Optimization of the Spring Design Parameters of a Circuit Breaker to Satisfy the Specified Dynamic Characteristics

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ABSTRACT

A spring-actuated linkage system is used to satisfy the desired opening and closing characteristics of the electric contacts of a vacuum circuit breaker. If the type of a circuit breaker and the structure of the linkage system are predetermined, then design parameters such as stiffness, free length and attachment points of the spring become the important issues. In this paper, based on the energy conservation, the total system energy is constant throughout the operating range of the mechanism; a systematic procedure to optimize the spring design parameters is developed and applied to a simplified mechanism of a circuit breaker. The developed procedure is converted to the environment of the multi-body dynamics program, ADAMS for an in-depth consideration of the complex dynamics of a circuit breaker mechanism.

Key Words : Vacuum Circuit Breaker, Spring Design Parameter, Least Square Error, Polynomial Function, Multi-body Dynamics Program

Nomenclature

F_V = contact force on the moving contact
g = gravity constant
I_o = moment of inertia of the link
k = spring constant
l_0 = free length of the spring
m_c = mass of the moving contact
m_f = mass of the follower
T = kinetic energy
T_f = friction torque acting on the rotational axis
V_e = potential energy of the elastic spring
V_g = potential energy by gravity
W^{nc} = work done by nonconservative force
θ_i = initial rotational angle of the link
θ_0 = rotational angle of the link
Ψ = sum of the square errors between the desired and the calculated velocities
h = strip thickness with strip

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1. Introduction

Power circuit breakers are used to switch on and off of short-circuit currents, overhead lines and cables under load and no load, transformers and generators, motors, ripple control systems, and capacitors. There are many different kinds of power circuit breakers. They are classified as air, gas, vacuum, and oil circuit breakers based on arc extinguishing mediums.[1] The vacuum circuit breaker(VCB), extinguishing the arc in the vacuum interrupter with its favorable features such as small size, high efficiency and easy maintenance is often used to break electricity in the power transmission lines ranging from 3.6 to 38 kV.

A spring-actuated linkage mechanism is a simple and reliable device to transfer the stored elastic energy of the spring to the mechanism composed of cams and links at a high speed. This mechanism is usually used in the vacuum circuit breaker, which completes switching action within several tens of milliseconds. The opening and closing dynamic characteristics of electric contacts must satisfy such specifications as the displacement and velocity constraints between fixed and movable electric contacts. Therefore, if the linkage is known, stiffness, free length and attachment points of a spring become the important design parameters in the spring-actuated linkage. The method of determining such spring parameters is required to satisfy the specified dynamic responses of the breaker mechanism.

In the research on the spring design parameters, Matthew and Tesar[2] developed a closed-form analytical formulation for synthesis of springs for planar mechanisms. Their procedure was only limited to tension springs with zero free length. Another less attractive feature was practicality since it was hard for engineers to use their procedure. Spring synthesis technique using energy methods has been presented for static balancing of mechanisms.[3,4] These studies were not concerned with spring attachment points and linkage's dynamics. Huang and Roth[5] developed a method of determining the dimensions of linkages that guide a rigid body through several positions and support a specified external load at each position. They applied the method to the spring synthesis with zero free length. Jenuwine and Midha[6] derived a means of synthesis of a mechanism which specifies lengths of linkages, stiffness and free lengths of springs, based on given displacement and energy absorption requirements.

In this paper, a systematic design procedure to synthesize spring parameters in a spring-actuated link mechanism of a circuit breaker is proposed. Using the energy method, the parameters are optimally determined to satisfy the dynamic characteristic of the mechanism. This is used to give the spring parameters for the simplified link mechanism of the circuit breaker. In order to use the dynamic model of ADAMS[7], the optimization procedure is converted to ADAMS environment. This is used for designing the circuit breaker with complex links and springs. Finally, the spring parameters of the circuit breaker with complex links and springs are designed using the optimization procedure in ADAMS.

