Power System Transient Current Sensor Based on Magnetoresistance Effect

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Abstract. Aiming at the problem that the mixed use of overhead lines and cables causes serious refraction and attenuation of the traveling wave signal in propagation, which makes the traditional traveling wave sensor unable to adapt to the weak signal identification and recording requirements. A wideband sensor for detecting transient current signal of power system is developed. The detection principle of the anisotropic magnetoresistive sensor is analyzed, and the tiny signal precision differential amplifier circuit is designed. Based on the actual situation of the power system, a corresponding test environment was built to conduct transient current transfer tests. The experimental results show that the sensor has a high linearity in the 0-5MHz bandwidth, and is suitable for the extraction of various transient signals, especially in the power system traveling wave protection has high application value.

Keywords: Magnetoresistance effect, current sensor, Broadband, Transient signal, Online monitoring, relay protection

1. Introduction

With the improvement of residents' living standards, the global power system continues to expand. At the same time, end users also put forward higher requirements for the reliability of electrical energy. In order to quickly and accurately locate and eliminate the fault after the line fault occurs, the relay protection method based on the principle of transient traveling wave is proposed by researchers. When a fault occurs, it usually produces instantaneous overvoltage and overcurrent, a series of transient electrical signals are generated and transmitted along the line to the remote end, which are recognized by the remote transient current sensor, and then complete the precise fault location [1], this method has been widely used in China's power transmission network, and has achieved good results [2].

However, in a distribution network with a larger scope and a wider coverage, due to the low voltage level, complex structure, and numerous branches of the distribution network, the fault traveling wave transient signal attenuation is serious. How to accurately extract and identify the fault traveling wave has become a major problem that restricts the development of traveling wave fault location technology [3]. Traditional transient signal sensors usually use Rogowski coil transformers [4], but due to their different response levels to different frequencies, especially their poor ability to transmit low-frequency signals, they can no longer meet the requirements for transient behavior of distribution network faults of accurate identification of wave signals. A power system transient current sensor with high consistency based on the magnetoresistance effect that can accurately transfer within 0-5MHz is proposed in this paper [5]. The sensor can also be extended to other fields and has great research value.
Research on a variety of new magnetic sensors, design comparative experiments to explore the transfer characteristics of new and old sensors, evaluate sensor output signals and actual current signals, and finally select the best device for production. To make up for the shortcomings of traditional sensors in the transmission of weak signals at medium frequency, the transmission difference of different batches of sensors is small, and it can be better applied to the traveling wave positioning of the distribution network.

2. Sensor Principle
Magnetoresistive sensors can be divided into the following categories: Hall Effect, Anisotropic magnetoresistance [6], Giant magnetoresistance, Tunnel magnetoresistance, Colossal magnetic resistance [7]. The colossal magnetoresistance effect sensor has harsh working conditions, it has not yet been widely used. In other types of magnetoresistive sensors, TMR sensors have the highest dynamic range and magnetic sensitivity [8].

Most magnetoresistive sensor chips have a Wheatstone bridge structure inside to obtain greater magnetic field sensitivity [9], as shown in figure 1.

![Figure 1. Schematic diagram of the bridge structure.](image)

Each bridge arm in the picture is composed of TMR components [10], the magnetic field direction in the figure is the reference sensitive direction of the chip, when the applied magnetic field intensity changes along the sensitive direction parallel to the chip, the differential voltage output by the sensor is positively correlated with the intensity of the magnetic field. When a current I flows through a current-carrying conductor, a magnetic field will form around the conductor, as shown in figure 2. According to the Biot-Savart formula, the magnetic induction intensity at any point K in space is:

\[
B = \frac{\mu_0 I}{2\pi r} \cos \theta_1 \cos \theta_2
\]

\[
\mu_0 \text{ is the vacuum permeability, Its value is } 4\pi \times 10^{-7} \text{N/A}^2, \text{r is the shortest distance between the point and the conductor. The direction of the magnetic induction intensity } B \text{ can be judged by the right-hand rule [11]. Further, if point } K \text{ is close to the middle of the conductor and very close to the conductor, that is, } r \text{ is small enough, } \theta_1 \rightarrow 0 \text{ and } \theta_2 \rightarrow 0, \text{ the visible conductor is infinitely long, at this time:}
\]

\[
B = \frac{\mu_0 I}{2\pi r}
\]

![Figure 2. Space magnetic field.](image)
The final output voltage of the sensor can be expressed as:

\[ U_o = kEB = \frac{RL\mu IL}{2\pi r} \]  

(3)

Where \( E \) is the sensor excitation voltage, from equation (3), we can see that the primary side current \( I \) and the secondary side voltage \( U_0 \), the relationship of the installation distance \( r \) is:

\[ I = \frac{2\pi rU_0}{kE\mu_0} \]  

(4)

3. Sensor Design and Implementation

The TMR magnetic sensor described in this article has a bridge structure inside, Output millivolt differential voltage signal, the signal amplification part uses three OP37s to form a high-performance three-op-amp instrumentation amplifier, it can meet high bandwidth requirements under different gains. The frequency selection network or the voltage follower terminal can be configured according to actual needs to send out analog signals that meet the requirements of the signal acquisition terminal. The sensor hardware block diagram is shown as in figure 3.

