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# Analysis and Design of a Thomson Coil Actuator System for an HVDC Circuit Breaker

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**ABSTRACT** In this study, we analyze and design a Thomson coil actuator system (TCAS) that ensures stable operation of a high voltage direct current circuit breaker. High voltage direct current circuit breakers require a high-speed actuator and proper brake system that can absorb the kinetic energy of fast-moving mass to prevent damage and malfunction of the device. However, existing brake systems degrade the responsiveness of TCAS. Therefore, the proposed TCAS is designed to improve the low responsiveness of the actuator, which is caused by braking forces, by applying a series spring brake system and latch type holding system. An equivalent circuit model of TCAS that reflects its electromagnetic and kinetic properties is derived and applied to the design of the TCAS. The validity of the proposed TCAS design and analysis model is verified through prototype experiments. The experimental results show that the proposed TCAS completes a 30 mm stroke opening operation in 5.4 ms at a drive voltage of 300 V, and the analysis results reveal that the error rate for the experimental results is 4.65%.

**INDEX TERMS** Actuators, equivalent circuits, HVDC circuit breakers.

## I. INTRODUCTION

High voltage direct current (HVDC) is a DC power transmission system that has high power efficiency in long-distance transmission. It has several advantages over AC power transmission systems, such as high efficiency in long-distance transmission, reduction in power transmission line installation costs, and ease of connection with power systems with different frequencies [1]–[4]. Therefore, it has attracted increased interest as an alternative to the conventional AC system.

However, to facilitate the use of HVDC systems, several technical difficulties must be addressed. One of the greatest obstacles to the widespread use of HVDC technology is the difficulty of developing a circuit breaker that can effectively break DC current. Unlike in an AC system where a zero current exists, in an HVDC system, the current does not pass through the zero point naturally. Consequently, the HVDC system has high blocking difficulty. This problem of effective blocking can be solved by employing a high-speed actuator that separates the contact quickly.

Hydraulic, electromagnetic or spring-type actuators used in conventional AC breakers do not easily meet the requirements of HVDC breaker operations owing to their long response time and low operating speed [5]–[14]. Contrastingly, Thomson coil actuators (TCAs), are propelled by the repulsive force between the drive current of the coil and the eddy current of the mover plate. Therefore, they have high responsiveness and operating speed, which makes them the most suitable effective system for HVDC breaker development.

Several studies have been conducted on the use of TCA as an HVDC breaker actuator [15]–[18]. However, these studies focused only on the movement of the mover to reach the target stroke and did not include subsequent procedures, such as braking and fixation of the mover. TCA requires a device to stably absorb kinetic energy and hold the mover to prevent damage or malfunction caused by impact and bounce. In this regard, several methods have been proposed for breaker actuators; the most common and simplest method is the use of

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a compression spring as a brake spring [19]–[21]. In this approach, the braking force acts strongly from the time of initial acceleration, thereby impeding TCA responsiveness and decreasing the operating speed. In another method, the braking coil utilizes the electromagnetic repulsion force as the braking force [22]. This method exhibits less interference with TCA operation because it can freely adjust the timing and magnitude of the braking force; however, it is not effective for circuit breakers that require several kN of contact force to decrease the contact resistance at the close state. Therefore, to overcome the limitations of conventional brakes, developing a new brake and hold system suitable for the circuit breaker environment and subsequently incorporating them in TCA is necessary.

In this study, a Thompson coil actuator system (TCAS) for HVDC circuit breakers was developed by adding a series spring to the basic TCA structure. Two series-connected springs were used to provide sufficient contact force to the contacts at the close state and to minimize interference from the operation of the TCA while maintaining a high braking force. Subsequently, the analysis model of the proposed TCAS operation was derived and used for the TCAS design. The design procedure of the proposed TCAS, including the braking and holding unit, was presented, and the operation of the proposed TCAS design was validated through prototype experiments. Finally, the experimental results were analyzed.

## II. STRUCTURE AND MECHANISM OF THE DEVICE

The proposed actuator system comprises an actuator unit that generates motion using the Thomson coil effect, a braking unit for absorbing the kinetic energy of the moving part, and a holding unit that prevents the movement of a mover after operation is completed.

