International Journal of Mechanical Engineering and Robotics Research

ISSN 2278 – 0149 www.ijmerr.com
Vol. 4, No. 1, January 2015
© 2015 IJMERR. All Rights Reserved

Research Paper

FAULT TREE ANALYSIS OF MAGNETO-RHOLOGICAL BRAKE

Bhau K Kumbhar[1]*, Sonal V Patil[1], Satyajit R Patil[2] and Suresh M Sawant[3]

*Corresponding Author: Bhau K Kumbhar, ✉ bkumbhar2050@gmail.com

To improve the reliability of any system, many tools have been introduced which will increase its possibility to satisfy the application requirements. In this work, an attempt has been made to carry out the Fault Tree Analysis (FTA) of Magneto-Rheological (MR) brake to ensure its effectiveness. The Fault tree analysis is a logical, graphical diagram that describes failure modes and causes. The FTA diagram graphically shows all failures for a system, subsystem, assembly, Printed Circuit Board (PCB), or module. The output from the FTA provides a better understanding of the causes that can lead to a failure mode.

Keywords: Magneto-Rheological (MR) Brake, Reliability, Fault Tree Analysis (FTA), Failure modes and causes, Recommendations

INTRODUCTION

Magneto rheological (MR) brake is type of brake, which works on the principle of properties of MR fluid (Olabi and Grunwald (2007; and Kerem Karakoc *et al.*, 2008). When magnetic field is applied viscosity of fluid suddenly increases which resists the motion of rotary disc and hence the wheel (Sukhwani and Hirani, 2008). Reliability is the probability of a device performing its purpose adequately for the period intended under the given operating conditions. Fault tree analysis is useful tool in performing a system analysis (Srinath, 2002; and Mark Levin and Ted Kalal, 2003).

Fault Tree Analysis (FTA) is a graphical design technique that is an alternative to reliability block diagrams (Elmer and Lewis, 1987). It is broader in scope than a reliability block diagram and differs from reliability block diagrams in several respects.

All failures are faults, but not all faults may be considered failures. The qualitative analysis consists of identifying the various combinations of events that will cause the top event to occur. This may be followed by a quantitative analysis

1 Mechanical Engineering Department, Gharda Institute of Technology, Khed (MH), India.
2 Automobile Engineering Department, Rajarambapu Institute of Technology, Sangli (MH), India.
3 Mechanical Engineering Department, Rajarambapu Institute of Technology, Sangli (MH), India.

to estimate the probability of occurrence of the top event (Charles Ebeling, 1997).

FAULT TREE ANALYSES (FTA)

Steps to FTA

There are four major steps to a fault tree analysis:

- Define the system, its boundaries, and the top event.
- Construct the fault tree, which symbolically represents the system and its relevant events.
- Perform a qualitative evaluation by identifying those combinations of events that will cause the top event.
- Perform a quantitative evaluation by assigning failure probabilities or un-availabilities to the basic events and computing the probability of the top event (Charles Ebeling, 1997).

Fault Tree Construction

The FTA is done by brainstorming process. In brainstorming, it is agreed that there are no bad ideas. This way everyone feels comfortable in submitting his or her thoughts. Begin by having everyone write his or her two to three ideas on Post-its. When the team is satisfied that everyone has recorded his or her ideas on Post-its, then FTA process is started.

Place the top-level (system-level) failure mode on top of the fault tree. Next, begin identifying failure causes associated with the above failure mode. You can go down several levels associating a second-, third-, and possibly fourth-level failure cause that is associated with the above failure mode. Place each subsequent failure cause beneath the previous failure cause using the Post-its statements. To get the next lower level of failure cause, ask the question, what event would have to occur to cause the higher-level failure? Usually, two to three levels of extraction in failure causes are adequate. The goal is not to drive to the root cause, but to bring to the surface failure causes in the design cycle that cannot be tolerated. Leave enough room between the levels for interconnecting lines and logic gates. Continue to the process till the desired level of abstraction has been reached.

In building the FTA, you eventually reach a point where a decision needs to be made. The decision is that you have reached a sufficient level of failure cause description to evaluate its effect on the design. These failure causes are circled. However, you may reach a point where you cannot go further because the team lacks the expertise, knowledge or understanding of the failure cause. All the lower level failure causes on FTA should be either circles or diamonds. At this point, you are done with the fault tree analysis (Mark Levin and Ted Kalal, 2003).

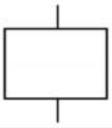
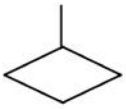
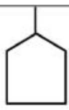
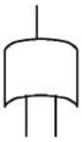
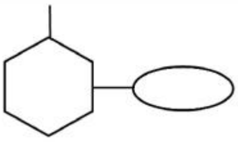
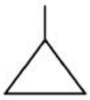
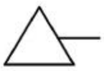
The FTA uses standard logic symbols shown in Table 1, commonly found in flowcharting for process control, quality control, safety engineering, and so on, to tie together the sequence of event.

Fault Classification

The faults can be classified into following types:

Primary Fault: Primary faults are caused by defective design, manufacture, or construction and are therefore most closely correlated to wear-in failure.

