Identification of Different Faults of Different Electrical Machines Analysed By Fault Tree Analysis

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Abstract*: A fault tree analysis can be simply described as an analytical technique, whereby an undesired state of the system is specified (usually a state that is critical from a safety standpoint), and the system is then analyzed in the context of its environment and operation to find all credible ways in which the undesired event can occur. The fault tree itself is a graphic model of the various parallel and sequential combinations of faults that will result in the occurrence of the predefined undesired event. The faults can be events that are associated with component hardware failures, human errors, or any other pertinent events which can lead to the undesired event. A fault tree thus depicts the logical interrelationship of basic events that lead to the undesired event- which is the top event of the fault tree. Here I try to construct the Fault Tree of different rotating electrical machines also try to reduce this Fault Tree using Boolean algebra.*

Keywords*: Faults in rotating electrical machines; Fault tree construction; Reduction of fault tree using Boolean algebra.*

I.   Introduction

Fault Tree Analysis is a graphical representation of the major faults or critical failures associated with the product. It helps to identify the faults associated with the product and also helps to take the corrective actions to reduce the faults.

To construct a fault tree of a given system following steps are followed:
* First select a component for analysis.
* Then identify critical failures or "faults" related to the component.
* Then identify the causes for each fault.
* Then work toward a root cause.
* Finally identify countermeasures for each root cause.

II.   General Faults in Rotating Electrical Machines

In rotating electrical machine there are mainly following types of faults are occur:

Electrical Fault

If the system or device is running in d.c. supply, if battery is discharge then electrical break down can occur. Alternator, which is the main supply of a.c., if alternator is failure any way then also electrical break down can occur. If the fuse which is connected in series with main supply is blown due to heavy current then also electrical break down can occur. If the fuse which is connected in series with main supply is broken due to mechanical stress then also electrical break down can occur.

Mechanical Fault

The case of mechanical break is more or over same for the all of motors and it is common one. By saying mechanical breakdown we mean to say problem in bearing, motor shaft, motor frame, bolts that holds tight stator and rotor, maintain the air gap in the motor. The most common fault is jamming of bearing in the motor frame.

Fault Due To Other Abnormal Conditions

Other abnormal conditions associated in rotating electrical machines are failure due to over current, failure due to over voltage, failure due to over speed, failure due to under frequency, unbalanced supply voltage, phase sequence reversal of supply voltage, mechanical overloads, wrong synchronization.

Fault Due To Human Operator

Due to the lack of the some reasons (experience of the operator, proper training of the operator, proper guidance to the operator, complexity of work) in the human   operators there will be sometimes faults are produced.

III. Fault Tree Symbols

Generally the followings symbols are used to construct a fault tree for a given system.
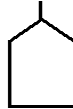
Basic Event

The circle describes a basic initiating fault event that requires no further development. In other words, the circle signifies that the appropriate limit of resolution has been reached.
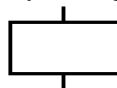
External Event

The house is used to signify an event that is normally expected to occur: e.g., a phase change in a dynamic system. Thus the house symbol displays events that are not, of themselves, faults.

Intermediate event

An intermediate event is a fault event which occurs because of one or more antecedent causes acting through logic gates. All intermediate events are symbolized by rectangles.

Logic Gates

Generally two types of logic gates are used to construct a fault tree for a given system.

3.4.1. The OR gate Output of OR gate is denoted by Boolean algebra, $Y = A+B$. In OR gate output event will occur when single or both input event will occur. The symbol of OR gate is shown below:
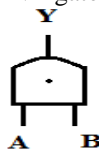
The truth table of OR gate is given below the table, e.g. Table 1.

Table 1. Truth table of OR gate

Input A	Input B	Output C
0	0	0
0	1	1
1	0	1
1	1	1

3.4.2. *The AND gate*

Output of AND gate is denoted by Boolean algebra, $Y = A \cdot B$. In AND gate output event will occur when both input events will occur. The symbol of AND gate is shown below:

The truth table of AND gate is given below the table, e.g. Table 2.

Table 2. Truth table of AND gate

Input A	Input B	Output C
0	0	0
0	1	0
1	0	0
1	1	1

IV. Basic Rules of Fault Tree

Ground Rule-I

Write the statements that are entered in the event boxes as faults; state precisely what the fault is and when it occurs.

Ground Rule-II

If the answer to the question, "can this fault consist of a component failure?" is "Yes", classify the event as a "state-of-component fault". If the answer is "No", classify the event as a "state-of-system fault".

No Miracles Rule

If the normal functioning of a component propagates a fault sequence, then it is assumed that the component functions normally.

Complete-The-Gate Rule

All inputs to a particular gate should be completely defined before further analysis of any one of them is undertaken.

No Gate-To-Gate Rule

Gate inputs should be properly defined fault events, and gates should not be directly connected to other gates.

V. Fault Tree of Different Rotating electrical Machines
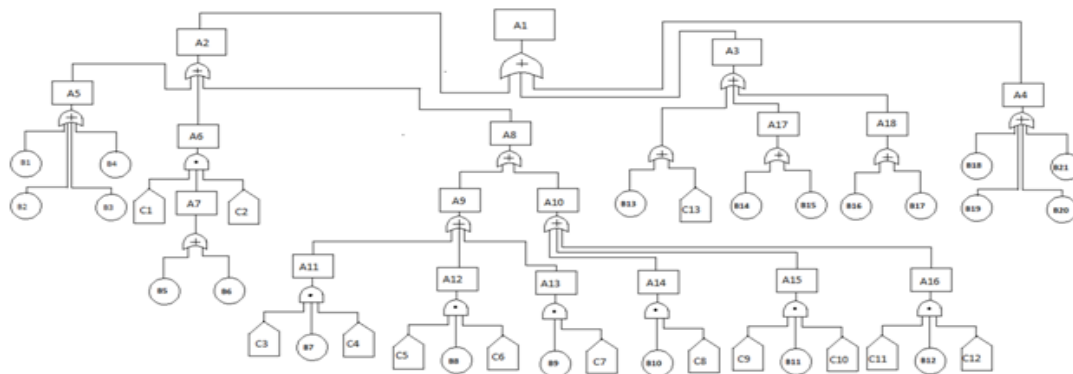
Fault Tree Of D.C. Machine

