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Analysis, Design and Dynamic Simulation of Novel Limited Swing Angle Torque Permanent Magnet Motor for High Voltage Circuit Breaker Application

Guanbao Zeng , Xiangyu Yang, Shiwei Zhao, Huajie Yin, Yunqing Pei and Jianghua Cao

School of Electric Power, South China University of Technology, Guangzhou 510641, China; yangxyu@scut.edu.cn (X.Y.); epswzhao@scut.edu.cn (S.Z.); epyin@scut.edu.cn (H.Y.); 201510101571@mail.scut.edu.cn (Y.P.); caojianghua@scut.edu.cn (J.C.)

* Correspondence: 201710101760@mail.scut.edu.cn

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Abstract: In this paper, a novel limited swing angle torque permanent magnet motor (LSATPMM) is proposed, and the operating principle of the circuit breaker of the proposed LSATPMM and a mathematical model are analyzed. The characteristics of the high voltage circuit breaker (HVCB) of the proposed machine are analyzed and calculated by numerical finite element analysis methods. The co-simulation of the Maxwell Circuit Editor and Ansoft Maxwell is used to analyze the dynamic characteristics of HVCB. The advantages of the presented operating mechanism for LSATPMM, such as the ability to adjust the opening and closing torque characteristic, high reliability, robust drive system and fault tolerance, are discussed. Finally, a prototype of LSATPMM is created and tested; and the characteristic curve of position versus torque is acquired in order to confirm the proposed design.

Keywords: HVCB; LSATPMM; reliability; operating mechanism; adjustable torque; dataset expressions and fault tolerance

1. Introduction

With the development of intelligent requirements for power systems, these requirements, i.e., controllability, security and reliability have been cumulatively researched in the last several years. The circuit breaker (CB) is the main mechanical contact device adopted in power systems, the performance of the actuator of which is essential for highly reliable power systems [1,2]. The ratio of faults occurring in various parts of the circuit breaker was investigated and counted in 2008. This indicated that the error probability of the operating mechanism in CB was up to 43 percent, and that of the control circuit reach to 29%. The circuit breaker itself has a failure probability of 21%, and the remaining 7% belonged to others [3]. Therefore, the operating mechanism and control driver for BC are extremely worthy of study and inspire a lot of interest. Traditionally, the actuator primarily has a spring operating mechanism and hydraulic pressure actuator [4–8]. These traditional actuators are mostly assembled by complex drive gears and many components, which require a difficult fabrication process and result in an uncontrollable movement process. Therefore, the circuit breaker of a permanent magnet actuator, which has a small volume and fewer components, as well as a simple and reliable structure, is studied [9–11].

However, with the emergence and development of a smart grid in the past decade, the novel structures of motor operating mechanisms on high-voltage circuit breakers are attracting great interest [12–14]. For example, in [15–18], an operating mechanism with a permanent-magnet synchronous motor (PMSM) was put forward in order to realize the full control capability during

the opening and closing operation. This operating mechanism has the advantage that the travel of the moving contact of HVCB is precisely controlled by controlling the motion of PMSM. However, the motor-drive operating mechanism needs speed, position, voltage, current and the other information to drive the circuit breaker's opening and closing along with a predesigned traveling curve, which increases the cost and reduces reliability.

In [19–21], a salient pole rotor coil excitation brushless DC motor operating mechanism, which is shown in Figure 1a, was presented for a high-voltage circuit breaker in order to improve the operating performances. The motor includes two double salient pole rotor motors and uses a field coil instead of permanent magnets, which not only eliminates the insufficiency of the PM but also simplifies the complexity of its structure. The salient pole rotor motor has many advantages, such as small torque ripple, high starting torque, favorable field-control performance and a good speed expansion capability. However, this operating mechanism needs a high-performance DSP processor, speed transducer, position transducer, voltage transducer and current sensor for realizing the controllability, which increases the complexity and cost and decreases the reliability of system.

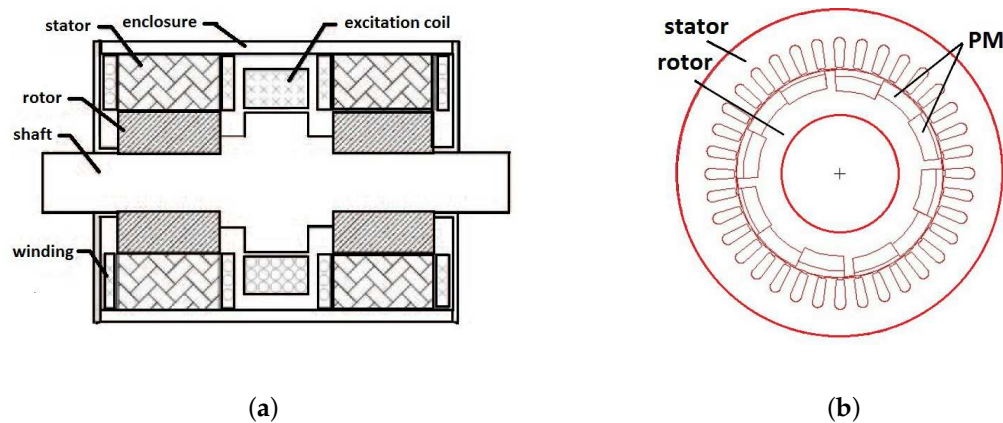


Figure 1. Schematic diagram of different motor structures: (a) salient pole rotor coil excitation brushless DC motor; (b) changed air-gap structure of a permanent magnetic swing angle torque motor.

In other aspects, the operating mechanism of a segment voltage starting motor and variable air-gap structure permanent magnet motor are studied and are shown in Figure 1b. This operating mechanism improves the controllability of HVBC, realizes the different speed requirements for the opening and closing motion process of HVBC and enhances the reliability of its control system. The segment variable air-gap structure motor is presented in [22], which takes advantage of the variable air-gap length combined with the variable range in the opening and closing operation. However, the speed, position, voltage and current sensor of this operating mechanism, with a segment structure permanent magnet motor, are also studied, and a segment structure permanent magnet motor also reduces the power density and torque density.

In [23,24], a limited angle permanent magnet brushless DC servo motor actuator in HVBC is proposed, and the characteristics and dynamic simulation of the actuator have been analyzed using the finite element method (FEM). The parameters of three different machines are shown in Table 1 [22–25]. The analysis results of this machine demonstrate that this rotary motor actuator can satisfy the mechanism characteristics of HVBC. However, the results of the analysis using Ansoft (Maxwell 16.0) are shown in Figures 2 and 3. The power density and torque density of the limited angle permanent magnet brushless DC servo motor actuator are too low to cut the costs and the operating mechanism of the volume with the same saturation. Slotted and slotless Limited-Angle Torque Motors were also introduced in [26–28]. However, the slotted Limited-Angle Torque Motor has similar torque to that of the multi-slots structure of a limited swing angle torque permanent magnet motor, and the slotless Limited-Angle Torque Motor has a lower torque density because of its low air gap magnetic

density [29–32]. In Table 1, Machine 1 represents the multi-slots structure of a limited swing angle torque permanent magnet motor. Machine 2 represents the less-slots structure of a limited angle permanent magnet brushless DC servo motor actuator, and Machine 3 represents the proposed LSATPMM.

