1  |  INTRODUCTION

The measurement of transient voltage is an important part of insulation coordination in power systems. The important role of transient voltage measurement lies in the fact that it directly affects the insulation design, overvoltage protection and faults analysis.

With the wide application of power electronic equipment in extra-high voltage (EHV)/ultra-high voltage (UHV) power grids, such as high voltage direct current (HVDC) converter [1], voltage source converter-HVDC converter [2] and HVDC circuit breaker [3], there is an urgent need for new method of transient voltage measurement.

The power electronic equipment is composed of power electronic components in series connection and supporting components. For example, an UHV-HVDC conversion equipment is composed of a number of power electronic components together with grading capacitor, matrix output amplifier (MOA), cooling system and smoothing reactor [4]. This equipment will be subject to various transient voltage during operation and testing [5, 6]. In order to ensure the reliability and safety of the equipment, it is necessary to study the technical measures for uniform distribution of transient voltage along the equipment [7]. To this end, in the design stage of the equipment, the simulation of the potential distribution is required. The goal of simulation is to find out the factors affecting potential distribution and the technical measures to optimize the design [8, 9]. Compared with the model used for simulation, the actual structure of the equipment is much more complex. In addition, some subsystems of the equipment such as cooling system for high voltage (HV) power electronic components are more difficult to describe in digital simulation. Therefore, the results of the simulation need to be verified by direct measurement during typical testing of the equipment. In addition, an important technical measure to ensure the safety of equipment in operation is the online monitoring. In order to achieve the on-line monitoring of the insulation conditions of the equipment, it is also necessary to study new method for measuring the potential distribution along the equipment [5]. Because the existing conventional measuring equipment, such as capacitive divider, has a large capacitance to the ground, using this type of measuring equipment for contact measurement will disturb the original potential distribution, resulting in unrealistic results. In order to achieve non-disturbing measurement of the potential...
distribution, new measuring device with very small capacitance to the ground needs to be studied. It seems that the wireless sensors are likely to be a possible solution.

With the development of modern information and communication technology, wireless sensors have been widely used in smart distribution networks [10, 11]. At the same time, wireless sensors for high voltage measurement have been also developed in recent years. In a recently published review, the optical fibre sensors are considered to be a powerful method for reliable sensing in harsh environments [12]. The wireless sensor is particularly suitable for the detection of electrical equipment characteristic state parameters. In recent years, the application of wireless sensors for measuring critical parameters of HV substation has been widely carried out. Some of the most challenging studies are closely related to the applications of wireless sensors.

Because of the presence of space charge, the measurement of electric field under HVDC lines is a challenging task. A wireless sensor network-based distributed measurement system is designed for monitoring the electric field under HVDC transmission lines [13]. The proposed system is composed of a group of wireless nodes with electric field sensors and a base station for data processing. This system can realize accurate and stable electric field measurement and monitoring.

Remote monitoring of critical parameters, such as current flowing through the conductor of HV equipment is a challenging task. A new approach has been developed to measure the current flowing in HV substation using non-contactable hall sensors and wireless communication [14]. The hall effect sensor produces a voltage signal proportional to the current in the conductor. Then the voltage signal is transmitted to the remote server. This approach is used to achieve reliable and cost-effective, wireless monitoring of critical parameters of HV substation.

Monitoring of partial discharge (PD) activity within high voltage electrical environments is critical for the assessment of insulation condition. A wireless sensor network is proposed [15] that utilizes only received signal strength to locate PD within HV substation. The network comprises low power and cost-effective radiometric sensor nodes which receive the radiation from a source of PD. The results obtained place the measured location within 2 m of the actual source location.

From the above research results, we can see that the increasing convergence of high voltage technology with modern information and communication technology is an important development trend of modern power grids. The wireless sensors are likely to be promising solution for HV measurement in difficult environment.