Fig. 1. Fault tree of d.c. machine

Here, A_1=faults in alternator, A_2=electrical faults, A_3=mechanical faults, A_4=faults due to human operator, A_5=electrical system failure, A_6=electrical insulation failure, A_7=insulation of wire or other component, A_8=winding faults, A_9=faults in field winding, A_{10}=faults in armature winding, A_{11}=open circuit fault in field winding, A_{12}=short circuit fault in field winding, A_{13}=earth fault in field winding, A_{14}=open circuit fault in armature winding, A_{15}=short circuit fault in armature winding, A_{16}=earth fault in armature winding, A_{17}=problem on bearing, A_{18}=problem in motor frame, B_1=battery discharge, B_2=alternator failure, B_3=broken fuse, B_4=blown fuses, B_5=no routine maintenance, B_6=due to mechanical stress, B_7=windings are kept open, B_8=two or more coils are shorted with each other in field winding, B_9=coils connected to earth in field winding, B_{10}=when machine is loaded, B_{11}=two or more coils are shorted with each other in armature winding, B_{12}=when two separate coils earthed in armature winding, B_{13}=problem on shaft, B_{14}=lubricant on bearing, B_{15}=friction on bearing, B_{16}=bolts that does not holds tight stator and rotor, B_{17}=jamming of bearings in the motor frame, B_{18}=no experience or lack of experience, B_{19}=no proper training, B_{20}=no proper guides, B_{21}=complexity of work, C_1=short circuit, C_2=blown fuses, C_3=interruption of supply, C_4=increase the speed of motor, C_5=heat produced in the coil in field winding, C_6=field winding may burn out, C_7=burning the field winding, C_8=damage the commutator, C_9=heat produced in the coil in armature winding, C_{10}= armature winding may burn out, C_{11}=sparking, C_{12}=unbalanced armature current flow, C_{13}=problem in movement of shaft.
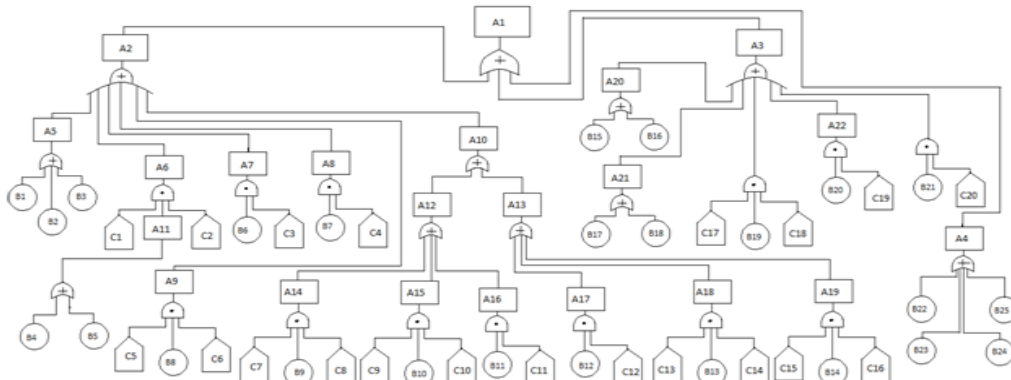
Fault Tree Of Alternator

Fig. 2. Fault tree of alternator

Here, A_1=faults in alternator, A_2=electrical faults, A_3=mechanical faults, A_4=faults due to human operator, A_5=electrical system failure, A_6=electrical insulation failure, A_7=failure of prime mover, A_8=failure due to over current, A_9=failure due to over voltage, A_{10}=failure of windings, A_{11}=insulation of wire or other component, A_{12}=failure of field or rotor winding, A_{13}=failure of stator or armature winding, A_{14}=open circuit fault in rotor winding, A_{15}=short circuit fault in rotor winding, A_{16}=earth fault in rotor winding, A_{17}=open circuit fault in stator winding, A_{18}= short circuit fault in stator winding, A_{19}=earth fault in stator winding, A_{20}=bearing problem, A_{21}=problems in frame, A_{22}=failure due to over speed, B_1=battery discharge, B_2=broken fuse, B_3=blown fuses, B_4=no routine maintenance, B_5=due to mechanical stress, B_6=prime mover is not able to move the alternator, B_7=due to insulation failure, B_8=due to variation of speed, B_9=rotor windings are kept open, B_{10}=two or more coils in rotor winding are shorted with each other, B_{11}=coils in rotor winding connected to earth, B_{12}=stator windings are kept open, B_{13}=windings of stator are shorted with each other, B_{14}=when stator windings are earthed, B_{15}=lubricants on bearing, B_{16}=friction on bearing, B_{17}=bolts that does not holds tight stator and rotor, B_{18}=jamming of bearings in the motor frame, B_{19}=problem on shaft, B_{20}=variations of speed on prime mover, B_{21}=problem on bolts, B_{22}=no experience or lack of experience, B_{23}=no proper training, B_{24}=no proper guides, B_{25}=complexity of work, C_1=short circuit, C_2=blown fuses, C_3=alternator may be turned into a synchronous motor and draws power from the source, C_4=serious problem occur in the alternator, C_5=voltage of alternator can be doubled, C_6=causing a serious fluctuation in load, C_7=interruption of supply, C_8=increase the speed of alternator, C_9=heat produced in the coil, C_{10}=rotor field winding may burn out, C_{11}=burning the rotor field winding, C_{12}=damage the stator winding, C_{13}=heat produced in the stator winding, C_{14}=stator winding may burn out, C_{15}=sparking, C_{16}=unbalanced stator or armature current, C_{17}=problems in movement of alternator shaft, C_{18}=vibration may produced, C_{19}=failure of any of the major part of the alternator, C_{20}=loose connection of stator and rotor.
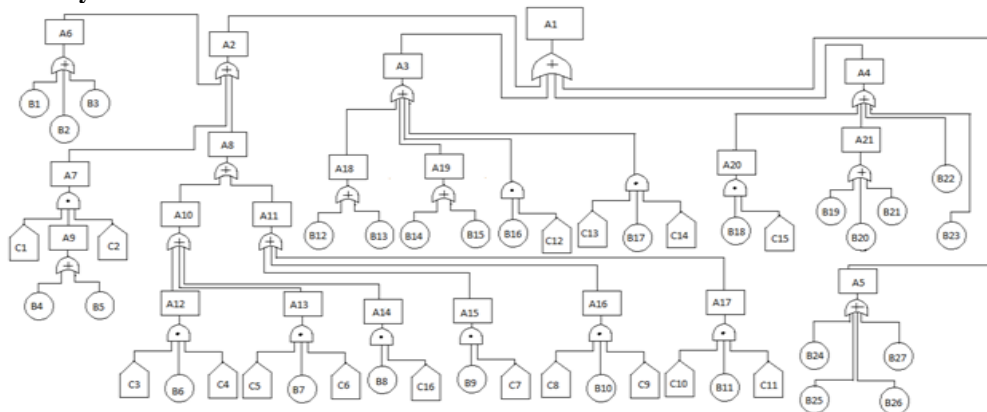
Fault Tree Of Synchronous Motor

