Development and Analysis of New Type of Switchgear for High Voltage Gas Circuit Breaker

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Abstract— In this paper, a new type of switchgear, electro magnetic force driving actuator (EMFA), is developed and analyzed, applicable to high voltage gas circuit breakers (HGCB). Transient analysis is performed in order to obtain the dynamic characteristics of the EMFA. The distribution of static magnetic flux is obtained using the finite element method (FEM). The governing electric and kinematical equations are solved using the time difference method (TDM). Fabrication and experiments were performed in order to prove the applicability of HGCB for overall class. In comparing the experiment with simulated data, it is confirmed that analysis of the dynamic characteristics of EMFA is appropriate for design.

Index Terms— dynamic characteristics, electromagnetic force driving actuator (EMFA), finite element method (FEM), time difference method (TDM).

I. INTRODUCTION

HE HGCB requires the actuator to be capable of carrying extremely high repulsive gas power during a large stroke length and short breaking time [1]. Typical mechanisms used to drive the circuit interrupter mechanism include manufactured pneumatic, hydraulic, spring and solenoids type actuators. In addition, now days electrical technologies such as advanced permanent magnetic actuators (PMA) and motors are used [2]. Pneumatic and hydraulic actuators are considered expensive, noisy and leaky. They lend themselves more to the transmission sector circuit breakers where mechanical drive linkages are very large and cumbersome. A spring mechanism is composed of many linked parts, and greater reliability is required to use this mechanism [3]. Therefore, many attempts of developing electrical actuator technologies have so far been made at the HGCB, because these systems have a simple structure, no link parts to drive the transmission line of the circuit interrupter and an anti-nose electrical damper system. However, these have not been successfully fitted on the HGCB [1]-[2].

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In this paper, EMFA was designed one of the electrical actuators with a moving coil, because it can satisfy the requirements of HGCB extremely well for large stroke length and high power. In order to obtain the dynamic characteristics of the EMFA, it is necessary to perform transient analysis, because some conditions, such as the voltage of a capacitor, the exciting current of a coil, electromagnetic force and exert an influence on the displacement of the moving coil, are changing during operation. In the transient analysis of the EMFA, the FEM and TDM are used. The static magnetization of the field is analyzed by the FEM and simultaneous equations include the results of the FEM, are solved by TDM.

This paper describes a new type actuator system, improving on the application of the rail-gun system, presented with accompanying experimental and simulated results. It is confirmed that the analysis of the dynamic characteristics of EMFA is appropriate for more advanced actuators to design.

II. STRUCTURE AND OPERATION

A. Basic structure

The basic structure of the EMFA is presented in Fig. 1(a). It has a very simple structure and mainly consists of five parts such as, a moving coil, an inserted moving iron core, a static core, permanent magnets and transmission rods. A single part drives the transmission rod on opening or closing operations and it is molded with coils and inserted iron core to enhance the magnetic force and latch the moving part on the closing and opening position without any external energy. The DC voltage source is connected with an energy banker (capacitor).

The Lorenz's force, which is the magnetic flux cross current density, affects on the EMFA directly and the inductance of the coils influence on the value of the excited



(a) Cross section of EMFA Fig. 1. Basic structure of EMFA.

(b) EMFA installed in the GIS system

current.

It is straightforward to control the force and velocity of the moving part by controlling the current and inductance of the coils appropriately [4]-[5].

Fig. 1(b) presents the gas circuit breaker (GIS) system, which is installed by the EMFA. It is linked with the circuit interrupter directly. It does not require any latch device on the EMFA component of the GIS system, because the permanent magnet holds the core inserted moving part to an opening or closing position. In order to reduce the velocity of the moving part at the end of the final traveling, the eddy current dash-pot and spring damper are used. This electro-mechanical damper is able to absorb the large force of the final traveling as much as possible to reduce the impact of the moving part.

B. Operation and Driving mechanism

The EMFA has an electro-magnetic force and this force moves the transmission rod to make the either contact opened or closed. Fig. 2(a) and (b) is presented the distribution of the magnetic field on the EMFA. The moving part is attached to both ends of the sides, the upper and lower side by auxiliary permanent magnet and the iron core on the moving part. This operation holds the circuit interrupters either opened or closed.

The traditional actuators have a constant power for all stroke length, are uncontrollable when working, and are therefore limited in use. Therefore, the controllable actuator is required to be developed, to obtain a successful circuit breaker for the HGCB. For a driving mechanism system of the EMFA, a trip signal comes into the input/output unit and transfers the operating order, which is either interrupting or generating current, to the control unit. Commonly, sufficient energy is charged in the capacitor unit in the form of the DC voltage. The Actuator properly resolves and immediately signals the converter to control the actuator and obtain an ideal speed curve by chopping the input voltage. It should operate actively according as the variety of the external circumstances, such as a fault current and voltage level, and the gas pressure of the repulsive power. It is extremely important point to develop the electrical actuator and the HGCB requires various velocity specs for the contacts on the partial section during all stroke length.



