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An Approximate Calculation Method of Broadband Impedance of GIS Pipe Brackets

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Abstract. In Gas Insulated Switchgear (GIS) substation, the grounding bracket of GIS pipe is used to support GIS pipe, meanwhile, it's a part of grounding system connecting GIS pipe to grounding grid. The frequency of transient enclosure voltage(TEV) generated during switching operation of disconnector in gas insulated switchgear (GIS) with no-load short busbar can be up to tens or even hundreds of megahertz(MHz). Because of the impact of skin effect and proximity effect, the impedance of bracket will vary considerably with frequency. A simple and effective method of broadband impedance modeling was proposed based on electromagnetic field numerical calculation method and the physical structure of the grounding bracket in this paper. At last, the validity of the method was verified through calculating and analyzing some typical grounding bracket.

1. Introduction

GIS has been widely used in 110kV and above voltage levels substations. The circuit breaker, disconnector, grounding switch, voltage and current transformer, lightning arrester, busbar, cable termination, inlet and outlet casing, etc. are integrated into GIS pipe. With the development of Ultra-high voltage power grid, TEV with high frequency and amplitude resulted from switching operation[1-2] or Lightning impulse[3] may cause serious interference on the normal operation of secondary equipment, surface insulation of pipe and grounding voltage[4-7].

The grounding bracket used to support GIS pipe is part of grounding system connecting GIS pipe to grounding grid meanwhile. The frequency of transient enclosure voltage(TEV) generated during switching operation of disconnector in gas insulated switchgear (GIS) with no-load short busbar can be up to tens or even hundreds of megahertz(MHz), so the calculation modelling of grounding bracket can be not used as usually[8-10]. The impedance of bracket is a constant when DC current flow past. As frequency increases, equipotential of enclosure and grounding grid cannot be maintained at a normal value due to high impedance characteristics of grounding lead and pipe supper caused by skin

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effect and proximity effect, so it's very meaningful to establish an accurate model of grounding bracket for studying TEV and its influence on secondary equipment.

Establishing an accurate model of grounding bracket is difficult because of unclear propagation characteristics of TEV in some complex structural bracket. A simple and accurate aproximate calculation method calculating and analysing some typical grounding bracket is studied in this article. The complex structural grounding bracket can be taken as a combination of multiple single conductors which internal resistance and partial self-inductance can be extracted from an electromagnetic field numerical calculation software based on moment method named ANSYS Q3D Extractor at a certain frequency[11-12]. There are some processes about aproximate calculation method as follows: At first, a circuit road must be composed by a variable resistance and a variable inductance extracted from software Q3D; And then, a complete broadband equivalent circuit model of bracket can be constructed by each circuit road connecting according to the physical structure of the bracket, meanwhile the mutual inductance of different circuit road need be considered in hole circuit model with frequency increasing[13-17]; Last, verifying the correctness of approximate calculation through comparing the impedance result calculating by circuit model and electromagnetic field numerical method.

2. Applicable frequency of electromagnetic field numerical method

2.1. Applicable frequency verification of simple circle conductor by numerical method

Skin effect existing in current-carrying conductors at high frequencies, the formula of internal impedance is shown as follows in formula (1):

$$Z_i = R_i + j\omega L_i = \frac{k}{2\pi\sigma r_w}\frac{\mathrm{J}_0(kr_w)}{\mathrm{J}_1(kr_w)} \tag{1}$$

Where, $k = \frac{1-j}{\delta}, \delta = \sqrt{\frac{2}{\omega\mu\sigma}}$, J0 and J1 are Bessel functions, r_w representing radius, l representing length, σ representing conductivity, L_i representing internal inductance of circle conductors.

