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Design of a Force-Based System to Achieve Current Limiting in a Circuit Breaker

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Abstract

In case of a short circuit fault current where the magnitude of the current increases to a high value it is needed to open the breaker as fast as possible simultaneously maintaining the features that are exhibited under normal operating conditions of the breaker. In this paper, a circuit breaker analyzer was used to measure the time taken by the existing Air Circuit Breaker to switch from ON to OFF condition once the signal is given. Mathematical models were developed to represent the positions of the linkages of the contact system and the forces that were generated in the contact system of the breaker. The present work aims to retrofit the existing breaker and therefore the initial challenge is to find out the space for using the secondary trip unit. The simulation for the concept is carried out in motion analysis software to analyze the system behavior. A Transfer function is developed to find out the forces coming on the various links in the short circuit condition and at different link configurations. A biasing torsion spring for flexible link Arrangement was designed and the Torque required on the Layshaft to reset the Mechanism is also estimated using the spring design tool. After finalizing the dimension and configuration of the secondary trip mechanism, the Transfer function was developed to find out the force required at the contact to delatch the mechanism. Crystal ball analysis was carried out on this transfer function to generates the mean and standard deviation values for the output variable and also the top sensitive dimensions for the design.

Keywords: *Circuit breaker, Dynamic analysis, Structural analysis, Spring design, Crystal Ball sensitivity analysis.*

1. Introduction

In an electric circuit when a short circuit fault occurs the magnitude of the electric current increases rapidly and reaches levels that are hazardous to the safe operation of the circuit and the components in the same. The role of an air circuit breaker is to open the circuit in such cases and hence protect the electrical components in the system. Essentially the breaker relies on a feedback system that detects the currents in the system to the electronic trip unit that uses the same to compare with the preset values in the current vs. withstand time and then opens the circuit. This system is very effective in case of conditions of minor overload where the magnitude of the current is marginally larger than rated values of the current and also providing features of selective tripping of breakers in an electric network. In the case of a short circuit fault current where the magnitude of the current increases to a high value, the time the circuit is broken via the electronic trip unit a few cycles of the short circuit current would have passed through the breaker.

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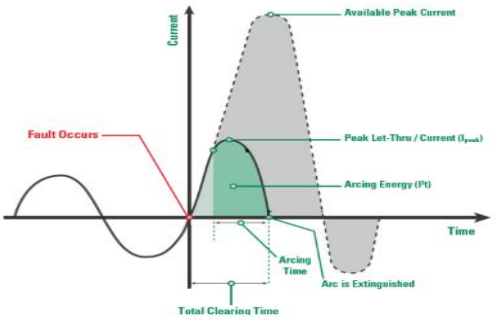

Figure 1: Normal Short Circuit and Current Limiting

This can prove to be hazardous to the systems that the breaker is intended to protect. The concept of breaking a circuit before the peak value of the current is reached during short circuit conditions is known as current limiting. It helps in better protection of the circuit from short circuits and other potential hazards that might be caused by the same. In the fig.1, the dotted line graph highlights the behavior of a conventional breaker that does not provide current limiting to the passing of a short circuit fault. In such cases, the circuit is broken in about one and a half cycles since the initiation of a fault current. The solid line graph represents a breaker that achieves current limiting by breaking the circuit before the first peak current is reached. The aim of the present work is to develop a breaker with an existing design as a footprint to achieve current limiting.

2. Measurement of Breaker Opening Times using a Circuit Breaker Analyzer

The circuit breaker analyzer is a device capable of conducting various tasks relating to controlling the functioning of the breaker and the measurement of various parameters simultaneously. The circuit breaker analyzer was used to measure the time taken by the existing Air circuit breaker to switch from ON to OFF. This measured time was used as a baseline for the development of the concepts for the fast opening of the breaker. The procedure for measurement of the opening times of the breaker main contacts is as listed below.

