Paper

An Electromagnetically Actuated Vacuum Circuit Breaker Developed by Electromagnetic Analysis Coupled with Motion

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A new electromagnetically actuated vacuum circuit breaker (VCB) has been designed and developed on the basis of the transient electromagnetic analysis coupled with motion. The VCB has three advanced bi-stable electromagnetic actuators, which control each phase independently. The VCB serves as a synchronous circuit breaker as well as a standard circuit breaker. In this work, the flux delay due to the eddy current is analytically formulated using the delay time constant of the actuator coil current, thereby leading to accurate driving behavior. With this analytical method, the electromagnetic mechanism for a 24 kV rated VCB has been optimized; and as a result, the driving energy is reduced to one fifth of that of a conventional VCB employing spring mechanism, and the number of parts is significantly decreased. Therefore, the developed VCB becomes compact, highly reliable and highly durable.

Keywords: vacuum circuit breaker, bi-stable magnetic actuator, coupled problem, eddy current, motion

1. Introduction

Recently, vacuum circuit breaker (VCB) has been designed to operate at a wide voltage rating of 3.6 kV to 84 kV. Most VCB utilize an operating mechanism using a stored-energy spring device since its earlier inception. The operating mechanism includes many complicated parts, and the contacts of three phases are operated by only one shaft linked to the rods of the three phases. All linked mechanical parts move at high speed and thus at high energy for interrupting current, resulting in limited durability. Based on this fact, an electromagnetically operating mechanism becomes promising as a next generation mechanism (1) (2). With this mechanism, the number of parts can be significantly reduced, and therefore the mechanism becomes simple and highly reliable. However, most electromagnetically standard VCB employs the mechanism which links three phases with one shaft (3) (4), and thus the standard VCB can not serve as a synchronous circuit breaker.

Very recently, we have developed an advanced electromagnetically actuated VCB based on the electromagnetic analysis coupled with motion. This breaker has an advanced bi-stable electromagnetic mechanism to move the contact for current interruption. The operating system is composed of three electromagnetic actuators and an electronic control system. Actuators assembled on a straight line for each phase can be operated independently, thereby minimizing mechanical loss. Furthermore, the electromagnetic loss of the actuator is reduced by the advanced structure.

In this work, we have employed an electromagnetic analysis coupled motion, which considers the delay of the magnetic flux due to the eddy current. The electromagnetic driving phenomenon has been successfully explained by this analysis. Using this analytical method, the mechanism of a new 24 kV rated VCB has been designed and optimized. The analytical method and the minimum losses have performed that the VCB serves as a synchronous circuit breaker as well as a standard circuit breaker.

2. Electromagnetically Actuated VCB

2.1 Description of Mechanism The developed VCB rating of 24 kV is shown in Fig. 1 and specifications of this VCB are listed in Table 1. This VCB has three sets of vacuum interrupter, insulating rod, contact pressure spring and electromagnetic actuator. All parts are assembled on a straight line and the interrupter is driven directly by the actuator, thereby minimizing mechanical loss. Moreover, the VCB allows emergency manual trip operation similar to the conventional VCB employing spring mechanism.

Figure 2 shows a model of the electromagnetic actuator and Fig. 3 illustrates its operating principle using calculation results by 3-D FEM electromagnetic analysis (5),

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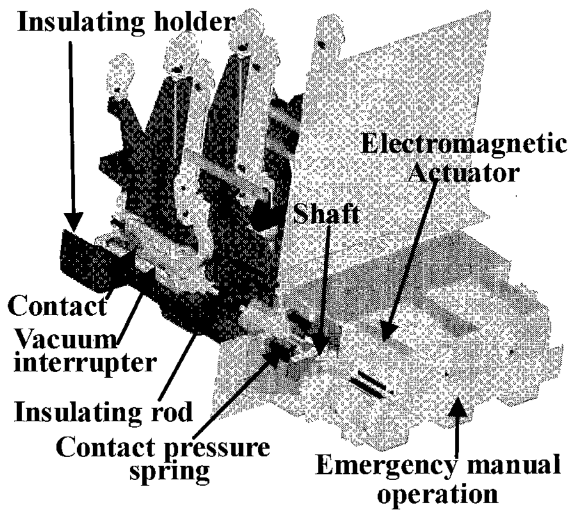


Fig. 1. Structure of 24 kV rated VCB

Table 1. Specifications of 24 kV rated VCB

Rated voltage (kV)	12	24
Rated normal current (A)	630/1250	
Rated short-circuit breaking current (kA)	25	
Rated making current (kA)	63	
Break time (cycles)	3	
Rated operating sequence : O-0.3s-CO-15s-CO		

