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Fault Diagnosis of Hydraulic Variable Pitch for Wind Turbine Based on Qualitative and Quantitative Analysis

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***Abstract* - Qualitative analysis and quantitative analysis are combined to carry on hydraulic variable pitch system fault diagnosis of wind turbine. Fault tree model of hydraulic system is established by the analysis of hydraulic system fault symptoms set. Petri net model of hydraulic system fault can be obtained by fault tree using the matrix operations of Petri net to achieve the conversion from qualitative to quantitative which can make up the shortcoming of fault tree model inclining to qualitative analysis when the basic event is difficult to determine its occurrence probability. The validity of the model is verified by simulation example.**

Index Terms* – *fault tree, Petri net, hydraulic variable pitch, fault diagnosis.

I. INTRODUCTION

Variable pitch system plays an important role in wind turbine generator to ensure effective utilization rate, stability and reliability of wind power. However variable pitch system fault will directly affect production safety of generating units and bring very big economic loss. Fault diagnosis research aimed at wind turbine hydraulic variable pitch system has vital significance. Due to wind power generation in China just at the starting stage, fault diagnosis researches of hydraulic system and variable pitch system for wind power generator are less, at present hydraulic system fault diagnosis are mainly: Shi Hongyan has studied high order statistics on hydraulic system fault diagnosis-fuzzy neural network method in [1] to solve low signal-to-noise ratio of fault characteristic and given an example in the form of valve controlled cylinder system as the research object. Pan Hong has studied hydraulic system leak detection method based on wavelet analysis and the change of pressure curve is detected by a pressure sensor which is transformed by wavelet transform in [2]. In [3], Wang Shaoping has adopted integration BP neural network to carry on fault diagnosis with the detection of pump pressure, flow and casing vibration signal to determine the pump fault types. Angell.c has studied on the expert system of hydraulic system fault diagnosis, which is focused on providing detection, prediction, compensation and fault diagnosis functions in [4].

In this paper, qualitative analysis and quantitative analysis are combined to carry on hydraulic variable pitch system fault diagnosis of wind turbine. Fault tree analysis method (FTA) is a qualitative analysis method that various factors may cause system failure from the whole to part according to tree branches gradually thinning the analysis [5]. Petri net is a kind of modeling tool for describing discrete and distributed system, fault diagnosis quantitative model of hydraulic variable pitch system is set up by using Petri net based on qualitative fault tree model which can make up the shortcoming of fault tree model inclining to qualitative analysis and quantitative analysis difficult, and give full play to the advantages of Petri net, the organic combination of the two makes Petri net fault diagnosis model more consistent with actual needs.

II. FAULT TREE QUALITATIVE ANALYSIS OF HYDRAULIC VARIABLE PITCH SYSTEM FOR WIND TURBINE

A. The Modeling Principle of Fault Tree Analysis

Fault tree analysis (FTA) is a top down, deductive failure analysis in which an undesired state of a system is analyzed using Boolean logic to combine a series of lower-level events. This analysis method is mainly used in the field of safety engineering and Reliability engineering to determine the probability of a safety accident or a particular system level (functional) failure.

Many different approaches can be used to model a FTA, but the most common and popular way can be summarized in a few steps. Remember that a fault tree is used to analyze a single fault event and that one and only one event can be analyzed during a single fault tree.

FTA analysis involves five steps:

(1)Define the undesired event to study

Definition of the undesired event can be very hard to catch, although some of the events are very easy and obvious to observe. An engineer with a wide knowledge of the design of the system or a system analyst with an engineering background is the best person who can help define and number the undesired events. Undesired events are used then to make the FTA, one event for one FTA; no two events will be used to make one FTA.

(2)Obtain an understanding of the system

Once the undesired event is selected, all causes with probabilities of affecting the undesired event of 0 or more are studied and analyzed. Getting exact numbers for the probabilities leading to the event is usually impossible for the reason that it may be very costly and time consuming to do so. Computer software is used to study probabilities; this may

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lead to less costly system analysis. System analysts can help with understanding the overall system. System designers have full knowledge of the system and this knowledge is very important for not missing any cause affecting the undesired event. For the selected event all causes are then numbered and sequenced in the order of occurrence and then are used for the next step which is drawing or constructing the fault tree.

(3)Construct the fault tree

After selecting the undesired event and having analyzed the system so that we know all the causing effects (and if possible their probabilities) we can now construct the fault tree. Fault tree is based on AND and OR gates which define the major characteristics of the fault tree.