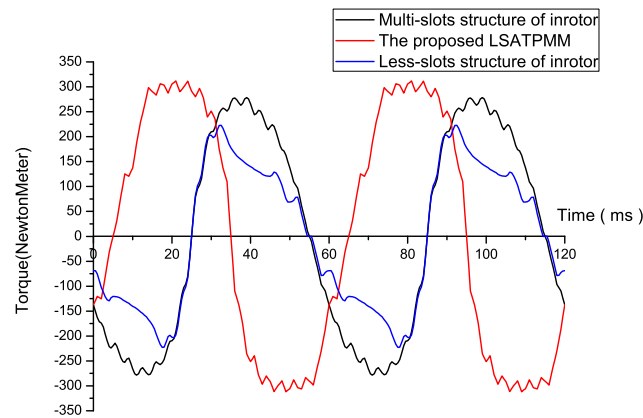


Figure 2. The comparison of torque characteristics.

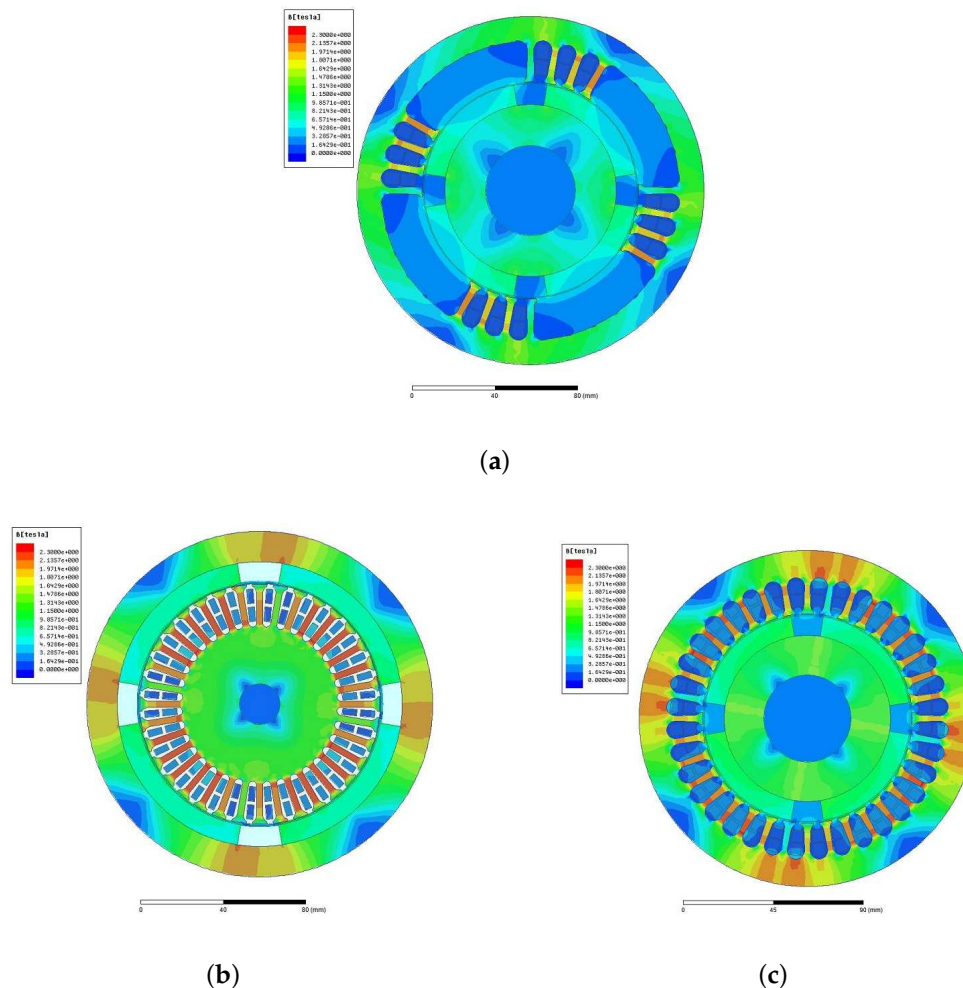


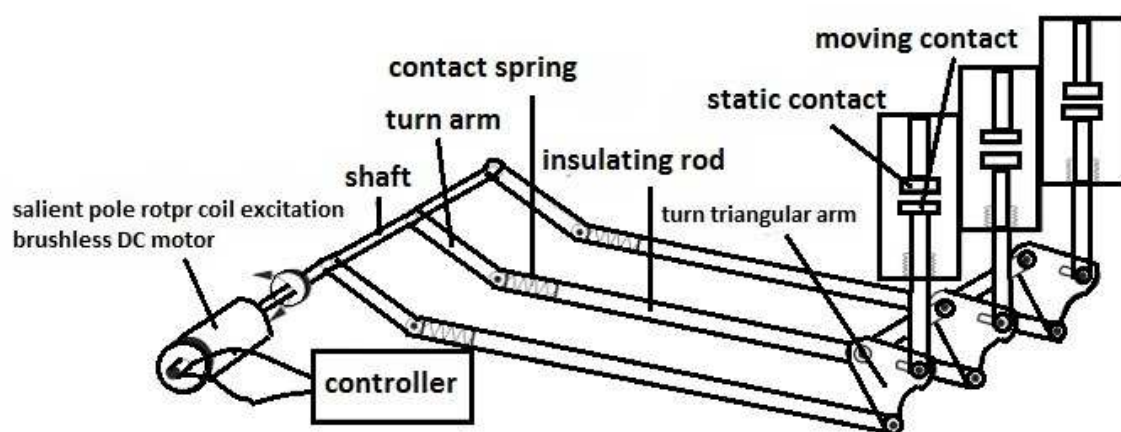
Figure 3. The magnetic results of 2D FE analysis are shown: (a) the less-slots structure of a limited angle permanent magnet brushless DC servo motor actuator; (b) the proposed LSATPMM; (c) the multi-slots structure of a limited swing angle torque permanent magnet motor.

Table 1. Parameters of three different machines.

Design Parameter	Machines 1	Machines 2	Machines 3
Number of Stator Slots	36	12	36
Outer Diameter of Stator (mm)	170	170	170
Inner Diameter of Stator (mm)	106	106	20
Number of pole pairs	2	2	2
Air Gap (mm)	1	1	1
Outer Diameter of rotor (mm)	104	104	170
Inner Diameter of rotor (mm)	44	44	120
Length of Rotor (mm)	212	212	212
Pole embrace	0.8	0.8	0.8
Magnet Thickness (mm)	10	10	10
Number of per slot of coil	20	20	20

In [33–36], different permanent magnetic actuators were presented to improve efficiency, reliability and other performance factors. Ref [5,6,37,38] used the monostable and bistable Thomson-coil actuator (TCA) to increase the rapidity, reduce the complexity and improve the reliability of a high-voltage circuit breaker. Many problems still need to be solved in relation to operating mechanism with TCA, such as the problem of contact bounce.

The general structure of HVCB, with the rotary motor actuator, is shown in Figure 4. The machine is an impetus source, and the only swing limited angle in the process of opening and closing. Between the crosier and insulation brace, the contact spring, which is compressed at the end of closing process and expanded at the start of opening process, is assembled to overcome the effect of electric-force in the short situation and provide contact force and a part of the opening energy. In the closing process, the machine must be able to overcome the counterforce of the contact spring and the counterforce of other frictions. Finally, as an example of the 126 kV high-voltage circuit breaker, the counter-torque characteristics of contact spring and the equivalent rotary inertia of the mechanism are derived by analyzing and computing the opening and closing process of the 126 kV HVCB, as shown in Figure 5 [38,39].

