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Research on Vacuum Arc Commutation Characteristics of a Natural-Commutate Hybrid DC Circuit Breaker

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Abstract: Vacuum arc commutation is an important process in natural-commutate hybrid direct current (DC) circuit breaker (NHCB) interruption, as the duration of vacuum arc commutation will directly affect the arcing time and interrupting time of NHCB. In this paper, the vacuum arc commutation model of NHCB was established by simplifying solid-state switch (SS) and vacuum arc voltage. Through theoretical analysis and experiments, the vacuum arc commutation characteristics of NHCB were studied. The mathematical formula of the effect of main parameters on the duration of vacuum arc commutation is obtained, and the changing law of the influence of the main parameters on the duration of the vacuum arc commutation is explored. The concept of vacuum arc commutation coefficient is proposed, and it is a key parameter that influences the vacuum arc commutation characteristics. The research on the characteristics of vacuum arc commutation can provide theoretical foundation for the structure and parameter optimization of NHCB and other equipment that uses vacuum arc commutation.

Keywords: hybrid dc circuit breaker; vacuum arc commutation; solid-state switch; vacuum arc voltage

1. Introduction

With the development of fully controlled power electronic devices (FPEDs), such as the gate turn-off thyristor (GTO), insulated gate bipolar transistor (IGBT), integrated gate commutated thyristor (IGCT), and injection-enhanced gate transistor (IEGT), the hybrid direct current (DC) circuit breaker based on power electronic technology has become an important technical solution and research hotspot for DC breaking [1–4]. This type of DC circuit breaker combines the advantages of solid-state switches (SSs) and mechanical switches (MSs), and shows the characteristics of a strong current carrying capacity, low on-state loss, fast breaking speed, and no need for cooling devices [5,6].

According to the difference of the current commutating method from MS to SS, hybrid DC circuit breakers based on power electronics technology are divided into forced-commutate hybrid DC circuit breakers (FHCBs) and natural-commutate hybrid DC circuit breakers (NHCBs) [7,8]. The FHCB is mostly used in the field of voltage above 10 kV [9,10], and one of the most representative FHCBs is the 320 kV/2.6 kA hybrid DC circuit breaker developed by ABB in 2011 [11]. NHCB is mostly used in the voltage field of 10kV and below, and there has been a lot of research on the NHCB [12]. Genji et al. [13] proposed the NHCB firstly in 1994, and SS of NHCB is mainly composed of GTO. Polman et al. [14] developed a 600V NHCB by fast MS and IGBTs in 2001, and it is a bi-directional switch. Luca Novello et al. [15] developed a prototype of 1 kV/10 kA NHCB by using IGCT's series and

parallel technology in 2011. Lv gang et al. [16] studied the vacuum arc commutation characteristics of NHCB, and a 10 kV/3.5 kA NHDB prototype was designed and tested.

There have been some studies on the vacuum arc commutation characteristics of NHCB. The vacuum arc commutation model was constructed in [16,17], and the theoretical calculation formula of the rate of the current rise in the commutation branch is given. In [18], a theoretical analysis model is established, and the influence of adding impedance on vacuum arc commutation was studied. The authors of [19] simplified an equivalent treatment of the IGBT module in SS, and the criteria of the vacuum arc commutation were obtained. The authors of [15] studied the vacuum arc characteristics at different breaking distances and different currents. The authors of [20] studied the two current commutation measures for hybrid DC circuit breakers, and proposed a new current commutation measure. The authors of [21] studied the influence of internal and external factors on vacuum arc commutation, and reasonable parameters that can promote vacuum arc commutation were summarized.

The duration of vacuum arc commutation is a very important parameter, as it will directly affect the arcing time and interrupting time of NHCB, and shortening it will facilitate the interruption of NHCB. However, little work has focused on the duration of vacuum arc commutation, and, especially, there is a lack of mathematical formulas about it. In this regard, we conducted research on the vacuum arc commutation characteristics of NHCB, and focused on the influence of the main parameters on the duration of vacuum arc commutation. Section 2 establishes a simplified vacuum arc commutation model of NHCB, and theoretically derives the influence of the main parameters on the vacuum arc commutation characteristics. Sections 3 and 4 establish a vacuum arc commutation test circuit, and experimentally study the influence of the main parameters on the vacuum arc commutation characteristics. Section 5 first discusses the theoretical derivation and experimental results of the previous two sections, proposes the concept of the vacuum arc commutation coefficient, and then discusses the influence of the main parameters on the vacuum arc voltage. Finally, Section 6 concludes this paper.