The formula of partial self-inductance of one circle conductor shows in formula (2):

$$L_p = \frac{\mu_0}{2\pi} l \left[\ln\left(\frac{l}{r_w} + \sqrt{\left(\frac{l}{r_w}\right)^2 + 1} \right) - \sqrt{\left(\frac{r_w}{l}\right)^2 + 1} + \frac{r_w}{l} \right] \tag{2}$$

So, the analytic formula for the total partial self-inductance of a single circular conductor can be shown as follows in formula (3):

$$L = L_i + L_p \tag{3}$$

Frequency changing from DC to 100MHz in this article, the single circle conductor is shown in figure 1 whose r_w is 0.5cm and l is 1.2m and σ is 1.1×10^6S/m.

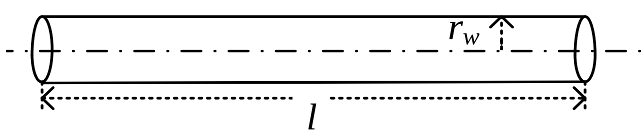

Figure 1. Schematic diagram of single conductor.

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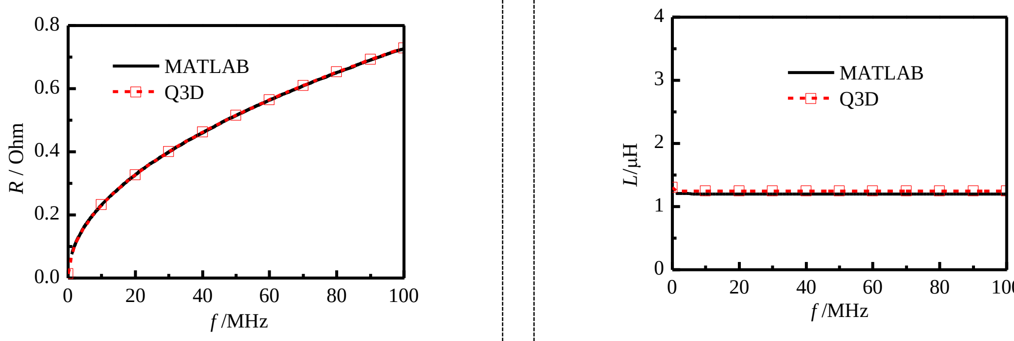


(a) Variable internal resistance changing with frequency

(b) Total partial self-inductance changing with frequency

Figure 2. Impedance parameters of single conductor

The value of variable internal resistance and total partial self-inductance changing with frequency of single circle conductor extracted from software Q3D is compared with the value from formula (1) and formula (3) showing in figure 2. From the figure 2, we can know that the value of internal resistance is increasing with frequency because of skin effect, but total partial self-inductance is not changing when the frequency reaches a certain level.

The result of two methods is completely same, and the electromagnetic field numerical calculation method is applicable within 100MHz.

2.2. Applicable frequency verification of simple rectangular conductor by numerical method

The analytical formula of internal impedance of rectangular conductor whose length is 2L, width is 2a, and height is 2D, the width of the overcurrent is 2b shown as formula (4)[18]:

$$Z_i=\frac{1}{4\sigma aD}\left[2L\frac{KD}{\mathrm{th}(KD)}+\sum_{m,n=1}^{\infty}\frac{\left(K^2+K_{yn}^2\right)\mathrm{th}\left(\sqrt{K^2+K_{xm}^2+K_{yn}^2}L\right)}{K_{yn}^2\sqrt{K^2+K_{xm}^2+K_{yn}^2}}\times C_m^2D_n^2\right.$$
$$\left.+\frac{KD}{\mathrm{th}(KD)}\sum_{m=1}^{\infty}\frac{\mathrm{th}(K_{xm}L)}{K_{xm}}C_m^2+\sum_{n=1}^{\infty}\frac{\sqrt{K^2+K_{yn}^2}}{K_{yn}^2}\mathrm{th}\left(\sqrt{K^2+K_{yn}^2}L\right)D_n^2\right] \quad (4)$$

Where, $K=\sqrt{j\omega\mu\sigma}$, $C_m=2\frac{\sin(K_{xm}b)}{K_{xm}b}$ $D_n=-2\frac{(-1)^nK^2}{K^2+K_{yn}^2}$. The value of Z_i gets convergence when $m=100, n=100$, L'_i representing internal inductance of rectangular conductors