Fig. 3. Fault tree of synchronous motor

Here, A_1=faults in synchronous motor, A_2=electrical faults, A_3=mechanical faults, A_4=faults due to other abnormal conditions, A_5=faults due to human operator, A_6=electrical system failure, A_7=electrical insulation failure, A_8=failure of windings, A_9=insulation of wire or other component, A_{10}=stator winding fault, A_{11}=rotor winding fault, A_{12}=phase-to-phase faults in stator, A_{13}=phase-to-earth faults in stator, A_{14}=inter turn

faults in stator, A_{15}=earth fault in rotor winding, A_{16}=short circuit fault in rotor winding, A_{17}=open circuit fault in rotor winding, A_{18}=bearing problems, A_{19}=problems in frame, A_{20}=local overheating, A_{21}=synchronization problems, B_1=broken fuse, B_2=blown fuses, B_3=battery discharge, B_4=no routine maintenance, B_5=due to mechanical stress, B_6=short circuit between two phases in stator winding, B_7=short circuit between one phase-to-ground in stator winding, B_8=short circuit between turns of stator winding, B_9=windings of rotor are connected to earth, B_{10}=windings of rotor are shorted with each other, B_{11}=rotor windings are kept open, B_{12}=lubricants on bearing, B_{13}=friction on bearing, B_{14}=bolts that does not holds tight stator and rotor, B_{15}=jamming of bearings in the motor frame, B_{16}= problem on bolts, B_{17}=problem on shaft, B_{18}=due to unbalanced loading, B_{19}=loss of synchronization, B_{20}=wrong synchronization, B_{21}=asynchronous running without excitation, B_{22}=moisture in the generator winding, B_{23}=leakage in hydrogen circuit, B_{24}=no experience or lack of experience, B_{25}=no proper training, B_{26}=no proper guides, B_{27}=complexity of work, C_1=short circuit, C_2=blown fuses, C_3=heat produced in the stator winding, C_4=stator winding may burn out, C_5=sparking, C_6=unbalanced stator current, C_7=burning the rotor winding, C_8=heat produced in the rotor winding, C_9=rotor or field winding may burn out, C_{10}=increase the speed of motor, C_{11}=interruption of supply, C_{12}=loose connection of stator and rotor, C_{13}=problems in movement of alternator shaft, C_{14}=vibration may produced, C_{15}=percentage regulation may decrease, C_{16}= increase 9th harmonics.

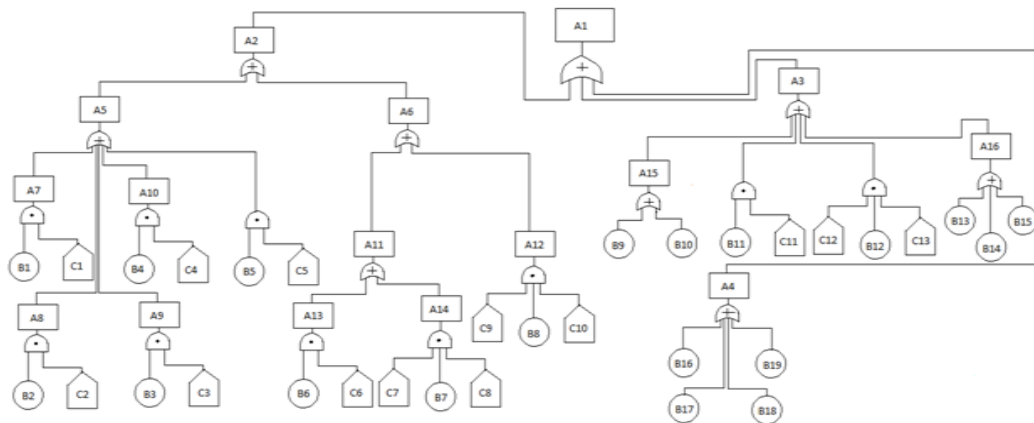## Fault Tree Of Induction Motor

Fig. 4. Fault tree of induction motor

Here, A_1=faults in induction motor, A_2=electrical faults, A_3=mechanical faults, A_4=faults due to human operator, A_5=disturbance in the supply, A_6=winding fault, A_7=over voltage or under voltage, A_8=supply voltage, A_9=supply current, A_{10}=phase reversal, A_{11}=rotor fault, A_{12}=stator fault, A_{13}=earth fault in rotor, A_{14}=short circuit fault in rotor, A_{15}=bearing problems, A_{16}=mechanical overloads, B_1=due to variation of speed, B_2=fixed supply voltage is not maintained, B_3=supply current is not maintained, B_4=interchanging of two phases, B_5=under frequency, B_6=if any rotor turns are earthed, B_7=when two turns are shorted with each other in rotor, B_8=when two or more turns are shorted with each other in stator, B_9=lubricants on bearing, B_{10}=friction on bearing, B_{11}=problem on bolts, B_{12}=problem on shaft, B_{13}=sustained overloads, B_{14}=prolonged overloads, B_{15}=stalling, B_{16}=no experience or lack of experience, B_{17}=no proper training, B_{18}=no proper guides, B_{19}=complexity of work, C_1=fluctuation in load, C_2=motor cannot start, C_3=serious problem may occur, C_4=may rotate in reverse direction, C_5=motor cannot operate, C_6=loss of excitation, C_7=local current will produced, C_8=large heat is developed which damage the motor, C_9=causes arcing, C_{10}=heat is developed, C_{11}=loose connection of stator and rotor, C_{12}=vibration may produced, C_{13}=problems in movement of motor shaft.