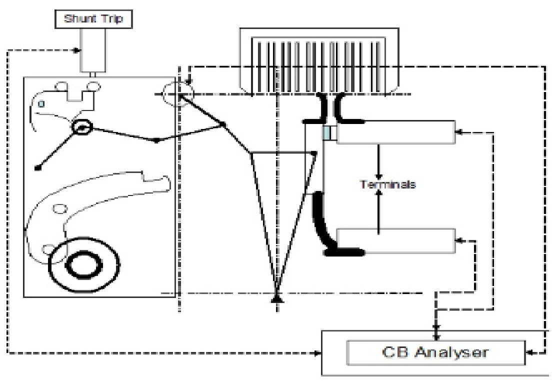

Figure 2: Schematic Representation of the CB Analyzer Test Setup

- Connecting the shunt trip that executes the switching OFF of the breaker to the breaker analyzer so that the tripping of the breaker can be controlled remotely.
- Connecting the current-carrying terminals of the breaker to the breaker analyzer. This was used to monitor the switching condition of the breaker and also the time instant at which it would switch off from the moment that the signal for the same was provided.
- Attaching a rotary transducer to the layshaft of the breaker. This is used to measure the rotation of the layshaft. Once the transducer is loaded the same had to be calibrated for the experiment.
- Another rotary transducer is mounted on the tripping shaft in the breaker mechanism. The above-listed connections are represented in the diagram below by dashed lines.
- Once the connections were made and the experimental setup was ready for testing, the breaker was switched ON. The rotation of the layshaft and the other components were noted.
- The signal to trip the breaker was sent to the shunt trip that executed the tripping action of the breaker. This leads to switching the breaker from ON to OFF condition. The rotation of the layshaft links and the times for opening of the breaker were noted by the analyzer.
- The procedure for switching OFF of the breaker was carried out for a few more times.

Results and conclusions from the experiments

It was noted that the breaker under testing showed an opening time in excess of 30ms. This would mean that under normal conditions of the operation of the breaker if short circuits faults were to occur, the breaker would pass a few cycles of the peak value of short circuit current before the circuit was broken. This would be very harmful to equipment like motors and transformers. This hence highlights the need of having a faster opening of the breaker current carrying contacts in case of a short circuit fault.

3. Mathematical Modeling

The development of mathematical helps in the development of the concepts for the fast opening of the breaker in case of a short circuit fault. Position Analysis of the contact system. Fig.3 shows the representation of the main links of the contact system.

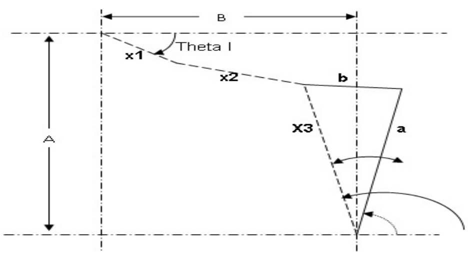

Figure 3: Representation of the contact system as a 4-bar linkage

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The X1 represents the layshaft of the breaker that is controlled by the operating mechanism of the breaker. The angle of the link X1 with respect to the horizontal is represented by theta1. The movement of the link X1 controls the position of the contact system a-X3-b Based on the input angle theta I the position of the contact system is achieved. The output angle of the contact system Theta O is found out by means of the relation

Theta O = Theta X3 + Theta X. (1)

Theta X3 is the resultant angle for the four-bar mechanism where Theta 1 is the input angle. The same is calculated from the relation:

$$ThetaX3 = A\tan 2\left[\frac{B}{A}\right] \pm A\tan 2\left[\frac{A^2 + B^2 - X^2}{X}\right]^{1/2}$$

(2)

Where,

$$A = \frac{[x_2^3 - A^2 - B^2 - x_3^2]}{2x_3},$$

$A = x_1 \cos\theta_1 + x_g \cos\theta_g$

$A = x_1 \sin\theta_1 + x_g \sin\theta_g$

Using these the various angles of Theta 3 were calculated for the corresponding values of Theta 1. The variation of the angles of input vs. output is as shown in the graph below. The validation of the values from the mathematical model was carried out using the sensitivity analysis tool in Pro-E and the values were found to match.

Force Analysis for the contact system:

Based on the various forces acting on the breaker during its operation, a mathematical model for the forces was developed. Force model of the contact system helps us in gaining the forces transmitted by it at various force current levels. The forces acting on the contact system are divided into two main categories. The same areas listed below:

The forces that do not vary with the magnitude of the current in the contact system:

- Contact opening spring forces
- Torsion spring forces

The forces that vary with the magnitude of the current in the contact system:

- Blow open forces at the current-carrying contacts in the contact system
- Loop forces due to the flexible current carrying element in the breaker

The physics-based formulae from which the blow open forces and the loop forces were calculated are discussed in the following section.