(4)Evaluate the fault tree

After the fault tree has been assembled for a specific undesired event, it is evaluated and analyzed for any possible improvement or in other words study the risk management and find ways for system improvement. This step is as an introduction for the final step which will be to control the hazards identified. In short, in this step we identify all possible hazards affecting in a direct or indirect way the system.

(5)Control the hazards identified

This step is very specific and differs largely from one system to another, but the main point will always be that after identifying the hazards all possible methods are pursued to decrease the probability of occurrence.

B. Construct Fault Tree

Fault tree is a logic structure diagram expressing between system specific events and its subsystems or components fault. Fault trees are built using gates and events (blocks). The two most commonly used gates in a fault tree are AND and OR gates. As an example, in Fig.1, consider two events (or blocks) comprising a Top Event (or a system). If occurrence of either event causes the top event to occur, then these events (blocks) are connected using an OR gate. Alternatively, if both events need to occur to cause the top event to occur, they are connected by an AND gate as shown next:

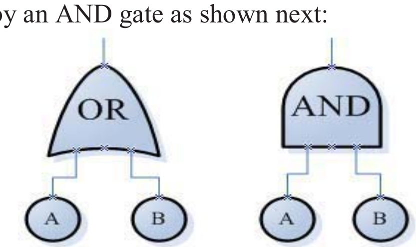
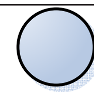
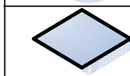
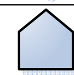
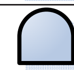
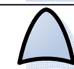


Fig.1 Two most commonly used gates in a fault tree

After selecting the undesired event and having analyzed the system so that we know all the causing effects (and if possible their probabilities) we can now construct the fault tree. Fault tree is based on AND and OR gates which define the major characteristics of the fault tree. The commonly used and basic symbols are shown in TABLE I.

TABLE I
COMMONLY USED AND BASIC SYMBOLS

Types	Symbols	Name
Event symbols		Top or intermediate event
		Basic events
		Omitting event or twice event
		Normal event
Logic gate symbols		“AND” gate
		“OR” gate

C. Fault Tree of Hydraulic Variable Pitch System for Wind Turbine

Hydraulic variable pitch wind turbine generator has more advantages which adapts to the development requirements of wind power turbine. VESTAS V39 is regarded as the research object to carry on fault diagnosis and research of hydraulic variable pitch system for wind turbine in this paper. Its work flow is shown in Fig.2.

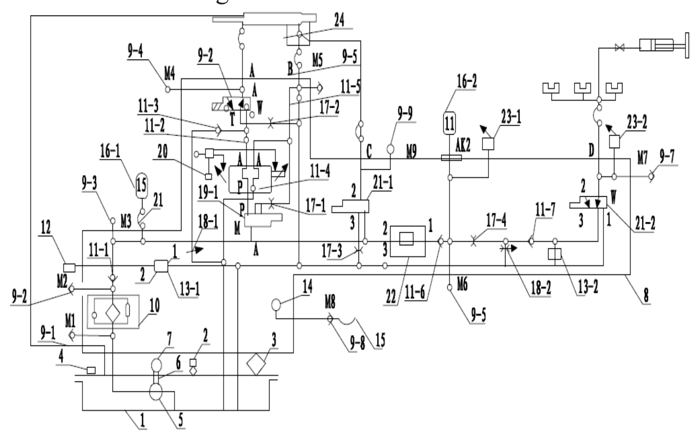


Fig.2 Hydraulic system of variable pitch wind turbine

Hydraulic system fault symptoms set of variable pitch wind turbine is collected in TABLE Ⅱ[6].

TABLE Ⅱ
FAULT SYMPTOMS SET OF HYDRAULIC VARIABLE PROPELLER PITCH SYSTEM

Fault	Symptoms			
	X18	X17	X16	X15
A1	Yes	Yes	Yes	Yes
A2	Yes	Yes	Yes	Yes
A3	Seal failure			
A4				Yes
A5		Severe wear	Severe wear	Severe wear
A6				Yes
A7		Fault	Fault	
A8			Fault	
A9		Fault	Fault	
A10			Yes	
A11		Fault		
A12				Yes
A13				Yes
A14			Fault	

Fault Symptoms: A1:hydraulic pump oil less; A2:accumulator pressure insufficient; A3:21-2 valve conduction of bad sealing; A4:19-1 valve without electrical; A5:plunger wear; A6:19-2 without electricity; A7:19-1 valve of electric fault; A8:20 valve direct state fault; A9:19-2 valve of electric fault; A10:21-1 valve leakage; A11:20 valve indirect state fault; A12:17-1 oil spill; A13:17-2 oil spill; A14: 24 double guide fault; **Fault Types:** X101:wind turbine hydraulic variable propeller pitch system of pitch fault; X15:boot feathering fault; X16:increases the power (inverse of paddle) fault; X17:reducing power (feathering) fault; X18:brake release circuit pressure is insufficient, the brake release failure.

