ABSTRACT
With the development of the flexible low frequency transmission technology following the improvement of offshore wind power transmission, it is of great significance to investigate the operation adaptability of the main equipment especially under the low frequency conditions. A comparative study was performed in the present work to discuss the dynamic operation performance of a 252 kV/50 kA puffer-type circuit breaker influenced by the system operational frequency. Since the decreased operational frequency would result in a longer arc duration, a pre-designed driving mechanism with characteristics of high speed control was proposed and compared with a conventional unit. Moreover, as one of the reasonable indicators to evaluate the interruption performance of the circuit breaker, the critical rate of rise of recovery voltage (RRRV) that the circuit breaker can withstand after the arc extinguishment under different low frequencies were computationally obtained by an established arc model. The effects of the frequency change on the arc dynamic characteristics during the interruption of circuit breaker were comprehensively discussed as well and it could reasonably provide technical optimisation for the development of low-frequency-based circuit breaker for further engineering applications by analysing its interruption feasibility.

INDEX TERMS
Offshore wind power, low frequency, high speed control, RRRV, arc dynamic characteristics, interruption feasibility.

I. INTRODUCTION
The power generated by the offshore wind farms, as a fast-growing and cost-effective energy sources, becomes more attractive in the past few years and numerous countries are increasing their offshore wind power industry rapidly with a sustainable manner because of the high demand for clean energy. The high voltage alternative current (HVAC) with the nominal frequency of 50 Hz or 60 Hz and high voltage direct current (HVDC) are two proposed approaches for the transmission of offshore wind power. At the very beginning, the offshore wind farm is mostly connected to main power system through the HVAC transmission technology with a reasonable distance approximately within 100 km [1]. Due to the limited transmission distance, HVDC technology is developed more feasible for the long distance transmission. However, it is noticed that the application of offshore wind farms should be equipped with expensive converter stations, resulting in high cost of construction and maintenance. The space charge accumulation caused by HVDC transmission is a non-negligible problem as well [2], [3], [4]. With an in-depth consideration of above limitations, the flexible low frequency AC (LFAC) system was proposed with reducing the expense and increasing system reliability for the grid interconnection, which not only achieves the technique extension of HVAC transmission but also reduces the cost for using the converter stations during DC transmission.

The selected frequency for constructing the LFAC system should be satisfied with the demand for offshore wind power transmission and this was firstly suggested by Xifan Wang in
the form of fractional frequency transmission system (FFTS) at a frequency of 16.7 Hz [5]. The upper limit of frequency is recommended to be lower than 16.7 Hz to reduce harmonics output when using cycloconverter as the frequency converter in the LFAC system [6]. Following a comprehensive review of the development of LFAC system [7], a typical value of 16.7 Hz was applied in some European countries for railway systems while 25 Hz in the USA for some train systems [8].

Different from the LFAC applications for the railway system, a 220 kV flexible low frequency power transmission project was firstly and officially initiated in Hangzhou with choosing the frequency of 20 Hz in the first half of 2021 in China. This value is determined with considering the actual requirements and transmission distance of this project. Such project mainly achieves the low-frequency-based interconnection of the two major load centers of Fuyang and the southern of Xiaoshan by constructing frequency-changing stations on both sides of the completed 13.2 km/220 kV Tingzhong transmission line.

The topology of the LFAC system primarily contains the wind farm collection system, offshore platform and main grid system as the receiving end. It is constructed with frequency converter, transmission cable and primary equipment such as circuit breaker and transformer. Such apparatus is required to operate in low-frequency-based power system with sufficient adaptability. Especially for the circuit breaker which mainly controls and protects the electric power system, the decreased frequency would lead to a longer arc duration but lower $\frac{\text{d}i}{\text{d}t}$ of the current before final zero. This is because the physical current zero point would be delayed as a result of frequency decrease in comparison with that under the power frequency condition. It also indicates that the opening distance between the two arcing contacts when the current reaches its final zero would be longer due to the increased arc duration and the arc would be drawn longer with the contact movement as well. A larger effective cross-sectional area of nozzle surface would be exposed to the hot arc column, resulting in the stronger contact erosion and nozzle ablation, and finally shorten the electrical lifetime of the circuit breaker.

Recently, Jianning Yin preliminarily explored the effect of frequency on the arc behaviour of low voltage circuit breaker [9]. Tuan Ngo researched the LFAC transmission system and corresponding fault clearance characteristics [10]. In addition, Takafumi Okuma and et al. also studied the effects of driving frequency on the temperature of a multiphase arc [11]. ABB and SIEMENS also researched and developed low frequency -based electrical apparatus at 16.7 Hz such as 132 kV (66 kV to ground) circuit breaker, transformer and lightning arrester for the railway traction systems. Relevant research provides important references to study the characteristic of apparatus under the LFAC system.

