Statistical analysis of audible noise generated by AC corona discharge from single corona sources

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Abstract: Time-domain waveforms of sound pressure pulses generated by alternate current (AC) corona discharge from single corona sources are measured. The pulse amplitude and time interval of sound pressure pulses in positive and negative half cycles are analysed separately due to large differences of the sound pressure pulses in positive and negative half cycles. The influences of instantaneous voltages on the pulse amplitude and time interval are obtained, and statistical distributions of pulse amplitude and time interval are also obtained. Besides, empirical formulas of the pulse amplitude and time interval are derived by numerical fitting method. Based on the statistical results, stochastic simulation of the sound pressure pulses is conducted, and the validity of the simulated results is given by comparing the frequency-domain results and A-weighted sound pressure level (SPL) with the measured ones. Finally, the stochastic simulation method is used to discuss modulating influence of AC voltage on the tones emission from AC corona discharge. Besides, the influence of the measurement time on the resultant SPL is also discussed on the basis of the stochastic model. In order to insure the SPL independent of the measurement time, the measurement time should be larger than 0.2 s.

1 Introduction

Corona discharge on the alternating current (AC) high-voltage overhead lines is usually induced by the protrusions such as pollution or water drops, defects or ice on the conductor due to high electric field in the vicinity of the conductor [1–5]. Accompanied with the corona discharge, some unwanted corona effects such as corona loss, audible noise (AN) and radio interference may be produced [2]. Among these unwanted corona effects, the AC corona-generated AN as a hissing or cracking sound can be directly heard by the people near the transmission lines. Besides, an additional tone component at twice frequency of power frequency can be generated and some of its higher harmonics can also be found for the AC corona-generated AN [1, 6]. The corona-generated AN is quite different from other environmental noise due to its wider frequency band characteristics. Thus, the criteria for public perception and acceptance of the corona-generated AN are different from those for environmental noises.

Once the corona-generated noise level from the transmission line is higher than the limit value, the noise may disturb the normal life of the people around the transmission line. People living near transmission line will react adversely to the construction of transmission lines. In fact, the AN has become a design factor for overhead lines. In 2011, Ueli Straumann explained the mechanism of the AN as acoustic sources of the tones emission. The investigations by Ueli Straumann promoted the cognition of generation mechanism of tonal component, while more investigations should be conducted to simulate the time and frequency domains of AC corona-generated AN.

Generally, the complete description for the AN should involve frequency spectrum, SPL, propagation characteristics and the time-domain waveform. However, previous investigations on the AC corona-generated AN have seldom dealt with the time-domain characteristics. Our earlier investigations on the time-domain characteristics of DC corona-generated AN have found that the corona-generated AN consists of a series of sound pressure pulses with the bipolar properties [19–20]. It has been proved that through measurement of time-domain waveform of sound pressure, real-time sound pressure signals which reflect the vibration of gas molecules can be obtained. The random nature of corona-generated AN and correlation between the AN and the corona discharge can be clearly reflected through the detail characteristics of the time-domain waveform of AN [17, 21]. Furthermore, the real-time background noise can also be recorded through time-domain measurement. The background noise can be clearly identified and...
discharge point should be obtained firstly. In order to avoid the instantaneous voltages on the sound pressure pulses are carefully distributed randomly on the transmission line. Moreover, the modulating influence of the sound pressure pulses and the frequency spectral of AC corona-generated AN under AC voltage. Moreover, correlations between the sound pressure pulses and frequency spectral of AC corona-generated AN have not been investigated before. However, the statistical characteristics of time domain, frequency domain and SPL s of corona-generated AN under AC voltage are simultaneously recorded by data acquisition card. The sample rate is set at 100 kS/s. The applied voltage is measured through a voltage divider with a voltage ratio of 1000:1. The microphone used in the experiments for measuring the AN Model AWA 14423 has a typical frequency range from 10 Hz to 20 kHz with a sensitivity of 50 mV/Pa and it is calibrated by a standard sound source before experiments. The microphone faces directly to the single corona source and is situated at the same height as the conductor but 1 m away from it horizontally. In order to obtain the statistical characteristics of the AC corona-generated AN, 1000 cycles of the waveforms are recorded at each applied voltage. During the experiments, the temperature is kept within the range 20–22 °C, and the relative humidity is kept within the range 40–42%. Therefore, the influence of variance of the temperature and the humidity on the results can be ignored.