**Figure 4.** Structure of a VCB fixed rotary motor actuator [40].

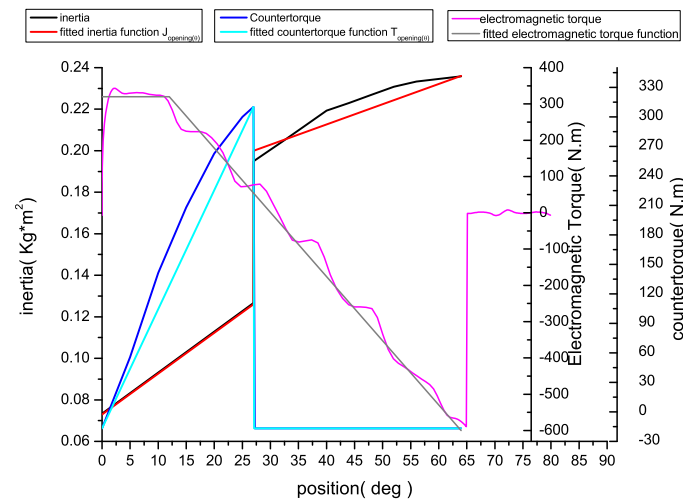


Figure 5. The equivalent rotary inertia, counter-torque and electromagnetic torque characteristics of LSATPMM and its fitted function.

Based on the required characteristics of the circuit breaker, this paper presents a novel limited swing angle torque permanent magnet motor (LSATPMM) for a high-voltage circuit breaker application, which makes groundbreaking use of the advantages of the free slot spaces of limited angle DC permanent magnet motors. The novel structure of the proposed LSATPMM is constituted by the traditional stator and rotor. However, LSATPMM has two sets of windings and have only one coil per winding, which is one coil less than the conventional three phase Limited-Angle Torque Motor has. Consequentially, the drive circuit for LSATPMM has two controllable thyristors, which is better than the drive circuit of the conventional Limited-Angle Torque Motor, which has six controllable thyristors. In this case, the reliability is improved and the cost is decreased. Moreover, the analysis and calculation of the opening coil distribution inside the proposed machine are necessary. It is also significantly important to predict and evaluate the closing coil distribution inside the proposed LSATPMM, which will be limited to a large extent by the opening coil distribution and reduce the available free vacuums. In addition, the numerical finite element analysis methods, such as Ansoft Maxwell and Maxwell Circuit Editor, are used to obtain more precise and correct results of the operational position and electromagnetic torques of the LSATPMM. In this study, two-dimensional finite element analysis (2D FEA) has been employed to verify the correctness of the calculated magnetization and force characteristics, which is important for this permanent magnet motor. A prototype of LSATPMM, which this paper presented, is made, and the characteristic curve of position versus torque with a direct-current is tested, which aids in the confirmation of the proposed design.

2. Novel Structure of LSATPMM

The novel proposed LSATPMM is shown in Figure 6a. The opening coil of the angle is defined as $\theta_{\text{opening_coil}}$. From the form shown in Figure 2, it is obvious that the torque of density is highest in the same stator radial. The density of torque is higher, and the volume is smaller, with the same output torque. Therefore, the structure of the out-rotor is chosen for the novel LSATPMM. Comparing the results in Figure 6b, it is evident that the proposed machines have the same closing and opening position-torque characteristics, except that the displacement is different if the other characteristics are the same.

The novel limited swing angle torque permanent magnet motor (LSATPMM) offers many advantageous features, for example, a higher torque density, higher power density, smaller volume with the same output torque and power, high reliability in some applications and greater freedom of choice with respect to the adjustment of the torque characteristics of high-voltage circuit breaker. The reasons for its merits will be shown in the following.

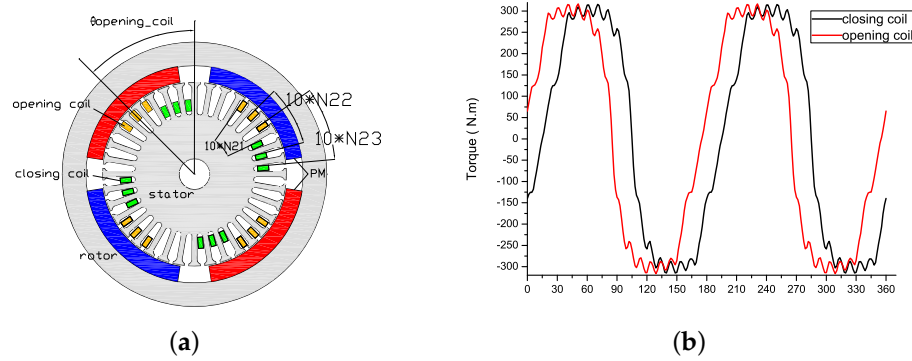


Figure 6. The structure of the machine and its torque characteristics: (a) the novel simple schematic of the proposed LSATPMM; (b) the comparison of torque characteristics when the closing coil and opening coil pass through a 150A DC.

3. Working Principle of LSATPMM

To make the analysis more convenient, the following simplifications and hypotheses are accepted:

1. The air gap is uniform.
2. The core magnetic path in the stator and rotor is not saturated, and its magnetic potential falling is negligible.
3. The effect of the open slot is insignificant.

Assuming that the current of the conductor is i_a , and the air gap flux density at the conductor is b_δ , the torque of conductor is shown in Equation (1) [41]. Since the number of conductors per pole equals $Z_a/2p$, the torque of the conductor at each pole can be expressed as Equation (2):

$$T_C = b_\delta l i_a \frac{D_a}{2}, \quad (1)$$

$$T_p = l i_a \frac{D_a}{2} \sum_1^{Z_a/(2p)} b_\delta(x_i) = \frac{Z_a}{2p} B_{av} l i_a \frac{D_a}{2}, \quad (2)$$

$$B_{av} \approx \frac{1}{Z_a/2p} \sum_1^{Z_a/(2p)} b_\delta(x_i), \quad (3)$$

where D_a is the armature diameter; Z_a is the total number of conductors; B_{av} is the average air gap flux density; p is the pole pairs; and l is the axial length of the machine.

The total torque of the armature winding in the motor can be expressed as Equation (4):

$$T_e = 2p T_p = Z_a B_{av} l i_a \frac{D_a}{2}. \quad (4)$$

3.1. The Equation of Opening Motion Analysis

Through the derivation, the equivalent rotary opening inertia of a single phase HVCB can be fitted by Equation (5) and is shown in Figure 5:

$$J_{\text{opening}}(\theta) = \begin{cases} 0.075 + \frac{0.053}{27\pi/180} \theta; & 0 \leq \theta < \frac{27}{180} \pi, \\ 0.2 + \frac{0.04}{37\pi/180} \left(\theta - \frac{27}{180} \pi \right); & \frac{27}{180} \pi \leq \theta < \frac{64}{180} \pi. \end{cases} \quad (5)$$

The counter-torque characteristic of HVDC is expressed as follows, due to its spring and self-closing force, which are decided by the moving mass of HVCB, the choice of a moving angle and the transmission mechanism of HVCB:

$$T_{\text{counter_torque}}(\theta) = \begin{cases} \frac{310}{27\pi/180}\theta; & 0 \leq \theta < \frac{27}{180}\pi, \\ -16.7; & \frac{27}{180}\pi \leq \theta < \frac{64}{180}\pi. \end{cases} \quad (6)$$

