International Journal of Research in Engineering and Science (IJRES)
ISSN (Online): 2320-9364, ISSN (Print): 2320-9356
www.ijres.org Volume 4 Issue 10 ǁ October. 2016 ǁ PP. 07-14

Research on Dynamics of MCCB Operating Mechanismbased on Singular Configurations

Wang Jun[1] Hang Lubin*[1] Huang Xiaobo[1] Xiang Honggang[2] Yu Yipeng[2]

[1]*College Of Mechanical Engineering, Shanghai University Of Engineering Science, Shanghai 201600;*
[2]*Shanghai Liangxin Electrical Co．, Ltd．, Shanghai 200137)*

Abstract: The design of operating mechanism of Molded Case Circuit Breaker (MCCB) should ensure various targets of the performance. However, the coupling of various performance, indexes and structure parameters results in difficulty of the design and optimization of operating mechanism. Based on the singular configurations of MCCB operating mechanism, the closing processis divided into three motion phases to study the different structure in different phase.Lagrange dynamics equationsare built and the characteristics of the first and second singular configuration are studied. The closing operation velocity curve of the operating mechanism is simulated in ADAMS. It provides theoretical basisfor the analysis of the MCCB performance.
Keywords: MCCB; operating mechanism;the first singular configuration;the second singular configuration; Lagrange dynamics equations

I. INTRODUCTION

With the development of smart grid, molded case circuit breakers(MCCBs) are required to achieve the following performance: 1)high breaking capacity; 2) high reliability; 3)high consistency [1,2]. As the core component of MCCB, operating mechanism plays an important role in the closing operation.

Degui Chen built a novel dynamic model of MCCB′s operating mechanism based on multi-body dynamics adopting virtual prototypingtechnology, and made an experiment to verify the mechanical properties of MCCB. Based on that, the effect of different factors to the operating velocities of mechanism was analyzed [3,4].A process model of MCCB operating characteristic multidimensional analysis and a dynamic model were established by Hongming Zhou. Based on Lagrange equations, design parameters of operating mechanism including breaking velocity, opening range, spring force were analyzed and optimized by simulation in ADAMS [5,6].

These existing papers focus on the movement process and kinematic properties for MCCB operating mechanisms using virtual prototypingtechnology in ADAMS, but literature on the singular configurations of the operating mechanism is limited. As a special position during the MCCB closing operation, the second singular configuration is important to the design of an operating mechanism.

The paper introduces the notion of the first singular configuration and the second singular configuration of MCCB operating mechanism. Based on the singular configurations, the closing process is divided into three motion phases and the different structure in different phase is studied. Dynamic model and static dynamics model are built to study connection between the first and second singular configuration. And in ADAMS, the closing operation velocity curve of the operating mechanism is simulated.

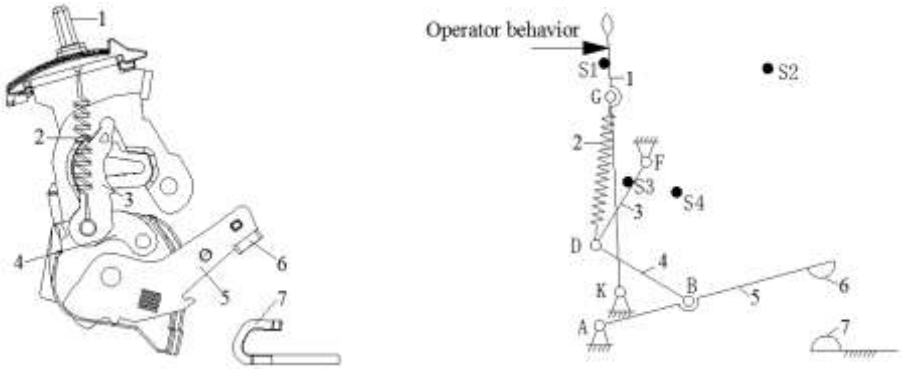
*Corresponding author. E-mail address: hanglb@126.com

II. TRUCTURE AND MOTIONPHASES OF OPERATING MECHANISM

2.1 Structure

A simplified version of the operating mechanism of a MCCB (Fig. 1a) is shown in Fig. 1b.Here, the handle KGand crank DFare pivoted to the ground at ‘K’and ‘F’respectively. The crankof a four-bar chain is connected to the handle via the main spring GDwhich is aninterconnected tension spring.S1, S2, S3, and S4 are the fourstoppers, determining the desired end states for the handle and crank respectively.User input to the handle is

transferred to the crankthrough the main spring, then thecrank drivesthe moving link AB making contactwith the fixedcontact during a closingprocess of a MCCB.



