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Design and Experimental Test for Non-contact Voltage Sensor of High-Voltage Transmission Line Based on Inverse Problem of Electric Field

[1]Gao Can, [1]Wang Jingang, [1]Yu Mengting, [2]Peng Hu and [2]Ma Jun
[1]State Key Laboratory of Transmission and Distribution Equipment and Power System Safety, New Technology Chongqing University, Chongqing, 400044, China
[2]Electric Power Design Institute of Chongqing, Chongqing, 401125, China

Abstract: This study proposes a new approach of voltage measurement in High Voltage (HV) grid. Modern power system has been developing to possess of large capacity, high voltage, miniaturization, digitalization and the characteristics of transmission and distribution system automation. The traditional electromagnetic voltage transformer can not meet the measurement requirements of the smart grid, because of these problems of low accuracy in static and dynamic range, ferromagnetic resonance occuring due to the over-voltage and output short-circuit. The designed electronic voltage transformer of new principle is that it measures electric field around the wire through the quasistatic electromagnetic field model and then it use the inverse problem of electric field to calculated the voltage value around the wire. The new electronic voltage transformer can not only solves the problems of the tradition electromagnetic voltage transformer but also access miniature and non-contact digital measurement. The error influenced by electric field distortion was analyzed and validated by the actual experiments. Experimental results showed that the effective value of detected voltage is precise and the distortion of voltage shape is small. The proposed sensor is suitable for detecting voltage of HV transmission and transformation equipment and mildly influenced by electric field distortion.

Key words: High voltage transmission lines, electronic sensors, electric field inverse problem, non-contact

INTRODUCTION

Modern power system has been developing to possess of large capacity, high voltage, miniaturization, digitalization and the characteristics of transmission and distribution system automation. Traditional electromagnetic sensor has been unable to provide a guarantee for the development of the power system with problems of hysteresis, magnetic saturation, inability of the open secondary circuit, low linearity, low accuracy in static and dynamic range which cannot meet the requirement of the smart grid construction nowadays (Xu *et al*., 2010). Electronic transformer has the incomparable advantages than traditional electromagnetic transformer and positive significance for the construction of smart grid, for it provides an important assurance for the safe and stable operation of digital substation with its accuracy of signal measurement and operational stability. From a global perspective, the electronic voltage transformer has been a hot topic of researches nowadays which is the key equipment of digital power system, digital substation and digital power plant. And it is the new direction of development of the future transformer technology. In addition, there are several problems in the new energy development of large-scale wind power grid, such as voltage rapid fluctuation, flicker and the high order harmonics. Therefore, it is essential to study the new methods about the monitoring of voltage and current in wind power generation system in order to meet the needs of measuring the current and voltage signals of wide dynamic range in the background of large-scale wind power grid (Ji *et al*., 2010). Therefore, the new principle of electronic voltage transformer's research and development inevitably has a great perspective and strategic significance. This study puts forward a method that induced charge is used to measure electric field and then makes the electric field inverse problem calculation to test new type voltage transformer. Moreover, the study measures the electric field intensity around the conductor to gain the potential value of the conductor.

PRINCIPLES OF SENSOR DESIGN

Calculation principle of field inverse problem: It can be solved by using the charge simulation methodfor the calculation of the inverse problem that it can get the wire

Corresponding Author: Gao Can, State Key Laboratory of Transmission and Distribution Equipment and Power System Safety, New Technology Chongqing University, Chongqing, 400044, China

voltage through the electric field around the wire. In the charge simulation's equivalent model, first it needs to calculate the quantity of charge simulation. As it can not directly get the quantity of charge simulation by solving the equation. So, according to the square method that solving the inverse problem is replaced by solving extremal problem. Suppose that a nonlinear operator is F(q), the quantity of charge simulation size is q and electric field intensity in the measuring point is E. The inverse problem is:

$$E = F(q) \quad (1)$$

Corresponding the equation of least square method is:

$$\min_{q \in Q} \|E - F(q)\|^2 \quad (2)$$

In engineering of actual measurement, in order to get the accurate field distribution around the power lines,the number of measuring points should be more than the number of the charges simulation. So, the Eq. 2 is the overdetermined equation. The nonlinear and least squares problems shown as Eq. 2, can use piecewise linear iterative algorithm to solve. Firstly, the nonlinear operator F should be approximated and when $\|\delta_q\|$ is sufficiently small:

$$F(q + \delta q) \approx F(q) + \frac{\delta F}{\partial q}\delta q \quad (3)$$

thus, a linear relationship is obtained between δE and δq:

$$\delta E \approx \frac{\delta F}{\partial q}\delta q \quad (4)$$

As for the least squares problem of Eq. 2, the necessary condition for q to be minimum is that it is the gradient in q is g(q) = 0:

$$g(q) = \nabla\phi = [F(q) - E]\frac{\partial F(q)}{\partial q} = 0 \quad (5)$$

Then the minimum value of q is obtained through Hessian matrix to calculate the objective function:

$$\phi = \|E\text{-}F(q)\|^2 \quad (6)$$

Finally, it can get the electric potential ϕ, thus, get the voltage U.

The electric field is affected little by the adjacent phase and objects on the ground for nearby the transmission line. Therefore, the electric field distributed regularly around the transmission line. So, the calculation of the inverse problem only require one-dimensional. The sensor is placed at a fixed position near the transmission line. We can get electric field strength values through the charge induced values which are measured by the sensor. Finally, the electric field strength values are used to get the surface potential of transmission line through the algorithm of inverse problem.

Once a sensor is located in an alternative electric field, induced charge will be created on its surface. Then we put measuring capacitor C_M between electrodes of the transducer and regard the capacitor voltage $U_M(t)$ which is generated by induced charge on measured capacitor as the measuring signal. The relationship between voltage $U_M(t)$ and electric field $E_0(t)$:

$$E_0(t)=\frac{U_M(t)C_M}{3\pi R^2\varepsilon_0} \quad (7)$$

E_0 = Electric field intensity
R = Radius of the transducer

Form Eq. 7 shows that, the electric field intensity $E_0(t)$ where is at the location of the sensor can be calculated by the voltage $U_M(t)$ which is from the sensor of measuring capacitance. In practical engineering measurement, the length of high voltage transmission line is much greater than the distance between sensor and line. So, we can regard the transmission line as an infinitely long straight line and set the electric potential of infinity as zero. Relationship between the quantity of electricity on the transmission line and field intensity at the position P of the sensor can be expressed in Yu (2007):

$$q(t)=\int_P^\infty E_0(t)2\pi\varepsilon_0\rho dl \quad (8)$$

where, ρ is the distance between wire and sensor.

Taking the Eq. 7 into 8, we can get q(t) through capacitor voltage $U_M(t)$ which is measured by the sensor:

$$q(t)=\int_P^\infty \frac{U_M(t)C_M}{3\pi R^2\varepsilon_0}2\pi\varepsilon_0\rho dl \quad (9)$$

According to the electromagnetic field theory,the electric potential of the conductor surface ϕ(t) is proportional to q(t). The electric potential of the conductor surface can be converted into the wire's voltage U(t):

$$U(t) \propto \int_{P}^{\infty} \frac{U_M(t)C_M}{3\pi R^2 \varepsilon_0} 2\pi\varepsilon_0 \rho dl \quad (10)$$

In conclusion, through calculating the inverse problem, electric potential of the line can be obtained by the voltage measured in sensor. In this method, there is no electrical connection between the sensor and transmission line. Without the consideration of insulation against ground, it realized a miniaturization and non-contact digital measurement.

DESIGN OF THE SENSOR DEVICE

Design of hardware structure: The sensor model design is shown in Fig. 1 which is equipped with the main plate of the sensor, a signal acquisition and processing board, the wireless transmission module and a data receiving terminal.