In order to realize the non-disturbing measurement of transient voltage in EHV/UHV power grids, an equipotential shielding voltage sensor (EPS-VS) is proposed in this study. This voltage sensor is designed based on ‘equipotential shielding technique’ which was proposed by the authors to improve the performance of high voltage capacitive voltage transformer [16]. The design goal of the proposed voltage sensor is to develop a new type of voltage sensor with the following innovative technical features:

i. Regardless of where the sensor is installed, its measurement accuracy and stability remain largely unchanged

ii. When used in an EHV/UHV substation, the sensor is able to resist strong electromagnetic interference from surrounding objects

iii. This sensor has very wide frequency bandwidth, so it can be used to measure various transient overvoltage in power grids, such as switching impulse, lightning impulse and chopped impulse

iv. When the sensor is integrated with suitable energy-harvesting device, it becomes a battery-free wireless sensor for long-term monitoring in EHV/UHV grids

The structure and working principle of this sensor together with two design versions for engineering application are described in this study. One version of the sensor is designed as a miniaturized sensor for non-disturbing measurement of potential distribution along power electronic equipment under transient voltage. The other version is designed as a battery-free wireless sensor for online measurement and monitoring in alternating current (AC) EHV/UHV power grids. According to the design parameters, the performance of the proposed sensor is analysed and evaluated, including accuracy and stability of measurement, shielding effect against the interference from surrounding objects and the frequency bandwidth. Finally, an experimental comparison between this voltage sensor and a standard capacitive voltage divider (CVD) in HV laboratory was carried out and the results of comparison are presented.

2 | STRUCTURE AND WORKING PRINCIPLE

The schematic diagram of EPS-VS is shown in Figure 1. The measuring electrode is a metal disk connected via a specially designed capacitor $C_{M1}$ to the conductor with high voltage to be measured. $C_{M2}$ represents the stray capacitance of the measuring electrode. $C_{M1}$ and $C_{M2}$ constitute a reversed capacitive divider for voltage measurement. $C_{M1}$ is used as low voltage arm of the divider installed at high potential to produce the input voltage for transceiver. The stray capacitance $C_{M2}$ of the measuring electrode is used as high-voltage arm of the divider to withstand nearly total high voltage to be measured.

2.1 | Stable measurement

The stability of measurement by using capacitive divider mainly depends on the stable capacitance of its components. In order to achieve stable measurement results by using this proposed divider, the capacitance of its two components must remain stable in working condition. However, in general, the stray capacitance of measuring electrode is a quantity that varies with ground distance and its geometry. To prove the feasibility of this proposed divider, it is necessary to illustrate what conditions are met in order to achieve stable capacitance in working conditions.

In order to answer the above question, the capacitance of three typical measuring electrodes shown in Figure 2 are calculated by using electric field simulation program (Ansoft).
The simulation result shows that, with the increase of ground distance, the capacitance of these electrodes decreases gradually and is approaching a stable value. In addition, the diameter of these electrodes has significant influence on the downward trend of capacitance. The smaller the diameter of the electrode, the smaller the ground distance for achieving stable capacitance.

The downward trend of capacitance with the increasing ratio of ground distance to the diameter of electrode (D/d) are shown in Figure 3. In the figure, D represents the ground distance, d represents the diameter of measuring electrode.

It is clear from the Figure 3, as long as the ground distance reaches 10 times diameter of electrode, the capacitance approaches a stable value. This ground distance represents a turning point in the downward trend of capacitance. The ground distance at the turning point can be called as critical distance for simplicity in later presentation.

The calculation indicates that compared with the capacitance of an isolated electrode (representing infinity ground distance), the capacitance at the critical distance is higher than that only by 2.5%. Therefore, as long as the sensor is working at a ground distance greater than critical distance, stable measurement results by the voltage sensor can be achieved. In other words, the measurement error caused by the change of operating position of the sensor is no more than 2.5%.

During the design phase, the capacitance at critical distance (D/d = 10) is defined as rated capacitance of the divider and is used to determine the corresponding division ratio and measurement results.

