Failure cause identification of tribo-mechanical systems using fault tree—a digraph approach

Rakesh Sehgal[a]*, O.P. Gandhi[b], S. Angra[c]

[a] [illegible]
[b] *ITMMEC, IIT, Delhi 110 016 India*
[c] *Department of Mechanical Engineering, REC, Kurukshetra 136 119 India*

Received 7 July 2000; accepted 14 April 2003

Abstract

A procedure for the failure cause identification of tribo-mechanical systems is presented based on fault-tree using a digraph approach. A variable-event system digraph for a tribo-mechanical system is suggested which takes into account structure of the system. A top event or undesirable event for the system is then defined and the fault-tree for this top event is deduced from the digraph by back-tracking it. The analysis of the fault-tree aids the design and practising engineers in design and development of reliable, safe and productive tribo-mechanical systems. The methodology is applied to journal bearing oil supply system in a power plant application.

Keywords: Tribo-mechanical system; Top event; Digraph model; Fault-tree synthesis

1. Introduction

A tribo-mechanical system is a combination of various tribo-components such as pumps, valves, filters, bearings; and non tribo-components such as heat exchangers, sensors, controllers etc. and these form a part of almost all industrial installations including power plants. The tribo-process of translation and transformation of functional quantities or parameters e.g. motion, work, transfer of materials (fluids, solids) within and between various components make these vulnerable to failures and breakdowns. The failure cause identification of these systems is desirable for satisfactory, safe and reliable operation of these systems. Literature [1-5] indicates clearly that a satisfactory description of a tribo-mechanical system is the one, which considers its structure i.e., its components and their connections. This is desirable for understanding the system failures as well.

Most of the modern industrial plants or installations are monitored based on the value of one or more operating parameters e.g. temperature, pressure, flow rate, speed etc. or abnormality in vibration and acoustic emission levels. The rise or fall of the value of these parameters beyond a certain value indicates abnormal event or condition of the system [6,7]. The occurrence of any such undesirable or top event gives an indication of the intending failure, which if analysed properly may lead to uncover certain basic or primary events responsible for it. The logical relationship of the top event with the primary or primal events is of interest to the designers or plant engineers, as the identification of these primal events will provide directions to the development of more reliable systems at the design stage and may also prompt the plant engineers to initiate suitable corrective or protective measures at the operational stage.

In case of chemical systems and process industries, a conventional approach available and used extensively to relate top event with the primal events is the fault-tree [8-15]. Despite the intrinsic limitations of this technique, especially related to the detailed modeling of physical phenomena and dynamic behaviour, fault-tree modeling allows one to easily breakdown a complex system in simpler subsystems and to manage complexity [16-20].

The fault-tree for a top event can be obtained with or without the construction of a digraph model. Fault-tree obtained without constructing a digraph model for the system is rather simpler, represents fewer primal events and does not take system structure explicitly into account. Whereas, a fault-tree deduced from a digraph model for the system is exhaustive and takes the system structure explicitly into account. Graph theory [21-24] is a well-established systems approach to represent structure in terms of a graph or digraph model. Structure or topology may be physical or abstract. Physical structure of a system implies its components/assemblies and their connections while an abstract structure relates an undesirable or top event with its primal events.

Literature also reveals that the synthesis of fault-trees for the failure cause identification using digraph models have mainly been limited to chemical systems and have not been applied to tribo-mechanical systems. In this paper, this approach is extended to tribo-mechanical systems. A variable-event system digraph for a tribo-mechanical system has been defined. This digraph is then used to deduce the fault-tree for a top event of the tribo-mechanical system. The analysis of the fault-tree thus obtained is useful in determining the paths whereby primal events (tribological or non-tribological) can propagate through the system to cause the top event. The major steps of failure cause identification methodology are listed and developed in the subsequent sections.

2. Failure causes identification—main steps

The main steps suggested for failure causes identification of tribo-mechanical systems are:

1. Component modeling and variable-event component digraphs development
2. Developing variable-event system digraph
3. Defining top event for the system
4. Fault-tree synthesis for the top event using the digraph

The failure cause identification procedure is developed below step-by-step.

2.1. Component modeling and variable-event component digraphs development

In order to develop variable-event system digraph of a tribo-mechanical system, one needs to construct input-output and digraph models for all the components of the system. The modeling of the individual components requires the identification of all the system or component variables (e.g. temperature, pressure, flow rate, speed etc.) which are transferred through it, their relative gain (+ve, 0, — ve) both when the component is working and when it is failed, and the type of failures/events (tribological and non-tribological e.g. coolant line choked, filter choked, pump shutdown etc.). This information is obtained by using system topology, physical conservation laws and physical models.

The components of the system are first of all represented by their input-output models. These consist of a symbolic representation of the components and a table in which input-output relations i.e., component variables and failure events are represented. The gain between two variables (or failure event-variables) is given at the intersection of the row and column corresponding to the first and second variables (or events) respectively. If a deviation in one variable or occurrence of an event causes a deviation (none, moderate, or high) in a second variable, then a number 0, 1, or 10 is assigned to represent gain. The sign of the number (+, —) reflects the relative direction of the deviations. If they are in similar direction, the number is positive, otherwise it is negative.

The input-output model for a bearing 2 in a system is shown in Fig. 1(a), (b). In Fig. 1(a), the bearing is numbered 2 within a square box, whereas input-output streams (e.g. 2 or 3) are shown within circles. During normal working, there is a gain of +1 between T2 i.e., temperature of input oil stream of the bearing and T3 i.e., temperature of output oil stream of the bearing. This is shown in the first row of the table, Fig. 1(b). The gain between pressure P2 and mass flow rate M3 and between M2 and M3 is also +1, as depicted in the 2nd and 3rd row of the table. The failure of bearing e.g. bearing seizure will be due to stoppage of the flow and thus results the gain in M2 to reduce from +1 to 0 (zero). This is shown in the fourth row of the table. The input-output model of the component (bearing 2) is then represented as its variable-event component digraph for better understanding of variable-variable and event-variable relationships of the component (bearing 2). The nodes of the digraph represent system variables (e.g. temperature, pressure, flow rate etc.) and certain types of failures/events (e.g. bearing seizure, pump shutdown etc.), and the edges show their relations or interactions. If a deviation in one variable or occurrence of a failure/event causes a deviation in a second variable (as indicated in the input-output model), then a directed edge is drawn from the node representing the first variable/event to the node representing the second variable. A number (0, 1, 10) and sign (+, —) is assigned to the edge depending upon the magnitude and direction of the second deviation relative to the first. If the deviation in second variable is very small compared with the first, no edge connects the nodes. However, edges with zero gain will be drawn only if these edges represent failures.