Blow open force at the contacts

The blow open force is generated due to the constriction created in the electrical joint between the current-carrying contacts of the breakers. This force exhibits a repulsive action trying constantly to push apart the current-carrying contacts. The electrical constriction/blow open force between two elements in contact with each other is given as:

$$F_H = \frac{\mu_0 \times I^2}{4\pi} \times \ln(\frac{R}{r}) \quad (3)$$

Where, $r = \sqrt{\frac{F_k}{\pi \times \xi \times H}}$

F_H = Blow Open Force,
μ_0 = Magnetic permeability in vacuum
I= Current through the contact system
R= Measured contact radius (mm
a= Average radius of constriction
F_k= Contact force
A= Apparent contact Area
H= Hardness of the contact tips in N/mm^2

Development of a mathematical model for forces on the pivot pin of fingers

Fig.4 shows the forces active in the contact system in closed condition

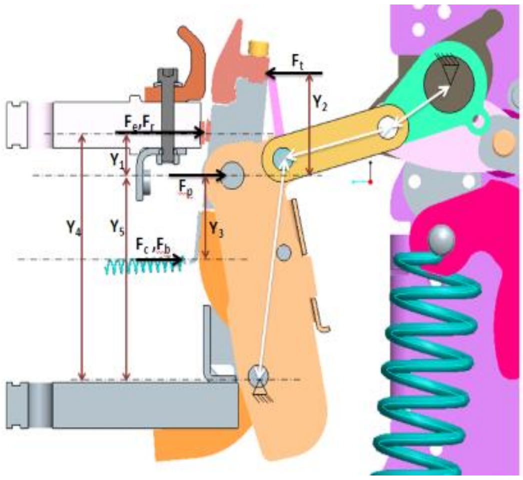

Figure 4: Forces acting on the contact system in ON position

Forces acting on the contact system are :
F_h= Blow open force at the contact.
F_t = Torsion Spring force acting on each finger.
F_c = Compression Spring force acting on each finger.
F_b = Magnetic loop forces.
F_r = Reaction force on the finger contact tip during equilibrium. Under equilibrium the torque acting about the finger pivot is

F_r X Y_1 – F_t X Y_2 – (F_c + F_b)X Y_3 (4)

Hence, F_r = F_t X Y_2 + (F_c + F_b)X Y_3 / Y_1. The total force acting at the contact tip is F_h + F_r. In the equilibrium condition in the closed position, this force will directly act on the contact carrier assembly. The Effective force F_p that is transferred from the finger assembly to the Contact carrier assembly is given by

$$F_p = (F_h + F_r) \times Y_4 / Y_5 \quad (5)$$

Using the equations given above the forces acting on the pole coupler of the system for different current levels are calculated. It was noted that the forces increased very rapidly after current levels exceeding 25kA to 50kA

4. Concept Development

Space Availability for secondary trip unit

The existing breaker as shown in fig.5 is a 6 finger, 3 poles Beaker. Each pole is confined in the housing with an arc chamber at the top. Housing consists of Arc Chute Assembly, front and rear housing.

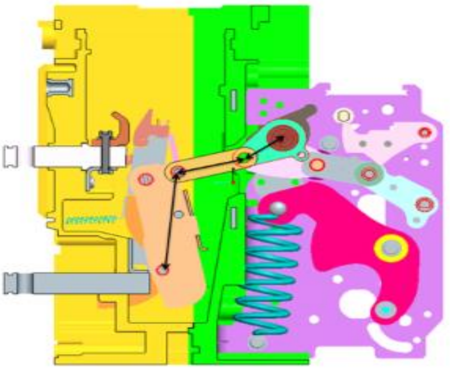

Figure 5: The existing Contact carrier assembly

The possible location of the Flexible Link Arrangement is Layshaft Link, Coupler and Contact Carrier Assembly. When heavy fault current flow huge blow open force is generated due to the reverse loop at the contact of the fingers and due to the constriction created in the electrical joints between the contacts. This blow open force has a repulsive action and it tries to push apart the contacts.