With the development of power electronics, the frequency conversion within the grid system becomes more flexible and it underscores an urgent challenge to study the adaptability of the power-frequency-based circuit breaker in LFAC system, which requires a comparative study of the frequency change and its effects on the dynamic operation performance of the circuit breaker. Considering the long-time interval before the current passing its zero point in LFAC system, the extended arcing time of the circuit breaker, the high arc energy and the difficulty for interruption, the corresponding study could not only reasonably propose modified solutions for interrupting low frequency-based short circuit currents, but also essential for product optimum design. It also could provide references for subsequent research of phase selection techniques.

With considering the reasonable frequency range to satisfy the demand of grid connection with far offshore wind farms, the frequency variation researched in the present work ranges from 12.5 Hz (50/4) to 25 Hz (50/2) and a kind of 252 kV/50 kA puffer type circuit breaker is chosen as the model circuit breaker. The research strategy of present work is organised in following order, presenting an overview of the conventional AC circuit breaker with discussing the involved factors that influence its operation performance in the first part of section 2. A magnetohydrodynamics (MHD)-based arc model and its validity is then described in the second part of section 2. The model settings are verified with experimental results obtained by performing an interruption test duty of the short line fault type (SLF) L.90 for the model circuit breaker, which is shown in the third part. To study the effect of the driving mechanism on the operational performance of the model circuit breaker, two different travel characteristics of the moving components driven by the driving mechanism are compared in section 3. Furthermore, the influences of frequency variation on the arc dynamic behaviour and interruption capability of the model circuit breaker are further discussed in section 3. Conclusions are finally drawn in section 4.

II. MHD-BASED MATHEMATICAL ARC MODEL

A. OVERVIEW OF CONVENTIONAL AC CIRCUIT BREAKER

As a key protection apparatus, the circuit breaker is operated to isolate a faulty part of the grid system timely and maintain the system stability. The essential role of the circuit breaker is to interrupt the fault current passing through it successfully and it involves complicated physical-chemical processes. The interruption capability of the circuit breaker is predominantly determined by the establishment of the dynamic environment of the flow field, especially before the current passes its final zero point. It is mainly affected by numbers of factors such as current level, arc duration, travel characteristic of the moving contacts and the design of nozzle geometry. To complete the interruption duty successfully, the circuit breaker should be designed with ensuring two representative aspects. First of all, the gas between the two arcing contacts would change from a conducting medium at high current to a poor conductor after the current passes the final current zero. Secondly, sufficient insulation of the gas needs to be restored at a short time scale (~100 $\mu$s) after current passes its final zero. A well-designed circuit breaker should also ensure that the arc can always be successfully quenched with the moving contact being at all its possible positions inside the arcing chamber and the core question is how to achieve the interruption
of a fault current with optimised gas dynamics and contact travel characteristic. It involves the in-depth understandings of the physical arcing process that directly determines the arc behaviour during the interruption.

With comprehensive understandings of the arc physics, the interruption capability of the circuit breaker can be evaluated using computer-aided design (CAD) tool appropriately. With the development of advanced computing technologies, there are numerous investigations related to the physical-chemical properties of the arc plasma [12], [13] and the accumulated understandings of such underlying processes also enable the arc modeling being a commonly used approach to study the arc dynamic behaviour during the circuit breaker interruption, especially the Computational Fluid Dynamics (CFD)-based simulation approach. This achieves great advantages through researching the operation performance of the circuit breaker affected by analysing the arc characteristics and it could also provide the basis for the product optimum design [14], [15], [16].

B. CONSTRUCTION OF THE MHD-BASED ARC MODEL

The arc is formed by the breakdown of the gas medium in the contact gap (SF₆ gas in present work) and the flow inside the arcing chamber is assumed to be the turbulent [13], [17]. The arc behaviour could be described by modified time-averaged Navier-Stokes equations with solving the mass concentration of PTFE vapour due to nozzle ablation based on the theories of hydrodynamics and electromagnetics. Influences of ohmic heating, electromagnetic, radiation and turbulent transport are also thought to theoretically describe the dynamic behaviour of the arc. The gas mixture of SF₆ with ablated PTFE vapour is assumed to be in local thermal equilibrium (LTE) and local chemical equilibrium (LCE) states because the arc pressure is well above the atmospheric value. The arcing chamber of the circuit breaker is rotationally symmetric. The general form of the N-S conservation equations can be written as:

$$\frac{\partial (\rho \phi)}{\partial t} + \nabla \cdot (\rho \phi \vec{V}) - \nabla \cdot (\Gamma_\phi \nabla \phi) = S_\phi$$  \hspace{1cm} (1)

where $\phi$ is the solved-for variable and $\rho$ is the density of the gas mixture, $\vec{V}$ the velocity vector which includes the radial ($r$) and the axial ($v$) velocity components. Source term $S_\phi$ and diffusion coefficient $\Gamma_\phi$ are shown in Table 1, of which each notation has its conventional meaning [13]. Besides that, the thermophysical properties of the SF₆-PTFE mixture used in present work are given in [18].

