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An experimental study on corona *q-u* curves under non-standard lightning impulses

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ABSTRACT

Considering that a majority of lightning surges intruding into substations present non-standard form, an experimental study is performed on the *q-u* (charge-voltage) curves under damped oscillation impulses in a corona cage. Based on the measured results, a comparison is made between the *q-u* curves under damped oscillation and double exponential impulses. The oscillation frequency and damping time constant are varied to investigate their effect on the characteristic parameters of the *q-u* curves. A preliminary discussion is also given for explanation of the formative mechanism of the oblate helix minor loops appearing on the *q-u* curves.

1. Introduction

Distortion and attenuation of lightning surges traveling along overhead transmission lines play a substantial role in the insulation coordination and lightning overvoltage protection of electric power equipment. These phenomena are mainly attributed to the impulse corona occurring on overhead transmission lines. As far as the lightning overvoltage analysis is concerned, the *q-u* (charge-voltage) curves are commonly employed to take account of the impulse corona effect [1–3]. Research on the *q-u* curves has been reported in literature [3–6]; however, the previous work was mostly carried out under the double exponential impulses. Actually, a clear majority of lightning surges intruding into substations present damped oscillation impulse waveforms owing to the refraction and reflection [7]. It is therefore highly significant to experimentally investigate the behavior of the *q-u* curves under surges of this type. Although a small number of experimental investigations were performed on the *q-u* curves under the damped oscillation impulses [8–10], the experimental data is deficient for investigating the basic features of the corona characteristics. In addition, there is still a lack of systemic analysis on the influence factors and characteristic parameters of the *q-u* curves under damped oscillation impulses. Therefore, an attempt is made in this paper to conduct an experimental study on the *q-u* curves under this type of impulses. The experimental measurements were made in a coaxial cylindrical corona cage. The *q-u* curves are obtained by varying the applied voltage waveforms in a wider rage. Then, the influence of the waveforms is examined and the characteristic parameters is evaluated on the basis of the measured *q-u* curves.

2. Experimental measurement

Fig. 1 shows the experimental setup. It mainly consists of a corona cage, a 360 kV/1890 J modified impulse generator, a capacitive voltage divider and an integral capacitor C_q. The high and low voltage arms of the voltage divider are C_1 and C_2, respectively. The corona cage is a coaxial cylindrical electrodes and their dimension is marked in Fig. 1. The similarity of corona geometry between the corona cage and actual overhead transmission lines have been discussed in Ref. [3].

The damped oscillation voltage can be produced by the modified impulse generator, and its waveform is generally expressed by Ref. [8].

$$u(t) = U_m\left[1 - Ke^{-t/\tau}\cos(2\pi ft + \theta)\right] \quad (1)$$

where the oscillation frequency f and damping time constant τ can be regulated by varying the wavefront inductance L_f (20 μH~2 mH) and resistance R_f (0–150Ω). If L_f is removed, the impulse generator

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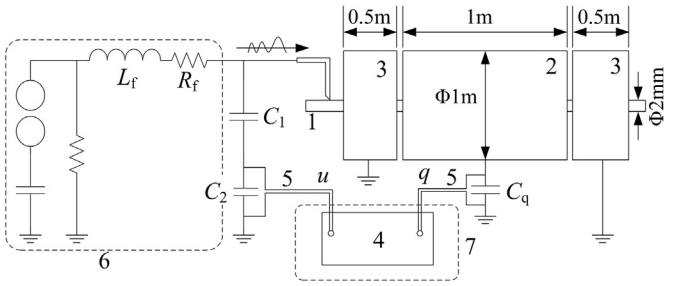

Fig. 1. Experimental setup. 1-inner electrode, 2-measured section, 3-shielded section, 4-digital oscilloscope, 5-coaxial cable, 6-modified impulse generator, 7-shieled room.

will generate the conventional double exponential impulse voltage. The impulse voltage is applied to the inner electrode of 2 mm diameter solid copper wire to produce corona discharge inside the corona cage. The voltage u and charge q are measured from the low voltage arm C_1 of the voltage divider and integral capacitor C_q, respectively. The u and q signals are introduced by two coaxial cables (characteristic impedance: 75Ω) to a shielded room, where they are recorded by a digital oscilloscope (bandwidth: 100 MHz; real-time sampling rate: 1 GSa/s). As the two coaxial cables are of equal length, the u and q signal can arrive at the oscilloscope exactly in step with each other. Rising edge triggering mode is used for signal recording and the discrete sampling is made for the u and q signals. The two sampled signals are inputted to a computer and subsequently the q-u curves are obtained through data processing.

