were studied with error analysis.

II. Current Source Reconstruction Methodology

Based on the Biot-Savart law, the phase currents and the source positions determine the distribution of the magnetic field emanated. With the magnetic field data measured at a number of field points, it requires solving an inverse problem to derive the phase currents as sources of the magnetic field. When the relative positions of field points and current sources are fixed, the source currents can be straightforwardly obtained by using deterministic optimization strategy. However, the spatial parameters of transmission lines can change due to the conductor sagging effect or galloping. As such, both the spatial and electrical parameters of current sources are not known. In order to solve the inverse problem, a stochastic optimization technique based on artificial immune system (AIS) algorithm is used to reconstruct both the electrical and spatial parameters from the magnetic field data. The source reconstruction process is described in Fig. 1. It starts with a group of default position parameters $\mathbf{P}_0$ of the transmission-line configuration, which are recorded under normal operation state. Based on the measured magnetic field $\mathbf{B}_{mea}$, phase currents $\mathbf{I}_p$ are estimated by inverse current program (ICP), which is based on least squares estimation by

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

where $\mathbf{A}$ is the coefficient matrix which depends on the position parameters of the current sources. Then the magnetic field $\mathbf{B}_{cal}$ is obtained by using $\mathbf{I}_p$ and matrix $\mathbf{A}$ in the magnetic field evaluation (MFE) module as

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

A defined minimum threshold value of the Euclidean distance $\|\mathbf{B}_{cal} - \mathbf{B}_{mea}\|$ is defined as the end condition for terminating the reconstruction process. If the $\mathbf{B}_{cal}$ generated by default position parameters $\mathbf{P}_0$ does not meet the end condition, the AIS algorithm randomly generates new position parameters $\mathbf{P}_s$ in a source position optimization (SPO) module. With reference to the $\mathbf{B}_{mea}$ and the newly generated $\mathbf{P}_s$, new $\mathbf{I}_p$ is computed by ICP again. New $\mathbf{B}_{cal}$ is calculated again with the $\mathbf{P}_s$ and new $\mathbf{I}_p$ in the MFE module and compared with the $\mathbf{B}_{mea}$ again. The Euclidean distance between them is found. When the Euclidean distance is less than the minimum threshold value, the optimizing process finishes. The resulting $\mathbf{P}_s$ and $\mathbf{I}_p$ are saved as the true values of the transmission-line parameters; otherwise, the iteration continues. This reconstruction process is repeated multiple times (N) in order to obtain the final results of $\mathbf{P}_s$ which are the averages of these N optimizations. Accordingly, the final $\mathbf{I}_p$ is obtained from the optimized $\mathbf{P}_s$ and the measured magnetic field.

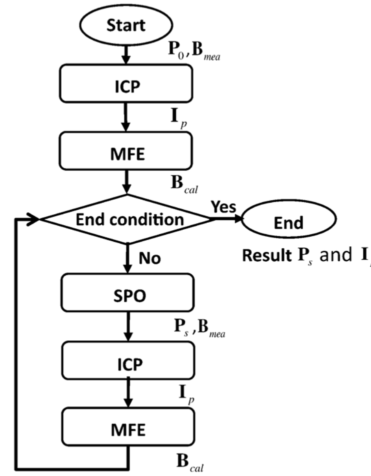

Fig. 1 Flowchart of current source reconstruction based on magnetic field sensing.

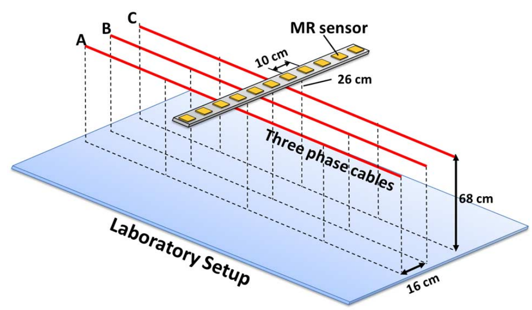

Fig. 2 Experimental setup for verifying the current source reconstruction method for transmission-line monitoring.