In summary, the proposed voltage sensor can provide stable measurement results as long as it is operated at a height above the critical distance. The measurement error caused by the change of operating position of the sensor is not greater than 2.5%. Since the critical distance is only related to the size of the sensor, the smaller the size of the sensor, the wider its stable operating range.

2.2 | Equipotential shielding

To eliminate the interference from surrounding energized or grounded objects, an external shielding electrode is arranged as shown in Figure 1. The shielding electrode is designed as a hemispherical shell connected via capacitor \( C_{S1} \) to the conductor with voltage to be measured. The capacitance of the shielding electrode \( C_{S2} \) and capacitor \( C_{S1} \) constitute an external divider for shielding purpose. The potential of shielding electrode can be regulated by adjusting capacitance \( C_{S1} \) to the same level as measuring electrode, thus blocking capacitive current exchange via the capacitance \( C_{MS} \) between the internal and external divider.

The important role of this equipotential shielding is to ensure independent operation of internal measurement divider. Another important feature of the shielding electrode is the protection against electromagnetic interference. The shielding effect of the equipotential shielding electrode will be evaluated in Section 4.
3 | DESIGN VERSIONS FOR PRACTICAL APPLICATION

Two versions of the proposed voltage sensor are designed for engineering application. Version A of the sensor is designed as a miniaturized sensor to realize non-disturbing measurement of potential distribution along power electronic equipment. Version B is designed as a battery-free wireless sensor used for online measurement and monitoring in AC EHV/UHV power grids. The structure and equivalent circuit of these sensors are described below.

3.1 | Version A—miniaturized voltage sensor

Version A of the sensor is a miniaturized sensor used to achieve non-disturbing measurement of potential distribution along power electronic equipment for HVDC transmission such as HVDC converter and HVDC circuit breaker. In order to minimize the influence on the original potential distribution, the dimension and corresponding capacitance of the sensor should be made as small as possible. For this purpose, version A is designed as double layer small plate sensor like a sandwich cookie as shown in Figure 4.

The front part of the sensor is a measuring electrode surrounded by a shielding electrode. The measuring electrode is a metal disk with a diameter of 120 mm. The shielding electrode is a metal concentric ring with inner diameter of 140 mm and outer diameter of 300 mm. The total capacitance to the ground of the two electrodes do not exceed 5 pF, thus avoiding disturbance on the original potential distribution of power electronic equipment.

Since the diameter of measuring electrode is 120 mm, as long as the mounting height of the sensor is greater than the critical height (1.2 m in this case), the sensor will provide stable measurement results. Therefore, this sensor is ideal to be used in wide range of working height to measure the potential distribution along power electronic equipment of UHV level.

The rear part of the sensor is a steel plate attachable to the electrode with potential to be measured. The measuring circuit is placed between the front and rear plate. In order to suppress possible oscillation caused by the presence of inductance of connecting conductor, the measuring circuit of voltage sensor is designed as a resistance and capacitance (RC) divider in series connection as indicated in Figure 5. The values of the parameters in Figure 5 is shown in Table 1.

The measured signal is transmitted by a battery-powered photoelectric converter installed behind the electrode at the potential to be measured.

At present, this voltage sensor is mainly used for measurement of the potential distribution along HVDC equipment under impulse voltage during typical testing. Because the testing takes a short time, the voltage sensor combined with battery-powered photoelectric converter can meet the requirement of time duration during the testing. However, in order to achieve the goal for long-term monitoring of equipment insulation condition, it is necessary to design a battery-free wireless sensor for this purpose. An energy-harvesting device using the energy stored in the grading capacitor of HVDC converter is under development for this purpose.

3.2 | Version B—battery-free wireless voltage sensor

Version B of the sensor is designed as a battery-free wireless sensor for online measurement and monitoring in AC UHV grids. This voltage sensor is composed of three components:
i. Equipotential shielding voltage sensor
ii. High frequency transceiver for transmitting measured signal to the receiving device on the ground
iii. Energy harvesting device using capacitive coupling

The structure and equivalent circuit of this wireless sensor is shown in Figure 6.