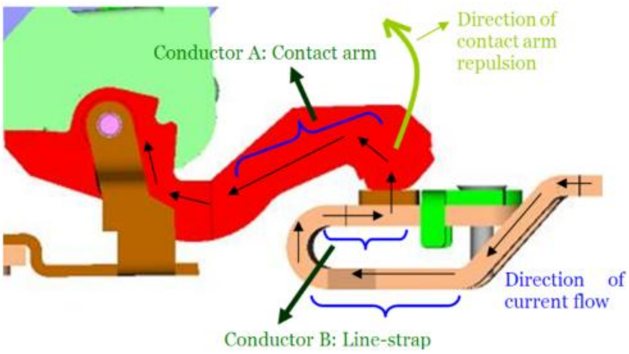

Figure 6: Reverse loop force at the contact

Hence it is required to develop a mechanism that will directly sense this blow open force and resist it till the current exceeds the threshold limiting value. Once the current exceeds the limiting value, blow open force will rapidly increase as force is directly proportional to the square of the current. The trip mechanism should then de-latch and open the contacts as fast as possible. This action of de-latching should take place before the fault current reach the peak value so that the current will be limited.

Use of Flexible Link Arrangement

The line diagram of the existing contact system of a breaker that is coupled to the Layshaft of a breaker mechanism is shown in the fig.7

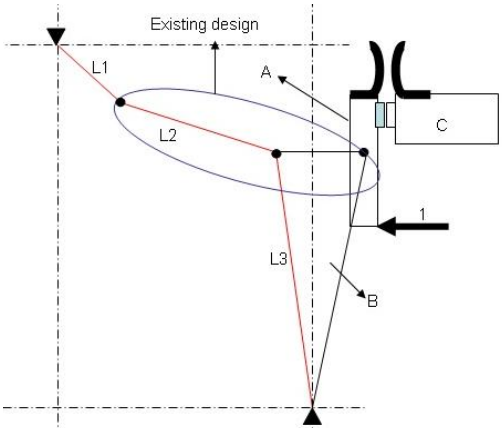

Figure 7: Existing Design as a 4-Bar Representation

In the case of a short circuit fault usually one of the phases of the three phases AC increases to very high magnitudes and that phase needs to be broken immediately. Each pole of the breaker is used for passing one phase of AC through the breaker. Fault can be in 3 phases or a single phase. In any case, the fault should be cleared. Hence in case of a fault in a pole of the breaker, that pole of the breaker will open and the electro-dynamic forces like the loop forces and the blow open forces will assist in a much faster opening of the current-carrying contacts. Once the contact system is collapsed by the trip unit, due to the short circuit the breaker switches to the OFF condition. During this operation of flexible Link arrangement, the main operating mechanism of the breaker is in ON condition as the trip unit didn't send the trip command. The reset of the mechanism takes place when the main mechanism of the breaker goes from the ON condition to OFF condition

5. Development, Analysis, and Validation of the Concept

The concept with line diagram for the secondary trip mechanism and geometry is created and the same were simulated and the results were analyzed. The designed mechanism is analyzed for its feasibility using motion analysis software.

Dynamic analysis through Motion Analysis software

The findings of this simulation were as follows:

a. The collapsing of the poles of the breaker could be achieved by means of a flexible link arrangement.
b. The concept helps in the quick opening of the contact system in case of a short circuit fault current.
c. The system helped in achieving the opening of the breaker pole within 10ms.
d. Further refinement of the system based on the findings of the motion analysis was carried out.
e. The system achieves independent pole collapsing in case of a short circuit fault and is an effective tool for achieving current limiting.
f. The quick opening will help in the reduction in the arc generation during the opening of the breaker.
g. It is possible to fit the system in the existing design without any major modifications to the same.

Design and Analysis of various links in the secondary trip unit

The transfer function was developed to find out the forces coming on the various links in the short circuit condition and at different link configurations. The various parameters influencing the transfer function are

1. Stiffness of the compression spring acting on the fingers.
2. Stiffness of the torsion spring mounted on the fingers.
3. Stiffness of the biasing spring acting on the Flexible Link.
4. The angle between the coupler and Flexible link.
5. Length of the flexible link.
6. The angle of the slot.
7. Coefficient of friction.

Forces coming on the flexible link arrangement are maximum when the breaker is in ON position. Using the transfer function and varying the different parameters, link positions were optimized depending on the space constraints and forces getting transferred along with the delatching pin. Once the position of the links was finalized, the maximum blow open force experienced by the various link at short circuit conditions was found out. Structural analysis of links was carried out using a Structural Analysis tool to finalize the dimensions of the link.

