Modeling of the Dynamic Characteristics of Spring-Operated Gas Circuit Breakers*

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Abstract
A dynamics simulator for Gas Circuit Breaker (GCB) with spring operating mechanism was developed. The spring stores mechanical energy. When opening and closing instructions are entered in the GCB, the solenoid opens the trigger, and mechanisms release the compression force of the spring at a high speed. A compact and light-weight mechanism is required for high-speed operation of the GCB. This means that the high-speed operation must be analytically investigated. We made a mechanical dynamics model of the whole GCB, including an FEM modal analysis. The dynamics simulator incorporates a solenoid electromagnetic field analysis and a gas pressure analysis of puffer chamber in the mechanical dynamics model. The operating characteristics of the GCB were analyzed with the simulator and measured in an operating experiment. The analytical results were in good agreement with the experimental results, and this proved that the simulator can be used to estimate the operating characteristics and appraise the stability of operation. The compact and light-weight GCB can be designed in short time by using the dynamics simulator.

Key words: Dynamics of Machinery, Modeling, Transient Analysis, Circuit Breaker, Spring, Solenoid, Electromagnetic Analysis

1. Introduction

Power circuit breakers protect systems by immediately interrupting an abnormal current generated by lightning strikes, etc. The main type of power circuit breaker uses sulfur hexafluoride ($\text{SF}_6$) gas, which has superior insulating and arc-extinguishing properties compared to air. This arc-extinguishing medium is filled in a grounded container, and it opens and closes the contact [1]. There are multiple operating methods of such circuit breakers including the pneumatic type, spring type, and hydraulic type. The spring type, which is easier to maintain and does not require any auxiliary devices unlike a hydraulic unit is widely used [1]-[5]. However, with the increase in electric power demand and insufficient space to install new devices, it is necessary to increase the output while reducing the size and weight of such gas circuit breakers. The period required to develop such electric power equipment also needs to be shortened.

The spring operating mechanism, as described later, mechanically retains energy in springs. It provides the driving force for opening or closing the circuit, and is controlled by the open/close controller. The controller uses open/close commands to release the power of the springs at high speed. Therefore, to increase the output of a gas circuit breaker without increasing its size, it is necessary to reduce the size and weight of the mechanism and to use...
smaller springs which produce the driving force. To shorten the development period, it is also necessary to analyze the high-speed operation of the spring operating mechanism that can completes operation within about 0.1 second after receiving the open/close command.

Various studies on the operating mechanism of springs have predicted the stroke characteristics of springs when the current is interrupted [6] [7] and have considered the surge phenomenon of coil springs, etc. [8], but no prior studies have modeled the internal parts of the mechanism. In the present research, we developed a model of the dynamic characteristics of a whole gas circuit breaker, from the input of an open/close command to the completion of operation. We used this model to analyze the opening and closing operations, and a comparison between the analysis and experimental results revealed that the performance can be predicted with sufficient accuracy for practical use, meaning that and the stability of operation can be evaluated before prototyping.

2. Structure of a gas circuit breaker

The general structure of a spring-operated gas circuit breaker is shown in Fig. 1. The breaker is composed of breaker components, such as the moving contact, fixed contact, and puffer cylinder, and a link mechanism connecting the opening component with the spring operating mechanism. The structure and operating principle of the spring operating mechanism are shown in Fig. 2. The mechanism consists of the opening spring and the closing spring, a cam, a main lever, the open controller component, and the close controller component.

The opening/closing operation of the spring operating mechanism is explained below. Figure 2(a) shows the state when the contact of the interrupter is turned on. The opening spring and the closing spring are compressed. If an open command is input in this state, it operates in the following order: 1) The solenoid of the open controller component is excited, and the plunger presses down the trigger lever. 2) The levers (middle lever, catch lever, main lever) of the open controller component are released. 3) The opening spring is released. 4) The contact of the interrupter is opened. The state of the completed opening operation is shown in Fig. 2(b). When a close command is input, the unit operates in the following order: 5) The solenoid of the close controller component is excited, and the plunger presses the close trigger. 6) The engagements between the close trigger and the close lever and between the close lever and the cam are released. 7) The closing spring is released. 8) The opening spring is compressed by the cam. 9) The contact of the interrupter is closed.