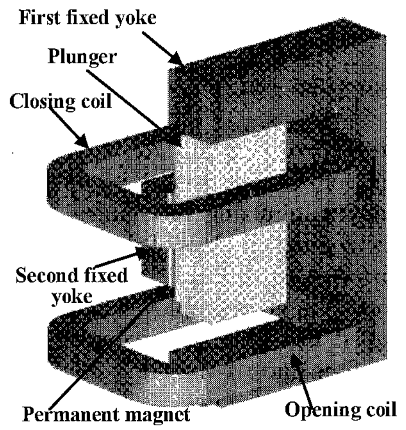
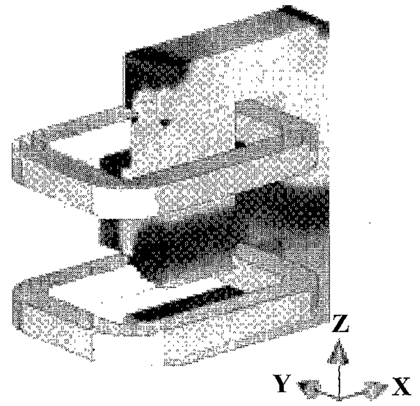
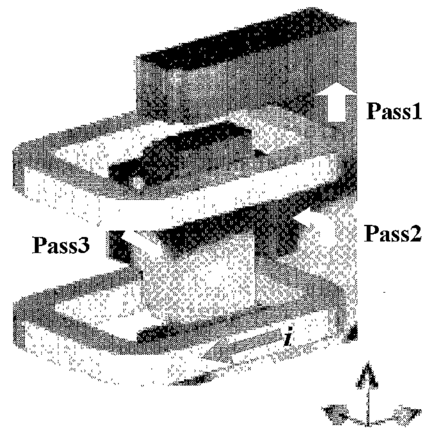


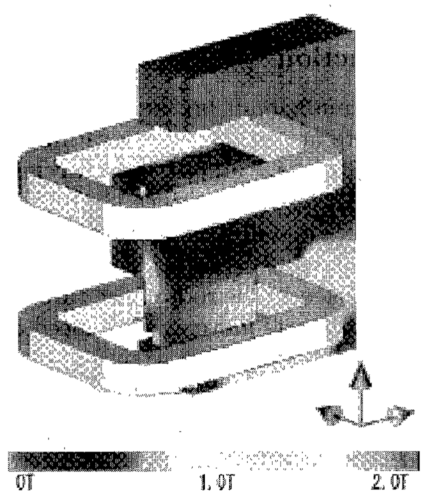
Fig. 2. 1/4 model of the magnetic actuator (coils are full models and materials are 1/4 models)



(a) Upper limit position: Contact closed



(b) Exciting lower coil: Open working



(c) Lower limit position: Contact opened

Fig. 3. Operating principle of the actuator (coils are full models and materials are 1/4 models)

where the driving direction of the plunger is Z-axis. The actuator is composed of an opening coil, a closing coil, a plunger, a first fixed lamination yoke, and two sets of second fixed yoke and permanent magnet. The actuator operates as a bi-stable magnet that latches the plunger at upper and lower limit positions. The latching force is generated by the permanent magnets of NdFeB attached to the second fixed yoke as shown in Fig. 3(a) and 3(c). With this magnetic force at the upper limit position, the electromagnetic repulsion force of the contact is held under the short circuit current. Subsequently, the plunger is switched by the magnetic fields of two electrically excited coils.

Figure 3(b) shows the change of magnetic field when the current is applied to the opening coil. At this time, a first fixed laminate yoke and two second fixed yokes separate the flux by the currents on pass1 pass2 and pass3. The field induced by the permanent magnets is reduced by the field on pass1, resulting in the reduction of the latching force at the upper limit position. On the other hand, the field on pass3 is the same direction of the magnetization of the permanent magnets, and thus the permanent magnets are never demagnetized. The plunger moves mainly by the change of the fields on pass1 and pass2. Because the plunger is also laminated, the system provides good stability and low energy operation.

