STUDY ON VOLTAGE MEASUREMENT BASED ON LEAKAGE CURRENT OF CAPACITIVE EQUIPMENT

Du Lin. Huang Xu
State Key Laboratory of Power Transmission Equipment and System Security and New Technology, Chongqing University,Chongqing, Country
*Email: <dulin@cqu.edu.cn>

Abstract: This paper proposed a voltage measurement method based on the leakage current of capacitive equipments. The leakage current of capacitive equipments is detected by a high precision wide-band current sensor. The current signal is converted into voltage signal by an active integrator. The equivalent circuit of the capacitive equipment and the transfer function between output voltage and leakage current are analyzed. The principle and influential factors of the current sensor are also studied. The amplitude-frequency characteristic of the output voltage is improved by using an active integrator. Experimental results of frequency voltage and switching over-voltage indicate that the voltage sensor has good precision and linearity, and it can be used to measure the voltage of high voltage power grids.

1 INTRODUCTION

Field experience shows that most of electrical equipment insulation faults are caused by overvoltage[1]. Waveforms and parameters of overvoltage are quite essential for analyzing the cause of power system accident and can be used to improve the insulation coordination[2-3].

The key for overvoltage's precisely measurement is to obtain accurate voltage signal[4]. The electromagnetic potential transformer can't reflect the real waveforms of power grid voltage, because the iron core of electromagnetic potential transformer will saturated under highvoltage. the output waveform will disformed and the transient response will be bad. High voltage divider has high accuracy and good transient response[5]. But there will be some potential insulation risks, for the divider will endure the voltage of bus bar[6]. The external voltage sensor in series with the capacitive equipment can obtain voltage signal[7]. The structure of this method is simple, but it may cause open circuit of the ground wire and cause spark. Another method based on capacitive current can only measure impulse overvoltage[8], and its frequency response is narrow. This paper presents a method of wideband voltage measurement, which is suitable for measurement of voltage in high-voltage power grid. By detecting the leakage current of capacitive equipment, and the voltage waveform of the bus bar can be reconstructed.

2 THE BASIC PRINCIPLE OF VOLTAGE MEASUREMENT

2.1 Capacitive equipment

Some high-voltage electrical equipment in power substation are capacitive equipments, such as coupling capacitors, bushings, current transformer and capacitive voltage transformer[9]. The equivalent circuit of capacitive equipment under AC voltage is shown in Figure 1.

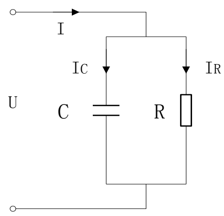


Figure 1: Equivalent circuit of capacitive equipment

In Figure 1, C and R are parallel capacitor and resistor. I_C and I_R are capacitive current and resistive current flowing through the dielectric. δ is the dielectric loss angle.

2.2 Structure and working principle

Measurement system includes a capacitive apparatus, a current sensor and an integrator. The structure is shown in Figure 2.

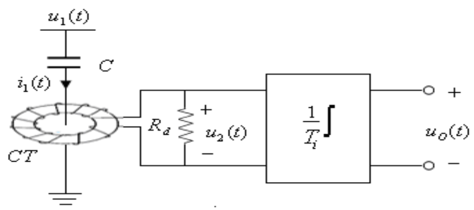


Figure 2: The ideal circuit model of voltage sensor

In Figure 2, C is the equivalent capacitance of the bushing. CT is a current sensor. R_d is an integral resistor of the current sensor.

When $u_1(t)$ is applied to the bushing, the insulation leakage current is:

$$i_1(t) = C\frac{du_1(t)}{dt} \qquad (1)$$

If the transfer ratio of the current sensor is k_m, the voltage on R_d is:

$$u_2(t) = k_m C\frac{du_1(t)}{dt}R_d \qquad (2)$$

After the integrator whose integral constant is T_i, the output voltage is:

$$u_O(t) = \frac{1}{T_i}\int u_2(t)dt = \frac{k_m C R_d}{T_i}u_1(t) \qquad (3)$$

Because k_m, C, T_i and R_d are constants, the output voltage of the voltage sensor is linear to the applied voltage. The equivalent voltage divider ratio of the sensor is $T_i/(k_m C R_d)$. So, it's feasible to obtain the grid voltage by measuring the leakage current of the capacitive equipment. The voltage sensor has simple structure and good safety performance because there is no direct connection between the sensor and the high voltage system.

