

Research Article

Simulation Analysis of Transient Earth Voltages Aroused by Partial Discharge in Switchgear

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Abstract: The authors investigated the properties of Transient Earth Voltages (TEV) Aroused by Partial Discharge in Switchgear by Simulation. The mechanism of TEV aroused by partial discharge in switchgears is analyzed. The Finite Integration Theory (FIT) was employed to simulate the propagation of TEV in the switchgear. The simulation results show that the pulse width of TEV increases as the pulse width of PD pulse increases and the amplitude of TEV is proportional to the PD pulse amplitude. There are time differences between the TEV signals of different detecting points when the TEV propagating on the switchgear's surface. Based on the simulation, a method of locating the PD of switchgear is proposed by positioning multi-sensors on the external surface of switchgear.

Keywords: Finite Integral Theory (FIT), Partial Discharge (PD), PD location, switchgear, Transient Earth Voltages (TEV)

INTRODUCTION

The switchgear is the key equipment of the urban distribution network and its operational reliability is closely related to the security and stability of the power system. In view of the important position of switchgears in the distribution network, Technical Specifications of Electric Power Apparatus released by the State Grid Corporation in 2010 made clear provisions of the substation switchgear, which required on-line detection in switchgear. The specification pushes the maintenance work of the switchgear to the state repairs.

Primary means of on-line testing of switchgear include infrared thermal image detection, ultraviolet, ultrasonic partial discharge detection and Transient Earth Voltage (TEV) detection (Reid *et al.*, 2011; Liu *et al.*, 2009; Wang *et al.*, 2011; Zhang *et al.*, 2005). TEV detection has been widely received by the operation and maintenance personnel in the power system due to its ease to operate.

The TEV detection was first proposed by British Dr. John Reeves in 1974 (Reeves, 1987). It is detecting the internal discharge phenomenon by detecting the transient earth voltage on the outer surface of the switchgear. In the UK, the technology has been widely used for 30 years in field application (James *et al.*, 2004; Davies and Jones, 2008). However, the domestic research started late. It is not until recent years that a number of colleges and universities began related studies (Cheng *et al.*, 2012; Ren *et al.*, 2010).

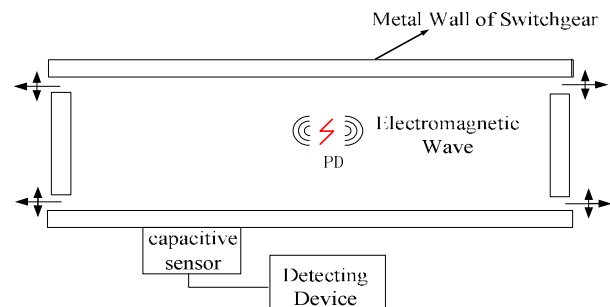


Fig. 1: Measuring principle of TEV

In this study, the basic principle of the TEV detection technology, as well as excitation and propagation characteristics of TEV signals has been researched systematically.

The basic principle of the transient earth voltage detection: Discharge inside the switchgear includes surface discharge, internal discharge and point discharge of high-voltage electrodes. In the discharge process, frequencies of electromagnetic waves excited by the PD pulse are up to several GHz (Wang *et al.*, 2012; Zheng *et al.*, 2011). A transient earth voltage is produced on the metal casing of the device and it can be detected by a special capacitive sensor installed on the outer surface of the device. Thereby, the PD situation inside the switchgear can be obtained. The principle of TEV detection is shown in Fig. 1.

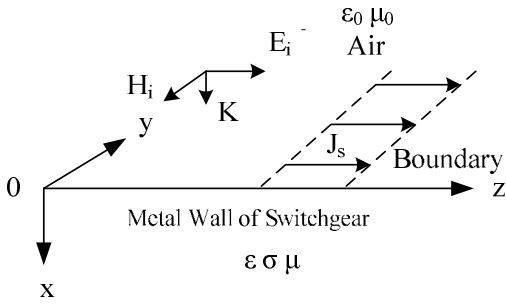


Fig. 2: Mechanism of TEV on switchgear surface

The principle of TEV formation is described in Fig. 2, showing PD electromagnetic waves incident on the interface of the air and the metal wall of the switchgear. Defining a plane between the air ($x < 0$) region and the metal wall of the switchgear ($x > 0$).