Fault tree of hydraulic variable pitch system can be constructed by fault symptoms set of variable pitch wind turbine shown in Fig.3.

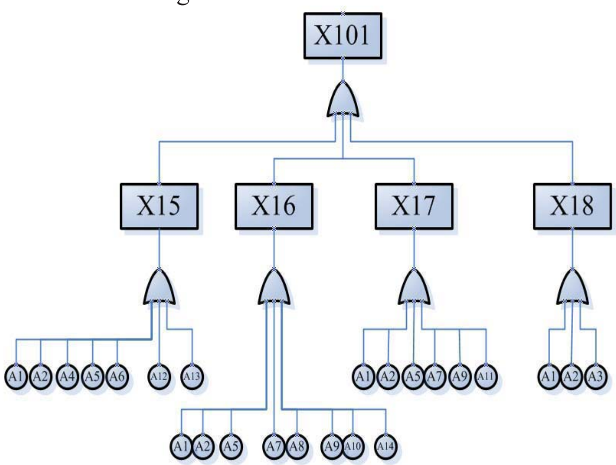


Fig.3 Fault tree of hydraulic variable pitch system for wind turbine

Case Study [7]: It appeared an increasing power (inverse paddle) failure during the system worked, oil spills had been found within hydraulic pump after a preliminary investigation. Fault reason can be quickly identified, that is, electromagnetic valve 21-1 exiting oil spills according to fault tree model shown in Fig.2.

The diagnosis result is consistent with [7], it can be seen that the fault tree model of hydraulic variable pitch system given in this paper is correct and feasible. Qualitative fault analysis of hydraulic variable pitch system is realized by establishing fault tree model, if it needs to be carried on quantitative analysis, the probability and some reliability indexes must be given in advance. But these data has uncertainty and is not subject to exponential function distribution which can bring about great inconvenience for fault tree analysis. Petri net model will be established by fault tree in this paper according to Petri net with algebraic operations function to achieve the conversion from qualitative analysis to quantitative analysis.

III. Fault Diagnosis Principle Based on Petri Net

A. Petri Net Basic Terminology

Petri net (also known as a place/transition net or P/T net) is one of several mathematical modeling languages for the description of distributed systems. A Petri net is a directed bipartite graph, in which the nodes represent transitions (i.e. events that may occur, signified by bars) and places (i.e. conditions, signified by circles). The directed arcs describe which places are pre- and/or post-conditions for which transitions (signified by arrows). Petri nets were invented in August 1939 by Carl Adam Petri for the purpose of describing chemical processes.

A Petri net consists of places, transitions, and arcs. Arcs run from a place to a transition or vice versa, never between places or between transitions. The places from which an arc runs to a transition are called the input places of the transition; the places to which arcs run from a transition are called the output places of the transition.

Graphically, places in a Petri net may contain a discrete number of marks called tokens. Any distribution of tokens over the places will represent a configuration of the net called a marking. In an abstract sense relating to a Petri net diagram, a transition of a Petri net may fire whenever there are sufficient tokens at the start of all input arcs; when it fires, it consumes these tokens, and places tokens at the end of all output arcs. A firing is atomic, i.e., a single non-interruptible step.

A fault Petri Nets can be defined as follows:

$$PN = (P, T, I, O, W, M_0) \tag{1}$$

P is a set of states, called places;

T is a set of transitions;

I is an input function matrix from T to P as arcs;

O is an output matrix from P to T as an arc;

W is the weight of arcs;

M_0 is the initial marking and marking vector.

In the diagram of a Petri net (see Fig.3), places are conventionally depicted with circles, transitions with long narrow rectangles and arcs as one-way arrows that show connections of places to transitions or transitions to places. If the diagram were of an elementary net, then those places in a configuration would be conventionally depicted as circles, where each circle encompasses a single dot called a token. In the given diagram of a Petri net (see left), the place circles may encompass more than one token to show the number of times a place appears in a configuration. The configuration of tokens distributed over an entire Petri net diagram is called a marking.

