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Use of Shainin Design of Experiments to Reduce the Tripping Force of an Air Circuit Breaker

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ABSTRACT
This paper essentially deals with lowering the tripping force in an Air Circuit Breaker (ACB) to desired levels. Cases of high tripping force (HTF) were reported during the assembly which led to rejection or rework of breakers at assembly level. The components in the breaker contributing to HTF were determined by Component Search technique of Shainin Design of Experiments (DOE). It was found out that Trip D Shaft and Roller Trip Link (RTL) were important components contributing to high tripping force. The changes were implemented and these were effective in bringing down the tripping force within desired limits.

Keywords - *Air Circuit Breaker (ACB), High Tripping Force (HTF), Roller Trip Link (RTL), Shainin Design of Experiments (DOE), Trip D Shaft.*

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I. Introduction

An air circuit breaker is switchgear, which works as switching and current interrupting device. Under normal continuous current rating, a circuit breaker is a single switching device. When the current is above the normal rating, either on overload or short circuit current, the circuit breaker is an automatic over-current protective device.

The function of protecting the device is relatively complex, as the fault currents are relatively high and should be interrupted within very short time viz. within a few seconds. The fault current can damage the equipment if allowed to fall for a longer duration. The mechanism, which is the heart of the circuit braker, must trip within a specific range of forces. If it trips at a force above the maximum set tripping force, it leads to the rejection of the breaker at the quality inspection stage because of HTF. In this project the root causes of HTF are determined by application of Component Search technique of Shainin DOE.

II. Literature Review

An alternative to the Classical and Taguchi experimental design is the lesser known but much simpler Shainin Design of Experiments (DOE) approach developed and perfected by Dorian Shainin [1]. Shainin's philosophy has been, "Don't let the engineers do the guessing; let the parts do the talking." Shainin recognized the value of empirical data in solving realworld problems. In Motorola's phenomenal success with six sigma approach, Shainin techniques played a pivotal role. According to Bhote [2], "Motorola's plants, suppliers, and customers all over the globe conducted about hundreds of Shainin experiments as part of their Six Sigma quality movement."

Shainin techniques are highly effective in determining the root cause and validating it. It does not require any statistical software to analyse the results. Moreover, it does not even require knowledge of difficult statistical tools. Shainin developed techniques [3][4][5][6][7][8] to track down the dominant source through a process of elimination [8], called progressive search. Thomas and Anthony [11] have successfully employed Shainin techniques in identifying the influencing variables that control the joint strength of honeycomb composite tongue and slot joints within an organization. The results of the study provided the stimulus for the wider application of this approach inother business processes within the company. Desai and Jugulkar [10] used Shainin DOE to identify the root causes of engine rejection in assembly and also for tappet setting defects in a water cooled engine at in process verification.

Shainin method called "Component Search" has been found to be quite popular among engineers. Component search is one of the clue generation techniques in a DOE study. It is applicable where there are unit to unit variations. With the help of component search, a large number of possible causes of variation can be reduced to a family of dominant causes or the dominant cause itself. This method is used when the product can be disassembled and assembled with relative ease and with no change or damage to the subassemblies and components. This method is suitable for an assembled product to find out whether the defect in the product is due to the assembly process or one of its constituent parts [11]. Component search, being an offline technique, does not hinder with the regular production.

Shanmugam and Kalaichelvan [11], in order to reduce the rejection & re-work, conducted a study to analyze the rejection using Shainin component search technique for assembly process. It indicated that two of the sub assembly components were the root causes for the rejection. This helped in improving the knowledge base of the manufacturing and assembly process and also helped narrowing down to the root cause or a number of root causes in short span of time. Reddy, Varadarajan and Prasad [12] employed Shainin component search successfully at Bosch Ltd, Banglore to deal with quality issues. They concluded that Shainin technique was simple and a strong statistical tool to handle problems during manufacturing of components.

The purpose of this project to determine the root causes of HTF in Air Circuit Breakers. Approximately **14 %** rejection was obtained in the breakers because of HTF in the quality inspection stage, which in turn led to,

- Around 30-35 minutes of re-work time per breaker to replace mechanism.
- Around Rs 1100 per hour Labor cost for each Re-work.
- Loss of Manufacturing Lead time due to high re-works.
- Cost of new components which are replaced in HTF mechanism.