Fig. 1  Schematic diagram of gas circuit breaker
3. Modeling of the operation

3.1 Overview of the modeling

The operation model developed based on the mechanism shown in Fig. 1 is outlined in Fig. 3. This model is based on an analysis model of the mechanism of the whole circuit breaker including the spring operating mechanism and is integrated with the analysis of the pressure of the puffer cylinder and the dynamic magnetic field analysis of the solenoid. MSC.ADAMS® (MSC Software, Inc.) is used for analyzing the mechanism; only the moving parts of the circuit breaker are modeled in this study.

Each component was modeled as follows. Since the deformation of the highly rigid puffer cylinder and the deformation of the controller lever of where the compression loads work are assumed to be negligible, the cylinder and lever were defined as rigid bodies. Since deformation of the isolated rod made of glass-fiber reinforced resin, the aluminum lever connected to it and the shaft affect the operation of the mechanism, these parts are considered to be elastic bodies. Figure 4 shows how the isolated rod, lever and shaft are incorporated as elastic bodies into the analysis model. Representative mode shapes (bending, twisting) acquired by calculating the constraint modes in the FEM modal analysis of the shaft are shown on the left side of the figure. The components modeled as elastic bodies are indicated with their flexibility determined by mode synthesis [9]. Each component was modeled so as to express a mode shape whose natural period is about 1/10th or less the optimal time for a puffer cylinder to make a full stroke ($t_o$); this is described later in more detail. The link connecting the interrupter and spring operating mechanism, the opening spring link, and the closing spring link shown in Fig. 3 are treated as beam elements that have a sufficient number of sections to express bending deformations. Regarding the main lever of the spring operating mechanism, the bending deformation caused by the
power of the spring is expressed as rotational spring element. It is assumed that the opening and the closing spring have equivalent masses, and one third of the mass of the spring itself is defined as a concentrated mass at the end of the spring. In addition, to define the contact at joint A, which is between the lever and the isolated rod of the link mechanism, the maximum gap determined by the dimensional tolerance is taken to be a slack, as shown in Fig. 3.

Fig. 3  Schematic diagram of dynamic modeling

Fig. 4  Mechanical dynamics model of GCB

The spring operating mechanism is modeled as follows. Figure 5 shows the moment, which is the force that acts on the open controller component of the spring operating mechanism at the instant an open command is input when the interrupter is in the closed state. The moment of inertia of each lever is $I_i$, the angle of rotation of each lever is $\theta_i$, the electromagnetic force of the solenoid is $F_0$, the contact force acting on each lever is $F_i$, the frictional torque between each lever and the rotational axis is $T_i$, the coefficient of friction at the contact surface between each lever and the roller is $\mu$, the spring constant of the return spring of each lever is $k_i$, and the local coordinate of the return spring is $x_i$. The equation of motion of each lever of the open controller component is expressed below. $l_{1,0}, l_{1,1}, l_{1,2}, l_{1,3}$ and $l_{1,4}$ in the equation respectively denote the contact reaction force acting on each lever or each moment arm around the rotational axis of the frictional force due to the electromagnetic force of the solenoid, the contact force, the return spring force, the frictional force and the contact reaction force. Regarding the signs of the terms, the direction when the lever rotates counter-clockwise in Fig. 5 is considered to be positive.