The variable-event digraph for the bearing based on above discussion is represented in Fig. 1(c).

In this case, it is not possible to quantify certain failure causes (tribological or non-tribological), the input-output

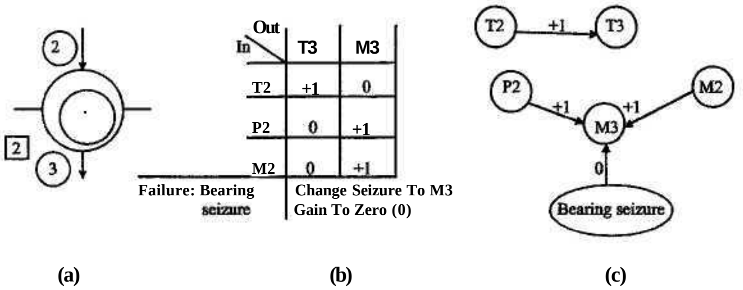


Fig. 1. (a) Symbolic representation of bearing (2) in a system, (b) input-output model and (c) variable-event component digraph.

models for such failure causes or events are not required to be represented and the nodes representing the failure causes or events are connected by un-numbered (i.e., representing no gain) directed edges in the digraph. For example, insufficient lubrication may cause seizure of the motor bearing leading to failure of lube oil pump motor and finally lube oil pump shutdown in the lubrication system. This part of variable-event component digraph for the lube oil pump based on above discussion is shown in Fig. 2.

The variable-event component digraphs obtained for individual components of tribo-mechanical systems are combined to obtain variable-event system digraph for the system.

Mathematically, variable-event system digraph, G_{ves}, for a tribo-mechanical system is defined as:

$G_{ves} = \{N,E\}$

Where $N= \{n_1,n_2,\ldots ,n_i\}_{i= 1 \text{ to } n}$ is a set of nodes and represent components variables or failure causes or failure events and $E = \{e_{ij}{:}g\}_{ij = 1 to n}$ with $i \pm j$ and $g = \pm 1, 0, \pm 10$ is a set of edges representing the deviation relationship among the nodes. The edge $e_{ij}{:}g$ with i =£ j represent the interconnection among the nodes i and j with gain, $g(g = \pm 1, 0, \pm 10)$ between the variables/events.

The variable-event system digraph obtained is a map of the variable-variable, variable-event or cause-event deviation relationship of the tribo-mechanical system. Thus, the digraph reflects the behaviour of the components involved in terms of system structure. This digraph is used for the synthesis of a fault tree for a top event of the system.

2.2. Variable-event system digraph construction

The main steps to develop variable-event system digraph of a tribo-mechanical system are as below:

1. Number the components and streams of the tribo-mechanical system. Enclose these in square box and circle respectively. Identify all the variables of the individual components (input and output streams) both when the component is working and when it is failed, and also the failure(s) of the components. (Refer section—Component modeling and variable-event component digraphs development).
2. Quantify deviations in the system or component variables in terms of magnitude (e.g. 0, 1, 10) and direction due to the deviations (+ or —). (Refer section—Component modeling and variable-event component digraphs development).
3. Develop the input-output models for all the system components as per discussions in section—Component modeling and variable-event component digraphs development.
4. Construct variable-event component digraphs for all the components of system by connecting the nodes assigned to variables, failure events and failure causes through directed edges and the gain as listed in the input-output model tables obtained in steps 2 and 3 and as per discussions in section—Component modeling and variable-event component digraphs development. Note that, the edges with zero (0) gain are drawn only if these edges represent failures.
5. Identify the failure causes (tribological or non-tribological) which are not possible to be quantified but lead to a failure event. Interconnect these failure causes and also connect them to the appropriate nodes (obtained in step 4) representing component failures through un-numbered directed edges. (Refer section—Component modeling and variable-event component digraphs development).
6. Combine the variable-event component digraphs obtained for individual components in steps 4 and 5 to obtain variable-event system digraph. This digraph will represent variable-variable, variable-event or cause-event relationships for the system.

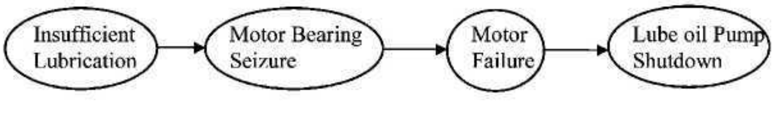


Fig. 2. Variable-event component digraph for lube oil pump shutdown.

This may contain negative feedback loops or feedforward loops or a combination of the two. A negative feedforward loop is a path which starts and ends at the same node and for which the product of the normal gains is negative. A negative feedforward loop is a structure within the system whereby one system variable affects another with opposite gain on different paths in the system. This loop can be identified if there are two or more paths from one node to another node and the sign of the product of the normal gains on one path is different from that of the others.

The variable-event system digraph thus obtained is used for the synthesis of a fault-tree for a top event of the tribo-mechanical system. This graph does not depend upon any particular top event considered. It, however, shows explicitly the physical structure and includes control loops of the system. Before taking up the fault-tree synthesis, a top event for the system is required to be defined and this is done in the following subsection.

2.3. *Defining a top event*

A top event or undesirable event for a tribo-mechanical system may represent variation in the value of any system or component variable (e.g. temperature, i.e., high temperature). This affects normal working of the system or will cause partial or complete system failure or breakdown. The top event may also include any abnormal event or failure condition (e.g. motor failure, pump shutdown etc.). For certain systems, for example, high temperature of the oil/fluid entering a particular component could be the top event, whereas in some other case this may be low oil or fluid level and/or pressure.

Once a top event for a system is defined, the fault-tree synthesis for this top event is carried out and is explained in the next section. In practice, a system may have more than one top event.