3 ANALYSIS OF PARAMETERS THAT WILL AFFECT THE CURRENT SENSOR

A lot of factors can affect the accuracy of the measurement. This paper mainly analyses how the parameters of capacitive equipment, current sensor and integrator affect the performance of our design.

3.1 Parameters of capacitive equipment

The equivalent circuit of capacitive equipment is shown in Figure 1. The transfer function of capacitive equipment is:

$$H_1(s) = \frac{I(s)}{U(s)} = sC + \frac{1}{R} \qquad (4)$$

If the current sensor is an ideal one, the transfer function between output voltage and grid voltage is:

$$H(s) = \frac{k_m C R_d}{T_i} + \frac{k_m R_d}{T_i R s} \qquad (5)$$

The amplitude-frequency characteristic of the voltage sensor is:

$$|G(j\varpi)| = \frac{k_m R_d}{T_i R}\sqrt{\frac{1}{\varpi^2} + (RC)^2} \qquad (6)$$

When the grid voltage is working frequency voltage, the tangent of dielectric loss $\tan\delta$ equals $1/(\varpi \mathrm{RC})$, then,

$$|G(j\varpi)| = \frac{k_m C R_d}{T_i}\sqrt{1 + (\tan\delta)^2} \qquad (7)$$

When the frequency is high:

$$|G(j\varpi)| = \frac{k_m C R_d}{T_i} \qquad (8)$$

At frequency voltage, $(\tan\delta)^2 << 1$.So, Equation (7) equals Equation (8).

3.2 Parameters of the current sensor

The equivalent circuit[10-11] of the current sensor with magnetic core coil is shown in Figure 3.

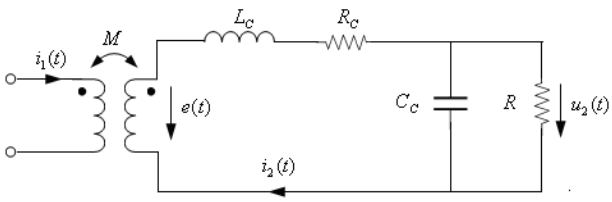


Figure 3: Equivalent circuit of current sensor

In Figure 3, $i_2(t)$ is the induced current flowing through the coil. M, L_c, C_c and R_c, respectively are mutual inductance， self inductance, distributive capacitance and internal resistance of the coil. $u_2(t)$ is the voltage across the integral resistor.

The transfer function of the current sensor which is at zero state is:

$$H_2(s) = \frac{U_2(s)}{I_1(S)} = \frac{Ms}{L_C C_C s^2 + (R_C C_C + \frac{L_C}{R})s + (1 + \frac{R_C}{R})} \qquad (9)$$

The transfer function of the voltage sensor is:

$$H(s) = \frac{MC}{L_C C_C T_i}\frac{s}{(s - s_1)(s - s_2)} \qquad (10)$$

In Equation (10) $\alpha = (L_C + R R_C C_C)/(2 L_C R C_C)$, $\beta = \sqrt{(R + R_C)/(L_C C_C R)}$, $s_{1,2} = -\alpha \pm \sqrt{\alpha^2 - \beta^2}$.

From Equation (9) and (10), we can discover that the transfer function of the current sensor and the voltage sensor are the same in the form. They are both second-order oscillation element. Their unit step responses are double-exponential in the time domain.

From Equation (10), we can get the lower cut-off frequency of the voltage sensor:

$$f_L = R/2\pi L_c \qquad (11)$$

The bandwidth and measurement error of the voltage sensor are related to the parameters of the coil. So in order to fulfil the voltage sensor's stability, dynamic performance, bandwidth and measurement error, we should choose appropriate parameters.

3.3 Parameters of the integrator

Figure 4 is a Circuit diagram of basic analog integrator. R_i and C_i are respectively the integral resistor and integral capacitor. The role of resistor R_f is to reduce the DC gain and output offset. And it can effectively inhibit the integration drift and prevent the output saturation.