Ohmic heating is a physical process that converts electric energy generated by the flowed current to thermal energy and the gas medium will be heated up to a high temperature. To determine ohmic heating ($\sigma E^2$), the electrical conductivity $\sigma$ is calculated as the function of temperature and pressure and the electric field is obtained by solving the following current continuity equation:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\sigma \nabla \phi) = 0$$  \hspace{1cm} (2)

The boundary conditions for solving the current continuity equation are defined following the long-range nature of the electric field. The computation domain should be sufficiently large and the uncertainties caused by the settings of boundary conditions would not affect the solution in domain of interest.

With the consideration of the turbulence model [19], it has been observed that the Prandtl mixing length model has more computational advantages in comparison with the k-ε model. The turbulence parameter is sensitive to the geometry of the nozzle [20] and the turbulence viscosity is calculated by:

$$\mu_t = \rho L_\delta^2 \left( \frac{\partial w}{\partial r} + \frac{\partial v}{\partial z} \right)^2$$  \hspace{1cm} (3)

where the length scale $L_\delta$ is assumed to be proportional to the local thermal radius of the arc column $r_\delta$,

$$L_\delta = cr_\delta$$  \hspace{1cm} (4)

and $c$ is the turbulence parameter which should be calibrated in accordance with at least one set of experiment results.

| Equation | $\phi$ | $\Gamma_\phi$ | $S_\phi$ |
|----------|--------|--------------|-----------|
| Mass     | 1      | 0            | 0         |
| Z-momentum | $w$   | $\mu_t + \mu_r$ | $-\frac{\partial p}{\partial z} + \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial p}{\partial r} \right)$ + viscous terms | |
| R-momentum | $v$   | $\mu_t + \mu_r$ | $-\frac{\partial p}{\partial r} - \frac{1}{r} \frac{\partial p}{\partial r}$ + viscous terms | |
| Enthalpy  | $h$   | $\frac{\lambda_1 + \lambda_2}{c_v} \sigma E^2 - q + \frac{\partial p}{\partial t}$ + viscous dissipation | |
| PTFE mass concentration | $\phi_m$ | $\rho (D_1 + D_2)$ | 0 |
| Current continuity | $\phi$ | $\sigma$ | 0 |

To scientifically describe the interactions between hot arc column and solid nozzle, a semi-empirical radiation model is applied by assuming that radiation only travels in the radial direction of the axis-symmetric arc column. It means that the cell on nozzle surface which is radially shadowed by a solid object receives no radiation from the arc [21]. Moreover, this model defines an arc core region which starts from axis to the isotherm of 83% $T_{max}$ and this is actually a defined radiation emission region and the emitted radiation energy from the arc column will reach the nozzle surface and cause ablation. The total amount of the radiation energy can be calculated by the net emission coefficient, which is expressed as a function of temperature, pressure and cylindrical arc column radius. For the puffer type circuit breaker, the cylindrical column radius is defined as the radial distance from the axis to the 4,000 K isotherm. Except for the emission part, the remained amount of radiation would be absorbed within the arc region from 83% $T_{max}$ to the 4,000 K isotherm [22], [23], [24]. In this model, the radiative flux normal to the defined surface
element of nozzle can be obtained by:
\[ Q_f = (1 - \alpha) \left( \int_0^{R_{0.83T_{\text{max}}}} q \cdot 2\pi r dr \right) \xi \]  
(5)

where \( \xi \) is a coefficient calculated by ablation surface incline, \( q \) is the net radiative power loss per unit volume, \( R_{0.83T_{\text{max}}} \) is the radius of the arc core and \( \alpha \) is the proportion of radiation re-absorption. Mass loss rate per unit length is calculated by:
\[ m = \frac{Q_f}{h_v} \]  
(6)

where \( h_v \) is the energy required to convert one kilogram of PTFE (nozzle material) to vapour of 3,400 K (11.9 MJ/kg) [25] and the mass density of PTFE is 2.2 g/cm³.

Schematic diagram of the model circuit breaker is shown in Figure 1. The insulating gas medium is SF₆ with absolute pressure of 0.7 MPa at 300 K. Pressure at two end boundaries is set to a fixed value of 0.7 MPa and the exit pressure is also set to 0.7 MPa. The gas is assumed to have a temperature of 300 K and it is free to enter or leave the two boundary sides of the domain. The pressure variation at Points A and B, and the mass flow through cross-sections C, D and E are recorded.

![FIGURE 1. The schematic diagram of the model circuit breaker under investigation. The yellow part is the main nozzle flat throat.](image)

In the mathematical model, the solid contact and piston are set to move while nozzle, hollow contact and puffer cylinder stay stationary. It is performed to simplify the model settings since nozzle, hollow contact and puffer cylinder are usually designed with irregular shape and the calculation complexity will inevitably increase if these objects are set as the moving components in the model. Although it is opposite in reality, it however does not affect the results since the puffer action on the gas to form the high pressure condition depends only on a relative motion of piston and puffer cylinder and the gas flow speed is much higher than that of moving contact or piston.