$$I_i \dot{\theta}_i = \pm F_{i-1} \cdot l_{i,0} + F_i \cdot l_{i,1} - k_i x_i \Delta l_{i,2} - \mu_i F_{i,3} l_{i,3} + \mu_i F_{i,4} - T_i(\theta_i) \quad (i=1-3) \quad (1)$$
The first term on the right-hand side of Eq. (1) indicates the contact reaction force which acts on the lever or the moment due to electromagnetic force of solenoid, the second term is the moment due to contact force, the third term is the load torque supplied by the return spring, the fourth term is the frictional torque on the contact surface between the roller and the lever, the fifth term is the load torque due to friction from the contact reaction force, and the sixth term is the frictional torque between the lever and the rotational axis. The electromagnetic force of the solenoid is acquired by coupled analysis of the motion of the solenoid, the dynamic magnetic field and the electric circuit (explained in Section 3.4). The equation of motion is derived for the close controller component shown in Fig. 2 in the same was as Eq. (1), so its explanation is omitted here. As mentioned in Chapter 2, the main lever starts after the controller component of the spring operating mechanism operates in the opening/closing operation of the circuit breaker. The equation of motion of the main lever is

\[ I_4 \ddot{\theta}_4 = k_4 x_4 + F_4 \dot{\theta}_4 + T_D \theta_4 - T_{\text{interrupter}} \]  

(2)

where \( I_4 \) is the moment arm around the rotational axis of the main lever due to the opening spring force, \( F_4 \) is the force converted from the driving force of the closing spring via the cam to the main lever position, and \( l_{24} \) is the moment arm around the rotational axis of the main lever due to \( F_4 \). Since the main lever and cam are separated in the opening operation in Fig. 2(a), \( F_4 \) of Eq. (2) is zero. On the other hand, in the closing operation indicated in Fig. 2(b), the cam and the main lever make contact, and \( F_4 \) is generated. \( T_{\text{interrupter}} \) is a load acting on the interrupter such as an increase in the puffer pressure. Since MSC.ADAMS® is used for analyzing the mechanism the equation of motion of the overall system is automatically generated by modeling the driving force and the load as given by Eqs. (1) and (2). In order to simulate the state in which the spring force of the driving force is retained, a balance analysis was conducted to calculate the equilibrium state of the system, and then a dynamic analysis was conducted. Variable order or variable step-size GSTIFF integration was used for integrating the equation of motion. Since the movements include the parts separating from the contact state and making contact again with the controller component of the spring operating mechanism, it is necessary to model them. Regarding contact, which is a key aspect of the modeling, Section 3.2 explains the stiffness and damping in contact with reference to the trip trigger and the middle lever of open controller as examples.

![Fig. 5 Modeling of spring operating mechanism](image-url)
3.2 Definition of stiffness and damping in contact

Figure 6(a) shows the state during closing operation of the trigger lever and the roller of the intermediate lever in which the trip trigger is separated from the middle lever and the stopper; Figure 6(b) shows an enlargement. The contact force when the two parts collide is assumed to follow elastic contact theory of Hertz [11] and is given by:

$$F = k(x_1 - x)^2 - c\dot{x} \quad \text{for} \quad x \leq x_1$$
$$F = 0 \quad \text{for} \quad x > x_1$$  \hspace{1cm} (3)

where $k$ is contact stiffness and $c$ is damping in contact. If a local coordinate system is defined between the center of the roller and the trigger lever end face, and it can be expressed as $x \leq x_1$, where the direction of radius is $x$: i.e., contact force is generated when the gap between the roller and the trigger lever end face is zero. The contact stiffness $k$ is derived from the elastic contact theory of Hertz:

$$k = \sqrt{\frac{16R^*E^*}{9}}$$  \hspace{1cm} (4)
$$\frac{1}{R^*} = \frac{1}{R_1} + \frac{1}{R_2}$$  \hspace{1cm} (5)
$$\frac{1}{E^*} = \frac{1 - \nu_1^2}{E_1} + \frac{1 - \nu_2^2}{E_2}$$  \hspace{1cm} (6)

where $R^*$ is effective radius, $E^*$ is the equivalent modulus of longitudinal elasticity, subscript 1 denotes the roller side, and subscript 2 the trigger lever side. $\nu$ is Poisson’s ratio.