![Figure 3. Sensor hardware block diagram.](image)

The transient current sensor uses a shielded multi-strand twisted pair cable to connect to the signal acquisition terminal, the acquisition terminal supplies power to the sensor, then the sensor returns the transient signal.

In actual applications, the cable length is variable and the environment is complex, and there may be multiple interferences that affect the accurate measurement of the sensor. Therefore, an isolated regulated power supply is designed in the module to output \( \pm 5V \) for the sensor and signal amplifier circuit.

The voltage fine-tuning part uses a simple form of resistor divider. The bridge resistance of the TMR2103 chip is 50kΩ, which can work under 1~7V DC excitation. In this module, \( \pm 5V \) is used for power supply, and the voltage is divided and leveled by adjusting the resistance value in the power supply loop of the chip. As shown in figure 4. If the resistances \( R_1 \) and \( R_2 \) are each 25kΩ, the sensor bridge will divide the voltage by 5V, and the output signal will be exactly 0V in the external magnetic field.

![Figure 4. Voltage trimming link.](image)

Signal amplification is a key part of the system. The three-op-amp differential amplifier circuit consists of three high-speed and low-noise operational amplifiers with unity gain bandwidth (GBW) up to 63MHz.as shown in figure 5.
Figure 5. Differential amplifier circuit.

In this circuit, \( R_1 = R_2 \), \( R_3 = R_4 \), \( R_5 = R_6 \), the total gain of the amplifier circuit can be expressed as:

\[
A = A_1 \times A_2 = \left(1 + \frac{2R_G}{R_G}ight) \times \frac{R_5}{R_1}
\] (5)

RG is adjusted by dial switch, the appropriate resistance value can be selected according to the actual needs of the project.

Considering the actual installation situation, the PCB board is placed in an ABS plastic shell, the interior is densely filled with epoxy resin, and the exterior is connected with a waterproof aviation connector to ensure the durability and stability of the module; the plastic shell is designed with strapping grooves on both sides to facilitate the sensor is fixed on a grounded flat iron or current-carrying wire; the bottom is precisely designed so that the sensor chip is 1cm from the bottom surface. By changing the thickness of the additional spacer, the relationship between the field strength at the chip and the actual current can be accurately grasped, and the size of \( r \) can be determined. The physical picture of the sensor module is shown in figure 6.

Figure 6. Sensor module.

This module package is easy to install and can be adapted to cables of different sizes. It can not only be used for power system AC and DC current measurement, but also for industrial cable current monitoring, with low cost and easy distributed installation and use.

4. Sensor Actual Test
The sensor control experiment process is shown in figure 7.
In order to detect the transmission characteristics of the TMR sensor, it is necessary to make the sensor work in the optimal position, that is, the position with the highest induction intensity, and build a test environment (figure 8) and on-site objects (figure 9). First, a test plan for the sensor to directly sample the current signal is designed. The current-carrying line is placed at the bottom of the sensor to keep the sensor in the best measurement state, and then different currents are generated through the high-frequency signal source (the signal source is connected to the power amplifier). In order to compare the difference between the new TMR sensor and the traditional Rogowski coil, a control sensor is also set up, and the current signal, Rogowski coil signal and TMR sensor signal are simultaneously observed using an oscilloscope to evaluate the sensor output signal and the actual current signal.

Figure 7. Experimental flowchart.

Figure 8. Test environment wiring diagram.
As shown in Figure 10, $CH_{1}$ is the resistance voltage in the line, it can represent current waveform, $CH_{2}$ is the traditional Rogowski coil transformer signal, $CH_{3}$ is the transmission signal of the TMR sensor. It can be observed that the Rogowski coil is sensitive to transient impulse response, which conforms to the actual situation. The transient current sensor output is similar to the primary current waveform, which can basically meet the transient signal extraction required for traveling wave positioning.

In order to test the working condition of the transient current sensor in the actual circuit, set the signal source to output 3A, 50Hz alternating current, superimpose a transient signal with a pulse peak value of 20A, use an oscilloscope to observe the current and sensor signal, as shown in Figure 11.

In the figure, $CH_{1}$ (x10) is the current waveform in the line, and $CH_{2}$ is the sensor output signal. The transient current sensor output is sensitive to the burst pulse of the primary current. It can be seen that the sensor can respond well to the burst pulse in the line, which can basically meet the transient signal extraction required for traveling wave positioning.
5. Conclusion
A sensor module based on magnetic field effect is proposed in this article, analyzes and tests different magnetic sensors, designs signal amplifier circuits, manufactures test modules in small batches, and conducts practical test experiment. Compared with traditional sensors, the module has greatly reduced volume, weight, cost, and is easy to install, adapting to the complex characteristics of the current distribution network environment. The characteristics of the measurable AC and DC signals make it have a higher sampling width, and the gain consistency for different frequency signals is better, which makes up for the lack of poor signal reduction of traditional sensors. Since the feedback signal strength can be adjusted through the gap between the actual installation and the current-carrying conductor, it can also meet the needs of fault wave full-wave recording after optimization in the future.

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