During the interruption process, the solid contact should be moved with a minimum velocity when separates with hollow contact and such velocity is obtained through the “over travel” distance, this is the cold flow phase. The high current phase is defined from the arc initiation to the instant when current falls below 15 kA before the final current zero. After the high current phase, the period until the final current zero point is defined as the current zero phase and the post arc phase starts from the final current zero point within a short time period of 10~15 \( \mu s \). This is also a necessary recovery process after the current interruption, regarding as thermal recovery process.

After current zero, a low post arc current still flows in the residual plasma between the arcing contacts under the action of the imposed system transient recovery voltage (TRV). The TRV appears across the circuit breaker terminals after current interruption and it is one of the decisive factors to assess the interruption capability of circuit breaker. It highly correlates to the occurred fault types and characteristics of the power grid system. This TRV is linearly increased immediately at a given rate of rise (dV/dt). The post arc current will be solved using Ohm’s Law with the given dV/dt to assess the thermal recovery of insulating gas medium, which indirectly implies the interruption capability of the circuit breaker. A successful interruption is achieved if the post arc current decreases to an insignificant low value in a few microseconds.

The critical RRRV which is the threshold value of dV/dt is determined by calculating the post arc current with different values of dV/dt. This critical value is an important indicator to describe the thermal interruption capability of circuit breaker. A value of dV/dt higher than this critical RRRV would lead to unsuccessful thermal recovery. In present work, the thermal interruption capability of the circuit breaker is evaluated by interrupting the SLF L90 since it is more difficult and harsher. The initial dV/dt is much higher, resulting in a more serious condition for the circuit breaker interruption.

C. VERIFICATION OF THE ARC MODEL SETTINGS

To study the impacts of the grid system frequency variation on the arc dynamic behaviour, the accuracy and reliability of the calculation results should be confirmed by proven CFD arc model with a satisfactory solution convergence. Actually, the model has been applied to predict the pressurisation in an auto-expansion circuit breakers [18] and the arc voltage in the puffer circuit breaker [26]. The results match reasonably well with the measurement results. In addition, during current zero and post arc phases, the turbulence cooling becomes the predominant mechanism to remove remained thermal energy in the residual arc. In present work, the Prandtl mixing length model was used, of which the calibration of the turbulence parameter \( c \) is performed with two experiment results.

The model circuit breaker has passed the L90 test in 50 Hz with an arcing time of 10 ms by sustaining the TRV imposed from power grid system with a RRRV of 9.18 kV/us while the test was failed when arc duration reduces to 8.8 ms. The second test is performed as a typical thermal recovery failure case to determine the shortest arc duration the circuit breaker could interrupt. Both of these two tests were controlled by a conventional driving mechanism. The average velocity of the moved arcing contact is 3.5 m/s before the separation of the two arcing contacts and it grows to 9.6 m/s during the arcing process with the short arc duration.

The selection of the turbulence parameter \( c \) depends on the calibration of the turbulence model. A normally used range of \( c \) from 0.32 to 0.35 is then chosen to calculate the post arc current. It is found that the results from prediction for
the two cases mentioned above were consistent with the test result for the model circuit breaker with a reasonable value of 0.35, as shown in Figure 2. It is found that the arc could not afford the increasing recovery voltage and breakdown approximately at 2 ms when this value decreases smaller than 0.35. It indicates that the circuit breaker could sustain the RRRV of 9.18 kV/us when c sets no less than 0.35 for the test case with the arcing time of 10 ms. However, the decreased 1.2 ms of arcing time results in a shorter distance between the arcing contacts and a smaller effective cross section area near the downstream exit so that the hot gas could not sufficiently flow out through the downstream exit, as shown in Figure 3, finally resulting in a failed thermal recovery. Therefore, the turbulence parameters larger than 0.35 will provide a satisfactory prediction for the thermal recovery process of the model circuit breaker.