3 Results and analysis

3.1 Basic characteristics of AN from AC corona discharge

When the applied voltages are 48, 52 and 58 kVrms, the measured waveforms of the applied voltages and the de-noised AN for 1# conductor are given in Figs. 3a–c. Only two cycles of the waveforms are given in these figures. The de-noised waveforms of AN are obtained on the basis of de-noised method in [18]. Through the de-noised method, the background noise and reflection noise from laboratory can be effectively removed. The statistical analyses of AN in the following parts are all based on the de-noised waveforms.

It can be found that the sound pressure pulses are first generated at the negative half cycle and the further increase in the applied voltage leads to an obviously increase in the repetition frequency of sound pressure pulses in negative half cycle. At higher applied voltage, the sound pressure pulses gradually emerge in positive half cycle while the amplitude is much higher and the repetition frequency is much lower than those in the negative half cycle. Similar phenomenon can also be found in the measurement of corona current pulses from AC corona discharge [23–25]. It should be pointed out that no sound pressure pulses can be detected in positive half cycle for 3# conductor in the experiments.

In this paper, a series of experiments using a cylinder corona cage are carried out to measure the time-domain waveforms of AC corona-generated AN from single corona source. The detail statistical characteristics of sound pressure pulses and influences of instantaneous voltages on the sound pressure pulses are carefully analysed. Furthermore, numerical fitting formulas are proposed and stochastic simulation of AC corona-generated sound pressure pulses is conducted. Moreover, the modulating influence of the AC applied voltage on the sound pressure pulses is presented to explain the generation of tone component and higher harmonics through the stochastic model. Finally, the influence of the measurement time on the SPL is discussed on the basis of the stochastic model.
emergency of sound pressure pulse in positive half cycle. The average value of ending instantaneous voltage ($U_{en}$) decreases with the increase of applied RMS voltages and is higher than that of starting instantaneous voltage. The reason for explaining this phenomenon may attribute to the accumulation, drift and suppression of corona-generated space charges. Before the occurrence of corona discharge in positive half cycle, the negative space charges generated in negative half cycle will be absorbed in positive half cycle, thus the influence of negative space charges on the onset corona of the next negative half cycle can be neglected, which results in the starting instantaneous voltage ($U_{sn}$) keeping unchanged [20]. Once the corona discharge in positive half cycle occurs, the positive space charges can promote the corona discharge in negative half cycle of next cycle. So the starting instantaneous voltage will decrease. Besides, once the corona discharge in negative half cycle is generated, the negative space charges will accumulate and suppress the occurrence of corona discharge, which makes the ending instantaneous voltage ($U_{en}$) increases with the applied voltage.

While for the positive half cycle, both the starting and ending instantaneous voltages increase with the increase of applied RMS voltages. Due to the lower repetition frequency of sound pressure pulse at lower applied voltage, the starting instantaneous voltage ($U_{sp}$) and ending instantaneous voltage ($U_{ep}$) are nearly equal. At higher applied voltage, the ending instantaneous voltage is higher than the starting instantaneous voltage. Due to the electron avalanches developing from the cathode to the anode for the positive corona discharge, the accumulated negative space charges may suppress the development of the electron avalanches. With the increased applied voltage, the suppression will become stronger, resulting in the increase of the starting instantaneous voltage ($U_{sp}$) in positive half cycle. Similarly, the accumulated positive space charges in positive half cycle will suppress the positive corona discharge, and thus the ending instantaneous voltage ($U_{ep}$) is higher than the starting instantaneous voltage ($U_{sp}$).

Due to the large difference of sound pressure pulse in positive and negative half cycles, the statistical analysis of the sound pressure pulse produces different results in positive and negative half cycles.
pressure pulses should be conducted separately in negative and positive half cycles.

3.2 Statistical characteristics of sound pressure pulses in negative half cycle

The sound pressure pulses in negative half cycle are shown in Fig. 5. As the instantaneous voltage is increased, the pulse amplitude decreases and repetition frequency increases. The pulse amplitudes are higher and time intervals are larger near the starting and ending voltages comparing to those near the peak value of the applied voltage. It can be found that the instantaneous voltages have large influences on the sound pressure pulses. In order to distinguish the influence of instantaneous voltage ($U_t$), the region between the starting voltage and ending voltage is divided into four bands (as shown in Fig. 5) based on the normalisation voltage using the peak value of the applied voltage ($U_m$) as the reference value. The four bands are given as $[K_s, 0.95]$, $[0.95, 0.975]$, $[0.975, 1]$, and $[K_e, 1]$. The parameters $K_s$ and $K_e$ are defined as the ratio of $U_{SN}/U_m$ and $U_{EN}/U_m$, respectively.