Table 1: Fault Tree Logic Symbols

Sr. No.	Symbol	Name	Description
1.		Rectangle	Fault event; it is usually result of the logical combination of other event
2.		Circle	Independent primary fault event
3.		Diamond	Fault event not fully developed, for its causes are not known; it is only as assumed primary fault event.
4		House	Normally occurring basic event ; It is not a fault event.
5.		OR Gate	The union operations of events; i.e. the output event occurs if one or more of the inputs occur.
6.		AND Gate	The intersection operation of events; i.e., the output event occurs if and only if all the inputs occur.
7.		INHIBIT Gate	Output exists when X exists and condition A is present; this gate functions somewhat like an AND gate and is used for a secondary fault event X.
8.		Triangle-in	Triangle symbols provide a tool to avoid repeating sections of a fault tree or to transfer the tree construction from one sheet to the next. The triangle-in appears at the bottom of a tree and represents the branch of the tree shown someplace else.
9.		Triangle-out	The triangle-out appears at the top of a tree and denotes that the tree A is sub-tree to one shown someplace else.

Source: Struss and Fraracci (2010)

Secondary Fault: Secondary faults occur in an environment or under loading for which the component is not qualified.

Command Fault: Command faults must look beyond the component failure to find the source of the erroneous command.

Passive Faults: Passive faults may usually be thought of as a mechanism for transmitting the output of one active component to the input of another.

Active Fault: Active faults contribute to the system function in a dynamic manner, altering in some way the system's behavior (Struss and Fraracci, 2010).

Fault Tree Evaluation by Cut-Set

The direct evaluation procedure helps us to assess fault trees with relatively few branches and basic events. When larger trees are considered, both evaluation and interpretation of the results become more difficult and digital computer codes are invariably employed. Such codes are usually formulated in terms of the minimum cut-set methodology (Struss and Fraracci, 2010). Basically fault tree evaluation cut-set is commonly divided into qualitative and quantitative analysis. In qualitative analysis information about the logical structure of the tree is used to locate weak points and evaluate and improve system design. In quantitative analysis the same objectives are taken further by studying the probabilities of component failures in relation to system design (Struss and Fraracci, 2010).

Qualitative Analysis

There are three steps to calculating the qualitative analysis. These steps are as follows:

Minimum Cut-Set Formulation: A minimum cut-set is defined as the smallest combination of primary failures which, if they all occur, will cause the top event to occur. It is a combination (i.e., intersection) of primary failures sufficient to cause the top event. It is the smallest combination in that all the failures must take place for the top event to occur. If even one of the failures in the minimum cut-set does not happen, the top event will not take place (Struss and Fraracci, 2010).

Cut-Set Determination: In order to utilize the cut-set formulations, it must express the top event as the union of minimum cut sets. For larger trees, containing perhaps 20 or more primary failures, this procedure becomes intractable, and must resort to digital computer evaluation. Even then the task may be prodigious, for a larger tree with a great deal of redundancy may have a million or more minimum cut-sets (Struss and Fraracci, 2010).

Cut-Set Interpretation: Knowing the minimum cut sets for a particular fault tree can provide valuable insight concerning weak points of complex systems, even when it is not possible to calculate the probability that either a particular cut set or the top event will occur. Three qualitative considerations, in particular, may be very useful: the ranking of the minimum cut sets by the number of primary failures required the importance of particular component failures to the occurrence of the minimum cut sets, and the susceptibility of particular cut sets to common-mode failures (Struss and Fraracci, 2010; and Tang Tingl *et al.*, 2011).

Fault Tree Analysis of MR Brake

Fault Tree Analysis (FTA) is used for finding top level event like 'brake is not actuating' and