Assume the air permittivity and permeability is ϵ_0 and μ_0 , respectively and the air characteristic impedance is μ_0 .

Assume that the strength of the electric field on the $x = 0$ plane is:

$$E = \bar{z}E_0 \quad (1)$$

For the electromagnetic waves propagating along the x direction in the air, their electric and magnetic fields magnitude is:

$$E_i = \bar{z}E_z = \bar{z}\epsilon_0 e^{-j\beta x} \quad (2)$$

$$H_i = -\bar{y}H_y = -\bar{y}\frac{\epsilon_0}{\eta_0} e^{-j\beta x} \quad (3)$$

β is the phase constant of an electromagnetic wave:

$$\beta = \omega\sqrt{\mu_0\epsilon_0}, \eta_0 = \omega\sqrt{\mu_0/\epsilon_0} \quad (4)$$

The dielectric constant and magnetic permeability of the metal wall of the switchgear is ϵ and μ , respectively and the conductivity is σ . The skin depth of electromagnetic wave in conductors is δ and the propagation constant is γ :

$$\gamma = \frac{1+j}{\delta}, \delta = \sqrt{\frac{1}{\pi f \mu \sigma}} \quad (5)$$

Wave equation of the electric field in a conductor is as follows:

$$\frac{d^2 E_z}{dx^2} - \gamma^2 E_z = 0 \quad (6)$$

Induced current density in conductors can be expressed as:

$$J_z = \sigma E_z \quad (7)$$

Assume the electric field parallel to the surface of the conductor (the tangential electric field at $x = 0$) is E_0 , we can obtain:

$$J_z = \sigma E_0 e^{-x/\delta} e^{-jx/\delta} \quad (8)$$

As is shown in Fig. 2, the total current of the unit area in the metal plate on the YOZ plane is:

$$I_z = \iint J_z \cdot ds = \frac{\sigma \delta E_0}{1+j} \quad (9)$$

The surface impedance of the unit area on switchgear metal wall is:

$$Z_s = R_s + jX_s = \frac{1+j}{\sigma \delta} \quad (10)$$

When a partial discharge occurs inside the switchgear, the high-frequency electromagnetic wave excited by the partial discharge is incident on the surface of the metal wall and excites surface currents. When the TEV sensor is mounted on the outer surface of the switchgear, the pulse voltage can be detected, i.e., TEV signal.

SWITCHGEAR PARTIAL DISCHARGE SIMULATION ANALYSIS

The switchgear simulation model: In this study, full-wave 3D electromagnetic simulation software CST based on finite integral (FIT) is used to simulate the generation and dissemination of TEV signals of switchgear surface. It provides a theoretical basis and technical guidance for on-line switchgear detection.

As is shown in Fig. 3, the overall size of the XNG15-12-type switchgear is $500 \times 1000 \times 1600$ (mm), including A: $500 \times 1000 \times 1250$ (mm) and B: $500 \times 1000 \times 350$ (mm) two spaces.

The 1:1 simulation model according to geometric dimensions of the switchgear shown in Fig. 3 is built, as is shown in Fig. 4. The two internal spaces A and B of the switchgear are mutually independent, as is shown in the front and back side in Fig. 3. Set slits for the leakage of electromagnetic wave. The slit width is 2 mm and slit position is shown in Fig. 3.