III. INFLUENCES OF FREQUENCY VARIATION ON ARC BEHAVIOUR AND INTERRUPTION OF THE MODEL CIRCUIT BREAKER

A. EVALUATION OF DIFFERENT TRAVEL CHARACTERISTICS OF THE DRIVING MECHANISMS

As a result of a longer arc duration caused by the frequency decrease, the mechanical property of the predesigned driving mechanism should be firstly considered and optimised since it is highly associated with the fluid flow dynamics inside the arcing chamber. The circuit breaker should be designed with sufficient capacity to interrupt different kinds of faults within a permitted arc duration. During the interruption of the circuit breaker, the moving contact has to accelerate to a minimum speed over the “over travel” distance. Such arcing time and contact acceleration are both realised by an effective control of the driving mechanism and the moving contact would stop at various axial positions with different arcing time. With the considerations of the LFAC system, there are two proposed scenarios for designing the driving mechanism characteristics, i.e. conventional driving mechanism and high speed driving mechanism. When uses the conventional driving mechanism in power frequency, the designed travel characteristic of the moving contact is sufficient to complete the establishment of the flow field for arc extinguishment. However, the physical current zero point is delayed due to the frequency decrease. It implies that the original travel distance of the moving contact becomes shorter and it needs a further movement to quench the arc at a new current zero point. The mechanical property of the conventional driving mechanism needs to be optimised with a much longer travel distance of the contact. The second approach is proposed based on the technology of high speed interruption. The high speed driving mechanism could reduce the breaking time of the circuit breaker by compressing the “over travel” time with
TABLE 2. Comparison of the characterised parameters.

| Parameters               | Com.1 | Com.2 |
|--------------------------|-------|-------|
| Minimum opening time (ms)| 28    | 8     |
| Arc duration (ms)        | 10    | 7     |
| Averaged velocity (m/s)  | 9.6   | 14    |

FIGURE 5. Comparison of the accumulated energy distributions during the interruption between Com.1 and Com.2.

an increased velocity. Short breaking time during the “over travel” which achieves the fast opening and closing could reasonably meet the requirements of rapid removal of the fault current.

The operational time for the circuit breaker mainly totally includes three intervals: time for relay operation, “over-travel” time for mechanical separation of arcing contacts and finally the arcing time. To analyse the feasibility of different driving mechanisms, a further comparison between conventional and high speed driving mechanism is discussed. These two cases are labelled as Com.1 and Com.2 for short and the designed travel curves of the moving contact for these two cases are respectively demonstrated in Figure 4 with its corresponding waveform of the interrupting current, which both measured from L90 interruption tests performed on the circuit breaker.

The high speed driving mechanism is improved following the used conventional CTY-16 type with the theoretical closing operation work of 5000 J and the breaking operation work of 22000 J. Table 2 provides a comparison of the characterised parameters for the two driving mechanisms.

From the comparison, the arcing time for the model circuit breaker interrupting the short arc duration case was shortened to 7 ms while that for the conventional driving mechanism is 10 ms. The total action time before arcing contacts separation also largely decreases from 28 ms to 8 ms while the averaged velocity of the moving contact is increased from 9.6 m/s to 14 m/s during the flow field establishment process and such faster acceleration leads to the shorten of the arc duration.

Figure 5 presents the accumulated electrical energy during the whole arcing process. The total energy input for Com.1 is 79.33 kJ while only 39.81 kJ is accumulated for Com.2.

Although the accumulated electric energy input for Com.1 is almost two times larger than that of Com.2, the maximum pressure inside the upstream puffer cylinder is almost equal, respectively 1.60 MPa and 1.61 MPa for Com.1 and Com.2, as shown in Figure 6. The fluctuation of the pressure curve is primarily resulted from the propagated pressure waves from arcing space to the puffer cylinder. The pressure wave cannot propagate immediately from one position to another and the compressible characteristics of the gas flow inside the arcing chamber also leads to the disturbance during the propagation and reflection of the pressure waves.
It is also found from Figure 6 that the pressure within the arcing space becomes higher than that in the puffer cylinder from 31 ms to 33.3 ms for Com.1 and from 10.3 ms to 12.2 ms for Com.2. Such period is defined as the “flow reversal period”. During this period, the arc current increases to its maximum value for Com.1 while it has already passed the maximum value and started to decrease for Com.2. In fact, the current increase theoretically indicates an increase of the instantaneous electric energy. Nevertheless, during this flow reversal period, the accumulated electric energy input to the arc column for Com.2 is higher with a fast accumulation rate in comparison with that of Com.1, as shown in Figure 5. The larger injected energy leads to a higher pressure within the arcing space for Com.2.

Actually for the model circuit breaker, the pressurisation in the puffer cylinder is achieved by a combining effect of inner gas compression and hot gas backflow from the contact space, of which the gas is compressed by the piston movement and the hot gas backflow is caused by the difference of pressure between contact space and puffer cylinder.

To explain the pressurisation process in the puffer cylinder, the mass and energy flow conditions through cross sections C and D (Figure 1) are presented in Figure 7, 8 and 9. The solid curves represent total mass and energy flow which is a sum of the gas flow respectively carried by SF$_6$ and ablated PTFE vapour. The broken curves are corresponding to the mass and the energy flow carried by SF$_6$ gas. Since the pressure shows obvious change when the piston starts to accelerate from 20.0 ms for Com.1, the results before 20.0 ms would not be shown in the figures. From Figure 7 (left figure), it is shown that the ablated PTFE vapour flows backwards the heating channel at 32 ms and the moving contact just travels to the start position of main nozzle flat throat at this time instant. The proportion of the PTFE vapour in SF$_6$-PTFE gas mixture flows through cross section C is less than 8% of the total mass flow while the thermal energy brought by PTFE vapour occupies 60.1% of the total thermal energy. Since the mass and energy flow through cross section C for Com.2 shows a similar pattern, it would not be discussed in this part (Figure 7 right figure).