The electromagnetic torque characteristic of LSATPMM is expressed as follows due to the choice of a moving angle:

$$J_{\text{electromagnetic}}(\theta) = \begin{cases} 0.075 + \frac{0.053}{27\pi/180}\theta; & 0 \leq \theta < \frac{27}{180}\pi, \\ 0.2 + \frac{0.04}{37\pi/180}(\theta - \frac{27}{180}\pi); & \frac{27}{180}\pi \leq \theta < \frac{64}{180}\pi. \end{cases} \quad (7)$$

At the same time, the opening resultant torque $T_{\text{opening}}(\theta)$ is the sum of the contact spring of counter-torque and the electromagnetic torque and it can be expressed as Equation (8):

$$T_{\text{opening}}(\theta) = \begin{cases} T_{\text{max}1} + \frac{310}{27\pi/180}\theta; & 0 \leq \theta < x, \\ T_{\text{max}1} + \frac{310}{27\pi/180}\theta - \frac{2T_{\text{max}1}}{\pi/6}(\theta - x); & x \leq \theta < \frac{27}{180}\pi, \\ T_{\text{max}1} - \frac{2T_{\text{max}1}}{\pi/6}(\theta - x) - 16.7; & \frac{27}{180}\pi \leq \theta < \frac{64}{180}\pi, \end{cases} \quad (8)$$

where θ is the turned angle; and T_{max} is the approximately maximum output torque of LSATPMM at the opening. The matter of the motor of the turned angle, angular speed and angular acceleration can be expressed as Equations (9)–(11):

$$\omega = \frac{d\theta}{dt}, \quad (9)$$

$$\alpha = \frac{d\omega}{dt} = \frac{d^2\theta}{dt^2}, \quad (10)$$

$$\alpha_{(\theta)} = \frac{T_{(\theta)}}{J_{(\theta)}}. \quad (11)$$

Substituting Equations (5) and (8) for Equations (9)–(11), the equation of the opening motion is expressed as Equation (12):

$$\frac{d^2\theta_{\text{opening}}}{dt^2} = \begin{cases} C_1 \frac{T_{\text{max}1} + \frac{310}{27\pi/180}\theta}{0.075 - \frac{0.053}{27\pi/180}\theta}; & 0 \leq \theta < x, \\ C_2 \frac{T_{\text{max}1} + \frac{310}{27\pi/180}\theta - \frac{2T_{\text{max}1}}{\pi/6}(\theta - x)}{0.075 - \frac{0.053}{27\pi/180}\theta}; & x \leq \theta < \frac{27}{180}\pi, \\ C_3 \frac{T_{\text{max}1} - \frac{2T_{\text{max}1}}{\pi/6}(\theta - x) - 16.7}{0.2 - \frac{0.04}{37\pi/180}(\theta - \frac{27}{180}\pi)}; & \frac{27}{180}\pi \leq \theta < \frac{64}{180}\pi. \end{cases} \quad (12)$$

C_i is the Carter coefficient. Substituting the parameters for the Equation (12), the opening characteristic curve is shown in Figure 7.

It is obvious that, from the above graph, the calculated results coincide with the simulated results from the soft of finite element analysis. In other words, Equation (12) is correctly calculating the position of the closing coil, and the deviation is caused by the nonlinear linearization process. The proposed machines of the electromotive torque meet the required characteristics of the circuit breaker and thus improve the characteristics of HVCB.

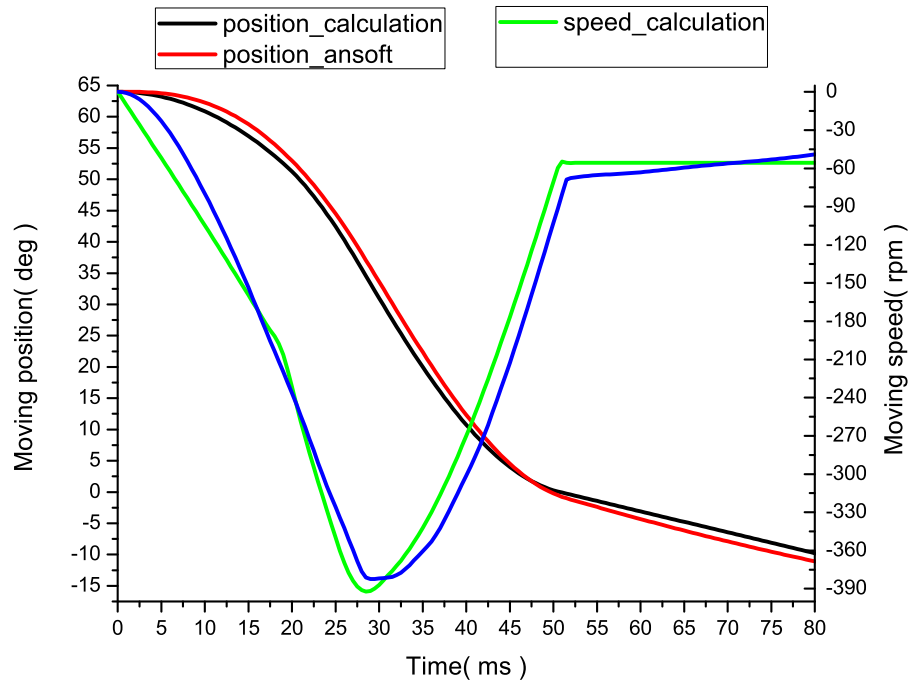


Figure 7. The calculated and simulated results of the opening characteristic curve of the opening of time versus the position and speed, whose calculated results are adjusted to meet the simulated reference system ($C1 = 0.28$, $C2 = 0.7$, $C3 = 0.74$).

3.2. The Equation of Closing Motion Analysis

Through the analysis, the torque of LSATPMM, with only one coil, can be expressed as Equation (13) and is shown in Figure 8:

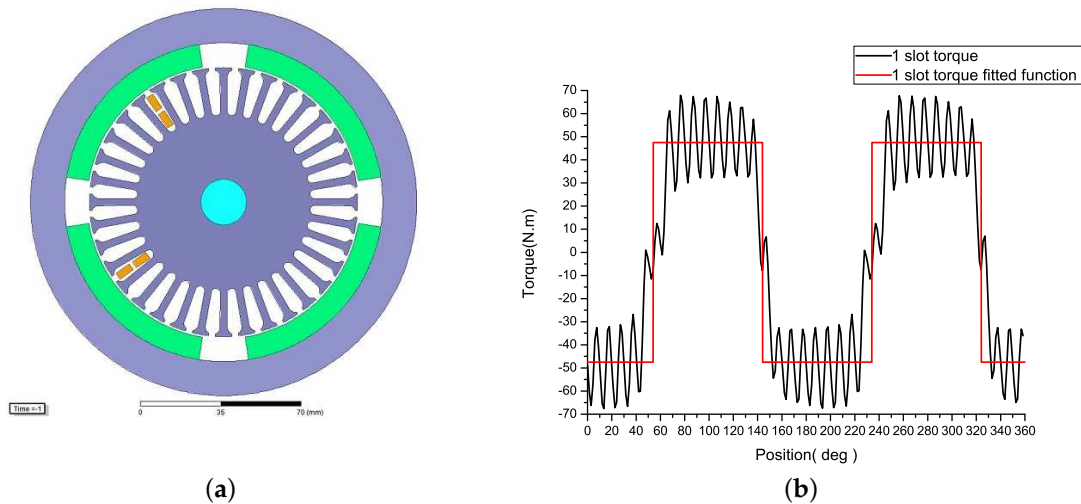


Figure 8. The model and torque characteristics: (a) the equivalent model of LSATPMM, with only one coil, (b) the torque characteristic and its fitted function.