Compared with the parallel plate type, box-type structure, etc., the front of the sensor adopted semi-cylindrical structure for the sensor plate. With the high-voltage transmission line passing through the center of the sensor, we can not only accurately calculate the surface charge and electric field, but also roughly calculate the distortion effects. And the sensor for this structure has an advantage of a relatively small distortion (Liu, 2012).

The Workflow of this sensor: Firstly, the current which got by the induced charge on the sensor plates is converted to the voltage signal. Secondly, we use the differential amplifier AD620 to amplify the signals. The AD620 can do well in the high cmrr for the weak voltage signals. Secondly, we use the low-pass filter to filter the high-frequency waves and the cutoff frequency is 1 kHz. Thirdly, we put the signals into the MCU to convert into the digital signals (AD conversion). The data sampling frequency is 12 kHz. Finally, the voltage data is transmitted by the WiFi module and the receiver. The rate is 1 Mbps. The rate meet the requirements of data transfer. After the Receiver receives the data message, we can do secondary data conversion and data processing. And then, it output the digital and analog signals to the secondary equipment (Yu, 2007).

Process of voltage calculation: With the above structure, the following derivation processes should be made to achieve a measured voltage. Figure 2 is Derivation process of voltage sensor numerical. We put the measuring sensor in wire nearby and induced charge σ should be measured by electrostatic induction; get the induced voltage on the capacitor measurement and amplify it, then filter it and then We can get measuring induced digital voltage (U_d) by A/D converted digital; Using Eq. 7, the U_d should be converted to the measuring point number field E and then go to calculate the inverse problem for getting the amount of charge on the wire (q). Finally, we can get the wire potential (ϕ) and the measured voltage (U).

Error analyses of sensor design: The sensor which is made of metal, can cause the movement of its surface charge when in electric field, consequently results in a distortion of the electric field around. So, in electric field measurement, we should consider how to reduce the distortion of previous field effected by the introducing of sensors into the measured field (Yu, 2007). It will be analyzed as following.

It was shown in Fig. 3, put the spherical sensor which is made of metal, in an infinite uniform electric field. The electric field strength which is unaffected by the distortion electric field is E_0, the permittivity of infinite space is ε_1, the permittivity of sensor filled with dielectric constant of the insulation material is ε_2, the radius of the sensor is r_0, the distance between M which is an outer point of the sensor and the origin O is r and the angle of the electric field direction is θ:

$$\begin{aligned} \overrightarrow{E_r} &= E_0 \cos\theta \frac{\varepsilon_2 - \varepsilon_1}{2\varepsilon_2 + \varepsilon_1} \cdot \frac{2r_0}{r^3} \overrightarrow{e_r} \\ \overrightarrow{E_\theta} &= -E_0 \sin\theta \frac{\varepsilon_2 - \varepsilon_1}{2\varepsilon_2 + \varepsilon_1} \frac{r_0^3}{r^3} \overrightarrow{e_\theta} \end{aligned} \quad (11)$$

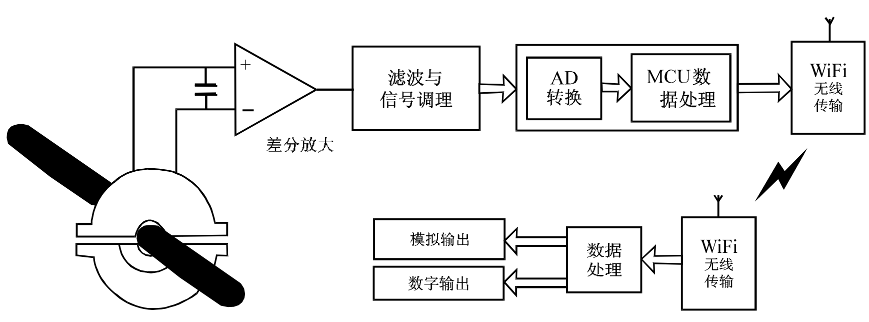


Fig. 1: Structure model of voltage transformer

When θ = 0, the value of electric field distortion reaches the maximum:

$$E_r = 2E_0 \frac{\varepsilon_2 - \varepsilon_1}{2\varepsilon_2 + \varepsilon_1} \frac{r_0^3}{r^3} \tag{12}$$

