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Electric Field Characteristics under Three-phase Voltage in Three-phase Gas Insulated Switchgear

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Abstract: This paper deals with electric field characteristics under three-phase voltage in three-phase gas insulated switchgear (GIS). Three-phase equipment differs from single-phase equipment in two aspects: configuration and applied voltage. In this paper the effects of these differences on electric field in three-phase GIS are reported. There are periodic changes in the electric field magnitude and direction produced by three-phase voltage at any point. While the voltage phase varies, the electric field vector changes and rotates continuously. The rotating characteristics of the electric field vector in three-phase power apparatus depended on the position inside the insulation of the tank. The electric field vector locus is circular, elliptic, or linear. The elliptical nature of rotating electric field is expressed as electric field ratio. The mathematic description of the rotating electric field is given considering the maximum and the minimum electric field and the position inside the insulation. There is no zero electric field under three-phase voltage. The areal velocity of the electric field vector locus is constant. The electric field vector moves slowly in a high electric field area, but moves quickly in a low electric field area.

Keywords: three-phase, rotating electric field, vector locus

1. Introduction

Application of three-phase equipment (three-phase in one tank) such as three-phase gas insulated switchgear (GIS) and three-phase gas insulated bus (GIB), has been increasing due to its compactness and low cost [1-9]. A three-phase in one-tank design has also been developed for 550 kV GIS [7]. Therefore, the knowledge on the electric field inside three-phase electric power apparatuses under three-phase voltage is very important. The knowledge on three-phase electric field is useful for electric equipment and insulation design and analyzing electric phenomena inside the insulation of equipment such as electric stress and internal discharges.

Three-phase equipment differs from single-phase equipment in two aspects: configuration and applied voltage as shown in Figure 1. It can be expected that the electric field characteristic will be different from that in single-phase equipment. In this paper the effects of these differences on electric field inside three-phase GIS are studied.

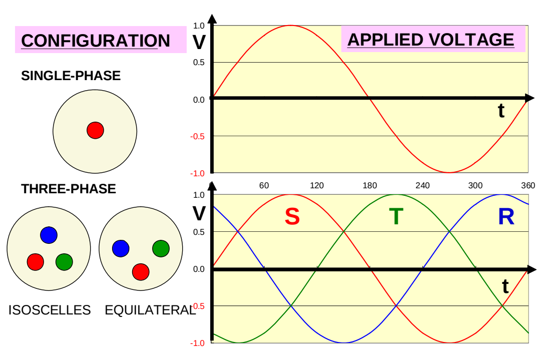

Figure 1. The difference between single-phase and three-phase equipment

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2. Model of Three-Phase GIS

A simplified model of three phase GIS was used in this research. It was composed of a tank model 150 mm in diameter, 300 mm in length, 2 mm in thickness, and three-phase conductors 25 mm in diameter.

The electrode system was arranged to simulate three-phase electric field in three-phase equipment. The conductors were arranged in an isosceles triangle construction. The layout and dimensions of the model are shown in Figure 2.

3. Electric Field Calculation

The calculation method of electric field inside three-phase equipment has been developed since more than thirty years ago [11-17]. The newest simulation method and the result in three-phase electric field calculation are described in [17].

In this research the electric fields inside the insulation of the construction were determined from a boundary element method simulation: along a circle among the phases and the tank, along vertical line starting from the bottom of the tank, along line connecting the centers of conductor phases, and around the conductor. The electric field calculation is two dimensional.

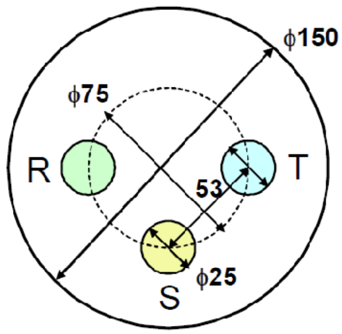


Figure 2. Layout of simplified model of three-phase gas insulated switchgear

4. Electric Field Analysis and Discussion

A. Distribution of Three-phase Electric Field

Figure 3 shows the change of electric field distribution with phase of applied voltage. Here,θs is the phase angle of S phase of applied voltage. The blue color in the figure reveals that the electric field intensity is the lowest, while the red color reveals that the electric field intensity is the highest. The electric field distribution pattern varies with phase of applied voltage. Every a half cycle the pattern of electric field stress is repetitive.