The measuring electrode of the sensor is a metal disk with diameter of 500 mm. The shielding electrode is a metal cylinder with diameter of 1000 mm and height of 500 mm. The measuring circuit together with the transceiver are installed within the shielding electrode container as shown in Figure 7. The shielding electrode can be designed as a hemispherical shell shown in Figure 1 for ensuring corona-free performance at UHV. Due to the need to easily install the transceiver and other components within the container, the prototype of this shielding electrode is designed as a metal cylinder.

Since the diameter of measuring electrode is 500 mm, as long as the mounting height of the sensor is greater than the critical height (5 m in this case), the sensor will provide stable measurement results. In order to suppress possible oscillation caused by the presence of inductance of the connecting conductor, the voltage sensor is designed as a RC divider in series connection indicated in Figure 6. The values of the parameters in Figure 6 is shown in Table 2.

The function of the high frequency transceiver is to transmit the measured signal to the receiving device on the ground. In the design of this sensor prototype, a traditional transceiver is used, which requires around 1–2 W input power.

In order to improve the performance of the wireless sensor, it is necessary to study low power transceiver combined with feasible energy harvesting device. Ultra-wideband (UWB) communication techniques have attracted a great interest in short-range wireless communication [17]. This is due to the potential advantages of this technology, such as very low power (as low as 10 mW), high rate, immunity to multipath propagation, and low interference [18]. Further investigation is needed to develop a low power UWB transceiver for this wireless sensor.

According to the well-known electric field-based energy harvesting method [19], an energy harvesting device shown in Figure 6 is designed for providing power to the transceiver.

![Figure 6](image6.png)  
**Figure 6** Equivalent circuit diagram of version B

![Figure 7](image7.png)  
**Figure 7** Equipotential shielding voltage sensor

This device is a stand-alone capacitive divider installed close to the wireless sensor. The device is composed of an energy harvesting electrode with large capacitance and a capacitor at high potential for delivering power to the transceiver. The inductance $L_K$ is used for compensating the internal capacitive reactance. The power level that this device can provide is determined by the capacitance of the energy harvesting electrode and the operating voltage.

4 | PERFORMANCE EVALUATION

According to the design parameters of the sensor, the main performance indicators of the sensor including stability of measurement, shielding effect against interference of surrounding objects and bandwidth characteristics are analysed and evaluated as follows.

4.1 | Stability of measurement

The simulation result shows that stable measurement results can be provided by this voltage sensor as long as the sensor is
working at a height greater than the critical distance (D/d = 10). In the design stage, the capacitance at critical distance is defined as rated capacitance of the sensor and is used to determine the division ratio and measurement result. Therefore, the rated capacitance is an independent indicator of the sensor which can be verified by experimental calibration. When the sensor is installed at the critical height, the measurement results are considered as normal.

Simulation calculations show that, compared with the capacitance of an isolated electrode (representing infinity ground distance), the capacitance at critical distance is higher than that only by 2.5%. Therefore, it can be assumed that no matter where the sensor is installed, the measurement error caused by the position change does not exceed 2.5%.

In order to determine the specific measurement error caused by the change of installation position, the calculation of capacitance at this position is required.

Taking version B sensor as an example to illustrate the measurement error due to the change of installation position. For this sensor, the diameter of measuring electrode is 0.5 m and the critical height is 5 m. The capacitance at critical height is 18.342 pF. Since this sensor is designed for application in an UHV substation, the normal installation height of this sensor is about 20 m (required insulation clearance). The capacitance of the sensor is reduced to 17.912 pF at this position. Compared with the measurement result obtained at the critical height, the resulting measurement error is 2.344%. The calculation results are shown in Table 3.

