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# RESEARCH ON CURRENT SENSOR FOR ELECTRIC VEHICLE CHARGING BILLING

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## ABSTRACT

A DC current sensor for electric vehicle charging billing is designed by using the magnetic modulation scheme of the duty cycle model. Based on the analysis of the working principle of the sensor, the mathematical model of the sensor is given by analytical method. The design principles of the core, coil and circuit parameters are analyzed, and the prototype of the DC current sensor is fabricated and tested. The test results show that the sensor has high measurement accuracy and good stability. Due to the full digital design, the measurement circuit is less interfered by the external electromagnetic environment, suitable in places with complex electromagnetic environment such as new energy vehicle charging piles.

**Keywords:** electric vehicle, DC current sensor, duty cycle, billing

## 1. INTRODUCTION

With the rapid growth of the global economy, environmental pollution and energy shortages are also growing. Due to the advantages of energy saving, environmental protection and low emissions, electric vehicles are receiving more and more attention from the society. As an important part of the new energy strategy, electric vehicles have strong advantages in clean and economic development. With the support of national policies, they have become an important part of automobile development. The large automobile manufacturing industries in the world are also increasing. Scientific research investment and research and development efforts are rapidly developing[1-3]. To realize the goal of popularizing electric vehicles in large scale across the country, it is particularly important to build electric vehicle charging piles and supporting intelligent charging billing control systems. To make power supply of electric vehicles convenient and fast, it is necessary to build “gas stations” as traditional cars, which have access to universal support for the construction of charging piles and billing control systems[4-5]. The high-precision and low-cost digital DC current sensor will greatly reduce the cost of the charging pile billing system and accelerate the popularization speed of electric vehicles.

The charging pile is generally made of direct current, and the charging current is less than 40A. The current sensor's range is set to 40A, and the accuracy is better than 0.2%, which is convenient for billing amount accuracy. Limited by the principle, the sensor needs to pass both the positive and negative poles of the power supply through the sensor at the same time, while the large charging pile has a large charging current, and the cable insulation layer and the sheath are thick. To facilitate the cable passing through the current sensor, the inner diameter of the sensor should be 20mm or so.

Precision detection of leakage current can usually be performed using type sensors such as Hall sensors, GMR sensors, TMR sensors, and magnetic modulation sensors. Literature [6] uses the programmable gain amplifier of the instrument and the Hall sensor to achieve the detection of 200Ω-200kΩ resistance with a resolution of 150Ω. Literature [7] can measure 10mA-25A current with GMR current sensor with an accuracy of 0.77%. Literature [5], based on the optimized design of the TMR component structure, a weak current sensor with a current resolution of 20μA was developed. Most of the leakage current sensors use a magnetic modulation detection scheme [8]. According to the literature [9], the magnetic modulation detection error can be controlled at about 0.2 mA.

Hall sensors, GMR sensors, and TMR sensors are all based on a magnetic field-sensing chip. The chip is usually placed at the opening of the sensor core. There

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are air gaps in these sensor cores, and the magnetic resistance of the magnetic circuit is large. When the inner diameter of the sensor core is increased, the magnetic flux inside the core becomes smaller, and the measurement error of the sensor increases. At the same time, due to the small space of the charging pile, the electronic equipment inside the power distribution board is densely arranged, and the electromagnetic environment is bad. The leakage current sensor should have the ability to work in an electromagnetic environment. If the sensor measurement circuit does not need digital-to-analog conversion and directly outputs digital signals, the sensor's anti-interference ability will be greatly improved. It is generally believed that the digital sensor is superior to the analog one. In this paper, the self-excited oscillation magnetic modulation principle based on the duty cycle model is used to design the DC current sensor for charging piles.

Based on the principle of deriving the DC current sensor, the design principle of the sensor core and the excitation coil is given, and the basic parameters of the circuit are obtained through calculation. The experimental platform is established, the experimental design of the sensor is verified, and the experimental results are analyzed.

## 2. MEASURING PRINCIPLE

The schematic diagram of the DC current sensor is shown in Figure 1.

