Design and Development of Miniature Non-contact Multi-range Current Sensor

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Abstract. High-performance sensors and high-efficiency and accurate measurement technology are the basis of power grid control, monitoring, analysis and decision-making. Current monitoring devices commonly used in power systems cannot meet the need for simultaneous measurement of steady-state current and transient current. In this paper, a high-performance current sensor based on giant magnetoresistance sensor is developed, and key technologies such as sensor structure, sensor chip selection, signal processing circuit and electromagnetic compatibility are designed. The experimental results show that the micro current sensor can accurately measure the steady-state current of 1000A and the transient current of 20kA. At the same time, it has the advantages of small size, high sensitivity, large measurement range, convenient installation and high integration, which meets the measurement requirements of smart grid.

1. Introduction

With the development and construction of smart grid, it is very important to accurately measure the state of key nodes and equipment in power grid [1]. High-performance sensors and high-efficiency and accurate measurement technology are the basis of power grid control, monitoring, analysis and decision-making [2].

Current signal parameters are the key parameters in power system, which are usually collected by current transformer. However, the application scenarios of power system are complex and diverse, and the requirements for the amplitude, frequency and accuracy of monitoring current vary greatly [3]. Presently, current transformers (CTs) is widely used in traditional current measurement in power system. The electromagnetic current transformer has the characteristics of simple principle and mature application, but it also has the disadvantages of complex insulation structure, large volume, easy filling of iron core and narrow measuring frequency band when large current occurs.[4] With the development of power system and the increase of power load, the traditional electromagnetic current transformer is more and more difficult to meet the complex application scenarios of power system. In addition, current sensors applied in power systems include Hall effect sensors, fiber-optic current transformers (FOCTs), Rogowski coils, fluxgate sensors and GMR effect sensors.

Hall sensor has the advantages of high precision, fast response and a wide bandwidth, However, the problems of the Hall effect sensor are low sensitivity, low breakdown voltage, and susceptibility to the
temperature, which limit it to applications in high voltage power systems. Fiber-optic current
transformers have developed rapidly in recent years, which has the advantages of effective isolation
from high potentials, immunity against electromagnetic interferences, and wide bandwidth. However,
the extremely complicated structure, high price, susceptibility to the temperature and polarization under
direct current are problems that need to be solved. The Rogowski coil has the advantages of high
bandwidth and capability of measuring large currents, is mainly used for transient large current sensing.
However, Rogowski coils have poor accuracy when sensing small and low frequency currents.
The fluxgate technology can significantly improve the accuracy of magnetic field sensors, but because of its
high cost and size requirements, fluxgate technology is usually only employed in calibration systems,
diagnosis systems and laboratory equipment. Magnetoresistance sensor has many advantages, such as
high sensitivity, low price, wide frequency bandwidth, low temperature coefficient and high linearity,
which is expected to become a new trend of current sensing measurement in smart grid [7].

In some distribution application scenarios, there are not only steady current of kiloampere level, but
also abnormal current of tens of kiloampere level, such as short circuit current and lightning current.
Current measurement devices in power system cannot meet this application scenario.

Based on the giant magnetoresistance (GMR) effect, this paper proposes a current monitoring method
and develops a current sensor device, which can be used in special application scenarios of measuring
small current and large current at the same time.

2. Current Sensor Based on GMR

2.1 Micro Multi-range Current Measurement Technology

GMR effect refers to the phenomenon that the resistivity of magnetic materials varies greatly in the
presence of external magnetic field than in the absence of external magnetic field. GMR is a quantum
mechanical effect, which results from layered magnetic film structure [8]. The structure is composed of
thin layers of ferromagnetic materials and thin layers of non-ferromagnetic conductive materials. The
principle of current sensor based on GMR is shown in Figure 1.

As shown in Figure 1, the measuring device is close to the conductor. A, B and C are three magnetic
field current sensing chips. A and B chips choose chips with low saturated magnetic field, C chips use
chips with high saturated magnetic field, steady-state current is measured by A and B chips, and
abnormal large current is measured by B and C chips. A, B and C chips are in a straight line, and their
planes are perpendicular to the conductors through structural design. A and C are single-axis chips. The
measured magnetic fields in the Y direction are \( B_0 \) and \( B_3 \). The output voltage is \( V_0 \) and \( V_3 \) respectively.
B chips are two-axis chips. The measured magnetic fields in the X and Y directions are \( B_1 \) and \( B_2 \)
respectively. The output voltage is \( V_1 \) and \( V_2 \) respectively. The distance between A and B and C chips
is \( d \), the distance between A and O is \( r \), the distance between B and C and O is \( l \), and the angle between
AOB and AOC is \( \theta \), of which \( d \) is known.

According to Biot-Savart Law [9]:
\[ B_0 = \frac{\mu_0 I}{2\pi r} \]  
\[ B_1 = \frac{\mu_0 I}{2\pi} \sin \theta = \frac{\mu_0 I d}{2\pi l} \]  
\[ B_2 = \frac{\mu_0 I}{2\pi} \cos \theta = \frac{\mu_0 I r}{2\pi l} \]  

Equation (4) can be obtained from simultaneous equations (2) and (3).

\[ r = \frac{d}{B_2} \frac{k_2 V_2}{k_1 V_1} \]  

Assuming that the sensitivity of the X and Y directions of the B magnetic field current sensor chip is \( k_1 \) and \( k_2 \) respectively, the relationship between the measured magnetic field and the output voltage \( B_1 = k_1 V_1, B_2 = k_2 V_2 \) can be obtained.

\[ B_3 = \frac{\mu_0 I}{2\pi l} \cos \theta = \frac{\mu_0 I}{2\pi l} \frac{r}{d^2 + r^2} \]  

Assuming that the sensitivity of C magnetic field current sensor chip is \( k_3 \), \( B_3 = k_3 V_3 \) can be obtained. The formula (9) can be obtained as follows:

\[ k_3 V_3 = \frac{\mu_0 I}{2\pi l} \frac{r}{d^2 + r^2} \]  

\[ I_0 = \frac{\mu_0 I}{2\pi l} \frac{r}{d^2 + r^2} \]  

Current \( I \) can be calculated by calibrating the sensor, and abnormal current can be calculated by output voltage of B and C sensors.