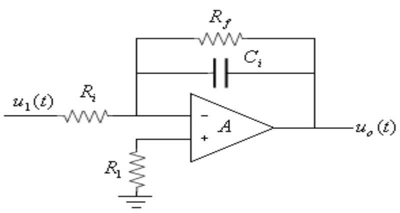


Figure 4: Circuit diagram of basic analog integrator

The transfer function of the integrator is:

$$H_3(s) = -\frac{R_f}{R_i} \cdot \frac{1}{1+R_f C_i s} \qquad (12)$$

The transfer function of the voltage sensor is:

$$H(s) = -\frac{kC_s R_f}{R_i} \cdot \frac{s}{1+R_f C_i s} \qquad (13)$$

The time domain expression of the voltage sensor's unit step response is:

$$G(t) = -\frac{kC_s}{T_i} \exp\left(-\frac{t}{R_f C_i}\right) \qquad (14)$$

From Equation (12), the integrator is an inertia element. R_f should be much larger than R_i in order to reduce integrated error. From Equation (14), the unit step response is a decaying exponential function, so we can reduce integrated error by choose larger C_i and R_f.

From Equation (11), the lower cut-off frequency of the voltage sensor relates to the integral resistor of the current sensor. If we replace the R in Figure 3 with the R_i in Figure 4, the lower cut-off frequency can be reduced because the resistance of R_i can be very small.

3.4 Error analysis

3.4.1 Current error

In actual measurement, the current flowing through the coil contains capacitive current, resistive current and surface leakage current. Among them, the capacitive current occupies the largest proportion, and the larger capacitance of the equipment is, the larger the proportion will be. “Preventive Test Code for Electric Power Equipment” provides that dielectric loss tangent of running capacitive bushing (110kV-500kV) shouldn't be larger than 0.8%~1.0%. Under overvoltage, capacitive current will be much larger. At this point, capacitive equipment can be approximately equivalent to a pure capacitor. After analysis and test, we discover that the magnitude error caused by insulation resistance is less than 1%, and the phase error is less than 2 degrees. They can meet the requirements of engineering measurement.

A slip ring placed at the bottom of the equipment's external insulation can bypass the surface leakage current. Therefore it can eliminate the affects of the surface leakage current.

3.4.2 Error caused by the change of capacitance

The change of capacitive equipment's capacitance is the main factor of amplitude error. “Preventive Test Code for Electric Power Equipment” provides that the change rate of running bushing's equivalent capacitance should be less than 5%. It's possible to correct the capacitance with preventive test measurements.

3.4.3 Error caused by electromagnetic interference

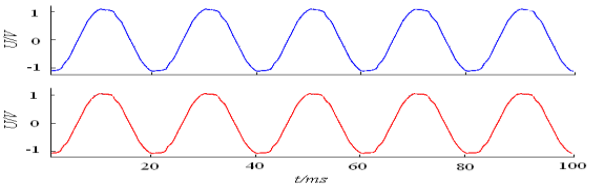
When conducting field measurements， the electromagnetic shielding of the current sensor, the integral circuit and the power supply should be strengthened. The waveform should be digitalised at the measurement site so that the signal won't be interfered during the transmission.

4 RESULTS AND PROSPECT

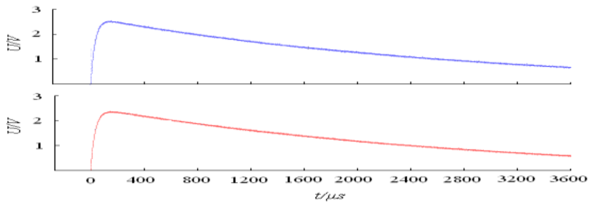
4.1 Measurement of frequency voltage and switching over-voltage

In order to verify the measurement principle， frequency voltage and switching over-voltage measurements have been carried out. The model of frequency test transformer is YDTW-2000/500. This transformer's output voltage is 20-200kV. Switching over-voltage is produced by a 2400kV/260kJ impulse voltage generator. The generator's output voltage is 110-330kV. The capacitance of the capacitive bushing's main capacitor is 497pF. MWF400-1600 capacitive divider is used as reference measurement system. The divider's voltage divide rate is 518.3. The output of the standard divider is connected to channel 1 of Tektronix 5052B oscilloscope, and the output of the voltage sensor is connected to channel 2.

