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ORIGINAL ARTICLE

Fault diagnosis of automobile systems using fault tree based on digraph modeling

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Abstract Fault diagnosis of automobile systems is critical, as it adds-up to repair and maintenance time. It is, therefore, desired to make it efficient and effective. One of the conventional approaches is to use the fault tree diagram. But this approach is inadequate with its implicit system structure. Structure of the system means system elements and their interrelations. To alleviate this limitation, a new approach is suggested wherein the structure is in-built, i.e. incorporated explicitly, through digraph modeling that employs a systems approach of graph theory. A system digraph is developed, considering relationships among input and output parameters of subsystems/components of the automobile system in normal and failed conditions. Fault tree of a failure symptom that represents abnormality or a breakdown of the automobile system is obtained from the system digraph. The novelty is extension of the structural approach to automobile systems using digraph model, which has been successfully applied to chemical and process systems. Step-by-step methodology of the structural approach is presented. Its two main two steps are Steps 1 and 2, i.e. 'Development of Fault tree diagram' and 'Diagnosis of fault using the tree diagram', respectively. The suggested approach is illustrated for hydraulic power steering, an automobile system that is fitted on all current automobiles and particularly, in special purpose vehicles like heavy-duty trucks, earthmovers, dumpers, etc. The suggested approach guides how to diagnose root causes of a fault. The approach is not only helpful to maintenance personnel in effective diagnosis but also in guiding designers in development of reliable automobile systems, accident investigations of automobiles, etc.

Keywords Automobile system · Fault diagnosis · Digraph model · Fault tree diagram · Hydraulic power steering · System structure

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1 Introduction

Maintenance is an indispensable activity for most engineering systems, and automobiles are no exception. It is time and resource consuming activity, which concerns automobile service organizations. One of its critical tasks is diagnosis of a fault (Jegadeeshwaran and Sugumaran 2015) and its efficiency and effectiveness of which can save time, cost, and increase productivity of the automobile service organizations and hence, their profitability (Hurdle et al. 2007). Mateyka et al. (1973) pointed out that diagnosing true causes of a vehicle fault is complex and difficult, and more so, with increase in its complexity. The automobile industry, all over the world, faces serious challenges, as the complexity and sophistication of the vehicles are growing day-by-day (Struss and Price 2003). Hence, accuracy and efficiency are the most desirable ingredients of fault diagnosis.

Failure of a system is the inability to perform its intended function, while the term fault is a momentarily failure or departure from the acceptable range of the observed variable or associated system parameter

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(Himmelblau 1978) and diagnosis of fault is the process of fault detection, isolation and recovery (Frank 1993), A diagnostic task involves identifying the symptom or undesirable/top event, and determining what went wrong, i.e. how the failure occurred (Krysander 2003). In case of automobile systems, abnormalities in parameters like speed, torque, temperature, etc. can be the symptom of an impending failure. Current/present day automotives are equipped with on-board diagnostic system to guide users and service personnel of the likely or impending failures. One or multiple DTCs (Diagnostic Trouble Codes) will set, if the diagnostic system detects a fault. The DTC information will indicate some of potential root causes. It has some level of diagnostic capability, but may not localize or pinpoint the faulty component, which means these are incapable of pinpointing the exact component. Fault diagnosis of non-electrical systems like, hydraulics, brakes, clutch, etc., is only possible through human, which require extensive knowledge of the systems (Snooke and Price 2007). Generally, maintenance personnel have been diagnosing faults through experience and know-how gathered over years. If the heuristic experience is systematized or handled through computer and information technology, it can help to diagnose faults quickly and precisely (Kim et al. 2009). Such a fault diagnosis methodology, which can easily be computerized and reproduced, is essential in today's competitive automobile service environment. However, this requires a complete understanding of the system structure.

Fault tree diagrams, by analyzing the failure logic, have been extensively used for fault diagnosis of industrial systems in various disciplines (Mahmood et al. 2013). It helps in analyzing system and its subsystems failures, leading to their root causes (Hiraoka 2016).This concept was developed by Bell laboratories in 1961. It is a logical tree, which initiates with the top or undesired event, i.e. fault symptom and terminates with its root causes, i.e. basic or primal events (Vesely et al. 1981). Fault tree analysis (FTA) is a top-down approach for analysis of failures (Jaise et al. 2013). FTA translates physical systems to corresponding structural logic diagrams (Karthikeyan et al. 2016). The fault tree diagram provides a graphical display of how failure events and their combinations lead to its top event and therefore, guides in troubleshooting and pinpointing the root causes. Fault tree analysis in general is of two types. The qualitative analysis helps to identify all possible combinations of events that lead to the top event that forms the minimal cut sets of the fault tree, whereas a quantitative level helps to determine the probability of occurrence of the top event based on the time-to-failure probability distributions of its basic events (Merle et al. 2016).

The quantitative analysis of fault tree helps in evaluation of system reliability. For this, the failure probability of each component of the system or event is necessary (Gupta et al. 2006). This requires sufficient data for statistical analysis for obtaining failure probability. Hence, quantitative analysis of fault tree is difficult in the absence of data. However, Gupta and Bhattacharya (2007) developed a methodology for quantification of fault tree by approximately calculating the failure probability based on subjective opinions of experts in the domain. The expert opinion, which are in linguistic forms are converted into fuzzy numbers. Later this fuzzy numbers were defuzzified to get the failure probability value. Based on these data, one can evaluate the overall system reliability.

The utility of the fault tree as a diagnostic tool for systematically screening of the potential vehicle performance problems and finding of faults has been suggested by many researchers, including Mateyka et al. (1973) Recently, the fault tree methodology has been applied for fault diagnosis of car engine (Lu 2013), Mercedes Benz (Wang 2013) and automobile clutch failures (Teixeira and Cavalca 2008; Bogicevic et al. 2014). Literature and experience show that the developed fault tree diagrams can be subjective and different analysts may come up with different fault tree diagrams for the same system (Andrews and Morgan 1986), which make these inconsistent with their structure. In addition, manual preparation of fault trees is time consuming (Andrews and Brennan 1990). Moreover, conventional/manual fault tree construction has failed to fully envisage control loop structures of the system (Andrews and Morgan 1986).

Literature survey also showed clearly a lack of system structure consideration, which is responsible for most of the drawbacks of fault tree development (Venkatasubramanian et al. 2003; Bartlett et al. 2009). The expected behaviour or otherwise of a system can be inferred from its structure (Snooke and Price 2007; Picardi et al. 2002). Struss and Price (2003) suggested diagnostic process of automobile system faults through behavioural descriptions based on the system structure. The relevance of structural hierarchy for knowledge-based diagnosis for automobile engines has also been advocated by Xiaojun et al. (1988). In this context, graph theory, a systems approach, can be employed for the fault diagnosis using graph and digraph models (Harary 1969; Deo 1987). These belong to a type of causal models that represent cause and effect behaviour within the system through which specific fault propagation can be understood (Kelly and Bartlett 2008). Although the other methodologies of fault tree synthesis claim to incorporate system structure explicitly, yet these fall short. The digraph models follow system topology (Andrews and Brennan 1990), which are derived from the system schematics by associating each component with a node and augmenting interaction between two components in terms of a directed edge (Sacks 1985). These models represent a vivid relationship among the system variables that are a close reflection of the physical system structure and capable of displaying control loops, if any, in the system. It is re-emphasized that consideration of system structure is vital to development of fault tree. This is possible and explicitly, using a digraph model. Lapp and Powers (1977) applied computer aided approach for fault tree synthesis for chemical systems and processes to overcome drawbacks of conventional fault trees by developing a tree diagram from the digraph model of the system and explicitly incorporating the system structure. Lapp and Powers (1977) methodology or similar has not been applied for fault diagnosis of automobile systems so far and hence, it can be extended to automobile systems to meet the objective. This is attempted in this paper. The fault tree should help in diagnosing the failure paths and can, therefore, identify the causes of failure, including the faulty subsystems and components.

