DC Arc Extinction Using External Magnetic Field in Switching Device

Hyun-Kil Cho†, Eun-Woong Lee* and Jong-Ho Jeong*

Abstract - In this paper, the electromagnetic force acting in the arc column of 3 different extinction units is compared with using the FEM (Finite Element Method) and the arc velocity is calculated by the drag force of the fluid mechanics. The experiment for breaking the arc current was performed in each model at 100 volts in order to measure the arcing time. The outcome was compared with the computing value. As a result, this paper proposes that the divided U-shaped grid is able to shorten arcing time and improve the electric performance. It also suggests a methodology for comparing and analyzing the result obtained by simulation and experiment.

Keywords: arc driving force, arc time, arc velocity, drag force, DC magnetic contactors, DC switching, FEM

1. Introduction

Magnetic contactors are widely used for industrial systems for switching off load current in low-voltage circuits. Since this situation is expected to continue for many years, it is necessary to improve the reliability and the performance of low-voltage magnetic contactors. The main subjects of magnetic contactors are the shortening of arcing time for the interrupting current in low-voltage circuits and the reduction of contact wear. Therefore, many studies on arc extinction and contacts wear have been performed [1-6].

Recently, the correlation of magnetic force, gas dynamic force and thermal effect on the arc mobility of devices using contacts has been studied by many researchers. They concentrate on the modeling of the magnetic and the gas dynamic force and the influence of the thermal energy in the contact area by the experiment at opening contacts [7, 8]. The erosion of contact material has been investigated in the relay for automobiles in order to improve the electrical life span [9, 10]. Horinouchi presented a simple practical method of simulating the behavior of an arc driven by magnetic force to study the arc extinguishing ability [11]. In his model, the arc is assumed to be the chain of small rigid cylindrical current elements. Each element receives magnetic force (Lorentz force) for the magnetic field and fluid drag from the surrounding gas. The behavior and the shape of arc elements can be predicted by combining these forces.

Moreover, the power transmission system is challenged to change DC from AC in the Anan Japane. So, the studies of DC insulators and switching method are required in order to prepare a normal DC power transmission system [12].

Therefore, this paper makes reference to the improvement of performance of arc extinction in air and suggests a new interrupting method in DC circuits. The electromagnetic force acting on the arc column of 3 different arc extinction units is compared with using the FEM (Finite Element Method) and the arc velocity is calculated by the drag force of the fluid mechanics. This paper shows that the arc clolumn is accelated by the eletromagnetic force and the arc velocity is related with the arc extinction time.

Types of arc extinction units have been made and results of the breaking tests were compared with simulating values The electromagnetic force is the dominant component for shortening the arcing time. As such, this paper proposes that the divided U-shaped grid is able to shorten arcing time and improve the electric performance. In addition, this suggests a methodology for comparing and analyzing the results obtained by simulation and experiment.

2. Arc Extinction

2.1 Construction and operation

Fig. 1 shows the switching mechanism in a magnetic contractor. The switching mechanism consists of fixed contacts, fixed conductors, moving contacts and conductor. When the moving contacts are separated from the fixed contacts, the pressure force at contacting points begins to decrease.

The cross section for a current passing across the con-

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tacts constricts and the joule heating leads to molten bridge formation [13]. As a result, arc columns form between contacts.

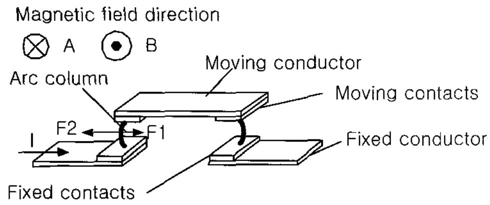
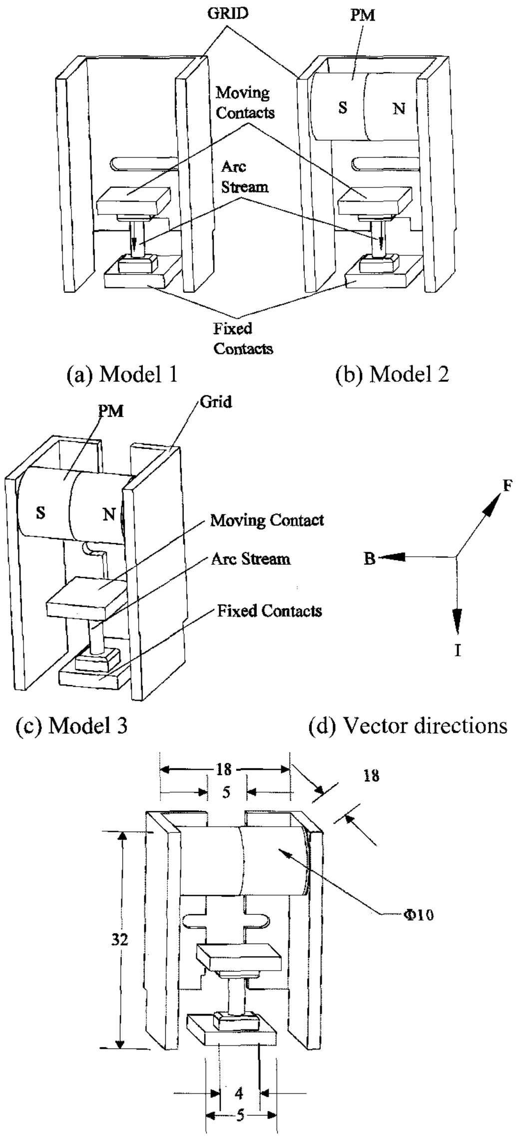