Figure 5(a) is the output waveform of frequency voltage. Figure 5(a) is the output waveform of 145/1940μs switching over-voltage. The upper part is the output of the standard divider, and the lower part is the output of the voltage sensor.

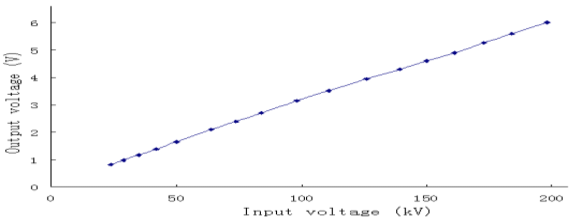


(a) Waveforms of frequency voltage measurement

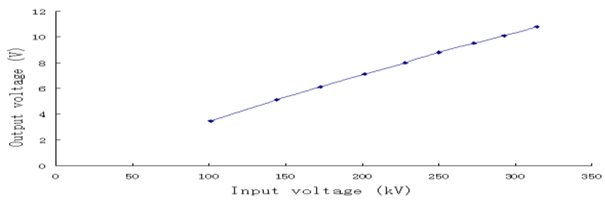


(b) Waveforms of switching over-voltage measurement

Figure 5: Waveforms measured by voltage sensor



(a) Amplitude of output frequency voltage



(b) Amplitude of output switching over-voltage

Figure 6: Linearity characteristic of voltage sensor

In Figure 6(a), input voltage is 20-200kV frequency voltage. The linear fitting degree between input and output R^2=0.9993. In Figure 6(b), input voltage is 110-330kV switching over-voltage. The linear fitting degree between input and output R^2=0.9989.

4.2 Sensor calibration and analysis of measurement results

When the standard divider and the voltage sensor have the same input voltage, the ratio of the standard divider' output voltage to the voltage sensor's output voltage is the voltage sensor's calibration factor. According to the experimental data, the calibration factor of the voltage sensor used in our experiment is 28500.

Table 1 and Table 2 list the frequency voltage and switching over-voltage data that is measured using the method of this paper. From Table 1, when the input voltage is 24-200kV, the deviation of output is between ±1%. The angle difference increases as the input voltage increase.

Table 1: Experiment data of AC voltage measurement by voltage senor

No.	Output of divider (kV)	Output of sensor (kV)	Deviation (%)	Angle difference (^{0})
1	24	24.225	0.94	0.43
2	64	64.125	0.20	0.71
3	111	111.5	0.45	1.12
4	161	161.03	0.02	1.45
5	198	198.08	0.04	1.80

From Table 2, in switching over-voltage experiment, the relative error of the peak is between ±2%. Deviation of time parameters is between ±3%. So this voltage sensor has good performance, and it can meet the engineering requirements.

Table 2: Experiment data of switching impulse measurement by voltage senor

No.	Peak voltage			wave-head time deviation /%	time-to-half value deviation /%
	Divider	Sensor	Deviation		
	kV	kV	%		
1	101	102.6	1.582	0.685	0.515
2	172.5	173.85	0.783	0	0.516
3	228	228	0	0.69	1.033
4	273	270.75	0.824	0	1.7
5	314.4	312.08	0.748	1.667	0.622

4.3 Prospects for measuring lightning overvoltage

If the input is lightning impulse voltage, the peak current flowing through the capacitive equipment can be as large as several hundred amperes, and the peak frequency can be 2MHz. The amplifier of the integrator will be damaged because its input will overrange. In order to overcome this difficulty, we can replace the active integrator with a passive integrator. Figure 7 is the circuit of a third-order passive integration.

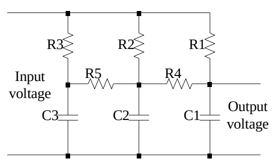


Figure 7: Circuit of a third-order passive integration

By using a passive integration lightning impulse overvoltage can be obtained. The measurement of lightning impulse has been simulated in Pspice. Picture 8 is the simulation result.