This paper is organized in six sections, with next section (Sect. 2) giving an overview of Lapp and Powers methodology. In Sect. 3, extension of the Lapp and Powers methodology to automobile systems is presented, including steps for system digraph development, fault tree generation and diagnosis. Application of methodology for hydraulic power steering system is demonstrated in Sect. 4. The observations and comments on the approach are given in Sect. 5. In the last section, conclusions of the work are presented.

2 Overview of Lapp and Powers methodology

Lapp and Powers (1977) suggested computer aided synthesis of fault trees that considered system structure explicitly and overcame problems of manual construction of fault trees; such as time for the synthesis, possibility of dissimilar results of the two analysts, handling of systems having complex control loops and inconsistency among failure events. The approach can analyze any type of chemical process and is capable of handling complex systems that incorporate multi-valued logic, direction and magnitude of the deviations of the system variables or parameters, including the failures. However, one needs to remove inconsistent events, e.g. two mutually exclusive events, not occurring at the same time. The approach is most appropriate for computer handling.

Development of a fault tree from the system digraph model requires an understanding of the system or process. This is by its line diagram or flow sheet, with its components numbered in square boxes and streams numbered within circles. The digraph model consists of nodes (or vertices) and edges. Variables or parameters of the streams and certain type of failures are the nodes or vertices, while the interconnections among the variables or parameters, i.e. deviation or gain, which are represented by the edges. For this, one needs to understand how variables are related in working and failed conditions of the components. For this, prepare a Table for each component of the system that shows the input–output relation of its variables/parameters, i.e. gain, with a value of '0, $\pm$ 1 or $\pm$ 10' that means no change, moderate or large increase/decrease respectively. The system digraph is obtained by combining digraphs of all components of the system.

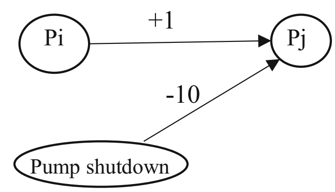
An example of a pump is considered to illustrate the above. Let 'P_i' and 'P_j' are the input and output pressure of fluid entering and leaving the pump respectively. The relationship between these two parameters can be represented in a Table. An increase in value of 'P_i' causes moderate increase in 'P_j' value; the gain will be '+ 1' as shown in Fig. 1. In case the pump shutdown, i.e. a failure case, there will be a large decrease in 'P_j'. This is also shown in the Table; Fig. 1. For digraph modeling of the pump (Fig. 1), its two parameters; 'Pi' and 'P_j', and the 'Pump Shutdown' are shown as three nodes, with their interrelations shown in the Table are represented by their directed edges.

For developing a fault tree diagram from the system digraph, one needs to identify a node that is the symptom, top or undesired event. This is the starting point of the fault tree diagram development. To move forward, find out which nodes are input to the top event node and how these input nodes are to be connected. In general, it will be through an 'OR' gate, but not so if the digraph contains a loop (feedback or feedforward). This requires checking, if the current node being examined is a part of the feedback or feedforward loop. A feedback loop in a digraph is a path that begins and ends at the same node for which the product of all normal gains is negative, whereas a feedforward loop has two or more paths between two nodes and the sign of the products of the gains is opposite for individual paths. The tree diagram is developed until only primal or basic events remain. The basic events are root causes for the symptom/top event that cannot be further developed, i.e. with no input nodes. In the process, one also needs to check the consistency that implies nonoccurrence of two mutually exclusive events, i.e., both the increase and decrease of one parameter cannot have the same influence on another parameter, e.g., P_1 (+ 1) should not be traced back to neither P_1 (− 1) or $P_1(0)$. This means that the inconsistent events are to be deleted.

Based on the above discussion, explicit consideration of the system structure, synthesis of a unique fault tree and easiness for computerization are positive features of the Lapp and Powers methodology for fault tree development.

Fig. 1 Interrelationship table between input and output parameters and digraph model for pump

Input parameters	Output parameters P_j
P_i	+1
Failure: Pump shutdown	-10



Due to these features, this methodology has been applied to various industrial applications, including fault diagnosis of aircraft fuel system(Kelly and Bartlett 2007; Kelly and Bartlett 2008), reliability assessment of tribo-pair (Sharma and Gandhi 2008), functional cause analysis of complex manufacturing systems(Loganathan et al. 2015) etc. In view of this, there is no apprehension is extension of this methodology to automobile systems. This is presented in the next section.

3 Extension of methodology to automobile systems

Fault diagnosis is a critical task in automobile maintenance. Even though Diagnostic Trouble Codes (DTCs) do aid in diagnosis, there are systems for which conventional diagnostic process is only feasible option. From the literature, it is revealed that the digraph based structural approach has not been attempted for fault diagnosis of automobile systems using fault tree. Hence, Lapp and Powers (1977) methodology that uses structural approach and is extended to automobile systems for development of fault trees and diagnosing of faults in this paper. However, this methodology needs to be refined and fine-tuned in this context.

First of all, structure of the automobile system needs to be understood and inbuilt in the tree. The structure means subsystems, assemblies and components of the automobile system and their interconnections. For chemical processes and systems, parameters like pressure, temperature, feed rate, flow, etc. are considered for developing their digraph models. These processes and systems do involve transfer of some working media. Variation in the process or system parameters is pertinent to fault detection (Isermann 1993). Moreover, diagnostic solutions that most automobile garages do use are based on specific parameters, e.g. temperature (Roussat 1990). A parameter is a characteristic, feature or measurable factor of the system or component. During normal operating conditions, system or component maintains interrelationships among input and output parameters as per its characteristics. However, its failures of fault conditions will result in change of the interrelationships corresponding to these and affected parameter(s) e.g. pump shutdown shown in Fig. 1, resulted in very large deviation in output parameter 'Pj'. Therefore, variation in the appropriate parameter(s) can be a start for development of fault tree of an automobile system for its symptom. It is possible to measure a parameter or its signal. It is also possible that the signal is available. In addition, a signal, one may be measuring or attempting to capture in future that has some specific property or characteristic will aid in fault detection or performance variation monitoring or assessment. The experience shows that not all parameters may be needed in fault diagnosis. It may be mentioned that the fault diagnosis of automobiles from repair manuals has not been so effective, as it fails to convey propagation of the fault, including relationships among parts/components of the system. In view of this and their parameters, the troubleshooting using the repair manual is difficult even for an experienced person (Liang 2014). Application of digraph model for automobile system will overcome the above and will lead to development of fault trees that would consider system structure explicitly, i.e. consideration of parameters and their interrelations in normal and failed conditions for subsystems/assemblies/components. For this, one can prepare a system diagram on the lines of the chemical process or otherwise, including hierarchical representations of systems, subsystems, assemblies and components. As the focus of this work is to diagnose faults of the automobile systems through structural approach, a tree structure that describes the failure path for the top event or failure symptom to basic events is to be developed from the automobile system digraph model. The basic events are the root causes of the top event. Since the tree structure development is primarily meant for the fault or its symptom, it is designated as fault tree diagram for the failure symptom or top/undesired event of the considered automobile system.

Since the main objective of this work is to develop a methodology for quick and effective fault diagnosis of automobile systems, only the quantitative analysis of the fault tree, which is developed from the system digraph model is performed in this paper. This is achieved by following two steps, i.e. Steps 1 and 2, which are mentioned below, including their sub-steps. This is based on the above discussions and overview of Lapp and Powers methodology (Sect. 2),

Step 1 Fault tree diagram development.

Sub-steps of step 1 for the development of the fault tree diagram for automobile systems are:

Step *1.1* Consider an automobile system and examine its structure, i.e. breaking down to its lower levels, i.e. subsystems, assemblies, components, etc. Number the subsystems/assemblies/components and streams, and enclose these in square boxes and circles respectively. Identify input and output parameters for each subsystem/assembly/component, for its normal and failed conditions.

Step *1.2* Model the interrelationships among input–output parameters, identified in the sub-step above, of subsystems/assemblies/components in terms of magnitude, i.e. 0, 1, 10 and direction (+ or −) and represent these in a Table on the lines of Fig. 1 for all subsystems/assemblies/components. This should be done for normal operation and failed conditions. The failed conditions, which the subsystem/assembly/component is likely to experience, are shown at bottom of the input –output parameter interrelationships Table. One may attempt for exploring the failed conditions to any lower levels and present them in the Table.