Fig. 1 Mechanism of extinguishing

Electric magnetic force F1 and F2 appears by magnetic field. Force F1 and F2 is caused by the magnetic field due to the arc current. The magnetic field of the F1 side directs to A and the magnetic field of the F2 side directs to B.



(a) Model 1 (b) Model 2

(c) Model 3 (d) Vector directions

(e) Dimension of arc quenching unit

Fig. 2 Model of arc quenching unit

If magnetic distortion does not occur, force F1 approximately equals force F2. Therefore, in order to increase the magnetic flux density acting force F2, a U-shaped grid is used in an arc chamber in the magnetic contactor. Also, a function of the optimizing grid is to quickly extinguish the arc between contacts.

2.2 Types of arc extinction units

Three kinds of grid models are presented in Fig. 2. The arc extinction model 1 of Fig. 2 (a) consists of a U-shaped grid used in the arc chamber of an AC magnetic contactor. The model 2 of Fig. 2(b) consists of a U- shaped grid and permanent magnet to increase the magnetic flux crossing the arc current.

The model 3 of Fig. 2 is the new interruption method. This has a divided grid and permanent magnet to increase the magnetic flux crossing the arc current. The vector direction of I, B and F is indicated in Fig. 2(d). The volume of the arc extinction unit and the size of the permanent magnet are shown in Fig. 2(e). All dimensions of 3 magnetic contactors of different arc extinction units are the same. The material of the grids is a SCP1 steel plate and the permanent magnet is an Alnico5.

The electromagnetic force F acting on the arc can be obtained by Eq. (1)

$$F_e = \int_{V_a} \bar{J}_a \times \bar{B}_a \, dV \quad (1)$$

where $\bar{J}_a$: current density, V_a : arc area , $\bar{B}_a$: magnetic flux density.

The arc is a current path, which is the stream of ions and electrons. The arc column is deformed freely by the electromagnetic force and the drag force of Eq. (2). Because it is very difficult to obtain the motion of all particles in the arc, the arc model is simplified as follows. The arc column contains strongly ionized gas at a high temperature and the boundary of the arc column is not clear from the surrounding gas. However, in order to calculate drag force, we assume that the arc boundary is clear from the surrounding gas.

The air layer enclosing the arc column is not driven by magnetic force because of neutral particles. The drag force is usually determined by formula (2),

$$F_d = \frac{1}{2} C_D \rho S u^2 \quad (2)$$

where S is the front area of the column exposed to the flow u is the moving velocity of the arc column and ρ is the free-stream gas density. N defines the unit of drag force and C_D is the drag coefficient $C_D = 0.62\left(\frac{L}{d}\right)^{0.12}$

The equation of arc motion is given by Eq. (3)

$$F_e - F_d = m\frac{du}{dt} \qquad (3)$$

where F_e is the electromagnetic force acting on the arc column, F_d the frictional force of the arc and m is the mass of the arc.

On the assumption that the arc consists of electrons and singly ionized silver atoms, the mass of the arc is provided by Eq. (4)

$$m = \left(\frac{M}{N_0}\right)\times\left(\frac{\pi}{4}D^2L\right)\times\left(\frac{P}{2kT}\right) \qquad (4)$$

where M is the atomic weight of ionized atoms, No is Avogadro's number, k is Boltzmann's constant, T is the arc temperature, and p is the arc pressure.