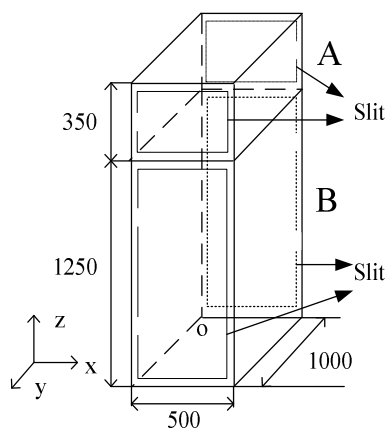


Fig. 3: Dimension of switchgear XNG15-12

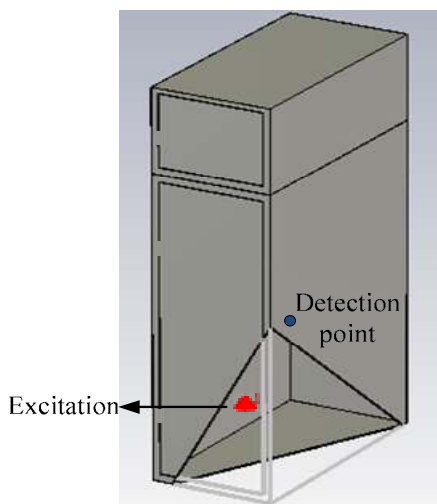


Fig. 4: The simulation model of switchgear XNG15-12

PD excitation source can be simulated by Gaussian current pulses. The time domain form of Gaussian current pulses is:

$$i(t) = I_0 e^{-(t-t_0)^2/2\sigma^2} \quad (11)$$

σ is the time constant, determining the pulse width; I_0 is the pulse peak.

Analysis of simulation results:

- **The effect of PD source frequency on TEV signals:** As is shown in Fig. 4, create a simulation model of the switchgear in accordance with the dimensions shown in Fig. 3 and set the partial discharge excitation source in the internal coordinate (250,500,250) of the switchgear. In addition, set up TEV detection points at the outer surface (500,900,550) in the switchgear.

