Research on Non-destructive Testing of Round Steel in Grounding Grids using Magnetostrictive Guided Waves

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Abstract. In this paper, a new kind of methods, using magnetostrictive ultrasonic guided wave technology, is introduced to the health detection of round steel used in industry of power system. Based on the magnetostrictive principle, designed a magnetostrictive guided wave sensor. According to the characteristics of the lap jointing round steel, studied on bending and horizontal lap jointing structures by simulation and experiment, analyzed the transmission characteristics of guided wave in complex round steel structures. To provide technical support for grounding grid in nondestructive testing.

Introduction

Grounding grid of substation is the important facility to maintain safe and reliable operation of a power system. Conductors constituting a grounding grid are buried in the ground, which is vulnerable to corrosion, subject to poor welding and lack of weld during construction as well as short-circuit force, leading to failures of the grounding grid.

Providing rapid real-time detection, non-destructive testing method can be perfectly applied to detect the structure of grounding grid in a substation with unparalleled advantages. By using ultrasonic guided wave technology in which a sensor is put near the detected object only for a short time of detection, test efficiency can be improved also with reduced test cost, and the technique, therefore, is suitable for in-service detection of clad or underground pole and plate structures as well as pipes. At present, theories and practices on plate, pole and pipe detection by ultrasonic guided wave at home and abroad are mature. Due to the complexity of grounding grid structure and diversity of substation environments, there is no round steel detection of grounding grid by ultrasonic guided wave at home and abroad. In the practical engineering application, further in-depth studies are required in development of special sensors for detection, selection of the optimal excitation signal, the influence of excitation signal frequency on guided wave transmission, effective access to guided wave signal as well as identification and quantitative analysis on defect detection.

This paper is focused on the design of round steel magnetostrictive guided wave sensor. According to the characteristics of the lap jointing round steel, studied on bending and horizontal lap jointing structures by simulation and experiment, analyzed the transmission characteristics of guided wave in complex round steel structures, to provide technical support for grounding grid in nondestructive testing.

Design of Magnetostrictive Guided Wave Sensor

The working principle of magnetostrictive guided wave sensor is based on magnetostrictive effect. When alternating current is switched on the spiral coil, a moving magnetic field is generated in the coil, and thus forming an alternating magnetic field in the round steel. Due to the interaction of alternating magnetic field, the round steel is under magnetostrictive strain which generates internal ultrasonic wave through excitation effect. The ultrasonic wave is in reciprocating reflection

on the discontinuous boundary surface of the medium, to produce complex interference and geometry dispersion, by which ultrasonic guided wave is formed and in two-way transmission along both ends of the round steel. When encounter defects or end faces, ultrasonic guided wave reflects and forms reflection echo with testing information. Due to inverse magnetostritive effect, the internal magnetic field changes when the reflection echo gets through receiving coil (the coil may also be used for excitation), which causes a coil in the magnetic field to produce induced current. According to Faraday's Law of Electromagnetic Induction, a voltage signal will be generated in the receiving coil, which illustrates the guided wave transmission. If the transmission velocity of guided wave in the round steel was known, the detection data such as length and defect position of round steel can be calculated.