The contact radius, r, is obtained by Eq. (5) from Holm's equation for the modeling of the arc.

$$r = \sqrt{\frac{P}{\pi\varsigma H_d}} \qquad (5)$$

where P is contact pressure [N], H_d is the Brinell hardness and ζ is a constant determined by the condition of the contact shape. In the case of AgCdO, Hd is 90, ζ 0.5, P 0.7kgf [1, 6].

3. Comparision of Simulations and Experiment

3.1 Simulations

To obtain magnetic flux density and the arc driving force of each model, FEM is used for simulation. The magnetic flux density consists of two components B_x and B_y inside of the arc area. But, B_y component doesn't contribute to increase the arc driving force.

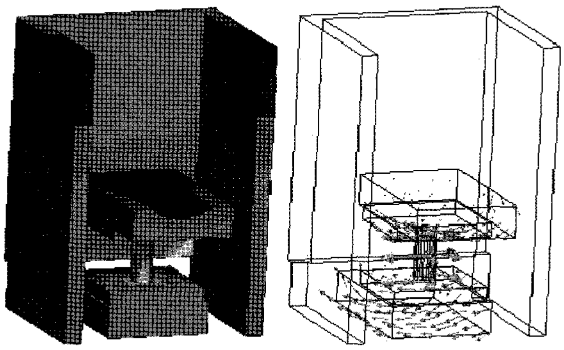
Fig. 3(a) shows the distribution of magnetic flux density generated by only arc current and the direction of the magnetic flux vector.

The magnetic flux vector around the arc column rotates through the arc column. The magnetic flux density crossing the arc column is 0.0037[T].

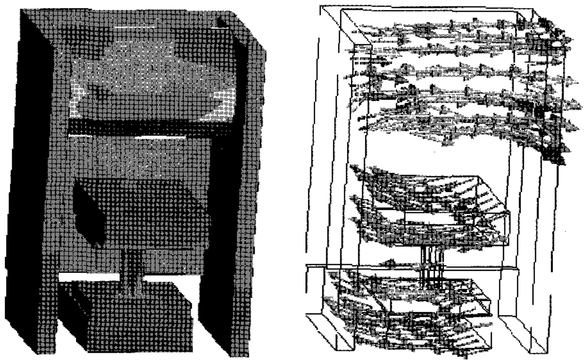
As Fig. 3(b) indicates in Model 2, the magnetic flux vector is heading toward the reverse direction of the magnetic field inside the permanent magnet and the magnetic flux density of the grid is increased. The resultant magnetic flux density crossing the arc column is 0.0252[T].

Fig. 3(c) illustrates the distribution of magnetic flux density and the direction of magnetic flux in Model 3. The resultant magnetic flux density crossing the arc column is 0.0595[T].

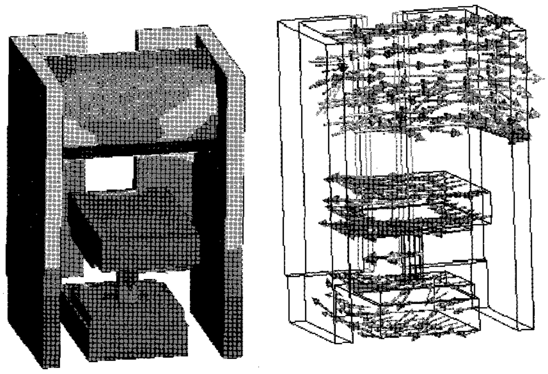
The magnetic flux density of Model 1 is mostly quite low in the 3 types because only the arc current without the external magnetic field generates a magnetic field. And magnetic flux density crossing the arc current in Model 3 is higher than in Model 2 because the almost magnetic flux of Model 2 flows through the grid and the leakage flux passes the current area. But, in the case of Model 3, the gap between grids is the reluctance. The reluctance has an effect on increasing the magnetic flux density in the arc area. So, the magnetic flux of Model 3 crossing the arc current increases more than Model 2.



(a) Flux density and field vector of Model 1



(b) Flux density and field vector of Model 2



(c) Flux density and field vector of Model 3

Fig. 3 FEM analysis of arc quenching unit (I=100A)

Fig. 4 (a) indicates the arc driving force as the function of current. The arc driving force increases proportionately with the current in each model and magnetic flux density.