### A. STRUCTURE OF THE PROPOSED ACTUATOR

The proposed TCAS comprises an actuator unit composed of a mover and drive coil, a brake unit composed of two spring series, and a holder unit composed of a spring latch, as shown in Fig. 1.

The mover is composed of a conductive plate, in which an eddy current is induced, and a mover guide, which connects the mover and moving contact of the interrupter.

The brake unit consists of a series of contact springs and brake springs. The contact spring has low elasticity; it applies a contact force at the close state and prevents damage to the mover guide that is caused due to collision between the mover and brake spring. The brake spring has high elasticity and plays a major role in absorbing the kinetic energy of the moving mass.

The holder unit consists of a spring and latch in contact with the mover guide surface; it operates when the mover passes through the target stroke. The spring moves the latch to the locking position of the mover guide surface to ensure that the mover does not return to its original state as a result of the compressive force of the brake spring.

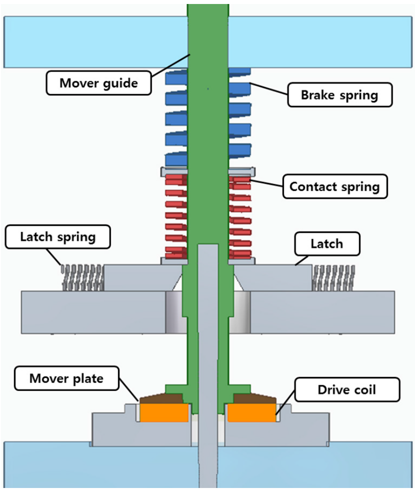


**FIGURE 1.** Structure of the proposed TCAS.

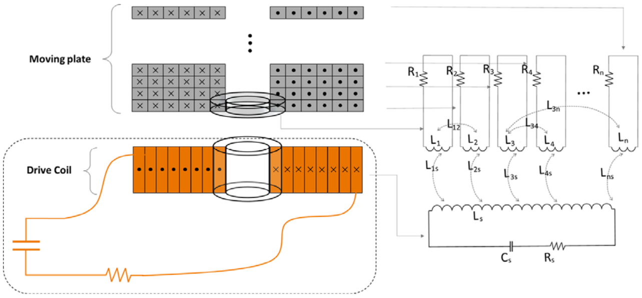


**FIGURE 2.** Equivalent circuit model of the proposed TCAS.

### B. OPERATION OF THE PROPOSED ACTUATOR

The proposed actuator system has three operating states: close state, open triggered, and open state; details of the operating process for each state are described below.

#### 1) CLOSE STATE

The force of the contact spring and brake spring ensures that the moving contact is in contact with the fixed contact with a sufficient contact force. Current is conducted through the connection between the two contacts. The switch of the drive circuit is opened, and the capacitor is charged with electrical energy to drive the actuator.

#### 2) OPEN TRIGGERED

The switch of the drive coil is closed using an open trigger; subsequently, the drive current flows from the capacitor to the drive coil. The magnetic flux that passes through the mover plate changes rapidly because of the coil current, and consequently, an eddy current is produced in the mover plate. The mover plate and the moving part connected to it move along the axis owing to the repulsive force between the eddy current and coil current.

#### 3) OPEN STATE

When the mover moves along the axis and passes the target stroke, the latch spring pushes the latch; consequently, the

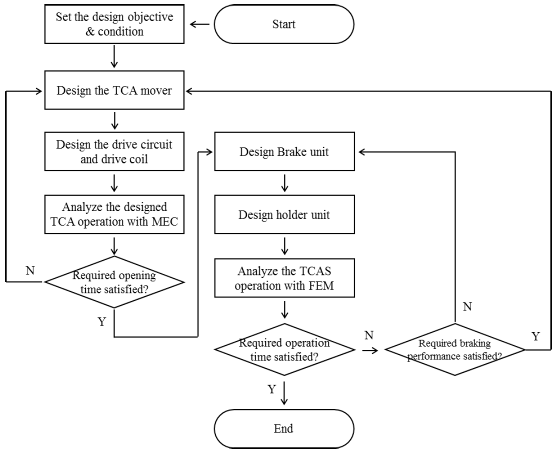


**FIGURE 3.** Flow chart of the proposed TCAS design.

latch contacts with the locking surface of the mover guide. A mover moved beyond the open stroke attempts to move back via a brake spring and stops at the target stroke position with the aid of a latch, thereby completing the operation of the entire actuator.