Structural Analysis of Delatching Pin

The forces coming on the delatching pin are biasing spring force and the Blow open force. The function of the delatching pin is that it should resist the blow open forces until the current level exceeds the threshold short circuit current level. Hence for static structural analysis of the pin the maximum force considered was at the point where the pin is just about to delatch. From the transfer function, this force comes out to be 1600N. Considering all the variations, the Crystal ball analysis gives the maximum force to be 2000N.

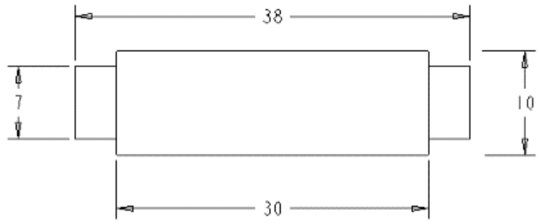

Figure 8: Delatching Pin dimensions

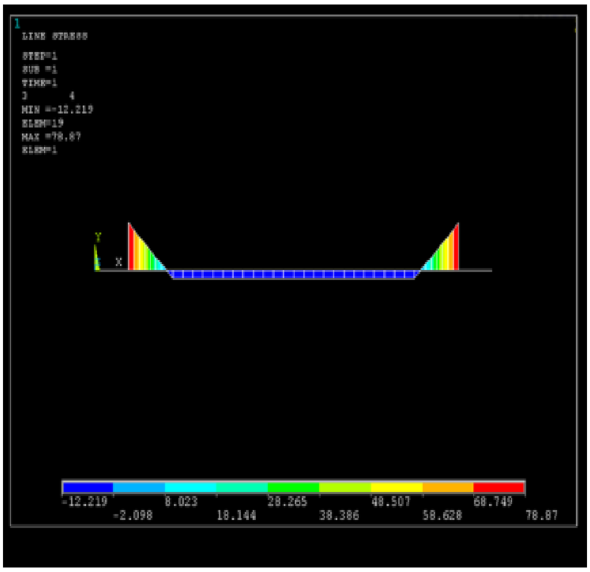

Figure 9: Maximum stress developed along the length of the Pin

The maximum stress coming on the delatching pin is 78.87 N/mm^2 . Since the yield strength for stainless steel AISI 205 is 250 N/mm^2, the pin is safe from crushing. A similar structural analysis was done to finalize the dimensions of the other links in the secondary trip mechanism.

Design of biasing torsion spring for flexible link Arrangement

The biasing spring should hold the flexible Link till the short circuit threshold current level is reached. The maximum force coming on the flexible link in this condition is found out from the transfer function. Before the delatching takes place, the maximum force that the spring should resist comes out to be 128N. Two torsion springs can be used in parallel to bias the flexible link arrangement. This will also help in applying equal forces on the flexible link at equidistance point from the center than applying a force of twice the magnitude at the center which may result in uneven movement of delatching pin in the slot. Hence the force required to be resisted by each biasing spring reduces to 64N.

When the contact opens in the short circuit condition, arching occurs. During arching ionization of the air takes

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places and heat is produced. This phenomenon increases the temperature around the contact assembly. Hence the spring material should be selected such that it will retain the stiffness at elevated temperature. Hence the material Stainless steel 17-7 PH which retains its properties at elevated temperature was chosen.

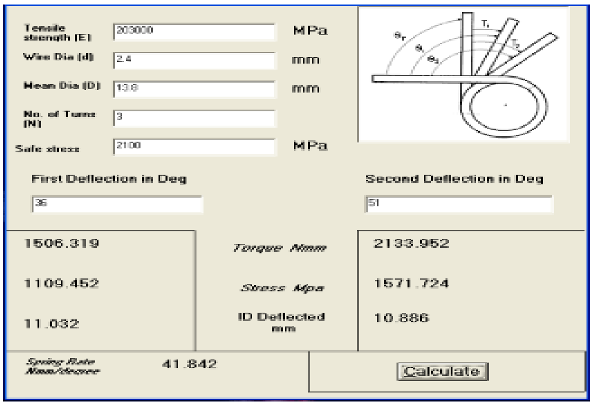

Figure 10: Spring design Tool

Torque produced in the initial assembles condition is found out to be1506 Nmm. And the force required to be applied by each spring on the delatching pin is 64N. The moment arm of the spring is 23.5 mm. Hence the spring is assembled such that the initial deflection of the legs is 36˚ and the point of contact of the spring with delatching pin should be at a distance of 23.5 mm.

