Calculation of electromagnetic field for very fast transient process in GIS

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Abstract. The calculation method of electromagnetic field generated by very fast transient process in GIS is studied. The VFTC is calculated, and the mathematical model of direct wire electromagnetic radiation is established according to the structure of GIS. The space electromagnetic field is calculated with VFTC as excitation source. The non-stationary VFTC simulation waveform is decomposed in combination with Hilbert yellow method. The electromagnetic field intensity of each decomposed waveform is calculated on the basis of mathematical model of direct wire electromagnetic radiation. Then the electromagnetic field intensity of fast transient process is reconstructed. The results show that the intensity of electromagnetic field decreases exponentially with the increase of distance. The method proposed solves the theoretical calculation of complex electromagnetic field for unsteady VFTC waveform that contains complex frequency components with transient characteristics in very fast transient process. That has theoretical guiding significance for the electromagnetic field calculation of very fast transient phenomenon in GIS.

Keywords. VFTC; The electromagnetic field; Hilbert yellow; Electromagnetic radiation model

1. Introduction
Fast Transient phenomena will appear as isolating switch work in gas insulated metal-enclosed switchgear, which generates very fast transient overvoltage (VFTO) and very fast transient current (VFTC) with the high frequency and large amplitude. Severe electromagnetic environment is caused by fast transient electromagnetic field. The normal operation of secondary equipment is disturbed seriously. So it is necessary to study the space electromagnetic field of transient process. The insulation of gas insulated substation (GIS) can be destroyed by VFTO when the voltage level more than 300kV. The winding of the transformer may be also invaded by VFTO to endanger insulation of the winding. Strong electromagnetic radiation is caused by VFTO and may damage secondary equipment and cause injury to personnel. The insulation margin of GIS equipment decreases with the increase of system voltage level, and the influence of VFTO is more prominent [1-4]. The electric power industry develops rapidly in our country. Insulation failures of GIS with different voltage levels were investigated by International Council on Large Electric Systems (CIGRE) in 1967-1992. The failure rate increases obviously with increase of voltage level. The reason is related to very fast transient overvoltage caused by switching operation of GIS with high voltage level [5-6]. The electromagnetic interference of the electromagnetic radiation generated by GIS on surrounding secondary equipment has been studied in Australia, Switzerland and Italy [7-10]. The measurement of electromagnetic field is realized for a 220kV GIS substation in Switzerland. The maximum value of the electric field is 38.8kV/m. The electric field intensity near the GIS enclosure is generally 10kV/m, and the amplitude of magnetic field intensity is tens of amperes per meter. The typical measured value
of electric field intensity near GIS enclosure is 3kV/m by American institute of electrical science. The VFTO interference electromagnetic field was measured by Italy for a 420kV substation. The results show that the electric field intensity decreases as the distance increases away from GIS. However, due to multiple reflection of wave, the frequency of electric field intensity increases on the ground side. The frequency of electromagnetic field is mainly 10–20MHz related to substation layout. The electric field intensity of a 500kV substation is calculated to be approximately 4–9kV/m [11-12]. The GIS model is built, VFTO and VFTC are calculated. The obtained data is used as the excitation source for study of electromagnetic compatibility radiation of GIS model. A simulation study of electromagnetic radiation has been conducted to obtain the distribution characteristics of space electromagnetic field [13]. According to the measured data in literature, the electric field intensity is about in tens of thousands volts per meter, magnetic field intensity in dozens of ampere per meter when the observation distance is a little greater than about 0.5 m. Orders of magnitude are similar for the calculated and measured electromagnetic field. The intensity of electromagnetic field changes exponentially with the change of different observation distance.

