GIS vibration principal analysis and modeling

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Abstract. Based on the most basic electromagnetic theorem, this paper analyses the most basic principle of GIS vibration formation. The characteristic formulas of magnetostriction and Ampere force vibration are deduced, and the characteristic frequencies of them are both 100Hz. Combined with the structural characteristics of GIS, this paper analyzes the two common vibration models of induced eddy current and induced circulation, and calculates their analytical formulas, which can easily calculate the induced current, and provides a reference for GIS vibration research.

1. Introduction
SF6 enclosed switchgear, also known as "gas insulated switchgear" (hereinafter referred to as GIS). With the extensive use of GIS and the increasing requirements of power grid for safe operation, more and more attention has been paid to the analysis and solution of GIS vibration fault. On the one hand, vibration will produce noise and affect the surrounding environment; on the other hand, long-term vibration will cause stress fatigue of components, accelerate the aging of equipment and increase the hidden danger of insulation failure. Therefore, it is an inevitable trend to carry out the research and application of GIS vibration technology. But for a long time, people pay more attention to the technical research of insulation and discharge, and the research on vibration is relatively less. At the same time, the structure of GIS is complex and diverse, and its vibration generation and propagation process is very complex. If we want to carry out vibration test and analysis, we must first understand the basic principle and mathematical model of GIS vibration [1]. This paper first introduces the electromagnetic force and magnetostrictive effect, then analyzes the eddy current effect and circulation effect, establishes the mathematical model of GIS vibration from micro to macro, and finally analyzes the influence factors of circulation induction through finite element modeling, trying to explain the vibration principle of GIS clearly.

2. Basic concepts of GIS vibration
Electromagnetic vibration is one of the main vibration sources of GIS in operation, and it is also one of the important parameters to measure the electromechanical state of GIS in operation. According to the different mechanism, the electromagnetic vibration of GIS can be divided into magnetostrictive vibration and Ampere force vibration. If the enclosure material of GIS is ferromagnetic, such as iron and stainless steel, the alternating magnetic field will cause magnetostrictive vibration after passing
through the ferromagnetic material; however, if the enclosure material of GIS is composed of aluminum or non-magnetic domain steel, the electromagnetic vibration of GIS is only the vibration excited by Ampere force [2]. The formation mechanism of magnetostriction and Ampere force are different, so the key to study GIS electromagnetic vibration is to realize the theoretical modeling and analytical calculation of GIS induced current.

Due to the closed and compact structure of the metal shell of the combined electrical apparatus, electromagnetic induction will occur between the shell and the grounding device and the internal high-voltage current device during operation, which is the fundamental cause of vibration. Figure 1 is a simple schematic diagram of GIS induced eddy current and circulation. When GIS is running, the current of conducting pole excites the magnetic field. When the magnetic field passes through the metal device such as the shell, the induced eddy current will form on the surface of the metal shell. In addition, because GIS mostly adopts complex grounding (multi-point grounding), GIS shell, grounding wire, (auxiliary) grounding grid, phase to phase diversion bar form external closed circuit. If the magnetic field excited by the current of the conducting pole passes through the GIS shell, ground wire and (auxiliary) ground grid to form an external loop, the external loop will generate the induced circulating current. For three-phase common box GIS, the three-phase current is relatively symmetrical, and the electromagnetic induction counteracts each other, so the electromagnetic induction phenomenon is weak; for three-phase sub box GIS, the electromagnetic induction phenomenon is obvious.

The magnetic field excited by the current of GIS conducting rod meets Biot-Savart law, the eddy current and circulating current induced by GIS meet the law of electromagnetic induction, and its direction can be determined according to Lenz’s law. The following is a brief introduction and analysis of these basic physical concepts:

1) Biot-Savart law

The magnetic induction intensity $dB$ of current element $ldl$ at a point P in vacuum is directly proportional to the size of current element, directly proportional to the sine of the angle $\theta$ between the vector $r$ from current element to point P, and inversely proportional to the second power of the distance $r$ from current element to point P,

$$dB = k \frac{ldl\sin\theta}{r^2}$$  \hspace{1cm} (1)
Where $k$ is the scale factor. Therefore, the magnetic induction $B$ of any current carrying wire at point $P$ can be calculated as follows:

$$B = \int dB = \int \frac{\mu_0 I}{4\pi} \frac{dl \times e_r}{r^2}$$  \hspace{1cm} (2)

Where $e_r$ is the unit vector along the vector $r$, and the calculation principle is shown in Figure 2. During the operation of GIS, the current of conducting rod can excite the magnetic field, and the current of enclosure can also excite the magnetic field. Under the joint action of the two, the off-site magnetic flux leakage can be formed.