## III. DESIGN OF THE PROPOSED TCAS

### *A. DESIGN FLOW OF THE THOMSON COIL ACTUATOR SYSTEM*

The proposed TCAS design comprises three parts: an actuator unit, brake unit, and holder unit. The design process was implemented using the design flow shown in Fig. 3, and details of the design process of each unit are described below.

### *B. DESIGN OF THE ACTUATOR UNIT*

The design of the actuator unit was implemented using the characteristic analysis results based on the magnetic equivalent circuit (MEC) model. MEC can be used to simultaneously analyze the magnetic coupling between the drive coil and mover plate, current induction phenomenon in the mover plate, motion of the mover, and voltage–current characteristics of the drive circuit at a low cost. The TCA performance can be evaluated based on the calculation results of the current and motion of the TCA obtained from the analysis; it can be subsequently used in the design of the TCA. The MEC of the TCA is derived as follows.

#### 1) EQUIVALENT CIRCUIT MODEL OF TCA

An equivalent circuit model was derived to analyze the electromagnetic and kinetic characteristics of the proposed TCAS, as shown in Fig. 2. This model can be used to calculate the current flowing in the drive coil and mover plate, as well as the displacement of the mover [23]. The mover plate can be modeled as a group of n small disk elements, as shown in Fig. 2. An equivalent circuit can be derived based on the calculation of the circuit constants, such as the mutual inductance between each disk element and the mutual inductance between the disk element and drive coil. Furthermore, the governing equation of TCA was derived from the equivalent circuit, as given in (1). By numerically integrating (1) with the initial value of the TCAS to be tested, each characteristic value can be calculated with respect to time.

$$\begin{pmatrix} L_{11} & L_{12} & \dots & L_{1n} & -L_{1s} & 0 & 0 & 0 \\ L_{21} & L_{22} & \dots & L_{2n} & -L_{2s} & 0 & 0 & 0 \\ \vdots & \vdots & -L_{2s} & \vdots & \vdots & \vdots & \vdots & \vdots \\ L_{n1} & L_{n2} & \dots & L_{nn} & -L_{ns} & 0 & 0 & 0 \\ -L_{s1} & -L_{s2} & \dots & -L_{sn} & -L_{ss} & 0 & 0 & 0 \\ 0 & 0 & \dots & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & \dots & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & \dots & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} \dot{i}_1 \\ \dot{i}_2 \\ \vdots \\ \dot{i}_n \\ i_s \\ \dot{q} \\ \dot{z} \\ \dot{v} \end{pmatrix} = \begin{pmatrix} \partial L_{1s}/\partial z - i_1 R_1 \\ \partial L_{2s}/\partial z - i_2 R_2 \\ \vdots \\ \partial L_{ns}/\partial z - i_n R_n \\ q/C_s + \sum_{j=1}^{n} \partial L_{js}/\partial z \cdot v \cdot i_j - i_s R_s \\ i_s \\ v \\ f_e/m \end{pmatrix} \tag{1}$$

### *C. DESIGN OF THE BRAKE UNIT*

The brake unit of the proposed TCAS was designed with a spring brake system using a compression spring. The design of the spring brake system was implemented by searching for a spring that can sufficiently absorb the kinetic energy $E_{mover}$ during the target braking time $t$ in the target braking distance $x$.

The process of determining $k$ that satisfies the braking distance $x$ for a moving person with a mass $m$ is as follows. The relationship between $E_{spring}$ and $E_{mover}$ of the spring compressed through the distance $x$ is given in (2).

$$E_{spring} = \frac{1}{2} \cdot k \cdot x^2 > \frac{1}{2} \cdot m \cdot v^2 = E_{mover} \tag{2}$$

By rearranging (2), (3) can be obtained; correspondingly, the spring constant $k$ must be designed to satisfy (3).

$$k \geq m \cdot \frac{v^2}{x^2} \tag{3}$$

The process of determining the value of $k$ that satisfies the braking time $t$ is as follows. Assuming that the deceleration factor of the mover is only the elastic force of the spring, the expression of the mover speed $v$ at time $\tau$ in the deceleration process of the mover speed $v_0$ is derived using (4).