Step 1.3 Develop digraph for each subsystem/assembly/component on the lines of Fig. 1, by using its relationship Table obtained in the sub-step above. It may be noted that the developed fault tree from the system digraph will represent both normal and failure conditions of the system unit. More the failure events or conditions one include in the digraph model, the more realistic will be the derived fault tree.

Step 1.4 Combine the developed digraphs of all the subsystems/assemblies/components, i.e. obtained in sub-step 3 above, to obtain 'System Digraph' for the considered automobile system.

Step 1.5 Consider the automobile system digraph obtained in the sub-step 1.4 above, and identify feedback and feedforward loop, if any.

Step 1.6 Identify the node in the system digraph, which is the top event/undesired event/symptom of the system.

Step 1.7 Consider the top event node. Identify all the nodes, which are input to this node. Connect these by 'OR' Gate, if the current node, i.e. top event, is not a part of the feedback or feedforward loop. Otherwise, use a generalized operator. Refer "Appendix" for generalized operators for feedback and feedforward loops. A fault tree is initiated from the system digraph for its symptom/top event. Its initial event or input event is assigned a sign (±), which means increase/decrease of the event or its parameter. It is based on the sign (±) of the directed edge connecting input node to the top event node in the system digraph. For example, if directed from any input node is positive to the top event node, its initial event is assigned a positive sign in the fault tree. On similar lines, the sign assignment is done for the events in fault tree.

Step 1.8 Check for the consistency, which means that two mutually exclusive events cannot occur together. Refer Sect. 2 for the details. This is the first stage of the fault tree for the system.

Step 1.9 Consider the tree obtained in Step 1.8, i.e. first stage. Repeat Steps 1.7 and 1.8 to obtain next stage of the fault tree.

Step 1.10 Continue Step 1.9 until only primary or basic failure events remains. This results in development of fault tree for the top event.

The extension of Lapp and Powers (1977) methodology to automobile systems for development of fault tree diagram seems to be appropriate, as it satisfactorily represents the system, including its complexities, incorporates multi-valued logic by considering the magnitude and direction of the deviations in input and output parameters and component failures, considers system topology/system as well as components and their parameters, and ensures consistency among failure events. It is well known that development of fault tree manually of a system is a cumbersome task and is likely to result in a dissimilar tree structure for two analysts. These problems are well taken care using the proposed methodology. The tree development using the approach will neither pose difficulty nor result in an altogether different tree. However, the complexity of the fault tree will depend on the number of subsystems/assemblies/components of the automobile system and a number of its input and output parameters. A major advantage of this approach is its capability to handle complex systems with control loops, which is true for automobile systems.

Once the fault tree is developed, Step 2 is followed for diagnosing the faults.

Step 2 Fault diagnosis using the fault tree.

The fault tree is a deductive model that deduces root causes of top event of the system or its constituent units using a top down approach, and the fault diagnosis is centered-around it. What is needed is its efficient and correct diagnosis. For expediting the fault diagnosis, there can be a need for some pre-requisite information or data, including failure rates/probability of events, service instructions, customer complaints and knowledge regarding the sequence of tests required for confirming the causal events, as this will prioritize some specific tasks or events to be checked first. On the other hand, for correct diagnosis; the system digraph is a reflection of this. The experience shows that the root causes for an automobile system will be different from user to user and it also depends on the terrain, including environmental conditions. But these will be reflected the system digraph.

A logical gate; ‘OR’ or ‘AND’, connecting, e.g. top event to first set of intermediate events, guides how one should move forward in the diagnosis, i.e. which event or events should be checked or tested, including their order. In case of an ‘OR’ gate, any one of the intermediate events will be the root cause for the top event. However, for prioritizing these; their failure probability will help in this regard. The events with the highest probability should be checked and the lowest probability events to be checked in the last. In case of an ‘AND’ gate, all intermediate events will be contributing, but choosing the right order as per failure probability will make the diagnosis task efficient.

Based on the above, following are sub-steps for diagnosis of faults for the failure symptom, top or undesired event. The top-down approach means moving from the top of the fault tree to its bottom, i.e. diagnosing top event to its root causes i.e. basic or primal events.

Step 2.1 Start with the top event, which is a failure symptom or undesired event. This means diagnosis is for this failure or fault.

Step 2.2 Identify the gate that immediately follows the top event, with one of the following options:

(a) If it is an ‘OR’ gate, any of the events that is input to the gate is causative. This requires verification of each of the input events. However, the event with highest probability among these will be checked first. If diagnosis fails, the event next in the order of probability will be checked until the diagnosis succeeds.

(b) If it is an ‘AND’ gate, all the events that are input to the gate are causative. This requires verification of all the input events. In some cases, the order is important.

Step 2.3 Identify the next gate and follow Step 2.2.

Step 2.4 Repeat Step 2.3 until no more logical gate remains, i.e. only basic events or root causes remain.

The above methodology is illustrated step-by-step by applying it to a hydraulic power steering system.

4 Application to hydraulic power steering system

One of the prime design considerations of automobiles is ease of driving (Yun et al. 2002). Hence, all current automobiles and particularly, special purpose vehicles like heavy-duty trucks, tractors, earth moves, dumpers, road rollers etc. are fitted with hydraulic power steering system that eases steering effort of the operator. It employs fluid power to assist the steering action that includes combination of hydraulic and mechanical systems. It is one of the complex and critical systems of automobiles, as its malfunction affects safety and reliability. The system is subjected to various kinds of stresses like mechanical, thermal and chemical, which gradually deteriorates and may lead to failures. Moreover, the system is expected to meet demands of high reliability (Janicijevic et al. 1998; Garrett et al. 2001). In view of this, the hydraulic power steering system is considered for illustration of the methodology.

A fault may impart undesirable deviation in input and output parameters of the system. Some of the common faults/failures of the hydraulic power steering system are identified, which in order of severity are: loss of power, inefficient operation, hard steering, interruptions in input–output parameters, impact and vibration of the steering wheel, noise etc. (Dobrivoje et al. 2013).

Figure 2 shows line diagram of hydraulic power steering system. Figure 2 also shows numbering of their streams and components, with number in square implies components and in circle as streams. Hydraulic oil from the tank ‘1’ is pumped through a vane pump ‘2’ after passing through a strainer ‘S’. It then enters the steering unit ‘3’ that includes steering mechanism, rotary spool valve, which is a four-way directional control valve and steering cylinder enclosed in the same housing. This arrangement facilitates compact design, minimum piping connections and quick response of the system (Janicijevic 1993; Jörnsen et al. 2001; Heisler 2002). The oil after performing work in the steering cylinder usually gets heated because of the work done by it in moving the piston in the steering cylinder. Additionally, other heat sources in the vicinity of hydraulic power steering system will also raise its temperature. Hence, the hydraulic oil coming out of the steering unit is admitted to a cooler ‘4’, which is essentially a heat exchanger that maintains a constant temperature of hydraulic oil. The constant output temperature of the cooler is maintained by the use of a feedback loop containing temperature sensor ‘5’, controller ‘8’ and coolant supply valve ‘9’. The sensors generate pressure signals proportional to temperature and sends to the controller. The controller upon receiving pressure signals actuates the pneumatically operated coolant supply valve. The flow of the coolant into the cooler ‘4’ is controlled by an appropriate valve action. The coolant is supplied by a coolant pump ‘10’. The flow rate of coolant into the cooler is controlled to maintain outlet oil temperature from the return filter ‘6’ constant. In addition to these, a pressure relief valve ‘7’ is provided to regulate pressure of hydraulic oil from the vane pump. Both the vane pump and coolant pump are driven by the engine through belt drive.

The proposed methodology is applied to the hydraulic power steering step-by-step, which is illustrated as below.