The formula of partial self-inductance of rectangular conductor shows in formula (5):

$$L_e=\frac{\mu 2L}{4\pi}\left[\ln\left(\frac{\sqrt{L^2+a^2}+L}{\sqrt{L^2+a^2}-L}\right)+\frac{L}{a}\ln\left(\frac{\sqrt{L^2+a^2}+L}{\sqrt{L^2+a^2}-L}\right)-1\right] \quad (5)$$

And the formula for the total partial self-inductance of a single rectangular conductor can be shown as follows in formula (6):

$$L'=L'_i+L_e \quad (6)$$

The value of total partial self-inductance changing with frequency of single rectangular conductor extracted from software Q3D is compared with the value from formula (6) showing in figure 3 when 2L=1m, 2a=5cm, 2D=2mm, $\sigma=1.1\times10^6$S/m.

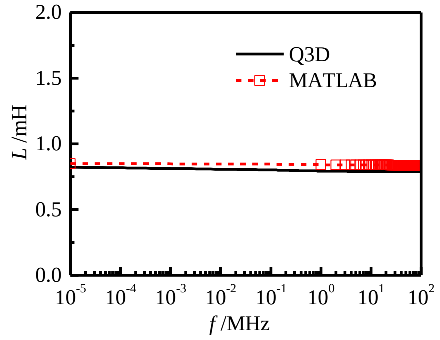


Figure 3. Frequency total partial self-inductance of single rectangular conductor.

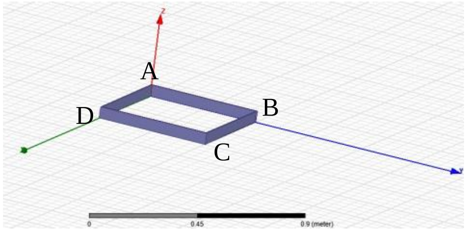


Figure 4. The simulation model of simple square bracket.

From figure 3, the maximum relative error is 6% when the frequency gets to 100MHz, satisfying the accuracy requirement of engineering computation. So the electromagnetic field numerical calculation method is applicable within 100MHz for rectangular conductor.

2.3. *Applicable frequency verification of simple grounding bracket by numerical method*

The simulation model of simple square bracket formed by rectangular conductors whose length is 0.5m, width is 5cm, and height is 5mm, σ is 1.1×10^{6}S/m shown as figure 4, *R* and *L* are for frequency dependent resistance and total partial self-inductance of rectangular conductors respectively extracted from software Q3D.

The formula of mutual inductance *M* of two parallel conductors in [11] is shown as formula (7).

$$M=\frac{\mu_0}{4\pi}\Big[(l+s+m)\sinh^{-1}\frac{l+s+m}{d}-(s+m)\sinh^{-1}\frac{s+m}{d} -(l+s)\sinh^{-1}\frac{l+s}{d}+s\sinh^{-1}\frac{s}{d}-\sqrt{(l+s+m)^2+d^2} +\sqrt{(s+m)^2+d^2}+\sqrt{(l+s)^2+d^2}-\sqrt{s^2+d^2}\Big] \tag{7}$$

Where, the length of two conductors are represented by *l* and *m*, vertical distance represented by *d* and *s*. For square bracket, the formula of circuit equivalent impedance *Z* of bracket can be deduced in (8), and its impedance also can be extracted from Q3D. The current flows from point A to point C in simulation, and the value of total partial self-inductance comes from two methods basically in coincidence within 100MHz in figure 5.

$$Z=R+j\omega(L+M) \tag{8}$$

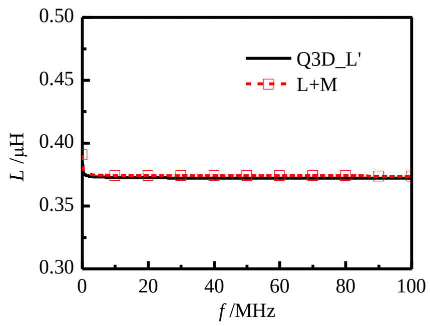


Figure 5. Frequency dependent inductance of simple square bracket.