Figure 1: FTA 1

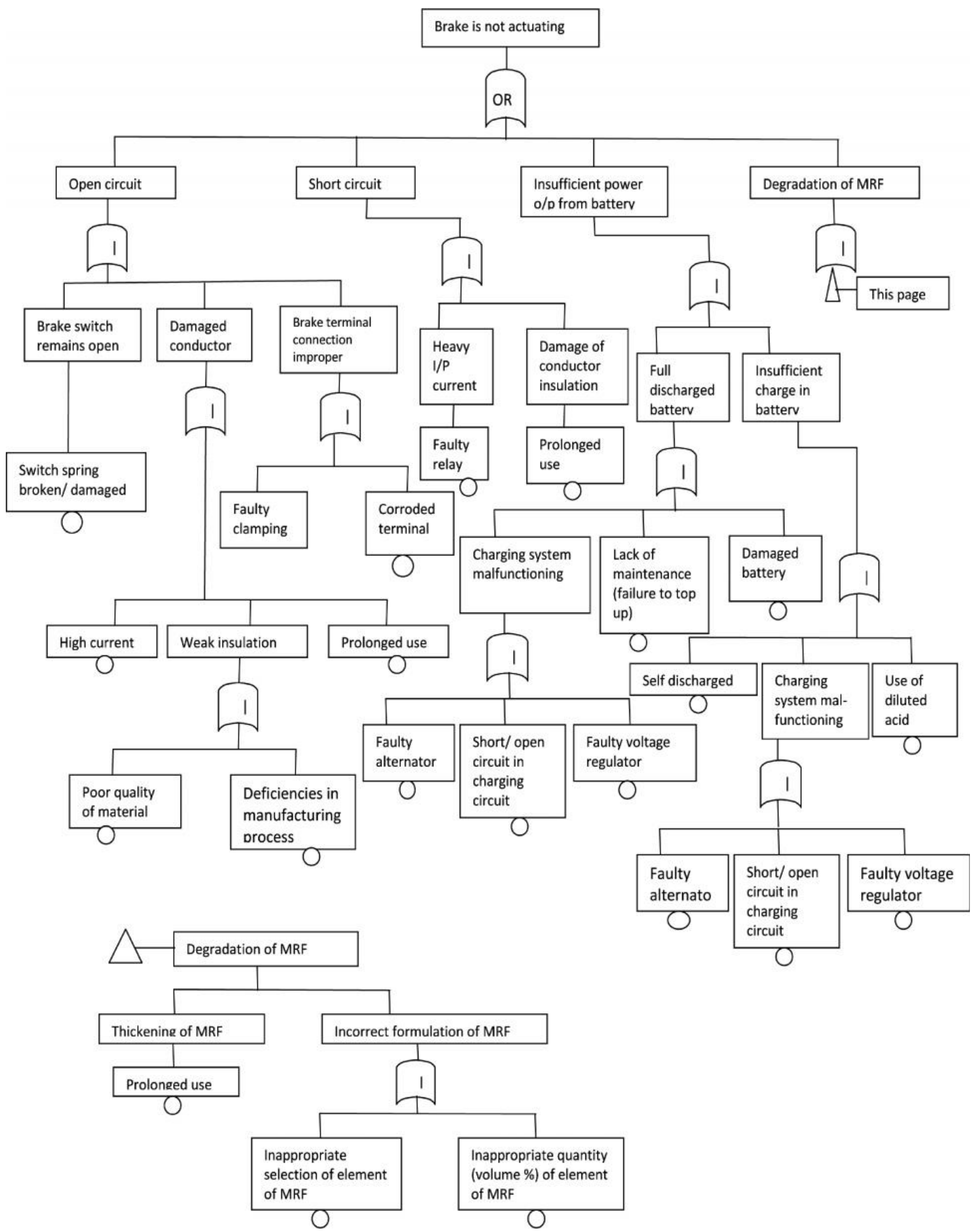


Figure 2: FTA 2

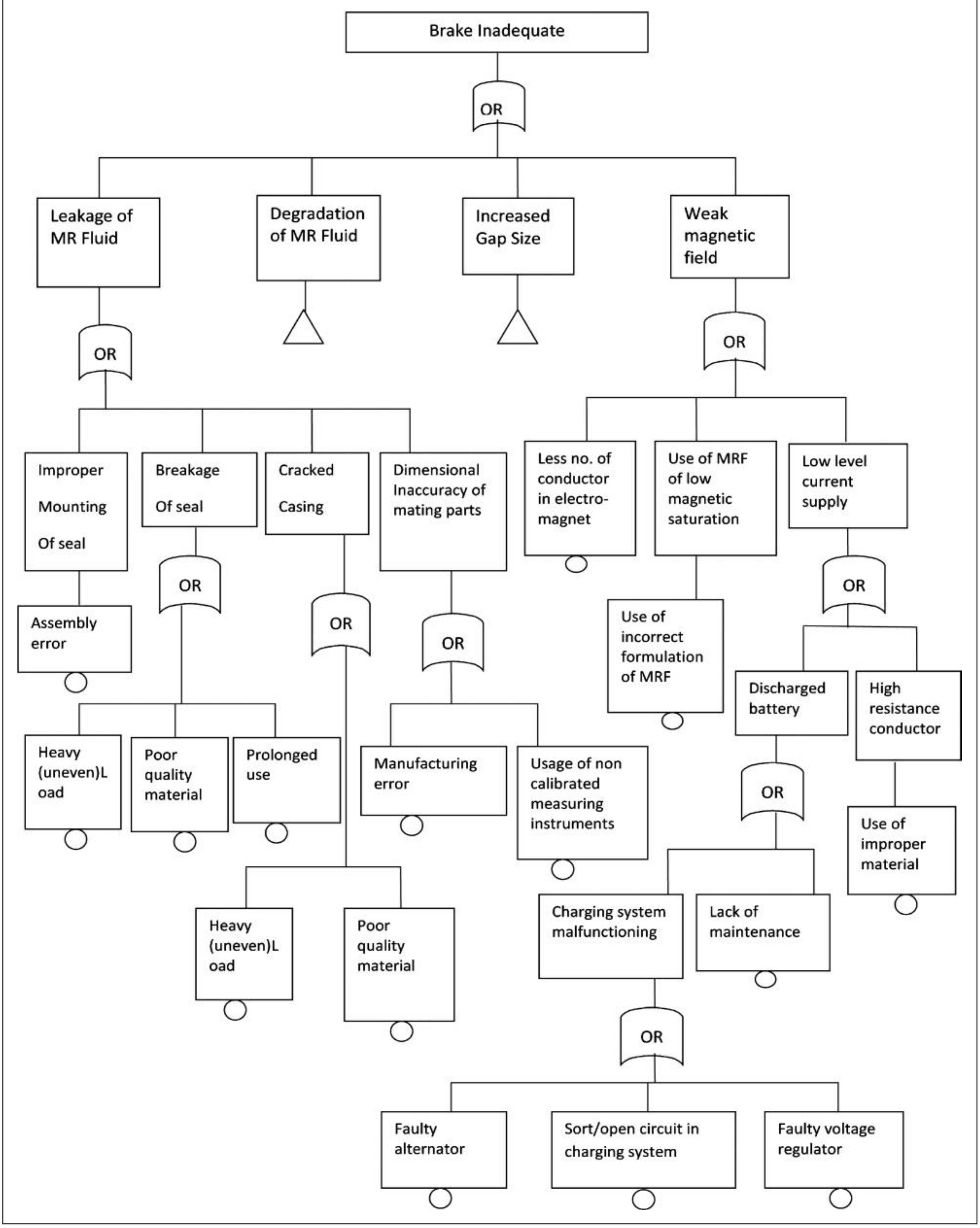


Figure 2 (Cont.)