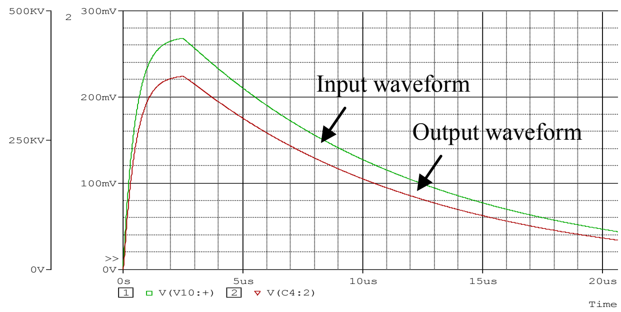


Figure 8: The simulation result of lightning impulse's measurement

But the passive integration can't measure AC voltage because the input power of AC voltage is too small. A double-coil sensor may solve this problem. One coil is connected with an active integrator to measure AC and switching over-voltage and the other one is connected with a passive integrator to measure lightning impulse voltage. Then the sensor's output is the sum of the output of the two integrators. This measurement method is what we need to study next.

5 CONCLUSION

A new method of power grid voltage and overvoltage measurement based on leakage current of capacitive equipment is raised up by the authors, and the measurement is achieved by using a current sensor. This paper has analysed the transfer function of the current sensor, the approach to broaden the band and the factors that can affect the accuracy of the measurement. To measure in this way is simple and convenient, and the wiring of the equipments won't be changed. The results show that frequency voltage and switching over-voltage can be precisely obtained by using this method.

6 ACKNOWLEDGMENTS

This work is supported by Chongqing Natural Science Foundation. The project No. is 2005BA6021.

7 REFERENCES

[1] Sun Caixin，Sima Wenxia，Zhao Jie， et al． Over-voltage in UHV transmission system[J]. Electric Power Automation Equipment，2005，25(9)：5-9(in Chinese).

[2] Yao Chenguo，Sun Caixin，Mi Yan，et al. An on-line monitoring system for over-voltage of distribution network[J]. Automation of Electric Power Systems，2004，28(9)：74-76(in Chinese).

[3] Hou Kai, Zhang Tao, Dong Xiucheng, et al. On-line Monitoring of Overvoltage in Power Distribution Network Based on the Capacitance Divider[J]. Automation of Electric Power Systems，2007，31(21)：86-89(in Chinese).

[4] DU lin, LIU Wei-ming, SIMA Wen-xia, et al. Power Grid Voltage Measurement Based on the Leakage Current of Capacitive Equipments[J]. Automation of electric power system, 2008, 32(19):67-76

[5] Zhang Renyu, Chen Changyu, Wang Changzhang, et al. High Voltage Test Techniques[M]. Tsinghua University press, 2003(in Chinese).

[6] Sima Wenxia，Lan Haitao，Du Lin，et al．Study on response characteristic of voltage sensor mounted at the tap of transformer bushing[J]． Proceedings of the CSEE，2006，26(21)：172-176(in Chinese).

[7] Lan Haitao，Sima Wenxia，Yao Chenguo，Yang Qing．Study on Data Acquisition of voltage online monitoring system of high voltage power grid [J]． High Voltage Engineering，2007，33(3)：79-82(in Chinese).

[8] Ren Wenzhu, W.Zaengl. The Capacitance-Current Method of H.V. Impulse Measurement [J]． High Voltage Engineering, 1991,(4):12-15 (in Chinese).

[9] Wang Nan,，Chen Zhiye, Lu Fangcheng．A survey of on-Line monitoring and diagnosis for capacitive equipment[J]． Power System Technology, 2006,26(21) ： 172-176(in Chinese).

[10]Bao Hai，Yang Yihan．Research on the control method of wide range measurement current transformer[J]．Proceedings of the CSEE，2003， 23(10)：67-71(in Chinese)

[11]Li Weibo，Mao Chengxiong，LiQiyan，et al．Simulation research on rogowski coils with SGIII high-power laser[J]．Proceedings of the CSEE，2003，23(5)：53-57(in Chinese).