2. Theoretical Analysis

2.1. Principle of NHCB

As shown in Figure 1, an NHCB mainly includes an MS, an SS and a metal-oxide varistor (MOV) [14]. The current limiting reactor is mainly used to limit the fault current. SS is mainly composed of FPEDs through series and parallel connection, and the most commonly used FPEDs are GTO, IGCT, IGBT, and IEGT. According to the literature [9], the interruption process of NHCB mainly includes vacuum arc commutation and the interruption process of SS. The interruption process of NHCB is shown in Figure 2. In this paper, we will focus on the vacuum arc commutation during NHCB interruption. I_m , I_s , and I_{mov} represent the currents of the MS, SS, and MOV, respectively.

Figure 1. The schematic of a natural-commutate hybrid DC circuit breaker (NHCB).

Figure 2. Interruption process of NHCB.

2.2. Vacuum Arc Commutation Model

The typical waveform of the vacuum arc commutation is shown in Figure 3 [18]. According to the research of the literature [16,17], the vacuum arc commutation model of NHCB is shown in Figure 4a. Then, according to the model shown in Figure 4a, the vacuum arc commutation should follow Formula (1). As shown in Formula (2), Formula (1) can be further rewritten as the relational expression about the current commuting speed dI_c/dt_c . U_{arc} represents the vacuum arc voltage. U_{se} represents the on-state voltage of the SS at the end of vacuum arc commutation. L_s represents the stray inductance of the SS. I_n represents the currents of NHCB. I_{si} represents the current of the SS at the initial moment of vacuum arc commutation. I_{se} represents the current of the SS at the end of vacuum arc commutation. I_c is called the commutation current, which represents the current commutated to the SS during the vacuum arc commutation. I_{ce} is called the final commutation current, which represents the current commutated to the SS from the beginning to the end of the vacuum arc commutation. t_c represents the time it takes for the commutation current to increase from zero to I_c . T_c represents the duration of vacuum arc commutation.

$$U_{arc} = L_s \frac{dI_c}{dt_c} + U_s \quad 0 \leq I_c \leq I_{ce}, \quad (1)$$

$$\frac{dI_c}{dt_c} = \frac{U_{arc} - U_s}{L_s} \quad 0 \leq I_c \leq I_{ce}. \quad (2)$$

Figure 3. Example of typical vacuum arc commutation.

Figure 4. The vacuum arc commutation model of NHCB (a) before and (b) after simplification.

For FPEDs, such as IGBT, IGCT, and IEGT, the relationship between their on-state voltage U_{CE} and collector current I is shown in Formula (3) [22]. As shown in Figure 5, the value of their on-state voltage U_{CE} is basically linear with the collector current I . Therefore, as shown in Figure 5, the relationship between U_{CE} and I can be linearly processed, and the relationship between U_{CE} and I is obtained as shown in Formula (4). Because SSs are made of FPEDs through series and parallel connection, the relationship between U_s and I_s can also be obtained as shown in Formula (5). U_{CE0} represents the on-state voltage of the FPEDs when the collector current is zero. r represents the on-state resistance of the FPEDs. U_0 represents the approximate on-state voltage of the FPEDs when the collector current is zero. R represents the approximate on-state resistance of the FPEDs. U_{s0} represents the approximate on-state voltage of the SS when the I_s is zero:

$$U_{CE} = U_{CE0} + rI, \quad (3)$$

$$U_{CE} = U_0 + RI, \quad (4)$$

$$U_s = U_{s0} + R_s I_s. \quad (5)$$

Figure 5. Collector-emitter saturation voltage characteristics of FZ1200R17HP4_B2 [23].