Due to small geometry, the version A sensor enters the range of stable measurement from relatively low installation height. This sensor is suitable for measuring the potential distribution along a large size power electronic equipment from top to bottom.

| Electrode diameter (m) | Height (m) | Capacitance (pF) | Error (%) |
|------------------------|------------|------------------|-----------|
| 0.12                   | 1.2        | 4.851            | /         |
|                        | 10         | 4.503            | -1.703    |
|                        | 20         | 4.467            | -2.489    |
| 0.5                    | 5          | 18.342           | /         |
|                        | 10         | 18.058           | -1.548    |
|                        | 20         | 17.912           | -2.344    |

4.2 Shielding effect

Considering that version B voltage sensor is used for online measurement and monitoring in UHV grids, the typical configuration and operating voltage of UHV AC substation shown in Figure 8 is used to verify the shielding effect of this sensor.

Based on the equivalent circuit shown in Figure 9, the shielding effect against the capacitive coupling interference of adjacent phase conductor is analysed for the case when phase B conductor is energized or grounded.

As indicated in Figure 9, C_{AB} of 4.6 pF which is calculated by the same program mentioned in Section 2.1 is the calculated capacitance between the voltage sensor installed at phase A conductor and adjacent phase B conductor. Since the capacitance of C_{S1} for adjusting the potential of shielding electrode is three orders of magnitude larger than C_{AB}, the potential change of shielding electrode caused by 1000 kV interphase voltage is greatly reduced. The measurement errors caused by
TABLE 4 Errors caused by interphase capacitive coupling

|               | Phase B grounded | Phase B energized |
|---------------|------------------|-------------------|
| Ratio error (%) | -1.14            | -1.96             |
| Phase angle error (minute) | 0              | -1.63             |

the potential change of the shielding electrode are further reduced.

The ratio error and phase angle error caused by the interphase capacitive coupling are shown in Table 4.

The results of above-mentioned simulation show that due to the effect of the equipotential shielding electrode, intensive capacitive coupling interference is effectively shielded, and the measurement errors caused by interphase capacitive coupling interference is greatly reduced. This error can be ignored in the measurement of engineering application.

4.3 | Step response characteristics

Step response is the most representative characteristics to evaluate the frequency bandwidth of an electric circuit. The step response characteristics of the voltage sensor can be achieved by using simulation program according to its circuit parameters.

The equivalent circuit for step response simulation of the sensor is shown in Figure 10.

In order to suppress the oscillation caused by the presence of inductance, the voltage sensor is designed as a series RC divider instead of previous capacitive divider. The total resistance of RC divider is selected to suppress the oscillation to achieve overdamped response. The value of RC divider parameters for version A and version B sensor are shown in Tables 1 and 2 respectively. In Figure 10, L represents the inductance of the connecting conductor between the sensor and the point with voltage to be measured. In the simulation calculation, the maximum value of L is selected with 10 μH, which represents about 10 m long conductor.

The goal of the step response simulation is to verify the wide frequency bandwidth of the voltage sensors. The measurement results of a voltage sensor with wide bandwidth function should be constant over the whole frequency band covering 50/60 Hz operating voltage and transient voltage.

The step response characteristics for version B sensor are shown in Figure 11.

The results of simulation show that the amount of inductance of connecting conductor has a significant influence on the front time (rise time) of the response. The relationship between the front time of step response and the inductance of connecting conductor is shown in Figure 12.

As can be seen from Figure 12, the front time of overdamped response for the sensors together with the connecting conductor with 10 m length is about 40 ns (for version A) and 75 ns (for version B). For the same sensors without the connecting conductor (in the case of contact measurement), the front time of step response is reduced to 5 ns (for version A) and 10 ns (for version B). This means that the sensor itself has very short front time and wide frequency bandwidth which is sufficient to meet the needs of measurement of various transient overvoltage in power grids, such as switching impulse, lightning impulse and chopped impulse.