VI. Boolean algebra and Application to Fault Tree Analysis
Table 3. Rules of Boolean algebra

Sl. No.	Mathematical Symbolism	Engineering Symbolism	Designation
1a	$X \cap Y = Y \cap X$	$X \cdot Y = Y \cdot X$	Commutative Law
1b	$X \cup Y = Y \cup X$	$X + Y = Y + X$	Commutative Law
2a	$X \cap (Y \cap Z) = (X \cap Y) \cup Z$	$X \cdot (Y \cdot Z) = (X \cdot Y) \cdot Z$	Associative Law
2b	$X \cup (Y \cup Z) = (X \cup Y) \cup Z$	$X + (Y + Z) = (X + Y) + Z$	Associative Law
3a	$X \cap (Y \cup Z) = (X \cap Y) \cup (X \cap Z)$	$X \cdot (Y + Z) = X \cdot Y + X \cdot Z$	Distributive Law
3b	$X \cup (Y \cap Z) = (X \cup Y) \cap (X \cup Z)$	$X + Y \cdot Z = (X + Y) \cdot (X + Z)$	Distributive Law
4a	$X \cap X = X$	$X \cdot X = X$	Idempotent Law
4b	$X \cup X = X$	$X + X = X$	Idempotent Law
5a	$X \cap (X \cup Y) = X$	$X \cdot (X + Y) = X$	Law of Absorption

5b	X∪(X∩Y)=X	X+X·Y=X	Law of Absorption
6a	X∩X'=Ø	X·X'=Ø	Complementation
6b	X∪X'=Ω=I*	X·X'=Ω=I	Complementation
6c	(X')'=X	(X')'=X	Complementation
7a	(X∩Y)'=X'∪Y'	(X·Y)'=X'+Y'	De Morgan's Theorem
7b	(X∪Y)'=X'∩Y'	(X+Y)'=X'·Y'	De Morgan's Theorem
8a	Ø∩X=Ø	Ø·X=Ø	Operations with Ø and Ω
8b	Ø∪X=Ø	Ø+X=Ø	Operations with Ø and Ω
8c	Ω∩X=X	Ω·X=X	Operations with Ø and Ω
8d	Ω∪X=X	Ω+X=X	Operations with Ø and Ω
8e	Ø'=Ω	Ø'=Ω	Operations with Ø and Ω
8f	Ω'=Ø	Ω'=Ø	Operations with Ø and Ω
9a	X∪(X'∩Y)=X∪Y	X+X'·Y=X+Y	Frequently used in reduction process
9b	X'∩(X∪Y')=X'∩Y'=(X∪Y)'	X'·(XY)=X'·Y'=(X+Y)'	Frequently used in reduction process

*The symbol I is often used instead of **Ω** to designate the Universal Set. In engineering notation **Ω** is often replaced by **1** and **Ø** by **0**.

Application Of Boolean Algebra Into Fault Tree Of D.C. Machine

From the fault tree of d.c. machine shown above Fig. 1. We get, $A_1=A_2+A_3+A_4$, $A_2=A_5+A_6+A_8$, $A_5=B_1+B_2+B_3+B_4$, $A_6=C_1 \cdot A_7 \cdot C_2$, $A_7=B_5+B_6$, $A_8=A_9+A_{10}$, $A_9=A_{11}+A_{12}+A_{13}$, $A_{11}=C_3 \cdot B_7 \cdot C_4$, $A_{12}=C_5 \cdot B_8 \cdot C_6$, $A_{13}=B_9 \cdot C_7$, $A_{10}=A_{14}+A_{15}+A_{16}$, $A_{14}=B_{10} \cdot C_8$, $A_{15}=C_9 \cdot B_{11} \cdot C_{10}$, $A_{16}=C_{11} \cdot B_{12} \cdot C_{12}$, $A_3=(B_{13} \cdot C_{13})+A_{17}+A_{18}$, $A_{17}=B_{14}+B_{15}$, $A_{18}=B_{16}+B_{17}$, $A_4=B_{18}+B_{19}+B_{20}+B_{21}$

Now,

$A_2=A_5+A_6+A_8=(B_1+B_2+B_3+B_4)+(C_1 \cdot A_7 \cdot C_2)+(A_9+A_{10})=(B_1+B_2+B_3+B_4)+\{C_1 \cdot (B_5+B_6) \cdot C_2\}+\{(A_{11}+A_{12}+A_{13})+(A_{14}+A_{15}+A_{16})\}=(B_1+B_2+B_3+B_4)+\{C_1 \cdot (B_5+B_6) \cdot C_2\}+[\{(C_3 \cdot B_7 \cdot C_4)+(C_5 \cdot B_8 \cdot C_6)+(B_9 \cdot C_7)\}+\{(B_{10} \cdot C_8)+(C_9 \cdot B_{11} \cdot C_{10})+(C_{11} \cdot B_{12} \cdot C_{12})\}]=B_1+B_2+B_3+B_4+C_1 \cdot C_2 \cdot (B_5+B_6)+C_3 \cdot C_4 \cdot B_7+C_5 \cdot C_6 \cdot B_8+B_9 \cdot C_7+B_{10} \cdot C_8+C_9 \cdot C_{10} \cdot B_{11}+C_{11} \cdot C_{12} \cdot B_{12}$

And, $A_3=(B_{13} \cdot C_{13})+A_{17}+A_{18}=(B_{13} \cdot C_{13})+(B_{14}+B_{15})+(B_{16}+B_{17})=B_{13} \cdot C_{13}+B_{14}+B_{15}+B_{16}+B_{17}$