The damping in contact $c$ of Eq. (3) is obtained as follows. In the case of contact between the trigger lever and the roller of the middle lever shown in Fig. 6(b), the collision behavior of the two parts is calculated by performing a mechanism analysis assuming that $k$ obtained from Eq. (4) is constant and $c$ is the parameter. In other words, by analyzing the behavior when the trigger lever collides with the roller of the middle lever at an angular speed $\omega_1$, the angular speed $\omega_0$ after collision is derived from the time history of the angular speed of the trigger lever. The coefficient of restitution is given by:

$$e = \left|\frac{\omega_0}{\omega_1}\right|$$  \hspace{1cm} (7)

The relationship between the input damping in contact $c$ and the calculated coefficient of restitution $e$ is shown in Fig. 7. Since the contact between the trigger lever and the roller shown in Fig. 6 is between iron parts, the coefficient of restitution $e$ becomes approximately 0.6–0.8, and the equivalent $c$ is obtained from Fig. 7. In the case of contact between the trigger lever and the stopper, since the structure of the stopper is an impact absorber sandwiched between iron plates and its coefficient of restitution is unknown, $c$ can be derived by conducting an element experiment and mechanism analysis as follows. The appearance of the device used for the element experiment and mechanism analysis as follows. The appearance of the device used for the element experiment is shown in Fig. 8. The trigger lever and stopper are modeled in a mechanism analysis and calculated with arbitrary $c$. $c$ is then adjusted so that the
displacement waveform matches that of the trip trigger acquired from the element experiment. The analysis values and the measured values of the trigger lever when \( c = 2000 \, N \cdot s/m \) are compared in Fig. 9. The second horizontal axis is the normalized time base by \( t_0 \), which is defined at the 4.1. This figure shows that the analysis reproduces measured behavior of the trigger lever colliding with the stopper and rebounding. Therefore, the damping in contact between the trigger lever and the stopper is found to be \( c = 2000 \, N \cdot s/m \).

Fig. 6  Three dimensional model of trigger lever

Fig. 7  Relationship between damping coefficient and coefficient of restitution

Fig. 8  Experimental element

Fig. 9  Displacement of trigger lever

3.3 Analysis of the pressure of the puffer cylinder

The gas pressure \( p \) which acts on the puffer cylinder is calculated by combining the mechanism analysis with an external subroutine program [10]. The arc generated between contactors is eliminated by blowing SF\(_6\) gas that has been raised to a high pressure by moving the puffer cylinder at high speed against the fixed contact in the opening operation. This increase in gas pressure places a load on the spring operating mechanism on the driver side. When interrupting an especially large current, a large pressure is generated that could affect the operating speed of the circuit breaker. The pressure at the puffer cylinder \( p \) is given by:

\[
p = \left( \frac{m}{V} \right)^\kappa \left( \frac{V_0}{m_0} \right)^\kappa \cdot p_0
\]

where the capacity of the puffer cylinder is \( V \), the mass flow rate of the gas at the puffer cylinder is \( m \), \( \kappa \) is the ratio of the specific heats of gas, and \( \kappa \) with the subscript zero indicates the initial state. Assuming that gas blows out iso-entropically from the nozzle with the a mass flow rate of gas \( m \), the time derivative \( \dot{m} \) is given by the following equations:
In these equations, $A_s$ is the cross-sectional area and is a function of the displacement of the puffer cylinder $x_p$. $p_1$ indicates the pressure outside the nozzle. The pressure $p_c$ (critical pressure) when the Mach number at the outlet of the nozzle is 1 is given by:

$$p_c = \left( \frac{2}{\kappa + 1} \right)^{\frac{\kappa}{\kappa - 1}} \cdot p$$

As shown in Fig. 3, $x_p$ based on the mechanism analysis is input to the puffer pressure calculation subroutine, and the output $p$ is reflected in the mechanism analysis.