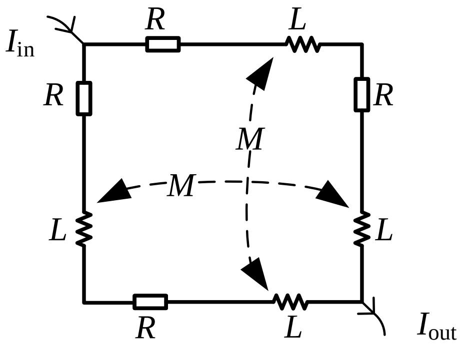


Figure 6. Approximate broadband circuit of simple square bracket.

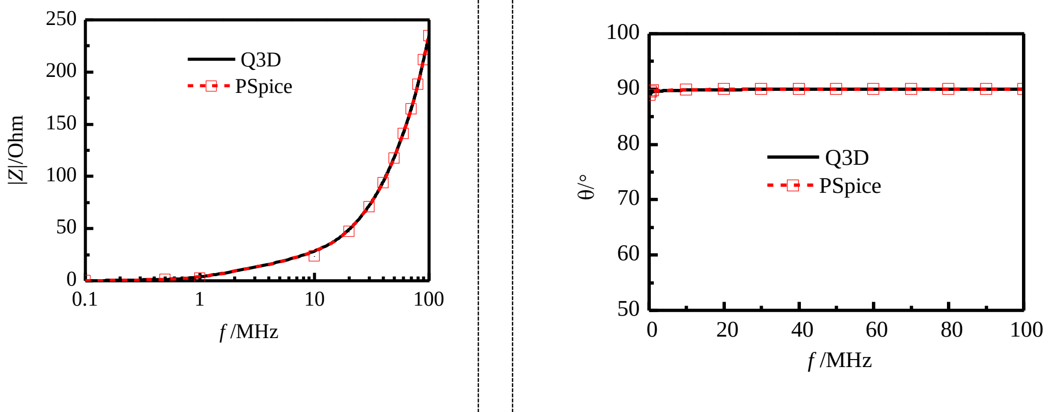
3. Approximate broadband circuit modelling of bracket

Different brackets can be formed by different signal conductors, and brackets in GIS substation are varied. The approximate broadband circuits of three kinds of brackets and their impedance characteristics analysis are discussed in this part.

The approximate broadband circuit of a bracket is formed by *R* and *L* extracted from software Q3D, and mutual inductance *M* in formula (7), and its each circuit branch is connected by bracket structure.

3.1. The square bracket and its approximate broadband circuit

Approximate broadband circuit of simple square bracket in figure 4 is shown in figure 6. The power condition in two methods that approximate broadband circuit method and numerical method is same and the results of two methods are shown in figure 7.



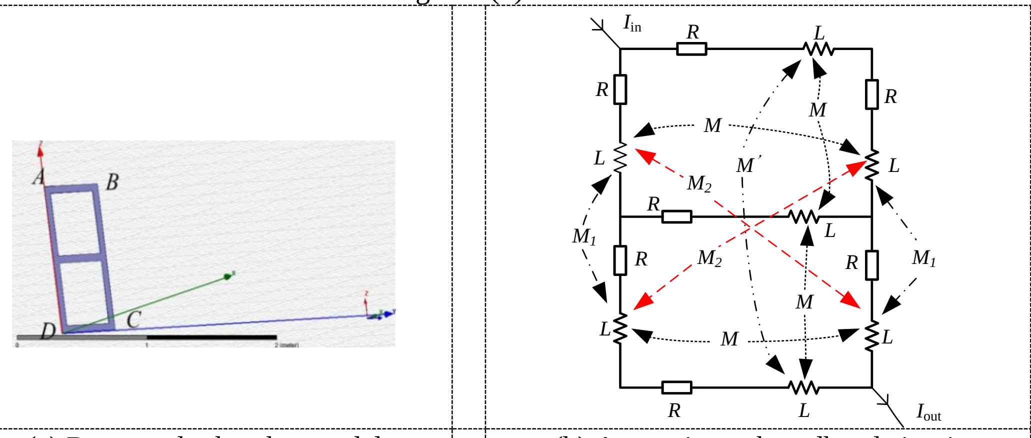
(a) Amplitude frequency characteristics (b) Phase frequency characteristics