III. Experimental Proof

In order to verify this current source reconstruction technology for HVTL monitoring, a laboratory setup including an MR three-axis sensor (Honeywell HMC2003) array and three-phase straight transmission power lines were established to act as the testbed. The schematic diagram of the setup is shown in Fig. 2. The eleven MR sensors of the array are evenly spaced. The vertical distance between the sensor array and transmission power lines is 26.0 cm. In the normal operation state, the heights of the three power lines are 68.0 cm from the ground. When the power supply was connected with the power lines, the measured phase current amplitudes were 16.2 A, 16.4 A and 16.2 A in phase A, B, and C, respectively. The emanated magnetic field was measured by the sensor array. As shown in Fig. 3(a), the measured magnetic field values by the MR sensor array coincide well with the calculated values based on Biot-Savart law. Based on the measured magnetic field values, the operation states of the power lines were reconstructed. The reconstruction result of phase currents is shown in Fig. 3(b). The reconstructed amplitudes of phase currents are 16.12 A, 16.40 A, and 16.11 A in phase A, B and C. The average error to the actual amplitude value is 0.35%. The current cycle is found to be 19.96 ms, corresponding to a system frequency of 50.1 Hz with an error of 0.2%. In order to verify this technology with abnormal operation states, tests were carried out in the four cases as shown in Table I. Cases 1 and 2 mimic the situations of cable sagging while cases 3 and 4 mimic the situations of current imbalance. The phase current reconstruction results for these cases are shown in Fig. 4. In these results, the errors of phase current amplitudes are all less than 0.4%. The error of the reconstructed system frequency to the actual value is less than 0.3%. These experiments performed with the testbed proved the principle of the current monitoring technology based on magnetic field measurement and current

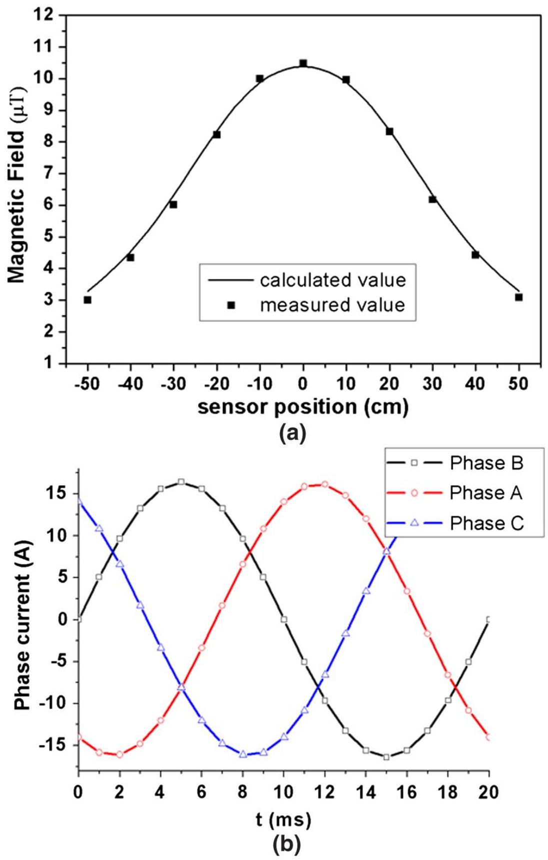

Fig. 3 Magnetic field values in the experiment and phase current reconstruction results by the current source reconstruction method: (a) magnetic field values measured by MR sensors and calculated values based on Biot-Savart law and (b) reconstructed phase current curve of each phase conductor.