Four typical q-u curves measured under different voltage amplitudes are given in Fig. 2(a), which are superimposed on a diagram to indicate certain similarity of curve trajectories. In Fig. 2 (a) the applied voltage waveforms with positive polarity have an oscillation frequency $f = 0.18$ MHz and a damping time constant $\tau = 5.9$ μs. For sake of comparison, the q-u curves under double exponential impulse are also measured, as shown in Fig. 2(b).

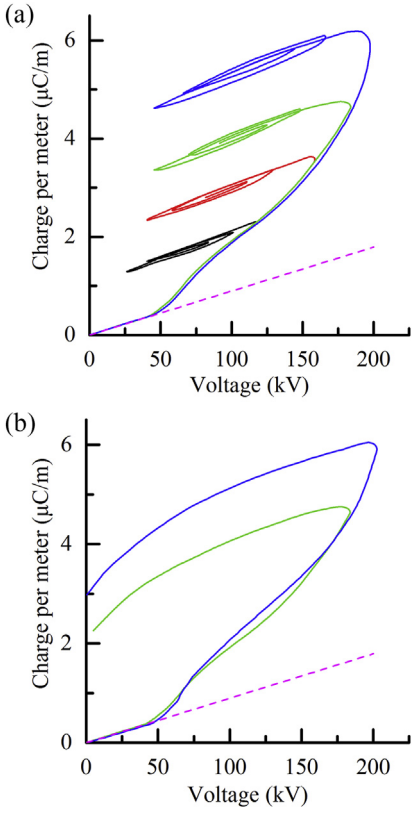

Fig. 2. (a)q-u curves under positive damped oscillation impulses with different voltage amplitudes, (b) q-u curves under positive double exponential impulses (1.5/50 μs) with different voltage amplitudes.

As can be seen from Fig. 2, the obvious feature of the measured q-u curves under the damped oscillation impulse is the narrow helixes appearance in their parts corresponding to the follow-up oscillation cycles. Basically, in the ascending parts on the q-u curves under the damped oscillation and double exponential impulses are coincident with each other before their ordinates reach the respective maximum charges. The difference between the two types of q-u curves appears in the parts subsequent to the maximum charges. In these parts, the q-u curves under double exponential impulse descend monotonically, whereas due to the oscillation of the applied voltage, the oblate helix minor loops appear on those under damped oscillation impulse.

3. Investigation on the q-u curves under damped oscillation impulses

In order to investigate the behavior of the q-u curves under damped oscillation impulse, the applied voltage waveforms are varied in a certain range of oscillation frequency and depth. The corresponding q-u curves are measured under both polarities. The characteristic parameters of the q-u curves are evaluated and the influence of the voltage waveforms on the q-u curves are further examined. The polarity effect of the q-u curves is also discussed.

3.1. Characteristic parameters of the q-u curves

The basic features of a q-u curves are usually described by a number of characteristic parameters [11]. They are mainly the corona inception voltage, capacitance increase coefficient and energy dissipated by corona. The corona inception voltage U_{in} is defined as the abscissa value of the knee point on the q-u curve, as illustrated in Fig. 3. When the applied impulse exceeds U_{in}, the corona discharge start to grow and the space charge is generated around the inner electrode. Thereafter the measured q-u curve deviates from the geometric capacitance with a steeper rising slope. The apparent capacitance on the rising part of the q-u curve is approximately taken as the average slope $C_a = \Delta q/\Delta u$, as illustrated in Fig. 3. Correspondingly, the capacitance increase coefficient is defined as [11]

$$\lambda_C = \frac{C_a}{Cg} = \left(\frac{\Delta q}{\Delta u}\right)\frac{1}{Cg} \tag{2}$$

where C_g is the geometric capacitance of the corona cage and takes

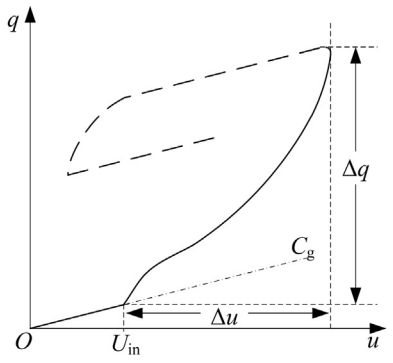

Fig. 3. Characteristic parameters of the q-u curves.