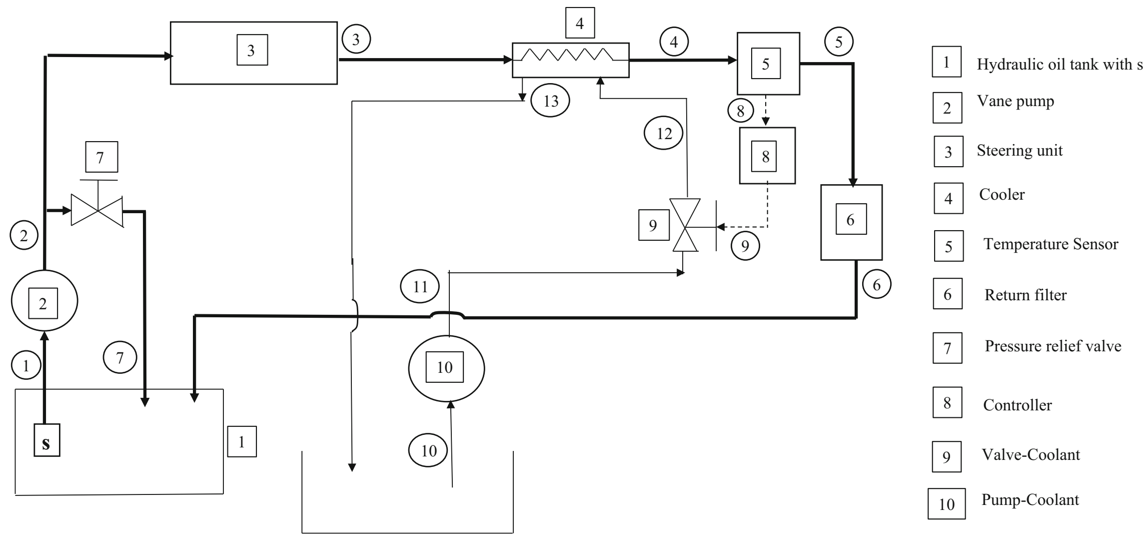


Fig. 2 Line diagram of hydraulic power steering system

Step 1 Fault tree diagram development.

Step 1.1 System and its structure.

The system chosen is a hydraulic power steering system that consists of two main subsystems; hydraulic system, steering mechanism and cooling system. Each subsystem has several assemblies and components. The hydraulic system includes hydraulic oil tank with strainer, vane pump, steering unit, return filter and pressure relief valve, while the cooling system includes cooler, temperature sensor, controller, coolant valve and coolant pump.

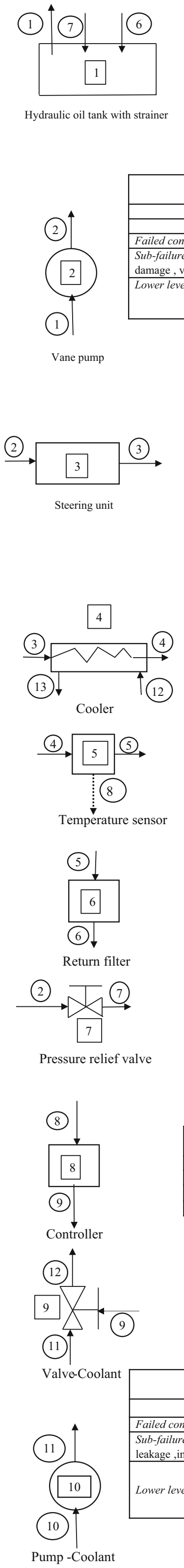
Step 1.2 Modeling the interrelationship among input–output parameters of subsystems/ assemblies/components.

A close look at the system reveals that the parameters whose deviations are critical to the working of hydraulic power steering are the Pressure (P), Mass flow rate (M) and Temperature (T) of the hydraulic oil as well as the coolant. Line diagram of each subsystem/assembly/component of hydraulic power steering system is shown in Fig. 3a, whereas Fig. 3b represents interrelationships of its input–output parameters in both conditions, i.e. normal and failed, in tabular form.

Hydraulic vane pump (Fig. 2), which is numbered '2' subsystem/assembly/component of the power steering system, is considered for illustration of Step 1.2. Its input and output streams; 1 and 2, This is shown in the second sub-fig; Fig. 3a. During its normal working, there is a gain of '+ 1' between input pressure P1 and output pressure P2 and mass flow rate M2, which is shown in the first row of its corresponding table; Fig. 3b. The gain between input temperature T1 and output temperature T2 is '+ 1', whereas the gain between input temperature T1 and output pressure P2 is '− 1', which is shown in the second row of the Table. However, during the failed condition, e.g. 'vane pump failure', the gain in both P2 and M2 will reduce from '+ 1' to '− 10' and shown in the third row of the Table. The sub-failures of the failed condition 'vane pump failure' such as vane pump stopped/slowed down, cavitation erosion, vane tip damage and cam ring damage are shown in the Table. The lower level failures of 'vane pump stopped/ slowed down' such as shaft broken, belt broken, engine stopped and bearing failure are shown in the Table. On the similar lines, input–output parameters interrelationships for other subsystems/assemblies/components are also established, which are shown in Fig. 3b. The input–output parameters interrelationships, failed conditions, etc. are generated based on garage experience and conditions prevailing. It may be noted in Fig. 3b that information under failure includes not only failed conditions but also failures levels down below, e.g. sub-failures and lower failures are included to reach to the root causes and also maintenance actions and/or their quality that one experience during operation and use of the automobiles. It is required to include all possible information in this regard that was experienced in operation and maintenance of the system. This will help in realistic representation/modeling of subsystems/assemblies/components of the system.

Step 1.3 Digraph modelling of subsystems/ assemblies/components.

Digraphs for all the subsystems/assemblies/components of the hydraulic power steering system are developed by considering input and output parameters interrelationships in normal condition as well failure condition, i.e. Fig. 3b; obtained in Step 1.2 and are shown in Fig. 3c.



Input parameters	Output parameters	
	T1	P1
T6	+1	0
M6	+1	0
Failed condition: Strainer blockage	0	-1
Failed condition: Tank leakage	+1	-1
Sub-failures/actions: corrosion, lack of maintenance, tank damage	Each sub-failure directly related to failed condition of tank leakage	

Input parameters		Output parameters		
		P2	M2	T2
P1		+1	+1	0
T1		-1	0	+1
Failed condition: Vane pump failure		-10	-10	0
Sub-failures/actions: cavitation erosion, vane tip damage ,cam ring damage , vane pump stopped/slowed down		Each sub-failure directly related to failed condition of vane pump failure		
Lower level failures	Shaft broken, belt broken, engine stopped, bearing failure	Each lower level failure directly related to sub-failure: vane pump stopped/slowed down		

Input parameters	Output parameters		
	P3	M3	T3
P2	+1	+1	0
M2	0	+1	+1
T2	0	0	+1
Failed condition: Steering cylinder leakage	-10	-10	0
Sub-failures/actions: sealing failure, loose hose connection, cylinder crack, lack of maintenance.	Each sub-failure directly related to failed condition of steering cylinder leakage		
Failed condition: Rotary spool valve stuck (RSVS)	Change P2 to M3,Gain to (0)		

Input parameters	Output parameters		
	M13	T4	M4
M3	0	+1	+1
T3	0	+1	0
M12	+1	-1	0
T12	0	+1	0
Failed condition: Coolant line choked	Change coolant line choked to M12 and M13, with Gain to -10 for each		

Input parameters	Output parameters	
	T5	P8
T4	+1	+1
Failed condition: Temperature sensor failure(TSF)	Change T4 to P8, Gain to (0)	

