Optimization of High Voltage Circuit Breaker Mechanism Design using Six Sigma Methodologies

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Abstract

The functions of circuit breaker spring operating mechanism are identified as closing spring charging, closing operation and opening operation. Suitable mechanisms for these identified functions are discussed based on gear, linkage, cam, and intermittent motion elements. This paper presents the structural synthesis of opening mechanism considering the higher pair joints which results in several combinations of mechanisms. The focus of this work is on the design of opening mechanisms that open with high velocity using minimum opening spring energy.

Two six-bar linkages are selected for detailed evaluation, one based on Watt's mechanism and the other on toggle linkage. The toggle linkage is considered with link lengths, mass and inertia same as that of the Watt's mechanism. This enhanced the opening speed by 30% for the same amount of input i.e. opening spring energy.

Effect of different parameters, such as spring stiffness, compression, stroke, rotation of the lever, the initial angle of the lever, on opening speed is studied. The range of each parameter for optimization process is finalized. Plackett-Burman design in the design of experiments (DOE) is used to eliminate the non-significant factors. Then a full factorial DOE is conducted on the vital factors to maximize the opening speed. 20% enhancement is achieved in the opening speed after optimization for the same opening spring energy. The optimized toggle mechanism exhibits 50% higher the opening speed than the Watt's mechanism for the same opening spring energy.

Keywords: Circuit breaker mechanism, Structural synthesis, Watt's mechanism, and DOE (design of experiments), Plackett-Burman design, full factorial DOE, Optimization

1 Introduction

Circuit breakers are crucial devices in an electrical substation. They are essentially switches that break (i.e., open) an electrical circuit manually or automatically to protect against faulty conditions. A circuit breaker should also be able to connect the circuit back (i.e., close) after normal conditions are restored. This is achieved in circuit breaker mechanisms with the help of potential energy stored in opening and closing springs. This warrants quick closing and opening of the circuit breaker contacts. The operation of a circuit breaker mechanism is divided into three stages: charging the closing spring, closing the contact, and opening the contact. The focus of this paper is on the study of dynamic characteristics of opening mechanism. The status of springs, links, and latches in closing and opening operations is illustrated in Table 1. Changing the status of six different parts shown in the table is achieved with mechanism topologies that connect them.

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The energy required for closing and opening operation increases with increase in voltage rating for the circuit breaker. Hence, the alternate mechanisms which require minimum energy for operating circuit breaker are desired. Structural synthesis [1] and creative mechanism design [2] are some of the approaches that are used by previous researchers. However, only lower pair joints were considered resulted in a limited number of alternative solutions.

Table 1: Status of links and springs in a circuit breaker

Operation	*Closing Link*	*Opening Link*	*Closing Spring*	*Opening Spring*	*Closing Latch*	*Opening Latch*
Closing contacts	Input	Motion	Dis-charged	Charged	Un-latched	Latched
Opening contacts	Fixed	Input	Fixed	Dis-charged	Fixed	Un-latched

This paper focuses on the structural synthesis of opening mechanisms considering lower and higher pair joints which result in several basic kinematic chains. Those further used for designing alternate mechanisms. The design of experiments (DOE) [6] approach is used for optimization of selected mechanism.

2 Identification of Mechanisms for the Functions

We first note that there should be at least three degrees of freedom in a circuit breaker mechanism because it uses three actuations, viz. the motor that charges the closing spring, and two solenoid coils that trigger closing and opening operations. In view of ease of construction, planar mechanisms are preferred. Both lower and higher pairs are acceptable. There should be at least three prismatic joints to accommodate helical springs for closing and opening the electrical contacts. The rest can be revolute joints and cam or other higher pairs.

The kinematic chain of the entire circuit breaker mechanism should be such that it has three distinct loops to perform three different tasks, viz. charging the closing spring, closing the contacts, and opening the contacts. The opening loop should be separated from the closing loop in such a way that after the closing operation they get separated upon charging of the opening spring. The closing loop should be unaffected during the opening operation. This means that the kinematic structure needs to change during operation. For simplicity, we divide the segments of the mechanism by their function and consider each separately.

3 Type Synthesis of Opening Mechanisms

Let us now consider how many bodies are needed for the opening mechanism. This should have two prismatic joints for accommodating the contact and opening spring. Thus, there should be at least two lower pairs in the kinematic chain. The kinematic chain should have one degree of freedom. As per Grübler’s formula [3],

$$\text{Degree of freedom} = f = 3(n-1) - 2j_1 - j_2 \tag{1}$$

Where, f is the number of degrees of freedom, n the total number of bodies including the grounded body, j_1 the number of joints that allow one relative freedom, and j_2 the number of joints that allow two relative degrees of freedom.