2. Optimization of spring design parameters

2.1 Design of the link mechanism

When the link mechanism of a circuit breaker is designed, it is necessary to know the response curve of the contact specified by the electrical characteristics. The detail designing procedures of the link mechanism shown in Fig. 1 are as follows:

- The link mechanism to activate the contact is selected or designed.
- The spring parameters such as stiffness, free length, and connecting positions of the spring are determined.
- The shape, diameter, and winding numbers of the spring are designed.

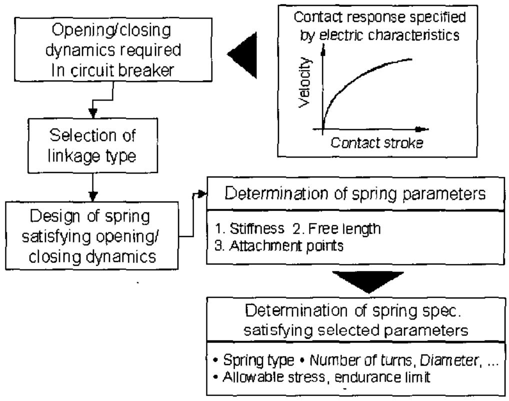


Fig. 1 Spring design process in a circuit breaker

2.2 Design procedure and optimization

A Newtonian approach requires calculations of constraint forces, force or moment directions, transmission angles, and etc. An energy approach, however, does not require calculating those parameters, so it considerably simplifies the analysis and design method. The energy approach is especially useful to design a circuit breaker mechanism because the mechanism is simply composed of spring and link elements.

The energy approach for the design of spring parameters in a spring-actuated linkage can be formulated by considering the dynamic response that is specified for a given mechanical system. The principle of work and energy of a system is expressed as follows:

$$W_{1\to 2} = T_2 - T_1 = V_1 - V_2 + W_{1\to 2}^{nc} \tag{1}$$

where T is the kinetic energy of the links, V is the potential energy due to gravity and elastic springs, and $W_{1\to 2}^{nc}$ is the non-conservative work done on the system from position 1 to position 2.

A simple spring-actuated linkage system with a single degree-of-freedom is considered in Fig. 2 where one end point of the spring is attached to the point B of the link, and the other end point of the spring is attached to the point A of the ground. The position of A is *(U, V)* in the *X-Y* reference frame, and that of B is *(s, t)* in the *x-y* reference frame that is fixed to the link. The angle of rotation of the *x* axis relative to the *X* axis is denoted as θ_i. The origins of the two frames coincide at O. When the link rotates from initial angle θ_0 to any angle θ_i, the work and energy equation of the system is expressed as follows:

$$V_e(\theta_0)+V_g(\theta_0)-V_e(\theta_i)-V_g(\theta_i)+W^{nc} -(T(\theta_i)-T(\theta_0))=0 \tag{2}$$

where

$$V_e(\theta_i)=\frac{k}{2}\left(\sqrt{\begin{array}{l}[U-(s\cos\theta_i-t\sin\theta_i)]^2\\+[V-(s\sin\theta_i+t\cos\theta_i)]^2\end{array}}-l_0\right)^2 \tag{3}$$

$$V_g(\theta_i)=m\,g\,e\sin\theta_i \tag{4}$$

$$T(\theta_i)=\frac{1}{2}I_O\,\dot{\theta}_i^2 \tag{5}$$

$$W^{nc}=T_f(\theta_i-\theta_0) \tag{6}$$

$V_e(\theta_0)$, $V_g(\theta_0)$, and $T(\theta_0)$ are obtained by replacing θ_i by θ_0 in above equations. Here, k and l_0 are the stiffness and the free length of the spring, I_O is the moment of inertia of the link about the rotating axis, and T_f is the friction torque acting on the rotating axis.

The spring parameters in Eq. (2) are stiffness (k), free length (l_0), position of the point B on the link (s,t), and position of the point A on the ground (U,V). The total number of parameters is six. These six design parameters are determined by considering Eq. (2) and the specified angular velocities at given rotating angles.