2. Analysis on the characteristics of very fast transient waveform in GIS

2.1. Establishment of GIS model

Very fast transient processes can be generated by switching operations of disconnecting switch, circuit breakers, load switches, intrusion of external lightning waves, and ground flashover of live parts in GIS. The opening and closing operation of disconnecting switch is the most frequent. And fast transient phenomenon is the most serious. The operation speed of the isolating switch in GIS is 3~10m/s when the switch is operated suddenly. And there is no special arc extinguishing device in GIS. Therefore, the breakdown of a dozen or even hundreds times will occur in the process of opening and closing no-load short bus in the contact gap. Each breakdown cannot occur at other point at the same time, but propagates at a certain speed to other part in the form of electromagnetic waves. The parameters of transmission line will change abruptly, which is also the abrupt node of wave impedance. The electromagnetic wave will be refracted and reflected when propagates along transmission line at the abrupt node. The amplitude and frequency of refracted and reflected voltage or current is diverse. The more discontinuous points of wave impedance, the more complex waveform[14]. The amplitude frequency characteristics of fast transient waveform mainly depend on the length of GIS which is affected by operation of isolating switch and the arc resistance. The base frequency is between 1 MHz and 40 MHz. The calculation model is 550kV three-phase split GIS, which includes three main transformer sets, two system outgoing ends and two reactance. The substation adopts 3/2 wiring mode which is flexible. The disconnecting switch is with a closing resistor. The electrical wiring diagram of substation is shown in Figure 1. CB is circuit breaker; DS is disconnecting switch; ES is earthing switch; CT is capacitance transformer; PT is potential transformer; RS is high voltage reactor; LA is lightning arrester.
2.2. Simulation results of very fast transient current
The substation adopts 3/2 wiring mode, and there are many operating modes. According to Figure 1, a typical switching operation is selected in this paper. The transient electromagnetic field generated in space is studied and calculated by taking this operation mode as an example. The selected operation mode is shown in Table 1.

| Transformer | Output line | CB     | DS     | DS     |
|-------------|-------------|--------|--------|--------|
| #3          | NO. 1       | CB05   | DS01\DS06 | DS09 |
|             |             |        | DS13\DS1 |       |

The bergeron equivalent model is used to calculate equivalent parameters of each component in GIS under the selected path. The VFTO and VFTC waveform is obtained at DS09 as shown in Figure 2. The current data is used as excitation source to calculate the space electromagnetic field.

3. Space radiation calculation of direct wire
The arc is located in the disconnecting switch, so it is difficult for the arc to interfere directly with the secondary equipment. The electromagnetic energy generated by the switching arc will interfere with the secondary side equipment indirectly through the coupling structure between the primary side equipment and the secondary side equipment along the conducting rod. Contact gap will produce a
strong arc phenomenon in the operation of high voltage switchgear. The electromagnetic radiation produced by the arc in the disconnecting switch is much stronger than that of the circuit breaker. The sensitivity of nearby sensors should be considered when monitoring mechanical characteristics of circuit breakers. Therefore, the arc in the operation of isolating switch and circuit breaker will produce serious electromagnetic radiation, including rogowski coil current sensor, signal acquisition device, isolating switch, circuit breaker and other device, will be affected. Therefore, it is necessary to study electromagnetic radiation characteristics of arc and GIS conducting rod.

Gap arc is a very complex electrophysical process. The feature includes wide frequency band, strong energy and unstable form. There is no precise mathematical formula to express it. But any complex physical process can always be thought of as consisting of several simple subprocesses. The arc pulsating between the two poles in an instant can be approximately simplified as the electromagnetic radiation of the dipole antenna [15-16]. The arc and GIS conducting rod are equivalent to a direct wire in this paper. The VFTC generated with VFTO is used as the excitation source for the direct wire. The distribution of space electromagnetic field are studied by establishing the direct wire model, which provides theoretical support for calculation of distribution of electromagnetic field in GIS.

3.1. The mathematical model of direct wire

Any current carrying wire is a radiating body. In fact, a single wire can serve as both a receiving and a transmitting antenna. The diagram of electromagnetic fields of a direct wire is shown in Figure 3. According to literature [17], the expressions of electric field intensity \( E \) and magnetic field intensity \( H \) using the direct wire antenna are as follows: (1) - (3). The use condition is that the current \( I \) is uniform, the length of wire is far less than the wavelength \( \lambda \), and the length of wire is less than the observation distance \( D \). The wire is located in free space and not close to ground.