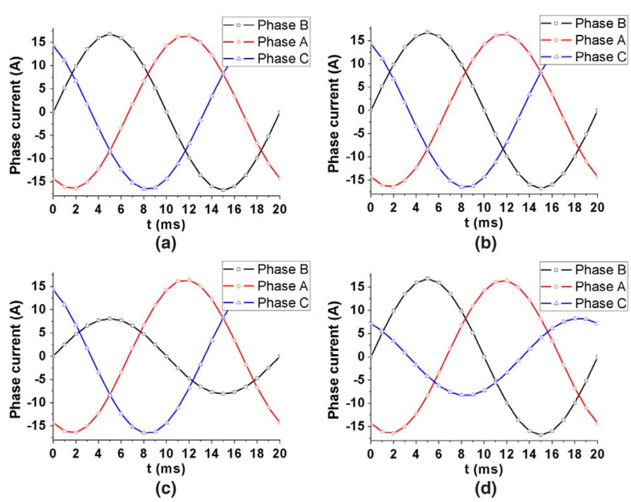

Fig. 4 Phase current reconstruction results for the abnormal cases experimented with the laboratory setup: (a) reconstruction results for Case 1, (b) reconstruction results for Case 2, (c) reconstruction results for Case 3, and (d) reconstruction results for Case 4.

source reconstruction. The technology can function properly regardless of whether the transmission lines are in normal operation state or in abnormal conditions.

IV. Application in 500 kV Transmission-line Model

This reconstruction method was tested with the simulation model of the 500 kV transmission lines in Fig. 5. A typical

TABLE I
Abnormal Operation States in Tests

Case	Current amplitudes (A)	Power lines heights (cm)
1	16.8, 16.5, 16.2	68.0, 48.0, 68.0
2	16.8, 16.5, 16.6	48.0, 68.0, 68.0
3	16.5, 8.1, 16.6	68.0, 68.0, 68.0
4	16.5, 16.3, 8.3	68.0, 68.0, 68.0

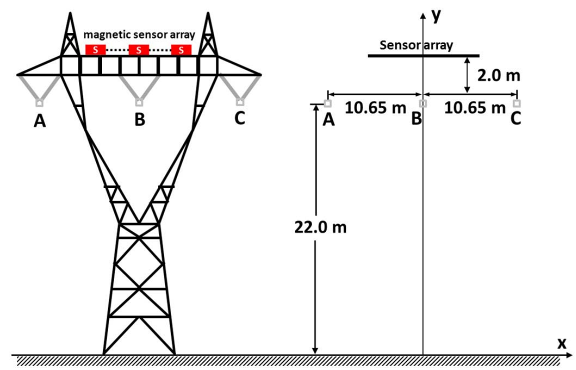

Fig. 5 Simulation model of 500 kV overhead HVTL. Red squares with "s" denote the MR sensor array.

HVTL emanates magnetic field in the amplitude of several hundred microTesla at the top level of the transmission tower. The magnetic field can be accurately measured by commercially available MR sensors which can provide sensitivity down to around 10^{-9} Tesla and spatial resolution of 0.9 mm [3]. Fig. 5 shows a transmission tower with three-phase 50 Hz 500 kV (maximum load current is 3.75 kA per phase) transmission lines [4]. The configuration of the three phase conductors is flat formation, as shown on the right side of the figure. A magnetic sensor array is installed on the top level of the tower and used to measure the magnetic field emanated by the phase conductors. The array is composed of 11 MR sensors with 1.0 m spacing among each other. FEA simulation was conducted to investigate the influence of the steel structure of the transmission tower on the magnetic field measurement. Only the upper framework of the transmission tower is considered because the lower part is relatively far away from the region of interest. The meshed FEA model of the transmission tower upper framework is shown in Fig. 6(a). In this FEA model, there is magnetic field emanating from the transmission lines operating in the normal state with 50 Hz 3.75 kA phase currents. The magnetic field distribution in the sensing zone where the magnetic sensor array is placed is simulated with the tower framework effect considered. On the other hand, the magnetic field distribution in the sensing zone is calculated analytically without considering the effect of the steel tower structure. The FEA simulation results with the steel tower structure considered and the calculation results without considering the framework of tower are shown in Fig. 6(b). The Euclidean distance between them is determined to be a very small value of 2.03×10^{-6}. It indicates that the influence of the upper tower framework to the magnetic field distribution in the sensing zone is negligible (approximately less than 1%). Thus the magnetic field emanated by the HVTL can be measured by the magnetic sensor array without distortion from the