5 | EXPERIMENTAL COMPARISON WITH STANDARD CVD

An experimental comparison between the voltage sensor and standard CVD in HV laboratory was carried out to verify the performance of the voltage sensor.

5.1 | Testing circuit configuration and testing procedures

The layout of testing equipment is shown in Figure 13.

During the test, typical impulse voltages are applied to the standard CVD and the EPS-VS at the same time. The impulse
control room by using a battery-powered photoelectric converter.

Version B sensor is suspended at a height of 8 m above the ground to ensure stable measurement. In the test, a battery-powered photoelectric converter is used for transmitting the measured signal to the control room. The layout of version B voltage sensor under testing is shown in Figure 14.

5.2 | Performance comparison of EPS-VS with standard CVD

The peak voltages and time parameters are calculated according to the oscillogram obtained by the two devices.

5.2.1 | Results obtained for design version A

The comparison of measured peak voltages is shown in Table 5.

The comparison of measured time parameters is shown in Table 6.

The oscillograms measured by the two devices are represented for lightning impulse and switching impulse respectively in Figures 15 and 16.

It can be seen from the above results that the difference of measured peak voltage between version A sensor and the standard CVD is no more than ±5% and the difference of measured time parameters between the two devices is no more than ±15%. The oscillograms obtained by the two devices are very similar.

5.2.2 | Results obtained for design version B

The comparison of measured peak voltage for version B sensor with CVD are shown in Table 7.

The comparison of measured time parameters is shown in Table 8.

The oscillograms measured by the two devices are represented for lightning impulse and switching impulse respectively in Figures 17 and 18.

The above measurement results show that the difference of measured peak voltage between version B sensor and the standard CVD is no more than ±5% and the difference of measured time parameters between the two devices is no more than ±15%.

Accurate recording of chopped lightning impulse is an important indicator for describing the wide frequency bandwidth of measuring system. The comparison results for the two devices under chopped lightning impulse are indicated in Table 9. The results of the comparison show that the measurement results of the two devices are very close.

In summary, to verify the performance of the proposed voltage sensor, a comparative test between the voltage sensor and standard CVD was carried out. Several typical impulse voltages covering wide range of frequency bandwidth are used for the experimental comparison.
TABLE 5  Comparison of measured peak voltages

| Voltage type   | Applied voltage (kV) | Version A (kV) | CVD (kV) | Difference |
|---------------|----------------------|----------------|----------|------------|
| Lightning impulse | 180                  | 171.83         | 178.55   | −3.73%     |
|                | 210                  | 197.35         | 207.53   | −4.85%     |
|                | 230                  | 214.99         | 225.64   | −4.63%     |
|                | 250                  | 238.24         | 247.85   | −3.84%     |
| Switching impulse | 250                  | 242.89         | 248.17   | −2.11%     |
|                | 300                  | 288.11         | 294.46   | −2.12%     |

Abbreviation: CVD, capacitive voltage divider.

TABLE 6  Comparison of measured time parameters

| Voltage type   | Applied voltage (kV) | T1 (μs) | CVD | Difference | T2 (μs) | CVD | Difference |
|---------------|----------------------|---------|-----|------------|---------|-----|------------|
|               |                      | Version A |     |            | Version A |     |            |
| Lightning impulse | 180                  | 0.85     | 0.81| 4.94%      | 46.5     | 45.5| 2.00%      |
|                | 210                  | 0.86     | 0.81| 6.17%      | 46.1     | 45.3| 1.77%      |
|                | 230                  | 0.84     | 0.79| 6.33%      | 45.5     | 44.9| 1.34%      |
|                | 250                  | 0.86     | 0.81| 7.50%      | 45.7     | 45.05| 1.44%    |
| Switching impulse | 250                  | 219.2    | 250.6| −12.53%    | 1981     | 2270| −12.73%   |
|                | 300                  | 220.3    | 252.8| −12.86%    | 1983     | 2270| −12.64%   |

Abbreviations: CVD, capacitive voltage divider; T1, peak time; T2, tail time.