![Figure 2. Direction of magnetic induction intensity of current element](image)

2) Law of electromagnetic induction

Electromagnetic induction phenomenon: when the magnetic flux passing through the enclosed area of a closed conductor circuit changes, no matter what the reason is, there is current in the circuit. This phenomenon is called electromagnetic induction phenomenon. For GIS in complex grounding system, the alternating magnetic field generated by high voltage pole current will pass through the closed circuit formed by external grounding. Based on the electromagnetic induction phenomenon, the closed conductor loop formed by GIS shell has electromagnetic induction phenomenon under the alternating magnetic field. In addition, each external loop is induced by each other, and the magnetic field excited by the loop current (circulating current) affects each other.

Law of electromagnetic induction: when the magnetic flux passing through the enclosed area of the closed loop changes, no matter what the reason is, the induced electromotive force will be established in the loop, and the induced electromotive force $\varepsilon$ is proportional to the negative value of the magnetic flux to the time change rate. Let $\Phi$ be the magnetic flux passing through the enclosed area of the loop. If the loop is composed of $n$ turns and the magnetic flux passing through each turn is $\Phi$, then the total magnetic flux turn is $\psi = N\Phi$ and $\psi$ is the flux linkage. The law of electromagnetic induction can be regarded as

$$\varepsilon = -\frac{d\psi}{dt}$$  \hspace{1cm} (3)

According to the characteristics of GIS grounding and enclosure, the enclosure, grounding wire and grounding grid of GIS form a closed conductor loop, and the conducting rod and interphase guide bar also form a closed conductor loop. If the loop resistance is $r$, the induced current is

$$I = -\frac{1}{R} \frac{d\psi}{dt}$$  \hspace{1cm} (4)
3) Lenz’s law
When the magnetic flux passing through the area surrounded by the closed loop changes, there will be induced current in the loop. The direction of the induced current always makes its own magnetic field pass through the magnetic flux of the loop area to compensate for the change of the magnetic flux causing the induced current. It is found that the direction of GIS induced circulating current is roughly opposite to the current direction of conducting rod. In the complex grounding system of GIS, due to the existence of induced circulating current, it plays a good role in electromagnetic shielding, which is consistent with Lenz’s law.

3. Principle analysis of electromagnetic vibration

3.1. Magnetostriction and Ampere force

3.1.1. Magnetostriction. There are two kinds of GIS shell materials, one is aluminum alloy or non-magnetic cast steel, the other is stainless steel. For the former, there is no vibration caused by magnetostriction. The latter belongs to ferromagnetic material. The alternating magnetic field will cause magnetostriction and vibration after passing through the ferromagnetic material

\[ \varepsilon = \frac{\Delta l}{l} = CH^2 = k_{\varepsilon} \cos^2(\omega t) \]  

(5)

Where, \( C \) is the magnetostrictive coefficient of GIS ferromagnetic component, \( H \) is the magnetic field intensity in the component, and \( k_{\varepsilon} \) is the coefficient. Then the acceleration of magnetostriction is

\[ a = \frac{d^2(\Delta l)}{dt^2} = -k_{\varepsilon}' \cos(2\omega t) \]  

(6)

According to equation (3-6), the frequency of GIS magnetostrictive vibration acceleration is twice of power frequency.

3.1.2. Ampere force vibration. The enclosure, conducting rod and grounding device of GIS are all metal components. During operation, the metal components vibrate under the action of current and magnetic field, that is ampere force vibration. Ampere force is the force of magnetic field on current element, which is equal to the product of the magnitude of current element, magnetic induction and the sine of the angle between current element and magnetic induction. The magnetic field in GIS is generated by the current in the conducting pole and each induced current, which is cosine and recorded as \( B_\tau \).

\[ B_\tau = k_\tau \cos(\omega t) \]  

(7)

Where \( k_\tau \) is the coefficient. The current in GIS component is also cosine, which is recorded as \( I_\nu \)

\[ I_\nu = k_\nu \cos(\omega t) \]  

(8)

Where \( k_\nu \) is the coefficient. Then the ampere force \( F \) in GIS component is

\[ F = I_\nu \cdot B_\tau = k_\nu k_\tau \cos^2(\omega t) = \frac{1}{2} k_\nu k_\tau (\cos(2\omega t) + 1) \]  

(9)
It can be seen from equation (3-9) that the frequency of Ampere force under GIS operation is twice that of power frequency. Therefore, the vibration of GIS under ampere force is 2 times of power frequency.