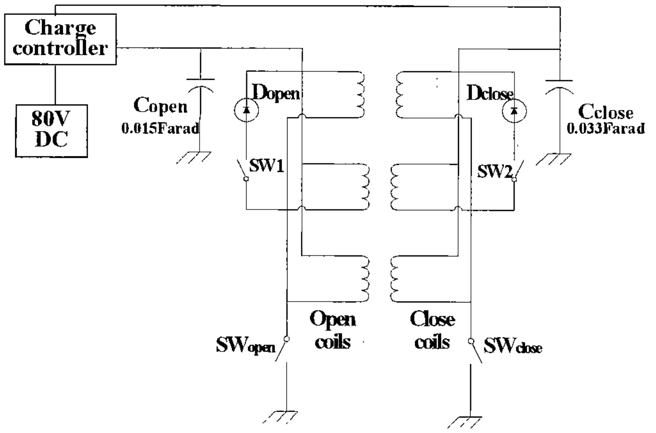


Fig. 4. Three-phase electric control system

2.2 Electric Control Unit The electric control unit is shown in Fig. 4. The coils are energized by an opening capacitor C_{open} and a closing capacitor C_{close}. An 80 V voltage is supplied to the capacitors. The voltage range is similar to the range of the trip actuator for the conventional VCB employing spring. The use of two capacitors reduces the stored energies during a complete O-0.3s-CO operation cycle. Therefore, the maximum charge energy can be used in every closing operation.

When the fault signal is received, SW1 and SW_{open} are turned on. Then, the opening coil is energized, and the contact, which is connected to the plunger, is opened. At this time, SW2 and SW_{close} are turning off. Note that SW1, SW2, SW_{open} and SW_{close} are thyristors. After the completion of opening operation, SW_{open} is turned off, and then SW1 is turned off. The closing operation is similarly.

With this control system, the reduction of the switching surge induced by the inductance of the coil is achieved by flywheel diode D_{open} and D_{close}. However, the current in the other nonenergized coil is induced in the direction such that the magnetic field of the energized coil is canceled. This increases the required electric energy, and therefore the driving operation becomes unstable. SW1 and SW2 are located to avoid this induced current, thereby leading to highest stability of the driving behavior.

3. Coupled Analysis

3.1 Method A transient electromagnetic analysis coupled with motion has been applied to the calculation of driving behavior of the electromagnet.

The electrical behavior of discharging stored energy from C_{open} can be expressed by

$$\left.\begin{array}{l}\dfrac{q(t)}{C} + I_{coil}(t) \cdot (R_{coil} + R_{out}) + \dfrac{d\phi(I_{coil}(t), z(t))}{dt} \\ \quad = E \\ \dfrac{dq(t)}{dt} = I_{coil},\end{array}\right\} \quad \cdots\cdots (1)$$

where C, q and E are the capacitance, the electric charge and the voltage of the capacitor, respectively; and I_{coil}, R_{coil} and R_{out} are the coil current, the coil resistance and the external series resistance of the capacitor and other devices, respectively; and ϕ is the total linkage flux across the energized coil. $z(t)$ is the position of the plunger.

Then, the coupling of electrical, magnetic and mechanical subsystem is described by Eq. (2):

$$\begin{aligned}&\frac{d\phi(I_{coil}(t), z(t))}{dt} \\ &\quad = \frac{d\phi(I_{coil}(t), z(t))}{dI_{coil}} \cdot \frac{dI_{coil}}{dt} \\ &\qquad + \frac{d\phi(I_{coil}(t), z(t))}{dz} \cdot \frac{dz}{dt} \quad \cdots\cdots (2)\end{aligned}$$

First term in the righthand side is a differential term of the flux to current I_{coil}, which corresponds to the inductance L of the actuator, and the second term is a differential term of the flux to position z.

The dynamic behavior of the moving parts, including the movable contact, the movable shaft, the plunger and the others, is given by Eq. (3):

$$\begin{aligned}m(z(t))\frac{d^2z}{dt^2} &= Fm(I_{coil}(t), z(t)) + Fs(z(t)) \\ &\quad + F_{friction}, \quad \cdots\cdots (3)\end{aligned}$$

where m is the mass of the moving parts, Fm is the electromagnetic force depended by the coil current and the position of the plunger, Fs and $F_{friction}$ are the force of the contact pressure spring and the mechanical friction, respectively.

The dynamic behavior of the plunger is drawn from Eqs. (1)~(3) [6][7]. In the first step, the flux $\phi(I_{coil}(t), z(t))$ and the electromagnetic force $Fm(I_{coil}(t), z(t))$ depending on the current $I_{coil}(t)$ and the position $z(t)$, are calculated using 3D FEM static electromagnetic analysis [5][8]. Next, $\phi(I_{coil}(t), z(t))$ and $Fm(I_{coil}(t), z(t))$ are linearly interpolated. Subsequently, numerical integrations of coupled Eqs. (1)~(3) with a time stepping gives the functions of $I_{coil}(t)$, $z(t)$, $\phi(I_{coil}(t), z(t))$, $Fm(I_{coil}(t), z(t))$. The calculation was performed by using *Mathematica* [9][10].

