Research and Experiment on Field Warning Device of Non-contact Type

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Abstract. In order to better understand the power frequency electric field around the transmission lines and device, this study introduces the mathematical measuring principle of one-dimensional spherical sensor for electric field, analysis the theoretical feasibility whether the ball-type sensors could be replaced by the parallel plate capacitive sensor and discuss the effects of different sizes of parallel plate capacitive sensor for electric field measurements and then complete the design of sensor. The design of overall system and operating principle of the safety warning instrument are introduced and the relevant hardware and software circuit design are completed. After debugging, a high voltage electric field measuring based on the C8051F410 microcontroller is designed. In the 750kV substation and transmission line space below, the measured data have greater relevance with good usability after comparing the foreign standards and the instruments designed.

Introduction

Measurement of electromagnetic field has a very important position among many scientific and engineering fields which is becoming a very effective means of scientific research especially in the power industry, for example insulation structural optimization of high-voltage electrical equipment, condition monitoring and electromagnetic compatibility of power system, and electromagnetic environment around the transmission lines, etc [1-6]. With the improvement of the voltage level as well as the development of the high voltage engineering, measurement of electromagnetic field technology has become the focus of the power industry research.

Electric field strength in some areas of the power frequency electric field around the high-voltage substations, transmission lines and other equipment is often higher than the value of 5kV/m [7], the national standards. For the staffs who are working in the transformer substation as well as near the high voltage transmission line, the accurate measurement of the electric field strength is quite important in order to guarantee the safety of the operating personnel.

There are usually two methods to determine the electric field strength, the calculation and the measurement. At present the calculation methods include charge simulation method, boundary element method and finite difference method, etc [8]. However, in some complex environments such as severe surface contamination, surface corona and to-discharge process, it becomes more accurate and convenient to use the method of measurement. Therefore, this paper would design and develop an inexpensive, durable and non-contact measuring device which is used in high voltage electric field for safety warning. This paper studies and designs the non-contact electric field sensor, and on this basis, develops a field warning device. Its function is to alarm and warn the staff to be away from the danger zone when the electric field strength is higher than the preset field strength.

Principles

A hollow metal spherical shell is divided into two parts to be the two electrodes of the sensor ball, the upper section and the lower section. The hollow section is bonded together with the insulating material. In the interior of the sensor, the two electrodes are connected by a measuring capacitor.

When the electric field is perpendicular to the two hemispheres face of the spherical sensor, the two electrodes would induct electric charge. The voltage which could be the measurement signals is induced in the measuring capacitor [9-10]. The model structure diagram of one-dimensional spherical sensor is shown in Figure 1.

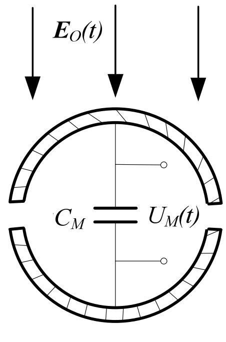

Fig. 1 One-dimensional spherical sensor

The equivalent coordinate system of spherical sensor is built and shown in figure 2. Assume that there is a point charge. The charge is *q(t)* which locates in the point *q(0, 0, d)*. The center of the sphere of spherical sensor coincides with the coordinate origin *O* and the radius of sensor is *R*. According to the mirror method, there will be a mirror charge $q_1(t)$ which is the opposite polarity to the point charge *q(t)* at the position *B(0, 0, b)*; and there will also be a mirror charge $q_2(t)$ which is the same polarity to the point charge *q(t)* at the position *O*. Choosing a point *A(R, θ, Φ)* on the outer surface of the spherical shell and the distance between point A and *q(t)*、$q_1(t)$、$q_2(t)$ are r_1、r_2、*R*.

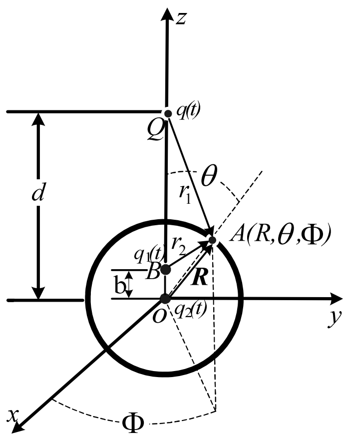

Fig. 2 Equivalent coordinate system of spherical sensor

Set $c=R/d$, $b=cR=R^2/d$, the electric field strength of point *A* is obtained according to the superposition theorem as below:

$$E_A(t)=\frac{1}{4\pi\varepsilon_0}\left[\frac{q(t)}{r_1^2}\boldsymbol{e}_{r_1}+\frac{q_1(t)}{r_2^2}\boldsymbol{e}_{r_2}+\frac{q_2(t)}{R^2}\boldsymbol{e}_{r_3}\right]. \tag{1}$$

By the model, *d* is the distance between the center of the ball and the point charge *q(t)*. *R*, θ, Φ are the coordinate of point *A*. ε_0 is the permittivity of vacuum. Therefore, the formula (1) can be simplified to:

$$E_A(t)=\frac{q(t)}{4\pi\varepsilon_0 dR}\left[1+\frac{c^2-1}{\sqrt{\left(1+c^2-2c\cos\theta\right)^3}}\right]. \tag{2}$$