2.4. *Fault-tree synthesis using variable-event system digraph*

The variable-event system digraph developed earlier in section—Variable-event system digraph construction is used for synthesis of the fault-tree for the top event of the tribo-mechanical system defined in the preceding section employing the algorithm suggested by Lapp and Power [12]. The salient steps of the algorithm are:

1. Locate all control loops [12,25]—negative feedback and feedforward in the variable-event system digraph. Refer discussion under step 6 under the section—Variable event system digraph construction.
2. Select the node representing the top event.
3. Search each edge directed to the selected node which is a cause of the top event. Determine also the local causes of this event in the digraph. These are the inputs to the selected node.
4. Delete any local causes which violate consistency. Consistency means that two mutually exclusive events cannot occur at the same time. For example, consistency requires that T4 (+1) not be traced to T4 (—1) nor to T4 (0). Any inconsistent events that are generated in the course of the synthesis must be deleted. All generated events must be checked for the consistency.
5. Select the appropriate logical operator (AND, OR, etc.) depending on whether negative feedback or feedforward loops pass through the current node [12]. Use the appropriate operator to connect the remaining local causes. If negative feedback or feedforward loops are involved, store the appropriate event for later consistency checks.
6. Return to step 3 for any undeveloped event. If only primary events remain, stop.

The synthesis of a fault-tree using variable-event system digraph saves considerable time and leads to a unique fault-tree for the system top event. The fault-tree obtained by using the above algorithm will be quite exhaustive and will provide direction for failure cause identification and thus help the practising engineers to initiate corrective action for prevention of the system top event.

The methodology discussed above is applied in the next section to a journal bearing oil supply system being used in a power plant.

3. Example: journal bearing oil supply system

The journal bearing oil supply system is used to supply lubricating oil at requisite temperature, pressure and flow rate to the primary fan bearings in a power plant application for their efficient operation. Fig. 3 shows the journal bearing oil supply system with temperature feedback loop being used for lubricating and cooling primary fan bearings in one of the thermal power plants in India. Oil from the tank (1) is pumped through a lube oil pump (2) after passing it through an oil strainer(s), which is then cooled in a heat exchanger (3) to a requisite constant temperature. The maintenance of constant output temperature is achieved using a feedback loop containing temperature sensor (4), temperature controller (9) and coolant supply valve (10). The inflow of the coolant (water) into heat exchanger (3) is controlled by appropriate valve (10) action. In other words, the rate of flow of coolant into the heat exchanger is controlled so as to maintain bearing (7) inlet oil temperature constant. The requisite supply pressure and flow rate of the oil into the bearing are achieved by manual control of the oil supply valve (6) and bypass valve (8) depending upon the load

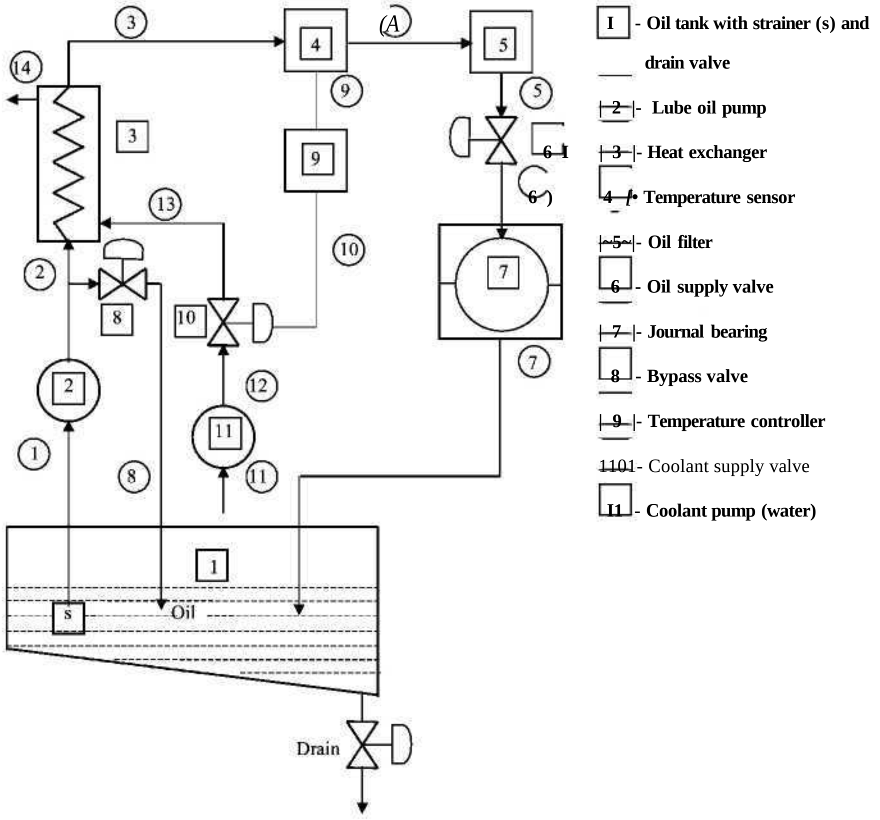
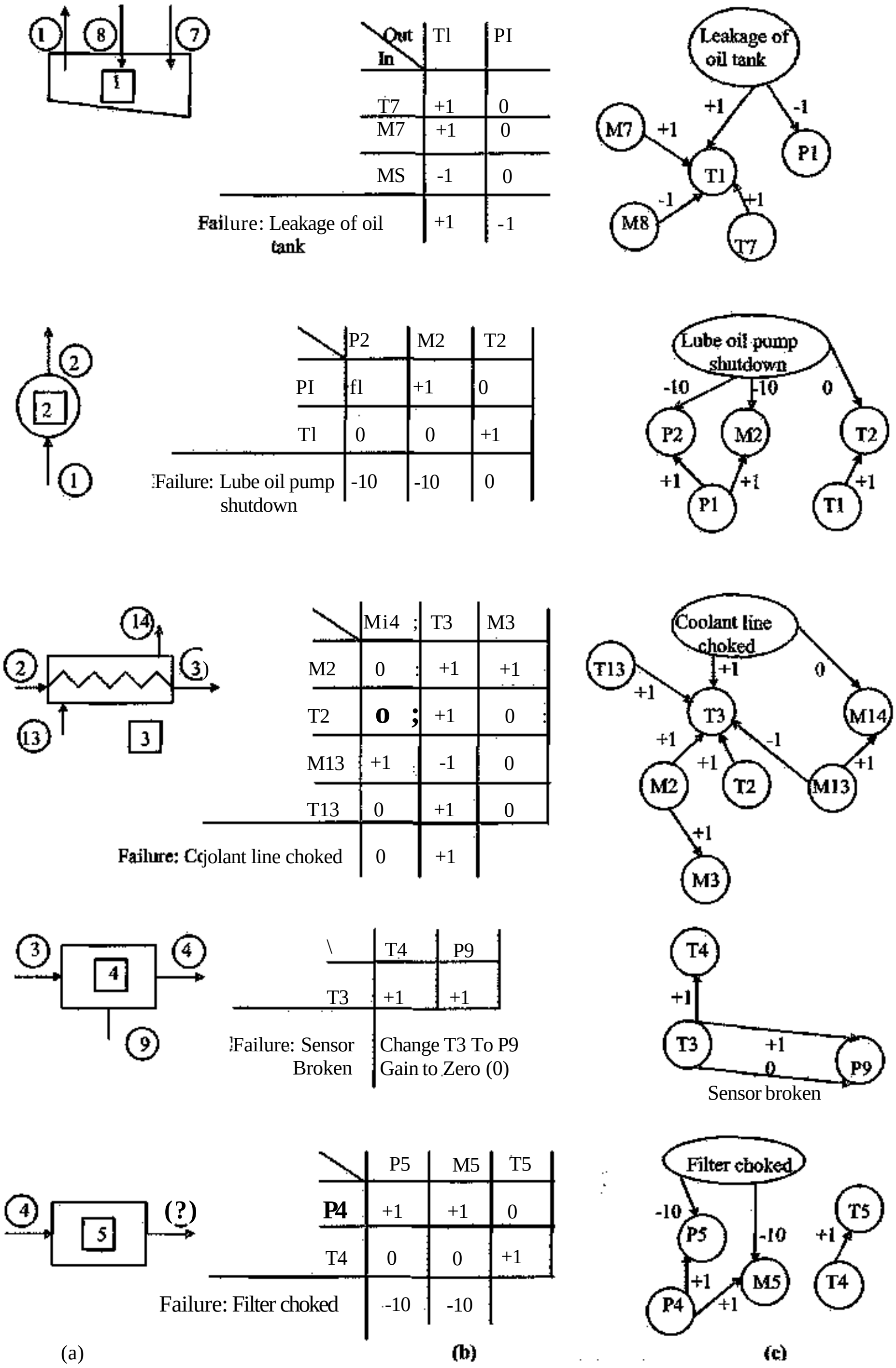