The pulse amplitude and time interval of the sound pressure pulses at the four bands for the three conductors are statistically analysed. The average time intervals in the four bands decrease with the increase of the applied RMS voltage as shown in Figs. 6a–c for the three conductors. It can be found that the time interval in band I is largest because the instantaneous voltage approaches the corona starting voltage in band I and corona-generated space charges should be completely cleared from the ionisation zone to resume the necessary corona condition. With the increase of instantaneous voltages, electric field around the conductor increases and it needs shorter time interval to disperse the charges. Thus, the time intervals of sound pressure pulse in bands II and III decrease. At band IV, the instantaneous voltage decreases from the peak value to the corona ending voltage. So the time interval is larger than that in bands II and III, but it is still smaller than that in band I. For different conductors, the time intervals varying with the RMS voltage can well be expressed as

$$T_I = k_1U^2 + k_2U + k_3$$

where $T_I$ is the time interval, s; $U$ is the RMS voltage, kV; $k_1$, $k_2$ and $k_3$ are the fitting parameters which are determined by least-squares method and are different for different conductors.

As shown in Fig. 7, due to random nature of the corona discharge, time intervals at the four bands of corona-generated sound pressure pulses have large randomness and can approximately be fitted as lognormal distributions. The results presented in Fig. 7 are from the 1# conductor when the RMS voltage is 51 kV. It has been proved that the statistical distributions of time intervals at other applied voltage and from other conductors all can be fitted as lognormal distributions. The probability density function of the time intervals can be represented as

$$f(T) = \frac{1}{\sigma_T T_1^{2\sigma_T^2}} \exp\left(-\frac{(\ln T_1 - \mu_T)^2}{2\sigma_T^2}\right)$$

where $f(T)$ is the probability density function of the time interval, $\mu_T$ and $\sigma_T$ are the mean and standard variance of the natural logarithm of $T_I$, respectively.

As for the amplitude of the sound pressure pulse, the average positive amplitudes varying with the applied RMS voltages in the four bands are given in Fig. 8. It can be found that the average positive amplitudes in band I are largest, and it gradually decreases from the band II to band IV. In fact, with the increase of instantaneous voltages, corona-generated space charges produced by each discharge gradually decrease. Besides, the accumulated space charges may suppress the development of corona discharge. Thus,
collisions between space charges and air molecules become weaker and the amplitude of sound pressure pulse will decrease. Fig. 8 also shows the numerical fitting results for the average positive amplitudes and the expression can be given as

\[ p_{MN} = k_{N1}U^2 + k_{N2}U + k_{N3} \]  \hspace{1cm} (3)

where \( p_{MN} \) is the positive amplitude of the sound pressure, \( P_a \); \( k_{N1}, k_{N2} \) and \( k_{N3} \) are the fitting parameters obtained by the least-squares method.

As it is shown in Fig. 9, the positive amplitudes of sound pressure pulses in the four bands approximately obey the normal distributions. The probability density function \( f(p_{MN}) \) can be expressed as

\[ f(p_{MN}) = \frac{1}{\sigma_p p_{MN} \sqrt{2\pi}} \exp \left( -\frac{(p_{MN} - \mu_p)^2}{2\sigma_p^2} \right) \]  \hspace{1cm} (4)

where \( \mu_p \) and \( \sigma_p \) are the mean and standard variance of the positive amplitude of sound pressure pulses, respectively.
3.3 Statistical characteristics of sound pressure pulses in positive half cycle

In the experiments, sound pressure pulses only emerge at high applied voltages, but the number of sound pressure pulses is far less than that in negative half cycle. While for the 3# conductor, even no sound pressure pulses can be measured in the positive half cycle. Therefore, only the statistical characteristics of pulse amplitude of sound pressure pulses are analysed in this part. The positive amplitude of sound pressure pulses varying with the applied voltage is shown in Fig. 10. The pulse amplitude in positive half cycle increases slightly with the applied RMS voltage, and the average amplitude also can be fitted as a quadratic function which is expressed as

$$ p_{MP} = k_{P1} U^2 + k_{P2} U + k_{P3} $$

where $p_{MP}$ is the positive pulse amplitude of sound pressure in positive half cycle, $P_a$, $k_{P1}$, $k_{P2}$ and $k_{P3}$ are the fitting parameters.