Meanwhile, the eddy current is not considered in Eqs. (1)~(3). The eddy current is obtained as the delay of magnetic flux by the coil current, and the electromagnetic force also delays accordingly. The delay is described in Eq. (4). When the time stepping is short enough, the current dependence of the flux is approximately linear. Consequently, we have assumed that the delay can be expressed as the delay of the coil current with a time constant τ. The Eq. (4) is reduced to Eq. (5). Similarly, the electromagnetic force is provided by Eq. (6). The delay time constant τ has been estimated by the comparison between measurements and calculations of a single phase experimental model. Then, the Eqs. (5) and (6) are simultaneously solved with Eqs. (1)~(3).

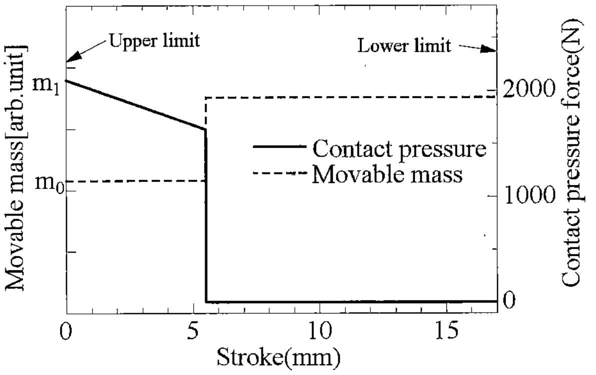


Fig. 5. Stroke dependence of the mass and the contact pressure force

Table 2. Specifications of the experimental model

Magnetic force at the upper position	2200N
Magnetic force at the lower position	500N
Plunger stroke	17mm
Contact stroke	12-13mm

$$\begin{aligned}\phi_{transient}(I_{coil}(t), z(t)) \\ = \phi_{static}(I_{coil}(t), z(t)) \\ -\phi_{eddycurrent}(I_{coil}(t), z(t)) \quad \cdots\cdots (4) \\ = \phi_{static}(I_{coil}(t), z(t))(1-\exp(-\tau t)) \\ = \phi_{static}(I_{coil}(t)(1-\exp(-\tau t)), z(t)) \cdots\cdots (5)\end{aligned}$$

$$Fm_{transient} = Fm_{static}(I_{coil}(t)(1-\exp(-\tau t)), z(t)) \quad \cdots\cdots (6)$$

The mass of the moving part and the contact pressure force have non-continuous behaviors as shown in Fig. 5. In the usual numerical integration, the change of the velocity at this non-continuous position is often ignored by setting the time stepping inappropriately large. In our analysis, the law of conservation of momentum has been applied at this non-continuous position.

3.2 Result and discussion The calculated results are described for the following single phase experimental model. The specifications of the model are shown in Table 2. The magnetic force at the upper position is 2200N, the plunger stroke is 17 mm and the contact stroke is 12∼13 mm. 2200 N is enough to hold the electromagnetic repulsive force of the contact at 63 kAp which is the maximum short-circuit current. Figure 6 shows the total linkage flux across the energizing coil calculated by 3-D FEM analysis. The actuator has a nonlinear electromagnetic behavior in a low current region, while nearly linear electromagnetic behavior is obtained in a high current region. On the other hand, when the current is increased, the inductance becomes smaller due to magnetic saturation. The nonlinear behavior should be considered for the accurate analysis.

Next, the stroke calculated with this analytical method is shown in the Fig. 7. Without considering the effect of the eddy current, the calculated drive motion starts earlier than the measured motion. Because the first fixed yoke and plunger are laminated, the eddy current is generated in the second fixed yoke. In the revised calculation using the delay time constant, the