$$v(\tau) = v_0 \cdot \cos\left(\sqrt{\frac{k}{m}} \cdot \tau\right) \tag{4}$$

In (4), the spring constant $k$ for the speed v to become zero at $\tau \leq t$ is obtained using (5).

$$k \geq m \cdot \left(\frac{\pi}{2t}\right)^2 \tag{5}$$

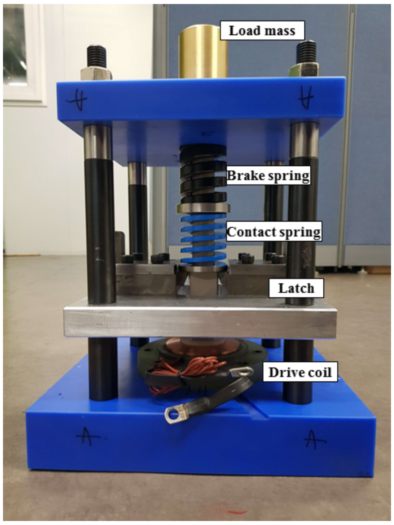


**FIGURE 4.** Prototype of the proposed TCAS.

For the designed spring brake system to operate within the target braking time and braking distance, it is possible to design the spring brake system to achieve the target performance by selecting a spring whose spring constant k of the brake spring satisfies both (3) and (5).

### D. DESIGN OF THE HOLDER UNIT

The holder unit of the proposed TCAS consists of a latch operated using a compression spring. The latch must travel a distance $x_{latch}$ sufficient to hold the position of the mover within time $t_{brake}$ until the mover passes through the target stroke and returns to the target stroke point using the compression force of the spring.

The travel distance $x(t)$ of the latch is derived as a function of the spring constant $k_{latch}$ of the latch spring, latch mass $m_{latch}$ and initial compression length $x_0$ of the latch spring, as given in (6).

$$x\left(t\right) = x_0 \cdot \sin\left(\sqrt{\frac{k_{latch}}{m_{latch}}} \cdot t\right) \tag{6}$$

The condition of $k_{latch}$ for the latch to move $x_{latch}$ in $t_{brake}$ is derived based on (6), as expressed in (7).

$$k_{latch} \geq \left(\frac{\sin^{-1}\left(x_{latch}/x_0\right)}{t_{brake}}\right)^2 \cdot m_{latch} \tag{7}$$

By selecting a spring that satisfies (7), the design of a latch system that reliably performs the holding function of the TCA according to the intended operation can be achieved.

**TABLE 1.** Dimensions of TCA prototype design.

| Parameter | Value | Unit |
|---|---|---|
| Outer diameter of mover plate | 80 | mm |
| Height of mover plate | 6 | mm |
| Number of turns of drive coil | 27 | turns |
| Outer diameter of drive coil | 80 | mm |
| Coil height | 10.5 | mm |
| Spring constant of brake spring | 400 | N/mm |
| Spring constant of contact spring | 126 | N/mm |
| Load mass | 2 | kg |
| Contact force | 2 | kN |
| Drive voltage | 200, 250, 300 | V |