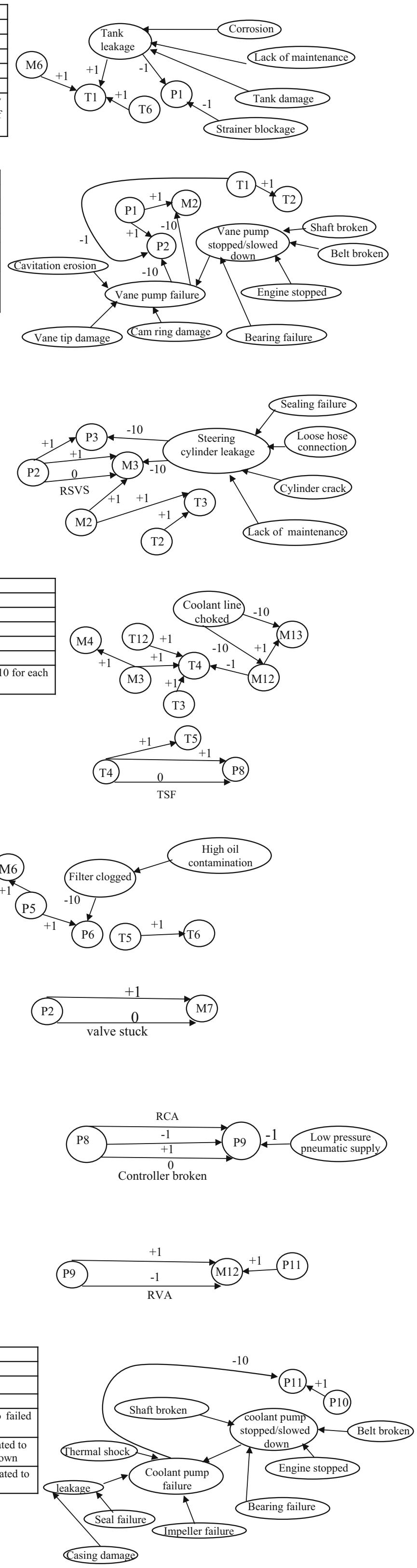
Input parameters	Output parameters		
	T6	M6	P6
P5	0	+1	+1
T5	+1	0	0
Failed condition: Filter clogged		0	-10
Sub-failures/actions: High oil contamination	Each sub-failure directly related to failed condition of filter clogged.		

Input parameters	Output parameters
	M7
P2	+1
Failed condition: Valve stuck	Change P2 to M7, Gain to (0)

Input parameters	Output parameters
	P9
P8	+1
Failed condition: Low pneumatic pressure	-1
Failed condition: Reversed control action(RCA)	Change P8 to P9,Gain to-1
Failed condition: Controller broken	Change P8 to P9,Gain to (0)

Input parameters	Output parameters
	M12
P11	+1
P9	+1
Failed condition: Reversed valve action (RVA)	Change P9 to M12, Gain to-1

Input parameters		Output parameters
		P11
P10		+1
Failed condition: Coolant pump failure		-10
Sub-failures/actions: coolant pump stopped/slowed down, thermal shock, leakage ,impeller failure.		Each sub-failure directly related to failed condition of coolant pump failure.
Lower level failures	belt broken, shaft broken, engine stooped, bearing failure	Each lower level failure directly related to sub-failure: pump stopped/slowed down
	seal failure, casing damage	Each lower level failure directly related to sub-failure: leakage



(a) **(b)** **(c)**

Fig. 3 **a**–**c** Line diagram, input–output and digraph models of subsystem/assembly/component

Step 1.4 Development of system digraph.

The individual component digraphs developed in the previous sub-step for the normal conditions and failed conditions, i.e. Fig. 3c, are combined to obtain the system digraph. This is shown in Fig. 4.

Step 1.5 Identification of feedback and feedforward loops in the system digraph.

In the system digraph of hydraulic power steering system (Fig. 4), there is one negative feedback control loop T4-P8-P9-M12-T4. Its product of normal gains is '-ve', which confirms it. However, there is no feedforward loop.

Step 1.6 Identifying node in the system digraph that is symptom or top event of the system.

An abnormal variation of a system parameter is the symptom of an impending failure of the hydraulic power steering system. One of the failures of hydraulic power steering system is the 'loss of power'. This is felt by the driver as insufficient power assistance for steering effort, which is mainly due to the loss of pressure (P2) of hydraulic oil, while it enters the steering unit. Hence, the equivalent parameter representation of 'loss of power' is P2 (− 1). Looking at the system digraph, the node representing pressure of hydraulic oil entering steering units is 'P2'. The reduction of this can be represented as 'P2 (− 1)', Hence, node; 'P2 (− 1)', in the system digraph (Fig. 4) is the top or undesired event for development of tree diagram. It may be mentioned that Dobrivoje et al. (2013) developed a fault tree for the top event; 'complete loss of hydraulic power steering', which is same as 'loss of power'. However, the events; high oil temperature and its impact on oil pressure were not included in the fault tree by the researchers. The fault tree developed in this paper does include this.

Step 1.7 Identification of input nodes to the top event node.

Nodes input to the node 'P2 (− 1)'are; T1 (+ 1), P1 (− 1) and 'vane pump failure' from the system digraph. T1 (+ 1) indicates temperature rise of hydraulic oil that will reduce P2 as the viscosity of oil will be decreased due to increase in temperature. P (− 1) indicates lack of hydraulic oil pressure at the tank side. Vane pump failure will also drastically reduce the hydraulic oil pressure. The current node, i.e. 'P2 (− 1)', is not part of a feedback or feedforward loop, hence the logical gate; 'OR', connects top event node to its input nodes, which is shown in fault tree, Fig. 5.

Step 1.8 Checking for consistency.

There is no consistency violation and hence, no event is deleted. Therefore, there is no change in the fault tree of Fig. 5. This is the first stage of the fault tree for the system.