Fig. 11 also shows the probability density distribution of positive pulse amplitude in positive half cycle, which shows that the pulse amplitude in positive half cycle also obeys the normal distribution.

4 Stochastic simulation of sound pressure pulses

4.1 Construction of sound pressure pulses

According to our previous work [26–27], once the statistical distributions of pulse amplitude and time interval were obtained, random numbers for describing the amplitude and time interval of sound pressure pulses can be generated. Then, the random sound pressure pulse trains can be constructed and simulated on the basis of typical waveform of single sound pressure pulse which can be expressed as

$$ p(t) = \begin{cases} 
  p_{M1} K_1 e^{-\alpha_1 t} [1 - e^{-\beta_1 (t - t_{01})}], & 0 < t < t_{01} \\
  p_{M2} K_2 e^{-\alpha_2 t} [1 - e^{-\beta_2 (t - t_{02})}], & t_{02} \leq t < t_d 
\end{cases} $$

(6)

where $K_1$, $K_2$, $\alpha_1$, $\alpha_2$, $\beta_1$ and $\beta_2$ are the fitting parameters, $p_{M1}$ and $p_{M2}$ are the positive and negative of the bipolar sound pressure pulses, respectively, $t_{01}$ is the zero-crossing point of the positive sound pressure pulse, and $t_d$ is the duration time of the sound pressure pulse. The ratio of $p_{M1}$ and $p_{M2}$ can be treated as a constant and the statistical result of the ratio is approximately equal to −1.8. The waveforms using (6) for fitting single sound pressure pulse in positive and negative half cycles are given in Figs. 12a and b, respectively. The fitting parameters for sound pressure pulses in positive and negative half cycles are listed below the figures.
Due to large differences of sound pressure pulses in positive and negative half cycles, sound pressure pulses in positive and negative half cycles should be simulated separately. In negative half cycle, (3) is used to generate the average positive pulse amplitudes $p_{M1N}$ at the four bands, and the corresponding negative pulse amplitudes $p_{M2N}$ are obtained through the constant ratio of $p_{M1}$ and $p_{M2}$. Then, a single sound pressure pulse in negative half cycle can be generated by using (6), and random pulse amplitudes are obtained by (4) through random number generation algorithm [28]. As for the time intervals, the average time intervals at the four bands are calculated through (1), and random time interval can be generated in (2). The random sound pressure pulse trains in negative half cycle can be simulated by superposition of the generated sound pressure pulses with random amplitudes and time intervals. In the positive half cycle, the average positive pulse amplitude is calculated in(5), and similarly the corresponding negative pulse amplitude is obtained through the constant ratio. The random pulse amplitudes are also obtained in (4). However, due to low repetition frequency of sound pressure pulses in positive half cycle, the binomial distribution is used to simulate whether the sound pressure pulse exists or not. The total waveforms of the sound pressure pulses can be obtained by the superposition of the generated sound pressure pulses in positive and negative half cycles.

When the applied voltages are 54 kVrms for 1# conductor, the measured and simulated sound pressure pulses are given in Figs. 13(a) and 13(b), respectively. The total simulation time is 120 ms, i.e. six cycles. It can be found the simulated sound pressure pulses are similar to the measured ones, and the randomness can be well reflected in the simulated waveforms.
5 Discussions

5.1 Discussions on the tones emission from AC corona discharge

High-frequency components can be found in the one-third frequency spectrums as shown in Fig. 14. Besides, the pure tones, i.e. 50 and 100 Hz frequency components, can be clearly identified. Many scholars have reported the humming noise at twice the power frequency (100 Hz) can be generated by the modulating influence of AC voltages. In the following part, modulating effects of AC voltage on the sound pressure pulses are well presented and the differences of tone emission from different types of corona discharge are discussed. We simulated sound pressure pulses under three types of corona discharge through the stochastic model. The simulated waveform of sound pressure pulses in Fig. 16c represents that corona discharge only occurs in negative half cycle (first case). Fig. 16e shows sound pressure pulses are generated both in positive and negative half cycles, but the discharge intensity in positive half cycle is far less than that in negative half cycle (second case). When the discharge intensity in positive half cycle approaches to that in negative half cycle, sound pressure pulses can be simulated as those in Fig. 16g (third case). The corresponding frequency spectral obtained by FFT for the three cases are given in Figs. 16d, f and h, respectively. The sound pressure pulses are generated randomly, while the sound pressure pulses in negative half cycle are identical for the three cases.