The torque required on the Layshaft to reset the Mechanism

The transfer function was developed to find the torque required on the Layshaft to reset the mechanism. Considering the pins as simply supported beams, frictional factors should be considered at both ends of the pin. Only one side frictional factor is considered during the development of the transfer function. Considering the frictional factor on another pivot point we need to design a torsion spring for a total torque of 30Nm. To develop this torque a torsion Spring is designed.

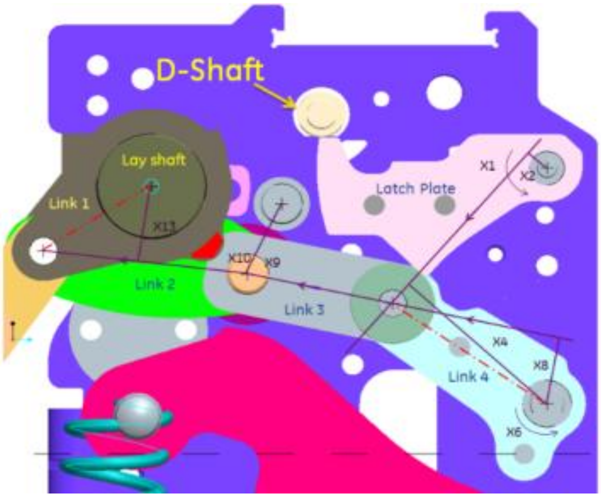

Figure 11: Transfer function to find torque required on Layshaft to rest

Table 1: Spring Design Parameters

	Parameters	**Without Friction**	**Considering friction factor, μ = 0.15**
X1	Latch plate spring torque, Nmm	700	
X2	Perpendicular distance of normal force,N	4.816	
X3	Normal Force , N	145.3488372	14.53488372
X4	Perpendicular distance of 4 Bar assembly (Link 4), mm	52.409	
X5	Induced Torque in 4 bar assembly,Nmm	7617.587209	8379.34593
X6	4 Bar assembly biasing spring, Nmm	700	
X7	Net Torque on 4 bar link assembly (Link 4) Nmm	8317.587209	9079.34593
X8	The perpendicular distance from the pivot to the line of action of force, mm	20.168	
X9	Force acting on link 3	412.4150738	495.20431

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X10	The angle between elephant link roller - stopper pin and link 3	77.125	
X11	The angle between elephant link roller - stopper pin and link 2	107.928	
X12	Force on link 2	422.5643427	558.1300654
X13	The perpendicular distance between the layshaft pivot and link 2	21.14	
X14	The torque required for turning layshaft, Nmm	8933.010206	12978.75654

The spring is designed in such a way that in OFF condition it is pre-stretched to 7˚ and in ON condition it is stretched to 69.5˚ to give the required torque of 15 Nm. Two such springs will be used in parallel. The spring material selected is Stainless steel 17-7 PH.

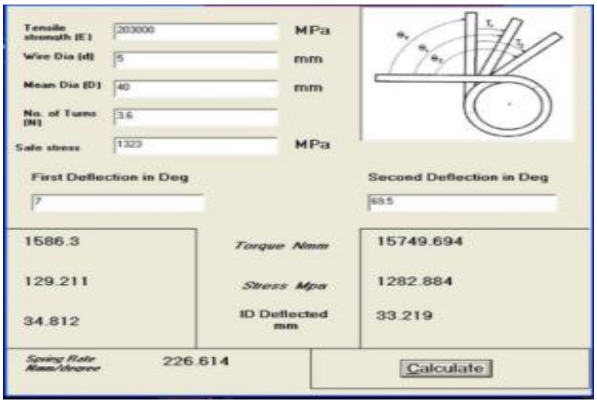

Figure 12: Torsion Spring Design tool

Sensitivity Analysis of the Flexible Link Arrangement

Once the dimension and configuration of the secondary trip mechanism were finalized, the transfer function was developed to find out the force required at the contact to delatch the mechanism. The various parameters influencing the transfer function are

1. Stiffness of the compression spring acting on the fingers.
2. Stiffness of the torsion spring mounted on the fingers.
3. Stiffness of the biasing spring acting on the delatching pin.
4. The angle between the coupler and flexible link.
5. Length of the flexible link.
6. The angle of the slot.
7. Coefficient of friction.