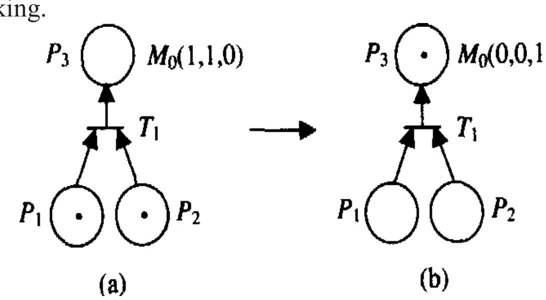


Fig.4 Graphical description of Petri Nets

In Fig.4, (a) is a Petri net with an enabled transition;(b) is the Petri net that follows after the transition fires (Initial Petri net).The place P_1 and P_2 are an input place of transition T_1; whereas, the place P_3 is an output place to the same transition. Let (a) be a Petri net with a marking configured $M_0(1,1,0)$ and (b) be a Petri net with a marking configured $M_0(0,0,1)$. The configuration of (a) enable transition T_1 through the property that all input places have sufficient number of tokens (shown in the figures as dots) "equal to or greater" than the multiplicities on their respective arcs to T_1. Once and only once a transition is enabled will the transition fire. In this example, the firing of transition T_1 generates a map that has the marking configured M_0 in the image of M_0 and results in Petri net (b). In the diagram, the firing rule for a transition can be characterized by subtracting a number of tokens from its input places equal to the multiplicity of the respective input arcs and accumulating a new number of tokens at the output places equal to the multiplicity of the respective output arcs.

B. Incidence Matrix and State Equation

Any Petri Net can be represented as an incidence matrix. In fault Petri Nets, incidence matrix is mainly used to describe the relation between fault propagation and event. In (1), $W(T_j, P_i)$ is the weighs of arcs from transition t_j to place p_i. Because of creating a "token" in output places after transition firing which only includes output incidence matrix $W(T_j, P_i)$.

Here set $A_{ij} = W(T_j, P_i)$, $(1 \le i \le n,\ 1 \le j \le m)$ is the incidence matrix of fault Petri Nets in (1).

The state equation is represented by

$$M_{k+1} = M_k + A^T V_k \tag{2}$$

Where M_k , M_{k+1} respectively denotes the initial sets and result sets in the moment K of transition firing; $A = [A_{ij}]$ is the correlation matrix of fault Petri Nets; V_k is the firing sequence in the moment K and an $m \times 1$ column vector called the firing count vector consisted of 0 or 1, $V_k^{'} = 1$ denotes the transition is fired, $V_k^{'} = 0$ denotes the transition is unfired. The state is used to solve the reachable problem. If M_k is reachable from M_0, then the state equation has a solution in nonnegative integers. If the state equation has no solution, then M_k is not reachable from M_0.

C. The Flow Chart of Incidence Matrix Algorithm for System Dynamics Based on Petri Net

The flow chart of the incidence matrix algorithm for system dynamics based on Petri net is shown in Fig.5.