From Figure 8, it is found that the PTFE vapour does not reach the interior part of the puffer cylinder, which total mass flow and thermal energy are both dominantly controlled by SF$_6$ gas. Therefore, it could be concluded that PTFE vapour backflow has a negligible effect on the pressurisation process in the puffer cylinder. In addition, the mass and energy both flow out from the puffer cylinder (value above zero) during the whole arcing time, which indicates that the effect of gas
compression due to piston movement for pressurisation is stronger than the hot SF$_6$ backflow and it dominantly controls the established gas flow.

During the current interruption, the main nozzle flat throat is totally cleared by the moving contact respectively at 34.22 ms and 12.25 ms with a time interval of 3.3 ms and 2.02 ms from arc initiation for Com.1 and Com.2. Such longer time interval for nozzle clogging is due to the slower acceleration controlled by conventional driving mechanism, as presented in Figure 4. After the unclog of the main nozzle flat throat by moving contact, the cold gas inside the puffer cylinder rushes out with a surge of the mass flow rate, as illustrated in Figure 9, correspondingly with the maximum value of 1.26 kg/s and 2.12 kg/s for Com.1 and Com.2. Such stronger gas flow is primarily influenced by a pressure difference between puffer cylinder and downstream exit.

During the high current phase, the energy dumped into the arcing space results in a relative high pressure. However, the current continuously decreases to its final zero point and the injected electrical energy to arc column becomes insufficient and it leads to a pressure decrease within the arcing space, as presented in Figure 6. Due to the pressure difference between the puffer cylinder and the downstream exit, which shows the convection and thermal energy removal capability of the gas flow, the compressed cold gas in the puffer cylinder speedily rushes out with a low temperature and a high mass flow rate. This mass flow rate largely impacts the gas flow velocity and energy transfer between hot arc column and surrounding cold gas. In addition, this high mass flow rate causes an additional mass flowing into contact space, leading to the last temporary pressure peak within the contact space, as shown in Figure 6. The stronger mass flow rate is designated by a lower pressure difference between the puffer cylinder and middle of main nozzle flat throat. Such relationship is due to the fact that the pressure within the heating channel starts to recover shortly before final current zero.
On this basis, it is observed from Figure 10 that the travel distance of moving contact for Com.1 is slightly longer than that of Com.2 due to its 3 ms longer arc duration. Moreover, the overall pressure in the puffer cylinder for Com.2 is also lower than that of Com.1, which proves that a lower pressure difference would result in a stronger mass flow rate. Energy exchange between surrounding cold gas and arc column also becomes more sufficient as a result of the stronger mass flow rate and the arc column diameter of Com.2 is thus thinner.

As presented in Figure 10, although the opening distance between the arcing contacts is shorter for Com.2, the smaller arc column size also provides a larger effective cross section area around main nozzle for gas flow, indicating a stronger thermal removal capability. This argument could be verified by evaluating the thermal interruption capability of the circuit breaker, which is computationally determined by performing a set of the post arc current calculations with different values of dv/dt to obtain the critical RRRV the circuit breaker could withstand. Computation uncertainty is less than 0.5 kV/us.

From experiments, the model circuit breaker can withstand the L90 test with RRRV of 9.18 kV/us. From the calculation, it is observed that the critical RRRV of Com.1 is 9.3 kV/us, as presented in Fig.11. According to the standards [27], [38], the applicable RRRV for the L90 test with interrupting the current of 50 kA is 9 kV/us under 50 Hz. It indicates that this model circuit breaker is designed with a larger margin in its thermal interruption capabilities with conventional driving mechanism. For Com.2, the reduced arcing time undoubtedly increases the interruption difficulty. However, the faster gas flow inside the arcing chamber reveals a sufficient energy exchange process. The critical RRRV for Com.2 is 9.5 kV/us which is slightly higher and the results indicate that the high speed driving mechanisms with different travel properties is also reasonable designed. It could thus be concluded that the thermal interruption capability of the circuit breaker not only depends on the distribution of the pressure inside the arcing chamber but also affects by the characteristics of the gas flow.

**B. INFLUENCES OF FREQUENCY VARIATION ON ARC BEHAVIOUR**

Based on previous studies, it could be known that high speed interruption could relatively reduce the breaking time and the moving contact travel to the specified position at particular time to establish the required flow field environment with the pre-designed fast motion characteristic. It still could ensure sufficient arc quenching capability although the arc duration is shortened.