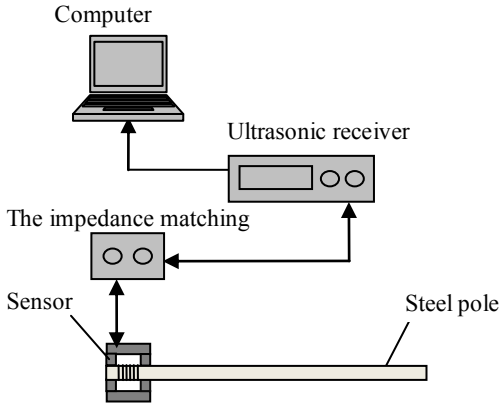


Fig .1 Schematic Diagram of Experimental System

Parameters design for magnetostrictive guided wave sensor mainly includes selection of center frequency, spiral coil design and bias magnetic circuit design. Both sensors solenoid and magnetic circuit design shall be considered, to determine the center frequency of the magnetostrictive guided wave sensor. The center frequency of L (0, 1) modal magnetostrictive guided wave sensor is within 40kHz-80kHz, which is used for long-distance detection; The center frequency of L (0, 2) modal magnetostrictive guided wave sensor is around 235 kHz, which is used for short-distance small-defect detection. The spiral coil is divided into three sections, with each section length half of the excitation guided wavelength. The first and the third sections of the coil are in the same winding direction, and the second section is wound in the reverse direction. The signal is strengthened through vibration phase superimposition. Diameter of the spiral coil enameled wire used in the experiment is 0.16 mm. In order to further optimize the sensor spiral coil, the experiment is conducted in a way that the enameled wire is wound on the solenoid and seven solenoids with different center frequencies are designed. Bias magnetic field in magnetostrictive guided wave sensor can be provided by permanent magnets or electric DC coils. According to the basic principle of magnetostrictive guided wave sensor, four permanent magnet magnetic circuit structures, i.e. single-magnetic circuit, double-magnetic circuit, three-magnetic circuit and four-magnetic circuit, are respectively designed. Because air permeability is far less than the permeability of round steel, the magnetic circuit shall be designed in a way so as to avoid air to become the “magnetic circuit component”, to reduce air gap as much as possible. Furthermore, only materials with relatively great permeability can be chosen as magnetic circuit components. Moderately increasing the cross-sectional area of the element and control the overall dimensions to avoid “magnetic leakage”.

Fig. 1 shows the magnetostrictive low-frequency guided wave experiment system. The diameter of round steel is 22 mm, with the length of 2 m and no defect. The magnetostrictive guided wave sensor is configured at one end of the round steel and is in self-excitation auto-receiving mode. The excitation signal is generated by an ultrasonic excitation receiver, for which power amplification is realized by a power amplify module. After impedance matching, the signal is used to stimulate the magnetostrictive guided wave sensor, and generates ultrasonic guided wave of particular frequency in the steel pole. When the guided wave spreads to the steel pole end, reflection echo is formed

before impedance matching. The data are received and through analog-digital conversion by acquisition module in the instrument, and then displayed, analyzed and saved in oscillographic software programmed in the computer. It can be learnt from the experimental result that by increasing the number of magnetic circuits, the amplitude of ultrasonic echo signal can be enlarged, which means the energy conversion efficiency of sensor can be improved. Four-magnetic circuit bias magnetic field provides stronger magnetic field intensity, with maximum amplitude of detection echo and good practicality, and thus is suitable for non-destructive testing the longitudinal guided wave of round steel in grounding grids.

To research the defect testing performance of sensor, by adopting the experiment system in Fig. 1, the round steel with corrosion defects, diameter of 22 mm and length of 2 m, are tested. The sensor adopts four-magnetic circuit bias magnetic field and an excitation frequency of 50kHz. Corrosion defects and the size are shown in Fig. 2. The center of corrosion area is 500 mm from the excitation end face, and the maximum section loss rate is around 7%. The experimental result is shown in Fig. 3.

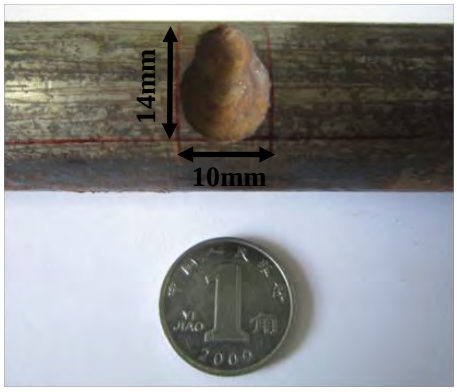


Fig.2 Corroded Defect and its dimension

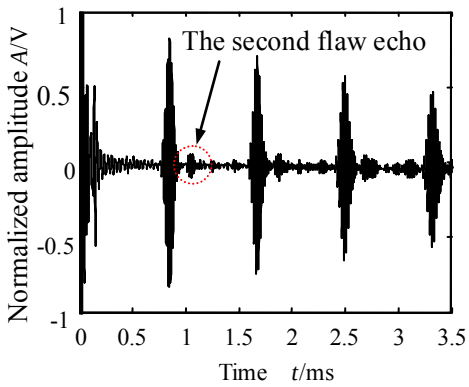


Fig.3 Waveform Received in Corroded Round Steel by Pulse-echo Mode

According to the peak time and the corresponding path of the first two ends face echoes displayed in Fig. 3, the speed of the excited L (0, 1) guided wave is calculated as 4000/(1.676-0.8485)=4834 m/s. Due to the interference of radio-frequency signal, the first corrosion defect echo is submerged by noise, and according to peak time of the second defect echo, the distance from the defect to the excitation end face can be accurately obtained, which is around 497 mm. From the above, it can be learnt that the sensor is highly sensitive to corrosion defects, and the detected section loss rate is below 10%, which meets the requirement on detection accuracy.