1-Handle 2-Main spring 3-Crank 4-Coupler
5-Follower 6-Moving Contact 7-Fixed Contact

(a)Molded Case Circuit Breakermodel (b)Simplified mechanism

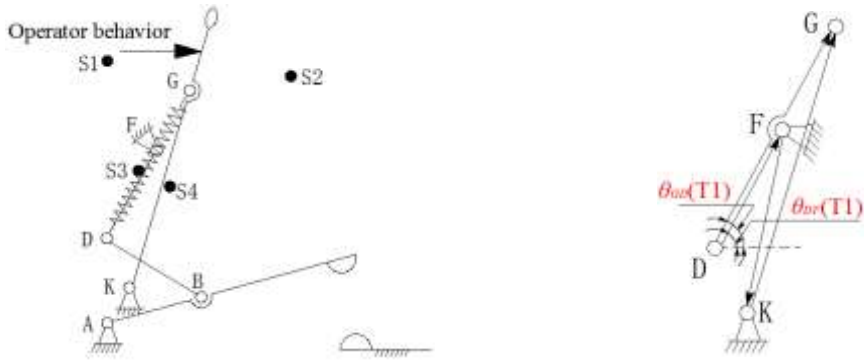
Fig. 1. A Molded Case Circuit Breakermechanism

2.2 Motion Phases Based on the Singular Configuration

2.2.1 The first and the second singular configuration

The most of mechanisms may perform special configuration in the motion process.At configuration, the system cannot continue to movein dead center, or loses stability, even changes its degrees of freedom.The configurationis then at a branch point and is referred to as a singular configuration[7].

The transientphenomenon of closing process happens through the sequential activation of the two links,the handle and crank. The bifurcation configuration for the crank is the collinearity of the points G, F and D (Fig.2a),which is called the first singular configuration, noted as$T1$. The vector-loop diagram of spring four-bar chainconsisting of the handle, crank and the main spring is shown in Fig.2b.



(a) Schematic diagram of mechanism at T1 (b) Vector-loop diagram at T1

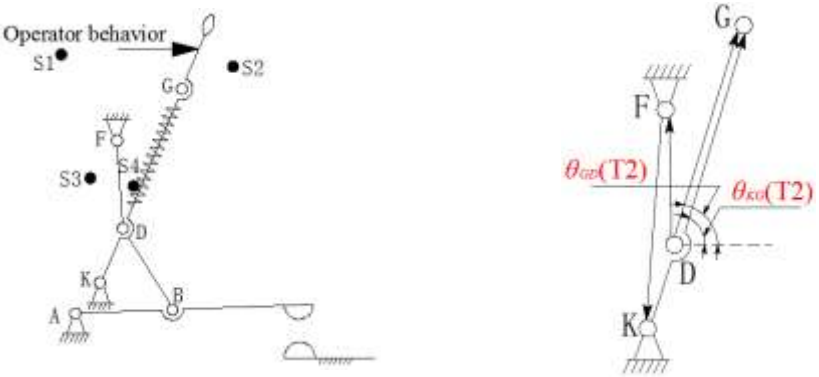
Fig. 2. The first singular configuration of operating mechanism

From Fig.2 b, thefollowing geometric equationof the first singular configurationcan be derived:

$$\theta_{DF}(T1) = \theta_{GD}(T1) \quad (1)$$

Where$\theta_{DF}(T1)$ and$\theta_{GD}(T1)$are the angular displacementsof the main spring GD and crank DFat the first singular configurationrespectively.

Similarly the collinearity of the points G, D and K defines the bifurcation configuration for thehandle (Fig.3a). This is the second singular configuration, noted as$T2$. The vector-loop diagram of spring four-bar chain is shown in Fig.3b.