Let $\dot{\theta}_{dj}$ denote the desired velocity at *j*-th angle, and $\dot{\theta}_j$ denote the velocity calculated from Eq. (2) for guessed spring parameters. Then the square error of the two velocities becomes $(\dot{\theta}_{dj}-\dot{\theta}_j)^2$. Let N denote the number of selected angles. Then the sum of errors between desired and calculated velocities is as follows:

$$\Psi=\sum_{j=1}^{N}(\dot{\theta}_{dj}-\dot{\theta}_j)^2 \tag{7}$$

If the spring parameters such as stiffness, free length, and attaching positions are determined by minimizing Ψ in Eq. (7), the spring link mechanism that approximates the specified design curve between the rotating velocity and the rotating angle can be obtained.

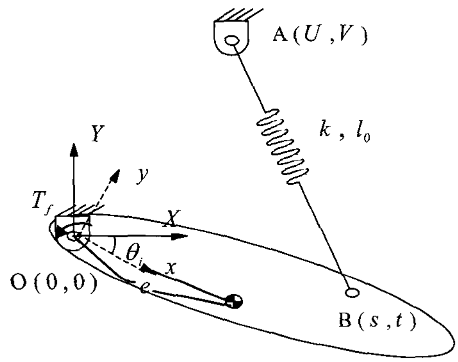


Fig. 2 Simple spring-actuated link mechanism with one degree-of-freedom

2.3 Application and Results

Fig. 3 shows the spring-actuated linkage system used in opening operation of VCB. The rated voltage and the interrupting current of the breaker are 12 kV and 40 kA, respectively. An electric contact is shown among three-phase electric contacts in the figure. Two pre-loaded symmetrical opening springs move the three-phase electric contacts down. The external force is acting on the movable contact by the pressure difference between vacuum interrupter and atmosphere. When the follower rotates from the initial angle θ_0 to the angle θ_i, the work and energy equation of the system is expressed as follows:

$$V_e(\theta_0)+V_g(\theta_0)-V_e(\theta_i)-V_g(\theta_i)+W^{nc} -(T(\theta_i)-T(\theta_0))=0 \tag{8}$$

Although Eq. (8) seems to be similar to Eq. (2), all terms of Eq. (8) except the elastic energies of the spring are different from those of Eq. (2).

By considering three phase moving contacts, the potential energy due to gravity and the kinetic energy are expressed as follows:

$$V_g(\theta_i) = m_f g d_f \sin(\psi + \theta_i) + 3m_c g d_c \sin(\phi + \theta_i) \quad (9)$$

$$T(\theta_i) = \frac{1}{2} I_o \dot{\theta}_i^2 + \frac{3}{2} m_c (d\dot{\theta}_i \cos\theta_i)^2 \quad (10)$$

where C_f and C_c are the mass centers of the follower and the movable contact, respectively, and d_f and d_c are distances from the origin to C_f and C_c, respectively. Also, $\psi = \angle C_f O B$ and $\phi = \angle C_c O B$. F_V is the external force considered as the work done on the system. The work done by the external force is as follows:

$$W^{nc} = 3F_V d(\sin\theta_i - \sin\theta_0) \quad (11)$$

where $V_e(\theta_0)$, $V_g(\theta_0)$, and $T(\theta_0)$ are obtained by replacing θ_i by θ_0 in equations (3), (9), and (10).

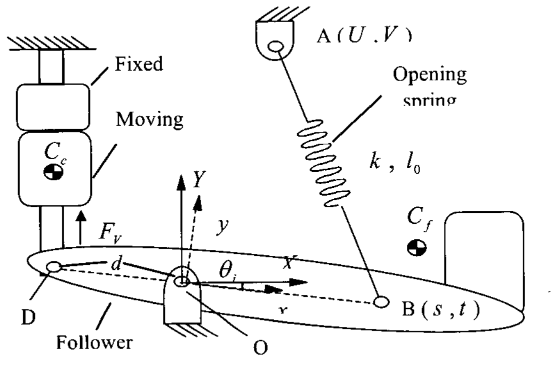


Fig. 3 Spring-actuated linkage of a vacuum circuit breaker for opening operation

2.3.1 Design of the specified follower motion

When the system shown in Fig. 3 is opened, the desired response of the follower is obtained by the following boundary conditions:

$\theta(t_0) = -2.0783 \times 10^{-3}$ rad
$\dot{\theta}(t_0) = 8.9226$ rad/s at $t_0 = 15.85$ $m\sec$
$\theta(t_s) = 9.5343 \times 10^{-2}$ rad at $t_s = 25.80$ $m\sec$

where t_0 is the initial time when contacts start to open, t_s is the time when the movable contact moves 10 mm downward.