Our requirement is that $j_1 \geq 2$ as two sliding joints are essential. The kinematic chain may consist of bodies each of which is connected to two, three, four, five etc. other bodies. They are called binary, ternary, quaternary, pentagonal etc. Let this connectivity be denoted by C where C = 2, 3, 4, 5, etc. Let there be n_2 binary, n_3 ternary, n_4 quaternary, etc., bodies. Then we can write,

$$n_2 + n_3 + n_4 + n_5 + ... = n \tag{2}$$

and,
$$2n_2 + 3n_3 + 4n_4 + 5n_5 + ... = 2(j_1 + j_2) \tag{3}$$

Since, f =1, Grübler's formula gives

$$1 = 3(n-1) - 2j_1 - j_2 \tag{4}$$

Equations (2) - (4) have many integer solutions. Each solution corresponds to a kinematic chain with one degree of freedom and consisting of at least two lower pairs, as required here to accommodate two sliding joints. Basic kinematic chains possible for the requirements set forth corresponding to the number of integer solutions of Eqs. (2) – (4) as noted in table 2(a) for a different number of links. Six-link basic kinematic chain with only lower pairs is selected is noted in table 2(b), which corresponds to Watt's linkage and Stephenson's linkage [3]. Six-bar opening mechanisms based on Watt's and toggle mechanisms are as depicted in Fig. 1. Slider 6 and slider 4 are opening spring shoe and moving contact respectively. Ternary link 2 in Watt's mechanism becomes a binary link in the toggle mechanism. Displacement of slider 6 by spring force enables a toggle at one point when links 2 and 5 becomes collinear. Toggle formed while opening operation results in the high mechanical advantage. The velocity of slider 6, i.e. the moving contact, can be increased to a large extent.

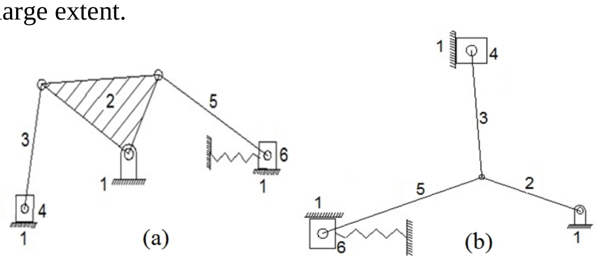

Figure 1: Opening mechanism (a) six-bar Watt's mechanism, (b) six-bar toggle mechanism

4 Study of six-bar opening mechanisms

Parameter-wise comparison between Watt's mechanism and toggle mechanism is as depicted in Table 3. The link lengths, masses are kept same for both six-bar Watt's mechanism and six-bar toggle mechanism. The initial angle between link 2 and link

5 is kept as 90^0 to obtain maximum mechanical advantage from slider crank mechanism formed by links 2, 5 and 6 (Fig. 1) for toggle mechanism. The dynamic analysis performed in SOLIDWORKS-premium on six-bar Watt's mechanism and six-bar toggle mechanism. The opposing forces such as friction force, pressure force are considered as in [4], [5]. The resulting opening speeds are 6.16 m/s and 8.1 m/s considering input parameters in table 3. The significant, 30% improvement in opening speed is observed in toggle mechanism is the result of high mechanical advantage. Since the toggle mechanism performs better than the Watt's mechanism for given parameters, the former is chosen for the parametric study and improvement using the design of experiments.

Table 2(a): Single degree of freedom basic kinematic chains for opening mechanism

Number of links n	3	4	5	6	7	8
Number of solutions	1	3	14	22	37	52

Table 2(b): Selected basic kinematic chain

Degree of freedom	*Number of links*	*Binary links*	*Ternary links*	*Quaternary links*	*Pentagonal links*	j_1	j_2
	n	n_2	n_3	n_4	n_5		
1	6	4	2	0	0	7	0

4.1 Effect of different parameters on the opening speed with six-bar toggle mechanism

Apart from link masses and inertias, the parameters affecting the opening speed are spring stroke, stiffness, compression, initial angle of link 2, angle between link 2 and 5. Dynamic analysis is carried out by varying these factors individually in SOLIDWORKS-premium to study their impact on opening speed.

Opening spring stroke is increased from 50 mm to 150 mm, keeping initial load constant as 15678 N to ensure, the same maximum reaction force seen by each variant mechanism. Opening speed increases with increase in spring stroke as effective mass decreases [5]. Opening speed decreases (Fig. 2) after 110 mm stroke as the final spring load becomes negative. Opening speed increases with increase in spring stiffness (Fig. 2).