Figure 7. Impedance characteristics of simple square bracket

In figure 7, it can be seen that the amplitude-frequency and phase-frequency characteristic curves of the two methods are in good agreement when the frequency is lower than 100MHz.

3.2. The rectangular bracket and its approximate broadband circuit

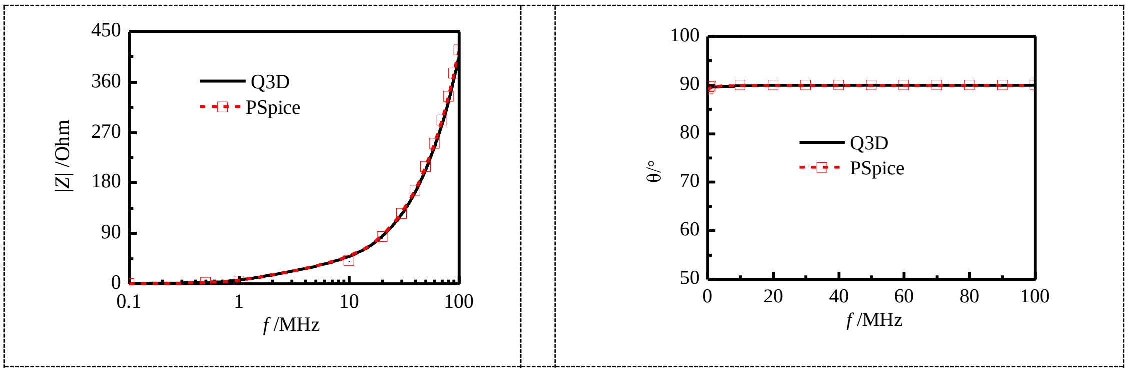
The rectangular bracket as shown in figure 8(a) which is composed of signal rectangular conductors with a length of 0.5 m, a width of 5 cm, a height of 5 mm and a conductivity of 1.1×10^{6} S/m, its approximate broadband circuit is shown in figure 8(b).



(a) Rectangular bracket model (b) Approximate broadband circuit

Figure 8. Rectangular bracket and approximate broadband circuit

Where, the amplitude frequency characteristics and phase frequency characteristics calculated by two methods that approximate broadband circuit method and numerical method of rectangular bracket vary with frequency are shown respectively in figure. 9(a) and 9(b). Current is injected from vertex A and flowed out from vertex C in simulation.



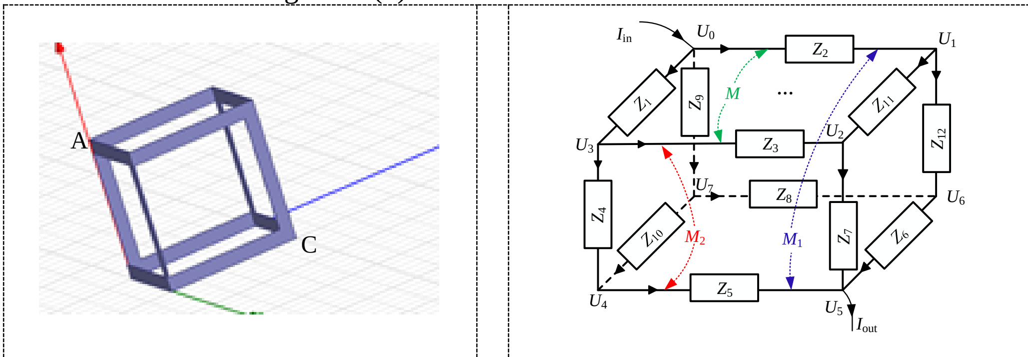
(a) Amplitude frequency characteristics (b) Phase frequency characteristics