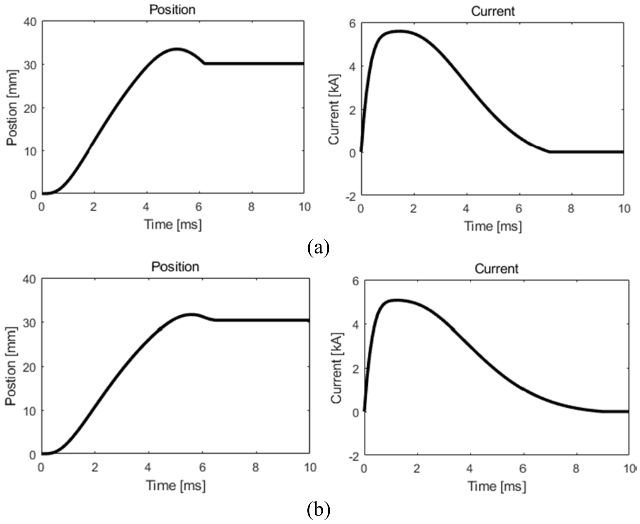


**FIGURE 5.** Operation result of the proposed TCAS at a drive voltage of 200 V (a) FEA and (b) prototype experiment.

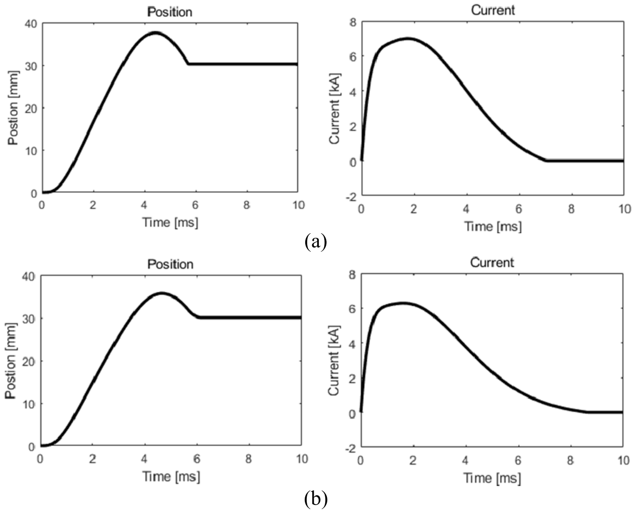
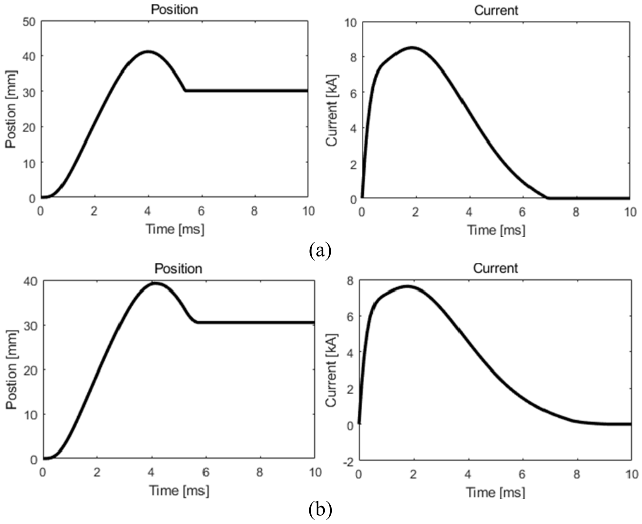


**FIGURE 6.** Operation result of the proposed TCAS at a drive voltage of 250 V (a) FEA and (b) prototype experiment.

## IV. EXPERIMENTAL RESULTS

The operation of the proposed TCAS was verified through a prototype experiment; a prototype of the proposed TCAS was constructed, as shown in Fig. 4. A drive circuit, which was configured using a capacitor bank and IGBT switch, was connected to a drive coil to apply drive power. Subsequently, the voltage, current, and displacement were measured. The drive voltage and drive current were measured using an



(a)

(b)

**FIGURE 7.** Operation result of the proposed TCAS at a drive voltage of 300 V (a) FEA and (b) prototype experiment.

**TABLE 2.** Comparison of experimental and simulation results at a drive voltage of 200 V.

| Parameter | FEA | Experiment | Error rate |
|---|---|---|---|
| Maximum displacement | 33.4 mm | 31.55 mm | 5.86 % |
| Time at maximum displacement | 5.1 ms | 5.4 ms | -5.56 % |
| Total operation time | 6.2 ms | 6.3 ms | -1.59 % |
| Maximum current | 5.58 kA | 5.05 kA | 10.5 % |

**TABLE 3.** Comparison of experimental and simulation results at a drive voltage of 250 V.

| Parameter | FEA | Experiment | Error rate |
|---|---|---|---|
| Maximum displacement | 37.52 mm | 35.8 mm | 4.80 % |
| Time at maximum displacement | 4.4 ms | 4.7 ms | -6.38 % |
| Total operation time | 5.7 ms | 5.8 ms | -1.72 % |
| Maximum current | 6.99 kA | 6.29 kA | 11.24 % |

**TABLE 4.** Comparison of experimental and simulation results at a drive voltage of 300 V.

| Term | FEA | Experiment | Error rate |
|---|---|---|---|
| Maximum displacement | 41.19 mm | 39.27 mm | 4.89 % |
| Time at maximum displacement | 4 ms | 4.1 ms | -2.44 % |
| Total operation time | 5.4 ms | 5.5 ms | -1.82 % |
| Maximum current | 8.5 kA | 7.61 kA | 11.7 % |

oscilloscope, whereas the displacement was measured using a laser displacement meter. The design dimensions of the TCAS prototype and the experimental conditions are presented in Table 1.