3.4 Analysis of the dynamic electromagnetic field of the solenoid

As mentioned in Chapter 2, the solenoid is an important part which triggers the operation of the circuit breaker. Therefore, to predict the operating characteristics of the circuit breaker, it is necessary to accurately calculate the operating characteristics of the solenoid. To do this, a coupled analysis of the movement of the solenoid, the dynamic electromagnetic field and the electric circuit was made using Maxwell®2D (Ansoft, Inc.). Figure 10 shows the structure of the solenoid and the mesh division. Since the solenoid has a cylinder-shaped iron core, it was analyzed as a two-dimensional and axisymmetric part.

In this analysis, the dynamic magnetic field is calculated with the finite element method, and the electromagnetic force between the iron cores is calculated. This is combined with the equation of motion of the plunger, and the displacement of the plunger $y$ is obtained. Assuming that the free running distance of the plunger is $y_1$ and the distance through which the plunger presses the trigger is $y_2$, the equations of motion can be expressed as:

1) The time the plunger runs freely ($0 \leq y \leq y_1$)

$$M \frac{d^2y}{dt^2} + D \frac{dy}{dt} + F_{friction1} + F_{spring1} = F_0$$

2) The time the plunger presses the trigger ($y_1 < y \leq y_1 + y_2$)

$$M \frac{d^2y}{dt^2} + D \frac{dy}{dt} + F_{friction1} + F_{spring1} + F_{spring2} + F_{friction2} + F_{friction3} = F_0$$

where $F_0$ is the electromagnetic force between the iron cores calculated by the dynamic magnetic field analysis, $M$ is the mass of the moving iron core and the plunger, $D$ is the viscous damping coefficient, $F$ with a subscript is the load, $F_{friction1}$ is the resistance of the sliding part of the moving iron core, $F_{spring1}$ is the return spring force of the plunger, $F_{spring2}$ is the reset spring force of the trigger, $F_{friction2}$ is the frictional force of the surface where the...
roller and the trigger are engaged, and $F_{\text{friction3}}$ is the frictional force between the trigger shaft and the bearing. In Fig. 10, a dash is attached to $F_{\text{spring2}}$ and $F_{\text{friction2}}$, which are the loads concerning the trigger lever. In Eq. (13), those forces are converted into values in the direction of the plunger axis by considering the lever ratio of the trigger lever, and are input to the simulator.

Figure 11 shows the coil current of the trip solenoid and the waveform of plunger displacement. The coil current is normalized by the maximum value of the first wave. The upper time base is normalized by the time constant $\tau_0$, which is the time taken for the coil current to reach the maximum value of the first wave (time to reach 63.2%). The lower time base is normalized $t_0$, which is defined at the 4.1. The displacement of the plunger is normalized by its full stroke ($y_1 + y_2$). The free running of the plunger is 0–0.5, and the trip trigger is pressed after that. In the range of displacement of 0–0.5, during which the plunger runs freely, the measured value and the analysis value of the coil current and the plunger displacement almost match. On the other hand, when the displacement of the plunger is 0.5 or more, the two values differ. This occurs because the load of the solenoid is calculated after being converted to displacement of the plunger, and the inertial force of the trip trigger is not considered in the analysis (see Eqs. (12) and (13)). However, the difference between the measured and the calculated times at which the motion of the plunger is completed is small. Thus, since the dynamic magnetic field analysis can estimate the operating characteristics of the plunger with sufficient accuracy. The electromagnetic force $F$ acquired from the analysis can be combined with the mechanism analysis and input to the analysis model of the circuit breaker’s operation.