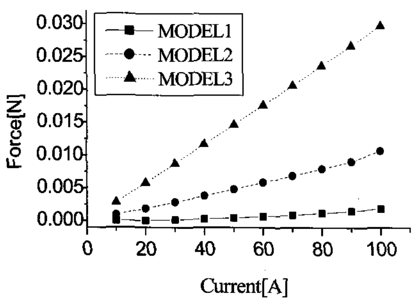
Fig. 4 (b) presents the driving velocity acting on the arc as the function of current on each model of silver vapor arc. The arc velocity depends on the magnetic driving force and the drag force acting on the arc column for each model.

Driving velocities of the arcs are 9.3 , 22 and 36.9 m/s respectively for Model 1, 2 and 3 when contacts are opening at I=100A. Teijiro Mori reported that the calculated velocities of a 100A arc with 5mm length under the magnetic flux densities of 10mT were 25m/s. Our calculation agrees approximately with the value calculated by Teijiro Mori [3].

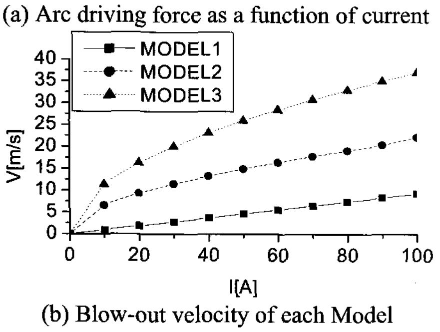
3.2 Experimental results

Dimensions of arc quenching unit including the new interrupting mechanism are shown in Fig. 2 (e). Volumes of the conventional mechanism are identical to those of the new interrupting mechanism, except for the volume of the included permanent magnet and the gap in divided grids. For all experimental contactors, the contact material is a silver-cadmium alloy and all operating mechanisms are equivalent. The contact opening speed and contact gap are about 1m/s and 5mm, respectively.

Fig. 5 demonstrates the shape of the current wave measured with an oscilloscope on 100A load with time constant 10ms at 100V. Arc time was measured from appearing 10V between identical pole contacts to disappearing current. In Fig. 5 (a), the arc current is smoothly reduced and the arc voltage is evenly increased along with changes in the arc current.