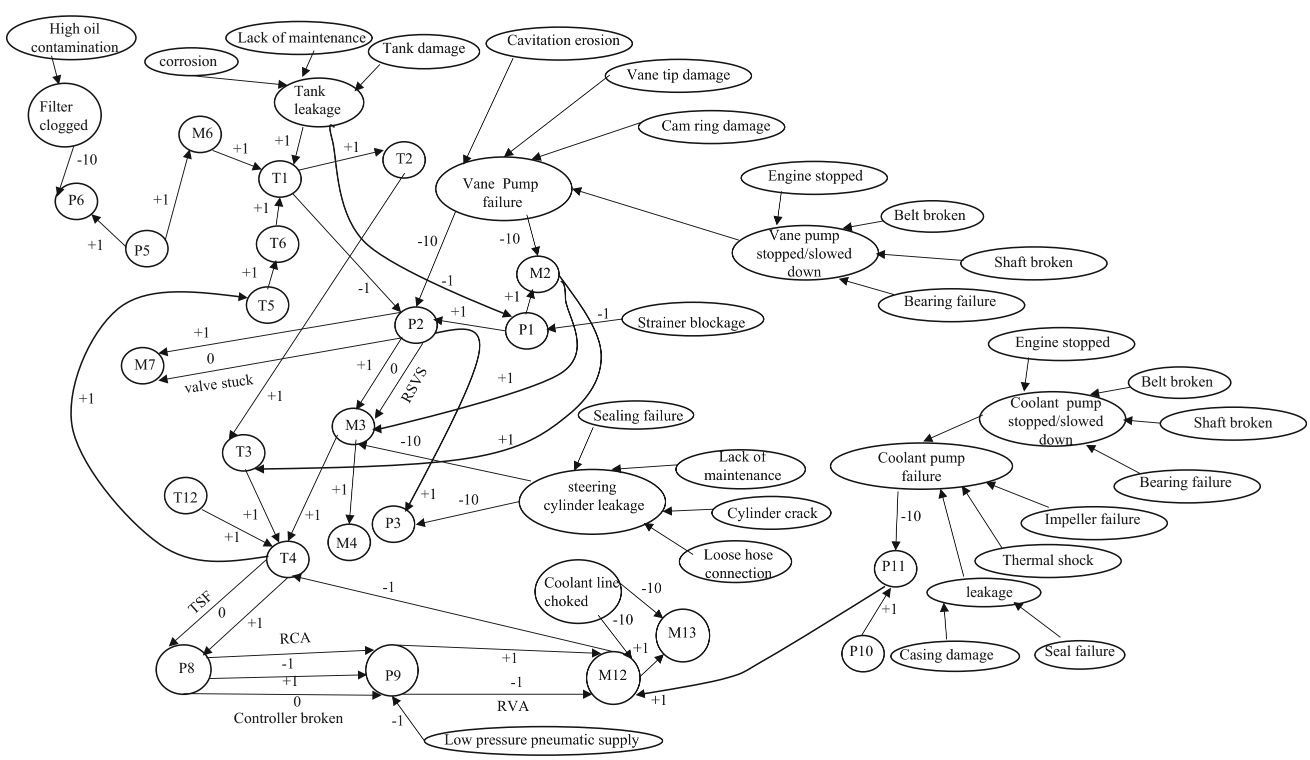


Fig. 4 Hydraulic power steering system digraph

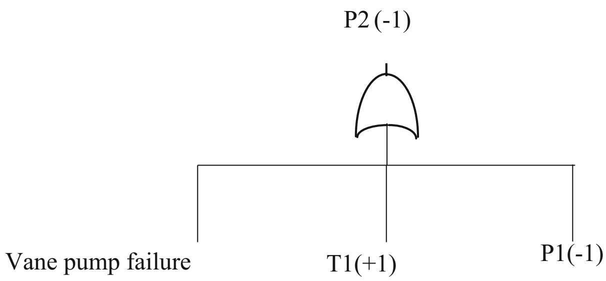


Fig. 5 First stage of fault tree development

Step 1.9 Consider the tree obtained in Step 1.8, i.e. first stage. Repeat Steps 1.7 and 1.8 to obtain next stage of the fault tree.

Start of this sub-step is from the fault tree in Fig. 5. There is a need to concurrently look at the system digraph (Fig. 4), i.e. to find input nodes to the nodes/events appearing in the current obtained fault tree (Fig. 5), which are 'P1 (− 1)', T1 (+ 1) and 'vane pump failure'. Consider the event/node; 'P1 (− 1)'. Its input nodes are 'tank leakage' and 'strainer blockage'. The nodes, which are input to the node T1 (+ 1) are M6 (+ 1), T6 (+ 1) and 'tank leakage'. For the 'vane pump failure', its input nodes are: cavitation erosion, vane tip damage, cam ring damage and vane pump stopped/slowed down. There is no consistency violation in this step and hence, no event is deleted.

There are no input nodes to 'strainer blockage'. The input nodes to 'tank leakage' are corrosion, lack of maintenance and tank damage. The input node to M6 (+ 1) is P5 (+ 1) and the input to T6 (+ 1) is node T5 (+ 1). From the digraph shown in Fig. 4, the input nodes to 'vane pump stopped/slowed down' are belt broken, shaft broken, engine stopped and bearing failure. There are no input nodes to P5 (+ 1) in the system digraph. However, the input to node T5 (+ 1) is T4 (+ 1). There is no consistency violation and hence, no event is deleted.

While screening the system digraph for getting the input nodes to T4 (+ 1), four nodes; M3 (+ 1), T3 (+ 1), M12 (− 1) and T12 (+ 1) are obtained. However, the node T4 (+ 1) is a part of the negative feedback control loop 'T4-P8-P9-M12-T4'. Hence, the four identified input nodes to T4 (+ 1) cannot be connected to it directly using 'OR' Gate. The operator suggested by Lapp and Powers (1977) is applied for connecting these nodes as inputs to T4 (+ 1), which is explained below. No event has to be deleted, as there is no consistency violation.

The system digraph suggests M3 (+ 1) as an input node to T4 (+ 1). However, this cannot be possible because the negative feedback control loop (T4-P8-P9-M12-T4) will act to neutralize the effect of M3 (+ 1) as per the negative feedback control loop operator ("Appendix"). The same argument is applied to prove that nodes T3 (+ 1) and T12 (+ 1) cannot be the input nodes to T4 (+ 1). It is observed from the system digraph that, if the mass flow rate of the coolant (M12) is increased, i.e. M12 (+ 1), the temperature T4 would decrease. However, if the mass flow rate of the coolant is decreased, i.e. M12 (− 1), it will increase T4 i.e. T4 (+ 1). This is because M12 is a part of the temperature control loop. In any circumstances, if it is observed that the coolant flow rate is reduced, i.e. M12 (− 1), it means that the control loop is actually promoting the top event of T4 (+ 1) rather cancelling it. Additionally, if either M3 (+ 1), T3 (+ 1) or T12 (+ 1) has to be the input to node T4 (+ 1), then the control loop must be inactive and take no action to cancel the disturbances or promote it. In addition to these, if the external disturbances are so large that the deviations in M3, T3 or T12 are very large (+ 10), the control loop might not be able to cancel their effects. The above arguments are incorporated in the second stage of development of the fault tree as shown in Fig. 6 by using the negative feedback operator (Refer "Appendix"), suggested by Lapp and Powers (1977).

Considering M12 (− 1), i.e. 'low coolant flow rate', it is clear that M12 has four inputs, two from node P9 one from node P11 and other from node 'coolant line choked'. M12 is in a negative feedback loop that includes P9 (− 1) and 'reversed valve action'. However, P11 (− 1) is an external failure event that will not be a part of the feedback loop. Therefore the only event to be checked for consistency is T4 (+ 1), which was developed earlier due to M12 (− 1). None of the nodes like P9 (− 1), P11 (− 1) or 'reversed valve action' violate the consistency criterion. Therefore, employing the negative feedback operator (Lapp and Powers 1977), the sub-fault tree is obtained for low coolant flow rate as shown in Fig. 7. The EOR (exclusive OR) gate is used, since a simultaneous occurrence of P9 (− 1) and 'reversed valve action' might cancel each other resulting in M12 (+ 1).

The event P11 (− 10) i.e. 'very low coolant pressure' has two input nodes, i.e. 'coolant pump failure' and P10 (− 10). There is no input node to P10 (− 10). However, there are four input nodes to coolant pump failure such as leakage, thermal shock, impeller failure and coolant pump stopped/slowed down. The input nodes to leakage are seal failure and casing damage, whereas the input nodes to coolant pump stopped/slowed down are shaft broken, belt broken, engine stopped and bearing failure. The sub-fault tree for the event P11 (− 10) is developed as shown in Fig. 8.

Repeat the sub-step 1.8, suggested for checking for consistency of the developed fault tree. Consider the event P9 (− 1) which would have been developed due to P8 (− 1). From the system digraph, the only input node to P8 (− 1) is T4 (− 1). However, this is violating consistency criterion, T4 (+ 1). This means P8 (− 1) has no input