And, $A_4=B_{18}+B_{19}+B_{20}+B_{21}$

So, $A_1=A_2+A_3+A_4=[B_1+B_2+B_3+B_4+C_1 \cdot C_2 \cdot (B_5+B_6)+C_3 \cdot C_4 \cdot B_7+C_5 \cdot C_6 \cdot B_8+B_9 \cdot C_7+B_{10} \cdot C_8+C_9 \cdot C_{10} \cdot B_{11}+C_{11} \cdot C_{12} \cdot B_{12}]+[B_{13} \cdot C_{13}+B_{14}+B_{15}+B_{16}+B_{17}]+[B_{18}+B_{19}+B_{20}+B_{21}]=B_1+B_2+B_3+B_4+C_1 \cdot C_2 \cdot (B_5+B_6)+C_3 \cdot C_4 \cdot B_7+C_5 \cdot C_6 \cdot B_8+B_9 \cdot C_7+B_{10} \cdot C_8+C_9 \cdot C_{10} \cdot B_{11}+C_{11} \cdot C_{12} \cdot B_{12}+B_{13} \cdot C_{13}+B_{14}+B_{15}+B_{16}+B_{17}+B_{18}+B_{19}+B_{20}+B_{21}=B_1+B_2+B_3+B_4+C_1 \cdot C_2 \cdot B_5+C_1 \cdot C_2 \cdot B_6+C_3 \cdot C_4 \cdot B_7+C_5 \cdot C_6 \cdot B_8+B_9 \cdot C_7+B_{10} \cdot C_8+C_9 \cdot C_{10} \cdot B_{11}+C_{11} \cdot C_{12} \cdot B_{12}+B_{13} \cdot C_{13}+B_{14}+B_{15}+B_{16}+B_{17}+B_{18}+B_{19}+B_{20}+B_{21}=(B_1+B_2+B_3+B_4+B_{14}+B_{15}+B_{16}+B_{17}+B_{18}+B_{19}+B_{20}+B_{21})+(B_9 \cdot C_7+B_{10} \cdot C_8+B_{13} \cdot C_{13}+C_1 \cdot C_2 \cdot B_5+C_1 \cdot C_2 \cdot B_6+C_3 \cdot C_4 \cdot B_7+C_5 \cdot C_6 \cdot B_8+C_9 \cdot C_{10} \cdot B_{11}+C_{11} \cdot C_{12} \cdot B_{12})$

Now, let, $X=B_1+B_2+B_3+B_4+B_{14}+B_{15}+B_{16}+B_{17}+B_{18}+B_{19}+B_{20}+B_{21}$

And, $Y=B_9 \cdot C_7+B_{10} \cdot C_8+B_{13} \cdot C_{13}+C_1 \cdot C_2 \cdot B_5+C_1 \cdot C_2 \cdot B_6+C_3 \cdot C_4 \cdot B_7+C_5 \cdot C_6 \cdot B_8+C_9 \cdot C_{10} \cdot B_{11}+C_{11} \cdot C_{12} \cdot B_{12}$

Now, $A_1=X+Y$

Now, the reduction of fault tree of d.c. machine using Boolean algebra which is shown in below:
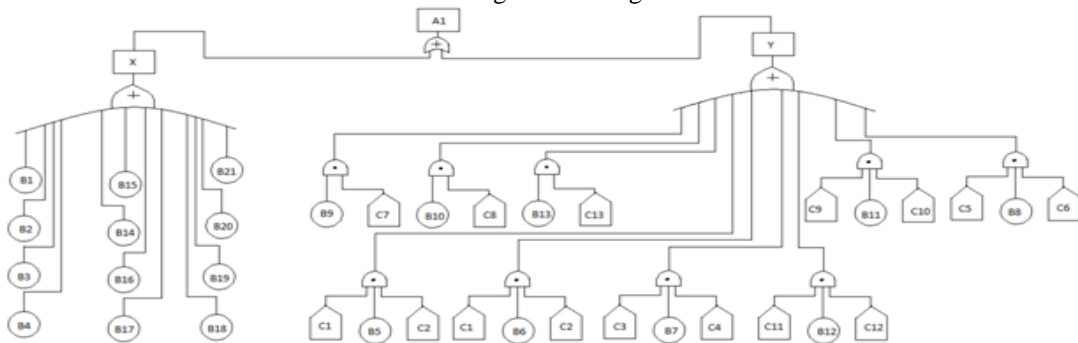

Fig. 5. Reduction of fault tree of d.c. machine using Boolean algebra

Application Of Boolean Algebra Into Fault Tree Of Alternator

From the fault tree of alternator shown above Fig. 2. We get, $A_1=A_2+A_3+A_4$, $A_2=A_5+A_6+A_7+A_8+A_9+A_{10}$, $A_5=B_1+B_2+B_3$, $A_6=C_1 \cdot A_{11} \cdot C_2$, $A_{11}=B_4+B_5$, $A_7=B_6 \cdot C_3$, $A_8=B_7 \cdot C_4$, $A_9=B_8 \cdot C_5 \cdot C_6$, $A_{10}=A_{12}+A_{13}$, $A_{12}=A_{14}+A_{15}+A_{16}$, $A_{14}=B_9 \cdot C_7 \cdot C_8$, $A_{15}=B_{10} \cdot C_9 \cdot C_{10}$, $A_{16}=B_{11} \cdot C_{11}$, $A_{13}=A_{17}+A_{18}+A_{19}$, $A_{17}=B_{12} \cdot C_{12}$, $A_{18}=B_{13} \cdot C_{13} \cdot C_{14}$, $A_{19}=B_{14} \cdot C_{15} \cdot C_{16}$, $A_3=A_{20}+A_{21}+A_{22}+(B_{21} \cdot C_{20})+(B_{19} \cdot C_{17} \cdot C_{18})$, $A_{20}=B_{15}+B_{16}$, $A_{21}=B_{17}+B_{18}$, $A_{22}=B_{20} \cdot C_{19}$, $A_4=B_{22}+B_{23}+B_{24}+B_{25}$

Now,

$A_2=A_5+A_6+A_7+A_8+A_9+A_{10}=(B_1+B_2+B_3)+(C_1 \cdot A_{11} \cdot C_2)+(B_6 \cdot C_3)+(B_7 \cdot C_4)+(B_8 \cdot C_5 \cdot C_6)+(A_{12}+A_{13})=(B_1+B_2+B_3)+\{C_1 \cdot (B_4+B_5) \cdot C_2\}+(B_6 \cdot C_3)+(B_7 \cdot C_4)+(B_8 \cdot C_5 \cdot C_6)+\{(A_{14}+A_{15}+A_{16})+(A_{17}+A_{18}+A_{19})\}=(B_1+B_2+B_3)+\{C_1 \cdot C_2 \cdot (B_4+B_5)\}$