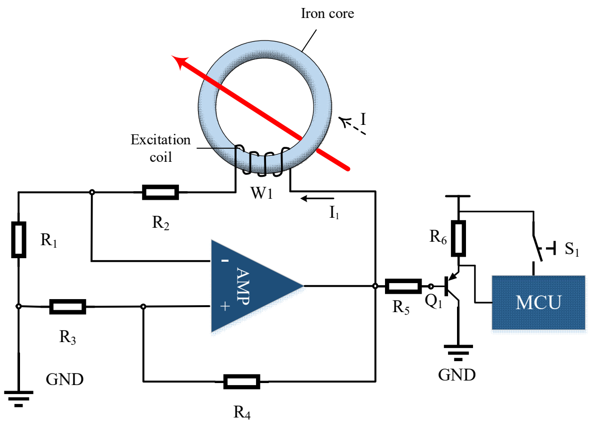


Fig 1 Schematic Diagram of DC Current Sensor

The measured current I is shown in Figure 1. It should be passed through the core at the same time. When an insulation fault occurs, the leakage current is *I*. The sensor core is made of a ring-shaped soft magnetic material, and excitation coil is wound around the iron core, and the number of turns is $W_1$, $R_1$, $R_2$, $R_3$, and $R_4$ are resistors, and the impedance of the excitation coil is equivalent to the resistor $R_2$. Four resistors are connected to the two input terminals of the operational amplifier, the operational amplifier operates in an open-loop amplification state, and the output directly drives the excitation coil.

According to the working principle of magnetic modulation technology, the circuit self-excited oscillation, operational amplifier output a certain frequency of square wave, such as rail-to-rail technology operational amplifier, the amplitude of square wave plus or minus half cycle should be equal to the operational amplifier supply voltage $U_P$. The operational amplifier drives the exciting coil so that the core is in a state of alternating positive and negative magnetic flux through saturation. When there is DC current in the cable under test, current *I* will generate a magnetic potential in the core, which will form a bias flux in the core, thus damaging the symmetric flux generated by the periodic square wave voltage in the excitation coil. As a result, the square wave output of the operational amplifier is no longer symmetric, and even harmonic components appear.

Suppose the initial time, the op amp outputs a negative voltage, the voltage value is $V_O=-U_P$, the non-inverting input terminal voltage $U_+=-\frac{R_3U_P}{(R_3+R_4)}$, the excitation current $I_1=0$, and the inverting input terminal voltage $U_-=0$. The excitation current $I_1$ gradually increases in phase, and the magnetic flux in the clockwise direction of the core gradually increases. When $I_1=-I_s$, the core is saturated, and the inductance of the excitation coil changes from $L_1$ in the unsaturated state to $L_0$ after saturation, due to the inductance. Decrease, the circuit time constant decreases, and the current change rate increases. When $I_1=-I_H$, the voltage on the resistor $R_1$ is equal to the voltage at the non-inverting input terminal, and the output of the operational amplifier is inverted, $V_o=U_P$.

$$I_H=\frac{R_3}{R_1(R_3+R_4)}U_P \tag{1}$$

Subsequently, the amplitude of the excitation current $I_1$ is continuously reduced under the driving of the forward voltage $V_O$. When $I_1=-I_s$, the excitation coil is out of saturation, the magnetoresistance becomes large, and the inductance changes from $L_0$ to $L_1$. When $I_1$ rises to $I_1=I_s$, the sensor core is again saturated. When $I_1=I_H$, the voltage on resistor $R_1$ is equal to the voltage at the non-inverting input terminal, the output of the operational amplifier is inverted, $V_o=-U_P$, and the excitation current begins to decrease. Small, so that the core is out of the saturation zone. The above process is repeated, the operational amplifier outputs a periodic square wave, and the excitation coil forms a self-oscillation. The output voltage of the operational amplifier and the current waveform in the excitation coil are shown in Figure 2.