3.2. Induced eddy current and circulation

3.2.1. Induced eddy current. Fig. 3(a) is the eddy current schematic diagram of conductive rod current induced in GIS shell. According to biotsavart's law, the magnetic field excited by the current of the conducting rod follows the right-hand rule, and the direction of the magnetic circuit is parallel to the cross section of the shell. When the magnetic field passes through the GIS shell, according to the principle of electromagnetic induction, the induced eddy current is generated to counteract the change of the magnetic field. The induced eddy current is concentrated on the inner and outer surface of the shell, and the direction is the same as the axial direction of the conductive rod [3]. The current density of the eddy current on the outer surface is slightly less than that on the inner surface because the area of the outer surface of the GIS is larger than that on the inner surface.

Figure 3. Schematic diagram of induced eddy current:
(a) Conducting rod; (b) External magnetic flux leakage

Fig. 3(b) is the schematic diagram of magnetic flux leakage induced eddy current in GIS shell. In addition to the magnetic field excited by the conductive rod, the external leakage magnetic field will also induce eddy current in the GIS shell. The external magnetic flux leakage field strength is roughly uniform, but the GIS shell is cylindrical, the magnetic flux leakage field strength at the axis is the largest, and the magnetic flux leakage field strength on both sides decreases slowly. Considering the symmetry effect of induced eddy current, the eddy current at the axis is zero and the eddy current at both sides
increases. It can be seen from Fig. 3(b) that the induced eddy current of external magnetic flux leakage on GIS shell is also consistent with the axial direction of conductive rod.

Above, the paper analyzes the induced eddy current and its distribution of GIS shell under the two factors of conductive rod and external magnetic flux leakage by using the method of principle graphics analysis, and finds that the direction of GIS eddy current is always the same as the direction of conductive rod, concentrated on the inner and outer surface of the shell, which is symmetrical.

According to the distribution of the induced eddy current in the GIS shell in Figure 4, and combined with the algorithm of Ampere force, it can be seen that the electromagnetic force of the eddy current excited by the conductive rod in the shell in the leakage magnetic field is perpendicular to the inner and outer surfaces of the shell and in the opposite direction; the electromagnetic force of the eddy current excited by the leakage magnetic field in the shell in the leakage magnetic field is perpendicular to the upper and lower outer surfaces of the shell and in the opposite direction; the two kinds of ampere forces are tensile and compressive. The frequency is 2 times of the power frequency.

3.2.2. Circulation

1) Calculation of self-inductance and mutual inductance parameters

GIS has the characteristics of compact structure. When GIS is running, there is a strong electromagnetic coupling phenomenon between the internal high voltage structure and the external grounding system.

![Figure 4. Calculation structure of GIS induction parameters](image)

Figure 4 is a representative structural unit of GIS. In reality, there is mutual inductance between the conducting rod and the external circuit; there is self-inductance between each external circuit; there is mutual inductance between any two external circuits. Take Figure 4 as an example to calculate the mutual inductance between the conducting rod and the external circuit.

In Figure 4, the electric field strength of the conducting pole at point P is as follows:

\[
B_{pl} = \frac{\mu_0 i}{4\pi(h_l - y)} (\cos \theta_1 - \cos \theta_2)
\]

\[
= \frac{\mu_0 i}{4\pi(h_l - y)} \left(\frac{l_1 + x}{\sqrt{(l_1 + x)^2 + (h_l - y)^2}} + \frac{l_2 + x}{\sqrt{(l_2 + x)^2 + (h_l - y)^2}}\right)
\]
In formula: \( \cos \theta_1 = \left( l_3 + x \right) \sqrt{\left( l_3 + x \right)^2 + \left( h_1 - y \right)^2} \); \( \cos \theta_2 = \left( l_2 + x \right) \sqrt{\left( l_2 + x \right)^2 + \left( h_1 - y \right)^2} \).