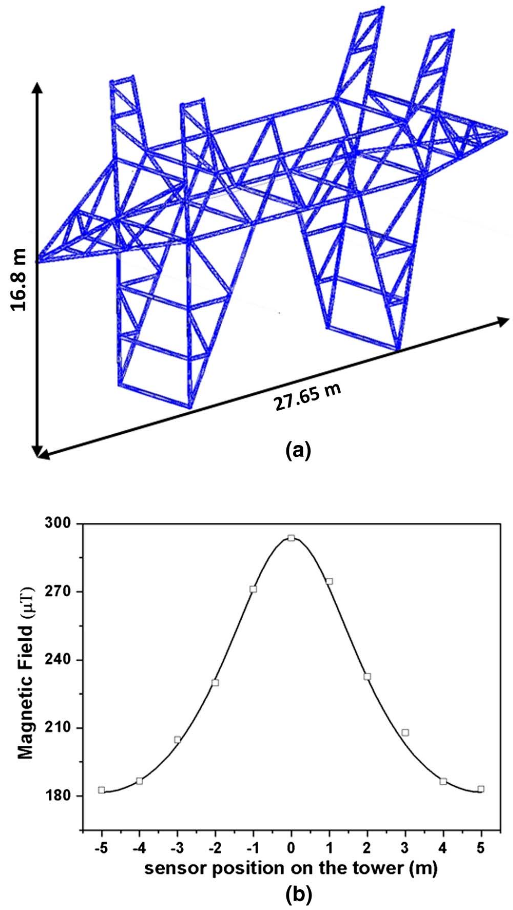

Fig. 6 Transmission tower simulation model and magnetic field distribution in the sensing zone where the magnetic sensor array would be placed. (a) Transmission tower upper framework. (b) Curve denotes the magnetic field distribution calculated without considering the tower framework effects, square denotes the magnetic field computed by FEA with the tower framework effect considered.

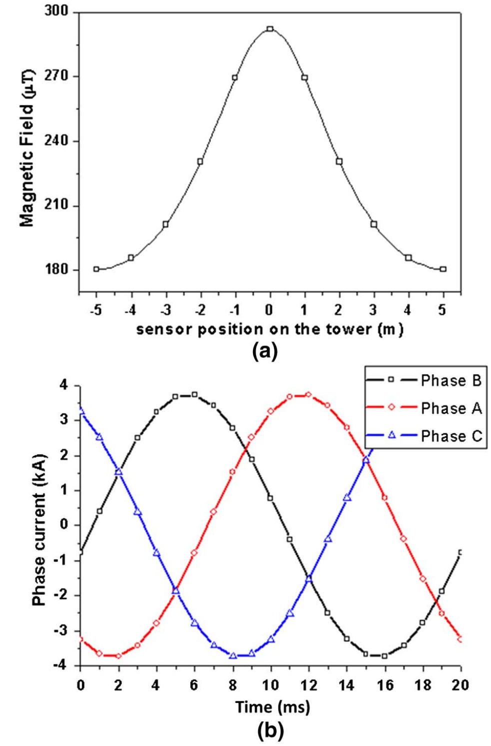

Fig. 7 Magnetic field at the top level of the transmission-line tower under normal operation state and the corresponding phase current reconstruction results: (a) square denotes the magnetic field values at the positions of the magnetic sensors and (b) reconstructed phase current curve of each phase conductor.