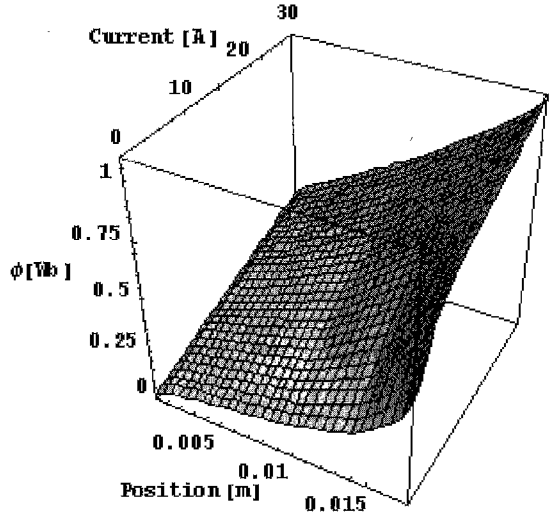


Fig. 6. Calculated total linkage flux across the energizing coil

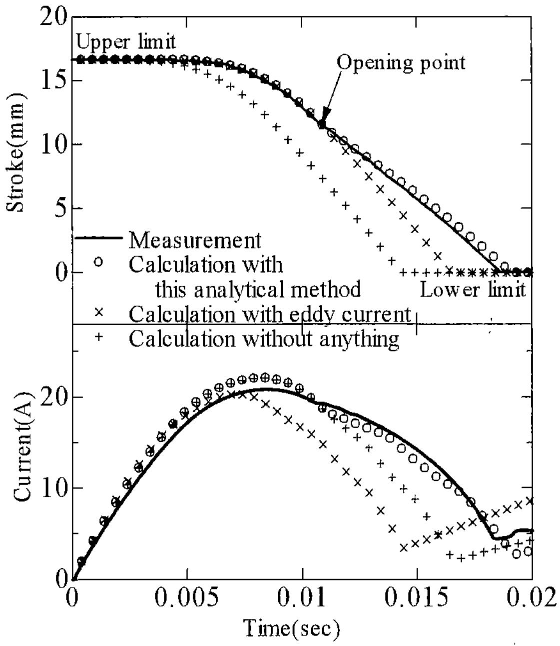


Fig. 7. Calculated and measured strokes and currents on the opening operation

initial behavior in stroke is simulated very well. Here, the time constant is nearly 4.5 ms, which is estimated by the measurement.

At the opening point, the measured velocity is smaller than the calculated one, even when the delay time constant is considered. By applying the law of conservation of momentum at the opening point, a good agreement between the calculated and the measured dynamic behavior is obtained. The current distribution is also well explained by the calculation.

Subsequently, this analysis using the same delay time constant has been applied to the closing dynamic behavior. We found that the delay due to the eddy current during the closing operation is the same as that in the opening operation, and thus the behavior is simulated very accurately as shown in Fig. 8. We have confirmed

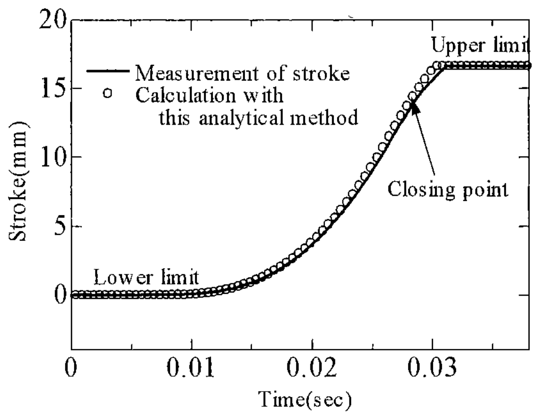


Fig. 8. Calculated and measured strokes on the opening operation

that our analytical method, which considers the delay time constant and the law of conservation of momentum, can be used for design optimization.

4. Design Optimization of a New 24 kV Rated VCB

4.1 Design of Three Phases A new 24 kV rated VCB has been designed and optimized using the analytical method. The opening and the closing time differences among three phases should be sufficiently small to use the new VCB as a conventional standard VCB. However, various errors are observed among three phases including total mass of the moving parts, force of the contact pressure, magnetic behavior of the plunger, resistances, stroke of the plunger, and the others. These errors increase the time differences, and thus the conventional standard VCB employing electromagnetically actuator [(3)(4)] or spring cancels these time differences by using the mechanism which links three phases with one shaft.

To solve this problem, the dynamic response with 100 or more combinations of 8 error parameters have been calculated using the analytical method. The probability of occurrence of a particular time difference was estimated assuming that each error obeys independent normal distribution. The estimated results are shown in Table 3. The opening time difference is less than 2.0 ms and the closing one is less than 2.4 ms in 99% error cases. Even in the worst case, both time differences are short enough for the VCB specifications. Measured opening time difference among three phases in the prototype is 0.5 ms, that is smaller than the specified goal. We have confirmed that the developed VCB serves as both a standard circuit breaker and a synchronous circuit breaker.