FIGURE 15  Oscillogram of lightning impulse. CVD, capacitive voltage divider.

Oscillogram recorded by the two devices are shown in Figure 19.

The results of the experimental comparison show that the difference of measured peak voltage between the two measuring devices is no more than ±5%. The difference of measured time parameters between the two devices is no more than ±15%.

According to the judgement of the authors, the possible causes of the difference in the measurement results between the two devices include:

i. The impulse voltage testing itself has dispersive nature

ii. The two devices use different methods to transmit the measurement signal to the control room. The measurement signal from the CVD is transmitted directly to the oscilloscope in the control room without passing through any equipment. The measurement signal from the voltage sensor is transmitted by using transceiver (photoelectric converter in this case) to the control room. On the path of measurement signal transmission, two time analogue-to-digital conversion are required

iii. The two devices use different method for reading the time parameters from oscillogram. The voltage sensor uses a manual reading system to achieve the time parameters, while the CVD adopts an automatic reading system

Considering the dispersive nature of impulse voltage testing and the above-mentioned influencing factors, the experimental comparison results obtained by using two different measuring devices can be considered quite close.
Such dispersion of measurement results is also permissible according to the national testing standards [20]. The experimental comparison results also prove that this voltage sensor is suitable for measuring various transient voltage in EHV/UHV power grids.
CONCLUSION

An EPS-VS is proposed to achieve effective contact measurement of transient voltage in EHV/UHV power grids. Two design versions of the proposed voltage sensor for engineering application are described.

One version of the sensor is designed for non-disturbing measurement of potential distribution along power electronic equipment. The other version is designed as a battery-free wireless sensor for online measurement and monitoring in AC UHV power grids. Based on the designed parameters, the performance of the voltage sensors is analysed and evaluated. The results of the performance evaluation can be summarized below:

i. Stable measurement results can be provided by this sensor as long as the sensor is working at a height greater than the critical height \(D/d = 10\). The measurement error caused by the change of operating position of the sensor is not greater than 2.5%. The miniaturized voltage sensor has a wide stable measurement range, enabling effective measurement of potential distribution along UHV power electronic equipment.

ii. The effective shielding capability of the equipotential shielding electrode is verified based on a typical configuration and operation conditions in AC UHV substation.

iii. Step response simulation indicates that the sensor itself has very wide frequency bandwidth sufficient to meet the needs for measuring various transient overvoltage in power grids.

In order to verify the performance evaluation, an experimental comparison between this voltage sensor and a standard capacitive divider in HV laboratory was carried out.

The comparison results indicate that the difference of measured peak voltage between the voltage sensor and CVD is no more than ±5%. The difference of measured time parameters between the two devices is no more than ±15%.

Considering the dispersive nature of impulse voltage testing and several device-related influencing factors, the experimental comparison results obtained by using two different measuring devices can be considered close. Such dispersion of measurement results is also permissible according to the national testing standards. The experimental comparison results also prove that these voltage sensors are suitable for measuring various transient voltage in EHV/UHV power grids.

In summary, through the performance evaluation and test comparison above, it is shown that the design goal of this proposed voltage sensor has been achieved.

ORCID

Jianchao Zheng https://orcid.org/0000-0002-3705-1026
Ningming Guo https://orcid.org/0000-0002-4178-3537

REFERENCES

1. Zha, K., Xiaoguang, W., Tang, G., et al.: Research and development of ±800kV/4750A UHVDC valve. 2012 Second International Conference on Intelligent System Design and Engineering Application, Sanya, Hainan, China, January, pp. 1466–1469 (2012)

2. Tang, G., He, Z., Hui, P.: Research, application and development of VSC-HVDC engineering technology. Autom. Electr. Power Syst. 37(15), 3–14 (2013)