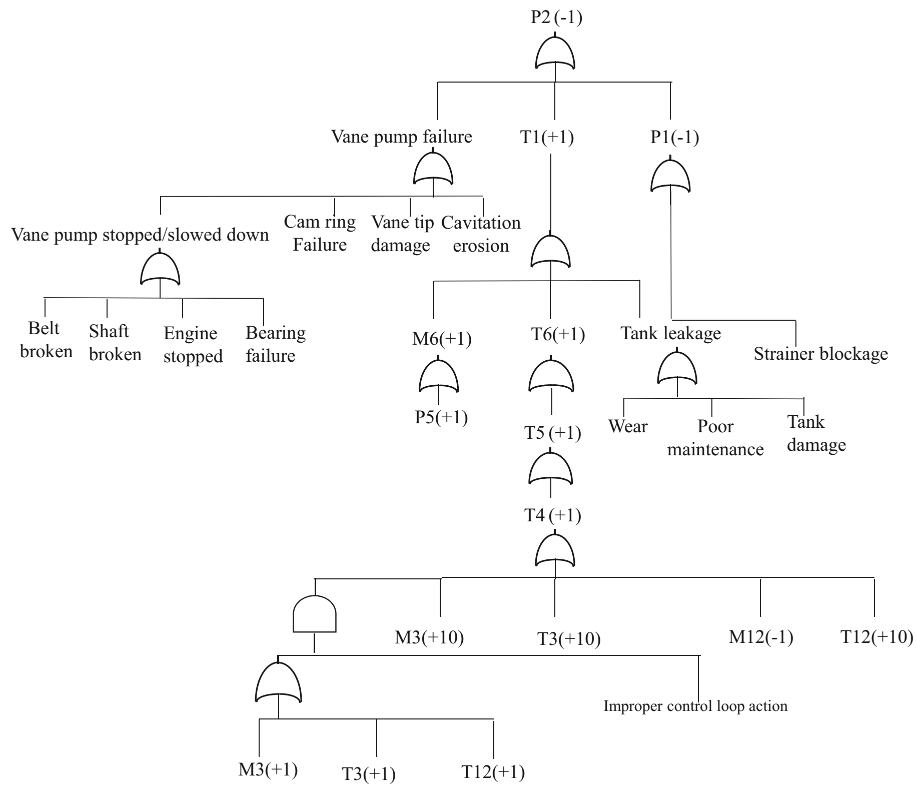


Fig. 6 Second stage of fault tree development

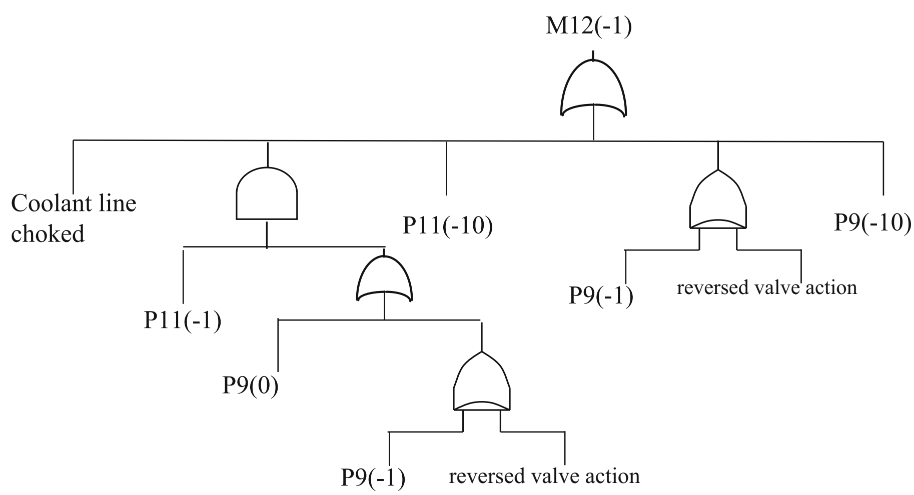


Fig. 7 Sub-fault tree for low flow rate of coolant

nodes and hence it must be deleted from fault tree, wherever it appears.

Step 1.10 Continue Step 1.9 until only primary or basic failure events remains.

The above steps are applied until primal or basic events remain. Using the above-mentioned parts of fault tree, complete fault tree for the top event, 'loss of power', i.e. P2 (− 1) is obtained as shown in Fig. 9.

From the fault tree diagram developed and shown in Fig. 9 above, one can diagnose for the symptom 'Loss of power' of hydraulic power steering system using the step 2 for fault diagnosis, which is as below.

Step 2.1 Start with the top event, which is a failure symptom or undesired event.

The diagnosis is initiated from the top event, i.e. 'Loss of power'.

Step 2.2 Identify the gate that immediately follows the top event.

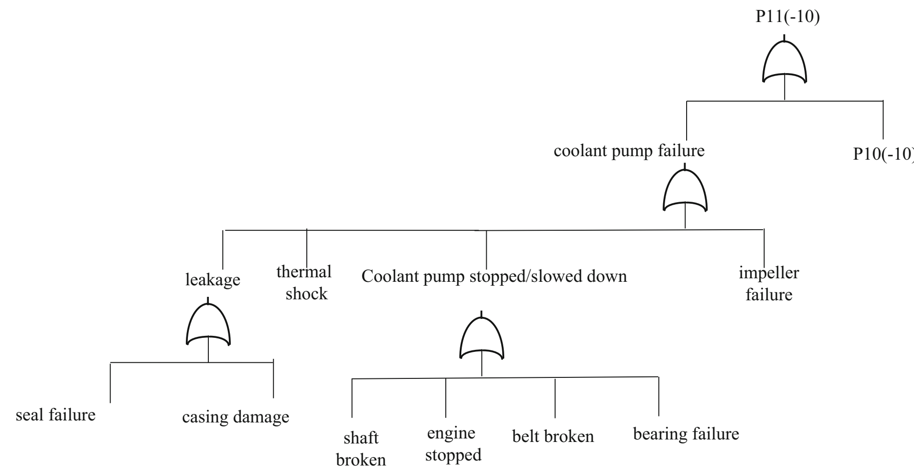


Fig. 8 Sub-fault tree for very low pressure of coolant

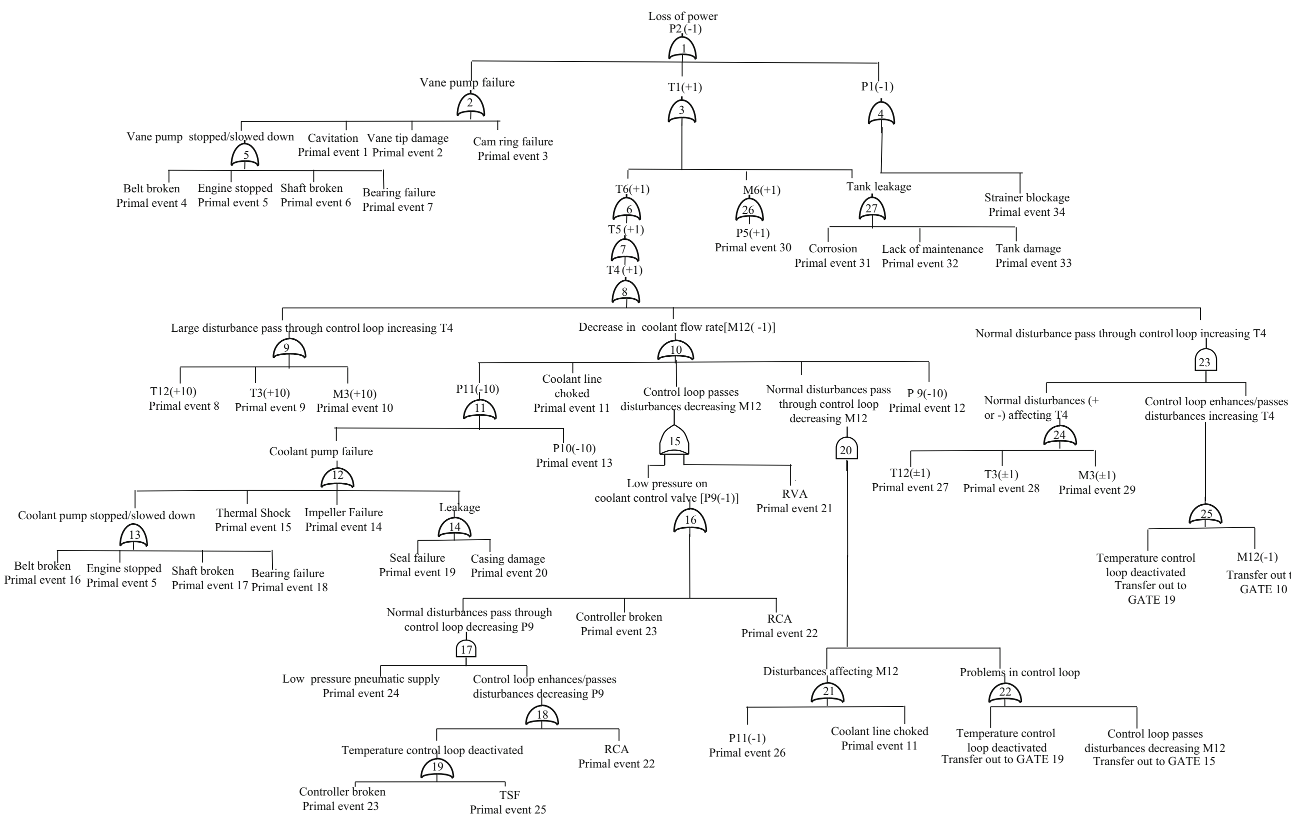


Fig. 9 Fault tree for loss of power

The gate following the top event is ‘OR’ gate. It is identified that ‘vane pump failure’, ‘low pressure of oil in hydraulic tank’, i.e. P1 (− 1) and ‘high temperature of hydraulic oil’ i.e. T1 (+ 1) are the events connected to the top event through ‘OR’ gate. From the garage experience and failure data of hydraulic power steering system, the event ‘hydraulic vane pump failure’ is the most probable cause of hydraulic power steering failure. This is to be verified first. For this, one may go for visual inspections and other functional checks/tests. If this input event is tested negative, pick the next most probable input event, i.e. ‘low pressure of hydraulic oil from hydraulic tank’ and check whether it is true or false. If this input event also tested false, pick the next input event, i.e. ‘high temperature of hydraulic oil’ for test.