As for a specific sensor, according to Eq. 9, ε_1 and ε_2 are constants and the size of r_0/r determines the electric field distortion. So, if electric field distortion is tend to be smaller, we must select a smaller sensor radius r_0 and adjust the distance r farther. In practical measurement, in order to control the electric field distortion caused by errors within the specified range, you should try to use the small size of the sensor (Liu, 2012).

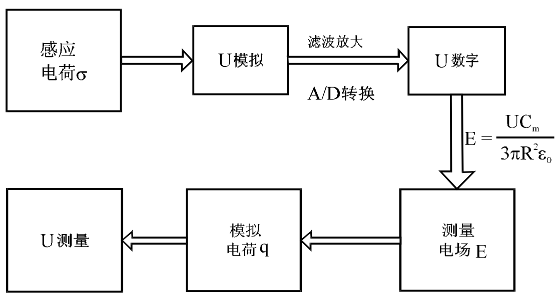


Fig. 2: Derivation process of voltage sensor numerical

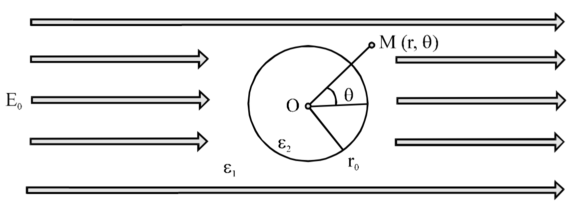


Fig. 3: Spherical sensor in a uniform electric field

MODEL TESTING AND DATA ANALYSIS

High voltage test platform: In order to verify the measurement accuracy of the sensor, we established a high pressure test platform, shown in Fig. 4. The voltage controlling box control the output voltage of boost transformer and the transformer output connect a copper line that is treated as a transmission line, in order to ensure the uniform distribution of the electric field (Thomson *et al*., 1988). External sensor owning measuring circuit can show the electric field values or voltage virtual value. And we take use radio transmission technology of transferring the signals to receiving device (Qian, 2004). Test should be taken in two steps: First, the voltage sensors should be placed at different distances from the transmission line for electric field measurement test (effective voltage) and aberration test; second, we make use HV probe of testing the voltage waveform synchronously and the accuracy test.

Test of electric field and distortion affect: By using the high-pressure test platform and change the distance between the sensor and transmission line (40, 60 and 80 cm), make it slow to adjust the output of the transformer according to test requirements, every time progressive value is 1 kV (from 3-10 kV). The average field strength values which the standard detection devices and sensors measured should be recorded and the field

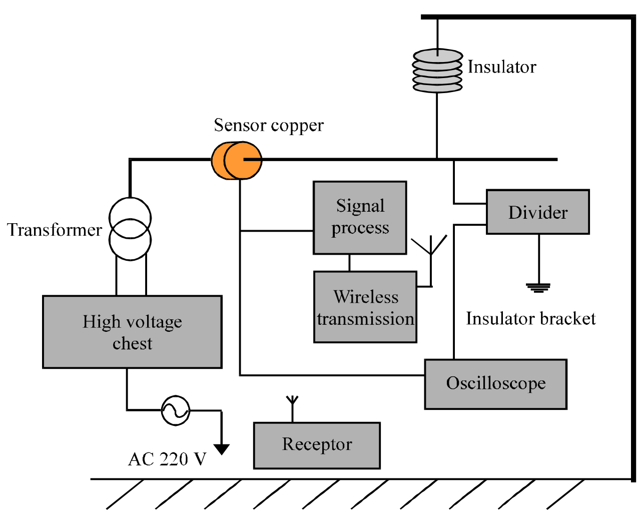


Fig. 4: Test platform of high voltage

strength values correspond to the field source (high voltage wire) voltage effective values. By this test, we can not only verify the relationship between the voltage and field strength but also get that electric distortion has impact on the accuracy of field strength which is measured by the sensor in different distance. The results are shown in Fig. 5.