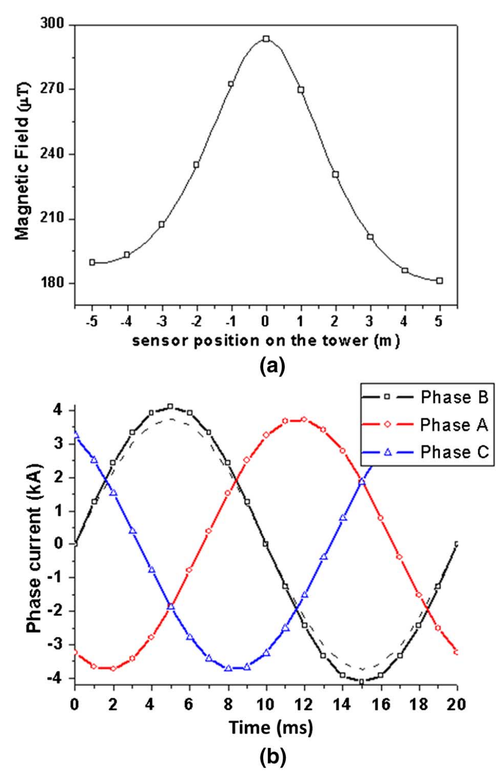

Fig. 8 Magnetic field at the top level of the transmission-line tower when there is current amplitude imbalance in phase B and the corresponding phase current reconstruction results: (a) square denotes the magnetic field values at the positions of the magnetic sensors and (b) reconstructed phase current curve of each phase conductor.

steel structure. Based on our simulation results, the influence of the tower frameworks is negligible on the magnetic field distribution in the vicinity of the lines. The influence of charges and currents induced in the tower can also be neglected. This fact has been verified theoretically and experimentally by the literature [5]. Thus in this work we only need to consider the effects of transmission-line conductor sagging and image current in the conducting ground when calculating the magnetic field distribution.

The magnetic field from the transmission lines can be accurately calculated by analytical method [6], [7]. The resulting magnetic field of multi-conductor power lines can be evaluated by superimposing the contribution from each phase current flowing in the conductors and the image currents. The detailed calculation of the magnetic field of the transmission line with sagging is described in [6].

Fig. 7(a) shows the magnetic field distribution of the 500 kV transmission lines in Fig. 5 on the top level of the tower. The magnetic field is simulated with conductor sag of 10 m. We assume that every conductor suffers the same sag. The maximum magnetic flux density of the resulting magnetic field is 292 μT obtained at the center sensor position. Fig. 7(b) shows the phase current reconstruction results from the measured magnetic field. It is found that the amplitudes of phase currents are reconstructed with an average error of 0.13% to the actual value. The current cycle is found to be 20.09 ms, corresponding to a

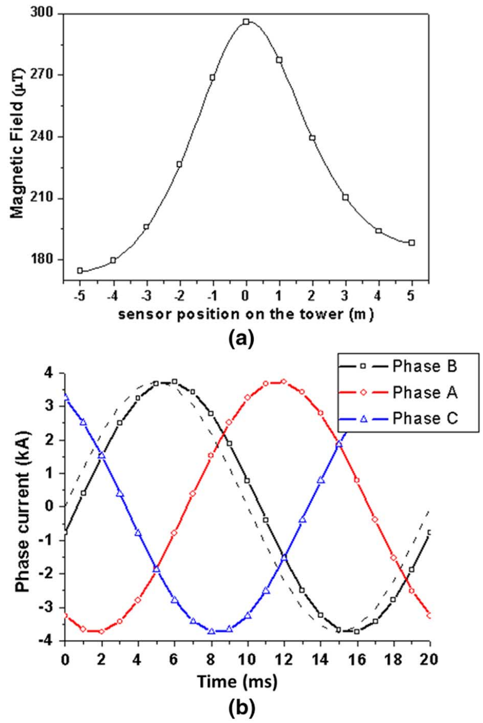

Fig. 9 Magnetic field at the top level of the transmission-line tower when there is phase angle imbalance in phase B and the corresponding phase currents reconstruction results: (a) square denotes the magnetic field values at the positions of the magnetic sensors and (b) reconstructed phase current curve of each phase conductor.

system frequency of 49.78 Hz with an error of 0.4% to the actual mains frequency.

Fig. 8(a) shows the magnetic field distribution when there is $+10\%$ current amplitude imbalance in phase B. Accordingly, the conductor sag of this transmission line extents from 10 to 12 m due to increased cable temperature induced by the current. In this case, the complete phase current curves for the three phases can also be reconstructed. It is shown in Fig. 8(b) that each reconstructed phase current matches well with the actual phase current and the $+10\%$ current amplitude imbalance (normal current amplitude is 3.75 kA) in phase B is also deduced. The reconstructed current amplitude of 4.124 kA accurately reflects $+10\%$ amplitude imbalance in the phase B.