![Fig. 10 Structure and mesh of solenoid](image1)

![Fig. 11 Comparison of the analysis and experiments on the solenoid](image2)
4. Results of motion analysis of the circuit breaker

4.1 Comparison of analytical and measured operating characteristics

This section describes an example of the analysis of the operating characteristics and the behavior of the circuit breaker using the developed motion analysis model. The time base of the results is made dimensionless by the time $t_0$. In other words, if it is assumed that the whole system uniformly accelerates at the maximum value of the opening spring force, $F_{o,max}$, in the opening operation of the circuit breaker, the time until the puffer cylinder makes a full stroke (typically several hundred mm), $t_o$, is obtained by

$$t_o = \sqrt{\frac{2M_{eq}x_{pp}r}{F_{o, max}}}$$

(14)

where $x_{pp}$ is the full stroke of the puffer cylinder, $r$ is the stroke ratio of the operating mechanism and the interrupter on the basis of the operating mechanism ($r > 1$). $M_{eq}$ is the equivalent mass of the whole moving part at the position of the interrupter’s puffer cylinder, and is expressed as the equation below with $M_1$ and $M_2$ (as described in Fig. 3), which are the total mass of the moving parts of the interrupter and the operating mechanism.

$$M_{eq} = M_1 + \frac{M_2}{r^2}$$

(15)

Figure 12 compares the measured values and the analysis values of the operating characteristics of the circuit breaker. The measured values were acquired by measuring the displacement of the moving end of the opening spring shown in Fig. 2 by a laser displacement sensor. The displacement is normalized by the full stroke in Fig. 12. The opening spring starts at point A after an open/close command is input and the mechanism of the controller component operates. The measured value matched the analysis value in all of the opening/closing operations in Fig. 12(a)(b). In section BC after the opening spring starts, the analysis value almost matches the measured values of the opening characteristics of Fig. 12(a), whereas there is a small difference in the closing characteristics of Fig. 12(b). In the opening operation, the opening spring force directly acts on the link mechanism shown in Fig. 1, but in the closing operation, the closing spring force acts on the link mechanism after being transferred to the opening spring side via contact with the cam and the roller of the main lever. In addition, in the closing operation, the moment arm changes according to the rotation angle of the cam, and the driving force at the position of the opening spring becomes nonlinear with respect to the stroke of the opening spring. Therefore, it is considered that errors occur more easily in the motion analysis of the closing operation. In section CD in Fig. 12, the circuit breaker stops receiving the braking force of the oil damper and the motion completes. In the oil damper, a piston moves in the cylinder filled with oil. In order to maximize the damping force at the end of the opening operation and the closing operation, there are small holes aligned in multiple lines on the side of the cylinder. In the motion analysis, compressibility of oil is ignored and steady flow is assumed thus, the damping force of the oil damper is given by

$$F_d = \frac{\rho X_s^2 A_1^4}{2C^2S(x_s)^3}$$

(16)
where \( \rho \) is the density of oil, \( x_2 \) and \( \dot{x}_2 \) are the displacement and velocity of the piston, \( A_d \) is the area receiving the pressure of the piston, \( C \) is the flow coefficient, and \( S \) is the total area of the small holes on the cylinder which are in the direction of movement from the position \( x_2 \) of the piston. The small holes are arranged such that \( S(x_2) \) is minimized at the end of the opening operation. In this simulation of the damping force of the oil damper, the analysis value matched the measured value in section CD of Fig. 12. These results show that it is possible to estimate the operating characteristics from the input of an open/close command to the circuit breaker to completion of the motion with sufficient accuracy for practical use.

**4.2 Result of analysis of the puffer chamber pressure**

The effect of the current load on the operating characteristics was considered in the motion analysis. The waveform of the input interrupting current is shown in Fig. 13(a). In the case of a load being applied, it was assumed that the frequency was 60 Hz, the AC component was 40 kA, the DC component was 49%, and the arcing time was 17 ms. Figure 13(b) shows the pressure of the puffer chamber, and Fig. 13(c) shows the displacement of the opening spring. The pressure in Fig. 13(b) is normalized by the initial pressure \( p_0 \), and the displacement in Fig. 13(c) is normalized by the full stroke of the puffer cylinder. Figure 13(b) indicates that the maximum value of the pressure of the puffer chamber when a load is applied is as much as approximately 2.5 times that when no load is applied. Thus, when the
load is applied, the reaction force on the spring operating mechanism increases, and as shown by the area surrounded by the dotted line in Fig. 13(c), the deceleration in the latter half of the stroke is large. To reduce the size and weight of the circuit breaker, it is necessary to reduce the opening spring force. However, excessive reduction could have adverse effects on the stroke of the puffer cylinder, as shown in Fig. 13(c). Therefore, it is necessary to determine the minimum value of the opening spring force to avoid deterioration of the puffer cylinder stroke by analyzing the operating characteristics when a load is applied.