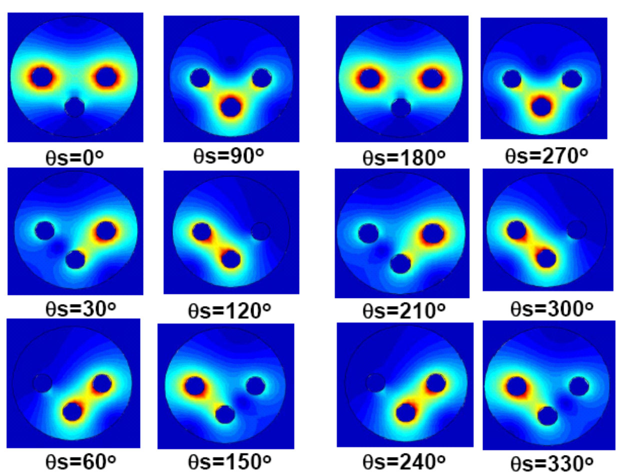
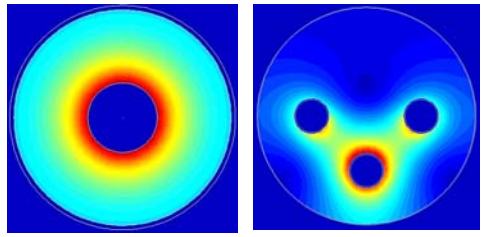


Figure 3. Change of electric field distribution with phase of applied voltage



Single Phase Three Phase

Figure 4. Electric field distributions inside single-phase equipment and three-phase GIS

Figure 4 shows the difference in electric field distribution between single-phase and three-phase equipment. The electric field distribution pattern in single-phase equipment is independent of phase of applied voltage, while one in three-phase equipment changes with the change of applied voltage.

B. Periodic Changes of Electric Field Vector under Three-phase Voltage

Figure 5 shows the change in the pattern of the electric field vector at 5 mm below the center of the tank during one cycle of applied voltage. It seems that there are periodic changes in electric field magnitude and direction produced by three-phase voltage at any point. While the voltage phase varies from 0 to 2π, the electric field vector changes and rotates continuously. Note, that there is no zero electric field in three-phase construction. When the voltage of one of phases equals to zero, the voltage in the other phases is not zero.

These results differ significantly with the electric field vector characteristics inside single phase GIS under single phase voltage. Figure 6 shows the change in the pattern of the electric field vector anywhere inside single-phase GIS during one cycle of applied voltage.

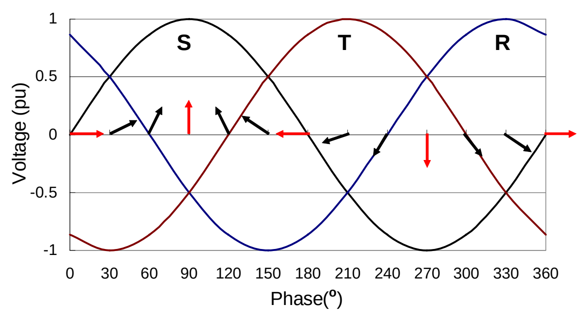


Figure 5. Pattern of the electric field vector at 5 mm below the center of the tank of three-phase GIS during one cycle of applied voltage

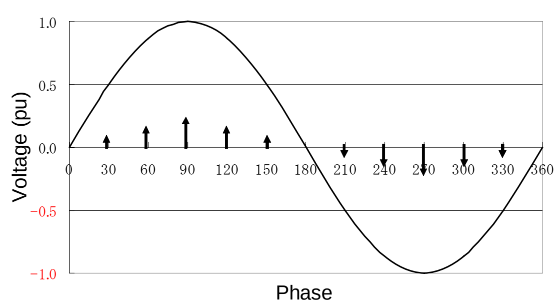


Figure 6. Pattern of the electric field vector during one cycle of applied voltage in single-phase GIS

The magnitude of electric field vector changes with the applied voltage, but the electric field vector direction is unchanged during half cycle. During the other half cycle, the directions of the electric field vector become the opposite. Note, that there are zero electric fields in single-phase construction. When the voltage is zero, the electric field is zero.

C. Rotating Characteristics of Three-phase Electric Field Vector

Figure 7 shows the change of the electric field vector at 5 mm below the center of the tank of three-phase GIS during one cycle of applied voltage in three-phase equipment. The locus is drawn based on the pattern of electric field vector in Figure 4.

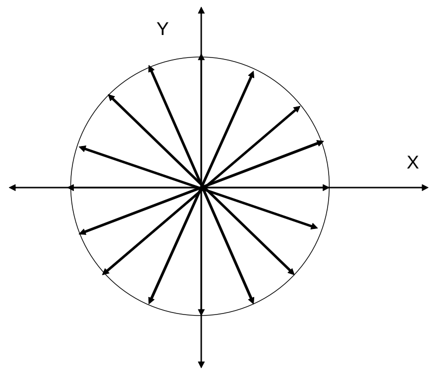


Figure 7. Locus of the electric field vector at 5 mm below the centre of the tank of three-phase GIS during one cycle of applied voltage

It appears that the electric field vector direction rotates and changes continuously. The electric field locus is circular during one cycle of applied voltage. Note, that there is no zero electric field in three-phase construction.