(a) Schematic diagram of mechanism at T2 (b) Vector-loop diagram at T2

Fig. 3. The second singular configuration of operating mechanism

From Fig. 3b, thefollowing geometric equation of the second singular configurationcan be derived:

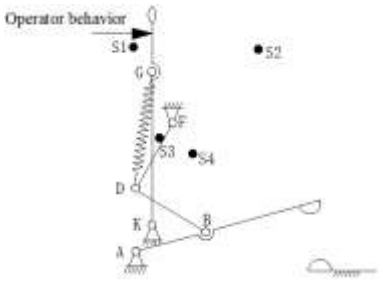
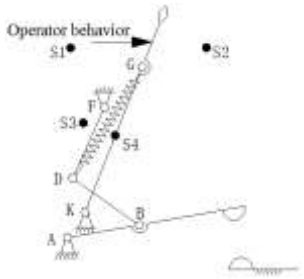
$$\theta_{KG}(T2) = \theta_{GD}(T2) \quad (2)$$

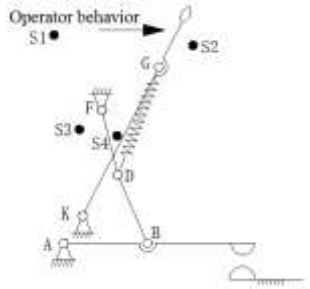
Where$\theta_{KG}(T2)$ and $\theta_{GD}(T2)$ are the angular displacements of the handle KG and main spring GDat the second singular configuration respectively.

2.2.2 Motion Phases

A MCCB mechanism has the capability to change configuration from one kind to another with a resultant change in thedirections of moment due to driving forcesand the number of effective links when it pass through two singular configurations during the closing process. So it can take the first and second singular configuration as the boundary conditions to divide the closing motion into three phases. Table1 shows different phases and effective links of motion of a MCCB mechanism.

Table 1Different phases and effective links of motion of a MCCB mechanism

Phases	Schematic diagram	effective links
Ahead of the first singular configuration		Handle KG Main spring GD （Due to the stoppers, other links stay static）
Between the first and second singular configuration		Handle KG Main spring GD Crank DF Coupler BD Follower AB

Behind of the second singular configuration		Handle KG Main spring GD Crank DF Coupler BD Follower AB

III. CHARACTERISTICS OF THE SINGULAR CONFIGURATIONS

3.1 The first singular configuration

In the case of a tension main spring, the stored potential energy is a monotonic function of its length. Actually, the spring energy reaches the local maximum when G–F–D becomes collinear which is the first singular configuration. Therefore, the internal force exerted by the spring GD attains a maximum value; also there is a maximumangle between the spring force and the handle.It can be obtained that there is the requirement of the maximumdrivingtorqueat the first singular configuration, and if a MCCB operating mechanism can reach the position of the second singular configuration, the input force must be able to overcome the spring force to cause the operating mechanism pass through the first singular configuration.

Let us make a static analysis of the handle without concerning frictionat the first singularconfiguration. In the Fig. 4, the user-input force and the handle's gravityall create a clockwise torque in the handle, which overcoming an anti-clockwise torque in the handleproduced by the spring force make the handle rotate in the clockwise direction.

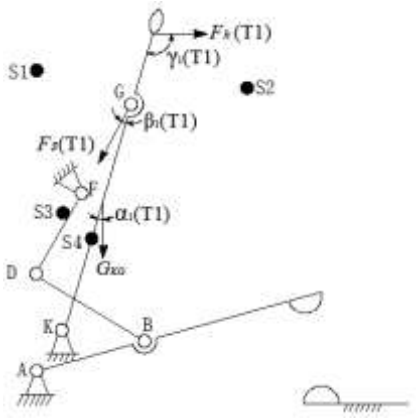


Fig. 4. Force analysis of the handle at T1

From the Fig. 4, the following statics equation (3) can be derived:

$$F_h(T1) \cdot L_{F_h} \cdot \sin\gamma_1(T1) + \frac{1}{2} \cdot G_{KG} \cdot L_{KG} \cdot \sin\alpha_1(T1) = F_S(T1) \cdot L_{KG} \cdot \sin\beta_1(T1) \quad (3)$$

where

$$\alpha_1(T1) = \frac{\pi}{2} - \theta_{KG}(T1),\ \ \beta_1(T1) = \theta_{KG}(T1) - \theta_{GD}(T1),\ \ \gamma_1(T1) = \pi - \theta_{KG}(T1)$$

Equation (3) can be recast to obtain the input force in the handle, $F_h(T1)$, which can make operating mechanism pass through the first singular configuration, i.e. connection between the first and second singular configuration.

$$F_h(T1) > \frac{F_S(T1) \cdot L_{KG} \cdot sin\,\beta_1(T1) - \frac{1}{2} \cdot G_{KG} \cdot L_{KG} \cdot sin\,\alpha_1(T1)}{L_{F_h} \cdot sin\,\gamma_1(T1)} \tag{4}$$

where L_{KG} is the length of handle, L_{F_h} is the arm of user-input force.

