Analysis of Ion Flow Field of UHV/EHV AC Transmission Lines

Han Yin, Bo Zhang, Jinliang He, *Fellow*, *IEEE*, Rong Zeng, and Wei Li
State Key Lab of Power Systems, Department of Electrical Engineering, Tsinghua University,
Beijing 100084, China
Email: hanyin1986@gmail.com

Abstract-- In this paper, the calculation algorithm of ion flow field of AC transmission lines based on charge simulation method (CSM) is improved. In previous works, the problem is solved in time domain with representing the space charges as discrete infinite line charges. In each discrete time step, the procedures of charge emission, displacement, and recombination are simulated. As improvements, the influence of nonuniform distribution of conductor surface electric field on corona discharge is counted in, so that the ion flow field of multi-phase and bundle conductors can be simulated in this work. Better agreement than the previous work is obtained between the calculation results and the experiment results, verifying the validity of the improved algorithm.

I. INTRODUCTION

Corona phenomenon is an important issue of HV power transmission lines. The discharge generates positive ions and negative charges (ions and electrons), which are called space charges [1]. On AC transmission lines, the space charges are constrained to the near vicinity of the conductor because of the periodic reversal of the electric field. The movement of the space charges consumes energy, which is called corona loss. Furthermore, the space charges may affect the space electric field, even on the ground level.

This work improves the AC corona loss calculation method proposed by Salam [4]-[5]. The major contribution is the new processing procedures of corona onset and charge emission calculation, taking account of the nonuniform distribution of conductor surface electric field. The algorithm is described at first. And then, the validation of the algorithm based on corona loss analysis is presented.

II. COMPUTATIONAL METHOD

A. Process overview

The first step of AC ion flow field simulation is to calculate the corona onset charge based on Kaptzov's assumption [2-4], according to which the electric field on coronating conductor surface is considered to maintain at the onset value. Then, the alternating cycle is divided into discrete time steps. In each time step, corona discharge takes place where the conductor simulation charge is larger than the corona onset charge. And then, a certain quantity of charge emits from conductor to space. The space charges migrate by the electric field force and reduce by the recombination effect. This procedure is carried out cyclically until meeting the termination criterion. Then, corona parameter such as corona loss can be gained with further calculation.

B. Calculation of the onset charge

The most important step of this algorithm is to calculate the charges emitted from coronating conductor surface into space according to Kaptzov's assumption. However, the emitted charges are difficult to be deduced directly from this assumption on field value. For this reason, the concept of corona onset charge is introduced in [4]. The corona onset charge is defined as the total conductor simulation charge when the maximum space-charge-free electric field on conductor surface exceeds the onset value and is assumed time-invariant and calculated once for all. If the total conductor simulation charge exceeds the corona onset charge, the corona discharge occurs uniformly and the excess charge emits to space evenly around the conductor surface.

However, the electric field on conductor surface is affected by the space charges and is not uniformly distributed especially for multi-phase and bundle conductors. In this work, the conductors are represented as infinite simulation line charges, as shown in Fig. 1. The corona onset charge is defined on each discrete point rather than a total value in [4]. The new definition of corona onset charge on a single point is the simulation charge of this point when the applied voltage and space charges make the surface field near this point equal to the onset value. Therefore, the corona onset charge is time dependent and calculated at the beginning of each time step with space charges of the last time step.

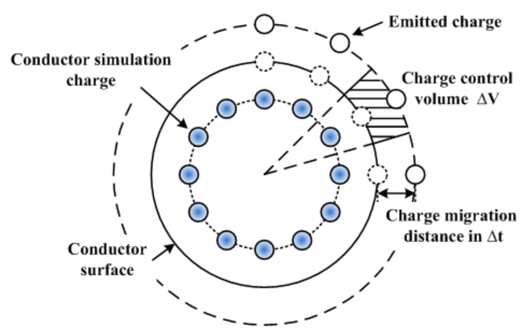

Fig. 1 Charge emission process

Assume the number of conductor simulation charges is m, the number of space charges is n (because of charge emission and recombination, n is a time dependent variable $n(t)$). The corona onset charge of point r on conductor surface can be calculated as follows:

$$\boldsymbol{P}_c \cdot \boldsymbol{q}_c' + \boldsymbol{P}_s \cdot \boldsymbol{q}_s = \boldsymbol{V}_{onset} \quad (1)$$

$$\boldsymbol{R}_{c,r} \cdot \boldsymbol{q}_c' + \boldsymbol{R}_{s,r} \cdot \boldsymbol{q}_s = E_{onset} \quad (2)$$

In (1), $\boldsymbol{P}_c$ ($m\times m$) represents the potential coefficient matrix between conductor charges and surface points. $\boldsymbol{P}_s$ ($m\times n$) represents the potential coefficient matrix between space charges and surface points. $\boldsymbol{q}_c'$ ($m\times 1$) represents the conductor charge vector when the field on point r just meets the onset value. $\boldsymbol{q}_s$ ($n\times 1$) represents the space charge vector. $\boldsymbol{V}_{onset}$ ($m\times 1$) represents the conductor potential when the corona discharge just occurs on point r, the values of which are equal as the conductor surface is equipotential.

In (2), $\boldsymbol{R}_{c,r}$ ($1\times m$) represents the field coefficient matrix between conductor charges and surface point r. $\boldsymbol{R}_{s,r}$ ($1\times n$) represents the field coefficient matrix between space charges and surface point r. $\boldsymbol{R}_{c,r}$ and $\boldsymbol{R}_{s,r}$ are actually scalar vectors, the elements of which are projected to the normal direction of the conductor surface. E_{onset} is the corona onset field, which can be calculated by Peek's formula [5].