4.3 Behavior during opening operation

(1) Releasing behavior of the lever of the open controller component

The motion analysis can show the behavior by which the contact force acting on the lever of the open controller component is released during the opening operation. Figures 14(b), (c) and (d) show the calculated and measured values of the contact force acting on each lever. The contact force is released in the order of the trigger lever, middle lever, and catch lever in the opening operation. The measured value shown in Fig. 14(a) was taken using a strain gage attached to the lever. The contact force was normalized by the load before inputting the open command when the opening spring force was maintained. A small difference was observed in the behavior of releasing the contact force with the trigger lever and the middle lever in Fig. 14, but these behaviors almost matched that of the catch lever. These results show that the motion analysis can estimate the behavior of the lever of the controller component.

(2) Comparison of the measured and calculated displacement between the operating mechanism and the interrupter

As shown in Fig. 1, the operating mechanism and interrupter are separate components in the circuit breaker, and they are connected by a link mechanism. Therefore, there is likely to be a delay in the transmission of the load between the opening spring, which is the driving force, and the puffer cylinder. For example, in the link mechanism, the looseness of the pin connector is expected to delay the operation. However, it is difficult to directly measure the displacement of the puffer cylinder since is placed in a container filled with SF\(_6\) gas. Instead, a motion analysis can be used to reveal the difference between the behaviors of the opening spring and the puffer cylinder.

Figure 15 show the results of motion analysis as the waveforms of displacement of the opening spring and the puffer cylinder. They reveal the following:
(a) There is a delay in starting the puffer cylinder in relation to the opening spring
(b) The puffer cylinder moves ahead of the opening spring in the uniform motion section
(c) There is a difference in the damping characteristic at the end of the stroke
The delay in starting (a) was approximately 0.08 in dimensionless time (from Fig. 15). The delay is analyzed below. The propagation velocity of a stress wave is given by:

\[ C = \sqrt{\frac{E}{\rho}} \tag{17} \]

where \( E \) is the modulus of longitudinal elasticity of a structural component, and \( \rho \) is the density. In the case of steel, \( C = 5139 \text{ m/s} \). The propagation time of a stress wave calculated on the basis of the length of the parts of the link mechanism is approximately 0.008 in dimensionless time, which is one tenth the delay in starting. As shown in Fig. 3, the looseness is in joint A between the lever and the isolated rod. In other words, a contact element is defined between the holes in the levers and the pins, and between the pin and the hole of the isolated rod. Since the puffer cylinder is inserted in the fixed contact before the opening operation, the isolated rod is pulled up to the puffer cylinder. Therefore, the pin makes contact with the puffer cylinder between the pin and the hole of the isolated rod. On the other hand, the lever connected to the link is pulled up to the spring operating mechanism by its own weight. Therefore, between the holes in the levers and the pins, the pins contact the opposite side of the puffer cylinder. Since the spring operating mechanism stores a driving force before the starting operation, the forces acting on the mechanisms above it are the self-weight of each part, the insertion force of the fixed contact and the static friction at the sliding part. Since a roller bearing is used to support the rotation of the lever and a translational seal component with a low coefficient of friction is on the sliding part between the puffer cylinder and the fixed piston, the frictional force resisting the driving force of the puffer cylinder is sufficiently low. The inserting force of the contactor was set to 1% (or less) of the driving force of the puffer cylinder. Therefore, it is considered that the effect of the propagation of force and friction on the delay in starting the puffer cylinder in relation to the opening spring is small, and that the effect of looseness in the mechanisms such as joint A is dominant. In Fig. 15, the delay in starting is resolved after the