3.2 The second singular configuration

In dynamics, the Lagrange equation is commonlyused to derive the equations of motion of a MCCB operating mechanism:

$$\frac{d}{dt}\left(\frac{\partial E_k}{\partial \dot{q}_i}\right) - \frac{\partial E_k}{\partial q_i} + \frac{\partial E_p}{\partial q_i} = Q_i \tag{5}$$

where q_i is generalized coordinates and Q_i is generalizedforces,$E_k$and E_p are total kinetic energy andthe total potential energy respectively. Fig. 5 shows the schematic diagram of the operating mechanism under dynamic analysis.

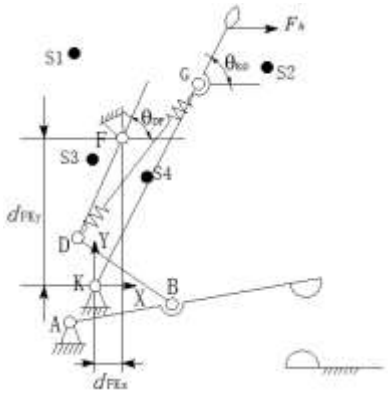


Fig. 5. Schematic diagram of dynamic analysis during closing process

Therefore,to use the Lagrange equation for deriving the motion equationsof a MCCB operating mechanism, its total kinetic and potential energies must first be formulated. The procedure for the energyderivation is shown as follows [8].

The vector-loop equations can be expresses:

$$r_1 + r_2 + r_3 + \cdots + r_j = 0 \tag{6}$$

By expressing equation (6) into X and Y scalarcomponent equations and rearranging, the resultanttwo equations are:

$$r_1 \cos\theta_1 + r_2 \cos\theta_2 + r_3 \cos\theta_3 + \cdots + r_j \cos\theta_j = 0 \tag{7}$$

$$r_1 \sin\theta_1 + r_2 \sin\theta_2 + r_3 \sin\theta_3 \cdots + r_j \sin\theta_j = 0 \tag{8}$$

During the closing operation, the handle angular displacementθ_{KG} is definedas the generalized coordinateq_1 and the crank angular displacementθ_{DF}as the generalized coordinate q_2. Taking the crank as the equivalent rod, the equivalent mass and equivalent moment of inertia of the rigid four-bar chain ABDF ism_e and $J_e$respectively [9].Hence, the totalkinetic energy, E_k, in the system is obtained as

$$E_k = \frac{1}{2} \cdot m_{KG} \cdot v_{KG}^2 + \frac{1}{2} J_{KG} \cdot \dot{\theta}_{KG}^2 + \frac{1}{2} \cdot m_e \cdot v_{DF}^2 + \frac{1}{2} \cdot J_e \cdot \dot{\theta}_{DF}^2 \tag{9}$$

Assuming that the potential energy is zero at the originof the coordinate system, the total potential energy,E_p, in the operating mechanism can be expressed as

$$E_p = \cdot m_{KG} \cdot g \cdot \frac{L_{KG}}{2} \cdot sin\theta_{KG} + m_e \cdot g \cdot \left(d_{FKy} - \frac{L_{DF}}{2} \cdot sin\theta_{DF}\right) + \frac{1}{2} \cdot k \cdot \Delta L_S^2 \quad (10)$$

Here, the relationship among the spring length L_S, the handle angular displacementθ_{KG} and the crank angular displacement θ_{DF} is as follows

$$\Delta L_S + L_{S0} = \sqrt{(d_{FKx} - L_{DF} \cdot cos\theta_{DF} - L_{KG} \cdot cos\theta_{KG})^2 + (d_{FKy} - L_{DF} \cdot sin\theta_{DF} - L_{KG} \cdot sin\theta_{KG})^2} \quad (11)$$

where J_{KG} is the moment of inertia of the handle KG, L_{S0} and $\Delta L_S$are the original length andincreaselength of the spring respectively,k is the stiffness of the spring,$d_{FKx}$and $d_{FKy}$are the horizontaland verticaldistance between the fixed point F and K respectively.