When magnetostrictive guided wave is used to detect round steel in grounding grids, bias magnetic field can not only eliminate frequency-doubled effect, but also magnetize the tested round steel and thus change the internal magnetic flux density. The magnetization state of the round steel directly affects the degree of magnetostrictive effect as well as the received signal strength. The internal magnetization states of the round steel in different bias magnetic circuits can be analyzed by adopting COMSOL MULTIPHYSICS simulation software, to reveal that how bias magnetic field affects the performance of a sensor, so as to provide further guidance for optimized magnetic field design.

Study on Transmission Characteristics of Ultrasonic Guided Wave in Complex Round Steel Structures

In view of practical situation of grounding grid project, an experimental study of numerical simulation and detection on the transmission characteristics of ultrasonic guided wave in complex bending and horizontal lap jointing structures of round steel is carried out.

An experimental detection is performed on the bending round steel shown in Fig. 4 by using magnetostrictive sensor with four-magnetic circuit based on the experiment system shown in Fig. 1. The excitation signal adopts signal waveform signal with 5 cycles with center frequency of 50kHz, excitation voltage of 250V and gain of 70dB. The experimental round steel corresponds to the simulation model, with a diameter of 22 mm, and a length of 1.6 m. The round steel is bent at the position of 1 m, with the bend radius $r = 60$ and bend angle $\theta = 90°$. The signal waveform detected is shown as Fig. 5.

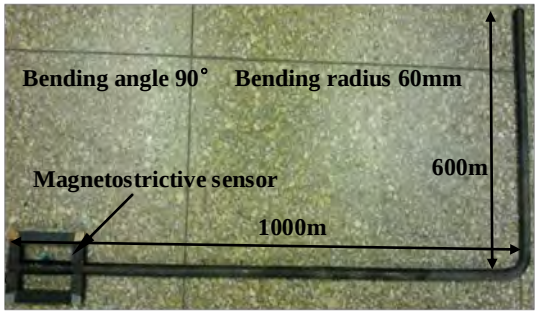


Fig.4 The Picture of Bended Round Steel

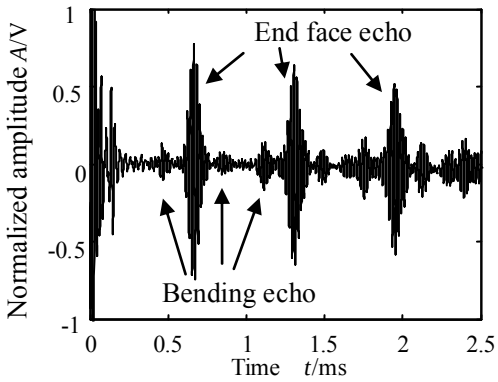


Fig.5 Detected Signals of Bended Round Steel

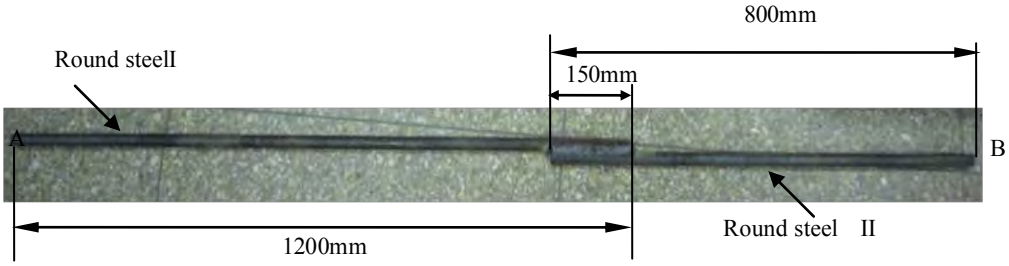
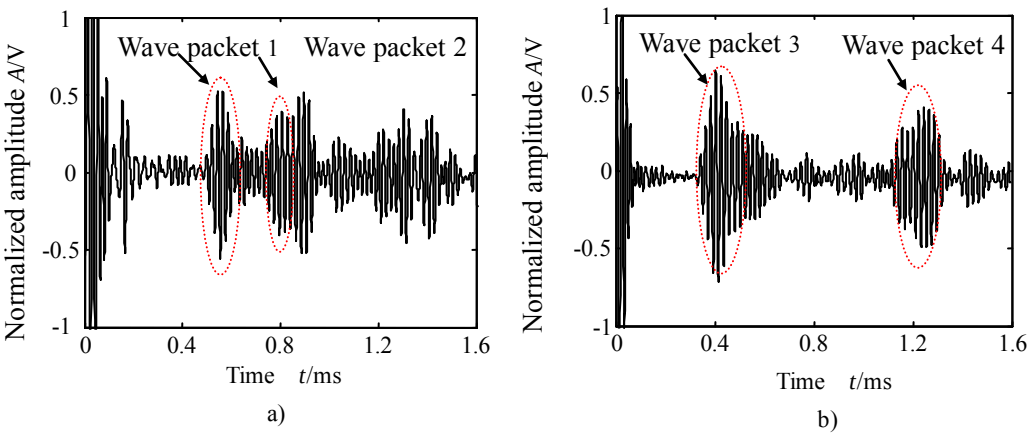