In the experiment, the motion and electrical characteristics of the device were determined by measuring both the displacement of the mover and the current flowing in the drive coil at drive voltages of 200 V, 250 V, and 300 V.

The experimental and analysis results obtained using Finite element method (FEM) are shown graphically in Figs. 5–7, and the important values in the graphs are summarized in Tables 2–4.

It can be observed from the experimental results that all the TCASs designed at drive voltages of 200–300 V operate normally and stably perform the opening operation of 30 mm stroke.

Furthermore, as presented in Tables 2–4, it was confirmed that the TCAS characteristic analysis method used in the design process can reliably analyze error rates of less than approximately 5% and 10% for the displacement characteristics and current characteristics, respectively.

## V. CONCLUSION

In this study, a TCAS that performs the opening/closing operation function of a breaker using the Thompson coil principle was designed, analyzed, and verified through experiments. Unlike previous studies that focused only on the analysis and design of the actuator unit, this study examined the design process of the entire TCAS, including the brake unit and holder unit.

The findings of this study can be used as a reference in the design of a real TCAS, including the braking system, as only very few studies have focused on the design of both braking and holding devices for the stability of TCA operation.

The proposed TCAS has a larger stroke opening of 30 mm compared with conventional TCASs (in the range of 10–20 mm). Therefore, it can contribute to a more stable operation of a circuit breaker in a high-voltage transmission system. Consequently, it can be used not only for breakers, but also for arc eliminators that require a large stroke.

In addition, the proposed brake system with serial springs can effectively improve TCAS performance because it significantly reduces the spring-induced acceleration inhibition effect in the acceleration interval of the mover without significantly complicating the structure compared with conventional single spring brakes.

## REFERENCES

[1] R. D. Garzon, *High Voltage Circuit Breakers Design and Applications*, 2nd ed., New York, NY, USA: Marcel, 2002.

[2] B. Mitra, B. Chowdhury, and M. Manjrekar, "HVDC transmission for access to off-shore renewable energy: A review of technology and fault detection techniques," *IET Renew. Power Gener.*, vol. 12, no. 13, pp. 1563–1571, Oct. 2018.

[3] P. Bresesti, W. L. Kling, R. L. Hendriks, and R. Vailati, "HVDC connection of offshore wind farms to the transmission system," *IEEE Trans. Energy Convers.*, vol. 22, no. 1, pp. 37–43, Mar. 2007.

[4] F. Mohammadi, K. Rouzbehi, M. Hajian, K. Niayesh, G. B. Gharehpetian, H. Saad, M. H. Ali, and V. K. Sood, "HVDC circuit breakers: A comprehensive review," *IEEE Trans. Power Electron.*, vol. 36, no. 12, pp. 13726–13739, Dec. 2021.

[5] P. G. Slade, *The vacuum interruptor: Theory, design and application*. Boca Raton, FL, USA: CRC Press, 2007.

[6] W. Liu, B. Xu, H. Yang, H. Zhao, and J. Wu, "Hydraulic operating mechanisms for high voltage circuit breakers: Progress evolution and future trends," *Sci. China Technol. Sci.*, vol. 54, no. 1, pp. 116–125, Jan. 2011.

[7] P. Barkan, I. Imam, and W. Premerlani, "A new rapid-response hydraulic actuator—Design, analysis and test results," *J. Mech. Des.*, vol. 102, no. 1, pp. 3–13, Jan. 1980.

[8] B. Xu, R. Ding, J. Zhang, L. Sha, and M. Cheng, "Multiphysics-coupled modeling: Simulation of the hydraulic-operating mechanism for a SF6 high-voltage circuit breaker," *IEEE/ASME Trans. Mechatronics*, vol. 21, no. 1, pp. 379–393, Feb. 2016.

[9] S. N. Yun, H. H. Jeong, S. C. Hwang, H. B. Kim, and I. S. Park, "High speed solenoid actuator for high-voltage circuit breaker," in *Proc. Int. Conf. Control. Autom. Syst.*, 2011, pp. 1006–1010.