It is a linear relationship between the applied voltage and field strength which is measured for every distance (40, 60 and 80 cm). The slope of relation curve doesn't change much under different distance which indicates the sensor's performance distorts a little bit according to distance variation.

The electric field distortion affects little and the effect is in the range of allowable error. With getting the voltage measured values and the electric field measured values, it can verify that the method that measuring the electric field intensity based on charge induction methods and then backstepping the voltages is feasible.

AC voltage test comparison test: The appearance of the designed a voltage sensor model is shown in Fig. 6. The sensor is a cylindrical, inner and outer material both are copper and middle is epoxy resin. The sensor should be set in the copper wire and fastened above, then adjust the transformer with the input AC voltage of 10 kV and it

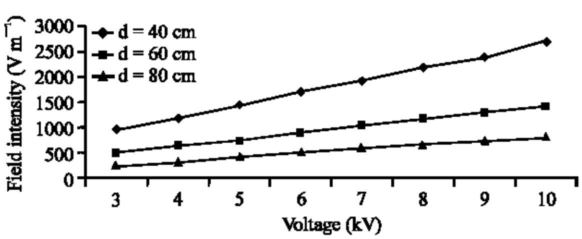


Fig. 5: Mathematical relationship between electric field strength and voltage of different distances

means for measuring the sensor by detecting the output voltage waveform. And then we use the detecting device to measure output voltage waveform of the sensor. We also make use HV probe of testing the voltage of transformer's output synchronously. Finally, the two waveforms are displayed on the handheld oscilloscope as follows (Feser *et al*., 1988).

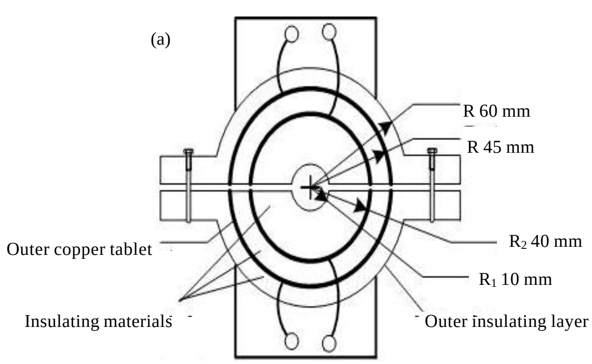
Then, we compare the sensor voltage waveform and the actual measured waveform by divider, we also compare the relative amplitude and phase of the two to verify the accuracy of the sensor voltage measurement. The type of the high voltage probe model is Tektronix P6015A, with the time base accuracy of 0.75% and the vertical accuracy of 1.5% (Schwab and Pagel, 1972). The output signal can be used as a test standard comparison.

The waveform shown in the Fig. 7 is a 10 kV AC voltage waveform and the voltage divider is measured sensor output waveform. Compared with the sensor waveform (CH1) and the measured waveform divider (CH2), it can be seen that the CH1 waveform distortion is smaller and so are the phase error and the voltage RMS error.

Conductor output voltages were the 2, 5, 10, 20, 40, 60, 80 and 120% of 10 kV rated voltage, namely 0.2, 0.5, 1, 2, 4, 6, 8 and 12 kV. We use an oscilloscope to measure the sensor output voltage U_s and divider voltage U_d. After the U_s are converted into absolute measurement values,we calculate the errors of value and phase between two instruments. Table 1 at different voltages, the voltage sensor accuracy test results with a divider ratio of 100:1.