Fig. 3. Journal bearing oil supply system with temperature feedback loop.

on the bearing and operating speed. Coolant pump (11) is used to feed coolant into heat exchanger (3). The cool oil from the heat exchanger is filtered in a duplex type filter (5) before supplying it to the bearing (7) through valve (6).

Consider developing a variable-event system digraph for the journal bearing oil supply system in order to develop the fault-tree for a top event of the system. The procedure discussed in section—Variable-event system digraph construction is applied step-wise to develop the variable-event system digraph for the oil supply system as given below.

1. All components and streams of the oil supply system shown in Fig. 3 are numbered. The components are numbered (1 to 11) within square boxes whereas the streams are numbered (1 to 14) within circles. Temperature, pressure, flow rate of oil and flow rate of coolant (water) are identified as system variables of the journal bearing oil supply system. These are to be represented as nodes in the variable-event system digraph of the system. The notation used to describe deviations in these variables are T, P, M denoting deviations in temperature, pressure and mass flow rate respectively.
2. The magnitude of the deviation of the variables identified in step 1 is denoted by 0, 1, 10 (none, moderate, very large) and their relative direction of deviation is denoted by '+' and '—' (positive or negative). As an example, let there be a large decrease in mass flow rate of stream 14, the notation to describe this deviation is represented as M14 (—10).
3. The input-output models for all the components of the system are developed as per discussions in section—Component modeling and variable-event component digraphs development and are shown in Fig. 4(a)-(c).
4. The variable-event component digraphs for all system components are developed using the input-output model tables obtained in step 3 and as per discussions in section—Component modeling and variable-event component digraphs development. These are also shown in Fig. 4(a)-(c).
5. Coolant pump and lube oil pump shutdown is attributed to three causes: Pump failure, coupling broken and motor failure. Further pump failure can be traced to gear seizure (if it is gear pump) or bearing failure (seizure). Both these events are then traced to contaminated lubricant, insufficient lubrication (tribological events). Similarly coupling broken can be attributed to shaft misalignment or over loading (non-tribological events). The motor failure can be traced to overloading and bearing failure (seizure). Motor bearing failure is also attributed to the same four events as in case of pump bearing failure i.e., contaminated lubricant, insufficient lubrication (tribological events), overload, displaced or bent rotor