The required time t_k can be obtained from the specified average opening velocity between 0% stroke and 90% stroke as follows:

$$t_k = t_0 + \frac{0.9d_c}{v_c} \quad (12)$$

where v_c , the average opening velocity, is 1 m/s and D , the full stroke between movable and fixed electric contacts, is 10 mm.

The follower should satisfy the following equation at $t = t_k$.

$\theta(t_k) = 8.5575 \times 10^{-2}$ rad at $t_k = 24.85$ $m\sec$

The rotational angle of the follower satisfying above four boundary conditions are represented as a polynomial function[8] as follows:

$$\theta(t) = -0.105 + 3.42t + 2.34 \times 10^2 t^2 - 2.53 \times 10^3 t^3 \quad (13)$$

The desired velocity of the follower can be obtained by differentiating the above equation. Finally, the relation between the desired follower angle and velocity is obtained and plotted as Fig. 4.

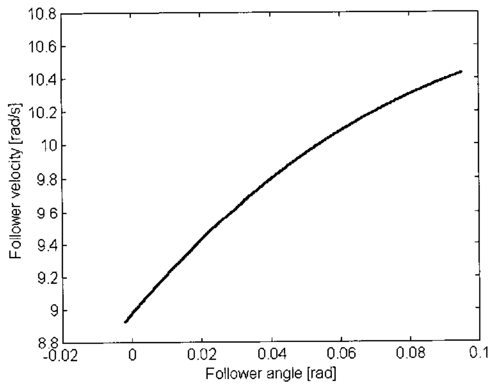


Fig. 4 Relation between desired angle and velocity

2.3.2 Determination of spring parameters

Since the attachment point B on the follower is on the line parallel to the x -axis of the follower, the component of y -direction of the point B, t , becomes zero. Therefore, the spring parameters, k, l_0, U, V, and s, are to be determined using the least square error method. The least square error method is not limited to the number of precision points. Six points from Fig. 4 are selected here.

First, with the initial values of the spring parameters, the angular velocities of the follower are calculated using Eq. (8) for the chosen six angles of the follower. Next, the errors between the designed velocities and the calculated velocities are obtained. The spring parameters are optimized to minimize the sum of the squares of the errors. The modified Simplex method[9] is used for optimization. Table 1 shows the final optimal values of the spring parameters, which approximate the required dynamic characteristics of the follower very well as shown in Fig. 5.

Table 1 Optimization of spring design parameters

Design parameter	Original value	Optimal value
k [N/mm]	14.59	25.82
l_0 [mm]	128	147
U [mm]	83	71.3
V [mm]	207	147
s [mm]	135	146

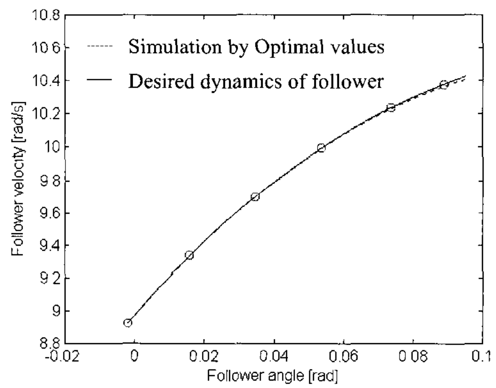


Fig. 5 Dynamic characteristics of follower

3. Optimization using ADAMS model

3.1 Conversion to ADAMS environment

The vacuum circuit breaker mechanism is composed of complex linkages. Applying the method of the previous section to determine the spring parameters of the breaker requires expressing all elements of the breaker mathematically. This needs a lot of time. Moreover, a new formulation is required whenever the link mechanism has a new shape or dimension.