Thus, there was a need to minimize the rejections in the breakers which could only be done by finding out the cause/s behind the HTF in the breaker and then take necessary steps to obtain it within the set limt of 1.1 Kgf.

III. Methodology

Initially one pair of Best of Best (BOB) and Worst of Worst (WOW) products is chosen for analysis. To narrow down to the dominant cause, we carry out the process of assembling and disassembling and also swapping the components between BOB and WOW. They are disassembled and reassembled twice to find out whether good remains good and bad remains bad consistently, through D/d test (D= Difference between median of BOB and WOW ; d = Average of the ranges of BOB and WOW). It is preferable to have a measurable response to do this D/d test. If the D/d ratio is greater than 1.25, it means the assembly process is consistent and the defect in the product is due to one of its constituent parts [13]. It is also important to set up decision limits for BOB and WOW using the formula:

- Decision limits (BOB) = Median (BOB) +/- 2.776d/1.81 …..**(1)**
- Decision limits (WOW) = Median (WOW) +/- 2.776d/1.81 …..**(2)**

After the components have been identified, a capping run is carried out to check whether the rest of the components can be eliminated and if there are still important components to be identified other than the originally identified components.

During the course of experiment it must be ensured that the assemblies are done as per Shop Standard Operating Procedure (SOP) and Assembly Instruction Sheet, at every stage.

IV. Research Models and Reporting

In stage 1, two breakers are indentified as BOB and WOW. The breaker with tripping force lower than 1.1 kgf is labeled as BOB and the one with tripping force greater than 1.1 kgf is labeled as WOW. To check the characteristics of BOB and WOW both were dissembled and assembled 2 times. From tables 1& 2:

D = Difference between median of BOB and WOW **= 0.75** …..**(3)**
d = Average of the ranges of BOB and WOW **=0.125** …..**(4)**
D/d = 0.75/0.125 = 6 >>> **1.25** …..**(5)**

Thus, it is established that the HTF is due to components and not due to assembly.

In stage 2, components critical to quality and performance of the breaker are interchanged between BOB and WOW one by one, and three readings were taken for each component. As it can been seen from the table 3 the tripping forces changed when the mechanisms were swapped between the two breakers. Thus, it is established that mechanism is the component contributing to high tripping force in WOW. The decision limits are as follows:

a. BOB = Median (BOB) +/- 2.776d/1.81 = **0.758 to 1.141** …..**(6)**
b. WOW = Median (WOW) +/- 2.776d/1.81 = **1.308 to 1.692** …..**(7)**

The mechanism consists of a number of components. Once it is established that mechanism is responsible for high tripping force, then to further narrow down to the exact component, important parts of the mechanism assembly were interchanged between BOB and WOW one by one in stage 3, and three readings were taken for each component. Table 4 clearly shows that the tripping forces changed when Trip D Shaft, Main Trip Link (MTL) and Roller Trip Link (RTL) were interchanged.

In stage 4, to validate the above results, new BOB and WOW are taken and the Trip D Shaft, Main Trip Link (MTL) and Roller Trip Link (RTL) were interchanged. The swapping for MTL and RTL was done one at a time, i.e. first the right RTL and then the left RTL and similarly for MTL. Table 5 shows that the characteristics of WOW changes when RTL and Trip D Shaft were switched.

In stage 5, the Trip D Shaft and RTL are swapped as a combination between new BOB and new WOW. This is done in order to verify the Trip D Shaft and RTL as important components causing HTF. In this stage the other components are switched between new BOB and new WOW to ensure that they do lead to change in the tripping force. While table 6 confirms that Trip D Shaft and RTL are responsible for HTF, table 7 validates that the other components do not lead to HTF.