Combined with preliminary discoveries of the feasibility to use the high speed interruption technology for the operation
of circuit breaker, the influences of frequency decrease on the arc dynamic behaviour during current interruption with high speed driving mechanism is comparatively studying as well. In this section, the high speed travel characteristic of moving contact keeps consistent for different frequencies. It indicates that the arc duration and moving position of moving contact at typical time instant keep the same. Besides that, the change of interruption condition reflected by the frequency decrease is appeared with a variation of interrupting current waveform, as shown in Figure 12. It is also found that the overall current becomes lower with reduced frequency for the low frequency condition. The variation of the accumulated electrical energy input as a result of frequency reduction is firstly studied, as shown in Figure 13.

For the two cases with frequency of 20 Hz and 25 Hz, the current increases to its maximum at the very beginning of the arc burning. Although the current is slightly lower during this stage, the overall accumulative impact is still stronger so that the total electrical energy input presents a growth with raised frequency.

The pressure distribution at point A also displays a similar pattern within the whole arcing time. The maximum pressure in the puffer cylinder slightly grows with increased frequency, as illustrated in Figure 14, respectively from 1.51 MPa, 1.52 MPa, 1.53 MPa, 1.56 MPa to 1.63 MPa. Actually, an initial filling pressure of the working gas inside the puffer cylinder is 0.7 MPa and it roughly increases to 0.88 MPa during the period of moving contact acceleration within the over-travel distance. The minor growth is resulted from gas compression due to the movement of the piston. After the arc initiation, the accelerated velocity of the piston becomes larger so that the pressure starts to increase considerably with a combined effect between gas compression and hot gas backflow.

As presented in Figure 15, the overall mass and thermal energy flowing out through cross section D inside the puffer cylinder are both reduced due to the increased frequency. As explained previously, the flow through cross section D is the summation of compressed gas with positive flowing direction and hot gas backflow with negative direction into the puffer cylinder. Because of the frequency increase, the total electric energy input to the arc column also increases, which results in an improvement of the flow reversal effect so that the total mass and thermal energy flow from arcing space backwards the upstream puffer cylinder becomes more. This is why the difference between outflow and inflow through cross section D respectively for the total mass and thermal energy becomes increasingly smaller. It implies that the gas

![FIGURE 16. A comparison of temperature distribution at final current zero with different frequencies from 12.5 Hz to 25 Hz.](image-url)

![FIGURE 17. A comparison of the predicted arc voltage with different frequencies ranging from 12.5 Hz to 50 Hz.](image-url)
heating up by the increased amount of the thermal energy becomes enhanced and the impact of the hot gas backflow for the pressurisation becomes stronger so that the overall pressure demonstrates a slight growth with the higher frequency. Compared with the 50 Hz power frequency condition, a slight variation occurs approximately between 11 ms and 13 ms. The transportations of mass and thermal energy both reach the first peak roughly at 11 ms, which is because the current just increases to its maximum of 56.1 kA under 50 Hz while the current for low frequency conditions has already decreased below 40 kA. It indicates that the energy injected into the arc column around this time instant becomes the largest for the 50 Hz case and the gas flow transportation also becomes stronger so that the total amount of mass and thermal energy flowing out through cross section D drops rapidly during 11 ms to 13 ms. After that, the current decreases to a lower value below 20 kA for all the cases. A lower value decreased by frequency indicates a less effect of the gas backflow so that the mass and energy flowing out become more.

Effect of frequency change on temperature distribution is discussed in Figure 16. The highest temperature is increased from 11,300 K to 12,300 K at different frequencies. It could be observed from the figure that the flat throat of main nozzle has already been completely cleared by the moving contact at final current zero. In the vicinity of moving contact, there is a stagnation area where the thermal energy produced by ohmic heating could not be sufficiently removed by the slower gas flow so that the temperature keeps high. It is due to a hitting of the arc flow on the contact surface. In addition, another stagnation area is existed between auxiliary nozzle and main nozzle since the gas flowing out from the heating channel splits into two directions: hollow contact and downstream exit. The imposed system TRV is later shared with these two sections which are divided by the flow stagnation point.

As discussed above, the pressure within arcing space drops during current zero phase since the electrical power supply is insufficient due to the current decrease. Then, the gas in the puffer cylinder rushes out towards arcing space with a high mass flow rate to speedily cool down the arc in comparison with that at high current phase. As a dominant mechanism for arc cooling before current zero, the turbulence is influenced by mass flow rate and corresponding velocity of the gas flow. With the turbulence cooling, the size of arc column is largely compressed by cold gas flow and the temperature is reduced by interacting with the surrounding cold gas and the arc will finally extinguish due to the stop of thermal ionization.

With the increased frequency, the maximum temperature of the arc is slightly increased when current passes its zero. It implies that the effect of cold gas blowing becomes relatively weak due to the insufficient flow field establishment. The arc column diameter is thus marginally bigger with the increased frequency, which undoubtedly increases the difficulty for arc quenching.