Figure 9. Impedance characteristics of rectangular bracket

With the increase of frequency, the impedance characteristic curves of the two methods basically coincide with each other, and the consistency is very good in figure 9. For this type of bracket, the pipeline bracket model can be established simply and conveniently by approximate broadband circuit method.

3.3. *The cube bracket and its approximate broadband circuit*

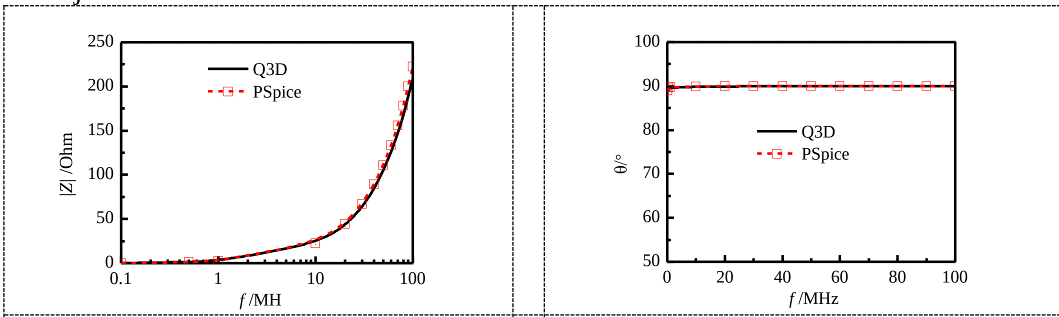
The cube bracket as shown in figure 10(a) which is composed of signal rectangular conductors with a length of 0.5 m, a width of 5 cm, a height of 5 mm and a conductivity of 1.1×10^6 S/m, its approximate broadband circuit is shown in figure 10(b).



(a) Cube bracket model (b) Approximate broadband circuit

Figure 10. Cube bracket and approximate broadband circuit

The amplitude frequency characteristics and phase frequency characteristics calculated by two methods of rectangular bracket vary with frequency are shown respectively in figure. 11(a) and 11(b). Current is injected from vertex A and flowed out from vertex C in simulation.



(a)Amplitude frequency characteristics (b) Phase frequency characteristics

Figure 11. Impedance characteristics of cube bracket

From the comparison of the amplitude-frequency characteristic curve and phase-frequency characteristic curve shown in Figure. 11, with the increase of frequency, it can be seen that the maximum relative error of the amplitude-frequency characteristic curve is 6% obtained by approximate broadband circuit method and the simulation of electromagnetic field numerical calculation software Q3D, and the phase-frequency characteristic curve is completely consistent, that the error is acceptable.

In the three different brackets discussed above, when the frequency is below 100MHz, the relative error of amplitude-frequency and phase-frequency characteristics of brackets between approximate equivalent circuit method and numerical method is within permissible limits. Combined with substation bracket structure, the approximate broadband circuit method can be used to model the bracket at 100MHz frequency.

4. conclusions

An approximate calculation method of broadband impedance of GIS pipe brackets is put forward in this article, and the conclusions are summarized as follows according to the data comparison from simulations above.

- Numerical analysis method can be used to calculate internal resistance and total partial self-inductance of single conductor and brackets exactly when the frequency is below 100MHz.
- Based on numerical calculation of electromagnetic field, combined with the physical structure of brackets, approximate broadband circuits of square bracket, rectangular bracket and cube bracket are established.
- The relative error of impedance characteristics of brackets is acceptable between approximate equivalent circuit method and numerical method with frequency in 100MHz. The approximate calculation method can be used in equivalent circuit modelling for complex crackets.

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