Table (1): Stage 1 BOB

STAGE 1				
BOB				
	1	2	3	Max
Initial	0.75	0.7	0.75	0.75
1st assembly	0.85	0.85	0.8	0.85
2nd assembly	0.8	0.85	0.85	0.85

Table (2): Stage 1 WOW

STAGE 1				
BOB				
	1	2	3	Max
Initial	1.5	1.5	1.55	1.55
1st assembly	1.5	1.6	1.5	1.6
2nd assembly	1.7	1.7	1.6	1.7

Table (3): Stage 2, readings after swapping components between BOB and WOW

STAGE 2									
BOB					WOW				
MECHANISM CHANGED					MECHANISM CHANGED				
	1	2	3	Max		1	2	3	Max
Change	1.85	1.85	1.45	1.85	Change	0.8	0.75	0.85	0.85
Initial	0.85	0.85	0.9		Initial	1.4	1.6	1.75	
FRONT HOUSING CHANGED					FRONT HOUSING CHANGED				
	1	2	3	Max		1	2	3	Max
Change	0.95	1	0.85	1	Change	1.3	1.25	1.3	1.3
Initial	0.8	0.85	0.85		Initial	1.4	1.25	1.25	
REAR HOUSING CHANGED					REAR HOUSING CHANGED				
	1	2	3	Max		1	2	3	Max
Change	0.8	0.95	0.85	0.95	Change	1.6	1.6	1.3	1.6
Initial	0.8	0.9	0.8		Initial	1.35	1.35	1.35	
TOP TERMINAL CHANGED					TOP TERMINAL CHANGED				
	1	2	3	Max		1	2	3	Max

Change	0.95	0.9	0.8	0.95	Change	1.4	1.5	1.4	1.5
Initial	0.9	0.95	0.9		Initial	1.55	1.4	1.5	
BOTTOM TERMINAL CHANGED					BOTTOM TERMINAL CHANGED				
	1	2	3	Max		1	2	3	Max
Change	0.7	0.8	0.9	0.9	Change	1.85	1.8	1.65	1.85
Initial	0.8	0.85	0.75		Initial	1.4	1.45	1.2	

Table (4): Stage 3, readings after swapping components between mechanisms of BOB and WOW

STAGE 3									
BOB					WOW				
POLE SHAFT WITH RETURN SPRING					POLE SHAFT WITH RETURN SPRING				
	1	2	3	Max		1	2	3	Max
Change	0.8	0.8	0.85	0.85	Change	1.25	1.2	1.2	1.25
Initial	0.9	0.95	0.9		Initial	1.2	1.2	1.25	
SIDE PLATE					SIDE PLATE				
	1	2	3	Max		1	2	3	Max
Change	0.9	0.95	0.95	0.95	Change	1.3	1.3	1.35	1.35
Initial	0.85	0.8	0.8		Initial	1.25	1.3	1.3	
MAIN SPRING					MAIN SPRING				
	1	2	3	Max		1	2	3	Max
Change	0.9	0.95	0.85	0.95	Change	1.35	1.2	1.2	1.35
Initial	0.75	0.85	0.75		Initial	1.2	1.3	1.5	
RTL					RTL				
	1	2	3	Max		1	2	3	Max
Change	1.3	1.3	1.3	1.3	Change	0.75	0.85	0.9	0.9
Initial	0.95	0.75	0.95		Initial	1.25	1.35	1.4	
TRIP-D SHAFT					TRIP-D SHAFT				
	1	2	3	Max		1	2	3	Max
Change	1.2	1.5	1.25	1.5	Change	0.85	0.95	0.85	0.95
Initial	0.85	0.95	0.85		Initial	1.2	1.5	1.25	
MTL					MTL				
	1	2	3	Max		1	2	3	Max
Change	0.8	0.75	0.7	0.8	Change	0.75	0.75	0.75	0.75
Initial	0.7	0.7	0.7		Initial	0.7	0.7	0.7	
CHARGING SYSTEM					CHARGING SYSTEM				
	1	2	3	Max		1	2	3	Max
Change	0.7	0.65	0.75	0.75	Change	1.3	1.25	1.45	1.45
Initial	0.75	0.75	0.75		Initial	1.35	1.2	1.4	

Table (5): Stage 4, readings after swapping Trip D Shaft, RTL and MTL between mechanisms of BOB and WOW

