Analysis of the Effect of Lightning on the Insulation Between Terminals of Capacitors for EHVDC

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Abstract. Proceeding with the characteristics of the lightning, this paper analyzed spread velocity of the lightning combined with the loop length between the terminals of the capacitor bank, dropped a conclusion that the model of distributed parameter suitable for capacitor bank and the model of Lumped parameter suitable for capacitor unit. The Fourier decomposition of the lightning wave indicates that the amplitude and energy of lightning are mainly accumulated a frequency above 10 kHz and the frequencies are outside the resonant frequency range of AC and DC filter in the HVDC system, so as the distribution parameter model is suitable for analyzing the effects of lightning on the capacitor insulation between terminals. Based on the analysis of the traveling wave angle, it is found that the wave impedance and voltage drop of the capacitor bank are very small, and the influence of lightning wave on the insulation of the capacitor bank is very small.

Keywords: Lightning · Wave impedance · Velocity of lightning · Fourier decomposition · Capacitor · Influence · Analysis

1 Foreword

For a long time, there have been many researches on lightning wave, but most of them are about substation lightning protection [1–6], and some about reactors [7, 8], but few about capacitor. In the design of capacitors, especially in the design of EHVDC engineering capacitors, only the influence of lightning wave on the insulation of the capacitor case or the insulation between layers is considered. The effect of lightning wave on the insulation between terminals of capacitors is rarely discussed in the literature [9–12]. In the bidding documents, the lightning overvoltage only has the request to the insulation between capacitor terminals to case (T-C), does not have the request to the capacitor T-C, but the osperating overvoltage has the request to the capacitor T-C. Standard [13] stipulates that the insulation between the terminals of C2 for AC filter capacitors used in DC transmission projects should be able to withstand 4.3 times the operating impulse voltage, and the relevant tender documents are basically the same. For DC filter capacitors and DC neutral bus impulse capacitors [14], the upper limit of their internal fuse test

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voltage is determined according to the SIL, which shows that the operation impulse voltage is considered in the insulation between terminals of the capacitors, but did not consider the influence of lightning impulse voltage.

For Lightning Impulse Voltages, in chapter 27 of Standard GB/T 11024.1–2019 (IEC60871–1) [15], "If the capacitors are grounded, the magnitude of the lightning impulse will be significantly reduced when it reaches the capacitor… this is why the basic lightning impulse level(BIL) is not specified in the B1 and B2 insulation". However, the effect of lightning wave on the insulation between terminals of capacitors needs further study. Why don't the standards and bidding documents specify the BIL for the insulation between the terminals of capacitors? Does the BIL have any effect on the insulation between the electrodes of the capacitor? If not, will it affect the operation of the capacitor? These questions perplex the author for a long time, the author has also been trying to solve these doubts.

The research object of this paper is capacitors for neutral grounding system, especially shunt and AC filter capacitors for UHV system. For capacitors with ungrounded neutral, the insulation between terminals will not be directly affected by lightning waves. Only when the neutral point is directly grounded, the terminals of the capacitors may be directly affected by the lightning wave.

In this paper, the lightning wave is analyzed from two aspects: The traveling wave characteristic and the fourier spectrum analysis. First of all, starting from the traveling wave characteristics of lightning wave, the propagation speed, propagation distance and wave impedance of lightning wave in the capacitor are analyzed, and its influence on the insulation between terminals of the capacitor is analyzed, the influence of the high-order harmonic component on the insulation between terminals of the capacitor is evaluated.

2 Analysis of the Influence of the Lightning Wave on the Capacitor from the View of Traveling Wave

2.1 The Influence of Lightning Wave on the Insulation Between the Capacitor and the Terminals of the Capacitor Group

Lightning wave is an electromagnetic wave. In general, electromagnetic waves travel through a medium at [16]:

$$V_c = \frac{1}{\sqrt{\mu\varepsilon}} = \frac{1}{\sqrt{\mu_0\varepsilon_0}} \cdot \frac{1}{\sqrt{\mu_r\varepsilon_r}} = \frac{c}{\sqrt{\mu_r\varepsilon_r}} \tag{1}$$

In Eq. (1), $\mu_0 = 4\pi \times 10^{-7}$, is permeability in vacuum, H/m; $\varepsilon_0 = 10^{-9}/36\pi$ is dielectric constant in vacuum, F/m; μ_r, ε_r is relative permeability and dielectric constant of medium respectively; Vc is the velocity of electromagnetic wave in the medium, m/s. c is the speed of light, m/s.