Out / In	Tl	PI
T7	+1	0
M7	+1	0
MS	-1	0
Failure: Leakage of oil tank	+1	-1

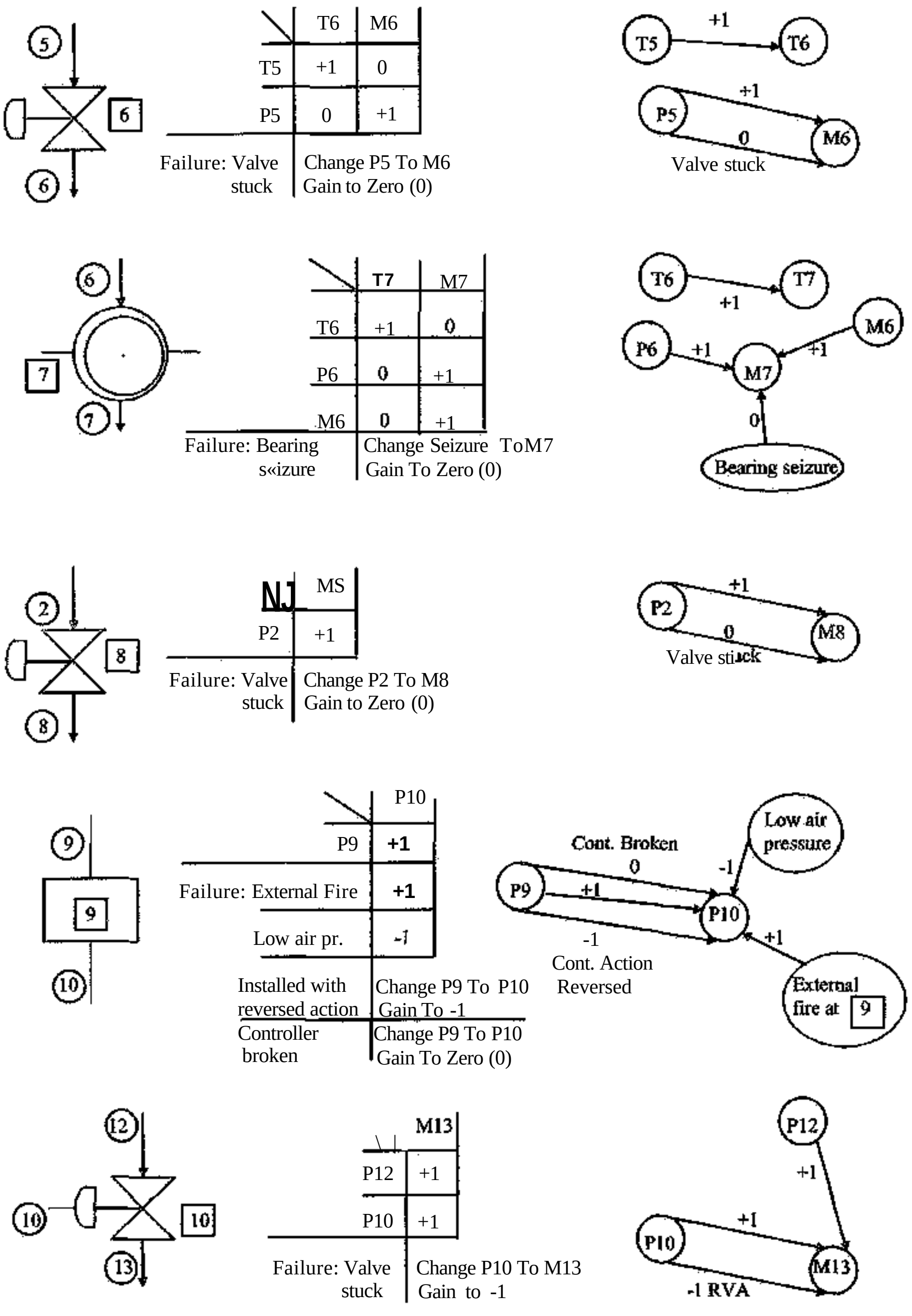
	P2	M2	T2
PI	fl	+1	0
Tl	0	0	+1
Failure: Lube oil pump shutdown	-10	-10	0

	Mi4	T3	M3
M2	0	+1	+1
T2	0	+1	0
M13	+1	-1	0
T13	0	+1	0
Failure: Coolant line choked	0	+1	

\	T4	P9
T3	+1	+1
Failure: Sensor Broken	Change T3 To P9 Gain to Zero (0)	

	P5	M5	T5
P4	+1	+1	0
T4	0	0	+1
Failure: Filter choked	-10	-10	

Fig. 4. (a) Symbolic representation, (b) input-output models and (c) variable-event component diagraphs of various components of journal bearing oil supply system.



	T6	M6
T5	+1	0
P5	0	+1
Failure: Valve stuck	Change P5 To M6 Gain to Zero (0)	

	T7	M7
T6	+1	0
P6	0	+1
M6	0	+1
Failure: Bearing seizure	Change Seizure To M7 Gain To Zero (0)	

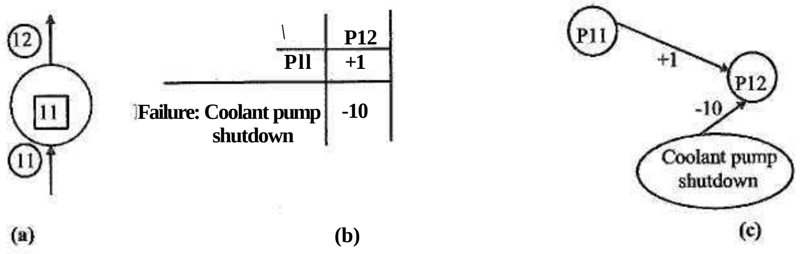
NJ	MS
P2	+1
Failure: Valve stuck	Change P2 To M8 Gain to Zero (0)

	P10
P9	+1
Failure: External Fire	+1
Low air pr.	-1
Installed with reversed action	Change P9 To P10 Gain To -1
Controller broken	Change P9 To P10 Gain To Zero (0)

	M13
P12	+1
P10	+1
Failure: Valve stuck	Change P10 To M13 Gain to -1

\(a) (b) (c)

Figs. 4(a), (b) and (c) *(continued)*



Figs. 4(a), (b) and (c) ***(continued)***

(non-tribological events). Connecting these failure and cause events by un-numbered edges and also connecting the variables and failure events for coolant pump, the variable-event component digraph is obtained and is shown in Fig. 5. The choked fitter is also attributed to two causes: highly contaminated lubricant (tribological) and insufficient pump pressure (non-tribological). Based on the above discussion, the variable-event component digraph for filter is obtained and is shown as Fig. 6.

6. The variable-event digraph of all the components of tribo-mechanical system obtained in steps 4 and 5 are combined to obtain variable-event system digraph for the journal bearing oil supply system and is shown in Fig. 7. The nodes of variable-event system digraph, Fig. 7, represent system variables and failure events. During the course of synthesis, these nodes will take on values. The value associated with a system variable node is the deviation in that variable while the value associated with a failure event node denotes whether or not the event occurs. Nodes having input are termed as connecting nodes. Some nodes have no inputs and these correspond to either primal variables or primal events. This digraph is used for the synthesis of a fault tree for a top event which is defined in the next section.

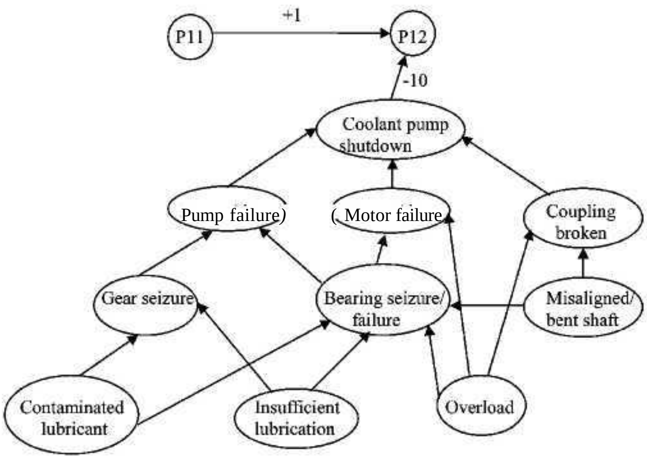


Fig. 5. Variable-event component digraph for coolant pump.