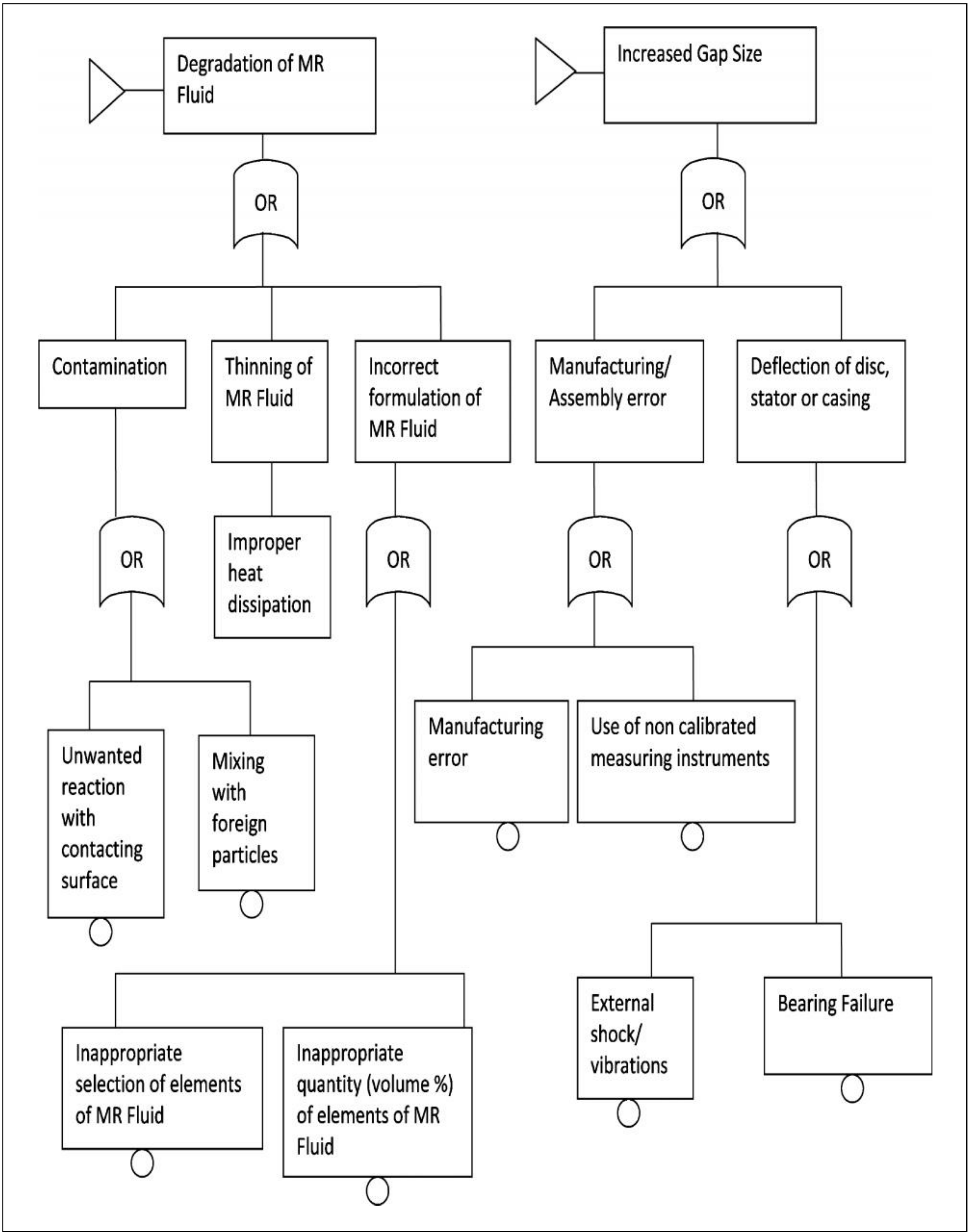


Figure 3: FTA 3-Simplified Tree of FTA 1