3. Hui, P., Xiaoguang, W.: Research on key technology and equipment for Zhangbei 500kV DC grid. 2018 International Power Electronics Conference, Niigata, Japan, May, pp. 2343–2351 (2018)

4. Zha, K., Cao, J., Ouyang, W., et al.: Design of 6250A/±800kV UHVDC converter valve. 13th IET International Conference on AC and DC Power Transmission (ACDC 2017), Manchester, UK, February, pp. 1–6 (2017)

5. Xu, W., Cao, J., Xiaoguang, W., et al.: The Development and type test of ±1100KV/5000A UHVDC valve. 2012 Asia-Pacific Power and Energy Engineering Conference, Shanghai, China, March, pp. 1–3 (2012)

6. Belda, N.A., Plet, C.A., Smets, R.P.P., et al.: Stress analysis of HVDC circuit breakers for defining test requirements and its implementation, 2017 CIGRE, Winnipeg, Canada, September–October, pp. 1–11 (2017)

7. Zhao, Z.: Research on measurement technique for impulse voltage across thyristor module and its voltage distribution characteristics in a HVDC valve. PhD Thesis, Xi’an Jiaotong University (2004)

8. Sun, H., Cui, X., Qi, L., et al.: Overvoltage distribution in HVDC converter valves and analysis of influencing factors. Proc. CSEE 30(22), 120–126 (2010)

9. Zhang, W., Tang, G.: Study on wide-band model and voltage distribution of 800kV/4750A UHVDC valves. Proc. CSEE 30(31), 1–6 (2011)

10. Vikram, K., Yuvaratn, P., Venkata Lakshmi Narayana, K.: A survey on wireless sensor networks for smart grid. Sens. Transducers 186(3), 18–24 (2015)

11. Liu, Y.: Wireless sensor network applications in smart grid: Recent trends and challenges. Int. J. Distributed Sens. Netw. 8(9), 492819 (2012). https://doi.org/10.1155/2012/492819

12. Chen, W., Wang, J., Fu, W., et al.: Review of optical fibre sensors for electrical equipment characteristic state parameters detection. High. Volt. 4(4), 271–281 (2019)

13. Cui, Y., Lv, J., Yuan, H., et al.: Development of a wireless sensor network for distributed measurement of total electric field under HVDC transmission lines. Int. J. Distributed Sens. Netw. 2014, 1–9 (2014)

14. Chakradhar, A., Mallikarjuna Rao, P., ManiPatro, G.: Remote monitoring of critical parameters of HV substation. Int. J. Eng. Res. Technol. 6(10), 653–656 (2019)

15. Upton, DW, Saeed, BI, Khan, U., et al.: Wireless sensor network for radiometric detection and assessment of partial discharge in HV equipment. XXXIInd General Assembly and Scientific Symposium of the International Union of Radio Science (URSI GASS), Montreal, QC, Canada (2017)

16. Zheng, J., Bo, L., Dong, W., et al.: Design of an equipotential shielding 1000 kV capacitor voltage transformer. CSEE J. Power Energy Syst. 6(2), 419–426 (2020)

17. Tim, S., Stadelmayer, M., Faseth, T., et al.: A review of ultra-low-power and low-cost transceiver design, 25th Austrochip Workshop on Microelectronics (Austrochip). Linz, Austria, October, pp. 29–34 (2017)

18. Varachiou, N., Benamrouche, B., Noudert, J.L., et al.: Application specific integrated circuit (ASIC) for an energy efficient impulse radio ultra-wideband transceiver. Testing and statistic assessment, 2018 International Semiconductor Conference (CAS), Sofia, Romania, October, pp. 169–172 (2018)

19. Guo, F., Hayat, H., Wang, J.: Energy harvesting devices for high voltage transmission line monitoring. 2011 IEEE Power and Energy Society General Meeting, Detroit, MI, USA, July, pp. 1–8 (2011)

20. DL/T 1351-2014: Guide for Transient Over-Voltage Measurement and Recording System Used in Electric System. (2015)