Stored energy in opening spring is kept constant as 0.86 kJ. Increase in the rotation angle of link 2 will decrease the length of link 2, increase variation in transmission angle; hence the opening speed decreases (Fig. 3) till 70^0. After that, a further increase in rotation angle, the decreased length of link 2 will decrease the effective mass which overcomes the effect of an increase in variation in transmission angle.

Stored energy, initial load and final load for opening spring are kept const. The early occurrence of toggle between link 2 and 5, results in speed enhancement. The increase in initial angle pushes occurrence of this point from 25.57° for 0° initial angle to 37.87° for 45° initial angle. Hence, the opening speed decreases with increase in initial angle (Fig. 3).

Increase in the initial angle between link 2 and 5 shifts the position of the toggle which results in the decrease in the opening speed (Fig. 4). Shifting of a position of the toggle is not significant till the initial angle becomes 70°. Therefore, opening speed varies slightly in this zone. No toggle occurs for the initial angle of 120°.

Table 3: Input parameters and opening speed comparison for six bar Watt's mechanism and six bar toggle mechanism

link mass no	*unit*	*six bar watt's mechanism*	*six bar toggle mechanism*
m_6	kg	1.93	1.93
m_5	kg	1.76	1.76
m_2	kg	2	2
m_3	kg	4.45	4.45
m_4	kg	17	17
l_2	mm	183	183
l_3	mm	200	200
l_5	mm	148.9	148.9
Transmission angle at slider 4 - contacts closed	deg	86	86
Transmission angle at slider 4 - contacts opened	deg	86	86
Initial angle between link 2 and 5	deg	NA	90
Transmission angle at slider 6 - contacts closed	deg	86	NA
Transmission angle at slider 6 - contacts opened	deg	86	NA
l_{16}	mm	148.9	57.6
Rotation of link 2	deg	45	45
spring stiffness k	N/mm	134	134
initial compression	mm	134	134
spring stroke	mm	92	92
stored energy	kJ	1.08	1.08
Opening speed	m/s	6.16	8.1

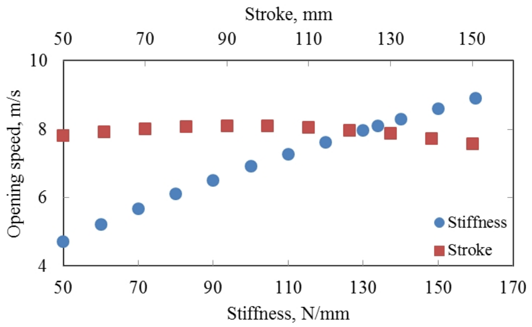

Figure 2: Effect of spring stroke and stiffness on opening speed

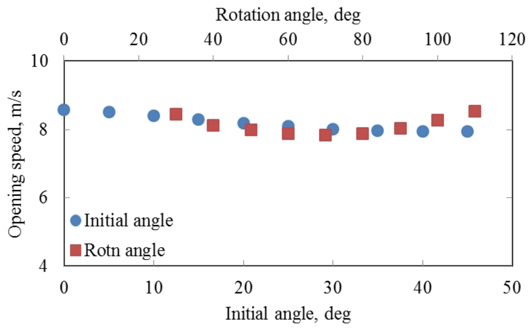

Figure 3: Effect of initial angle and rotation angle of link 2 on opening speed

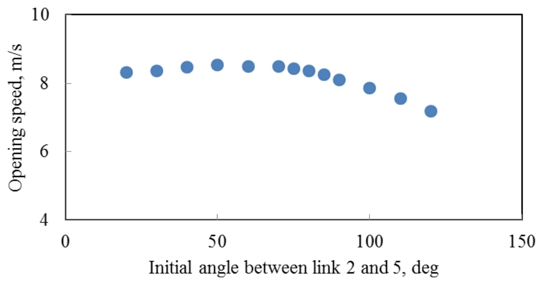

Figure 4: Effect of initial angle between link 2 and 5 on opening speed

4.2 Optimization of toggle mechanism

Largest speed observed is 8.91 m/s for stiffness 50 N/mm. The parameter interaction may result in a further enhancement in the opening speed. DOE can be used to study the effect of the different parameters simultaneously on the opening speed. DOE is a statistical tool to study the effect of different input parameters on the final outcome. The parameters under the study of opening speed and their corresponding levels are depicted in Table 4. In two-level DOE, the number of experiments for full factorial DOE is 2^k, where k is the number of factors. In our case, a number of factors are 5. Then the number of experiments required to be conducted for the full factorial method are $2^5 = 32$. We can filter out the least significant factors and then conduct a full factorial DOE on the important ones.