As shown in Figure 3, because the change in the vacuum arc voltage is relatively small during the vacuum arc commutation [24], $U_{arc-avg}$ can be taken as the vacuum arc voltage value, and $U_{arc-avg}$ is the average value of the maximum value $U_{arc-max}$ and the minimum value $U_{arc-min}$ of the vacuum arc voltage. According to Formula (5), the model shown in Figure 4a can be rewritten as shown in Figure 4b. Then, according to the model shown in Figure 4b, the vacuum arc commutation should follow Formula (6). It is easy to know that $I_s = I_{si} + I_c$, and according to Formula (5), the system of equations shown in Formula (7) can be easily obtained. U_{si} represents the on-state voltage of the SS at the initial moment of vacuum arc commutation:

$$\frac{dI_c}{dt_c} = \frac{U_{arc-avg} - U_s}{L_s} \quad 0 \leq I_c \leq I_{ce}, \quad (6)$$

$$\begin{cases} U_{si} = U_{s0} + R_s I_{si} \\ U_s = U_{si} + R_s I_c \quad 0 \leq I_c \leq I_{ce} \end{cases} \quad (7)$$

After solving Formulas (6) and (7), the relationship expression of t_c about I_c is obtained as shown in Formula (8). It is easy to know that when $I_c = I_{ce}$, $t_c = T_c$, then according to Formula (8), the relationship between T_c and I_{ce} can be obtained as shown in Formula (9). From Formula (9), we can see that L_s , R_s , I_{ce} , $U_{arc-avg}$, and U_{si} are the main parameters that affect T_c . Meanwhile, according to Formula (6), if $dI_c/dt_c \leq 0$, the current will stop commuting to the SS branch, so $dI_c/dt_c > 0$ should always be ensured during the vacuum arc commutation. By solving $dI_c/dt_c > 0$, Formula (10) can be obtained:

$$t_c = -\frac{L_s}{R_s} \ln\left(\frac{U_{arc-avg} - U_{si} - R_s I_c}{U_{arc-avg} - U_{si}}\right) \quad 0 \leq I_c \leq I_{ce}, \quad (8)$$

$$T_c = -\frac{L_s}{R_s} \ln\left(\frac{U_{arc-avg} - U_{si} - R_s I_{ce}}{U_{arc-avg} - U_{si}}\right), \quad (9)$$

$$U_{arc-avg} - U_{si} - R_s I_{ce} > 0. \quad (10)$$

2.3. Influence of Main Parameters on Vacuum Arc Commutation Characteristics

In this section, the effects of parameters, such as L_s , R_s , I_{ce} , $U_{arc-avg}$, and U_{si} , on T_c are further studied. Firstly, it is easy to know from Formula (9), under the condition that other parameters remain unchanged, T_c has a linear relationship with L_s .

Assuming that the parameters L_s and R_s remain unchanged and $L_s/R_s = b$, let $k = (U_{arc-avg} - U_{si})/R_s I_{ce}$, then as shown in Formula (11), Formula (9) can be further rewritten as a function about k , and it is easy to know from Formula (10) that $k > 1$:

$$T_c = -b \cdot \ln\left(1 - \frac{1}{k}\right) \quad k > 1. \quad (11)$$

It is easy to know that changing the parameters $U_{arc-avg}$, U_{si} , and I_{ce} is equivalent to changing the parameter k , and the relationship curve between T_c and k is plotted according to Formula (11), as shown in Figure 6. It can be seen from Figure 6, T_c decreases with increasing k , but the rate of decrease becomes slower and slower and even tends to be constant. k is the ratio of the parameters $U_{arc-avg} - U_{si}$ and $R_s I_{ce}$.

Assuming that the parameters L_s , I_{ce} , $U_{arc-avg}$ and U_{si} remain unchanged and $L_s = a$, the variation of T_c with R_s is explored. Let the value of R_s at the initial time be a fixed value R_{s0} . Correspondingly, $k = (U_{arc-avg} - U_{si})/R_{s0} I_{ce} = k_0$; let the changed $R_s = x R_{s0}$, and correspondingly, $k = (U_{arc-avg} - U_{si})/x R_{s0} I_{ce} = k_0/x$. Then, as shown in Formula (12), Formula (9) can be further rewritten as a function about x , and it is easy to know from Formula (10) that $x < k_0$:

$$T_c = -\frac{a}{x} \ln\left(1 - \frac{x}{k_0}\right) \quad x < k_0. \quad (12)$$

When k_0 takes the values of 4 and 8, respectively, as shown in Figure 7, the variation curves of T_c and k are plotted with x according to Formula (12). It can be seen from Figure 7, T_c increases with increasing x , and the rate of increase becomes faster and faster; k decreases with increasing x , but the rate of decrease becomes slower and slower. The change curve of T_c with k is plotted in Figure 7 as shown in Figure 8. As it can be seen from Figure 8, T_c decreases with increasing k , but the rate of decrease becomes slower and slower and even tends to be constant. k_0 is the ratio of the parameters $U_{arc-avg} - U_{si}$ and $R_{s0}I_{ce}$, and R_{s0} is the initial value of R_s .

