Design and Implementation of Arc-Induction Type DC Circuit Breaker Confirming Prototype Model

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DC Circuit Breakers-Overview

- In Direct Current[DC] circuit,the voltage is continuous and has no frequency.
- In case of any fault,a surging transient current develops,and results in equipment failures due to severe heating.
- Therefore, fast cut-off operation is required simultaneously with the occurrence of a transient current.
- The use of power semiconductors is an emerging method to extinguish the DC arc.But they have not been commercialized.

DC Circuit Breakers-Overview

- The existing mechanical type circuit breakers use arc chute to extinguish the arc.
- If the arc chute fails to extinguish the arc,then:
  1. arc generation time will increase
  2. Severe damage will occur at the contacts

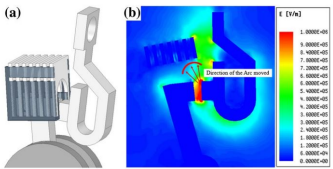

Figure: Breaking contacts of DC Circuit Breaker and Electric Field Distribution

- Therefore, a new arc-induction type DC circuit breaker is proposed and studied.

Arc-Induction Type DC Circuit Breaker-Construction

- Key Components include:
  1. Mechanical Contacts
     - Mechanical contacts are anode(+) and cathode(-).
     - Anode is fixed electrode and cathode is movable electrode.
  2. Induction Needle-Induction needle induces an arc generated between the blocking contacts to the ground line.
  3. Superconducting Magnet-It is positioned on either side of the central mechanical contact.

Arc-Induction Type DC Circuit Breaker-Construction

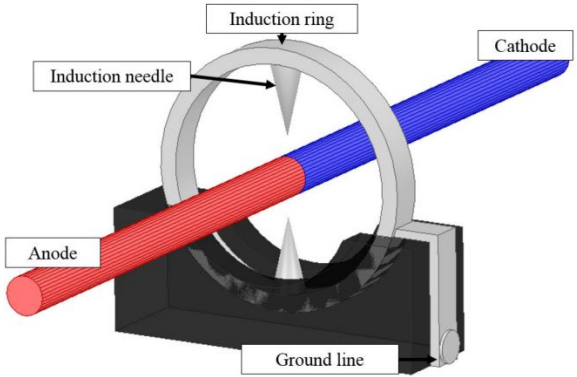

Figure: Model of Arc-Induction Type DC Circuit Breaker

Mathematical Model

- The figure shows the force experienced by the electrons between the contacts when contacts are opened.

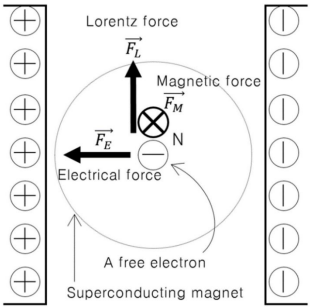

Figure: force experienced by the electrons between the contacts when contacts are opened.

Mathematical Model

- In the steady state condition,when the contacts are closed, normal current flows.

$$I_{normal} = \frac{Q_{normal}}{t_{normal}} \text{ [A]}$$

- In the transient state, the blocking contact opens, and an arc occurs.
- The high magnetic field of the superconducting magnets should be considered.
- Let the total number of free electrons of the arc is Ntransisents.

Mathematical Model

$$\vec{F} = Q_{transients}(\vec{E} + \overrightarrow{v_{transients}} \times \vec{B}) \text{ [N]}$$

$$\vec{f} = \frac{Q_{transients}(\vec{E} + \overrightarrow{v_{transients}} \times \vec{B})}{N_{transients}} \text{ [T]}$$

- Thus Lorentz force is obtained from the vector product of the electron movement speed.

$$\vec{f} = \frac{Q_{transients}(\vec{E} + \overrightarrow{v_{transients}} \times \vec{B})}{N_{transients}} = q(\vec{E} + \overrightarrow{v_{transients}} \times \vec{B}) \text{ [N]}$$

$$\vec{f} = q(\vec{E} + |v_{transients}||B|sin\theta) \text{ [N]}$$

Working

- In the transient state, a fault current is generated from the accident point,activating the DC cut-off unit.
- When contacts are opened,inelastic collision occurs between the electrons and the gas atoms.
- In this process,electrons undergo constant excitation and ionization.
- Electric field is created.
- The arc is subjected to Lorentz force under the influence of the magnetic field of the superconducting magnet.
- The guide needle is located along the direction of this force.
- Eventually, the arc flows out to the ground along the ground wire to extinguish it.

Working

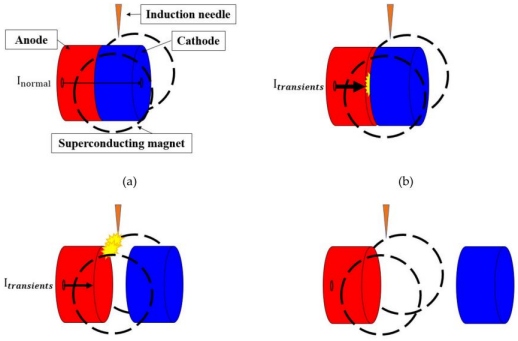

Figure: Operation mechanism of superconducting arc-induction type DC circuit breaker. (a) Normal state; (b) Transient state (1st); (c) Transient state (2nd); (d) Transient state (3rd).