(a) Closed (b) Opened Fig. 2. Distribution of the magnetic flux on the cross section of EMFA.

III. CHARACTERISTIC ANALYSIS

The dynamic characteristic analysis of the EMFA is required in order to design and predict performance as a switch gear for the HGCB. The analysis of the static magnetic density and current density according to time variety is required in advance, to calculate the electro-magnetic force through magnetic field and electrical equations. In using a kinetic equation, finally the displacement and velocity of the moving part is known.

In this paper, to analyze the magnetic field and the electromagnetic force, the FEM is used. To reduce the couple problems of the two governing equations, which includes an electrical and a kinetic equation, the TDM is applied.

A. Static magnetic field equation

Some fundamental static magnetic equations are described, as presented in the below equations.

$$\nabla \times \vec{H} = \vec{J}_0 + \vec{J}_e. \tag{1}$$

$$\dot{B} = \mu_0 (\dot{H} + \dot{M}). \tag{2}$$

$$\vec{B} = \nabla \times \vec{A} \,. \tag{3}$$

$$\vec{H} = \frac{1}{\mu} (\nabla \times \vec{A}) - \frac{1}{\mu_r} (\vec{M}_r).$$
⁽⁴⁾

Equations (1) - (4) are solved simultaneously using the vector potential and magnetic (5) is derived.

$$\nabla \times (\frac{1}{\mu} \nabla \times \vec{A}) = \vec{J}_0 + \vec{J}_e + (\nabla \times \frac{1}{\mu_r} \vec{M}_r).$$
 (5)

Where, *B* (Wb/m²) is the magnetic flux density, *H* (A/m) is the magnetic field intensity, J_0 (A/m²) is the current density, J_e (A/m²) is the eddy current density, *M* (A/m) is the amount of magnetization, M_r (A/m) is the amount of residual magnetism, *A* (Wb/m²) is the magnetic vector potential and μ (H/m) is the permeability.

In order to solve simply the magnetic flux, A is used and is derived at (6).

$$\Phi = \oint \vec{A} \, dl \,. \tag{6}$$

Where, Φ (Wb) is the magnetic flux, and l (m) is the total coil length.

The electro-magnetic force is divided into two basic types, the holding force and operating force, such as (7) and (8). The holding force is generated by permanent magnet without external current, such as (7).

$$\vec{F}^{hold} = \iint_{s} \{ \frac{1}{\mu_{0}} (\vec{B} \cdot \vec{n}) \vec{B} - \frac{1}{2\mu_{0}} \vec{B}^{2} \cdot \vec{n} \} ds \,. \tag{7}$$

Where, F^{hold} (N) is the electro-magnetic holding force, s (m²) is the area of the outer surface around the iron core of the moving part and n is the unit vector of the normal direction along the surface.

The external current is excited, therefore the electromagnetic operating force is generated by the magnetic density cross the current density and it is presented in (8) [1]-[2].

$$\vec{F}^{operate} = q \, \vec{v} \times \vec{B} = \vec{J} \times \vec{B} \,. \tag{8}$$

Where, $F^{operate}$ (N) is Lorenz's force, which is the magnetic force during the moving part's traveling, q (C) is the electric charge and v (m/s) is the velocity vector.

B. Electrical equation

During an opening or closing operation, the external current flows into the moving coil from the capacitor and its value changes as time passes. Therefore, the transient analysis is necessary and it is used by the TDM.

Generally, an electrical equation includes back electromotive force (emf) and inductance witch is formulated as follows,

$$V_c = (I_0 + di)R + e. (9)$$

$$e = N \frac{d\Phi(i,x)}{dt}.$$
(10)

$$\Phi = L(i, x)I. \tag{11}$$

Where, V_c (V) is the voltage of the capacitor, I_0 (A) is the initial value of the exerted current, di (A) is the variation of exerted current, R (Ω) is the resistance of coils, dt (s) is the unit of the time variation, N (turn) is the turns of coils and L (H) is the inductance.

In using the FEM result, which is the magnetic flux, the inductance and back-emf can be derived, such as (10) and (11). Using (9), the variation in exerted current can be computed.

The magnetic flux depends on the current variation and the position variation of the coil itself. In order to reduce the electrical equation for transient analysis, inductance variations according as the exerted current variation as well as the coil position variation should be considered.

