Research on Breaking Arc Characteristics of Circuit Breakers Under Harmonic Current

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***Abstract*—In recent years, a large number of new energy sources such as wind power and photovoltaics have been continuously connected to the grid, and the power system has gradually shown a trend of power electronics. The problem of excessive harmonics has gradually become prominent, which has greatly affected the safe and stable operation of the power grid. There is a risk of failure to break the circuit breaker when the harmonic is exceeded. Studying the influence of harmonics on the breaking of switchgear and formulating effective countermeasures are important technical measures to ensure the safe and reliable operation of the power grid. In this paper, by establishing an arc magnetohydrodynamic model under harmonic currents, the circuit breaker breaking characteristics under harmonic currents are developed. Studies have shown that the existence of harmonics in the system will cause the current change rate di/dt to increase significantly at the time of the current zero-crossing point in the circuit breaker opening process, and with the increase of the harmonic amplitude, the di/dt becomes larger; Existence will cause the arc voltage amplitude and rate of rise before zero crossing during the circuit breaker opening process to decrease; the presence of harmonics will cause the temperature of the arc extinguishing chamber to rise during the circuit breaker opening process; the above harmonics will affect the opening process It is not conducive to the successful opening of the circuit breaker.**

Keywords—harmonic, arc model, arc characteristics

I. INTRODUCTION

In recent years, a large number of new energy sources such as wind power and photovoltaics have been continuously connected to the grid, and the power system has gradually shown a trend of power electronics. The problem of excessive harmonics has gradually become prominent, which has greatly affected the safe and stable operation of the power grid. There is a risk of failure to break the circuit breaker when the harmonic is exceeded. Studying the influence of harmonics on the breaking of switchgear and formulating effective countermeasures are important technical measures to ensure the safe and reliable operation of the power grid.

Since the 1990s, domestic and foreign scholars have carried out a lot of research work on arc simulation. In order to estimate the thermal breaking capacity of the SF6 circuit breaker, Fang [1] et al. used Prandtl mixed length turbulence model theory to analyze the dynamic characteristics of the nozzle SF6 arc before and after the current zero crossing. Professor Wu Yi from Xi’ an Jiaotong University studied the joint solution method of switching arc and circuit in MRTB, studied the interaction law of SF6 arc volt-ampere characteristics and circuit parameters [2], and calculated the critical breakdown field of SF6 and its mixed gas Strong changes with temperature, the calculation results have been verified by experiments [3]. Sun Hao of Xi'an Jiaotong University and others established an arc non-equilibrium model of the zero current zone of the nozzle arc extinguishing chamber, and proposed a method to verify the calculation model by means of plasma diagnosis [4]. Based on researches at home and abroad, it is found that the theoretical research on the internal arc of SF6 circuit breakers is still concentrated under the conditions of DC or power frequency AC. There are few reports on the numerical calculation model of SF6 breaking capacity under harmonic current, and there is a lack of complicated actual working conditions. Quantitative calculation research on the degree of influence of each harmonic on the breaking capacity of the switch.

In this paper, by establishing an arc magnetohydrodynamic model under harmonic currents, the effects of different harmonic frequencies and harmonic content on the arc breaking characteristics of circuit breakers are studied respectively.

II. MODELING OF THE ARC PLASMA

A. The governing equations of arc plasma

To simplify the analysis, numerical simulation of arcs in SF6 follows the assumptions below: (1) The arc plasma is in local thermodynamic equilibrium condition. (2) The arc plasma has axisymmetric structure. (3) The electron emission and ion bombardment on the electrode surface are neglected. (4) Ablation effects of the electrodes and nozzle are neglected.