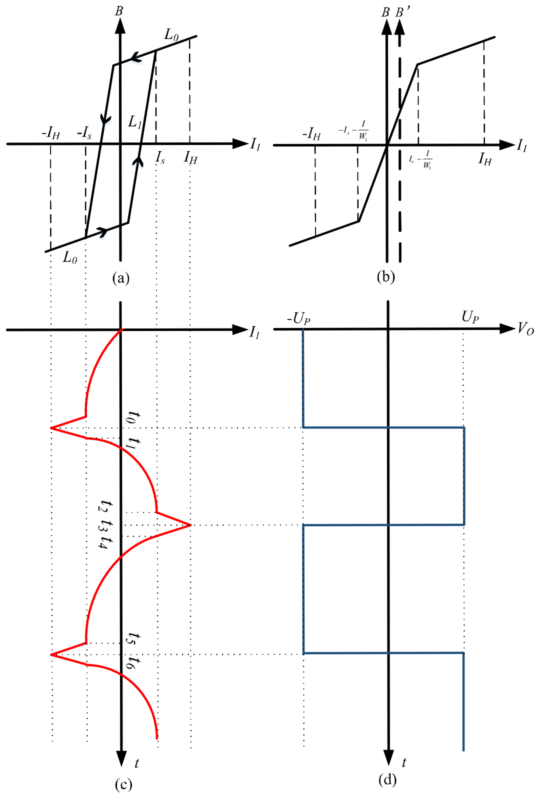

Fig 2 Magnetization Curve/Waveforms of Excitation Voltage and Current

Assuming DC current $I=0$, due to the symmetry of the core magnetization curve, the parameters of the whole self-excited oscillation circuit are in a symmetrical state, and the average value of the excitation voltage and the excitation current in one cycle is zero, and the square wave excitation voltage duty cycle theory The value is 50%. When the cable insulation fails and there is leakage current, according to the right-hand rule, a counterclockwise magnetic flux will be generated in the iron core (the DC current direction is as shown in Fig. 1), and the magnetic flux direction and the operational amplifier output a positive voltage. The direction of the excitation flux generated in the excitation coil is the same, and the excitation current generated by the negative voltage of the operational amplifier is opposite to the direction of the magnetic flux generated by the negative voltage of the operational amplifier. The excitation current required for the core to reach the forward saturation is reduced, and the excitation current required to achieve the negative saturation becomes. The core magnetization curve is shown in Figure 2(b), and the coordinate system is shifted to the right. According to the circuit principle, the excitation current value $I_H$ of the output level of the operational amplifier is not changed. When the excitation current is in the positive half cycle, the iron core enters the saturation state earlier, and the series RL circuit composed of $R_1$, $R_2$ and the excitation coil The time constant is small, and the rate of change of current is large; when the negative half cycle is reached, the amplitude of the current that the iron core enters into saturation is large, and it needs to be longer into saturation, the average time constant of the circuit is large, and the rate of change of current is small. Therefore, the operational amplifier outputs a positive voltage time less than the output negative voltage, that is, the duty cycle of the square wave excitation voltage is less than 50%. Similarly, when the leakage current exists and is in the negative direction, the duty cycle of the square wave excitation voltage is greater than 50%.

The iron core is usually made of soft magnetic material, and the coercive force of the material is low. To facilitate the analysis of the dynamic process of the sensor operation, we can assume that the coercive force is 0, the excitation coil inductance is $L_0$. when the iron core is saturated, and the excitation coil inductance is $L_1$ when the iron core is not saturated, $L_0 \ll L_1$. The column writes the voltage-current equation of the circuit under ideal conditions:

$$V_O=\begin{cases}(R_1+R_2)i_1(\mathrm{t})+L_0\dfrac{di_1(\mathrm{t})}{dt}\\(R_1+R_2)i_1(\mathrm{t})+L_1\dfrac{di_1(\mathrm{t})}{dt}\end{cases}\qquad(2)$$

According to the three-element method of the circuit, the time expression of the excitation current can be easily calculated.

$$i_1(\mathrm{t})=\begin{cases}\dfrac{U_P}{R_1+R_2}-(\dfrac{U_P}{R_1+R_2}+I_H)e^{\frac{t_0-t}{\tau_0}} & t_0<t<t_1\\ \dfrac{U_P}{R_1+R_2}-(\dfrac{U_P}{R_1+R_2}+I_S+\dfrac{I}{W_1})e^{\frac{t_1-t}{\tau_1}} & t_1<t<t_2\\ \dfrac{U_P}{R_1+R_2}-(\dfrac{U_P}{R_1+R_2}-I_S+\dfrac{I}{W_1})e^{\frac{t_2-t}{\tau_0}} & t_2<t<t_3\\ -\dfrac{U_P}{R_1+R_2}+(\dfrac{U_P}{R_1+R_2}+I_H)e^{\frac{t_3-t}{\tau_0}} & t_3<t<t_4\\ -\dfrac{U_P}{R_1+R_2}+(\dfrac{U_P}{R_1+R_2}+I_S-\dfrac{I}{W_1})e^{\frac{t_4-t}{\tau_1}} & t_4<t<t_5\\ -\dfrac{U_P}{R_1+R_2}+(\dfrac{U_P}{R_1+R_2}-I_S-\dfrac{I}{W_1})e^{\frac{t_5-t}{\tau_0}} & t_5<t<t_6\end{cases}\qquad(3)$$