$$t_{(\theta)} = \begin{cases} T_1 = N_a B_{av} l i_a \frac{D_a}{2}; & T_{\text{cycle}} \leq \theta < \frac{\pi}{2} + \frac{T_{\text{cycle}}}{2}, \\ -T_1 = -N_a B_{av} l i_a \frac{D_a}{2}; & \frac{\pi}{2} + \frac{T_{\text{cycle}}}{2} \leq \theta < \pi + T_{\text{cycle}}, \end{cases} \quad (13)$$

where N_a is the number of conductors of one coil. For convenience, five slots per pole of LSATPMM is taken as an example. The resultant electromagnetic torque $T_{\text{motor}(\theta)}$ is the sum of all coils and can be expressed as Equation (14). The counter torque $T_{\text{counter}(\theta)}$ is expressed as Equation (15):

$$T_{motor}(\theta) = \sum_{i=1}^{i=4} \sum_{j=1}^{j=5} t_{(\theta+10N_{ij})}, \quad (14)$$

$$T_{counter}(\theta) = \begin{cases} 16.7; & 0 \leq \theta < \frac{37}{180}\pi, \\ \frac{310}{23\pi/180}(\theta - \frac{37}{180}\pi) - 310; & \frac{37}{180}\pi \leq \theta < \frac{64}{180}\pi. \end{cases} \quad (15)$$

The resultant torque of HVCB T_θ can be expressed as Equation (16):

$$T(\theta) = T_{motor}(\theta) + T_{counter}(\theta). \quad (16)$$

The opening equation of motion can be expressed as Equations (17)–(20):

$$\omega_{closing} = \frac{d\theta_{closing}}{dt_{closing}}, \quad (17)$$

$$\alpha_{closing} = \frac{d\omega_{closing}}{dt_{closing}}, \quad (18)$$

$$\alpha_{closing} = \frac{d^2\theta_{closing}}{dt_{closing}^2}, \quad (19)$$

$$\alpha_{closing}(\theta) = \frac{T_{closing}(\theta)}{J_{closing}(\theta)}. \quad (20)$$

From the above-mentioned equations, the closing coil will only be determined by the number of N_{ij} . In other words, the closing torque characteristic of LSATPMM can be adjusted to meet the requirement of the circuit breaker by choosing the armature resistance, the number of N_{ij} and N_a .

4. Numerical Analysis and Simulation Results

Thanks to the friendly use of the numerical techniques of Ansoft Maxwell, the complex construction and inherent nonlinear properties of the magnetic materials for the presented LSATPMM are used to estimate and analyze the characteristics of this machine and the HVCB. This paper designs the conventional limited angle machine and the presented novel LSATPMM in order to compare their performances.

First, the calculation of the electromagnetic torque, with different numbers of slots per pole, is analyzed by 2D FEA, based on Ansoft Maxwell, and is shown in Figure 9. It is obvious that, in the same stator current, the electromagnetic torque of the presented machine increases with the number of slots per pole. In Figure 9, the average electromagnetic torque of LSATPMM is disproportionate to the current density, which illustrates the saturated phenomenon of the core. In other words, the ratio of torque to current density does not all increase with the number of slots per pole.

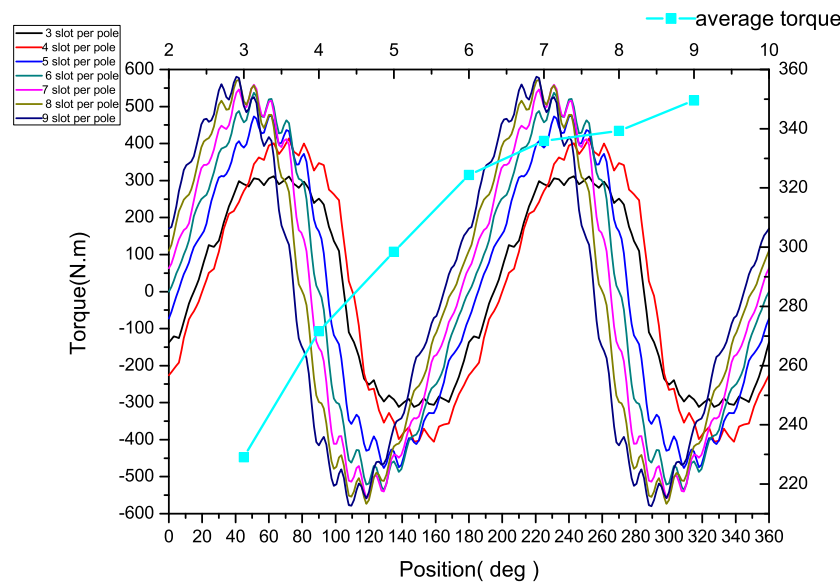


Figure 9. The characteristic curve of the electromagnetic torque and the average torque with different numbers of slots per pole, when the armature current is 150 A.

4.1. The Opening Characteristic

The opening characteristic curves of position versus torque, time versus speed and armature current versus time are shown in Figure 10, according to the co-simulation results of Ansoft Maxwell and Maxwell Circuit Editor. It is obvious from Figure 10a that the armature current decreases as the number of slots per pole is increased, and the pulse current is also minimized due to the increase of inductance. Moreover, the electromagnetic torque value of the presented machine is negative at the first time and then becomes positive. Consequently, the speeds of the motor and operating mechanism also accelerate at the beginning and then slow down at the end of the opening of the circuit breaker. In other words, the speed of the moving contact is rapid at three-quarter distance, after the instance of separate contacts, and is slow at the end of the opening. This meets the required characteristics of the circuit breaker, i.e., a short closing process time, short contact bounce time and as few excess strokes as possible. The parameters of the emulational model of LSATPMM are shown in Table 2.

In Figure 11, the opening time of the operating mechanism of the high-voltage circuit breaker of the proposed LSATPMM moves from 0 to 64 degrees in approximately 49.75 ms, 49.63 ms, 49.99 ms, 50.05 ms, 51 ms, 49.9 ms, and 50.02 ms with the following numbers of slots per pole: 3, 4, 5, 6, 7, 8, and 9, respectively. It is clear that the opening time of the operating mechanism meets the standard of HVCB, i.e., the opening spend time of operating mechanism less than 50 ms.

Table 2. Parameters of LSATPMM.

Design Parameter	Value
Number of Stator Slots	36
Outer Diameter of Stator (mm)	148
Inner Diameter of Stator (mm)	20
Number of Pole Pairs	2
Air Gap (mm)	1
Outer Diameter of Rotor (mm)	200
Inner Diameter of Rotor (mm)	150
Length of Rotor (mm)	250
Pole Embrace	0.8
Magnet Thickness (mm)	10
Number Coil of per Slot	20