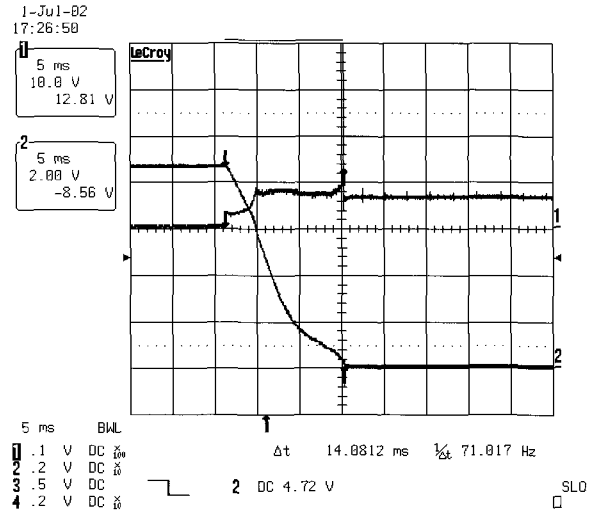


(a) Arc driving force as a function of current

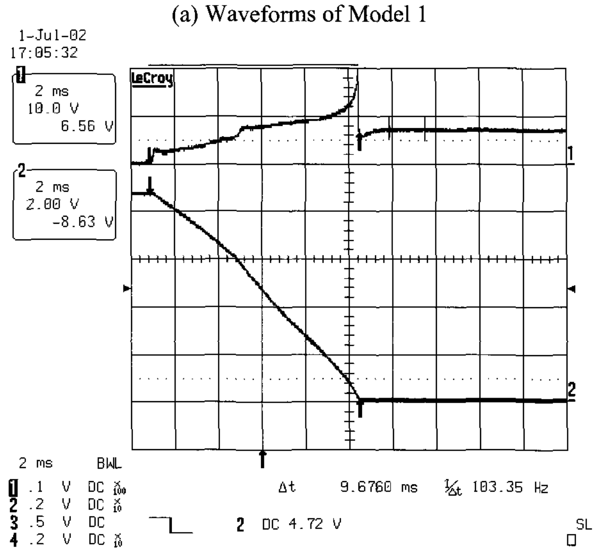


(b) Blow-out velocity of each Model

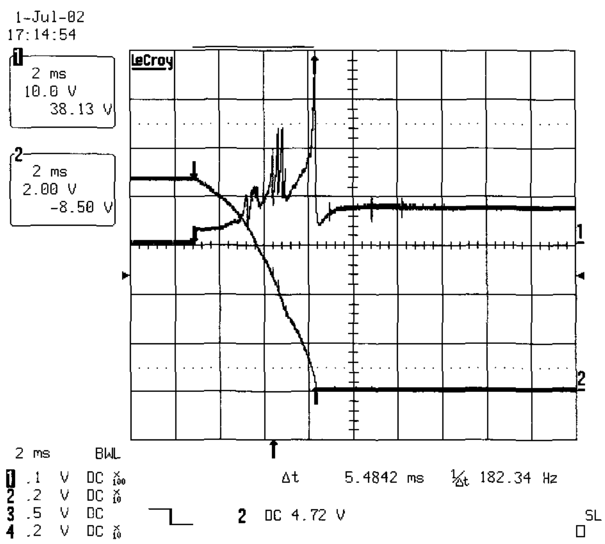
Fig. 4 Results of Analysis



(a) Waveforms of Model 1



(b) Waveforms of Model 2



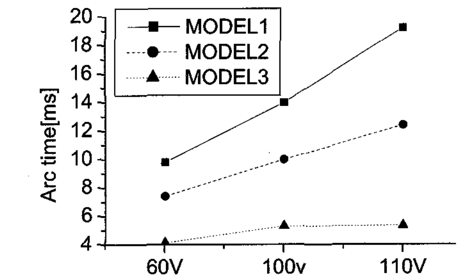
(c) Waveforms of Model 3

Fig. 5 Waves of arc current and voltage

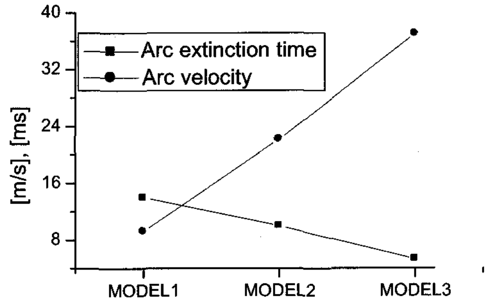
Fig. 5 (b) shows that the arc current is rapidly reduced and the arc voltage has a steep slope. And Fig. 5 (c) indicates that the arc current rapidly comes down and the arc voltage has many peak voltages with a steep slope due to the rapidly reducing arc current.

Measured results of arc time are indicated in Fig. 6(a). Experiments for interrupting load current were made in dc circuits at 60V, 100V and 110V. Interrupting experiments were repeated many times for each model and each voltage level. It shows the difference of arcing times between the three types of models. In the case of Model 1, average arcing time was increased remarkably with increasing voltage. On the other hand, for Model 3, average arcing time was increased gradually with increasing voltage. At 100V, the average arcing time of Model 3 was about 38% of that of Model 1.

Fig. 6 (b) presents the estimating method of comparing simulation results with measured results. The velocity of the moving arc for each model was achieved through the simulation at the current 100A. Arc extinction time and velocity of arc driving force can be compared relatively due to identical arc quenching room. The result indicates that the bigger arc blow-out force leads to the shorter arc extinction time, which coincides with the FEM analysis data and drag force



(a) Measurement of arc extinction time



(b) Comparing simulated velocities with measured arcing time (I=100A)

Fig. 6 Simulation and measurement

4. Conclusion

Through this research, 3 different models of DC arc extinguishing mechanism were formed and the appropriate contact area between the moving contacts and fixed contacts were estimated to calculate the flux density of all 3 types.

The arc driving force of each model was calculated by 3D FEM. As well, the arc velocity was calculated using the electromagnetic force and the arc driving force. The arc column received Lorentz's force from the magnetic field and drag force from the surrounding gas.

The arc breaking time of each model was measured. This paper showed that arc blowout force is a main factor for arc velocity and that the arc breaking time is inversely proportional to the arc velocity. The result demonstrates that the fast moving velocity of the arc column shortens the arc time. The high velocity contributes to quick cooling of the arc column by the surrounding gas. Therefore, this paper suggests that increasing the flux density of crossing the arc current shortens the arcing time.

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In order to improve the performance of the DC contactor, a new grid type is suggested.

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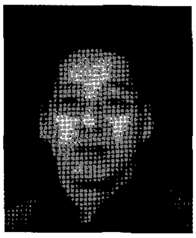

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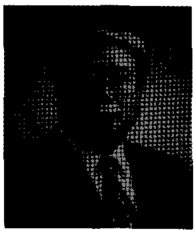

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