Recently, many kinds of link mechanisms such as circuit breakers have been modeled and analyzed using a multi-body dynamics program such as ADAMS.[10,11] The dynamic model based on ADAMS has a merit that it can analyze the realistic response of the link mechanism easily with small modification whenever the shape or the dimension of the mechanism changes. In order to use the dynamic model of ADAMS, the optimization procedure developed in the previous section should be converted to ADAMS environment. The method to optimize spring parameters of a circuit breaker using ADAMS is introduced in this section.

The optimization procedure of the spring parameters of a circuit breaker using ADAMS model is shown in Fig. 6. Here, the difference between previously proposed design procedure and this procedure is to use the ADAMS model of the breaker instead of energy equation. First, desired contact response is designed. This is done by numerical program without using ADAMS. Next, the dynamic response is obtained for the dynamic model of the breaker with initial design parameters. Here, the error between the designed velocity and the calculated velocity of the contact point is obtained, and the spring parameters are optimized to minimize the square of the error. DOT3 of ADAMS has been used as an optimization program.

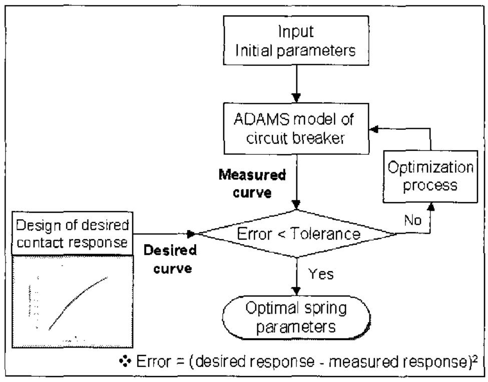


Fig. 6 Optimal design process of spring parameters using ADAMS

3.2 Optimal design of the opening spring

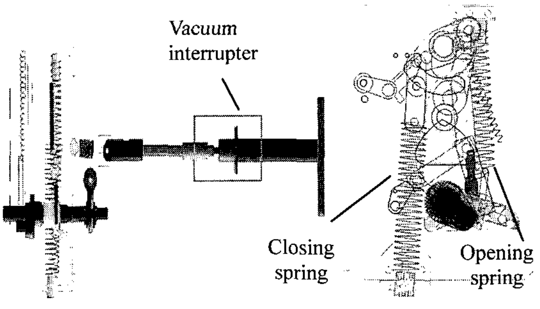
The design procedure based on ADAMS model is applied to a VCB with rated voltage, 24 kV, and interrupt current, 40 kA. The total structure and the complex linkage mechanism are shown in Fig. 7. Here, the contact stroke is 17 mm. The VCB is to be optimally designed for the moving contact to have the desired opening velocity of 1.8 m/sec. It is assumed that the connecting position of the spring is not changed because of assembly process of the breaker. Thus, x and y coordinates of the position of the spring are eliminated from the design parameters.

The opening velocity of the contact is calculated as 2.64 m/s with the initial stiffness of 50 N/mm and free length of 100 mm for the opening spring. This value is higher than the design value of 1.80 m/s. The optimization procedure shown in Fig. 6 determines the stiffness and the free length of the spring. First, the velocity curve of the contact is designed with opening velocity of 1.80 m/s using the method of section 2.2.1. Using this curve, optimization of the spring parameters is done to have optimal stiffness and free length shown in Table 2.

The solid line in Fig. 8 shows the desired velocity curve of the moving contact, and dotted line shows the calculated velocity curve obtained through optimization. The calculated velocity well approximates the desired velocity. The average opening velocity of the moving contact is obtained as 1.77 m/s, which is almost same as the desired velocity of 1.80 m/s with error less than 2 %.