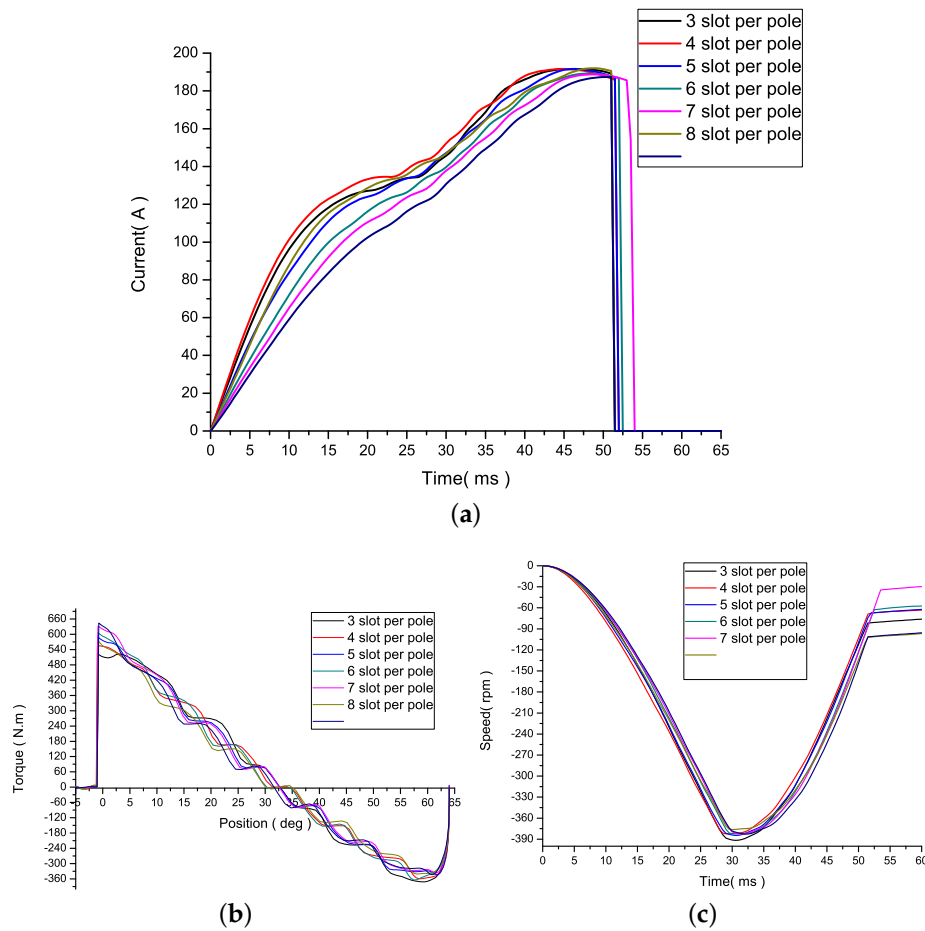


Figure 10. The simulation results of the 2D FE model are shown: (a) the opening characteristic curves of armature current versus speed; (b) the opening characteristic curves of position versus torque; (c) the opening characteristic curves of time versus speed.

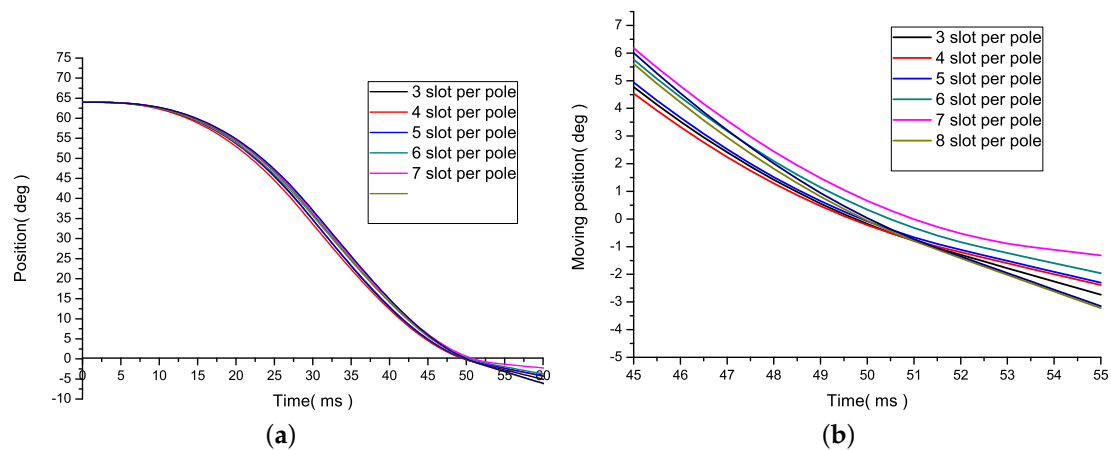


Figure 11. The calculation results of the 2D FE simulation concerning the opening characteristic of time-position: (a) the opening characteristic curve of time versus position with different numbers of slots per pole; (b) the partial enlargement of the opening characteristic curve of time versus position.

4.2. The Closing Characteristic

In Figure 12, the torque decreases as the armature resistance increases and the number of conductors of one coil decreases. Consequently, the speed of HVCB is slower, and the time is longer, which is beneficial for improving the contact bounce. This confirms that the armature resistance and

number of conductors of one coil in LSATPMM can be adjusted to meet the different requirements of the circuit breaker and improve its characteristics.

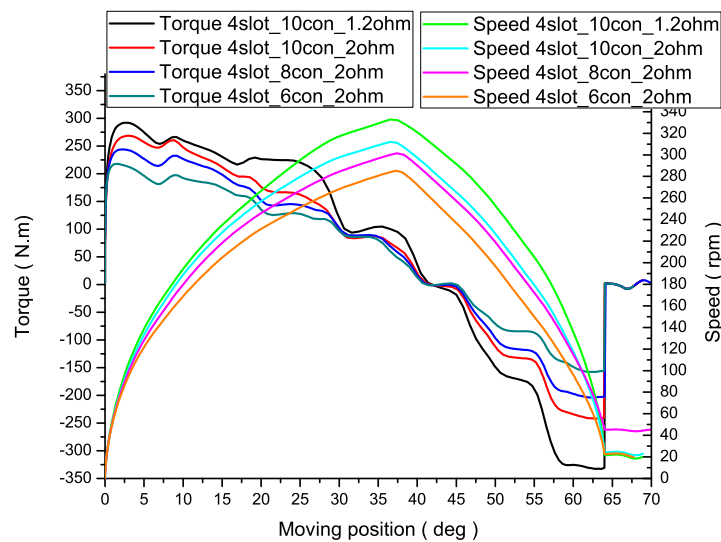


Figure 12. The torque and speed closing characteristic of the HVCB with LSATPMM, with different armature resistances and N_a at four slots per pole. Node: 10con_1.2 ohm means that the number of conductors of one coil is 10, and the armature resistance is 1.2 ohm, etc.

In Figure 13, the model of LSATPMM, with opening and closing coils at five slots per pole, and the closing characteristic are shown. The closing time of the operating mechanism of the high-voltage circuit breaker of the proposed LSATPMM moving from 0 to 64 degrees in approximately 64.5 ms, 61 ms, 59.5 ms, 59 ms, 58 ms, 58 ms, and 53.2 ms with the following numbers of slots per pole: 3, 4, 5, 6, 7, 8, and 9, respectively. It is clear that the closing time of the operating mechanism meets the standard of HVCB, i.e., the closing time of the operating mechanism is less than 90 ms. The closing time with nine slots per pole is too short since the current is turned off in advance. The average speed at all stages are shown in Table 3, from which it is obvious that the speeds of the moving contact are rapid at one-third distance, before the instance of touching contacts, and is slow at the end of the closing. From Table 3, it can be seen that the closing speeds at different moving stages are improved by using the LSATPMM.

Based on the above analysis, the design flow chart of LSATPMM for a high-voltage circuit breaker application is shown in Figure 14. In this figure, it is clear that the LSATPMM is first designed to meet the opening requirements of the operating mechanism for high-voltage circuit breakers and then the closing coil of LSATPMM is designed to fulfill the closing requirements. The design flow chart can be described as follows.