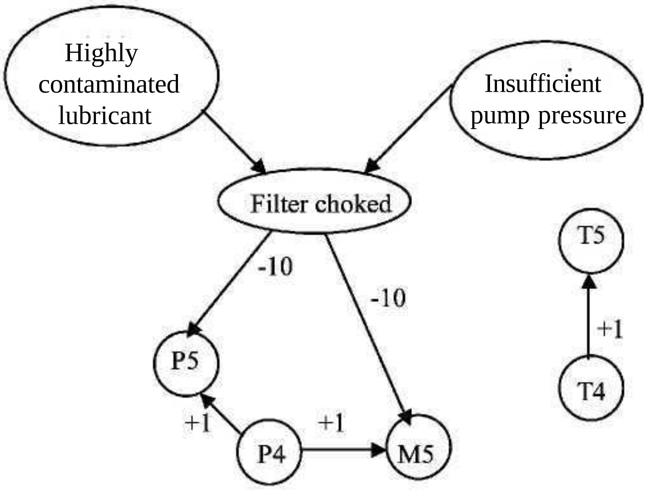


Fig. 6. Variable-event component digraph for oil filter.

4. Top event—high temperature of the lube oil

A top event for the oil supply system is a high temperature of the lubricant fed to the bearing i.e., T6. This would result in a change (decrease) in oil viscosity and hence decrease in load carrying capacity of the bearing, which will further lead to inefficient operation, and even failure of the bearing. Moreover, a reduced flow rate of lubricant may result in decrease of load carrying capacity due to reduction in oil film pressure and excessive heating. A fault-tree for the top event, high T6, of journal bearing oil supply system is synthesized using the vari-

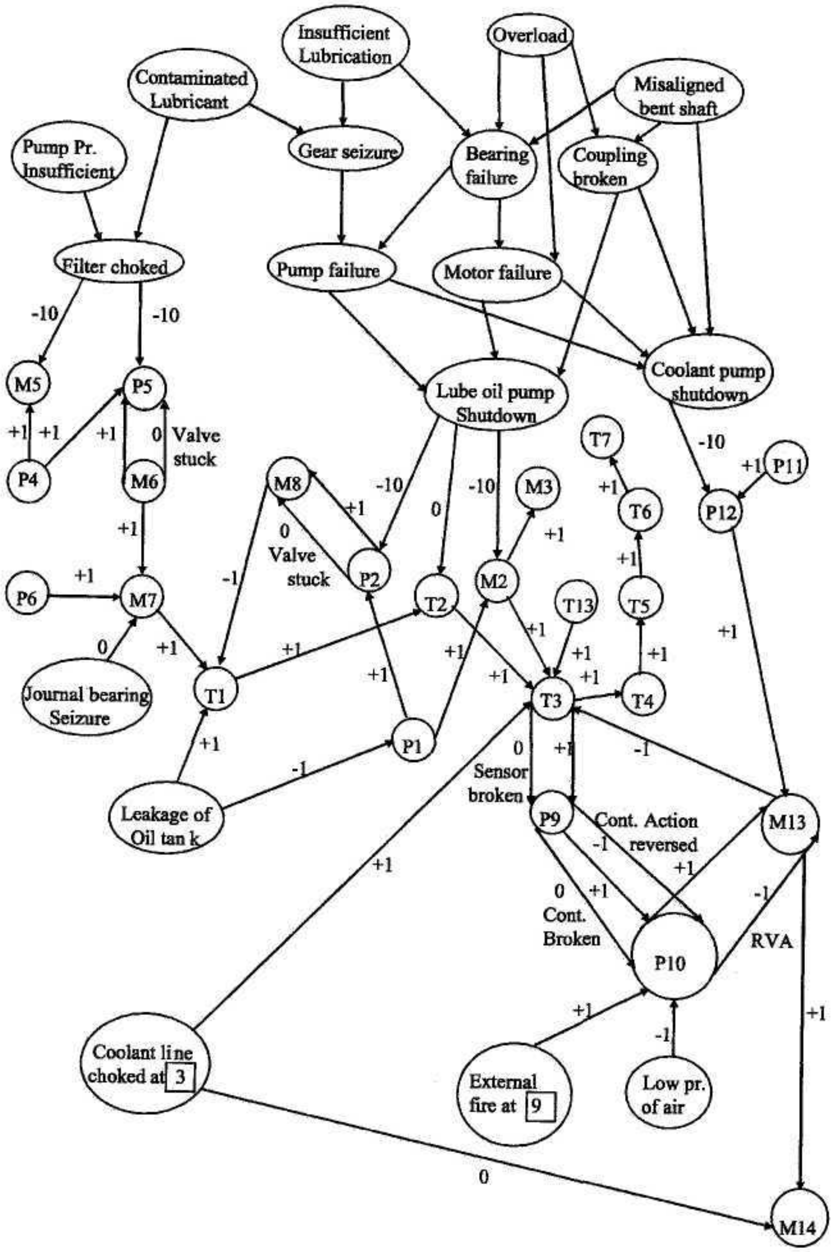


Fig. 7. Variable-event system digraph of the journal bearing oil supply system.

able-event system digraph Fig. 7. This is developed in the following section.

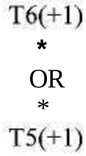
5. Fault-tree synthesis for the top event

The variable-event system digraph, Fig. 7, is used for the synthesis of a fault-tree for the chosen top event, i.e., high T6, employing the step-wise procedure discussed in section—Fault-tree synthesis using variable-event system digraph.

1. There is one negative feedback loop in the digraph which comprises of the variables T3-P9-P10-M13-T3. This path, which starts and ends at the same node—T3 and for which product of the normal gains is -ve. However, there is no negative feedforward loop in the digraph. This is evident as

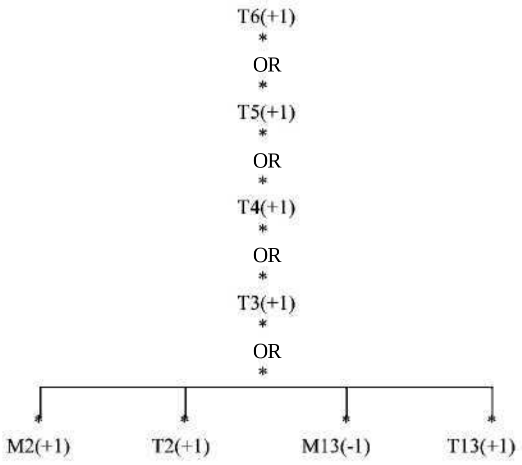
there are no two or more paths from one node to another node.