Fig.6 The Picture of Lap Jointing Round Steel



a) Signals receive from A b) Signals receive from B

Fig.7 Detected Signals of Lap Jointing Round Steel

An experimental detection is performed on the lap jointing round steel shown in Fig. 6 by using the magnetostrictive sensor with four-magnetic circuit based on the experiment system shown above. The excitation signal adopts signal waveform signal with 5 cycles with center frequency of 50kHz, excitation voltage of 250V and gain of 70dB. The experimental round steels correspond to the simulation model, in which, round steel I and round steel II are respectively 1200 mm and 800

mm in length, both of them have the same diameter of 22 mm, and the lap jointing length is 150 mm. Put the magnetostrictive sensor at the end A of round steel I, and select end A and end B as the signal receiving terminals to conduct self-excitation auto-receiving experiment as well as one-excitation one-receiving experiment. The signal waveform detected is shown as Fig. 7.

Through the above experimental study of numerical simulation and detection, we can draw the conclusion that (1) when passing through the bending position of round steel, the guided wave reflects and generates bending echo. At the same bending angle, with the increase of bending radius, the bending degree decreases, the bending echo weakens gradually and the duration of echo gets longer. When the wavelength is far shorter than the bend radius, there is no bend echo generated in bending round steel. At the same bend radius, the amplitude of bend echo doesn't vary significantly with the change of bending angle. At the same time, as the bending angle increases, the bending arc length reduces and the duration of echo shortens accordingly. That's is to say, in detection of the guided wave of round steel, the bend radius determines the amplitude of the bend echo, and the bending arc length determines the duration of bend echo. (2) Complex reflection and interference will occur when the guided wave passes through the lap-jointing position of round steel, forming multiple reflection echoes, which will make the detection signal more complex and difficult to be distinguished, therefore, detection by guided wave through welding seam shall be avoided.

Conclusion

In this paper, a nondestructive testing on round steel conductor in grounding grid is carried out by applying magnetostrictive ultrasonic guided wave technology. Magnetostrictive sensor is the core of non-destructive testing of round steel in grounding grid, whose excitation and receiving performances have a direct influence on the reliability of the testing result. Based on magnetostrictive effect, the magnetostrictive sensor excites the low-frequency ultrasonic guided wave of longitudinal mode. Owing to its advantages such as easy-to-be-excited, rapid transmission velocity and long detection distance, it possesses a good prospect of application combined with its characteristic of non-contact detection. Generally, the grounding grid in substation is formed from more than thousand of lap-jointed round steel (or flat steel) conductors in the form of welding, and the method of lap jointing for conductors is complex and various. In view of the practical situation of grounding grid project, an experimental study of numerical simulation and detection on the transmission characteristic of ultrasonic guided wave in complex bending and horizontal lap jointing structures of round steel is carried out, to provide technical support for the non-destructive testing of grounding grid.

Reference

[1]Pavlakovic B, Lowe M. Disperse: A general purpose program for creating dispersion curves [C]. Review of Progress in Quantitative Nondestructive Evaluation, 1997, 1: 185-192.

[2]D. N. Alleyne, B. Pavlakovic, M. J. S. Lowe, P. Cawley. Rapid long-range inspection of chemical plant pipework using guided waves [J]. Insight, 2001, 43(2): 93-96.

[3]A. Demma. P. Cawley. M. Lowe. A.G. Roosenbrand. B. Pavlakovic. The reflection of guided waves from notches in pipes:a guide for interpreting corrosion measurements [J]. NDT and E International, 2004, 37(3): 167-180.

[4]Lindsey M. S. Khajeh E. Van Velsor J.K. Lissenden C.J. Rose J.L. In-line corrosion inspection using circumferential and longitudinal ultrasonic guided waves [C]. AIP Conference Proceedings, 2011, 1335(1): 231-8.

[5]Rose J.L. The upcoming revolution in ultrasonic guided waves [C]. Proceedings of the SPIE - The International Society for Optical Engineering, 2011, 7983.