Figure 6. The relationship curve between t_c and k .

Figure 7. The variation curves of T_c and k with x .

Figure 8. The relationship curve between T_c and k in Figure 7.

It can be seen from Figures 6 and 8 that when k is small, T_c changes greatly with the increase of k , and when k is large, T_c changes little or even tends to be constant with the increase of k ; therefore, the larger the value of k , the more effective it is to reduce the value of T_c .

3. Test Configuration

As shown in Figure 9, the test platform is mainly composed of an LC oscillation circuit, NHCB, controller, and data acquisition system. The LC oscillation circuit is composed of a capacitor C_i and an inductance L_i , and is mainly used to generate the large current required for the experiment. K_m is the experimental control switch, responsible for introducing current into NHCB. K_v represents the MS of NHCB. The SS of NHCB is mainly composed of impedance Z_a and the IGBT module, and the impedance Z_a is formed by the inductance L_a and the resistance R_a in series. The on-state resistance and stray inductance of the SS are changed by changing R_a and L_a , respectively, to explore the effects of on-state resistance and stray inductance on vacuum arc commutation characteristics of NHCB. The IGBT selected in this experiment is CM1000HA-24H, the collector current of a single CM1000HA-24H is up to 2 kA, and two IGBTs are connected in parallel to form an IGBT module. C_{t1} and C_{t2} are current sensors, which are used to collect the currents of the MS and SS branches, respectively. P_t is a voltage sensor used to collect the vacuum arc voltage. The controller is used to control the operation sequence of the entire experiment. The data acquisition system is used for data collection and display.

Figure 9. Vacuum arc commutation test platform.

4. Experimental Results

4.1. Influence of Stray Inductance of the SS

Under the condition that R_a is 5 mΩ, and I_{se} is approximately 0.5, 1, and 1.5 kA, respectively, we obtained the waveforms of vacuum arc commutation with different stray inductances. When the I_{se} is approximately 1 kA, the waveforms when the added stray inductance L_a is 0 and 2 μH are shown in Figure 10a,b, respectively. As shown in Figure 10, when the added stray inductance L_a increases from 0 to 2 μH, T_c increases from 66 to 346 μs, and $U_{arc-avg}$ increases from 11.7 to 15.8 V. Both T_c and $U_{arc-avg}$ increase with the increase of L_a .

Figure 10. Waveforms of vacuum arc commutation when the added stray inductance L_a is (a) 0 and (b) $2 \mu\text{H}$.

When the added stray inductance L_a ranges from 0 to $4 \mu\text{H}$, the relationship curve between T_c and $U_{arc-avg}$ and L_a is shown in Figure 11. As shown in Figure 11, the relationship between T_c and L_a is approximately linear, which conforms to the law shown in Formula (9), and $U_{arc-avg}$ also increases with the increase of L_a , but the magnitude of the increase becomes smaller and smaller.

Figure 11. Curve of T_c and $U_{arc-avg}$ with different stray inductances.

4.2. Influence of the Final Commutation Current

Under the condition that R_a is 2 m Ω , and L_a is 0 μ H, we obtained the waveforms of vacuum arc commutation with different commutation currents I_{ce} . The waveforms when the commutation current I_{ce} is 0.28 and 2.68 kA are shown in Figure 12a,b, respectively. As shown in Figure 12, when the commutation current I_{ce} increases from 0.28 to 2.68 kA, T_c increases from 13 to 195 μ s, $U_{arc-avg}$ increases from 9.2 to 12.9 V, U_{se} increases from 2.7 to 11.8 V, and I_{si} increases from 0.02 to 0.48 kA. All of T_c , $U_{arc-avg}$, U_{se} , and I_{si} increase with the increase of I_{ce} .

Figure 12. Waveforms of vacuum arc commutation when the final commutation current I_{ce} is (a) 0.28 and (b) 2.68 kA.