+(
$B_6 \cdot C_3)+(B_7 \cdot C_4)+(B_8 \cdot C_5 \cdot C_6)+\{(B_9 \cdot C_7 \cdot C_8+B_{10} \cdot C_9 \cdot C_{10}+B_{11} \cdot C_{11})+(B_{12} \cdot C_{12}+B_{13} \cdot C_{13} \cdot C_{14}+B_{14} \cdot C_{15} \cdot C_{16})\}=B_1+B_2+B_3+$
$(B_4 \cdot C_1 \cdot C_2)+(B_5 \cdot C_1 \cdot C_2)+(B_6 \cdot C_3)+(B_7 \cdot C_4)+(B_8 \cdot C_5 \cdot C_6)+(B_9 \cdot C_7 \cdot C_8)+(B_{10} \cdot C_9 \cdot C_{10})+(B_{11} \cdot C_{11})+(B_{12} \cdot C_{12})+(B_{13} \cdot C_{13} \cdot C_{14})$
$+(B_{14} \cdot C_{15} \cdot C_{16})=B_1+B_2+B_3+(B_6 \cdot C_3)+(B_7 \cdot C_4)+(B_{11} \cdot C_{11})+(B_{12} \cdot C_{12})+(B_4 \cdot C_1 \cdot C_2)+(B_5 \cdot C_1 \cdot C_2)+(B_8 \cdot C_5 \cdot C_6)+(B_9 \cdot C_7 \cdot C_8)+$
$(B_{10} \cdot C_9 \cdot C_{10})+(B_{13} \cdot C_{13} \cdot C_{14})+(B_{14} \cdot C_{15} \cdot C_{16})$
And, $A_3= B_{20}+B_{21}+B_{22}+(B_{21} \cdot C_{20})+(B_{19} \cdot C_{17} \cdot C_{18}) =(B_{15}+B_{16})+(B_{17}+B_{18})+(B_{20} \cdot C_{19})+(B_{21} \cdot C_{20})+(B_{19} \cdot C_{17} \cdot C_{18})$
And, $A_4=B_{22}+B_{23}+B_{24}+B_{25}$
So, $A_1=A_2+A_3+A_4= B_1+B_2+B_3+ B_{15}+B_{16}+ B_{17}+B_{18}+ B_{22}+B_{23}+B_{24}+B_{25}+(B_6 \cdot C_3)+(B_7 \cdot C_4)+(B_{11} \cdot C_{11})+(B_{12} \cdot C_{12})+$
$(B_{20} \cdot C_{19})+(B_{21} \cdot C_{20})+(B_4 \cdot C_1 \cdot C_2)+(B_5 \cdot C_1 \cdot C_2)+(B_8 \cdot C_5 \cdot C_6)+(B_9 \cdot C_7 \cdot C_8)+(B_{10} \cdot C_9 \cdot C_{10})+(B_{13} \cdot C_{13} \cdot C_{14})+(B_{14} \cdot C_{15} \cdot C_{16})+$
$(B_{19} \cdot C_{17} \cdot C_{18})$
Now, let, $X= B_1+B_2+B_3+ B_{15}+B_{16}+ B_{17}+B_{18}+ B_{22}+B_{23}+B_{24}+B_{25}$
And,$Y=(B_6 \cdot C_3)+(B_7 \cdot C_4)+(B_{11} \cdot C_{11})+(B_{12} \cdot C_{12})+(B_{20} \cdot C_{19})+(B_{21} \cdot C_{20})+(B_4 \cdot C_1 \cdot C_2)+(B_5 \cdot C_1 \cdot C_2)+(B_8 \cdot C_5 \cdot C_6)+(B_9 \cdot C_7 \cdot C_8)$
$+(B_0 \cdot C_9 \cdot C_{10})+(B_{13} \cdot C_{13} \cdot C_{14})+(B_{14} \cdot C_{15} \cdot C_{16})+(B_{19} \cdot C_{17} \cdot C_{18})$
Now, $A_1=X+Y$

Now, the reduction of fault tree of alternator using Boolean algebra which is shown in below:
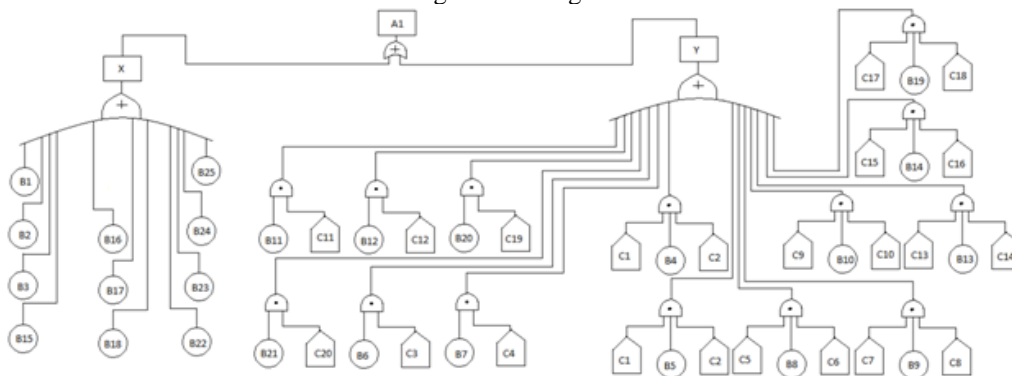

