A Predictive Maintenance Method of Series-parallel System Based on Condition Monitoring

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Abstract **—In this paper, a predictive maintenance method for maintenance sequence planning problem of series-parallel systems is proposed, which minimizes the system maintenance cost based on the opportunity maintenance. Firstly, the influence relationship diagram is established by considering the topological structure relationship and the function influence relationship. Secondly, with the condition monitoring information of each equipment, the predictive maintenance strategy and optimal maintenance sequence of series-parallel system are presented dynamically by combining the method of life time prediction and maintenance planning. Finally, a splice assembly production line is taken as an example to validate the reasonableness and economy of predictive maintenance strategy. This method can reduce the failure rate and shorten the total downtime to improve the reliability of equipment and profitability of enterprises.**

Keywords—Condition monitoring; Life time prediction; Maintenance sequence planning; Series-parallel system

I. NTRODUCTION

Preventive maintenance (PM) is defined as a set of activities aims to improving the overall reliability and availability of system. More and more researches have focused on PM problems in recent years [1~4]. For the multi-set of equipment systems, an optimal maintenance strategy must be taken account of the interactions among the various equipment, which including economic dependence, structural dependence and stochastic dependence [5]. The objective can be categorized into two groups: maximizing system reliability and minimizing maintenance cost [6]. In view of the maintenance of series-parallel system, the scholars both at home and abroad have put forward many theories and methods. Lin and Wang [7] minimized the cost of periodic preventive maintenance for a series-parallel system by using an improved particle swarm optimization algorithm. Wang and Tsai [8] established a bi-objective imperfect PM model of a series-parallel system. They developed a unit-cost cumulative reliability expectation measure, and the improvement factor method was used to evaluate the repairing components which can restore the system reliability. Maillart and Pollock [9] analyzed predictive maintenance policies for systems exhibiting 2-phase system based on decomposing the expected cost (per unit time) into 2 components: the expected cost due to maintenance actions, the expected cost due to monitoring actions. Huang and Wang [10] aimed at constructing an optimal preventive maintenance model for a multi-state degraded system under the condition that individual components can be monitored in real time. Verl et al. [11] presented an automated condition monitoring (SACM) algorithms, which was based on comparing with current characteristic parameters. Lin and Tseng [12] synthesized low level information (such as vibration signals) with high level information (like reliability statistics) to form a rigorous theoretical base for better machine maintenance.

Many studies, as reviewed above, massive achievements have been made, but they still have some limitations. According to the condition monitoring of various equipment, if the topological structure relationship and function influence relationship among various equipment can be fully considered, life prediction and maintenance planning can be closely combined. So, the predictive maintenance (PdM) methods for series-parallel system are proposed. This paper focus on the maintenance cost minimization of series-parallel systems. The influence relationship, condition monitoring, life time prediction and maintenance sequence planning are fully combined, then a predictive maintenance strategy and sequence are provided dynamically.

The paper is organized as follows: in section 2, an influence relationship diagram of series-parallel system is established, moreover, the predictive maintenance strategy and the detailed operation steps of series-parallel system are proposed. In section 3, there is a case study provided to demonstrate the proposed method. In section 4, conclusions of this paper are made.

II. SOLUTION

A. Influence diagram for series-parallel system

The influence relationship diagram of series-parallel system is built mainly based on the function influence relationship and topological structure relationship. Because the function influence relationship of series-parallel system is extremely complex, the influence relationship diagram can be sketched according to the topological structure relationship firstly. Then, on the basis of the practical operating experience and methods such as expert evaluation, when there is a function influence relationship between two parallel equipment, turn the parallel relationship

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into a series relation without changing other topological structure. Finally, the influence relationship diagram is obtained. As shown in Fig. 1, the left block of the diagram shows the topological structure relationship of 6 sets of key equipment. Analytically, there is a function influence relationship between B and E, in accordance with the method above, the relationship can be changed into a series relation. Similarly, two kinds of influence relationship diagrams are obtained, which are shown in the right block of the diagram.

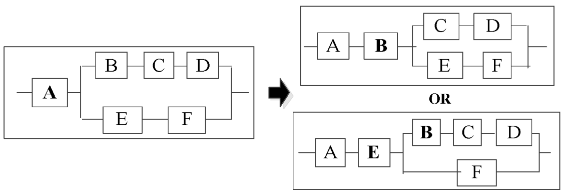

Fig. 1. The case of constructing the influence relationship diagram.