Table 3. The closing speed of the operating mechanism is shown at different moving stages. (Node: A is the mean of the average speed, with the scope of two-thirds distance, at the beginning (m/s); B is the mean of the average speed, with the scope of one-third distance, before the instance of touching contacts (m/s); C is the mean of the average speed, with the scope of distance, after touching contacts (m/s)).

Design Parameter	A	B	C
reference	more than 0.77 m/s	more than 1.31 m/s	less than 1.31 m/s
[3]	1.31147541	2.564102564	0.916030534
[4]	1.398601399	2.739726027	0.956175299
[5]	1.413427562	2.898550725	0.987654321
[6]	1.423487544	2.777777778	1.012658228
[7]	1.418439716	2.777777778	1.061946903
[9]	1.47601476	3.03030303	0.987654321
[10]	1.413427562	3.076923077	1.304347826

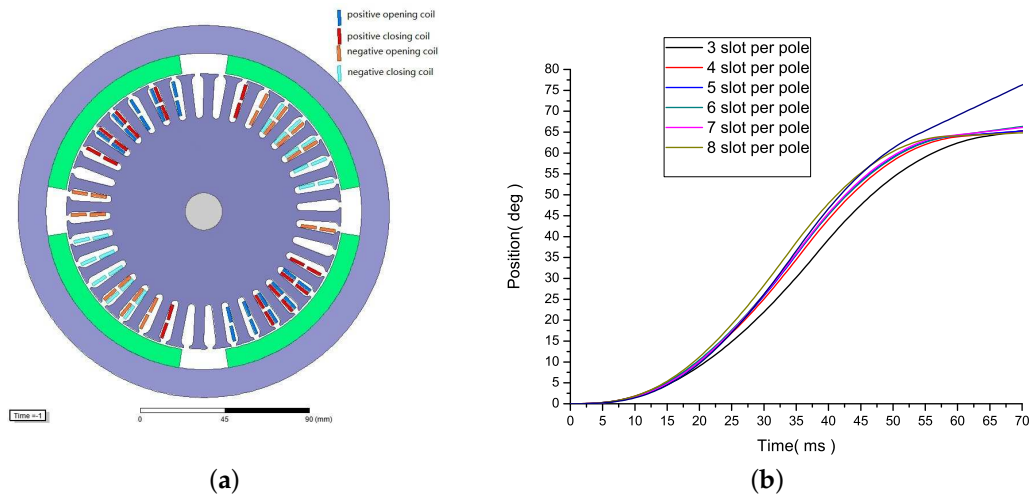


Figure 13. The model of LSATPMM, with opening and closing coils at five slots per pole, and the closing characteristic: (a) the equivalent model of five slots per pole of LSATPMM; (b) the closing characteristic of the HVCB with LSATPMM.

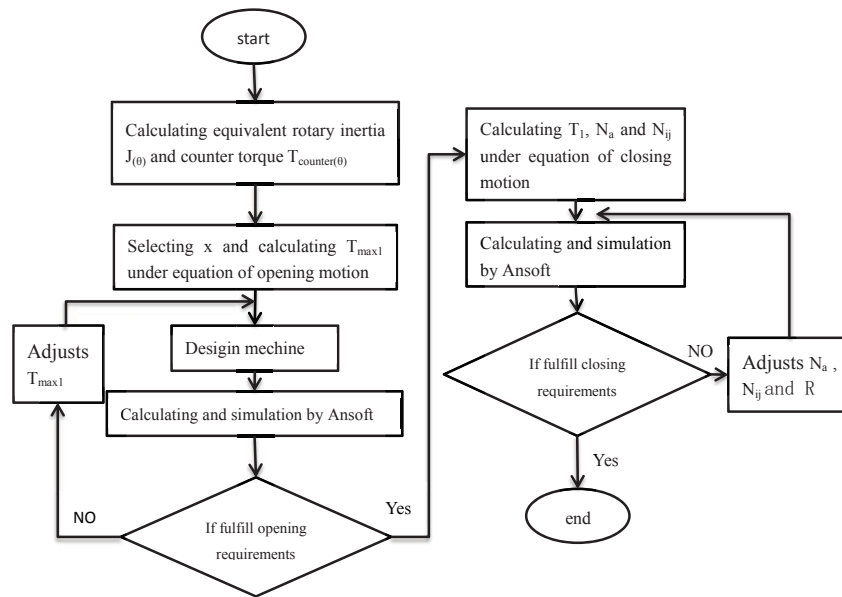


Figure 14. The design flow chart of LSATPMM for a high-voltage circuit breaker application.

First, the equivalent rotary inertia $J(\theta)$ and counter torque $T_{counter(\theta)}$ are calculated by Equation (5). Moreover, x is selected between 0 and $\frac{10\pi}{180}$, and T_{max1} is calculated by Equations (8) and (12) to meet the requirement of the opening motion.

Secondly, the machine is designed, and the FEA method is used, in order to determine whether the characteristics of the machine fulfill the opening requirements or not. If the characteristics of the machine do not fulfill the opening requirements, adjusting T_{max1} and repeating the second step are necessary; if not, the process is complete.

Thirdly, T_1 , N_a and N_{ij} are calculated by the results simulated above and Equations (13)–(20). Fourthly, the FEA method is used to determine if the characteristics of the machine fulfill the closing requirements or not. If the characteristics of machine do not fulfill the closing requirements, adjusting N_a and N_{ij} and repeating the fourth step are necessary; if not, the design procedure is complete.

4.3. The Fault Tolerance Characteristic

It can be predicted that a fault in the circuit breaker with LSATPMM will often occur, i.e., that the HVCB refuses to open or close due to a malfunction in the opening circuit or closing circuit, respectively. For fault tolerance, the closing coil and opening coil can open and close the circuit breaker. The opening characteristic of the HVCB, with a closing coil, and the closing characteristic of the HVCB, with an opening coil, are shown in Figure 15. It is obvious, from Figure 15, that the closing circuit and opening circuit can realize the opening and closing of the circuit breaker by sacrificing some performances.

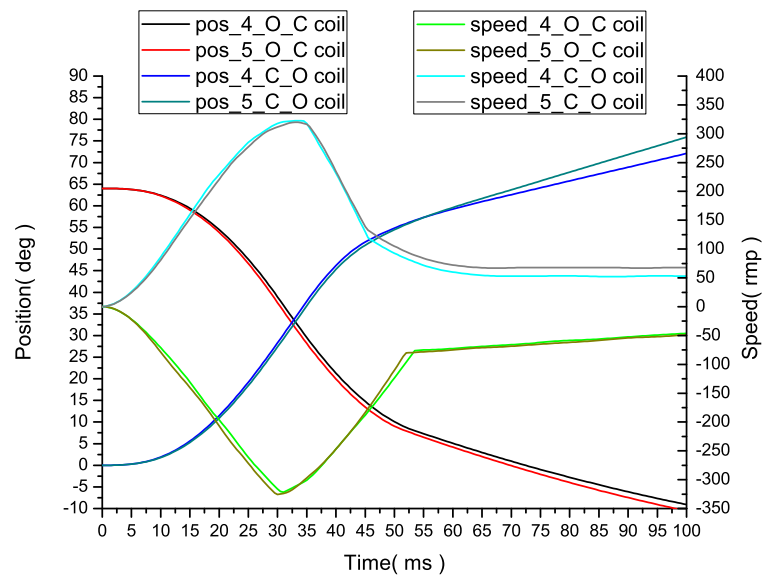


Figure 15. The fault tolerance characteristic of HVCB Node: Pos_4_O_C coil means the opening position characteristic of the HVCB with a closing coil and four slots per pole, etc.