These results differ significantly with the electric field vector locus inside single phase GIS under single phase voltage. Figure 8 shows the electric field vector locus anywhere inside single-phase GIS during one cycle of applied voltage.

The magnitude of electric field vector changes with the applied voltage, but the electric field vector direction is unchanged during half cycle. During the other half cycle, the direction of the electric field vector becomes the opposite. There are zero electric fields in single-phase construction. When the voltage is zero, the electric field is zero.

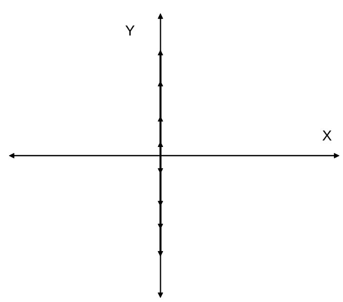


Figure 8. Locus of the electric field vector during one cycle of applied voltage in single-phase GIS

D. Pattern and Locus of Rotating Electric Field Vector

Figure 9 shows the locus of the electric field vector at different points. Here, while the vector locus is elliptic, its shape varies locally. On the electrode surface the locus is linear because the electric field lines are vertical to the conductor surface.

At some regions, for example at point A, the locus is elliptic. Meanwhile, at point B, which is 5 mm below the centre of the tank, the locus is truly circular. It is also found that the electric field vector locus between the phases and the tank is almost linear, resembling that in a single-phase configuration; while that between phases has variations: linear, elliptic, and circular.

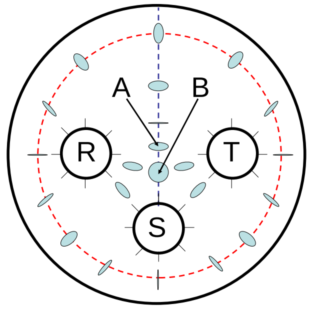


Figure 9. Electric field vector loci in isosceles triangle arrangement of three-phase construction without particle

E. The Mathematics Description of Rotating Electric Field Vector

The rotating electric field at a certain position (x,y) can be described by four parameters: the maximum Emax (x,y) and minimum Emin (x,y) field strength, the phase angle of applied voltage θ max (x,y) at maximum field Emax (x,y), and field direction ϕ max (x,y) at maximum field [11]. These parameters are illustrated in Figure 10.

δ_V in the figure is defined as the angle that designates the intersection width of the electric field vector locus and critical electric field circle Ecr.

The elliptical nature of rotating electric field is expressed as electric field ratio, η . It is defined as the ratio between the magnitudes of the elliptical field along the main axes,

η = Emin / Emax (0< η <1)

where:

Emin: minimum electric field intensity at a certain point during a cycle of applied voltage

Emax: maximum electric field intensity at a certain point during a cycle of applied voltage

When the electric field ratio $\eta = 0$, the electric field vector locus is linear. When the electric field ratio $0 < \eta < 1$, the electric field vector locus is elliptic. When the electric field ratio $\eta = 1$, the electric field vector locus is circular.

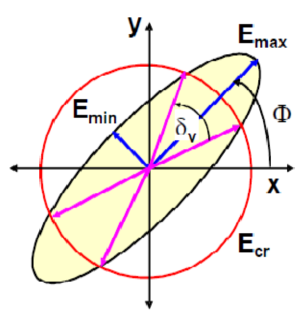


Figure 10. Rotating electric field parameters

F. Elliptical Nature of The Electric Field Vector Locus

The electric field vector locus at different points, those are at the distances 0 mm (A), 5 mm (B), 10 mm (C), 15 mm (D), 20mm (E), and 25 mm (F) away from S conductor in the absence of particle are shown in Figure 11.The points are laid between S conductor and the center of three-phase GIS. The electric field ratio changes from η =0 at S conductor surface (point A) to η =0.2 at point B, η =0.4 at point C, η =0.7 at point D, η =1 at point E.

Here, while the vector locus is elliptic, its shape varies locally. On the electrode surface (at Point A) the locus is linear because the electric field lines are vertical to the conductor surface. At some regions, for example at point B, C, D, the locus is elliptic. Meanwhile, at point E, which is 5 mm below the center of the tank, the locus is truly circular.

If a point approaches the center of the cross section of the tank, the maximum electric field reduces; while the minimum electric field increases as shown in Figure 12. The minimum and maximum electric fields are same at point E (20 mm from S conductor). The electric field vector locus changes from linear to circular when the points keep away from S conductor (point A) to the point 5 mm below the center of the three-phase construction (point E). The electric field ratio (η) changes from 0 until 1 from point A until E.