As shown in Figure 12, it is easy to know that changing I_{ce} is achieved by changing I_{se} . When the I_{se} ranges from 3.0 to 3.16 kA, the relationship curve between $U_{arc-avg}$, U_{se} , I_{ce} , I_{si} , and I_{se} is shown in Figure 13a. As shown in Figure 13a, all of $U_{arc-avg}$, U_{se} , I_{ce} , and I_{si} increase with the increase of I_{se} , and according to Figure 5 and Formula (7), as shown in Formula (13), the linear expressions between U_{se} and I_{se} and U_{si} and I_{si} can be obtained, respectively, and then we can get the calculation formula of k about $U_{arc-avg}$, U_{se} and U_{si} :

$$\begin{cases} U_{se} = U_{s0} + R_s I_{se} = 2.0 + 3I_{se} \\ U_{si} = U_{s0} + R_s I_{si} = 2.0 + 3I_{si} \\ k = \frac{U_{arc-avg} - U_{si}}{R_s I_{ce}} = \frac{U_{arc-avg} - U_{si}}{U_{se} - U_{si}} \end{cases} \quad (13)$$

Figure 13. (a) The relationship curve between $U_{arc-avg}$, U_{se} , I_{ce} , I_{si} , and I_{se} ; (b) Curve of T_c and k with different final commutation currents; (c) The relationship curve between T_c and k in (b).

Therefore, according to Figure 13a and Formula (13), the k value corresponding to different I_{ce} values can be calculated, and the relationship curve between k and T_c and I_{ce} is shown in Figure 13b. As shown in Figure 13b, k decreases with the increase of I_{ce} , and the rate of decrease becomes slower and slower; T_c increases with the increase of I_{ce} , and the rate of increase becomes faster and faster. The relationship curve between T_c and k was plotted according to Figure 13b, as shown in Figure 13c. It can be seen from Figure 13c that T_c decreases with increasing k , and the rate of decrease becomes slower and slower; the change law shown in Figure 13c basically coincides with the change law shown in Formula (11) and Figure 6.

4.3. Influence of the On-State Resistance of the SS

Under the condition that L_a is 0 μH , and I_{ce} is approximately 1 and 2 kA, respectively, we obtained the waveforms of vacuum arc commutation with different on-state resistances. When the I_{ce} is approximately 1 kA, the waveforms when the added on-state resistances R_a is 0 and 9 m Ω are shown in Figure 14a,b, respectively. Because when the added on-resistance is different, the value of I_{si} will also be different; so, to eliminate the impact of different I_{si} , as shown in Figure 14, the IGBT module is turned on after the vacuum arc is generated, and in this case, $I_{si} = 0$ and $I_{ce} = I_{se}$. As shown in Figure 14, when the added on-state resistances R_a increases from 0 to 9 m Ω , T_c increases from 34 to 99 μs , $U_{arc-avg}$ increases from 9.5 to 12.8 V, and U_{se} increases from 3 to 12.1 V. All of T_c , $U_{arc-avg}$, and U_{se} increase with the increase of R_a . Meanwhile, it can be seen in Figure 14 that when the IGBT module is turned on, the vacuum arc voltage drops.

Figure 14. Waveforms of vacuum arc commutation when the added on-state resistances R_a is (a) 0 and (b) 9 m Ω .

When I_{ce} is 1 and 2 kA, respectively, the relationship between $U_{arc-avg}$, U_{se} , and R_a is shown in Figure 15a. It can be seen from Figure 15a that whether I_{ce} is 1 or 2 kA, both $U_{arc-avg}$ and U_{se} grow approximately linearly with R_a . As it is known from the previous section that $U_{s0} = 2.0$, and $I_{si} = 0$, we can easily get $U_{si} = U_{s0} + I_{si}R_s = 2.0$. Therefore, according to Figure 15a and Formula (13), the k value corresponding to different R_a values can be calculated, and the relationship between k and T_c and R_a is shown in Figure 15b. It can be seen from Figure 15b that whether I_{ce} is 1 or 2 kA, k decreases with the increase of R_a , and the rate of decrease becomes slower and slower; T_c increases with the increase of R_a , and the rate of increase becomes faster and faster; the change law shown in Figure 15b basically coincides with the change law shown in Figure 7. Meanwhile, when $R_a = 0$, the corresponding k_0 value is 8.2 when the I_{ce} is 1 kA, and the corresponding k_0 value is 4.3 when the I_{ce} is 2 kA. The relationship curve between T_c and k was plotted according to Figure 15b, as shown in Figure 15c. It can be seen from Figure 15c that T_c decreases with increasing k , and the rate of decrease becomes slower and slower and even tends to be constant; the change law shown in Figure 15c basically coincides with the change law shown in Formula (12) and Figure 8.