The MHD model which contains fluid equations and electromagnetic equations was adopted in this paper. The governing equations are shown in (1)-(8):

$$\frac{\partial \rho}{\partial t}+\nabla\cdot\left(\vec{u}\rho\right)=0 \qquad (1)$$

$$\frac{\partial}{\partial t}\left(\rho\vec{u}\right)+\nabla\cdot\left(\rho\vec{u}\vec{u}\right)=-\nabla p+\nabla\cdot\left(\vec{\tau}\right)+\vec{j}\times\vec{B} \qquad (2)$$

$$\frac{\partial}{\partial t}\left(\rho E\right)+\nabla\cdot\left(\vec{v}\left(\rho E+p\right)\right)=\nabla\cdot\left(k\nabla T+\left(\vec{\tau}\cdot\vec{v}\right)\right)-P_{rad}+\sigma E^2 \qquad (3)$$

$$\vec{j}=\sigma\vec{E}=-\sigma\nabla\varphi=-\sigma\left(\frac{\partial\varphi}{\partial r}\vec{e}_r+\frac{\partial\varphi}{\partial z}\vec{e}_z\right) \qquad (4)$$

$$\nabla\cdot\vec{j}=0 \qquad (5)$$

$$\nabla^2 A_r=\mu_0 j_r-\frac{A_r}{r^2} \qquad (6)$$

$$\nabla^2 A_z=\mu_0 j_z \qquad (7)$$

$$\vec{B}=\nabla\times\vec{A} \qquad (8)$$

Where ρ : mass density, t: time, μ : gas flow velocity, p: pressure, μ_0 : magnetic permeability, ∇ : Lagrange derivative, τ : stress tensor, j: current density, B: magnetic flux density, E: energy, k_{ef} : thermal conductivity, σ : electrical conductivity, E: electrical field, P_{rad} : radiation loss, φ : electrical potential, A: component of the magnetic vector potential.

The thermodynamic and transport properties of SF6 used in (1)-(4) at different temperatures and pressures were get from the Chen's [5] work. The approximate radiation transport model of Fang [6] which is based on the net emission coefficient has been used to calculate the radiation loss. Two-equation turbulence models allow the determination of turbulent length and time scale by solving two separate transport equations. For the K-epsilon model, they are related to the time-averaged turbulent kinetic energy, k, and dissipation rate ε [7].

B. *Calculation domain and boundary condition*

In order to reduce the computational complexity, the structure of a certain type of AC filter breaker was reasonably simplified, as shown in Fig. 1, which contained electrode, hollow electrode, cylinders, nozzle and fluids in the calculation domain. The boundary where Z=0m was set to the axis. The main electrode was neglected due to its small influence to the arc near the nozzle domain. The cylinder and the electrode were moved towards right in constant speed of 12 m/s.