2. The top event is T6(+1); hence begin with the node labeled T6.
3. Input to node T6 i.e., cause of T6(+1) is T5(+1).
4. There is no consistency violation as this is the only local cause to T6(+1).
5. The appropriate logic operator to connect T6(+1) with T5(+1) is 'OR'. Thus, first step in constructing the tree would be to place an 'OR' gate under T6(+1) with T5(+1) as its input.

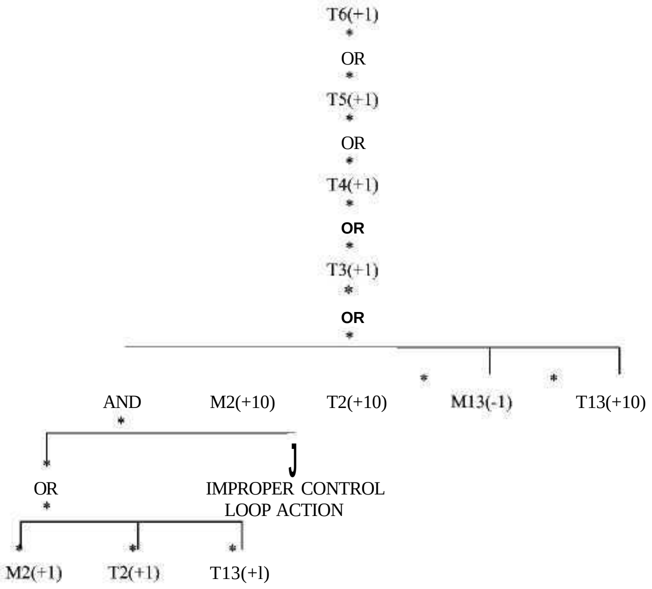


6. As evident from variable-event system digraph, Fig. 9, the cause for T5(+1) is T4(+1) whereas the cause for T4(+1) is T3(+1) and the fault-tree is now extended as:

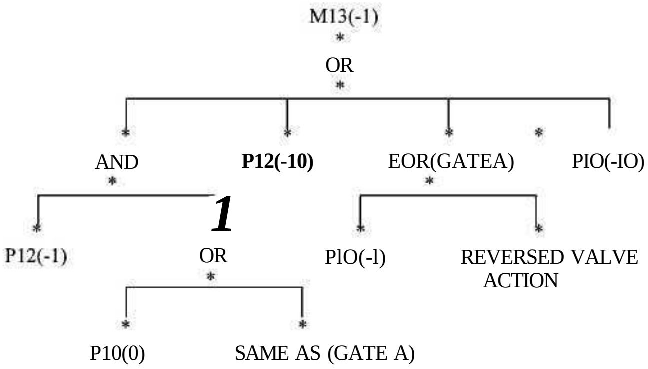
Further, identifying the causes of T3(+1), four causes emerge: M2(+1), T2(+1), M13(-l) and T13(+1). Again the operator 'OR' is used to logically connect these four causes to T3(+1), thus making the structure as:



This tree suggests that M2(+1) would cause T3(+1). Obviously this isn't since the negative feedback control loop (T3-P9-P10-M13-T3) would act to cancel the effect of M2(+1) [12]. Similar arguments can be made to show that T2(+1) and T13(+1) will not cause T3(+1). On the other hand, M13(+1) will cause T3(+1) and hence the top event. The reason for this is that M13 is itself a part of the temperature control loop. Under conditions when T3(+1), the appropriate response for the control loop is M13(+1). M13(—1) is an indication that the control loop is actually working to promote the top event instead of canceling it out, and this is why M13(—1) will cause T3(+1). This discussion suggests that if either M2(+1), T2(+1) or T13(+1) is to cause T3(+1), the control loop must either take no action to cancel the disturbances or promote it. If deviations in M2, T2 or T13 are very large, however, the control loop might not be able to cancel them out. Hence these large deviations would cause T3(+1). With these arguments, the following tree results.

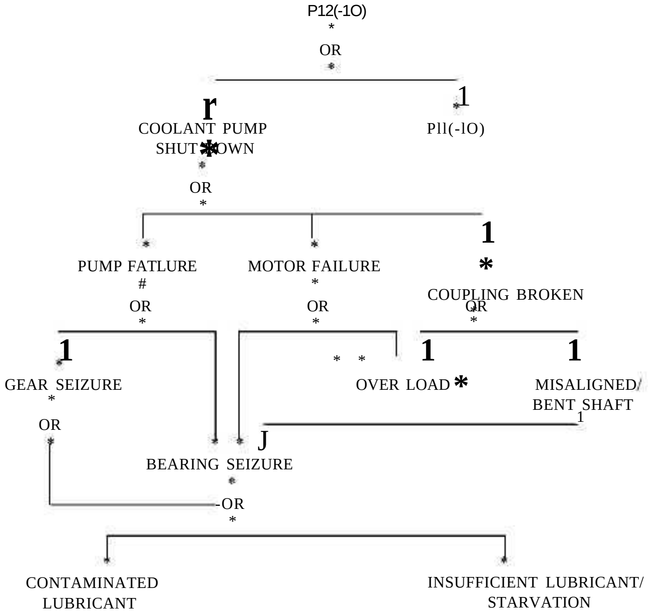


Concentrating on M13(— 1), it can be observed that M13 has three inputs, two from node P10, and one from node P12. M13 is on a negative feedback loop and P1O(-l) and REVERSED VALVE ACTION are also on the feedback loop. P12(—1) is an external cause event since it is not on the feedback loop. Therefore, only one event need to be checked for consistency and that is T3(+1) which was developed previous to M13(-l). None of the three causes [P12(-l), P1O(-l) or REVERSED VALVE ACTION] violate the consistency criterion. Therefore employing the negative feedback operator, the following sub-tree is obtained.