STAGE 4 (New mechanism used as BOB and WOW)									
BOB					WOW				
Right RTL					Right RTL				
	1	2	3	Max		1	2	3	Max
Change	0.7	0.7	0.7	0.7	Change	0.8	0.8	0.8	0.8
Initial	0.6	0.7	0.6		Initial	0.8	0.9	0.9	
Left RTL					Left RTL				
	1	2	3	Max		1	2	3	Max
Change	0.7	0.7	0.7	0.7	Change	1.3	1.3	1.4	1.4
Initial	0.7	0.7	0.7		Initial	1.3	1.4	1.5	
TRIP-D SHAFT					TRIP-D SHAFT				
	1	2	3	Max		1	2	3	Max
Change	1.3	1.4	1.6	1.6	Change	0.8	0.8	0.8	0.8
Initial	0.8	0.9	0.7		Initial	1.1	1.2	1.1	
Right MTL					Right MTL				
	1	2	3	Max		1	2	3	Max
Change	0.7	0.7	0.7	0.7	Change	1.3	1.4	1.5	1.5
Initial	0.7	0.6	0.7		Initial	1.4	1.3	1.5	
Left MTL					Left MTL				
	1	2	3	Max		1	2	3	Max
Change	0.7	0.7	0.7	0.7	Change	1.2	1.3	1.2	1.3
Initial	0.7	0.7	0.7		Initial	1.4	1.5	1.4	

Table (6): Stage 5, readings after swapping Trip D shaft and RTL as a combination between mechanisms of BOB and WOW

STAGE 5									
BOB					WOW				
TRIP D SHAFT AND RTL CHANGED					TRIP D SHAFT AND RTL CHANGED				
	1	2	3	Max		1	2	3	Max
Change	1.2	1.3	1.3	1.3	Change	0.8	0.8	0.8	0.8
Initial	0.8	0.8	0.8		Initial	1.3	1.4	1.4	

Table (7): Stage 5, readings for the validation of unimportant components of BOB and WOW

STAGE 5									
NEW BOB					NEW WOW				
Remaining Components					Remaining Components				
	1	2	3	Max		1	2	3	Max
Change	0.7	0.7	0.7	0.7	Change	1.2	1.3	1.3	1.25
Initial	0.7	0.7	0.7		Initial	1.3	1.3	1.3	

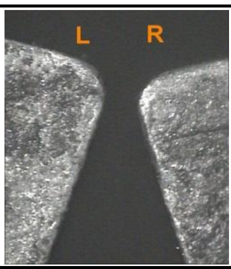
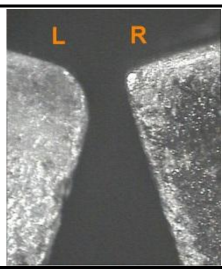
V. Results and Discussions

The RTL and trip D shaft were observed carefully in a profile projector. The observations are summarized in tables 8 & 9 respectively.

4.1. RTL

In the RTL of WOW breaker, it was observed that the radius of the contact portion was uneven. Also, the sharp tip of RTL caused high localized stresses on trip shaft resulting in denting (Pitting) in Trip D Shaft. Thus, to rotate the Trip D Shaft, initially RTL has to be dislodged from the dent (cam effect). Hence, excessive force is required to rotate trip-shaft leading to high tripping force.

Table (8): RTL observations under a profile projector

	BOB	WOW
PICS		
OBSERVATION	1.Both the radius are within tolerance limits	1. The radius in L is on higher side. And both radius are uneven