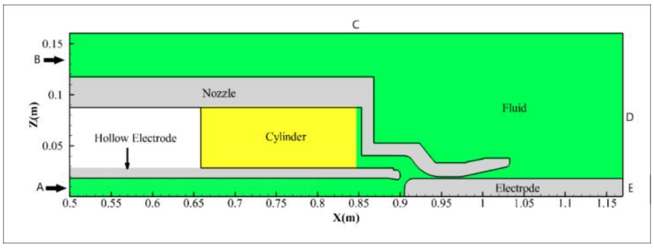


Fig. 1. Calculation domain of arc plasma

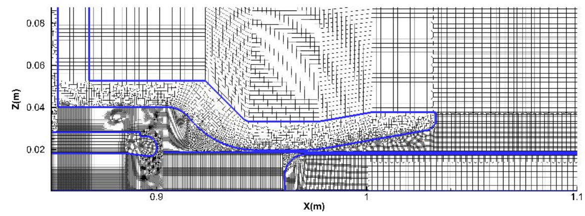


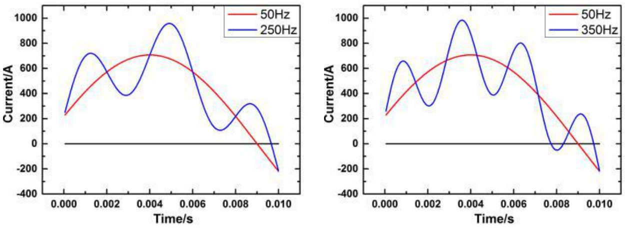
Fig. 2. Mesh of calculation domain

The initial pressure of fluid domain was set to 6E5 Pa, while the boundaries A,B,C and D were set to the pressure outlet with a constant pressure of 6E5 Pa and a constant temperature of 300K. The electric potential of the hollow electrode was set to zero. Since the current was mainly 50Hz in the simulation, the skin effect would not have a significant effect on the distribution of current density in the electrode, and the most accurate current density would be concentrated on the root of the arc, so the distribution of current density would not affect the calculation of arc plasma. In order to simplify the calculation of the electromagnetic field, the current density was evenly distributed on the cross section E in this paper. Other boundaries such as A, B, C and D were set to Norman boundary conditions, i.e. the current density was zero.

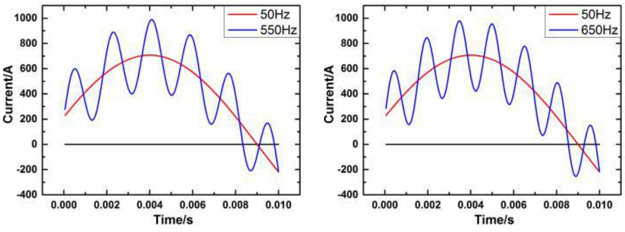
III. CALCULATION RESULTS AND ANALYSIS

A. *Arc current under different harmonic frequencies*

Under the conditions of fundamental wave current 500A and harmonic current 200A (harmonic content rate 40%), the arc current changes at different harmonic frequencies are shown in Fig. 3. It can be seen from the Fig. that the zero-crossing time of the power frequency current is 9ms, and when the 5th harmonic content rate is 40%, the zero-crossing point will be delayed. The zero-crossing time is 9.65ms with a delay of 0.65ms. When the 7th, 11th, and 13th harmonics have a content rate of 40%, the zero-crossing point will be advanced, and multiple zero-crossing oscillations will occur near the zero-crossing point. The higher the frequency, the more severe the multiple zero-crossing oscillations. Among them, the zero-crossing moments of 7 times, 11 times, and 13 times under this working condition are respectively 7.75ms, 8.35ms, and 8.55ms, which are respectively 1.25ms, 0.65ms, and 0.45ms earlier.



（a） 5th harmonic （b） 7th harmonic



（c） 11th harmonic （d） 13th harmonic

Fig. 3. Arc current waveforms at different harmonic frequencies

B. *di/dt of current zero-crossing point under different harmonic frequencies*

Under the conditions of fundamental wave current 500A and harmonic current 200A (harmonic content rate 40%), the change of arc current zero-crossing point under different harmonic frequencies is shown in Fig. 4. It can be seen from the Fig. that in the presence of harmonic currents, the arc current change rate at the zero crossing point is greater than the current change rate at the power frequency arc zero crossing point. Among them, when the harmonic content rate is 40%, the current change rate at the 5th, 7th, 11th and 13th zero-crossing points is 2.7 times, 1.6 times, 4.7 times and 5.9 times that of the power frequency respectively.Avoid combining SI and CGS units, such as current in amperes and magnetic field in oersteds. This often leads to confusion because equations do not balance dimensionally. If you must use mixed units, clearly state the units for each quantity that you use in an equation.

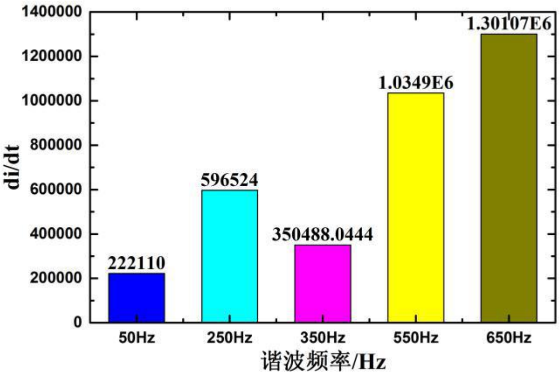
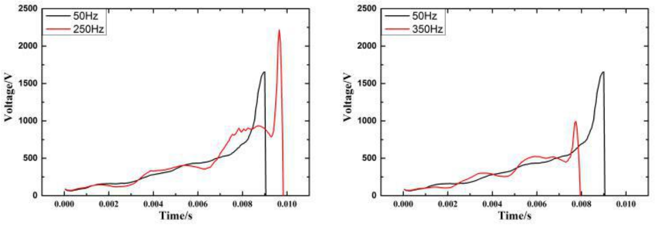