4.2 Performance of the 24 kV Rated VCB The performance of the 24 kV rated VCB is summarized in Table 4. The electromagnetically operating mechanism has been optimized with this analytical method. Especially, CO operating energies has been reduced by optimizing the number of turns and the wire diameters of the coils. As a result, the number of individual parts has been reduced to 65% and CO operating energies have also been reduced to only 20% of the conventional spring mechanism. These results clearly indicate high durability and high reliability.

Table 3. The calculated time difference of the driving behavior among three phases

	Worst (100%)	3σ (99%)	2σ (95%)
Opening time difference (ms)	2.8	2.0	1.3
Closing time difference (ms)	3.4	2.4	1.6

Table 4. Comparison with the new and the conventional mechanism

	Advanced electromagnetically Mechanism	Conventional spring Mechanism
Number of parts	65%	100%
Operating energies	20%	100%
Contact pressure at the upper limit	86%	100%
Opening velocity	67%	100%
Break time	3cycles	3cycles
Power supply	80V DC	80V DC

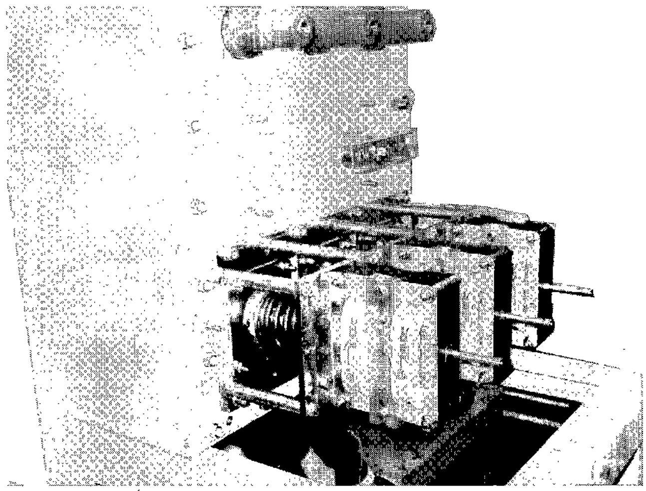


Fig. 9. Photograph of the advanced electromagnetically VCB rating of 24 kV

Compared to the conventional mechanism, the interruption of short circuit current has been succeeded under the conditions of the smaller magnetic force at the upper limit and the lower opening velocity. This result shows the reduction of the mechanical loss, and thus then the high efficiency of this VCB. The other characteristics of the present VCB are the same as those in the conventional VCB employing the spring mechanism.

The photograph of the developed 24 kV rated VCB is shown in Fig. 9. Total capacitor for a complete O-CO operating cycle is 0.048 Farad. This value has been determined by considering temporal and temperature capacitance reduction, with a time span of 30 years and temperature range of −25°C to 40°C. Therefore, no maintenance of the electromagnetic mechanism has been achieved. Now, 80000 CO operations have been confirmed in the prototype electromagnetically mechanism.

5. Conclusion

A new electromagnetically actuated VCB has been developed on the basis of the transient electromagnetic analysis coupled with motion. This VCB has an advanced bi-stable electromagnetic mechanism using permanent magnets in order to move contacts for the current interruption. A coupled analytical method, which considers the delay of magnetic flux due to the eddy current, is proposed. With this analytical method, the electromagnetic mechanism for a 24 kV rated VCB was optimized, and thus driving energies was highly reduced compared to conventional VCB having spring mechanism. We have confirmed that this VCB is compact, highly reliable and highly durable. The VCB has three actuators which control each phase independently. This suggests a possibility as a synchronous VCB in the future.

(Manuscript received July 25, 2003,
revised Aug. 8, 2003)

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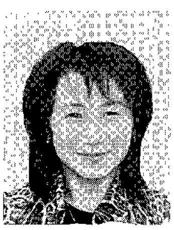

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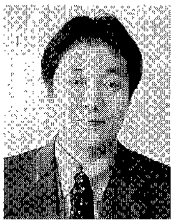

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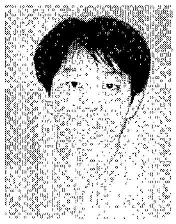

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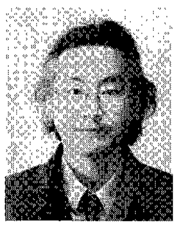

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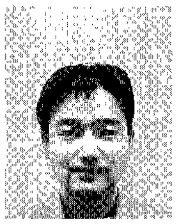

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