In order to study the relation of TEV signal and PD source signal frequency, make the Gauss current pulse the excitation source, whose amplitude is 1A and time constants are 0.4ns, 0.6 ns, 0.8ns, 1ns, 2ns, 3ns, 4ns and 5ns. The excitation source waveform is shown in Fig. 5.

Due to the above parameters of the simulation, you can get TEV signals excited by PD excitation sources of different frequencies. Figure 6 shows the TEV pulse time-domain waveform obtained by the detection points when time constant of the excitation source is 0.2 ~ 5ns. Amplitude of the TEV signal is shown in Table 1.

The curve of the relationship of the TEV signal amplitude (TEV amp) and the time constant

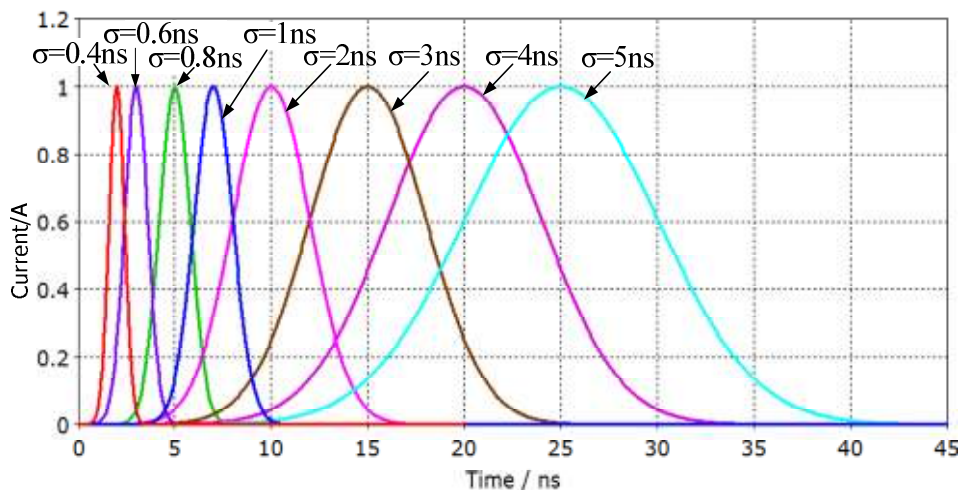
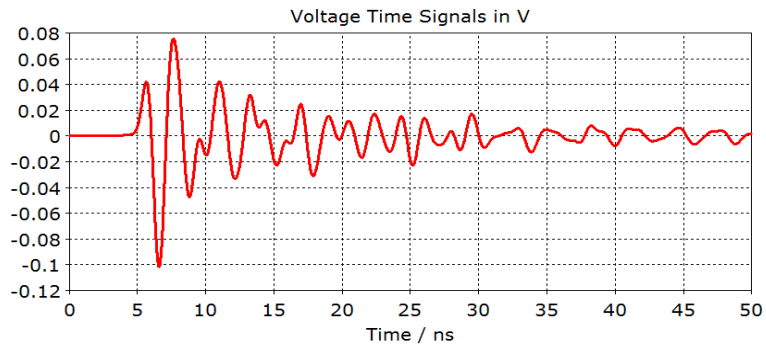
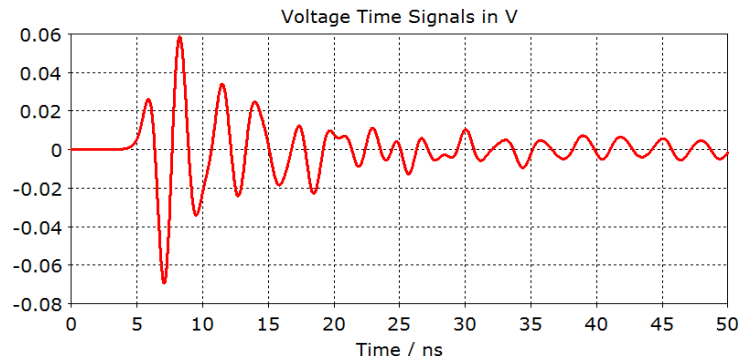