Fig. 9(a) shows the magnetic field distribution where there is 10% imbalance in phase angle (phase angle changes from 0 to -12 degrees) in phase B. From Fig. 9(b), the phase imbalance is reflected in 0.67 ms delay of phase B current curve along time-axis. The error to actual value 0.673 ms is 0.4%.

In the above cases, the reconstructed electrical values agree with the actual values with very small errors. The current monitoring technology based on current source reconstruction and magnetic field measurement can successfully provide the electrical parameters of the transmission lines including current amplitude, phase, and frequency accurately with error less than 1%. The technology can function in normal operation state of the transmission lines and also in abnormal situations including current amplitude imbalance and phase imbalance.

V. Conclusion

A novel current monitoring technology for overhead HVTL was developed and demonstrated in this paper. The source reconstruction method based on stochastic optimization strategy was proposed to reconstruct the phase currents of the transmission lines from the magnetic field measured by magnetic sensors at the transmission tower. When a group of magnetic field data is obtained, the information of the phase currents can be obtained even when the position parameters of the phase conductors are changed. The principle of this method was experimentally proved and verified by our laboratory setup. The effect from the steel structure of the transmission tower is found to be negligible to the magnetic field at the field points at the transmission tower. This TLCM method was implemented at the top of a 500 kV three-phase transmission tower by simulation. The reconstruction results of the electrical parameters of the transmission lines agree well with the actual values under the conditions of normal operation state, current amplitude imbalance, and phase angle imbalance. Therefore, by measuring magnetic field at the top of a transmission tower and adopting this TLCM technology, monitoring of the phase currents of the overhead transmission lines can be performed with high accuracy and reliability. Moreover, MR sensors, being simple, compact-in-size, and low-cost, can be adopted as the magnetic sensors for this technology, making this TLCM technology feasible for large-scale deployment and thus realizing wide-area monitoring of the transmission network.

Acknowledgment

This work was supported in part by the Seed Funding Program for Basic Research and Small Project Funding Program from The University of Hong Kong, ITF Tier 3 funding (ITS/112/12), RGC-GRF Grant (HKU 704911P) and by the University Grants Committee of Hong Kong under Contract AoE/P-04/08.

References

[1] A. Cataliotti, D. Cara, P. A. Franco, A. E. Emanuel, and S. Nuccio, “Frequency response of measurement current transformers,” in *Proc. IEEE Int. Instrumentation Measurement Technol. Conf. IMTC 2008*, Victoria, Vancouver Island, Canada, 2008.

[2] A. Cataliotti, D. Cara, A. E. Emanuel, and S. Nuccio, “Characterization of current transformers in the presence of harmonic distortion,” in *Proc. IEEE Int. Instrumentation Measurement Technol. Conf. IMTC 2008*, Victoria, Vancouver Island, Canada, 2008.

[3] MicroMagnetics, STJ-300 [Online]. Available: http://www.micromagnetics.com/docs/STJ-300_TMR_magnetic_sensor.pdf Jan. 10, 2012

[4] Transmission line reference book, 345 kV and above [Online]. Available: http://www.ece.mtu.edu/ Apr. 26, 2013

[5] W. Krajewski, “Numerical evaluation of the magnetic field exposure near the transition tower of an overhead-underground hv line,” *Progr. Electromagn. Res. M*, vol. 14, pp. 247–261, 2010.

[6] A. V. Mamishev, R. D. Nevels, and B. D. Russell, “Effects of conductor sag on spatial distribution of power line magnetic field,” *IEEE Trans. Power Delivery*, vol. 11, pp. 1571–1576, 1996.

[7] X. Sun, K. S. Lui, K. K. Y. Wong, W. K. Lee, Y. Hou, and Q. Huang *et al.*, “Novel application of magnetoresistive sensors for high-voltage transmission-line monitoring,” *IEEE Trans. Magn.*, vol. 47, no. 4, pp. 2608–2611, Apr. 2011.