Fig. 4. di/dt of current zero-crossing point under different harmonic frequencies

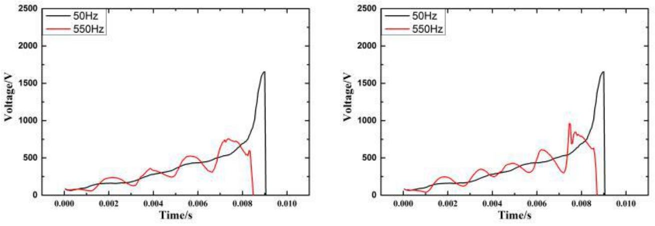
The arc process in the circuit breaker breaking process is the result of the combined effect of electron ionization and dissipation, and the gas temperature in the arc extinguishing chamber has a huge influence on both. The greater the change rate of the arc current at the zero-crossing point is, the gas energy in the arc extinguishing chamber is too late to dissipate. Under this working condition, the higher the temperature in the arc extinguishing chamber, the longer it takes for the SF6 gas to change from a conductor to an insulator through dissipation, which is not conducive to the success of the circuit breaker. Switch off. It can be seen from Fig. 4 that as the harmonic frequency increases, the greater the zero-crossing arc current change rate, the more unfavorable the successful opening of the circuit breaker.

C. *Arc voltage under different harmonic frequencies*

Under the conditions of fundamental current 500A and harmonic current 200A (harmonic content rate 40%), the arc voltage changes at different harmonic frequencies are shown in Fig. 5. Under the power frequency current, as the contact distance increases during the opening of the circuit breaker, the arc length increases, and the arc resistance increases. The arc voltage presents a nearly linear growth trend in the early stage. When approaching the current zero-crossing point, the current drops, the temperature in the arc extinguishing chamber drops, and the telephone resistance increases sharply. At this stage, the arc voltage presents a rapid rise trend, and the current zero point drops to zero instantaneously as the arc extinguishes. Under the power frequency current, SF6 fully demonstrates its excellent performance in arc extinguishing, that is, the arc voltage is low in the arc phase, the waveform is stable, and the arc voltage rises very quickly during the zero-crossing phase.



（a）5th harmonic （b）7th harmonic



（c）11th harmonic （d）13th harmonic

Fig. 5. Arc voltage under different harmonic frequencies

When there is a harmonic current, the arc voltage fluctuates in the early stage under the influence of arc current fluctuations, and as the harmonic frequency increases, the arc voltage fluctuates more severely. When approaching the current zero-crossing point, the existence of harmonics reduces the arc voltage amplitude and rise rate, which is more obvious in the case of the 11th and 13th harmonics. This is because under harmonic conditions, the zero-crossing current change rate is large, the heat in the arc extinguishing chamber is too late to dissipate, the gas conductivity decreases slowly, the arc voltage amplitude is low, and the rising rate becomes small. When the harmonic current exists, it reduces the excellent performance of SF6 gas in arc extinguishing.

D. *The temperature and pressure distribution of the arc extinguishing chamber under different harmonic frequencies*

During the breaking process of the circuit breaker, the temperature in the arc extinguishing chamber reflects to a certain extent the performance of SF6 gas thermal ionization and electrical conductors, and the pressure reflects to a certain extent the strong gas blowing generated by the pressurized cylinder. The temperature and pressure of the area on the axis below the nozzle are selected, as shown in Fig. 6.