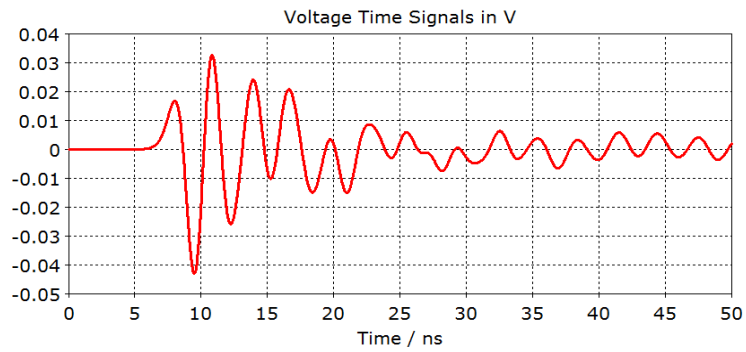
Fig. 5: Excitations waveforms with pulse width variation



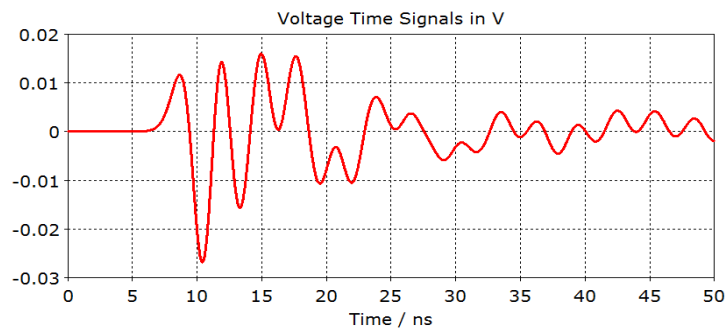
(a) $\sigma = 0.4\text{ns}$



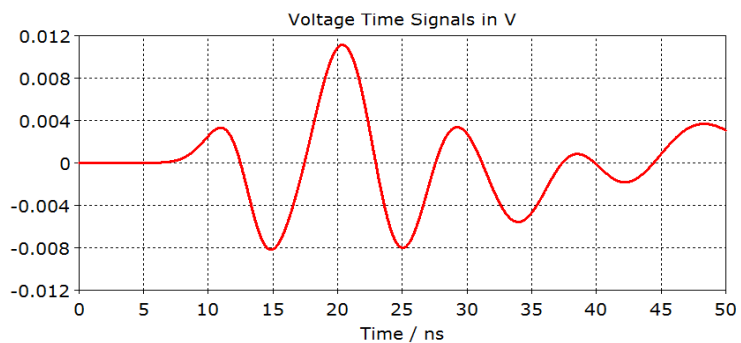
(b) $\sigma = 0.6\text{ns}$



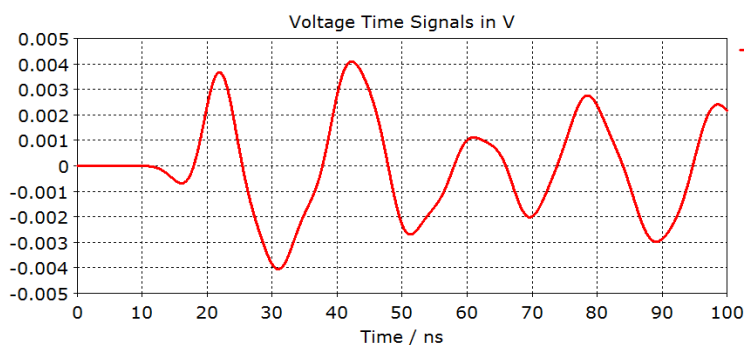
(c) $\sigma = 0.6\text{ns}$



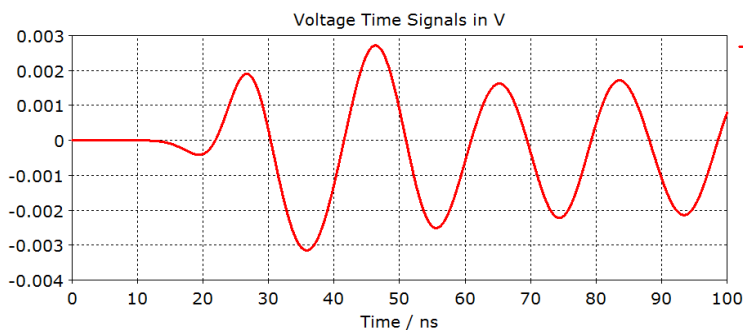
(d) $\sigma = 1\text{ns}$



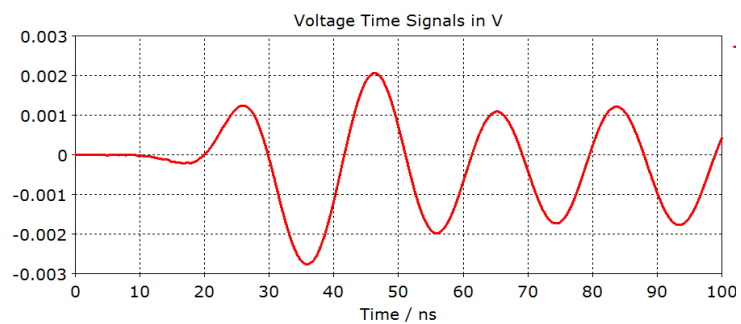
(e) $\sigma = 2\text{ns}$



(f) $\sigma = 3\text{ns}$



(g) $\sigma = 4\text{ns}$



(h) $\sigma = 5\text{ns}$

Fig. 6: Waveforms of TEV with pulse width variation

Table 1: Amplitude of TEV with pulse width variation

σ (ns)	0.4	0.6	0.8	1.0	2.0	3.0	4.0	5.0
TEV amp (mV)	175.1	126.4	75.0	43.2	19.3	8.3	5.8	4.9