Crystal ball analysis was carried out on this transfer function. It generates the mean and standard deviation values for the output variable. The Crystal Ball evaluation will also provide the top sensitive dimensions for the design. The results of the analysis are as follows:

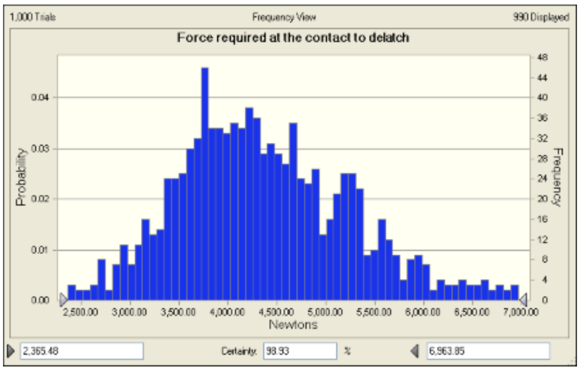

Figure 13: Forecast chart for the force required at the contact

Table 2: Force Required at the contact to delatch

Statistic	Forecast values
Trials	1,000
Base Case	3,073.51
Mean	4,394.81
Median	4,272.93
Standard Deviation	917.51
Minimum	2,365.48
Maximum	8,716.12
Mean Std. Error	29.01

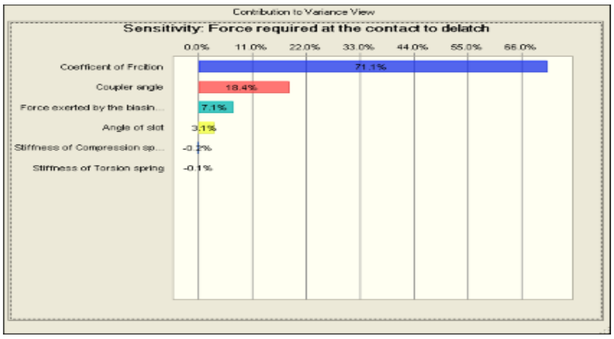

Figure 14: Sensitivity chart showing the contribution of each parameter.

The part level critical parameters are identified based on the sensitivity and contribution of the specific dimension on the product performance. After running the analysis it is found that the coefficient of friction is showing higher sensitivity of 71.1% which plays a major role in the force required to delatch the mechanism. It is found from the analysis that the force varies from a minimum value of 2,365.48N to a maximum force of 8,716.12. In order to control the variation of force different types of methods are studied to control the friction factor. With the present configuration, it is found that bushing would be the best suggestive method to control the friction between the delatching pin and the de-latching link cam surface.

Thus solid sleeve bushing of bronze material is finalized for the initial design. The bush is mounted on the delatching pin and the delatching cam surface rolls over the bush. Hence we are able to reduce the variation of coefficient of friction. With the new configuration, crystal ball analysis is done and the following results were observed.

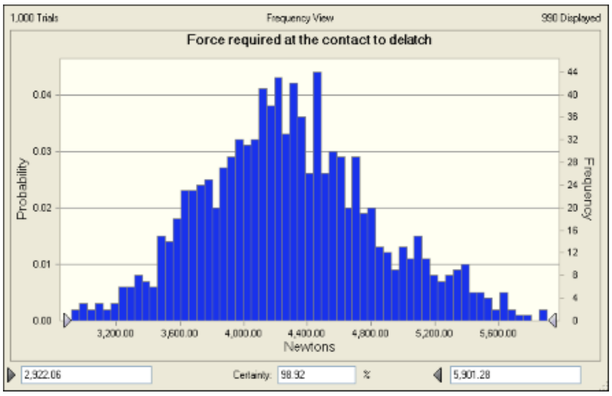

Figure 15: Forecast chart for the force required at the contact with Bushing

Table 3: Force Required at the contact to delatch

Statistic	Forecast values
Trials	1,000
Base Case	3,073.51
Mean	4,307.38
Median	4,271.88
Standard Deviation	569.25
Minimum	2,922.06
Maximum	6,417.03
Mean Std. Error	18