In the formula, $\tau_0 = \frac{L_0}{R_1 + R_2}$ , $\tau_1 = \frac{L_1}{R_1 + R_2}$ . The time interval of $t_1$, $t_2$, $t_3$, $t_4$, $t_5$, and $t_6$ can be calculated according to the formula (3) if $\tau_0 \ll \tau_1$ , $\frac{U_P}{R_1 + R_2} \gg I_s$ , and $\frac{U_P}{R_1 + R_2} \gg I$ can be guaranteed during design, the expression of the excitation voltage duty cycle can be calculated:

$$D = \frac{T_P}{T} = \frac{t_3 - t_0}{t_6 - t_0} \approx 0.5 - \frac{(R_1 + R_2)}{2W_1 U_P} I \qquad (4)$$

It can be seen from equation (4) that the duty cycle of the square wave excitation voltage is linear with the measured leakage current. When the leakage current is 0, the duty ratio is about 50%; when there is a positive leakage current, The empty ratio is less than 50%; the duty ratio is increased when the leakage current direction is negative, and the positive square voltage of the excitation square wave is longer than the negative voltage time. Therefore, it is only necessary to measure the duty ratio of the excitation voltage by using the MCU's GPIO port to calculate the leakage current. The sensor can be digitized without the assistance of the ADC, and the measurement circuit should not be interfered. It is suitable for dense places such as ships and other electronic equipment. application.

## 3. SENSOR PARAMETER DESIGN

The DC current sensor is mainly composed of core, coil, self-oscillating circuit and measuring circuit.

### *3.1 Core Material Selection and Structural Design*

According to the working principle of the sensor, the iron core works in the periodic saturation state. In order to achieve accurate measurement, the iron core usually needs to meet the following conditions:

（1）High magnetic permeability, the higher the magnetic permeability of the core unsaturation, the greater the change of magnetic permeability when saturated, and the larger the effective signal provided by the sensor, which is beneficial to the sensitivity of the sensor. However, materials with excessive magnetic permeability are generally more sensitive and sensor noise is greater.

（2）Low coercivity, the magnetic field generated by small DC current is also weak, the lower the coercive force, the higher the resolution for small current measurement. It also reduces the overall power consumption of the sensor.

（3）Low saturation magnetization, the easier the core is saturated, the higher the sensitivity of the sensor.

（4）The difference between the outer diameter and inner diameter of the iron core is small. The principle of the magnetic modulation sensor requires the iron core to enter the saturation state when it is excited. If the inner and outer radius of the iron core is too large, the magnetic flux is prone to be uneven, leading to measurement errors.

In addition, the core needs to have higher resistivity, lower electromagnetic noise and lower magnetostriction. These features can effectively reduce the power consumption of the sensor and improve the signal-to-noise ratio of the sensor.

It can be seen from the requirements that the material satisfying the above conditions is usually a soft magnetic material, and therefore the magnetic modulation sensor core is generally made of permalloy, amorphous material or nanocrystalline material.

Permalloy, cobalt-based amorphous and iron-based nanocrystals are both used as sensor cores, in which permalloy, Cobalt-based amorphous parameters are better, but amorphous materials are generally brittle and brittle, and are not suitable for used , and they are very expensive. Therefore, sensors should be preferred for permalloy materials.

In this paper, the inner diameter of the sensor core is D=37mm, and the cross-section of the core is 14mm×8mm (width×height), which is made of permalloy.

### *3.2 COIL PARAMETER DESIGN*

The excitation coil is usually wound with an enamel wire along the outer insulation layer of the core. Uniform winding is usually required to suppress the occurrence of leakage flux between turns. The number of windings should meet the following restrictions:

（1）When the square wave voltage is excited, the core flux density can exceed the saturation flux density and enter the deep saturation state, and the number of turns cannot be too small.

（2）The inductance formed by the excitation coil should not be too large. If the voltage square wave is too large, the coil turns should not be too large.

（3）The large-diameter sensor core has a large circumference. In order to reduce the magnetic flux leakage, the enameled wire can cover the iron core substantially when winding. The outer diameter of the enameled wire should be as large as possible. It is preferred to use an enameled wire of 0.1mm or more. Small aperture sensors can be wound in multiple layers.

（4）The oscillation frequency of excitation voltage shall not be too low, which will slow down corresponding speed of the sensor. Generally, the leakage current is a slow variable, and the frequency shall be higher than 10Hz.

Therefore, in order to make the iron core deeply saturated, and the oscillation frequency is higher than 10 Hz, the number of excitation coil turns is 3000, and the enamel line of $\phi_q = 0.1\,\text{mm}$ or above is selected for winding.