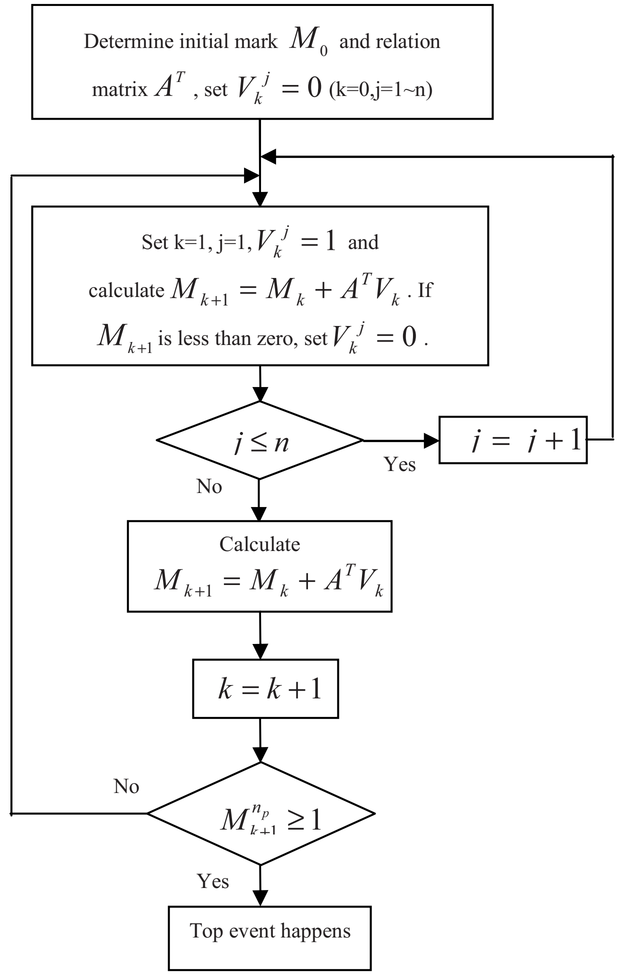


Fig.5 Flow chart of the incidence matrix algorithm based on Petri net

IV. Petri Net Fault Diagnosis Model of Wind Turbine Hydraulic Variable Pitch

A. Petri Net Fault Diagnosis Model of Hydraulic Variable Pitch System Established by Fault Tree

Petri Net model of hydraulic variable pitch system (see Fig.6) can be established by the fault tree structure of hydraulic variable pitch system given in Fig.3.

Where the row of incidence matrix A^T represents places A^i (i=1,2,...,14) and C^i (i=15,...,18,101), the column of it represents transitions T^j (j=1,2,...18).

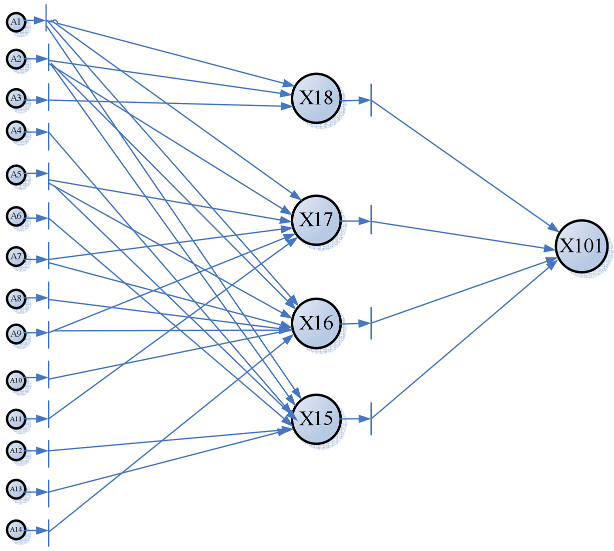


Fig.6 Petri Net model of hydraulic variable pitch system

B. Case Study

According to Petri net fault model of hydraulic variable pitch system, the incidence matrix can be yielded as follows:

$$A^T = \begin{array}{c} A_1 \\ A_2 \\ A_3 \\ A_4 \\ A_5 \\ A_6 \\ A_7 \\ A_8 \\ A_9 \\ A_{10} \\ A_{11} \\ A_{12} \\ A_{13} \\ A_{14} \\ X_{15} \\ X_{16} \\ X_{17} \\ X_{18} \\ X_{101} \end{array} \begin{vmatrix} -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 \\ 1 & 1 & 0 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & -1 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 1 & 0 & 1 & 1 & 1 & 1 & 0 & 0 & 0 & 1 & 0 & -1 & 0 & 0 \\ 1 & 1 & 0 & 0 & 1 & 0 & 1 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & -1 & 0 \\ 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 \end{vmatrix}$$

According to the operating state of hydraulic variable pitch system of **Case Study** given in Section Ⅱ, the initial mark matrix of fault Petri net can be yielded:

$$M_0 = [0000000001000000000]^T$$

The sequence of transition V_0 being fired is

$$V_0 = [000000000100000000]^T$$

The marking M after transition V_0 being fired can be solved by (2), that is

$$M_1 = M_0 + A^T V_0 = [0000000000000001000]^T$$

The sequence of transition V_1 being fired is

$$V_1 = [000000000000000100]^T$$

The marking M_2 after transition V_1 being fired can be solved

$$M_2 = M_1 + A^T V_1 = [0000000000000000001]^T$$

The diagnostic result is top event fault, that is, when the initial event A10-21-1 valve appears leakage, top events, (variable pitch system) fault occurs [7]. The diagnosis result is consistent with fault tree model.

IV. Conclusion

Fault tree model is only limited to qualitative analysis when the basic event is difficult to determine its occurrence probability. Petri net and fault tree are combined to realize hydraulic variable pitch system fault diagnosis of wind turbine. Fault tree model of hydraulic system is established by the analysis of hydraulic system fault symptoms set. Petri net model of hydraulic system fault can be obtained by fault tree using the matrix operations of Petri net to achieve the conversion from qualitative to quantitative. The simulation results verify the validity of the model.

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