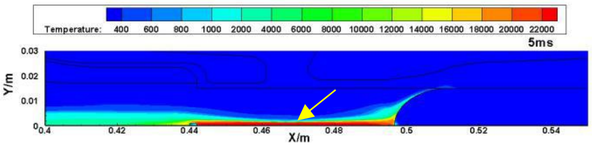
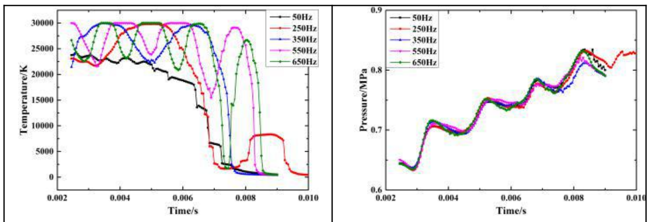


Fig. 6. Schematic diagram of the temperature and pressure monitoring area in the arc extinguishing chamber

Under the conditions of fundamental current 500A and harmonic current 200A (harmonic content rate 40%), the temperature and pressure in the arc extinguishing chamber under different harmonic frequencies change with time as shown in Fig. 7. It can be seen from the Fig. that the overall temperature in the arc extinguishing chamber under different harmonic conditions is higher than the temperature under the power frequency, and the existence of harmonics causes the temperature in the arc extinguishing chamber to fluctuate.

With the increase of the harmonic frequency, the temperature fluctuation becomes greater. obvious. The pressure in the arc extinguishing chamber presents a wave-shaped upward trend over time, and the pressure change trend under different harmonic conditions is less different from the power frequency. It can be considered that there is no influence on the pressure in the arc extinguishing chamber under harmonic conditions.



（a）The temperature distribution （b）The pressure distribution

Fig. 7. The temperature and pressure distribution of the arc extinguishing chamber under different harmonic frequencies

IV. CONCLUSION

1) The existence of harmonics in the system will cause the delay or advancement of the current zero-crossing time. Among them, the fundamental current is 500A, and the harmonic current is 200A (harmonic content rate is 40%), the 5th harmonic is delayed by 0.65ms, and the 7th is delayed. , 11 times and 13 times are advanced by 1.25ms, 0.65ms and 0.45ms respectively..

2) The existence of harmonics in the system will cause the current change rate di/dt to increase significantly at the time of the current zero crossing point during the breaking of the circuit breaker, and with the increase of the harmonic amplitude, the di/dt becomes larger.

3) The presence of harmonics will cause the arc voltage amplitude and the rise rate to decrease at the moment before zero crossing during the breaking of the circuit breaker.

4)The existence of harmonics will cause the temperature of the arc extinguishing chamber to increase during the breaking of the circuit breaker.

5)The influence of the above harmonics on the breaking process is not conducive to the successful breaking of the circuit breaker.

REFERENCES

[1] Fang M T C, Zhuang Q, Guo X J. Current zero behavior of an SF6 gas blast arc. Part II: turbulent flow[J]. Journal of Physics D-Applied Physics,1994,27(1):74-83.

[2] Li Yang, Yang Fei, Rong Mingzhe, et al., "Numerical Simulation of Self-excited Oscillation Switching Current in HVDC MRTB", High Voltage Engineering, 39(10), pp. 2547-2552, 2013.

[3] Wu Y, Wang W Z, Rong M Z, et al. Prediction of critical dielectric strength of hot CF 4 gas in the temperature range of 300-3500 K[J]. IEEE Transactions on Dielectrics and Electrical Insulation, 2014, 21(1): 129-137.

[4] Sun H, Tanaka Y, Tomita K, et al. Computational non-chemically equilibrium model on the current zero simulation in a model N2 circuit breaker under the free recovery condition[J]. Journal of Physics D: Applied Physics, 2015, 49(5): 055204.

[5] Chen Z, Wu Y ,Yang F , et al. 2017, Journal of Physics D: Applied Physics, 50.

[6] Bin W, Xiangxiang W, Guohui Z, et al. 2018, Proceedings of The Chinese Society for Electrical Engineering, 38:1496.

[7] Xiaofa Z, Xiangxiang W, Bin W , et al. 2017, Power System Protection and Control, 20:44.