When the total kinetic and potential energies aresubstituted into the Lagrange equation, the dynamic equations can be expressed as follows

$$\begin{cases} \frac{d}{dt}\left(\frac{\partial E_k}{\partial \dot{\theta}_{KG}}\right) - \frac{\partial E_k}{\partial \theta_{KG}} + \frac{\partial E_p}{\partial \theta_{KG}} = M(F) & (12) \\ \frac{d}{dt}\left(\frac{\partial E_k}{\partial \dot{\theta}_{DF}}\right) - \frac{\partial E_k}{\partial \theta_{DF}} + \frac{\partial E_p}{\partial \theta_{DF}} = 0 & (13) \end{cases}$$

Where

$$\frac{d}{dt}\left(\frac{\partial E_k}{\partial \dot{\theta}_{KG}}\right) = \frac{1}{4} \cdot (m_{KG} \cdot L_{KG}^2 + J_{KG}) \cdot \ddot{\theta}_{KG} + \left(\frac{1}{4} \cdot m_e \cdot L_{DF}^2 + J_e\right) \cdot \frac{\partial \dot{\theta}_{DF}}{\partial \dot{\theta}_{KG}} \cdot \ddot{\theta}_{DF}$$
$$+ \left[\frac{\partial \dot{\theta}_{DF}}{\partial \dot{\theta}_{KG}} \cdot \left(\frac{1}{4} \cdot \frac{dm_e}{dt} \cdot L_{DF}^2 + \frac{dJ_e}{dt}\right) + \left(\frac{1}{4} \cdot m_e \cdot L_{DF}^2 + J_e\right) \cdot \frac{d}{dt}\left(\frac{\partial \dot{\theta}_{DF}}{\partial \dot{\theta}_{KG}}\right)\right] \cdot \dot{\theta}_{DF}$$
$$+ \frac{1}{2} \cdot \left[\frac{1}{4} \cdot \frac{d}{dt}\left(\frac{\partial m_e}{\partial \dot{\theta}_{KG}}\right) \cdot L_{DF}^2 + \frac{d}{dt}\left(\frac{\partial J_e}{\partial \dot{\theta}_{KG}}\right)\right] \dot{\theta}_{DF}^2 + (\frac{1}{4} \cdot \frac{\partial m_e}{\partial \dot{\theta}_{KG}} \cdot L_{DF}^2 + \frac{\partial J_e}{\partial \dot{\theta}_{KG}}) \cdot \dot{\theta}_{DF} \cdot \ddot{\theta}_{DF}$$

$$\frac{\partial E_k}{\partial \theta_{KG}} = \left(\frac{1}{4} \cdot m_e \cdot L_{DF}^2 + J_e\right) \cdot \frac{\partial \dot{\theta}_{DF}}{\partial \theta_{KG}} \cdot \dot{\theta}_{DF} + \frac{1}{2} \cdot \left[\frac{1}{4} \cdot \left(\frac{\partial m_e}{\partial \theta_{KG}}\right) \cdot L_{DF}^2 + \left(\frac{\partial J_e}{\partial \theta_{KG}}\right)\right] \dot{\theta}_{DF}^2$$

$$\frac{\partial E_p}{\partial \theta_{KG}} = \frac{1}{2} \cdot m_{KG} \cdot g \cdot L_{KG} \cdot cos\,\theta_{KG} - \frac{1}{2} \cdot m_e \cdot g \cdot L_{DF} \cdot cos\,\theta_{DF} \cdot \frac{\partial \theta_{DF}}{\partial \theta_{KG}}$$
$$+ \frac{\partial m_e}{\partial \theta_{KG}} \cdot g \cdot \left(d_{FKy} - \frac{1}{2} \cdot L_{DF} \cdot sin\theta_{DF}\right) + k \cdot \Delta L_S \cdot \frac{\partial \Delta L_S}{\partial \theta_{KG}}$$