The EOR (i.e., exclusive OR) is necessary in GATE A since a simultaneous occurrence of P10(—1) and REVERSED VALVE ACTION will cancel each other resulting in M13(+1).

Now consider the event P12(—10). There are two local causes: P1l(-1O) and COOLANT PUMP SHUT DOWN. The event COOLANT PUMP SHUT DOWN has been further expanded as discussed earlier, and the resulting sub-tree is:



As an example of consistency violation, consider the event P9(— 1) which would have resulted from the development of P10(—1). According to the digraph, the only cause of P9(—1) is T3(—1), but this is in violation of consistency criterion, T3(+1). Thus P9(—1) event itself must be deleted wherever it appears in the tree. Follow step 6 to develop the remaining fault-tree.

The complete fault-tree thus obtained is exhaustive and is shown in Fig. 8. Such a fault-tree will aid in the task of failure (tribological and non-tribological) source location and help the plant engineers to initiate suitable corrective action in vital installations such as thermal power plants. Moreover, this will also help them in planning the maintenance for the system to enhance its reliability.

The suggested approach can also be applied to develop the fault-trees for top events of other closed cycle systems in thermal power plants involving components such as boilers, turbines, condensers, pumps etc; refrigeration systems; air conditioning systems etc. The approach can also be extended to fluid power systems and other tribo-systems such as gear drives, chain drives, hydraulic drives, conveyors etc.

6. Potential of the approach

A fault-tree constructed for a top event of the system is of considerable value in determining the paths whereby primal events (tribological and non-tribological) can propagate through system to cause the top event. Using a relevant algorithm [26], one can determine cut sets—a set of primal events which will cause the occurrence of top event. If occurrence-probability or failure rate data are available for the primal events, a number of useful data or information can be computed [27] e.g. probability or failure rate of the top event, and the relative importance of each primal event to the top event etc. Such statistics lead to valuable information as to which part of the system should be modified to decrease the possibility of the top event and thus enhance the reliability and safety of the system. This approach is applicable not only for the design and development of high performance tribo-mechanical systems but also in their reliable, safe and productive operation.

7. Conclusion

A variable-event system digraph for a tribo-mechanical system is defined and developed from the variable-event component digraphs of the individual components of the system. This digraph is then used to synthesize the fault-tree for a top event of the system. The analysis of the fault-tree will aid the practicing engineers and designers to initiate suitable corrective measures to minimise the occurrence of the top event during operation and design stages.

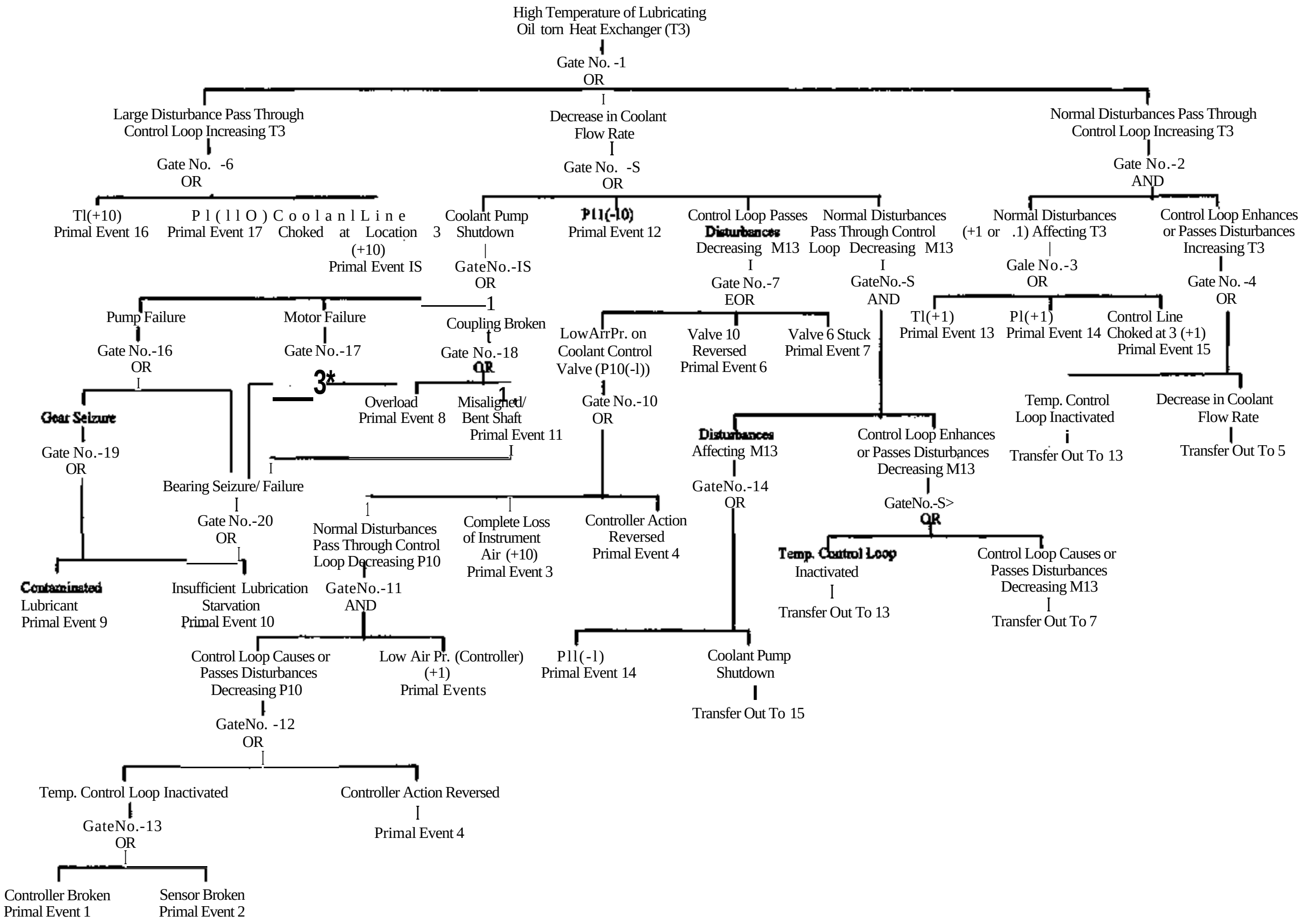


Fig. 8. Fault-tree for the top event T6(+1) for the journal bearing oil supply system.

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