Fig. 6. Reduction of fault tree of alternator using Boolean algebra

Application Of Boolean Algebra Into Fault Tree Of Synchronous Motor

From the fault tree of synchronous motor shown above Fig. 3. We get, $A_1=A_2+A_3+A_4+A_5$, $A_2= A_6 + A_7 +A_8$, $A_6=B_1+B_2+B_3$, $A_7=A_9 \cdot C_1 \cdot C_2$, $A_9=B_4+B_5$, $A_8=A_{10}+A_{11}$, $A_{10}=A_{12}+A_{13}+A_{14}$, $A_{12}= B_6 \cdot C_3 \cdot C_4$, $A_{13}= B_7 \cdot C_5 \cdot C_6$, $A_{14}= B_8 \cdot C_{16}$, $A_{11}=A_{15}+ A_{16} +A_{17}$, $A_{15}=B_9 \cdot C_7$, $A_{16}=B_{10} \cdot C_8 \cdot C_9$, $A_{17}=B_{11} \cdot C_{10} \cdot C_{11}$, $A_3=A_{18}+A_{19}+(B_{16} \cdot C_{12})+(B_{17} \cdot C_{13} \cdot C_{14})$, $A_{18}=B_{12}+B_{13}$, $A_{19}=B_{14}+B_{15}$, $A_4=A_{20} +A_{21} +B_{22}+B_{23}$, $A_{20}=B_{18} \cdot C_{15}$, $A_{21}=B_{19}+B_{20}+B_{21}$, $A_5=B_{24}+B_{25}+B_{26}+B_{27}$
Now,
$A_2=A_6+A_7+A_8=(B_1+B_2+B_3)+(A_9 \cdot C_1 \cdot C_2)+(A_{10}+A_{11})=(B_1+B_2+B_3)+\{(B_4+B_5) \cdot C_1 \cdot C_2\}+\{(A_{12}+A_{13}+A_{14})+(A_{15}+A_{16}$
$+A_{17})\}=(B_1+B_2+B_3)+(B_4 \cdot C_1 \cdot C_2+B_5 \cdot C_1 \cdot C_2)+[\{(B_6 \cdot C_3 \cdot C_4)+(B_7 \cdot C_5 \cdot C_6)+(B_8 \cdot C_{16})\}+\{(B_9 \cdot C_7)+(B_{10} \cdot C_8 \cdot C_9)+(B_{11} \cdot C_{10} \cdot$
$C_{11})\}]=B_1+B_2+B_3+(B_8 \cdot C_{16})+(B_9 \cdot C_7)+(B_4 \cdot C_1 \cdot C_2)+(B_5 \cdot C_1 \cdot C_2)+(B_6 \cdot C_3 \cdot C_4)+(B_7 \cdot C_5 \cdot C_6)+(B_{10} \cdot C_8 \cdot C_9)+ (B_{11} \cdot C_{10} \cdot C_{11})$
And, $A_3=A_{18}+A_{19}+(B_{16} \cdot C_{12})+(B_{17} \cdot C_{13} \cdot C_{14}) =(B_{12}+B_{13})+(B_{14}+B_{15})+(B_{16} \cdot C_{12})+(B_{17} \cdot C_{13} \cdot C_{14}) =B_{12}+B_{13}+B_{14}+B_{15}+$
$(B_{16} \cdot C_{12})+(B_{17} \cdot C_{13} \cdot C_{14})$
And, $A_4= A_{20}+A_{21}+B_{22}+B_{23}=(B_{18} \cdot C_{15})+(B_{19}+B_{20}+B_{21})+B_{22}+B_{23}=B_{19}+B_{20}+B_{21}+B_{22}+B_{23}+(B_{18} \cdot C_{15})$
And, $A_5= B_{24}+B_{25}+B_{26}+B_{27}$
So,$A_1=A_2+A_3+A_4+A_5=\{B_1+B_2+B_3+(B_8 \cdot C_{16})+(B_9 \cdot C_7)+(B_4 \cdot C_1 \cdot C_2)+(B_5 \cdot C_1 \cdot C_2)+(B_6 \cdot C_3 \cdot C_4)+(B_7 \cdot C_5 \cdot C_6)+(B_{10} \cdot C_8 \cdot C_9$
$)+(B_{11} \cdot C_{10} \cdot C_{11})\}+\{B_{12}+B_{13}+B_{14}+B_{15}+(B_{16} \cdot C_{12})+(B_{17} \cdot C_{13} \cdot C_{14})\}+\{B_{19}+B_{20}+B_{21}+B_{22}+B_{23}+(B_{18} \cdot C_{15})\}+\{B_{24}+B_{25}+B_{26}+B_{27}\}=B_1+B_2+B_3+B_{12}+B_{13}+B_{14}+B_{15}+B_{19}+B_{20}+B_{21}+B_{22}+B_{23}+B_{24}+B_{25}+B_{26}+B_{27}+(B_8 \cdot C_{16})+(B_9 \cdot C_7)+(B_{16} \cdot C_{12})+($
$B_{18} \cdot C_{15})+(B_4 \cdot C_1 \cdot C_2)+(B_5 \cdot C_1 \cdot C_2)+(B_6 \cdot C_3 \cdot C_4)+(B_7 \cdot C_5 \cdot C_6)+(B_{10} \cdot C_8 \cdot C_9)+ (B_{11} \cdot C_{10} \cdot C_{11})+(B_{17} \cdot C_{13} \cdot C_{14})$
Now, let, $X= B_1+B_2+B_3+ B_{12}+B_{13}+ B_{14}+B_{15}+ B_{19} + B_{20} +B_{21}+ B_{22}+B_{23}+ B_{24} + B_{25} +B_{26}+B_{27}$
And,$Y=(B_8 \cdot C_{16})+(B_9 \cdot C_7)+(B_{16} \cdot C_{12})+(B_{18} \cdot C_{15})+(B_4 \cdot C_1 \cdot C_2)+(B_5 \cdot C_1 \cdot C_2)+(B_6 \cdot C_3 \cdot C_4)+(B_7 \cdot C_5 \cdot C_6)+(B_{10} \cdot C_8 \cdot C_9)+(B_{11} \cdot$
$C_{10} \cdot C_{11})+(B_{17} \cdot C_{13} \cdot C_{14})$
Now, $A_1=X+Y$
Now, the reduction of fault tree of synchronous motor using Boolean algebra which is shown in below:
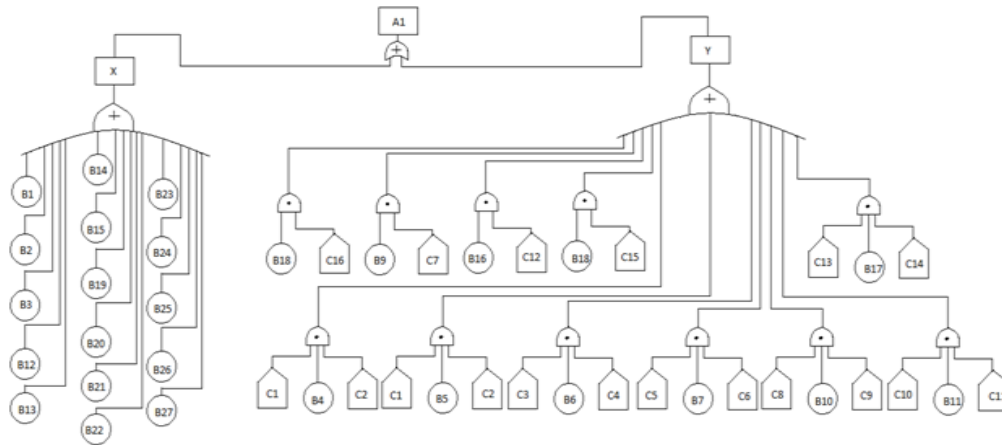
Fig. 7. Reduction of fault tree of synchronous motor using Boolean algebra