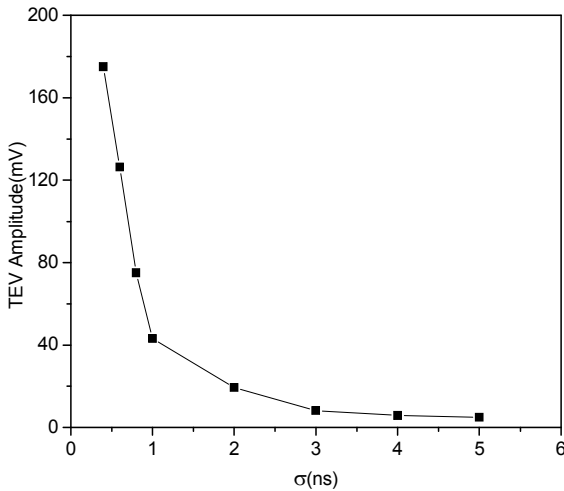


Fig. 7: Curve of TEV amplitude with pulse width variation

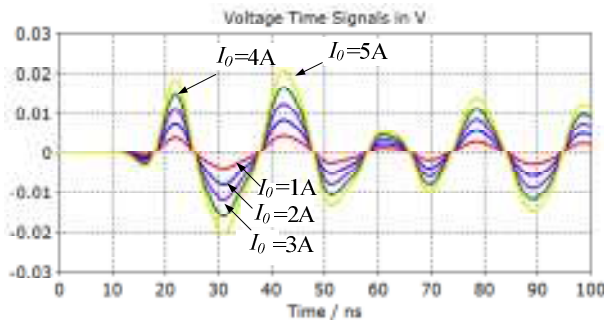


Fig. 8: Waveforms of TEV with pulse amplitude variation

Table 2: Amplitude of TEV with pulse amplitude variation

Excitation amplitude (A)	1.0	2.00	3.00	4.00	5.00
TEV amplitude (mv)	5.5	11.0	16.5	22.0	27.5

of excitation source can be obtained corresponding to Table 1, as is shown in Fig. 7.

From Fig. 6, 7 and Table 1, when the time constant σ of the excitation source increased from 0.4ns to 5ns, TEV signal amplitude decreases rapidly from 175.1mV to 4.9 mV. With the increase of time constant of the excitation source pulses, the pulse width increases, but the detected TEV signal amplitude would reduce, i.e., the higher frequency of the partial discharge source, the stronger TEV signal of the switchgear surface.

- **The effect of the excitation source amplitude on the TEV signal:** Set coordinates of the excitation source and the detection point as above one, seen in Fig. 4. Make Gaussian current pulses the

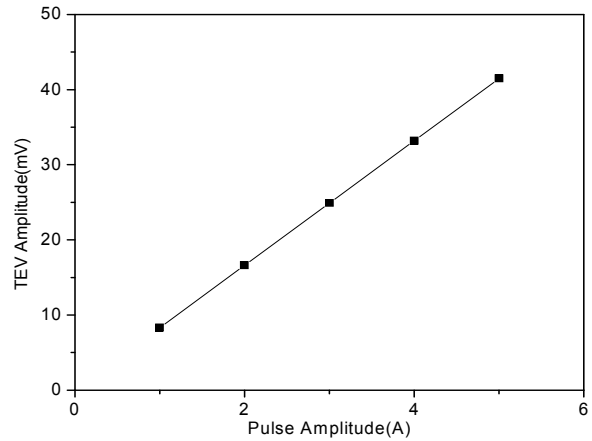


Fig. 9: Curve of TEV amplitude with pulse amplitude

excitation source, whose time constant is 3ns and the amplitudes are respectively 1A, 2A, 3A, 4A and 5A.

According to the above simulation parameters, you can get TEV signals excited by excitation sources of different intensity. Figure 8 shows TEV pulse waveforms obtained by different excitations and TEV signal amplitudes are shown in Table 2.

The relationship curve between the TEV signal amplitude and the excitation source amplitude I_0 can be obtained from Table 2, as is shown in Fig. 9.

Figure 8, 9 and Table 2 show that the TEV signal intensity at detection points is proportional to the pulse current amplitude of the excitation source; the higher the pulse amplitude of the excitation source, the stronger the TEV signal of the surface of the switchgear.

- **TEV signal distribution of the switchgear surface:** In order to study the TEV distribution of the shell surface when partial discharge occurs inside the switchgear, set the excitation source coordinates (150,700,500). The time constant of the excitation source is 3ns and amplitude is 1A. Select four detection points of the same horizontal plane with the excitation source on the switchgear outer surface. Coordinates of detection points are shown in Table 3. The horizontal cross section of the switchgear is divided into four sections along the X axis and the Y-axis direction of the switchgear, as is shown in Fig. 10.

TEV pulse waveforms of four detection points on the switchgear outer surface are shown in Fig. 11. From Fig. 11, when TEV signals propagate on the surface of the switchgear, signal amplitude variation of different detection points is not obvious, but there is a significant time delay. The switchgear interior discharge source can be located initially using this feature.

Detection point number	1	2	3	4
Coordinate (mm)	(0,900,500)	(0,100,500)	(150,1000,500)	(350,1000,500)

Figure 11a shows TEV signal of the detection point 1 leads that of the detection point 2, according to the generation mechanism of TEV signal, the partial discharge source is located in (1) or (4) interval of Fig. 10.