\[
E_r = 60I \left( \frac{1}{D^2} - \frac{j \lambda^2}{2\pi D} \right) \cos \sigma \quad (1)
\]

\[
E_z = \frac{Z_0 I l}{2\pi D} \left[ 1 - \frac{\lambda^2}{2\pi D^2} \right] \left( \frac{\lambda}{2\pi D} \right)^2 \sin \sigma \quad (2)
\]

\[
H_\phi = \frac{I l}{2\pi D} \left[ \frac{\lambda}{2\pi D} \right]^2 \sin \sigma \quad (3)
\]

Where, \( I \) is the current, and here is the arc current, the unit is A; \( l \) is the dipole length that is the arc column length, the unit is m; \( \lambda \) is wavelength in m; \( D \) is the distance of observation point, the unit is m; \( Z_0 \) is free space wave impedance equal to 120\( \pi \), because the \( E_r \) on the axis of the wire will decay rapidly with \( 1/D^2 \) and \( 1/D^3 \), it is not considered [18]. Therefore, here the main computing \( E_r \) and \( H_\phi \). At \( \sigma=90 \), both \( E \) and \( H \) are maximized. In fact, for \( \sigma=(90 \pm 25)^\circ \), the error is less than 10% [19].

The switching arc and GIS conducting rod are equivalent to a simple current-carrying direct wire to calculate space electromagnetic radiation according to the mathematical model of direct wire electromagnetic radiation. The simulated VFTC is used as the electromagnetic excitation source to calculate the space electromagnetic distribution of the direct wire. The VFTC waveform includes a variety of frequency components, the wavelength is related to the frequency according to the requirements of the electromagnetic radiation model. So it is necessary to decompose the waveform into a single frequency spectrum waveform, and calculate the wavelength of each specific frequency waveform for electromagnetic fields calculation.

3.2. Hilbert yellow decomposition and calculation of electromagnetic field intensity

The VFTC is the electromagnetic interference source of electromagnetic radiation simulation calculation. The spectrum analysis waveform of VFTC is shown in Figure 4. VFTC waveform is a non-stationary waveform with strong randomness. The frequency component is complex. VFTC has frequency components from tens of kHz to hundreds of MHz. According to the requirements of the mathematical model of direct wire electromagnetic radiation, it is impossible to extract the specific frequency and calculate the wavelength. Therefore, it is necessary to decompose the waveform and then study on calculation of electromagnetic radiation. In this paper, Hilbert yellow method is used to decompose the VFTC waveform and calculate frequency components of each decomposed component.
Electromagnetic field intensity is calculated using a decomposed waveform. Finally, the calculation results of electromagnetic field intensity are reconstructed to obtain the electromagnetic field intensity time domain waveform of the original signal source. The spectrum analysis and decomposition waveform of VFTC is shown in Figure 4.

The non-stationary VFTC waveform was decomposed by Hilbert yellow method [20-21]. The obtained independent frequency waveform is carried into the direct wire radiation mathematical model for electromagnetic radiation calculation. The Hilbert yellow decomposition waveform and the spectrum of each decomposition waveform are shown in Figure 4. In this study, the frequency of each decomposed waveform was calculated and the corresponding frequency of each decomposed waveform was marked in the Figure 4. The spectrum data of each component are obtained by decomposing spectrum of the results as shown in table 2.

| Imfn | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|------|---|---|---|---|---|---|---|---|---|----|
| Frequency (MHz) | 59 | 22 | 22 | 13 | 6 | 3 | 2 | 1 | 0.543 | 0.271 |

The decomposed current waveform mainly contains ten frequency components between 0.271MHz and 59MHz. Each decomposed waveform has a unique frequency component. The decomposed current waveform is considered as uniform current, which can be used as excitation source to meet application requirements of the mathematical model of electromagnetic radiation of direct wire. Among them, the electric field intensity and magnetic field intensity of each decomposed waveform under different observation distances are shown in Figure 5.