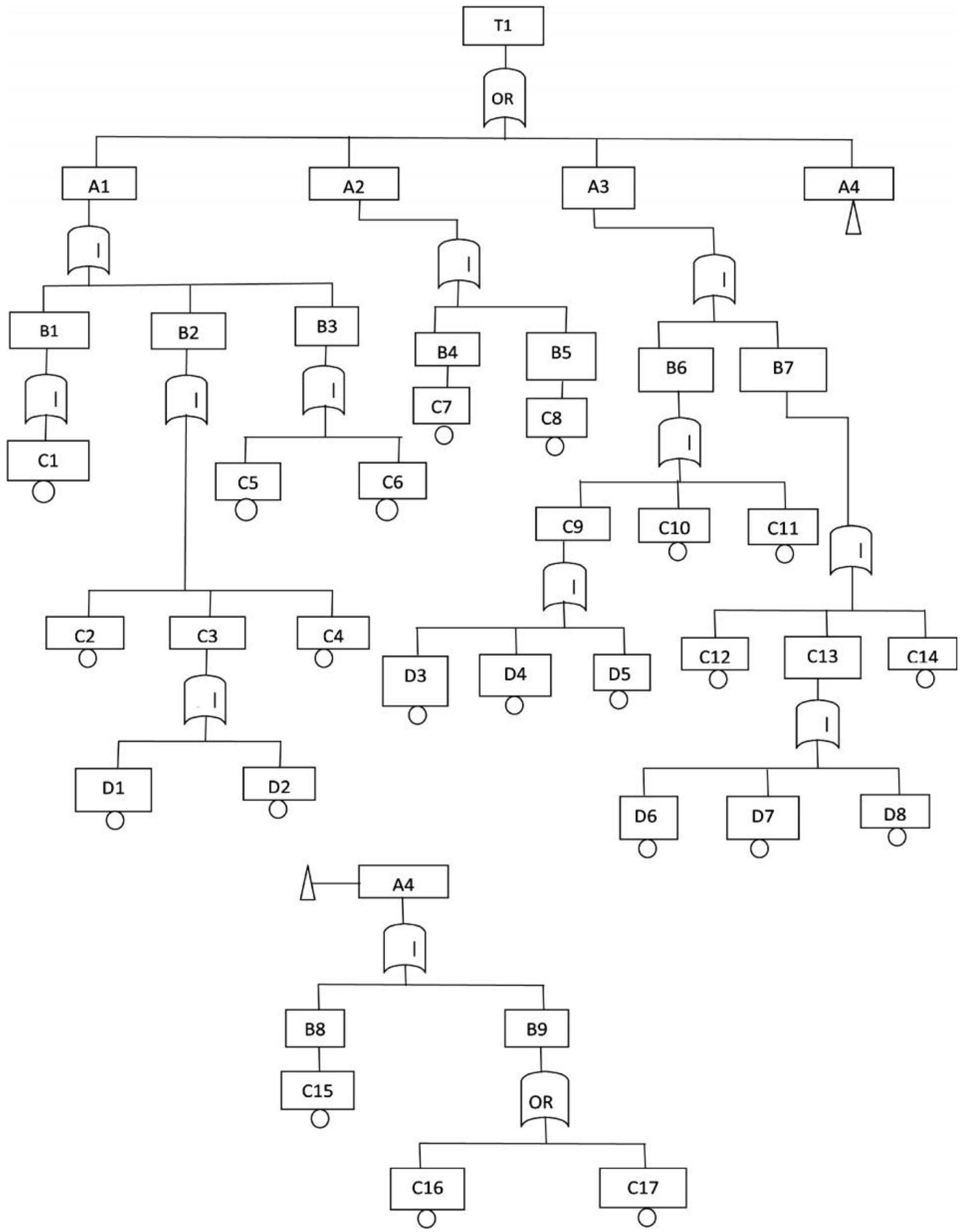


Figure 4: FTA 4-Simplified Tree of FTA 2