The Placket-Burman analysis is one of the DOE methods to analyse the factor effects on the final output [6]. Here, the number of experiments is limited to 12. Mainly, this method is used to identify the vital factors which influence the most on the output. The outcome of the Placket-Burman analysis is a Pareto chart (Fig. 5), which indicates the effect of factors on the opening speed. The factors whose bar is above the red line on Pareto chart are considered as significant. The spring stroke is the most significant factor and “Initial angle 25” is the least significant factor. Hence, the latter is dropped in further study. The initial angle bar just touches the red line in Fig. 5. Yet, it is considered for further analysis to evaluate the effect of simultaneously varying different factors that influence the opening speed. The remaining four factors: stroke, rotation angle, stiffness, and initial angle are depicted in Table 5 for full factorial DOE study. The combinations of factor values for full factorial DOE are given in Table 6.

Table 4: Selected range of parameters for optimization

		min	*max*	*centre*
stiffness	N/mm	120	160	140
stroke	mm	70	110	90
rotation angle	deg	30	50	40
initial angle of link 2	deg	0	30	15
initial angle between link 2 and 5	deg	70	90	80

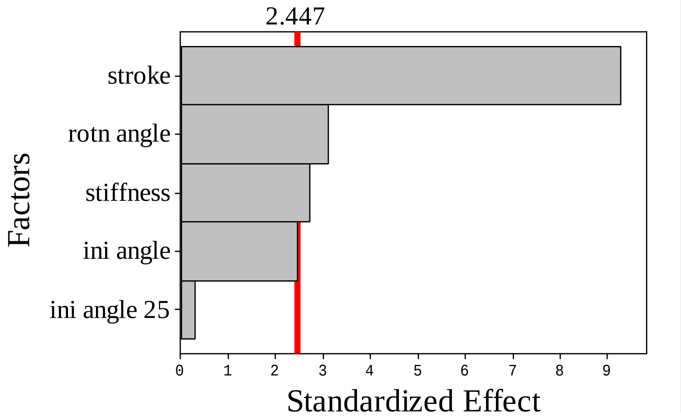

Figure 5: Pareto chart for opening speed

Table 5: Factors for Full factorial – Design of experiments

		min	*max*	*centre*
stiffness	N/mm	120	160	140
stroke	mm	70	110	90
rotation angle	deg	30	50	40
initial angle	deg	0	30	15

The maximum opening speed achieved is 9.63 m/s with 0.88 kJ stored energy in the opening spring for combination 8, which is 19% higher than the reference toggle mechanism. The effects of stiffness, stroke, rotation angle and initial angle on opening speed are depicted in Fig. 6(a). The opening speed slightly increases from 8.55 m/s to 8.63 m/s for the increase in stiffness from 120 N/mm to 140 N/mm, and then it decreases to 7.65 m/s for stiffness 160 N/mm. The stroke has the highest slope on main effect plot and rotation angle has the least. The opening speed is 9.02 m/s for 70 mm stroke which decreases to 8.63 m/s for 90 mm stroke and further decreases drastically to 7.185 m/s for 110 mm stroke. The opening speed is 8.65 m/s for 0^0 initial angle which reduces to 7.55 m/s for the increase in initial angle until 30^0.

Simultaneous effect of different factors on the opening speed is depicted in Fig. 6(b), interaction plots. The opening speed decreases with increase in stroke. The lower the stiffness the higher the speed. Stroke and stiffness have a very steep relationship with speed. Lower values of stroke, stiffness results in higher speed. 120 N/mm stiffness and 70 mm stroke results in higher opening speed as 9.44 m/s. 160 N/mm stiffness and 70 mm stroke give opening speed 8.605 m/s. The opening speed slightly decreases from 8.73 m/s to 8.36 m/s with the increase in rotation angle from 30^o to 50^o, for 120 N/mm stiffness, whereas, it decreases by 1 m/s for the same change in rotation angle with 160 N/mm stiffness. The opening speed decreases from 8.41 m/s to 6.9 m/s for 160 N/mm stiffness with increase in initial angle from 0º to 15º. It reduces with a lower slope with 120 N/mm stiffness for the same change in initial angle.