Application Of Boolean Algebra Into Fault Tree Of Induction Motor

From the fault tree of synchronous motor shown above Fig. 4. We get, $A_1=A_2+A_3+A_4$, $A_2=A_5+A_6$, $A_5=A_7+A_8+A_9+A_{10}+(B_5 \cdot C_5)$, $A_7=B_1 \cdot C_1$, $A_8=B_2 \cdot C_2$, $A_9=B_3 \cdot C_3$, $A_{10}=B_4 \cdot C_4$, $A_6=A_{11}+A_{12}$, $A_{11}=A_{13}+A_{14}$, $A_{13}=B_6 \cdot C_6$, $A_{14}=B_7 \cdot C_7 \cdot C_8$, $A_{12}=B_8 \cdot C_9 \cdot C_{10}$, $A_3=A_{15}+A_{16}+(B_{11} \cdot C_{11})+(B_{12} \cdot C_{12} \cdot C_{13})$, $A_{15}=B_9+B_{10}$, $A_{16}=B_{13}+B_{14}+B_{15}$, $A_4=B_{16}+B_{17}+B_{18}+B_{19}$

Now, $A_2=A_5+A_6=\{A_7+A_8+A_9+A_{10}+(B_5 \cdot C_5)\}+\{A_{11}+A_{12}\}=\{(B_1 \cdot C_1)+(B_2 \cdot C_2)+(B_3 \cdot C_3)+(B_4 \cdot C_4)+(B_5 \cdot C_5)\}+\{(A_{13}+A_{14})+(B_8 \cdot C_9 \cdot C_{10})\}=(B_1 \cdot C_1)+(B_2 \cdot C_2)+(B_3 \cdot C_3)+(B_4 \cdot C_4)+(B_5 \cdot C_5)+(B_6 \cdot C_6)+(B_7 \cdot C_7 \cdot C_8)+(B_8 \cdot C_9 \cdot C_{10})$

And, $A_3=A_{15}+A_{16}+(B_{11} \cdot C_{11})+(B_{12} \cdot C_{12} \cdot C_{13})=(B_9+B_{10})+(B_{11} \cdot C_{11})+(B_{12} \cdot C_{12} \cdot C_{13})+B_{13}+B_{14}+B_{15}$

And, $A_4=(B_{16}+B_{17}+B_{18}+B_{19})$

So,

$A_1=A_2+A_3+A_4=\{(B_1 \cdot C_1)+(B_2 \cdot C_2)+(B_3 \cdot C_3)+(B_4 \cdot C_4)+(B_5 \cdot C_5)+(B_6 \cdot C_6)+(B_7 \cdot C_7 \cdot C_8)+(B_8 \cdot C_9 \cdot C_{10})\}+\{(B_9+B_{10})+(B_{11} \cdot C_{11})+(B_{12} \cdot C_{12} \cdot C_{13})+(B_{13}+B_{14}+B_{15})\}+\{B_{16}+B_{17}+B_{18}+B_{19}\}=B_9+B_{10}+B_{13}+B_{14}+B_{15}+B_{16}+B_{17}+B_{18}+B_{19}+(B_1 \cdot C_1)+(B_2 \cdot C_2)+(B_3 \cdot C_3)+(B_4 \cdot C_4)+(B_5 \cdot C_5)+(B_6 \cdot C_6)+(B_{11} \cdot C_{11})+(B_7 \cdot C_7 \cdot C_8)+(B_8 \cdot C_9 \cdot C_{10})+(B_{12} \cdot C_{12} \cdot C_{13})$

Now, let, $X=B_9+B_{10}+B_{13}+B_{14}+B_{15}+B_{16}+B_{17}+B_{18}+B_{19}$

And, $Y=(B_1 \cdot C_1)+(B_2 \cdot C_2)+(B_3 \cdot C_3)+(B_4 \cdot C_4)+(B_5 \cdot C_5)+(B_6 \cdot C_6)+(B_{11} \cdot C_{11})+(B_7 \cdot C_7 \cdot C_8)+(B_8 \cdot C_9 \cdot C_{10})+(B_{12} \cdot C_{12} \cdot C_{13})$

Now, $A_1=X+Y$

Now, the reduction of fault tree of induction motor using Boolean algebra which is shown in below:
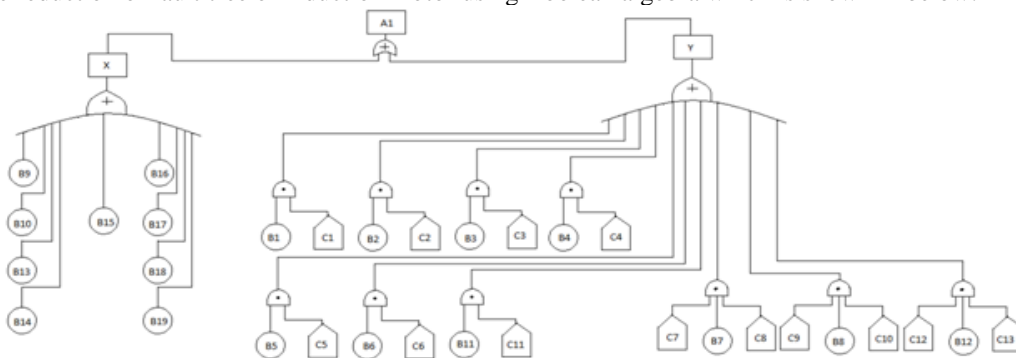

Fig. 8. Reduction of fault tree of induction motor using Boolean algebra

VII. Conclusion

It is important to understand that a fault tree is not a model of all possible system failures of all possible causes for system failure. A fault tree is tailored to its top event which corresponds to some particular system failure mode, and the fault tree thus includes only those faults that contribute to this top event. Moreover, these faults are not exhaustive-they cover only the most credible faults as assessed by the analyst. It is also important to point out that a fault tree is not in itself a quantitative model. It is a quantitative model that can be evaluated quantitatively and often is. This qualitative aspect, of course, is true of virtually all varieties of system models. The fact that a fault tree is a particularly convenient model to quantify does not change the qualitative nature of the model itself.

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