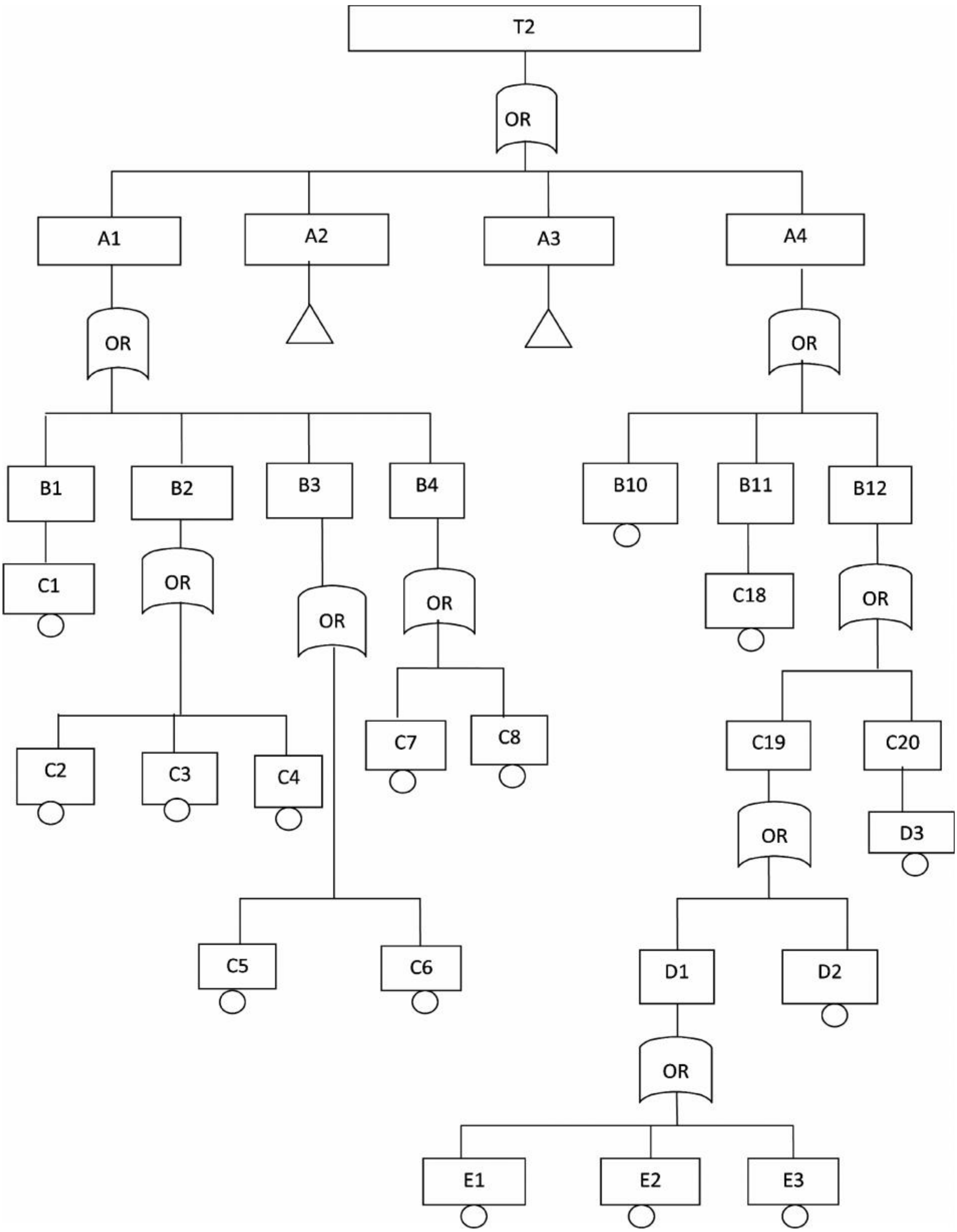
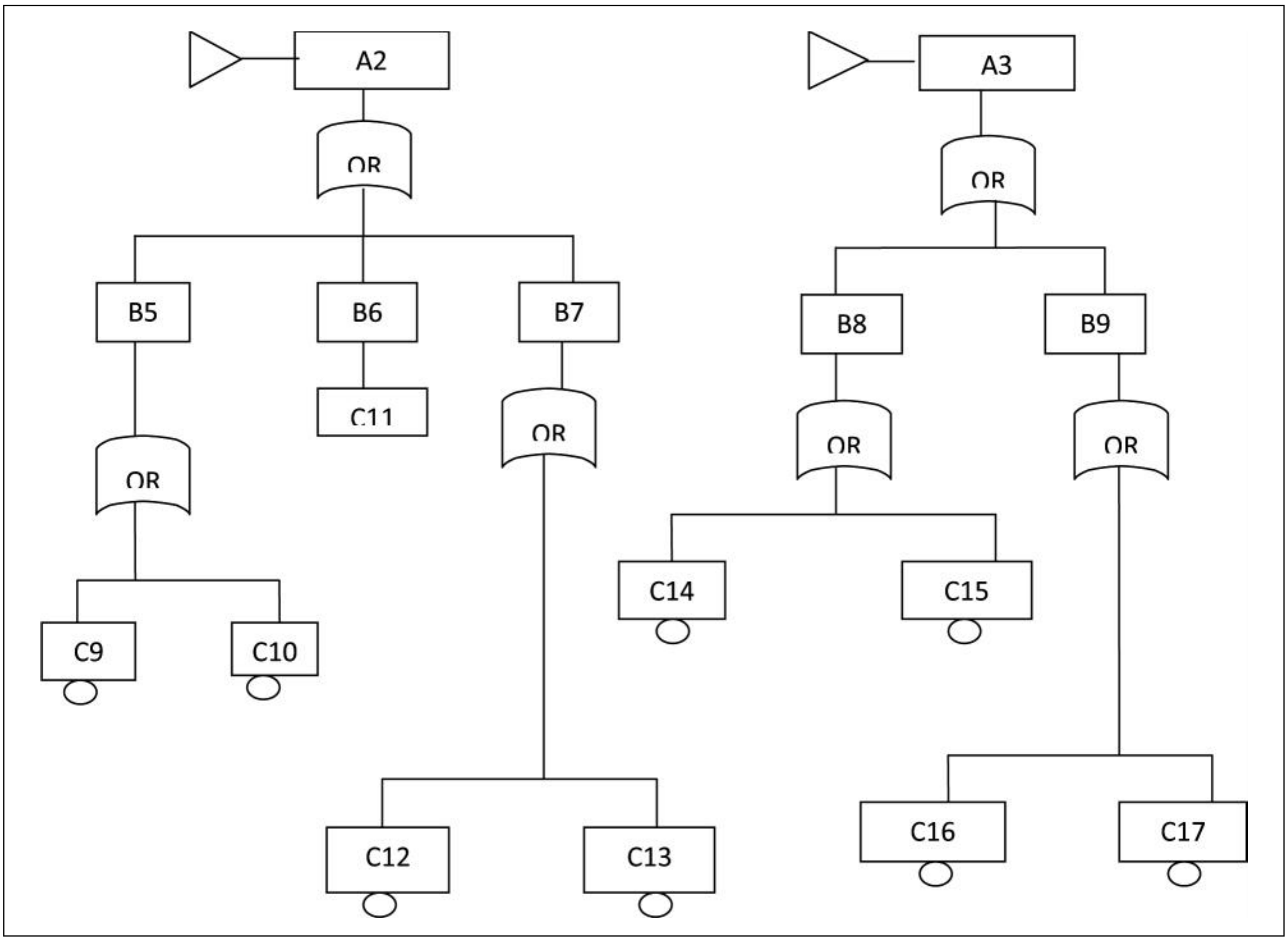