According to the calculation formula of electric field of point charge, the electric field strength of point *O* before the sensor is put at the measure point is:

$$E_O(t)=\frac{q(t)}{4\pi\varepsilon_0 d^2}. \tag{3}$$

Then:

$$E_A(t)=\frac{E_O(t)d}{R}\left[1+\frac{c^2-1}{\sqrt{\left(1+c^2-2c\cos\theta\right)^3}}\right]. \tag{4}$$

According to Gauss's law, the relationship between charge density and field strength of point A is:

$$\sigma_A\left(R,\theta,\Phi,t\right)=\varepsilon_0 E_A(t). \tag{5}$$

Then the charge density of spherical shell surface σ_A is [11]:

$$\sigma_A(t)=\frac{\varepsilon_0 E_O(t)}{c}\left[1+\frac{c^2-1}{\sqrt{\left(1+c^2-2c\cos\theta\right)^3}}\right]. \tag{6}$$

When $c\to 0$, as $R\to 0$ or $d\to\infty$, the surface of the electric field sensor can be approximated as a uniform field. The expression of surface charge density can be simplified. After the integration of surface charge density along the upper hemisphere surface, the limit value of the induced charge *Q(t)* can be obtained:

$$Q(t)=\iint\sigma_A(t)dS=\int_0^{2\pi}\int_0^{\pi/2}\sigma_A(t)R^2\sin\theta d\theta d\Phi=$$

$$-3\pi R^2\varepsilon_0 E_O(t). \tag{7}$$

If there is a measuring capacitor C_M connected between the two electrodes of the ball type sensor, the voltage $U_M(t)$ of the sensor can be measured by the formula $U=Q/C$:

$$U_M(t)=-\frac{3\pi R^2\varepsilon_0 E_O(t)}{C_M}. \tag{8}$$

Therefore, when the type of one-dimensional ball sensor is used to measure the electric field, the voltage $U_M(t)$ of the C_M is proportional to the electric field strength $E_o(t)$. The electric field strength of the point can be calculated by measuring the voltage of the capacitor.

Design of Software and Hardware

Design of Sensor.

The sensor structure is shown in Figure. 3. The part 1 is the sensor support and its material is insulation of PVC. The part 2 and 3 are both metal plates as the electrodes of the sensor. And the part 4 and 5 are the electrode wire. The charge can be induced on the metal plate due to the electrostatic induction phenomenon when the sensor is placed in the electric field. According to the principle above, the surrounding electric field could be detected from the voltage difference between the two metal plates and the correction factor.

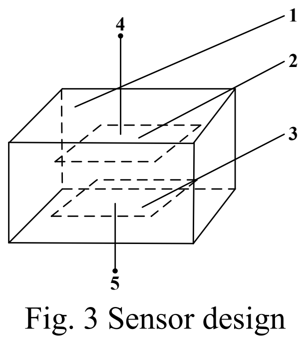

Fig. 3 Sensor design

Hardware Design.

Based on the design of the sensor, the signal is detected by differential amplification, filtering and A/D conversion, and the signal is processed and displayed in MSP430. The hardware design of the warning device is shown in Figure 4.

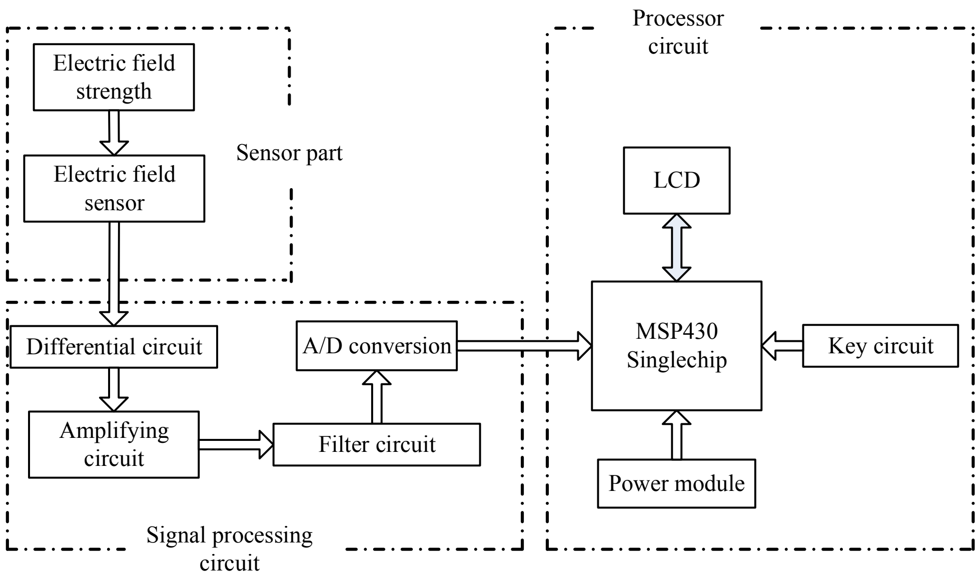

Fig. 4 Hardware circuit design of field warning instrument

Software Design.