From the above test results show that:

- The waveform distortion of sensor is low and the error between the measured effective value and actual value is up to1.4%, the average error is 0.59%. The data is measured in different voltages and its square error of the linear regression equation is



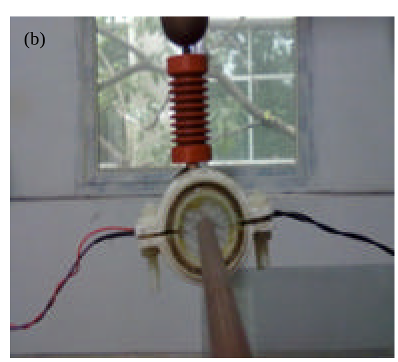


Fig. 6(a-b): Structure and appearance of transducer (a) Internal and (b) External structure

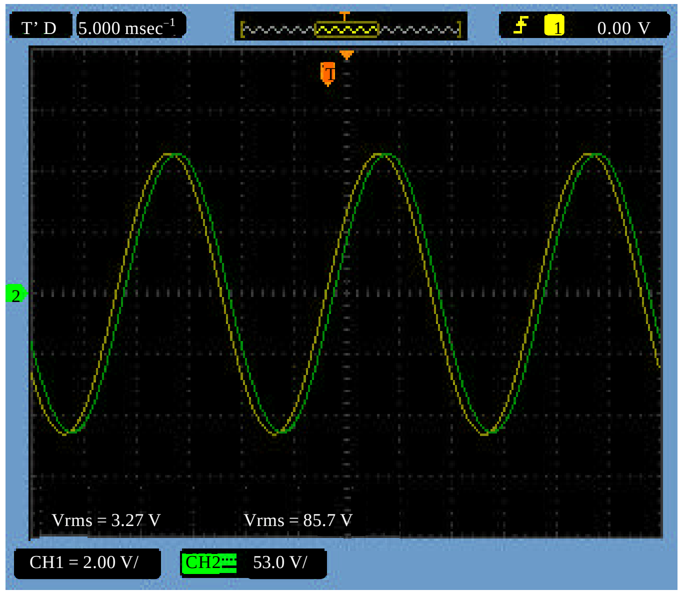


Fig. 7: Comparison of a 10 kV AC voltage waveform

Table 1: Accuracy test results of transducer

Measurements points (%) U_n	Us (kV)	Ud (V)	Difference (%)	Angle difference (θ')
2	0.214	0.163	1.40	22
5	0.512	0.382	0.78	24
10	1.018	0.758	0.61	17
20	2.000	1.517	0.99	21
40	3.987	3.021	0.89	22
60	6.120	4.612	0.30	21
80	8.033	6.041	0.11	18
100	10.050	7.563	0.11	18
120	12.138	9.133	0.16	19

0.0144 which indicates that the sensor measuring voltage and the actual voltage is kept strictly linear relationship

- The phase error data from Table 1 can be seen, there is a certain phase deviation between the two and the error range from 17'-24'. The reasons for the problems that the phase error is a little big: (1) Oscilloscope has a certain phase error, (2) The oscilloscope reading artificially have large errors and (3) The sensor works by capacitor inducting charge, so there is an inherent phase deviation
- According to the IEC60044-7, during the rated voltage range form 80-120%, the design transducer's precision can satisfy the measurement standard which is 0.5 level

CONCLUSION

By the calculation inverse problem of electric field, a electronic voltage sensor is designed based on the inverse problem of the electric field. Experimental results show that the voltage sensor affected by the electric field distortion is small, the precision of measured voltage virtual value is high and the measured voltage waveform distortion is small. Research methods and the designed voltage sensor have a certain value in use and further research value but there are still some problems in waveform phase. The sensor can be seen as a new member of the family of electronic transformer. Not only the development of electronic transformer provides a new direction but also to further improve the electronic voltage transformer theory. Further research will be conducted in sensor structure, phase compensation and digitization optimization, so that it can meet the design requirements.

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