$$\frac{d}{dt}\left(\frac{\partial E_k}{\partial \dot{\theta}_{DF}}\right) = \left(\frac{1}{4} \cdot m_{KG} \cdot L_{KG}^2 + J_{KG}\right) \cdot \left[\frac{\partial \dot{\theta}_{KG}}{\partial \dot{\theta}_{DF}} \cdot \ddot{\theta}_{KG} + \frac{d}{dt}\left(\frac{\partial \dot{\theta}_{KG}}{\partial \dot{\theta}_{DF}}\right) \cdot \dot{\theta}_{KG}\right] + \left(\frac{1}{4} \cdot m_e \cdot L_{DF}^2 + J_e\right)$$
$$\cdot \ddot{\theta}_{DF}$$
$$+ \left(\frac{1}{4} \cdot \frac{dm_e}{dt} \cdot L_{DF}^2 + \frac{dJ_e}{dt}\right) \cdot \dot{\theta}_{DF} + \left(\frac{1}{4} \cdot \frac{\partial m_e}{\partial \dot{\theta}_{DF}} \cdot L_{DF}^2 + \frac{\partial J_e}{\partial \dot{\theta}_{DF}}\right) \cdot \dot{\theta}_{DF} \cdot \ddot{\theta}_{DF}$$
$$+ \frac{1}{2} \cdot \left[\frac{1}{4} \cdot \frac{d}{dt}\left(\frac{\partial m_e}{\partial \dot{\theta}_{DF}}\right) \cdot L_{DF}^2 + \frac{d}{dt}\left(\frac{\partial J_e}{\partial \dot{\theta}_{DF}}\right)\right] \dot{\theta}_{DF}^2$$

$$\frac{\partial E_k}{\partial \theta_{DF}} = \left(\frac{1}{4} \cdot m_{KG} \cdot L_{KG}^2 + J_{KG}\right) \cdot \frac{\partial \dot{\theta}_{KG}}{\partial \theta_{DF}} \cdot \dot{\theta}_{KG} + \frac{1}{2} \cdot \left[\frac{1}{4} \cdot \left(\frac{\partial m_e}{\partial \theta_{DF}}\right) \cdot L_{DF}^2 + \left(\frac{\partial J_e}{\partial \theta_{DF}}\right)\right] \dot{\theta}_{DF}^2$$

$$\frac{\partial E_p}{\partial \theta_{DF}} = \frac{1}{2} \cdot m_{KG} \cdot g \cdot L_{KG} \cdot cos\,\theta_{KG} \cdot \frac{\partial \theta_{KG}}{\partial \theta_{DF}} + \frac{\partial m_e}{\partial \theta_{DF}} \cdot g \cdot \left(d_{FKy} - \frac{1}{2} \cdot L_{DF} \cdot sin\theta_{DF}\right)$$
$$- \frac{1}{2} \cdot m_e \cdot g \cdot L_{DF} \cdot cos\,\theta_{DF} + k \cdot \Delta L_S \cdot \frac{\partial \Delta L_S}{\partial \theta_{DF}}$$

where $M(F_h)$ is the torque of input force on the handle.

Based on the dynamic model of the operating mechanism,the simplifiedsimulation modelof the MCCB′s

operating mechanism is established in ADAMS software.

IV. SIMULATION IN ADAMS

In the case of a simulation, the manual operation is represented by a pushing rod on the handle to drive the operating mechanism. Through changing the velocities of the pushing rod, hence the position of the second singular configuration under the different operator behavior velocities can be obtained. A simplified simulation model in ADAMS is shown in Fig. 6:

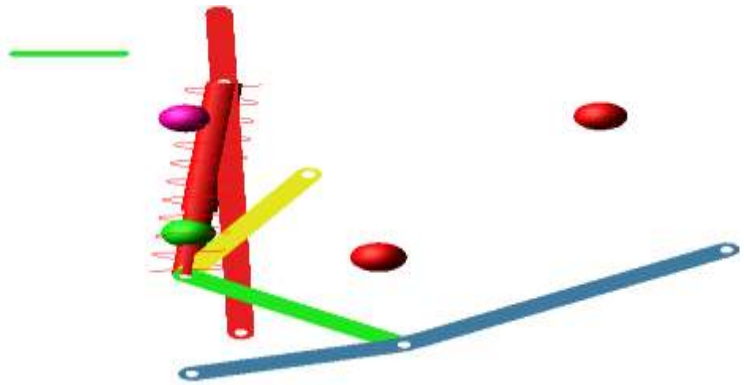


Fig. 6. Simulation of MCCB operating mechanism

Through simulation in ADAMS, the result of the angulardisplacement $\theta_{KG}$with respect to the angular velocity$\dot{\theta}_{KG}$ is shown in Fig. 7:

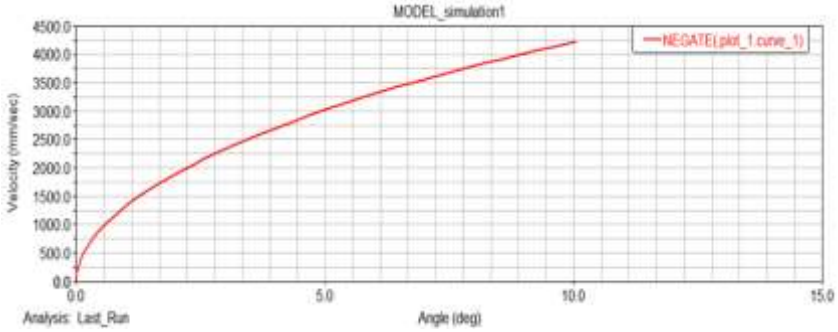


Fig. 7 The result curve of$\theta_{KG}$with respect to $\dot{\theta}_{KG}$

CONCLUSION AND DISCUSSION

The contributions of the study aiming at the design and optimization of MCCB operating mechanisms are summarized as follows:

1) Based on the singular configurations, the closing process is divided into three motion phases to study the different structure in different phase;

2) Based on Lagrange dynamics equations, dynamic model and static dynamics mode are built to studyconnection between the first and second singular configuration, and the necessary condition of passing through the second singular configuration is proposed by static analysis.

3)The analysis and simulation providetheoretical basis for the analysis of the MCCB performance.

ACKNOWLEDGMENT

The authors would like to acknowledge the financial support of the Shanghai Committee of Science and Technology Key Support Project under Grant 12510501100 andschool-enterprise cooperation project E4-6000-15-0225- (15)JX-015.

REFERENCES

[1]. He Ruihua．The State of Low-voltage Circuit Breaker in China and Its Development Trend [J]．Electrical Engineering，2009，(6)：9-13．

[2]. Chen Degui．Smart Grid and Recent Development of Intelligent Low Voltage Electrical Apparatus [J]．Low Voltage Apparatus，2010，(5)：1-6, 48．

[3]. Zhang Jingshu，Chen Degui，Liu Hongwu．DYNAMIC SIMULATION AND OPTIMUM DESIGN OF LOW-VOLTAGE CIRICUIT BREAKER [J]．Proceedings of the CSEE，2004，24(33)：102-107．

[4]. Chen Degui，Liu Qingjiang，Kang yan．Effect of Different Factors to the Operating Velocity of Molded Case Circuit Breakers [J]．Low Voltage Apparatus，2005，(12)：9-12．

[5]. Zhou Hongming，Shen yan，Huang shenquan，et al．Dynamic model of molded case circuit breaker operating mechanism and its performance analysis [J]．Computer Integrated Manufacturing Systems，2015，21(5)：1350-1358．

[6]. Huang shenquan，Zhou Hongming，Zhou Yuqing，et al．Evaluation of low-voltage circuit breaker virtual prototype operating characteristic based on extension analysis [J]．Computer Integrated Manufacturing Systems，2015，21(1)：217-225．

[7]. Huang zhen，Zhao Yongsheng，Zhao Tieshi．Aduanced Spatial Mechanism (Second Edition) [M]．Beijng：Higher Education Press，2014：255-284．

[8]. F-C Chen，Y-F Tzeng．On the dynamics of a spring-type operating mechanism for a gas-insulated circuit breaker in open operation using the Lagrange equation [J]．Proceedings of the Institution of Mechanical Engineers，2002，216(C8)：831-843．

[9]. Ye Xinquan，Zhao Rongxiang，Wu Maogang．Study on breaking action characteristics of moulded case circuit-breaker contact [J]．Journal of Zhejiang University(Engineering Science)，2006，40(3)：448-453．