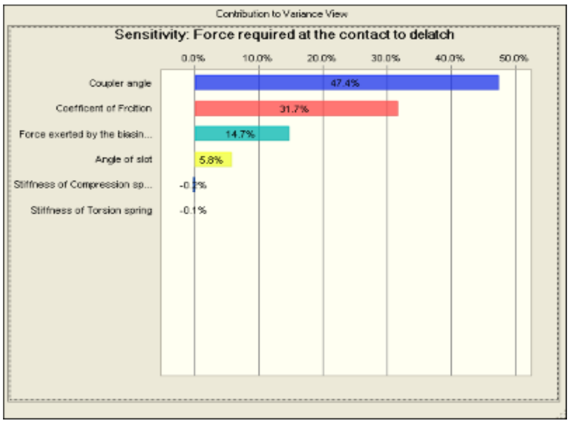

Figure 16: Sensitivity chart showing the contribution of each parameter with bushing

With the new configuration, it is found that the sensitivity of coefficient of friction reduced from 71.1% to 31.7% which helped in controlling the variation of force required de-latching from a minimum value of 2922N to a maximum of 6471N.

6. Validationo the Concept

Part drawings and assembly drawings are made after applying tolerance based on the sensitivity analysis performed and released for prototype manufacturing. The Prototype contact carrier assembly is assembled in the existing breaker and the whole setup is fixed to the test bench. The set up was used for the measurement of the forces on the pole connector up to current levels of 25KA. The setup was designed and assembled in the facility. The jig was used for pushing the linkages and closing contacts as shown below. The proper closing of the breaker was ensured by means of the gap to be maintained between the arcing contacts. Using these readings the load falling on the pole connector assembly was calculated and the same was tabulated. Force is applied manually and using strain gauge the force acting on the contact assembly is constantly monitored. The sequences are repeated multiple times and the results were recorded. The recorded results are compared with the Crystal Ball sensitivity analysis and found that the test values fall under the predicated range. This gave the indication that the values of the forces derived from the mathematical models were matching with the values from the experiment and hence the physics-based model was found to be valid.

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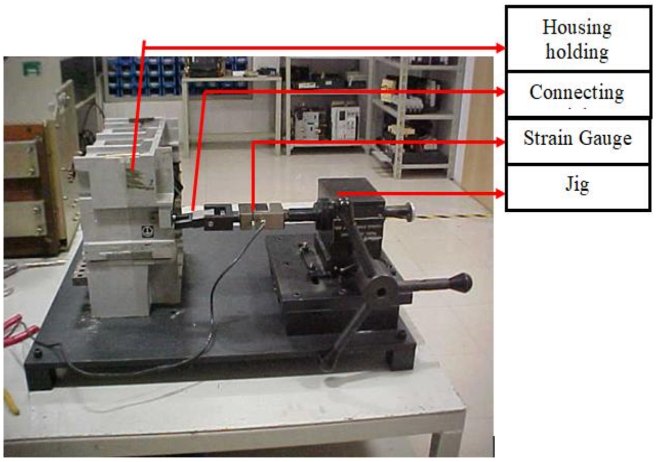

Figure 17: Test Setup for Prototype Testing

7. Conclusion

It was needed to develop a system to provide for a fast opening of a breaker when it confronts a short circuit fault. Listed below are the results and conclusions that were inferred from the work carried out.

- A force-based system was possible to be developed that would respond directly to the magnitude of currents that the breaker is subjected to.
- This stated feature of the breaker would make it possible to reduce the opening times for a breaker in case of a fault current.
- It was possible to achieve a single-phase opening of the breaker poles in case of a single-phase short circuit fault.
- The modular design that the concept incorporated would help in achieving the target of using the same design for various ratings of the breaker.
- Different ratings of the breaker could be achieved by means of changing a set of biasing springs.
- The concepts developed helped in achieving the target of developing the system with minimal changes to the footprint of the breaker.
- The designs were able to achieve the feature of non-bouncing of the contact assembly and helped in negating the problem of a restrike. The same was also seen in the simulation of the concepts.
- The system was able to function independently of the main mechanism of the breaker and still work properly in coordination with the main mechanism.

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