On the other hand, the opening and closing characteristic of the HVCB with a lower voltage and higher voltage is shown in Figure 16. With a higher voltage, the turn-off angle is constant, and the turn-off angle advances at a lower voltage. It is evident, from Figure 16, that the HVCB with LSATPMM can also realize the opening and closing of the circuit breaker at 85 percent of rated voltage and 110 percent of rated voltage.

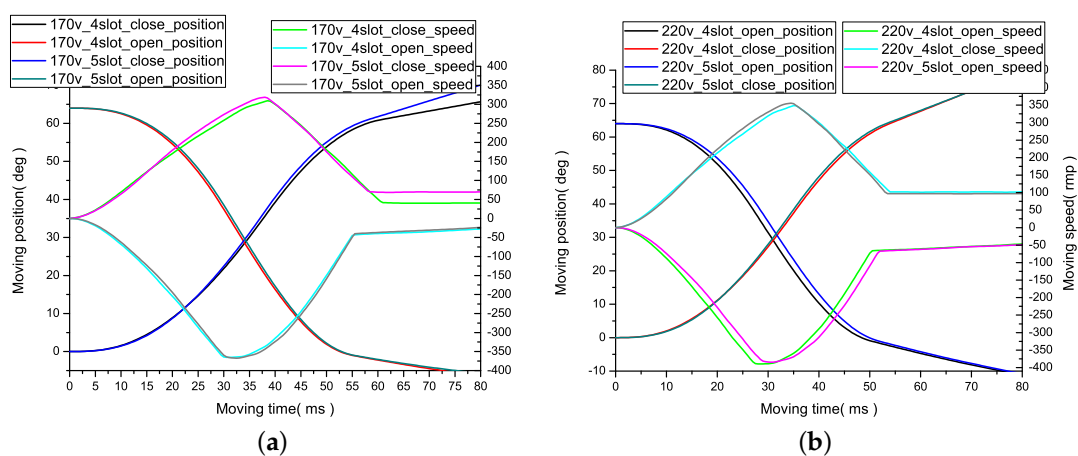


Figure 16. The fault tolerance characteristic of HVCB, with the lower rated voltage and higher rated voltage, at four and five slots per pole of LSATPMM: (a) the opening and closing characteristic of the HVCB at 85 percent of rated voltage; (b) the opening and closing characteristic of the HVCB at 110 percent of rated voltage.

5. Experimental Test-Stand and Results

To further research and certify the presented LSATPMM, a prototype of the proposed machine is created and tested in our study work, which is shown in Figure 17. The principal sizes of the proposed motors are shown in Table 4. The test platform has four DC power supplies, one Magnetic brake, one Torque sensor and one Oscilloscope. Each DC power supply has a power Magnetic brake (with a rated torque of 25 N.m and Maximum excitation current of 0.94 A). The torque sensor was powered by one DC power supply (with a Maximum limited current of 20 A and Maximum limited voltage of 60 V). Another two power supplies power the presented LSATPMM. The magnetic brake is used to fix the machine. In the experiment, an Oscilloscope is used to ready the output signal from the Torque sensor.

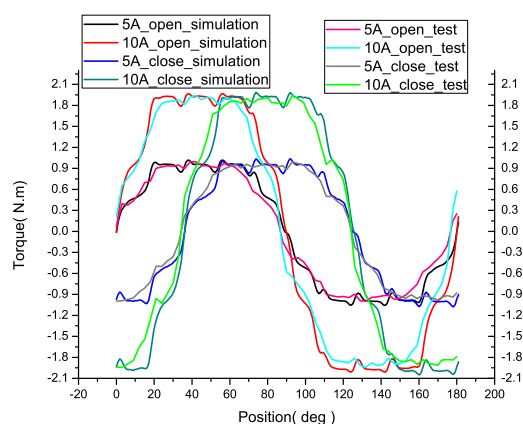
The divergence of characteristics between the simulation results and the test results are mainly caused by the material and processing technology. The advantageous characteristics of LSATPMM are shown in Figure 17. It can be seen in Figure 17 that the measuring results agree with the simulation results, which confirms the accuracy of the above analysis. However, the dynamic characteristic of the prototype will be studied in the near future due to limited experimental conditions.

Table 4. Parameters of prototype.

Design Parameter	Value
Number of Stator Slots	20
Outer Diameter of Stator (mm)	80
Inner Diameter of Stator (mm)	38
Number of Pole Pairs	2
Air Gap (mm)	1
Outer Diameter of Rotor (mm)	108
Inner Diameter of Rotor (mm)	82
Length of Rotor (mm)	52
Pole Embrace	0.8
Number coil of per Slot	40
Magnet Thickness (mm)	8
Rated Voltage (v)	36
Continuously Working Current (A)	16
Rated Power (W)	360
Rated Torque (N.m)	3.5
Rated Speed (rpm)	1000
Resistance (ohm)	0.9
Average Mutual Inductance (mH)	0.288
Average Self Inductance (mH)	1.9043



(a)



(b)

Figure 17. The measurement results and simulation results are shown: (a) the test platform; (b) the characteristic curve of position versus torque of the proposed machine.

6. Discussion

In this paper, a novel limited swing angle torque permanent magnet motor (LSATPMM) is presented, and the operating principle of the proposed LSATPMM and mathematics model are analyzed. The work of this paper can be summarized as follows:

1. A novel LSATPMM is presented, which has two sets of windings that are mounted at a specific location to react the reactive force at the end, moving without a change in the current, which is difficult for a conventional Limited-Angle Torque Motor.
2. In published papers, the coils, per pole per phase, are normally continuous in the slots. However, the coils, per pole per phase, of LSATPMM are not all continuous.
3. The LSATPMM has only one coil per winding, which is one phase less than the conventional three phases Limited-Angle Torque Motor.
4. The fault tolerance and design procedure of LSATPMM for HVCB are discussed.

7. Conclusions

The following conclusions are drawn in light of the above-mentioned results.

1. LSATPMM has two sets of windings, and only one coil per winding, which is one coil less than the conventional three-phase Limited-Angle Torque Motor.
2. The opening and closing torque of LSATPMM can theoretically be adjusted to meet the required characteristics of the circuit breaker, i.e., short closing process time, short contact bounce time and as few excess strokes as possible.
3. The drive circuit for LSATPMM has two controllable thyristors, which is better than the drive circuit of the conventional Limited-Angle Torque Motor, which has six controllable thyristors. In this case, the reliability is improved and the cost is decreased.
4. If the drive circuit adds two controllable thyristors, the closing circuit and opening circuit can realize the opening and closing of the circuit breaker with LSATPMM by sacrificing some performance, which improves the fault tolerance and the reliability of HVCB.
5. The torque density of LSATPMM is higher, and thus the volume of HVCB is smaller.

In brief, the results show that the presented machine obtains the advantages of adjusting the opening and closing torque characteristic, high reliability, robust drive circuit and fault tolerance. The LSATPMM is also suitable for swing moving, which requires different torques in forward and reverse motions. However, the novel machines and the HVCB, with this proposed machine, also have some problems and should be researched in follow-up work.

Author Contributions: The LSATPMM structure was designed by G.Z., X.Y. and S.Z. G.Z. designed the research methods and designed strategies. G.Z. and Y.P. designed and performed the experiments. H.Y. and J.C. provided the experimental environment. G.Z. wrote the paper.

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