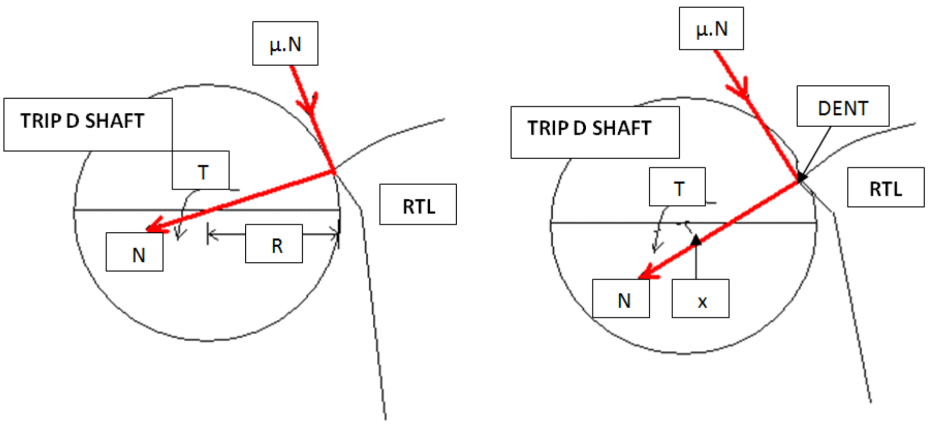


Fig. (1): Representation of denting on Trip D shaft by RTL

OK condition: Torque required to rotate Trip-D-shaft= $T = \mu.N.R$ …..**(8)**

Not OK condition: Torque required to rotate Trip-D-shaft= $T' = \mu.N.R' + (N.x)$ …..**(9)**

$N.x$= Undesired increase in torque which leads to increase in Trip force.

If there is dent on trip-d shaft the additional torque will required for lift the RTL from dent, so effective torque on trip-d shaft with dent will be calculated as follows:

Calculations –

Torque on Trip-d shaft: $\mu * R * N$ …..**(10)**

Torque on Trip-d shaft with dent (T): $\mu * R' * N' + (x * N')$ **…..(11)**

% increase in Torque on Trip-d shaft, considering dent =76.3%

% increase in Trip Force, considering dent = 44.60%

To prevent this dent formation, radius at the contact end was slightly increased.

4.2. Trip D Shaft

In the Trip D Shaft of WOW breaker it was observed that during operations RTL gives indentation on plating which resists the Trip D Shaft rotation while tripping. Moreover, uneven removal of plating results in non uniform surface area which also resists the trip d shaft rotation. Thus, Trip D shaft latching area should be plating free and surface finish should be improved. In order to incorporate this, following changes were made in the manufacturing process:

- In the process of manufacturing the trip link was plated before it was ready for assembly; as a result, maintaining the surface finish of the trip link was not possible.
- It was decided to introduce grinding operation for the mating parts i.e. the top and bottom surfaces of the trip link after plating to achieve desired surface roughness.

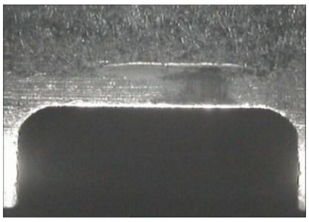
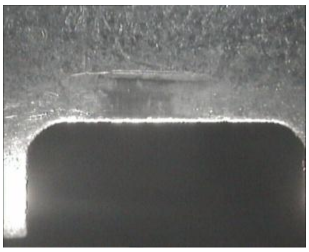
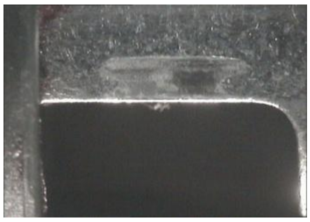
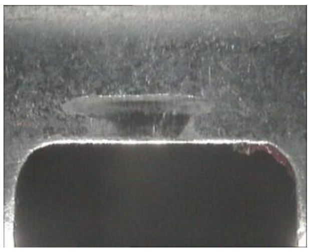
	BOB	WOW
PICS	 Left side  Right side	 Left side  Right side
OBSERVATION	1. Plating removal is uniform and smooth surface 2. Very less indentation mark in plating	1. Plating removal is non-uniform and surface is not so smooth 2. Heavy Indentation mark in plating

Table (9): Trip D Shaft observations under a profile projector

VI. Conclusion

A Set of RTL & Trip D Shaft as per DOE result was made and tried out on 8 Rejected Breakers. Trip force lowered down to 0.9 Kgf in all breakers. 40 Mechanisms with RTL & Trip D shaft made and handed over to assembly shop for use in new breakers. All got cleared with average trip force of 0.7 Kgf. Set process for both the components was implemented for regular production. 880 breakers were made with the DOE components, the rejection percentage dropped down to 0.58% from 14.6%. The avoidance of rework helped the company to prevent expenditure of INR 2.1 million.

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