Therefore, the electrical equation is required to be described separately, such as (12) and (13) [1]-[2].

As the exerted current is varied without the coils position variation, the magnetic flux effect on the exerted current variation is as follows.

$$V = (I_0 + di) + N(\frac{\partial \varphi}{\partial i})(\frac{di}{dt}).$$
(12)

As the exerted current as well as the coils position varies, the magnetic flux effects on the exerted current variation and the displacement of the coils position is as follows.

$$V = (I_0 + di) + N(\frac{\partial \varphi}{\partial i})(\frac{di}{dt}) + N(\frac{\partial \varphi}{\partial x})(\frac{dx}{dt}).$$
(13)

The second term of the right side is the named transformer voltage and the third is speed voltage. Actually, at the very beginning, the holding force is greater than the operating force. Even though the current is rising into the coil, the moving part does not move. During this period, (12) is applied.

As the current is rising continuously, the operating force is greater than the holding force. Eventually the moving part is traveling. During this period, (13) is applied.

C. Kinetic equation

This is a system where the electrical energy is converted to kinetic energy. The basic kinematical equation is

$$\begin{cases} m(\frac{d^2z}{dt^2} + g) \\ = F^{hold} + F^{operate} + F^{gas} + F^{fric} + K(z). \end{cases}$$
(14)

Where, *m* (kg) is the moving part mass, which includes moving parts of the actuator in addition to the mass of the transmission rod and circuit interrupter, *z* (m) is the operating length, *g* (m/s²) is the acceleration of gravity, F^{gas} (N) is the repulsive insulating SF₆ gas power, F^{fric} (N) is the friction force, *K*(*z*)(N/m) is the stiffness of the small oil-dashpot. The velocity and displacement of the moving part are computed using (15).

$$\begin{cases} dv = \frac{\left\{ (F^{hold} + F^{operate} + F^{fric} + F^{gas} + K(z)) - mg \right\} \cdot dt}{m}. \quad (15) \\ \Leftrightarrow v_n = dv - v_{n-1} \\ \Leftrightarrow v_n = \frac{dz}{dt} \\ \Leftrightarrow z_n = dz - z_{n-1} \end{cases}$$

IV. DYNAMIC CHARACTERISTIC

The dynamics characteristics of the EMFA in a HGCB are analyzed using the FEM and TDM. Fig. 3 presents the manufactured model of EMFA and is linked with the circuit interrupter directly. The basic specifications of the EMFA for this HGCB system, a 72.5kV/20kA GIS system, listed in table I. The HGCB system requires a high repulsive insulating SF_6 gas power and its curve as shown below, in terms of the stroke length in Fig. 4.

The comparison between the simulated and experiment results for the opening operation without connection of the circuit interrupter are presented in Fig. 5 and 6. It is confirmed that the simulated results are a good match with experimental data. It is a necessary process to design the actuator with load situations, connected to the circuit interrupter, with experiment results according to the various voltages presented in Fig. 7, and listed in table II. As presented the table II, the proposed method is proven to be sufficient in operating at this high voltage class. The average velocity of the total moving part continues, increasing as the voltage rises. Namely, the operating characteristic of the EMFA is not related to the saturation on the station iron core, because the principle operating mechanism of the EMFA is moving according to the force of the energy density difference around the coils, and the magnetic permeability around the exited coils is like air. Therefore there is not any saturation on the magnetization and it is extremely useful for an actuator to be able to apply various voltage classes to the circuit breaker, while easily maintaining control during the moving part traveling.

In this paper, EMFA is already designed and manufactured at a saturation state to reduce the mass of the moving coils.



Fig. 3. Manufactured model of EMFA..

TABLE I





Fig. 4. Repulsive insulation gas power during the stroke length.



Fig. 5. Displacement of the moving part and average velocity without a circuit interrupter by DC 110[V].



Fig. 6. Current variation without circuit interrupter by DC 110[V].

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TABLE II The average velocity of the experments with load on the opening operation

Voltage	Average velocity
220 [V]	3.50 [m/s]
250 [V]	3.84 [m/s]
220 [V]	4.00 [m/s]



Fig. 7. Displacement of the total moving part with circuit interrupter connection.

V. CONCLUSION

In this paper, analysis of the dynamic characteristics of the EMFA for HGCB using the FEM and TDM, and development to apply the class of the 72.5kV/20kA GIS system is presented. The calculated results are consistent with the experimental results. It is confirmed that the analysis method of dynamic characteristics presented in this paper has excellent performance in calculating the dynamics of the EMFA. In demonstrating good performance of the EMFA on the HGCB, it offers significant technical performance improvement as well as a cost-effective mechanism for manufacture and maintenance, and extends circuit breaker life for users.

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