### 3.3 CIRCUIT PARAMETER DESIGN

The excitation voltage of square wave is also the power supply voltage of the operational amplifier, namely $U_P = 25\,\text{V}$, which cannot be directly connected to the MCU for measurement, otherwise it will cause damage to the MCU port. The shaping circuit composed of $R_5$, $R_6$ and PNP transistor Q1 as shown in Figure 1 can be used. The resistor $R_6$ is connected at one end to the emitter of the triode and at the other end to the MCU power supply voltage. When the square wave output is high, the triode is off, the shaping circuit output high point is flat, the voltage amplitude is MCU power supply voltage; When the square wave output is low level negative voltage, triode on, shaping circuit output is low level, voltage amplitude is 0V, meet the MCU input requirements.

An input button S1 is installed to set the zero point of sensor. When the measured DC current is 0 A, the duty cycle of present excitation voltage square wave is recorded as the system zero point when the button is pressed.

## 4. EXPERIMENTAL VERIFICATION

According to the design, the experimental platform is set up, as shown in Fig. 3. The platform adopts stm32 chip development board as the duty cycle measuring equipment, square wave signal is directly connected to the chip input capture port, and the time interval between the up and down jumps of the waveform is directly measured by the 32-bit timer inside the chip. To improve the measurement accuracy, the internal clock of the chip is set to 216MHz. The platform uses KEITHLEY 2461 source meter as the measured reference current.

In the experiment, the measured reference current range is 0-42 A, and 32 sets of current values are selected for measurement. The experimental results are shown in Fig. 5. The measurement equation is obtained by linear fitting:

$$D = 0.94711I + 48.926 \tag{11}$$

According to the fitting equation and the duty cycle data captured by the MCU, the magnitude of the measured current can be calculated and the function of measuring the DC current is realized.

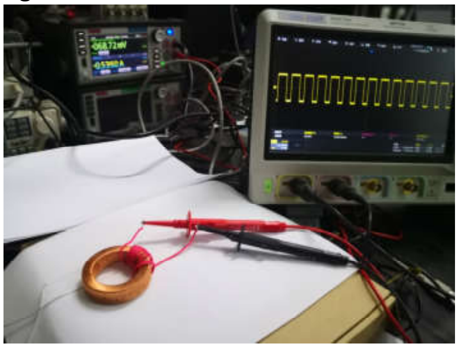

Fig.3 Testing Platform

The measurement error of sensor can be obtained by comparing the calculated current value with the actual measured current value. As shown in Fig. 5, the maximum absolute error is 90 mA, and the sensor accuracy is 0.2%, which meets the design accuracy. It can be found from the distribution of the error that since the magnetic permeability of the core is non-linear, the error will increase as the current to be measured increases. If it is necessary to improve the linearity and accuracy of the sensor, a zero-flux scheme can be considered.

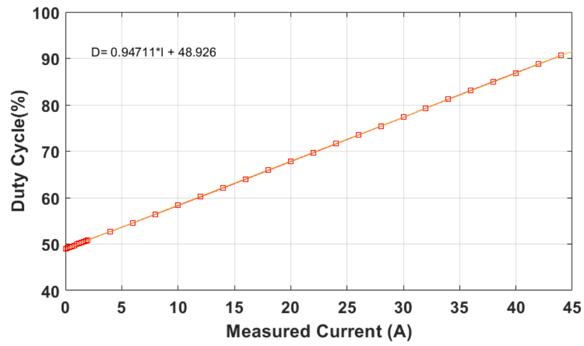


Fig.4 Experimental Data and Fitting Curve

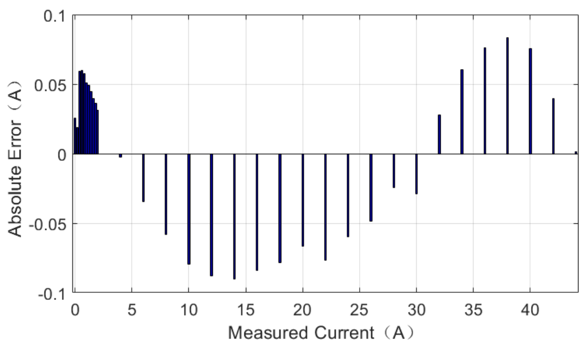


Fig.5 Absolute Error of the Sensor

## 5. CONCLUSION

An electric vehicle charging billing DC current sensor is designed by using the magnetic modulation scheme of the duty cycle model. The measurement accuracy is high and the stability is good. Due to the full digital design, the measurement circuit is less interfered by the external electromagnetic environment, suitable in places with complicated electromagnetic environment such as new energy vehicle charging piles. The sensor also can be applied in leakage current measurement of DC system, stray current monitoring of pipelines and other occasions. If the magnetic shielding layer could be added to the outer layer of the sensor, the zero-flux design scheme can be used to further improve the measurement accuracy and stability.

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