Since the relative permeability of a non-magnetic medium is essentially 1, the velocity in the medium can be calculated simply:

$$V_c = \frac{c}{\sqrt{\varepsilon_r}} = \frac{3 \times 10^8}{\sqrt{\varepsilon_r}} \tag{2}$$

In this way, the propagation speed of lightning wave in the film is about $c/\sqrt{2.2} = 2.02 \times 10^8$ m/s, and that in Benzyl-toluene is about $c/\sqrt{2.66} = 1.84 \times 10^8$ m/s, which are slightly lower than that of light. If this is the case, the propagation distance of the peak value is $1.2 \times 10^{-6} \times 2 \times 10^8 = 240$ m. Even for a lightning wave with a wave head of 1.2 μs. In general, for a EHVDC capacitor banks, the length of the main circuit is between 80m and 240 m, so the propagation distance of peak of the lightning wave is large enough, even for EHVDC capacitor banks, the effect of lightning on the insulation between terminals of EHVDC capacitor banks should be considered using a distributed parameter model similar to that of transmission lines.

Considering that the loss of capacitor is very small, especially for all-film capacitor, the loss is only about 0.0001–0.0002, we can regard the inter-electrode of capacitor as a lossless circuit. Moreover, the capacitor itself is composed of several components through different series-parallel combination, which can be regarded as distributed parameters. Considering lightning waves are mostly high-frequency components. Thus, according to reference [16], the propagation velocity of lightning waves between the capacitor terminals can be calculated as follows:

$$V = \frac{1}{\sqrt{LC}} \tag{3}$$

In Formula (3), V is electromagnetic wave propagation velocity between capacitor terminals, m/s; L is Stray inductance of the capacitor, H; C is capacitance of the capacitor, μF.

Comparing the (1) and (3) formulas, it can be seen that because the capacitance between the electrodes of the capacitor is very large, it is much larger than the dielectric constant of the main insulating material of the capacitor, therefore, the propagation speed of the lightning wave between the capacitor electrodes is much lower than that of the main material of the capacitor. For a capacitor with a capacitor C = 72 μF, if its stray inductance L = 2 μH, the propagation speed of lightning waves in the capacitor circuit is 0.833×10^6m/s, which is only 1/3600 times the speed of light. This is also about 1/2400 times faster than the speed at which lightning waves travel through the capacitor's main insulation. According to the propagation speed, the propagation distance of the lightning wave in the capacitor circuit is about 4 m, which is more than the length of one capacitor loop, but much less than the length of the capacitor bank loop. That is to say, for the lightning wave, the capacitor unit is suitable for the centralized parameters, for the capacitor group, only the distributed parameters can be used. This further shows that it is reasonable to use the distributed parameter model to analyze the influence of lightning wave on the terminals of EHVDC capacitor banks. In fact, because there is a reactor in the capacitor circuit, the inductance of the circuit is very large, the propagation speed is slower, basically will not affect the insulation between terminals of the capacitor.

In the same way, it can be obtained that the propagation wave-length of the lightning wave between the capacitor terminals is:

$$\lambda = V * T_l = \frac{T_l}{\sqrt{LC}} \tag{4}$$

In formula (4), λ is the wave-length of the lightning wave propagating between the capacitor terminals, m; T_l is the wave-length time of the lightning wave, s.

2.2 Analysis of Resonance Possibility of Lightning Wave in Capacitor Bank

The distributed parameter model is used to analyze the influence of the lightning wave on insulation between the terminals of the capacitor bank. It is also necessary to analyze whether the lightning wave will produce resonance in the circuit of the capacitor bank, the influence of lightning wave on the insulation between terminals of capacitor bank can not be ignored.

According to reference [17], the correlation amplitudes, amplitude accumulations and energy accumulations of the standard lightning wave of 1.2/50 µs are shown in Table 1.

Table 1. The amplitude, the accumulation of amplitude and energy spectrum of standard lightning wave of 1.2/50µs

Frequency/Hz	10	100	1k	10k	100k	1M	10M
The amplitude	$7.03*10^{-5}$	$7.03*10^{-4}$	$7.014*10^{-5}$	$5.816*10^{-5}$	$1.023*10^{-5}$	$9.332*10^{-7}$	$2.018*10^{-9}$
The accumulation of amplitude	$1.361*10^{-4}$	$1.361*10^{-3}$	0.0136	0.1255	0.4780	0.8606	0.9965
The energy accumulation	$4.352*10^{-4}$	$4.352*10^{-3}$	0.0434	0.3823	0.9131	0.9956	0.9999

As can be seen from Table 1, the frequency spectrum of lightning waves is mainly concentrated in the region above 10 kHz.