Figure 4 (Cont.)



'brake inadequate' which may be cause of failure of MR brake. We applied this tool for finding out the faults like primary, secondary, command, active and passive. For that we have found out minimal cut set for MR brake failure.

We carried out FTA by brain storming process. We all group members and our guide sat together and found out and noted down all possible failure causes by discussing within us. The Fault Tree which we have made, i.e., FTA 1 and FTA 2 is shown in Figures 1, 2, 3 and 4.

Faults Classification of MR Brake FTA

The fault of MR Brake is classified into five main faults and tabulated in Table 2.

Minimal Cut Set Evaluation

For the purpose of evaluation, FTA 1 and FTA

Table 2: Faults Classification of MR Brake FTA

Primary	Secondary	Command	Passive	Active
Open circuit	Leakage of MR Fluid	Bearing failure	Breakage of casing	Relay
No supply or insufficient current	Degradation of MR Fluid Increased gap size	Insufficient torque	Bearing failure	Switches Electric signals

2 has been simplified into FTA 3 and FTA 4 as follows:

Boolean Algebra for FTA 3

The Boolean algebra given below gives the final iterations for FTA 3. It shows the number of minimal cut set present in the FTA 3.

$T_1 = C_1\ UC_2\ UD_1\ UD_2\ UC_4\ UC_5\ UC_6\ UC_7\ UC_8\ UD_3\ UD_4\ UD_5\ UC_{10}\ UC_{11}\ UC_{12}\ UD_6\ UD_7\ UD_8\ UC_{14}\ UC_{15}\ UC_{16}\ UC_{17}$

The minimal cut set for FTA 3 = 24.

Table 3 shows the result for FTA 3. It is characterized in three steps, i.e., singlet, doublet and triplet.

Table 3: Iteration for FTA 1

1	2	3	4
A1	B1	C1	C1
A2	B2	C2	C2
A3	B3	C3	D1
A4	B4	C4	D2
	B5	C5	C4
	B6	C6	C5
	B7	C7	C6
	B8	C8	C7
	B9	C9	C8
		C10	D3
		C11	D4
		C12	D5
		C13	C10
		C14	C11
		C15	C12
		C16	D6
		C17	D7
			D8
			C14
			C15
			C16
			C17

Boolean Algebra for FTA 4

The Boolean algebra given below gives the final iterations for FTA 4. It shows the number of minimal cut set present in the FTA 4.

$T = C_1\ UC_2\ UC_3\ UC_6\ UC_7\ UC_8\ UC_9\ UB_{10}\ UC_{10}\ UC_{11}\ UC_{12}\ UC_{13}\ UC_{14}\ UC_{15}\ UC_{16}\ UC_{17}\ UC_{18}\ UE_1\ UE_2\ UE_3\ UD_2\ UD_3$

The minimal cut set for FTA 4 = 26.

Table 4 shows the result for FTA 4. It is characterized in three steps i.e. singlet, doublet and triplet.

Table 4: Iteration for FTA 2

1	2	3	4	5
A1	B1	C1	C1	C1
A2	B2	C2	C2	C2
A3	B3	C3	C3	C3
A4	B4	C4	C4	C4
	B5	C5	C5	C5
	B6	C6	C6	C6
	B7	C7	C7	C7
	B8	C8	C8	C8
	B9	C9	C9	C9
	B1O	B10	B10	B10
	B11	C10	C10	C10
	B12	C11	C11	C11
		C12	C12	C12
		C13	C13	C13
		C14	C14	C14
		C15	C15	C15
		C16	C16	C16
		C17	C17	C17
		C18	C18	C18
		C19	C19	C19
		C20	C20	C20
			D1	D1
			D2	D2
				E1
				E2
				E3

Result of Fault Tree Analysis

The Fault Tree Analysis is resulted by using minimal cut set. A cut set is a collection of basic events that will cause the top event. A cut set can be characterized by the number of basic events comprising it. For example Singlet, Doublet, Triplet, etc.