Spectral analysis indicates that frequency components at the harmonics of power frequency (50 Hz) can be generated due to the modulating influence of AC voltage. For the first case shown in Fig. 16d, pure tones at integer harmonics can be clearly identified. The frequency components at the base frequency and twice frequency are domain and at the same level. With the generation of sound pressure pulses in positive half cycle, the pure tones at frequencies corresponding to the even harmonics gradually increase, and the odd harmonics decrease. At the third case in which discharge intensities in positive and negative half cycles are at the same level, the even harmonics are domain and many higher harmonics can be generated as shown in Fig. 16h. Besides, it can be concluded that the twice frequency component always exists and is connected to the occurrence of corona, no matter corona discharge occurs in positive or negative half cycles. Thus, the twice frequency component emission can be treated as independent of the occurrence of the type of corona discharges [15].

5.2 Influence of the measurement time on the sound pressure level

The waveforms of corona-generated AN consisted of a series of sound pressure pulse with random nature. As it is shown in (7), the SPL reflects the comprehensive result of the sound pressure pulse trains. The SPL has close relationship with the length of the sound pressure pulse trains, i.e. the measurement time and also should be independent of the measurement time. If the measurement time is too short, the number of sound pressure pulses in the pulse trains is not enough to reflect the randomness, which may result in the inaccurate SPL. However, if the measurement time is too long, it will take long time to analyse the frequency spectrum and the SPL. Therefore, the influence of the measurement time on the SPL should be given. Based on the stochastic model of the sound pressure pulses, the duration time of the sound pressure pulse trains can be controlled and the randomness can be well reflected. The calculated SPLs varying with the measurement time at different applied voltages are shown in Fig. 17. In the calculation, the statistical distributions of the pulse parameters of sound pressure pulses obey the experimental results. It can be found that the SPL first increases with the increase of measurement time, and then gradually turns to be stable after the measurement time is larger than 0.2 s. Therefore, the measurement time should be >0.2 s in order to insure the resultant SPL is independent of the measurement time.

6 Conclusion

In this paper, time-domain waveforms of AC corona-generated AN from single corona source are measured and statistically analysed. Due to lower onset voltage of negative corona discharge, sound pressure pulses are first generated in negative half cycle. With the increase of applied voltage, sound pressure pulses in positive half cycle will occur, but the pulse amplitude and time interval in positive half cycle have great differences with those in negative half cycle.
In negative half cycle, the instantaneous voltages have great influences on the pulse parameters. Sound pressure pulses between the onset starting and ending instantaneous can be divided into four bands. The statistical results show that the pulse amplitudes in the four bands all obey the normal distribution, and the time intervals can approximately follow the lognormal distribution. The relationships of pulse amplitude and time interval with the RMS voltage can be fitted as the quadratic functions. In positive half cycle, the average pulse amplitude varying with the RMS voltage can also be fitted as a quadratic function, and the statistical distribution of pulse amplitude follows normal distribution.

On the basis of the obtained statistical results, a stochastic model is proposed to simulate the sound pressure pulses from AC corona discharge. After the validity of stochastic model is given, the stochastic model is used to analyse tones emission under the modulating influence from AC voltage. Furthermore, the influence of measurement time on the SPL is discussed on the basis of the stochastic model. It can be found that measurement time should be >0.2 s in order to insure the resultant SPL is independent of the measurement time.

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Fig. 16 Simulated waveforms of sound pressure pulses and corresponding frequency spectral

Fig. 17 Calculated SPL varying with the measurement time

In negative half cycle, the instantaneous voltages have great influences on the pulse parameters. Sound pressure pulses between the onset starting and ending instantaneous can be divided into four bands. The statistical results show that the pulse amplitudes in the four bands all obey the normal distribution, and the time intervals can approximately follow the lognormal distribution. The relationships of pulse amplitude and time interval with the RMS voltage can be fitted as the quadratic functions. In positive half cycle, the average pulse amplitude varying with the RMS voltage can also be fitted as a quadratic function, and the statistical distribution of pulse amplitude follows normal distribution.

On the basis of the obtained statistical results, a stochastic model is proposed to simulate the sound pressure pulses from AC corona discharge. After the validity of stochastic model is given, the stochastic model is used to analyse tones emission under the modulating influence from AC voltage. Furthermore, the influence of measurement time on the SPL is discussed on the basis of the stochastic model. It can be found that measurement time should be >0.2 s in order to insure the resultant SPL is independent of the measurement time.

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