On that basis, the impact of frequency difference on the arc voltage is evaluated as well, as shown in Figure 17. The arc voltage is sensitive to the arc column size (diameter and length), electrical conductivity of the arc medium and the gas pressure distribution in the contact space. Actually during the high current phase, the current influences the energy dumped into the contact space and the pressure. From Figure 14, it is noticed that the pressure slightly increases with the increased frequency. Due to the variation of interrupting current, the time interval for high current phase which stops at the current below 15 kA becomes marginally longer with the increased frequency.
FIGURE 19. A comparison of the calculated post arc current with different frequencies from 12.5 Hz to 25 Hz. (a) f = 12.5 Hz, (b) f = 15 Hz, (c) f = 16.7 Hz, (d) f = 20 Hz, (e) f = 25 Hz.

frequency. For these six cases, the time instant at the end of the high current phase is respectively 12.0 ms, 12.5 ms, 12.7 ms, 13.1 ms, 13.5 ms and 14.1 ms. The higher pressure leads to a higher arc voltage, corresponding to Figure 17.

During the current zero phase, the arc voltage is gradually decreased with frequency increase as well as the voltage peak at the final current zero point. It is then increased rapidly to its peak shortly before current passes final zero point. In fact, the di/dt of current before final current zero grows obviously with the increased frequency, which leads to a higher current level. This also results in an increase of the injected electrical energy and thus the dissipation degree of the thermal energy slightly lags behind the energy injection, which leads to the higher axial temperature of the arc, as illustrated in Figure 10 and 16. The higher temperature means the higher electrical conductivity but lower arc resistance, and thus the arc voltage gradually decreases.

As shown in Figure 18, the temperature of arc is almost stable during the high current phase so that the arc resistance is also roughly stable and the variation of the arc voltage is insignificant. Before final current zero, the arc temperature significantly reduces and results in a sharp growth of the arc resistance, which consequently increases the arc voltage to a much higher value. The higher peak voltage at final current zero point indicates that the ionization degree of the particles within the arcing medium becomes insufficient so that the arc conductance is reduced faster correspondingly, which means that the recovery process of the gas medium becomes faster.
accordingly and enhanced the thermal interruption capability of the circuit breaker.

Finally, the effects of arc behaviour variation resulted from the changed frequency on the interruption capability of the circuit breaker in terms of the critical RRRV is investigated accordingly. The critical RRRV reduces from 16.0 kV/us for the case under 12.5 Hz gradually to 15.0 kV/us, 14.5 kV/us, 13.5 kV/us and 11.5 kV/us with the increased frequency. The reduced critical RRRV that the circuit breaker can withstand inevitably deteriorates its thermal interruption capability.

The arc column has the highest axis temperature for case of 25 Hz (Figure 16) and decreases with reduced frequency before the final current zero. It is evident that the turbulence cooling is the strongest for the case of 12.5 Hz and its critical RRRV is expected to be the highest. It can be concluded that the critical RRRV is largely affected by the established flow field condition before final current zero. In low-frequency-based condition, the model circuit breaker controlled by the high speed driving mechanism still has sufficient interruption capability and the corresponding critical RRRV also satisfies the requirement of standards, which is no less than 9.0 kV/us. It indicates that the combination of the conventional 252 kV high voltage circuit breaker structure design with the high speed interruption technologies could reasonably realize the interruption of the circuit breaker in a wide frequency range, which indicates a sufficient adaptability in the LFAC system. Besides that, to solve the problem of interrupting the long arc duration case with low-frequency-based short circuit current, the technology of phase selection whichrupting the long arc duration case with low-frequency-based LFAC system. Besides that, to solve the problem of interrupting the long arc duration case with low-frequency-based short circuit current, the technology of phase selection which applies the real-time collection of the line current signal with algorithms to rapidly identify the fault and predict the corresponding current zero point is also recommended with further considerations.

IV. CONCLUSION
Effects of frequency variation on the arc dynamic behaviour and the corresponding thermal interruption capability of the 252 kV/ 50 kA puffer type circuit breaker are comparatively studied. The established flow field distributions in the arcing chamber are predicted as well. Several conclusions could be drawn:

1) During current interruption of the model circuit breaker in power frequency condition, both the conventional driving mechanism and the high speed driving mechanism are pre-designed with an adequate thermal interruption capacity. The thermal interruption capability of the model circuit breaker when controlled by high speed driving mechanism is slightly higher although the interrupting condition is harsher.

2) In low-frequency-based environment, during the whole arc quenching process, the peak voltage at final current zero, as a critical indicator to evaluate the ionization degree of the gas medium, is decreased due to frequency increase and the critical RRRV also reduces gradually. Such decrease implies a deterioration of thermal interruption capability of the model circuit breaker.

3) Since the arcing time will be prolonged with frequency drop, the model circuit breaker is recommended to operate with high speed interruption technology to expand its scope of the applications within a wide frequency range. Detailed knowledge gained from the research would be useful for the optimization of the circuit breaker in terms of identifying the effects of the frequency change on arc behaviour during the interruption especially for reliable interruption with different arc durations in LFAC system.

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