The total flux of the current of the conducting rod in the rectangular area of ABCD is as follows:

\[
\psi_L = \iint_{D} B_{PL} \, dx \, dy
\]  

(11)

The integral region is \( D = \{(x, y)|0 < a < x < l_1 - a, 0 < b < y < h_2\} \). The mutual inductance between conducting rod and shell circuit is as follows:

\[
M_{L} = \frac{\psi_L}{I_L}
\]  

(12)

The external loop of GIS can be regarded as a single turn rectangular coil. The field strength of point P can be regarded as the vector sum of field strength produced by four current carrying conducting poles. The electric field strength at point P under the action of external loop current is as follows:

\[
B_{ps} = \frac{\mu_0 I_s}{4\pi} \left[ \frac{\sqrt{x^2 + y^2}}{xy} + \frac{\sqrt{x^2 + (h - y)^2}}{x(h - y)} + \frac{\sqrt{(l_1 - x)^2 + y^2}}{l_1 - x} + \frac{\sqrt{(l_1 - x)^2 + (h - y)^2}}{(l_1 - x)(h - y)} \right]
\]  

(13)

The total flux of the external loop in the rectangular area of ABCD is:

\[
\psi_S = \iint_{D} B_{ps} \, dx \, dy
\]  

(14)

The self-induction of ABCD in rectangular region is as follows:

\[
L_S = \frac{\psi_S}{I_S}
\]  

(15)

2) Calculation of induced current

At present, there are few researches on GIS induced circulation, mainly relying on field test, and there is no theory to systematically express GIS external circulation. Here, we put forward the balance equation of GIS external flux linkage, which can be used to calculate the induced current of GIS.

For three-phase split GIS, if the external loop is n, the flux balance equation is as follows:

\[
\hat{I}_{loop} = -K^{-1} P \hat{I}_{phase} + \hat{I}_c
\]  

(16)

The parameter matrices in the above formula are as follows:
$K = \begin{bmatrix}
L_1 & M_{11} & \cdots & M_{11} & \cdots & M_{11} \\
M_{12} & L_2 & \cdots & M_{12} & \cdots & M_{12} \\
\vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\
M_{1n} & M_{2} & \cdots & L_1 & \cdots & M_{1n} \\
M_{2n} & \cdots & \cdots & \cdots & \cdots & \cdots \\
M_{nn} & M_{nn} & \cdots & M_{nn} & \cdots & L_n
\end{bmatrix}$

(17)

$I_{\text{loop}} = \begin{bmatrix}
\dot{I}_1 \\
\dot{I}_2 \\
\vdots \\
\dot{I}_i \\
\vdots \\
\dot{I}_n
\end{bmatrix}^T$

(18)

$I_{\text{phase}} = \begin{bmatrix}
\dot{I}_{A} \\
\dot{I}_{B} \\
\dot{I}_{C}
\end{bmatrix}^T$

(19)

$\psi_\sigma = \begin{bmatrix}
\psi_{1\sigma} \\
\psi_{2\sigma} \\
\vdots \\
\psi_{i\sigma} \\
\vdots \\
\psi_{n\sigma}
\end{bmatrix}^T$

(20)

$P = \begin{bmatrix}
M_{1A} & M_{1B} & M_{1C} \\
M_{2A} & M_{2B} & M_{2C} \\
\vdots & \vdots & \vdots \\
M_{iA} & M_{iB} & M_{iC} \\
\vdots & \vdots & \vdots \\
M_{nA} & M_{nB} & M_{nC}
\end{bmatrix}$

(21)

Where $K$ is the self-inductance and mutual inductance matrix of GIS external circuit, $P$ is the mutual inductance matrix between GIS conductive pole and external circuit, $I_{\text{loop}}$ is the calculation circulating current matrix, $I_{\text{phase}}$ is the phase current matrix, and $\psi_\sigma$ is the residual flux matrix. According to the above equation, the external induced circulation can be calculated only by determining the induction parameters of GIS.

The circulating current distributed on the GIS shell and the grounding rod and the magnetic flux leakage on site will also produce electromagnetic force, which will cause the GIS structure vibration.

4. Conclusion

(1) Electromagnetic force and magnetostriction are two basic sources of GIS vibration. The electromagnetic force is caused by the electromagnetic field excited by conductive parts such as conducting pole and coil. Magnetostriction occurs in GIS whose enclosure is made of ferromagnetic materials such as iron and stainless steel, but it does not occur in GIS with aluminum or steel enclosure without magnetic domain.

(2) The vibration characteristic frequency of electromagnetic force and magnetostriction is twice the power frequency, that is 100Hz.

(3) Eddy current and circulating current are two kinds of macroscopic vibration forms of electromagnetic induction in GIS structure. Their analytical equations have been listed steadily. The characteristic frequency is the same as that of electromagnetic force, which is twice as high as that of power frequency of 100Hz.

(4) The formation mechanism of eddy current and induced circulation is clarified, and their vibration model and analytical formula are obtained. The current value can be obtained by substituting the specific parameters of GIS into the formula.
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