Figure 15. (a) Curve of $U_{arc-avg}$ and U_{se} with different on-state resistances; (b) Curve of T_c and k with different on-state resistances; (c) The relationship curve between T_c and k in (b).

5. Discussion

5.1. Vacuum Arc Commutation Coefficient

Compared to the theoretical analysis and experiments above, it is easy to find that the experimental results can better match the theoretical Formulas (9)–(12). This shows that Formulas (9)–(12) can better reflect the influence of the main parameters, such as the vacuum arc voltage U_{arc} , final commutation

current I_{ce} , on-state resistance R_s , and stray inductance L_s , on the vacuum arc commutation characteristics. Meanwhile, according to Formulas (11) and (12) and Figures 6, 8, 13c and 15c, the ratio k of $U_{arc-avg} - U_{si}$ to $R_s I_{ce}$ is a key parameter that affects T_c ; and according to Formula (10), it is necessary to ensure that $k > 1$ so that the current can be commutated to the SS branch. Overall, k is a very important parameter during the vacuum arc commutation. Therefore, this paper defines k as the vacuum arc commutation coefficient.

According to Figures 6, 8, 13c and 15c, when k is small, T_c will increase significantly. Therefore, in order to reduce T_c , the value of $U_{arc-avg} - U_{si}$ should be increased or the value of $R_s I_{ce}$ should be decreased. The main method of increasing the value of $U_{arc-avg} - U_{si}$ is to increase the vacuum arc voltage. Applying an external magnetic field and connecting multiple MSs in series are currently common methods of increasing the arc voltage [25,26]. The main method to reduce the value of $R_s I_{ce}$ is to reduce the on-resistance R_s and final commutation current I_{ce} , but reducing I_{ce} will reduce the interrupting ability of NHCB. The method to reduce the on-resistance R_s is to select FPEDs with low on-resistance or to increase the number of parallel FPEDs [27,28]. Meanwhile, it can be seen from Formula (9) and Figure 11 that reducing the stray inductance L_s in the SS is also an effective method to reduce T_c .

5.2. Influence of the Main Parameters on the Vacuum Arc Voltage

It can be seen from the experiment that when the parameters L_s , I_{ce} , and R_s increase, not only T_c increases but the vacuum arc voltage also increases, which is consistent with the positive feedback characteristics of the vacuum arc voltage. This can explain the sudden drop of the vacuum arc voltage in Figure 14, before the IGBT module is turned on, the vacuum arc commutation is very difficult, so the vacuum arc voltage at this time is higher. When the IGBT module is turned on, the difficulty of vacuum arc commutation decreases rapidly, so the vacuum arc voltage also decreases accordingly. Meanwhile, to better describe the influence of parameters L_s , I_{ce} , and R_s on T_c , in the future work, the influence of the parameters L_s , I_{ce} , and R_s on the vacuum arc voltage should be considered in Formula (9).

Although this paper focuses on NHCB, it is also applicable to other devices that use vacuum arc commutation, such as fault current limiters [29,30]. In the future work, further research will be conducted on other devices that use vacuum arc commutation.

6. Conclusions

In this paper, the vacuum arc commutation model of NHCB was established by simplifying SS and vacuum arc voltage, and the vacuum arc commutation characteristics of NHCB were studied through theoretical analysis and experiments. The mathematical expression of the relationship between the main parameters of the vacuum arc voltage, on-state resistance, and stray inductance and the duration of vacuum arc commutation was obtained.

The concept of the vacuum arc commutation coefficient was proposed based on the mathematical expressions and experiments, and it is a key parameter that influences the vacuum arc commutation characteristics. The value of the vacuum arc commutation coefficient should not be small; when it is small, the duration of vacuum arc commutation will increase significantly. Further, it is not the bigger the better, as when it is bigger, the duration of vacuum arc commutation will decrease slowly. Meanwhile, it must always be ensured that the value of the vacuum arc commutation coefficient is greater than one, so that the current can be commutated to the SS branch.

In the process of vacuum arc commutation, when the difficulty of vacuum arc commutation increases, the vacuum arc voltage will also increase, and from the extremely difficult vacuum arc commutation to the easier vacuum arc commutation, the vacuum arc voltage will also be reduced immediately. This paper can provide the theoretical foundation for the structure and parameter optimization of NHCB and other devices using vacuum arc commutation.

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