[10] J. Z. Zhang, C. H. Cai, and C. G. Wu, "Design and analysis of a new permanent magnet actuator for medium voltage vacuum circuit breakers," *Appl. Mech. Mater.*, vols. 313–314, pp. 20–26, Mar. 2013.

[11] S.-J. Kim, S.-C. Hahn, Y.-I. Kim, H.-R. Koh, and M.-S. Choi, "Numerical investigation for dynamic characteristic analysis of electromagnetic actuator for gas circuit breakers," in *Proc. 3rd Int. Conf. Electr. Power Equip. Switching Technol. (ICEPE-ST)*, Oct. 2015, pp. 367–371.

[12] G. Y. Ahn and K. Y. Jeong, "Optimization of the spring design parameters of a circuit breaker to satisfy the specified dynamic characteristics," *Int. J. Precis. Eng. Manuf.*, vol. 5, no. 4, pp. 43–49, 2004.

[13] L. Wang and E. Wang, "Reliability prediction for the spring-cam actuator of vacuum circuit breaker," in *Proc. Int. Symp. Discharges Electr. Insul. Vacuum (ISDEIV)*, vol. 2, Sep. 2004, pp. 644–647.

[14] G. Chen, B. Sun, X. Liu, and E. Wang, "Robust optimisation of the spring actuator in a vacuum circuit breaker," *Math. Struct. Comput. Sci.*, vol. 24, no. 5, Oct. 2014, Art. no. e240520.

[15] S. Liu, P. Hu, D. Jiang, Y. Liang, and J. Zhuang, "A fast LVDC vacuum hybrid circuit breaker: Dielectric recovery and design consideration," *IET Gener., Transmiss. Distrib.*, vol. 15, no. 21, pp. 3058–3065, Nov. 2021.

[16] T. Augustin, M. Parekh, J. Magnusson, M. Becerra, and H.-P. Nee, "Thomson-coil actuator system for enhanced active resonant DC circuit breakers," *IEEE J. Emerg. Sel. Topics Power Electron.*, vol. 10, no. 1, pp. 800–810, Feb. 2021.

[17] A. Al-Qarni and A. EL-Refaie, "Design and analysis of double-sided Thomson coil actuator for extra fast opening operation," in *Proc. IEEE Energy Convers. Congr. Expo. (ECCE)*, Oct. 2021, pp. 4361–4368.

[18] B. Lequesne, T. Holp, S. Schmalz, M. Slepian, and H. Wang, "Frequency-domain analysis and design of Thomson-coil actuators," in *Proc. IEEE Energy Convers. Congr. Expo.*, Oct. 2021, pp. 4081–4088.

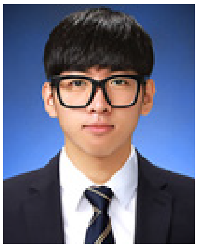
[19] Y. Kishida, K. Koyama, H. Sasao, N. Maruyama, and H. Yamamoto, "Development of the high speed switch and its application," in *Proc. 33rd IAS Annu. Meeting Ind. Appl. Conf.*, vol. 3, Oct. 1998, pp. 2321–2328.

[20] W. Wen, Y. Huang, M. Al-Dweikat, T. Cheng, S. Gao, and W. Liu, "Research on operating mechanism for ultra-fast 40.5-kV vacuum switches," *IEEE Trans. Power Del.*, vol. 30, no. 6, pp. 2553–2560, Dec. 2015.

[21] M. Zhang, Y. Wang, P. Li, and H. Wen, "Comparative studies on two electromagnetic repulsion mechanisms for high-speed vacuum switch," *IET Electric Power Appl.*, vol. 12, no. 2, pp. 247–253, Feb. 2018.

[22] C. Peng, L. Mackey, I. Husain, A. Q. Huang, W. Yu, B. Lequesne, and R. Briggs, "Active damping of ultrafast mechanical switches for hybrid AC and DC circuit breakers," *IEEE Trans. Ind. Appl.*, vol. 53, no. 6, pp. 5354–5364, Nov. 2017.

[23] W. Li, Y. W. Jeong, and C. S. Koh, "An adaptive equivalent circuit modeling method for the eddy current-driven electromechanical system," *IEEE Trans. Magn.*, vol. 46, no. 6, pp. 1859–1862, Jun. 2010.



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