Fig. 15  Comparison of the calculated and measured characteristics of the operating mechanism with an interrupter
dimensionless time 0.75 of the operating characteristics, and the puffer cylinder moves ahead of the opening spring through its inertial force. In addition, in the final phase of the opening operation (c), deceleration of the opening spring increases at the dimensionless time 1.7, but the deceleration becomes small due to the inertial force of the puffer cylinder, and there is a difference in damping between the two parts.

4.4 Behavior during closing

The levers in the open controller component disengage in the opening operation and engage in the closing operation. As the closing operation proceeds from the state of Fig. 2(b), the cam rotates, and it contacts the roller of the main lever at the part of maximum radius of the cam. At that time, the opening spring is compressed more than the prescribed amount: this is called over-stroke, and it is illustrated in Fig. 12(b). During over-stroke, the return operations of the catch lever, the middle lever, and the trigger lever are consecutively reset. At the certain degree of cam rotation angle, the cam separates from the roller of the main lever, then, the opening spring force starts releasing, but quickly the lever of the open controller component engages, finally the opening spring force becomes to be held. If each lever of the open controller component has not finished at this moment, the opening operation will be performed incorrectly. This may happen, for example, if the spring force of the return spring attached to each lever of the open controller component is smaller than the specification. Therefore, it is important to ensure the stability of the reset movement at the open controller component in the final phase of the closing operation. Regarding this issue, there was a study that verified the reset movement in which the movements of the open controller component were captured with a high-speed video camera [12].

Figure 16 shows the results of analyzing the displacement and the angular displacement of the trip trigger in the final phase of the closing operation. The main lever starts to over-stroke at 5.8 in dimensionless time, the main lever engages the catch lever at 7.15. On the other hand, the trigger lever rotates rapidly at over 5.9 in dimensionless time, and it collides with the stopper and rebounds. The trigger lever stops colliding at about 6.9 and the reset movement of the open controller component finishes. The time difference $\Delta t$ between when the trigger lever is reset ($t_1$) and the instant the main lever engages with the catch lever ($t_2$) is 0.25. To stably hold the opening spring force, $\Delta t$ must be greater than 0. These results show that it is possible to verify the stability of the return operation of the open controller component in the final phase of the closing operation without using a high-speed camera.

Fig. 16  Displacement of opening spring and rotational angle of trip trigger
5. Conclusions

In order to shorten the time taken to develop the spring operating mechanism used in gas circuit breakers, a behavioral model of the whole circuit breaker that combines electromagnetic field analysis of the solenoid, FEM modal analysis, analysis of the gas pressure of the puffer cylinder and mechanism analysis was developed. The following findings were obtained.

(1) In electromagnetic field analysis of the solenoid which triggers the operation of the gas circuit breaker, the time at which the plunger moves could be estimated with sufficient accuracy by considering the resistance of the sliding part, reset spring force, frictional force, etc.

(2) The calculated values of the operating characteristics of the gas circuit breaker and the contact force release characteristics of the lever during the opening operation almost matched the measured values, thus verifying the validity of the behavioral model. It is possible to shorten the development time by estimating the operational performance with this behavioral model before creating a prototype of the gas circuit breaker.

(3) The spring operating mechanism and the interrupter are connected by a linkage mechanism which has some looseness. The operating characteristics specific to gas circuit breakers were clarified: the interrupter is delayed in relation to at the start of the operation, whereas it interrupter takes a lead in the middle of the operation, and damping of the interrupter is delayed in the final phase of the operation.

(4) The stability of the re-engaging operation between levers in the final phase of the operation could be verified by analyzing the closing operation (in the past, such an operation has had to be verified experimentally using a high-speed camera, etc.).

References