The target position in the radial space of the direct wire is 0.1m, 3.4m and 6.7m respectively in calculation program. The electromagnetic field intensity of each decomposed component is obtained. By comparing the variation of electromagnetic field intensity with distance, the variation trend and attenuation amplitude of electromagnetic field intensity with observation distance can be known. The attenuation between 0.1m and 3.4m was $10^{-3}$ times, while the electric field intensity from 3.4m to 6.7m attenuates about 0.5 times. The calculated results of magnetic field intensity show that the magnetic field intensity is very small. The higher frequency, the smaller magnetic field. The magnetic field tends to decrease exponentially with increasing in distance. In addition, the difference of magnetic field intensity at 0.1m and 3.4m is up to three orders of magnitude, and the difference of magnetic field intensity at 3.4m and 6.7m is less than 5 times. It can be seen that the magnetic field intensity decreases sharply at the near position of the arc. As the observation distance increased, the magnetic field intensity decreases gradually and tends to be stable.
4. Reconstruction calculation of electromagnetic field intensity of VFTC decomposition waveform

The variation trend of the electromagnetic field intensity of the decomposed waveform at different distances is studied. The electromagnetic field intensity of each decomposed component is reconstructed to obtain the electromagnetic field intensity of the original signal. The electromagnetic field intensity of each distance reconstructed is shown in Figure 6. The observation distances are 0.1 m, 1.3 m, 2.5 m, 3.7 m, 4.9 m, 6.1 m and so on, respectively. The maximum value of electric field intensity waveform are $1.67 \times 10^7$ V/m, 7008 V/m, 1030 V/m, 350.1 V/m, 184.1 V/m, 118.1 V/m. The maximum value of magnetic field intensity waveform is 348.6 A/m, 2.892 A/m, 1.047 A/m, 0.6202 A/m, 0.4498 A/m, 0.3631 A/m. The electric field intensity is very high at 0.1 m away from the direct wire. The electromagnetic field intensity attenuation tends to be gentle with increase of observation distance. The variation of space electromagnetic field intensity with distance is summarized. The variation rule of space electromagnetic field intensity is universal, and that has certain guiding significance. The theoretical value can provide reference for relevant research, but it is necessary to verify whether the electromagnetic intensity calculated by a specific model is reasonable through relevant experiment.
The peaks of the time domain electromagnetic field intensity waveform at 20 kinds of observation distance are selected. The variation of electromagnetic field intensity with observation distance is plotted as shown in Figure 7. The Figure shows that electric field intensity decreases exponentially with increase of distance. Comparing the electric field intensity at 0.1m and 1.3m, the electric field intensity at 0.1m is 2383 times higher than that at 1.3m. The results show that there is a strong electromagnetic field near direct wire. The decay rate is also very obvious.

The calculated results of three dimensional electromagnetic fields intensity after reconstruction are shown in Figure 8. The time interval range is from 0 us to 4 us. The space distance is from 0 m to 10 m. In the diagram, the distance coordinate of electromagnetic field intensity are respectively logarithmic coordinate, which can clearly show the attenuation trend of electromagnetic field intensity as the distance changes. It can be seen that the reconstructed electromagnetic field intensity energy is mainly concentrated in the range of 1m. The electromagnetic field intensity also tends to decrease with time.

5. Conclusion

The Hilbert yellow method is used to decompose the VFTC simulation waveform based on the direct wire electromagnetic radiation mathematical model. The electromagnetic field intensity of each decomposed waveform under the direct wire model is calculated. The electromagnetic field intensity of original signal was reconstructed and the distribution of electromagnetic field intensity at different distances was studied. This method can be used to analyze engineering electromagnetic field for the non-stationary signal. The following conclusions are drawn:

(1) The VFTO waveform is calculated at DS09 of GIS model. The maximum value within 4us is about 650kV. The maximum value of VFTC waveform within 4us is about 6.5kA. The frequency range is from tens of kHz to hundreds of MHz, which belongs to non-stationary signal.

(2) The electromagnetic field intensity decreases exponentially with increase of distance around the direct wire model. The maximum electromagnetic field intensity is respectively 7008V/m
and 2.892A/m at 1.3m. and the maximum electromagnetic field intensity was 92.94 V/m and 0.2624 A/m at 8.5m under the working conditions described in this paper. The calculated results are similar to the measured data in literature [7-10]. However, the numerical error should be determined by further research.

6. References
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