Superconducting Magnet

- Two types of superconducting magnets can be used:
  1. DC field type bulk magnet-
     - Generates a high magnetic field after being magnetized by an electromagnet.
     - Generate magnetic fields up to 5T.
     - Does not require additional equipment.
  2. Pulse type magnet-
     - Generates a high magnetic field in a short time through a superconducting wire.
     - Requires an auxiliary current source.
     - Has a time delay.

Superconducting Magnet

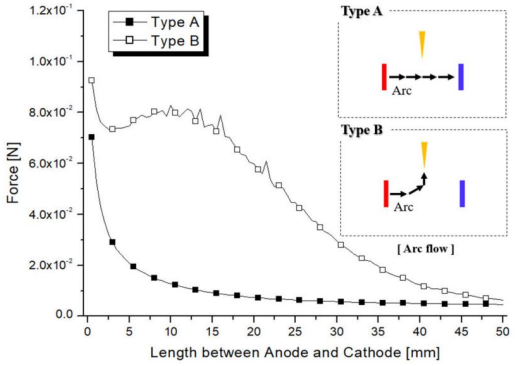

Figure: Graphs of the force received by an electron with or without the superconducting magnets.

Simulations

- The performance of circuit breaker was analysed using Maxwell 3D Program.
- The optimal distance between the poles was identified by changing the pole spacing from 0mm to 50mm in steps of 0.5mm
- The electric and magnetic fields generated was analysed graphically for each change in the distance.

Distance between poles(mm)	Electric Flux Density(V/m)	Magnetic Flux Density(T)
0.5	4.39×10^{17}	2.14
10	o 7.94×10^{16}	2.38
30	3.58×10^{16}	1.70

Figure: Variation of E and B with the change in pole spacing

Simulations

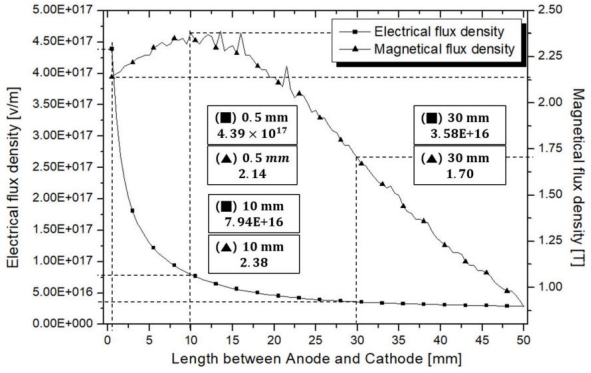

Figure: Variation of E and B with the change in pole spacing

Design of Prototype

- Induction needle,contacts,induction ring are made of copper with a plating of silver to increase conductivity.
- A pneumatic cylinder was used for the movement of the cathode.
- The atmospheric pressure level that was used in the experiment ranged from 7.9 to 8 kPa.
- The distance between the induction needle and the blocking contact was designed to be approximately 2 mm.

Design of Prototype

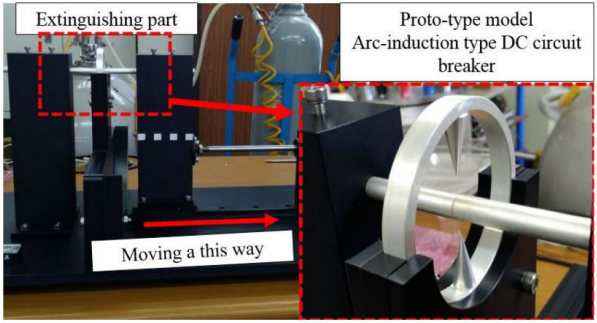

Figure: The prototype model of the Arc-induction type circuit breaker.

Advantages

- Faster operation.
- Maintenance cost is less.
- It has the economic advantage of maintaining the superconducting state through low-cost liquid nitrogen.
- Reduces the mechanical damage to contacts.
- Reduces system downtime occurrences.

Disdvantages

- Initial cost is high.
- Bulky.
- Optimum positioning of induction needle is required which require complex simulations .
- Shape of induction needle affects the performance.

Conclusion

- The arc-induced DC circuit breaker is a new type of circuit breaker that induces the arcs generated between the blocking contacts to induction needles.
- A simulation model was designed using the Maxwell software, and the blocking characteristics were analyzed through the electrical field distribution.
- It was thus proven in the simulation that the induction needle of the arc-induction type DC circuit breaker is advantageous for inducing arc.
- Based on these results, a prototype was fabricated.
- It is expected that this arc-induced DC blocking technology will be established as one of the various DC circuit breaker types.

References

- S. Park, H. Gu and H. Choi, "Design and Implementation of Arc-Induction Type DC Circuit Breaker Confirming Prototype Model," in IEEE Transactions on Applied Superconductivity, vol. 30, no. 4, pp. 1-5, June 2020, Art no. 5000205, doi: 10.1109/TASC.2020.2978796.
- Park, Sang-Yong Choi, Hyo-Sang. (2019). Characteristics of Arc-Induction Type DC Circuit Breaker Depending on Alteration of Induction Needle. Journal of Electrical Engineering Technology. 15. 10.1007/s42835-019-00320-9.
- Park, S.; Choi, H. Operation Characteristics for the Superconducting Arc-Induction Type DC Circuit Breaker. Energies 2020, 13, 3897. https://doi.org/10.3390/en13153897

Thank you!