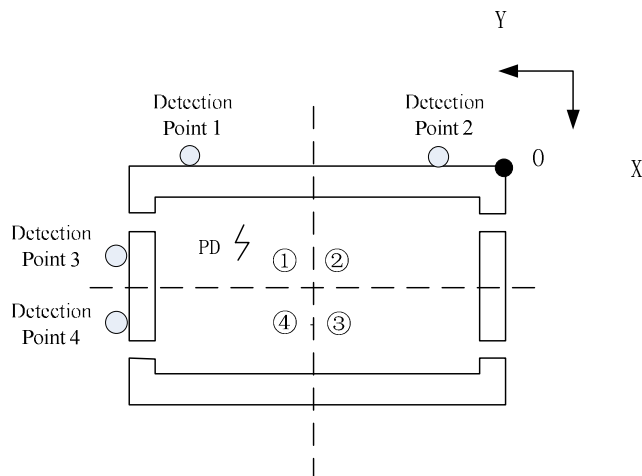
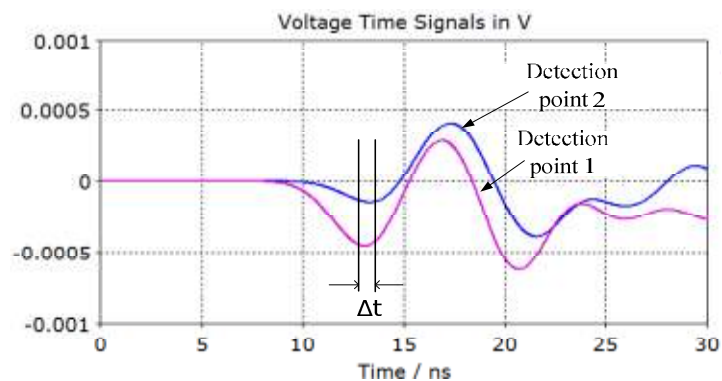
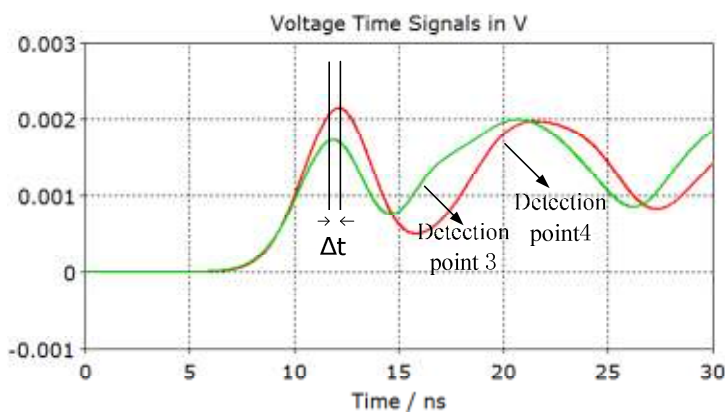


Fig.10: Position of four detection points



(a)



(b)

Fig. 11: TEV waveforms of different detection points

Similarly, from Fig. 11b, TEV signal of the detection point 3 leads that of the detection point 4 and the partial discharge source should be located in (1) or (2) interval.

From TEV signals of four detection points, the PD source located in (1) interval.

CONCLUSION

In this study, simulation model of XNG15-12 switchgear is created by CST software to simulate and study the relationship of TEV signal and the PD pulse frequency, amplitude and TEV distribution of the switchgear surface:

- When PD occurs in the switchgear, the generated electromagnetic waves come from the gap of the opening, connector and the cover of the switchgear, exciting TEV signal on the outer surface of the metal cabinet.
- TEV signal intensity and pulse characteristics of the excitation source are closely related. The TEV signal amplitude is proportional to the amplitude of the excitation source pulses. TEV signal amplitude increases with the increase of the excitation frequency of the source pulses.
- TEV signal will generate obvious time delay when propagating along the switchgear surface. The discharge source can be located through the arrangement of multiple TEV sensors.

ACKNOWLEDGMENT

This study is supported by National High Technology Research and Development Program (863 Program) under Grant No. SS2012AA050803.

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