According to reference [13, 14], AC/DC filters for HVDC transmission are mainly single-tuned filters (such as HP3, BP11\BP13 and SC, etc.), double-tuned filters (HP12/24, HP24/36, etc.) and triple-tuned filters (such as TT2/24/36, etc.), therefore, the tuning point frequency of AC or DC filters for EHVDC is between 100 Hz to 2500 Hz, which is not much different from the resonance frequency of the circuit and is lower than the main frequency spectrum of lightning waves. Therefore, the lightning wave will not produce resonance in the filter circuit, so in the capacitor bank, we can use the distributed parameters to analyze the lightning wave on the insulation between the terminals of the capacitor bank.

2.3 Analysis of the Influence of Lightning Wave on Capacitor from Wave Impedance

Since the effect of lightning wave on the insulation between terminals of Capacitor Bank is suitable for distributed parameters, the effect of lightning wave on the insulation between terminals of Capacitor Bank can be analyzed by wave impedance. According to reference [16], the wave impedances of lightning waves propagating in isotropic homogeneous media are:

$$Z_c = \sqrt{\frac{\mu}{\varepsilon}} = \sqrt{\frac{\mu_0}{\varepsilon_0}} \cdot \sqrt{\frac{\mu_r}{\varepsilon_r}} = Z_0\sqrt{\frac{\mu_r}{\varepsilon_r}} \tag{5}$$

In Eq. (5), $Z_0 = \sqrt{\frac{\mu_0}{\varepsilon_0}} = 377\Omega$ is the wave impedance in vacuum, and Z_0 is the wave impedance in isotropic homogeneous medium, Ω. Remainder is the same as (1).

From the previous analysis, for non-magnetic media, $\mu_r = 1$. The (5) expression can then be reduced to $Z = 377/\sqrt{\varepsilon_r}$. For the main insulating materials of capacitors, the wave impedance of polypropylene film is 254Ω, that of HBT is 231Ω, and that of PEPE is 238Ω.

For the circuit between the terminals of capacitor, its wave impedance is different from the general medium. Also according to reference [16], the wave impedance of the circuit between the terminals of capacitor is:

$$Z = \sqrt{\frac{L}{C}} \tag{6}$$

The symbolic meaning of (6) is the same as that of (3). For a capacitor with C = 72 μF, if its stray inductance L = 2 μH, its wave impedance is 1/6Ω. This is 1/2262 times less than the impedance in vacuum, and about 1/1400 times less than the impedance of a capacitor's main material. This wave impedance is so small that even if the current in the capacitor reaches 100 kA, the voltage across the capacitor is only about 16.7 kV, which is acceptable for a capacitor of average voltage. That is to say, from the view of capacitor wave impedance, the impact of lightning wave on the capacitor insulation between the terminals is very small.

As can be seen from formula (6), for a reactor, due to the reactor inductance is very large, capacitance is very small, so the reactor wave impedance is very large, lightning overvoltage may mainly act on the reactor.

3 Brief Summary

3.1 Analysis of the propagation speed of lightning waves in the main insulating materials between the terminals of the capacitors and the length of the transmission circuit of EHVDC capacitor banks, the propagation of lightning wave between terminals of capacitor bank is suitable for distributed parameter model, and the propagation of lightning wave in capacitor unit is suitable for concentration parameter model.

3.2 Lightning waves travel between capacitor terminals much slower than they do in the main insulation in the capacitor (about 1/2400).

3.3 The main frequency spectrum of the lightning wave obtained from Fourier decomposition is concentrated above 10 kHz, and the lightning wave will not produce resonance in the AC and DC filters for EHVDC system, it is feasible to analyze the electrical behavior of lightning wave between terminals of capacitor bank by using distributed parameters.

3.4 The wave impedance of a lightning wave in the main insulating material of a capacitor is $377/\sqrt{\varepsilon_r}$, ***and the wave impedance propagating between terminals of a capacitor is*** $Z = \sqrt{\frac{L}{C}}$, ***much lower than the wave impedance of the main insulating material in capacitor (about 1/1400), the voltage generated by lightning waves between capacitor terminals is very low. From the point of view of lightning wave impedance, the effect of lightning wave on the insulation between the capacitor terminals can be ignored.***

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