- Singlet—A single event that will cause the top event is singlet.

Table 5: Result of Minimal Cut Set for FTA 1

Singlet	Doublet	Triplet
Switch spring broken/damaged	Damaged conductor	Charging system malfunctioning
Faulty relay	Weak insulation	
Prolonged use	Brake terminal connection	
Thickening of MRF	Full discharged battery	
	Insufficient charge in battery	
	Incorrect formulation of MRF	

Table 6: Result of Minimal Cut Set for FTA 2

Singlet	Doublet	Triplet
Assembly error	Cracked casing	Breakage of seal
Improper heat dissipation	Dimensional inaccuracy of mating parts	Charging system malfunctioning
Less no. of conductors in electro-magnet	Contamination	
Use of incorrect formulation of MRF	Incorrect formulation of MRF	
Use of improper material	Manufacturing/ Assembly error	
Lack of maintenance	Deflection of disc, stator/casing	

- Doublet—A two-event minimal cut set is a doublet.
- Triplet—A three-event minimal cut set is a triplet.

Table 5 shows the result of minimal cut set for FTA 1.

RECOMMENDATIONS ON FTA

After successful implementation of FTA on MR Brake in two stages, i.e., ‘Brake is not actuating and brake is inadequate’, it has been found that the top level faults affects the most on the MR Brake system.

There are three areas where the top level faults are found and the recommendations on same are as follows:

- Recommendations for faults related to battery problems:
  - Top up and cleanliness of battery terminals should be done periodically.
  - The charging system should be checked periodically.
  - The conductors used for electrical devices should have good quality.
- Recommendations for faults related to MR Fluid:
  - MR Fluid should be selected as per specified by Lord Corporation.
  - Correct formulation of MR Fluid should be ensured during Design stage.
  - To avoid contamination good quality seals should be selected.
  - Chemical analysis should be mandatory.

- Recommendations for faults related to Design, Manufacturing and assembly:
  - To avoid dimensional inaccuracy $\overline{x}$ and $\overline{R}$ chart should be used.
  - Tolerance fits should be ensured and inspected during Manufacturing and Quality control process.
  - Seals should be mounted properly during assembly of MR Brake.
  - A visual check should be compulsory to ensure proper mounting.
  - For proper heat dissipation, high thermal conductivity material like aluminum and its alloys be recommended.

CONCLUSION

The work has confined the scope to the Qualitative Analysis only which comprises FTA as a Reliability tool.

After performing FTA on MR Brake system, it can be concluded that there is no appearance of AND gate but there are only OR gates. It means that the system is more sensitive for a single fault which leads to top level event. Also we have suggested recommendation for such faults by applying minimal cut-sets theory. These are as follows:

1. Top up and cleanliness of battery terminals should be done periodically OR maintenance free battery is recommended.
2. The charging system should be checked periodically.
3. MR Fluid should be selected based on study of specifications and properties of MR fluids.
4. Chemical analysis of MR fluid should be mandatory.
5. For proper heat dissipation, high thermal conductivity material like aluminum and its alloys is recommended.
6. A visual check should be compulsory to ensure proper mounting.

With the help of these recommendations one can improve the reliability of MR brake system.

REFERENCES

1. Charles E Ebeling (1997), "An Introduction to Reliability and Maintainability Engineering", pp. 145-187, McGraw Hill.
2. Elmer E and Lewis I N C (1987), "Introduction to Reliability Engineering", pp. 372-400, John Wiley & Sons.
3. Kerem Karakoc, Edward J Park and Afzal Suleman (2008), "Design Considerations for an Automotive Magneto-Rheological Brake", *Elsevier, Mechatronics*.
4. Mark A Levin and Ted T Kalal (2003), "Improving Product Reliability: Strategies and Implementation", pp. 64-84, John Wiley & Sons, SBN: 978-0-470-86449-4.
5. Olabi A G and Grunwald A (2007), "Design and Application of Magneto-Rheological Fluid", *Elsevier, Materials and Design*, Vol. 28, pp. 2658-2664.
6. Srinath L S (2002), "Reliability Engineering", pp. 17-18, East-West Press Pvt. Ltd.
7. Struss P and Fraracci A (2010), "FMEA of a Braking System—A Kingdom for a Qualitative Valve Model", QR2011: 25th

International Workshop on Qualitative Reasoning Tech. Univ. of Munich, Munich, Germany.

8. Sukhwani V K and Hirani H (2008), "Design, Development, and Performance Evaluation of High-Speed Magneto-Rheological Brakes", Proceedings of the Institution of Mechanical Engineers, Part L: *Journal of Materials Design and Applications*, Vol. 222, p. 73.

9. Tang Tingl, Lu Yuel, Zhou Tao-tao, Ing Hai-Iongl and Sun Hail (2011), "FTA and FMEA of Braking System Based on Relex 2009", Deepwater Engineering & Technology Center, Harbin Engineering University, PR China 15000.