After the hardware circuit design is finished, it is necessary to control the system using the software program. The programming software, Keil μ Vision4, is used. The main program flow is shown in Figure 5.

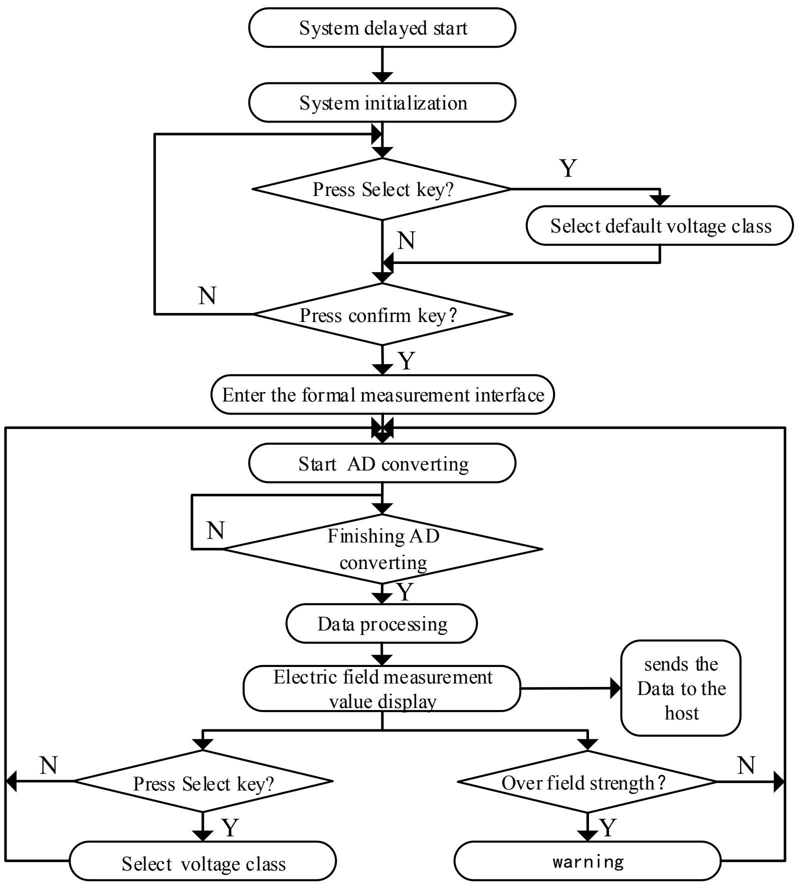

Fig. 5 The main program flow

The main work flow of the warning device is as follows: The system starts and then enters the stage of measurement initialization and gradually completes each circuit module self-test. The ADC0 part converts the voltage signal. After a sampling conversion cycle and analysis and processing of the data by the microcontroller, the electric field value is displayed in the LCD screen. If the measured voltage exceeds the upper limit of the rated voltage level, the system would alarm.

Field Test

The warning device of the electric field strength is shown in Figure 6. At the same position (the same location and the same height) of the 330kV-750kV main transformer of 750kV terminal, the designed device and the standard equipment PMM8053 is placed respectively to measure the electric field strength. The experimental data are recorded and compared to verify the accuracy of the warning device and the function of alarm.

Fig. 6 Warning device of electric field strength

At first, the standard equipment PMM8053 is placed in the main transformer 750kV, A phase near the outlet. The measuring probe is 1.40M above the ground to measure and record the electric field strength. Then the staff holds the warning device which is also 1.40M above the ground to measure the electric field strength at the same position. After several measurements and the average value is calculated. The measurement data is shown in Table 1 below.

Table 1 The electric field strength detection value of A phase 750kV main transformer from the outlet side to 1.40m

Number of measurements	Measurements (kV)	Standard values from PMM8053 (kV)	Error (kV)
1	8.202		
2	8.186		
3	8.349		
Average value	8.245	8.258	0.013

The data from the main transformer 750kV, B phase near the outlet is in Table 2 below.

Table 2 The electric field strength detection value of B phase 750kV main transformer from the outlet side to 1.40m

Number of measurements	Measurements (kV)	Standard values from PMM8053 (kV)	Error (kV)
1	7.162		
2	7.096		
3	7.214		
Average value	7.007	7.104	-0.097

Conclusions

The following conclusions can be drawn through the analysis of the results of the two experiments in table 1 and table 2:

The electric field strength from the designed device agrees well with the standard measurement, the PMM8053, within acceptable error range. It proves that the warning device of the electric field strength could accurately measure the electric field strength in the substation space;

During the experiment, the warning device of the electric field strength is set to the alarm value when measuring the electric field strength of the main transformer terminal A, B and C, the

Three-phase circuit. Under the supervision of the experimental personnel, the device could alarm when the electric field strength is over the alarm-limit. It proves that the warning device of the electric field strength could realize the function of alarm accurately.

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