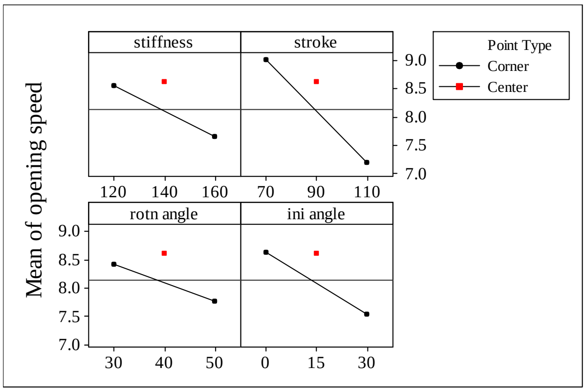

Figure 6(a): Main effect plot for opening speed

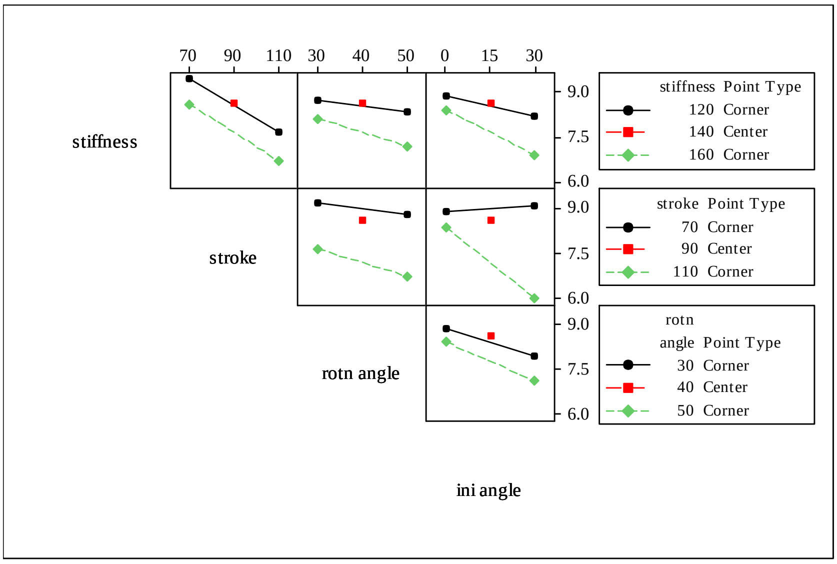

Figure 6(b): Interaction plot for the opening speed

Lower stiffness is the least significant for change in rotation angle. Lower stroke and lower rotation angle are desired for higher opening speed. 70 mm stroke and 30^0 rotation angle give 9.2 m/s speed. Opening speed decreases from 9.21m/s to 7.64m/s with the increase in stroke from 70 to 110 mm for 30º rotation angle. The opening speed increases from 8.92 m/s to 9.12 m/s for 70 mm stroke with the increase in initial angle from 0º to 30º. The opening speed drastically reduces from 8.38 to 5.98 m/s for 110 mm stroke with the increase in initial angle from 0º to 30º. Opening speed decreases with increase in rotation angle and initial angle. Vital interactions are 1) stiffness vs. stroke, 2) stroke vs. rotation angle, 3) stroke vs. initial angle. Maximum opening speed observed is 9.63 m/s for 0.88 kJ stored energy in opening spring which is 20 % higher than the reference toggle mechanism.

Table 6: Full factorial – Design of experiments for factors in Table 5

Sr no	*Stiffness*	*Stroke*	*Rotn angle*	*Ini angle*	*Opening speed*
	N/mm	*mm*	*deg*	*deg*	*m/s*
1	160	110	50	0	8.05
2	120	110	50	0	8.38
3	160	110	30	0	8.47
4	140	90	40	15	8.63
5	160	70	30	0	9.11
6	120	70	50	0	9.23
7	120	70	50	30	9.58
8	120	70	30	30	9.63
9	120	110	30	30	7.35
10	160	110	50	30	4.21
11	160	110	30	30	6.12
12	120	110	30	0	8.64
13	160	70	50	30	8.5
14	120	70	30	0	9.33
15	160	70	30	30	8.8
16	120	110	50	30	6.26
17	160	70	50	0	8.01

5 Conclusion

Structural synthesis of opening mechanism considering lower as well as higher pair joints is proposed. Several basic kinematic chains are derived and 129 are listed. Two mechanisms Six-bar Watt’s mechanism and toggle mechanism are selected for dynamic analysis. The link lengths, inertia, spring parameters are kept same for both mechanisms to compare the opening speed. The toggle linkage exhibited 30% improvement in opening speed as compared to that with Watt’s mechanism. The optimization through DOE resulted in further 20% enhancement (i.e. 50% improvement over six-bar Watt’s mechanism) in the opening speed. The optimal level of parameters are stiffness = 120 N/mm, stroke = 70 mm, rotation angle = 30^o and initial angle = 30^o.

6 References

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