Step 2.3 Identify the next gate and follow Step 2.2.

If the any of the input events mentioned in the above step is tested positive, identify the next immediate gate following this event and repeat the Step 2.2.

Step 2.4 Repeat Step 2.3 until no more logical gate remains.

This means that all the events are explored in depth until primal/basic events are reached.

On the similar lines, other top events/symptoms of the system are examined. It may be mentioned that establishment of input–output parameters interrelationships, digraph representation and fault tree development of the hydraulic power steering are based on understanding of the system, its structure, failure experience in the field or garage experience.

5 Observations, comments and other applications of the proposed approach

Fault tree development of hydraulic power steering system has been successfully illustrated above using the digraph model, which is encouraging. Conventional method of developing fault tree for hydraulic power steering system will not able to handle the feedback control loop existing in the system that maintains the temperature of hydraulic oil. However, development of fault tree based on the diagraph model was capable to handle this complexity. The fault tree developed in this work is exclusively for the qualitative analysis of failures that would help to determine the list of all possible combinations of events, which lead the top or undesired event and helps in fault diagnosis. The developed fault tree provides analyst root causes of a top event of the automobile systems and show how its failure events are connected or related. It also guides how to minimize or avoid the top event.

The development of fault tree has applications in the following aspects related to automobiles.

- As a tool for generating instructions or documents for ‘repair and maintenance’ for maintenance personnel and garage technicians to undertake repair for a fault.
- Development of automobile systems based on reliability and safety: From the fault tree developed, one can obtain its cut-sets or path/tie sets. This will help in identifying failure events that are critical in occurrence of the top events. Therefore, avoidance of these events will improve system reliability. Moreover, this information will be useful in analysis of ‘callback’ investigations.
- Accident investigation of automobiles: Accidents are caused by multiple number of factors such as automobile faults, human errors, traffic, signals, road conditions, environment, etc. Fault tree diagrams will help to identify the factors and their combinations leading to the accidents.

With computerization of the algorithm, time taken for development of tree and diagnostics can be significantly reduced. There is also flexibility in updating fault tree based on the failure data of system and its components failure.

6 Conclusions

In this paper, structural approach using digraph model has been suggested for fault diagnosis of automobile system. The proposed approach is independent of the analyst and takes care of the system complexity. The fault tree starts with top or undesired event of the system and terminates with primary or root causes. What events to be checked in the order are derived from the system digraph. The fault tree, which is obtained from the developed system digraph, which is suited for computer processing. Hence, this methodology can be automated for automobile fault diagnosis. Computerization of the methodology will help in building a knowledge base of failures and their paths. Therefore, this approach is especially useful for service and maintenance engineers. In addition, this approach can provide direction to designers in developing automobile systems considering safety, reliability and maintenance aspects.

Appendix: Generalized operators for control loops—feedback and feedforward

A major advantage of digraph based fault tree development for systems is its easiness in handling control loops. There are two types of control loops in the systems; feedback and feedforward. Lapp and Powers (1977) have suggested a generalized operator for the node that is on the path of feedback and feedforward loop, which is proposed for each type of loop.

Negative feedback loops

A control loop is designated as a negative feedback loop, when it has the capability to correct moderate disturbances in the system parameters. One can identify the negative feedback loop in a digraph as a path that begins and ends at the same node and for which the product of the normal gains is negative. Functionally, a disturbance can propagate through a feedback control loop in the following ways.

1. Large external disturbance enters loop; or
2. The control loop parameters themselves causing the disturbance;or

Fig. 10 Operator for negative feedback loop

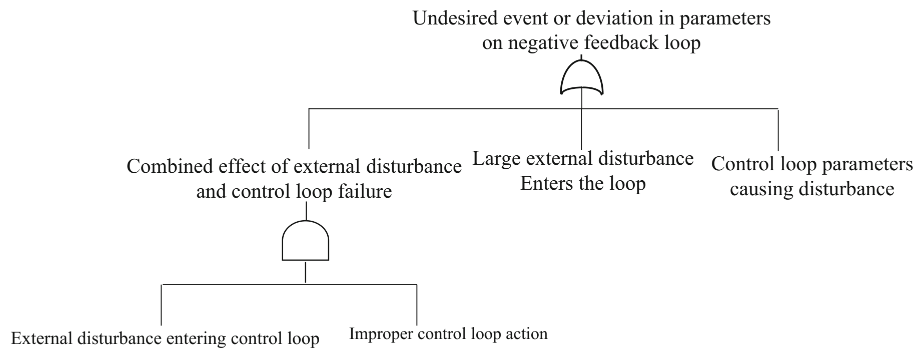
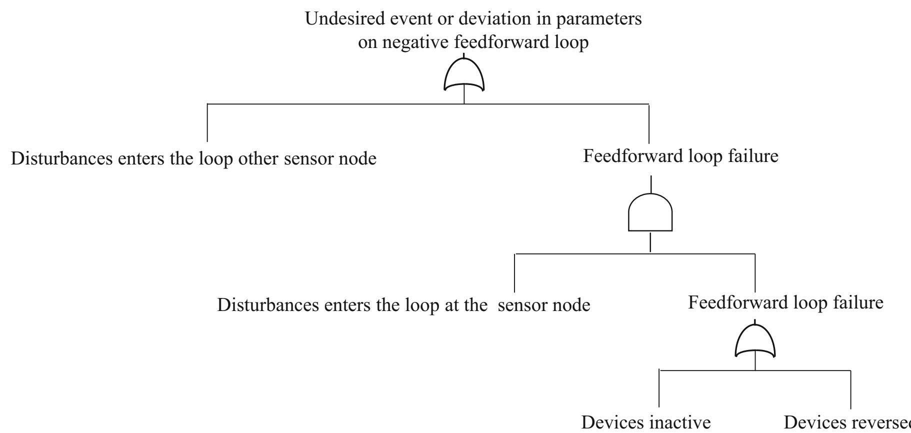


Fig. 11 Operator for negative feedforward loop



3. Combined effect of external disturbance entering the system and control loop fails to cancel it.

Based on the above conditions, a generalized operator that can be applied to any negative feedback control loop of any systems and represented diagrammatically in Fig. 10.

Negative feedforward loops

A negative feedforward loop, prevent the disturbance propagating through the system by sensing an upstream parameter and manipulating the downstream parameter. A negative feedforward loop in a digraph has two important characteristics, i.e. it will be having two or more paths from one node to another node and sign of the product of the normal gains on one path is different from that of the others. In a negative feedforward loop, there is causative branch that propagates the disturbances along the path with the net positive gain and corrective branch that controls or cancels the disturbances by the path with the net negative gain. However, a negative feedforward loop will cancel disturbances that enter at the node, which is at the starting point of loop, i.e. the sensor node. A disturbance can propagate through a feedforward control loop in the following ways.

1. The feedforward loop fails to sense the disturbances, if it enters the loop at a node other than the sensor node.
2. The failure of the loop due to inactive or reversed devices that causes a correctable disturbance to enter the loop at the sensed node and pass through it without any corrective action.

The operator used for feedforward control loop is diagrammatically represented in Fig. 11.

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