4. Conclusions

A systematic optimal design procedure to synthesize spring parameters of a vacuum circuit breaker mechanism has been proposed. To apply optimal design of the parameters, it is required to express all elements of the breaker mathematically. This needs a lot of time. The dynamic model based on ADAMS has a merit that it can analyze the realistic response of the link mechanism easily. In order to use the dynamic model of ADAMS, the optimization procedure is converted to ADAMS environment. The optimization procedure of the spring parameters of the circuit breaker using ADAMS model is applied to design the opening spring of the circuit breaker. The average opening velocity of the contact approximates the desired velocity with error less than 2 %. The proposed procedure can be extended to determine kinematic and dynamic variables such as link length and mass.



(a) Total structure (b) Driving mechanism

Fig. 7 Total structure and driving mechanism of the vacuum circuit breaker

Table 2 Optimal Design results of opening spring

Iter. No.	Objective function	Stiffness (m/sec)	Free length (mm)
0	1.72E9	50	100
1	2.70E7	57.07	151.8
2	1.55E7	57.65	148.2
3	1.47E7	57.52	148.9

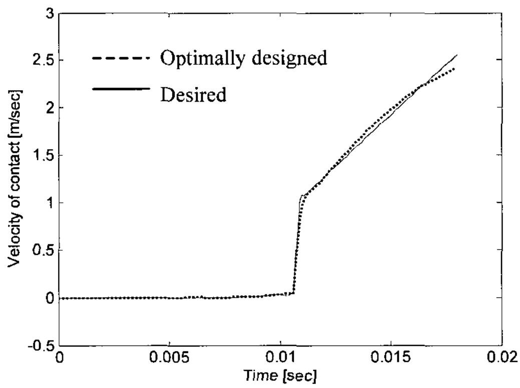


Fig. 8 Desired and optimally designed opening characteristics of the moving contact

References

1. Flurscheim, C. H., Power Circuit Breaker Theory and Design, Short Run Press Ltd., 1975.
2. Matthew, G. K. and Tesar, D., "Synthesis of Spring Parameters to Satisfy Specified Energy Levels in Planar Mechanisms," Transaction ASME-Journal of Engineering for Industry, May, pp. 341 - 346, 1977.

3. Streit, D. A. and Gilmore, B. J., "Perfect Spring Equilibrators for Rotatable Bodies," Transaction ASME-Journal of Mechanisms, Transmission and Automation in Design, Vol. 111, pp. 451 - 458, 1989.
4. Walsh, G.; Streit, D. A. and Gilmore, B. J., "Spatial Spring Equilibrator Theory," Mechanism and Machine Theory, Vol. 26, No. 2, pp. 155 - 170, 1991.
5. Huang, C. and Roth, B., "Dimensional Synthesis of Closed-Loop Linkages to Match Force and Position Specifications," Transaction ASME-Journal of Mechanical Design, Vol. 115, pp. 194 - 198, 1993.
6. Jenuwine, J. G. and Midha, A., "Synthesis of Single-Input and Multiple-Output Port Mechanisms with Springs for Specified Energy Absorption," Transaction ASME-Journal of Mechanical Design, Vol. 116, pp. 937 - 943, 1994.
7. ADAMS(Automated Dynamic Analysis of Mechanical System) Reference Manual., Mechanical Dynamics incorporated, U.S.A, 2002.
8. Erdman, A. G. and Sandor, G. N., Mechanism Design, Analysis and Synthesis Vol. 1, Prentice-Hall, 1984.
9. Rao, S. S., Optimization Theory and Application, Wiley Eastern Limited, New York, 1978.
10. Ahn, K. Y., Kwon, B. H., Oh, I. S., Yoon, Y. K. and Choe, J. W., "Dynamic Analysis of Air Circuit Breaker with Spring-Actuated Linkage," Proc. of the KSPE Fall Conference, pp. 812 – 815, 2001.
11. Ahn, K. Y. and Kim, S. H., "Dynamic Model and Analysis of a Vacuum Circuit Breaker Mechanism for High-Speed Closing and Opening Simulations," J. of the KSPE, Vol. 19, No. 10, pp. 163 – 170, 2002.