From (1) and (2) we can obtain (m+1) equations. If the values of $\boldsymbol{q}_s$ are taken as that of the last time step, the unknown (m+1) variables $\boldsymbol{q}_c'$ and $\boldsymbol{V}_{onset}$ are solved. The r-th element $q_{c,r}'$ of $\boldsymbol{q}_c'$ is the corona onset charge $q_{onset,r}$ of point r.

The above process is taken on every conductor surface points. Then, the corona onset charge $\boldsymbol{q}_{onset\pm}$($m\times 1$) is solved.

C. Space charge emission

Similar as (1), the conductor simulation charge $\boldsymbol{q}_c$ ($m\times 1$) corresponding to the conductor voltage can be calculated as:

$$\boldsymbol{P}_c \cdot \boldsymbol{q}_c + \boldsymbol{P}_s \cdot \boldsymbol{q}_s = \boldsymbol{V}_c \tag{3}$$

where, $\boldsymbol{V}_c=\boldsymbol{V}_{\max}\sin[\omega(i\text{-}1)\Delta t]$, i=1, 2, …, N, N+1, …, 2N, … is the conductor voltage at the present time step, $\omega=2\pi/T$ is the angular frequency, $\Delta t=T/N$ is the time step, T is the period.

On each time step, conductor simulation charge $\boldsymbol{q}_c$ and corona onset charge $\boldsymbol{q}_{onset\pm}$ are calculated respectively and compared. If $q_{c,r} > q_{onset+,r}$ or $q_{c,r} < q_{onset-,r}$, corona discharge occurs on point r, and the exceeded charge ($q_{c,r}$-$q_{onset\pm,r}$) emits from point r into space.

D. Space charge displacement

The displacement of a charge in time interval Δt is [5]:

$$\Delta\vec{d}_j[(i-1)\Delta t] = \mu\vec{E}_j[(i-1)\Delta t]\Delta t \tag{4}$$

where, μ is the ion flow mobility, 1.5×10^{-4} $m^2\cdot V^{-1}\cdot s^{-1}$ for positive charge and 1.8×10^{-4} $m^2\cdot V^{-1}\cdot s^{-1}$ for negative charge. $\vec{E}$ is the total field calculated by CSM.

E. Space charge recombination

For the calculation of space charge recombination, volume dominated by each charge is defined by the location of the charge in two successive time steps, as the shadow part shown in Fig. 1. Positive and negative charge densities are:

$$\rho_{j\pm} = \frac{q_{s,j\pm}}{e\Delta V_j} \tag{5}$$

where, ΔV_j is the charge control volume, $q_{s,j\pm}$ is the positive or negative space charge, $e=1.6\times10^{-19}$ C is the electron charge.

Then the recombination process can be expressed as [5]:

$$q_{s,j\pm}(t+\Delta t) = \frac{1}{1+\left|\gamma\rho_{j\pm}\Delta t\right|} q_{s,j\pm}(t) \tag{6}$$

where, $\gamma=1.5\times10^{-12}$ $m^2\cdot s^{-1}$ is the recombination coefficient.

The space charge, decreasing due to the recombination, is removed from the calculation process if the density is lower than a certain value.

F. Termination criterion

The convergence is considered to be achieved if the total space change between two adjacent periods is less than a certain value. That means:

$$\left|\frac{q_{s,sum}(MT) - q_{s,sum}[(M-1)T]}{q_{s,sum}[(M-1)T]}\right| < \varepsilon \tag{7}$$

where, $q_{s,sum}(MT)$ represents the total space charge generated in the M-th period, and ε represents the error tolerance.

G. Calculation of corona loss

The average power consumed in one period caused by the charge movement in the electric field can be calculated as:

$$P = f\sum_{i=1}^{N}\sum_{j=1}^{n(i)} q_{s,j}[(i-1)\Delta t]\vec{E}_j[(i-1)\Delta t]\cdot\Delta\vec{d}_j[(i-1)\Delta t] \tag{8}$$

where, f=1/T is the AC frequency.

III. VALIDATION BASED ON CORONA LOSS ANALYSIS

Literature [5] provides the simulating and experimental results of corona loss of a single line-to-plane structure. The radius of conductor is 3.28 mm, and the height is 2.59 m. The results are illustrated in Fig. 2, where curve A is experimental result, B is the calculating result in [5] with conductor roughness factor of 0.7, and C is the calculating result in our work with the same roughness factor. The results indicated that the new approach is better than the previous one.

The actual multi-phase and bundle conductor transmission lines can also be analyzed, which will be presented in the full paper owing to the limit of the 2 page digest.

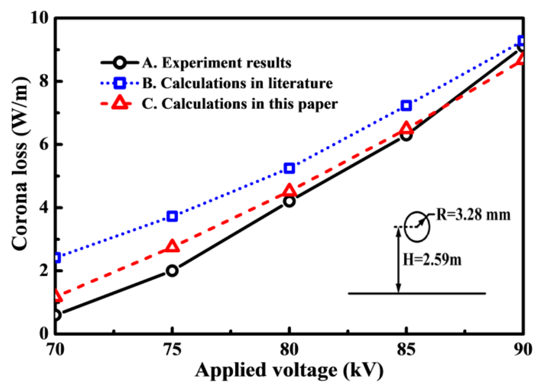

Fig. 2 Corona loss calculation and experiment result of single conductor

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