2.2 Error Analysis of Current Sensor

According to the calculation process in Section 2.1, the installation position of the sensor will affect the accuracy of the current sensor. The main error sources of sensors include B-point position deviation, C-point position deviation, the deviation of sensor plane and xoz plane, and the deviation of sensor plane.
and yoz plane, as shown in Figure 2. The position deviation of point B and point C can be corrected by calibration, so the actual deviation of the sensor mainly comes from the angle deviation during installation.

In order to ensure the accuracy of current measurement, it is necessary to ensure that the sensor plane is perpendicular to the wire when it is installed. The position deviation of point B and point C can be controlled by high precision welding machine. The angle deviation of current sensor needs to be controlled by structural processing. The shell material with lower deformation can be used and the precision machine tool can be used to ensure that the angle deviation meets the design requirements.

3. Design of Current Sensor

3.1 Overall Architecture of Current Sensor

The structure of current sensor device is shown in Figure 3, including GMR sensor, signal conditioning circuit, AD module, MCU, communication module and power module [10]. The current in the wire to be measured generates magnetic field in the surrounding space. The GMR chip is affected by magnetic field. Its internal bridge resistance changes and is further converted into voltage signal. The signal is amplified and filtered by signal processing. The signal is converted from AD module to digital signal and processed and calculated by MCU. The calculated data is uploaded to the wireless communication module. Receive the data collection module to collect and analyze the current signal. The circuit diagram is shown in Figure 4.

3.2 Selection of Current Sensor Chip

In order to measure steady and transient currents simultaneously, two different ranges of GMR sensor chips are needed. THSC_1 and THSC_2 GMR sensor chips are selected for the development of current
sensor in this paper. THSC_1 has high magnetic field sensitivity (1.1mV/V/Oe) and moderate measurement range (+500Oe, goodness of fit 0.42%) and is suitable for 1kA range current measurement. THSC_2 has moderate magnetic field sensitivity (0.26mV/V/Oe), extremely wide measurement range (+1500Oe, goodness of fit 3.5%) and is suitable for 1kA range current measurement. Both types of chips have band response greater than 1MHz, meet the requirements of the index, and have a large limit of external magnetic field (> 2000Oe), which ensures that the chip will not be saturated and damaged.

3.3 EMC Design of Current Sensor
Current sensor works at high voltage end and needs wireless communication to transmit data. Therefore, the shielding case of the sensor cannot be grounded, so it is necessary to design the electromagnetic compatibility of PCB.

In order to reduce the stray capacitance of signal pathway, PTFE board is selected. In addition, in order to achieve the purpose of EMC design, layout and wiring meet the general high-speed PCB design techniques such as 20-H principle and 3-W principle. The circuit board is designed with multi-layer board, the signal line and power line are arranged in layers, and the components are packaged by surface bonding to reduce stray capacitance.

3.4 Structure Design of Current Sensor
In practical application, the angle deviation between circuit board and cable should be controlled to reduce measurement error. The shell structure of the current sensor is shown in Figure 5. The shell is made of Engineering insulating plastics, which can meet the insulation requirements after laboratory test and verification. Epoxy resin is used to encapsulate the inside of the shell, which can reach IP67 protection level. The current sensor is fixed on the wire through the strap, which can ensure the stability of the sensor.

![Figure 5. Structure Design of Current Sensor](image)

4. Calibration Test of Current Sensor

![Figure 6. Linearity Test of Current Sensor](image)
After solving the above sensor problems, a sample of current sensor is developed. For 1000A range current sensor, power frequency current source is used for calibration. For the large range current sensor of 20kA, EMCPro is used to generate 8/20s lightning current waveform with different amplitudes, and the results are shown in Figure 6. Among them, the abscissa is the standard current generated by the current source, and the longitudinal coordinate is the output current of the current sensor. It can be seen that the measurement range of steady-state current is 1000A, and the correlation coefficient of linear fitting is 99.99%.

5. Conclusions
(1) In view of the fact that current sensors in power system cannot meet the special requirements of monitoring both steady-state current and abnormal current, a micro-current sensor based on GMR principle is developed from theoretical analysis, which can meet the special monitoring needs of transmission lines in power system.

The current sensor sample developed in this paper can measure the steady-state current of 1000A at the same time and the transient current of 20kA at the same time. Its linearity reaches 99.99%. It has the advantages of small size, convenient installation and wide measurement range, and can meet the needs of current monitoring in smart grid.

(2) The current sensor developed in this paper can be applied to the current measurement scenarios of distribution cabinet cable branch conductor, overhead line conductor, cable trench cable and so on. However, for some special scenarios, current sensors need to be optimized and improved. Distribution cables have many branches and wires, and the distance between them is relatively close. The electromagnetic environment is complex. How to measure the conductor current in the distribution cabinet without contact is a subject worthy of study. The spatial magnetic field distribution of multi-core cables and split overhead lines is complex. It is necessary to eliminate the interference of external magnetic field by optimization algorithm, and then realize accurate measurement of current.

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