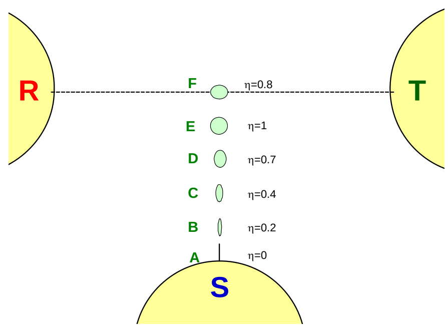


Figure 11. The electric field vector locus at the distances 0 mm (A), 5 mm (B), 10 mm (C), 15 mm (D), 20mm (E), and 25 mm (F) away from S conductor

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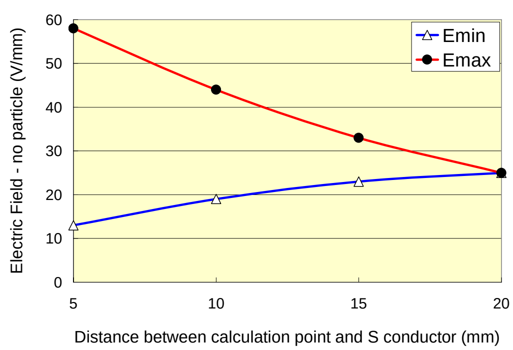

Figure 12. Minimum and maximum electric field from point B (5mm from S conductor) until point E(20mm from S conductor) without particle

G. Rotating Electric Field Characteristics

Figure 13 illustrates the absolute electric field for three different positions during a cycle of the applied voltage V_a. E_{max} at each position is the same, while the electric field ratio η is different, designated by η_1, η_2, and η_3, where $\eta_1 > \eta_2 > \eta_3$.

It is clear that at a certain position (x,y) inside the three-phase construction, the field is rotating with varying magnitudes, i.e, sinusoidal in two perpendicular directions without necessarily coinciding at zero crossings. For the same maximum electric field, there may be various values of the electric field ratio η at different positions.

The other important characteristic of three-phase electric field is the difference in the angular velocity of the applied voltage and the angular velocity of the electric field vector. The angular velocity of the applied voltage Va is constant, while the angular velocity of the electric field always changes. The areal velocity of the electric field vector locus is constant. The electric field vector moves slowly ina high electric field area, but moves quickly in a low electric field area.

$v_{avr} = v = \omega_{min} E_{max} = \omega_{max} E_{min}$

The maximum angular velocity ω_{max} of electric field vector locus is estimated as change in the direction of the electric field vector with time at minimum electric field, i.e.

$\omega_{max} = d\varphi / dt$ at $E = E_{min}$

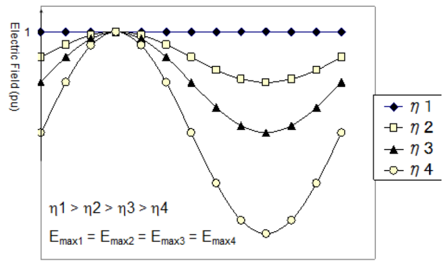

Figure 13. The absolute electric field for three different positions during a cycle of the applied voltage V_a

5. Conclusions

Three-phase equipment differs from single-phase equipment in two aspects: configuration and applied voltage. In this paper effects of these differences on the electric field in three-phase gas insulated system (GIS) are reported. The electric field in a three-phase construction of a simplified GIS model was analyzed. The following conclusions were drawn:

1. The electric field distribution pattern varies with phase of applied voltage.
2. Every a half cycle the pattern of electric field stress is repetitive.
3. There are periodic changes in the electric field magnitude and direction produced by three-phase voltage at any point.
4. While the voltage phase varies from 0 to 2π, the electric field vector changes and rotates continuously.
5. There is no zero electric field in three-phase construction.
6. The results are compared with the electric field characteristics under single-phase voltage in single-phase electric power apparatuses.
7. Electric field vector locus in the region between conductor and the enclosure is almost linear, resembling a single-phase construction; while ones between conductors have variations: linear, elliptic, circular.
8. The elliptical nature of rotating electric field is expressed as electric field ratio. The mathematic description of the rotating electric field is given considering the maximum and the minimum electric field and the position inside the insulation.
9. The areal velocity of the electric field vector locus is constant. The electric field vector moves slowly in a high electric field area, but moves quickly in a low electric field area.

The results are compared with the electric field characteristics under single-phase voltage in single-phase electric power apparatuses. There is a distinct difference between electrical field characteristics of single-phase and three-phase configurations.

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