As we see, the influence relationship diagrams in the right of the diagram are only changed B and E series-parallel relationship, it is no effect on the topological structure relationship of the other sets of equipment.

B. Predictive maintenance for series parallel system

To formulate the concrete strategy of predictive maintenance for series-parallel system, the influence relationship diagram is built firstly. Secondly, the residual life time is predicted, and the maintenance sequence with single set of equipment is computed bases on the condition monitoring data. Finally, the single set of equipment maintenance sequence is integrated again to obtain the system predictive maintenance sequence planning. In this way, the reliability can be guaranteed while it reduces the risk. The predictive maintenance strategy for the series-parallel system is shown in Figure 2. The strategy is presented as following.

Step1: Life prediction for single set of equipment.

In the life time prediction stage of single set of equipment, according to the characteristics of the recession of different sets of equipment condition monitoring signal, the residual life time of the equipment can be predicted by choosing the proper life time prediction model. At the same time, by the historical records of the same kind of equipment, the optimal life time margin value of each set of equipment can be determined by using formula (1) [13].

$$\Omega = \max_{j=1,2,\ldots,N} \left\{ PRUL_j(t) \middle| ARUL_j(t) = \Delta t \right\} \qquad (1)$$

Where $j=1,2, \ldots, N$ indicates the samples of same equipment. $ARUL(t)$ indicates the actual residual life time, $PRUL(t)$ indicates the predicted residual life time, Ω indicates the life time margin.

Step2: Maintenance sequence calculation.

To minimize the total risk value by using the condition monitoring information, each set of equipment maintenance sequence at every condition monitoring sampling point can be calculated by choosing the appropriate maintenance sequence scheduling model. When one set of equipment residual life time of prediction is bigger than its life time margin, it should continue monitoring and count the maintenance sequence of every condition monitoring sampling point, until the sum of the sampling point and the length of the sampling interval time are bigger than the maintenance sequence at this sampling point, which indicates the system meets the starting conditions of system maintenance sequence planning integration. The discriminant is shown in formula (2) [13].

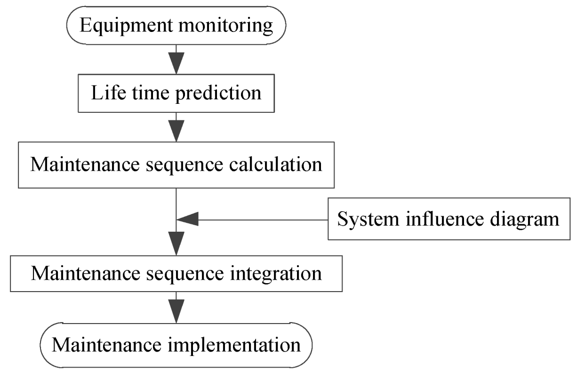

Fig. 2. The predictive maintenance strategy of the series-parallel system.

$$t + \Delta t \geq T_{next}(t) \qquad (2)$$

Where t is defined as a condition monitoring sampling point, Δt is the length of the sampling interval time, $T_{next}(t)$ is the maintenance sequence at the sampling point.

Step3: Twice integration of Maintenance sequence planning.

When a set of equipment meets the starting conditions of system maintenance sequence planning integration, the maintenance sequence planning can be integrated twice with the influence relationship diagram. Prior to this, a pile set of equipment is defined which meets the starting conditions of system maintenance sequence planning integration, and the series-parallel relationship between the pile equipment and others with influence relationship diagram are analyzed. If the sets of equipment in series with the current prediction residual life time of pile equipment are less than the life time margin, the primary integration of system maintenance sequence planning with the set of pile equipment is implemented simultaneously. Then, if the sets of equipment in parallel with the pile equipment meet the starting condition of system maintenance sequence planning integration in N times of the length of the sampling interval time, the final integration of system maintenance sequence planning with the pile equipment is implemented simultaneously. In addition, the appropriate value N can be chosen to meet the actual needs and circumstances according to the different maintenance planning requests.

III. CASE STUDY

A. Relationship diagram description

In this section, a splice assembly production line is chosen. To simplify the research process, 4 key sets of equipment are analyzed only. At first, the topological structure among equipment is analyzed, and the topological structure is shown in Fig. 3.

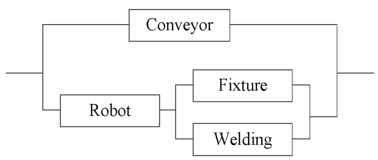

Fig. 3. The topological structure diagram for splice assembly production line.

Secondly, according to Fig. 3, the function influence among equipment is analyzed.

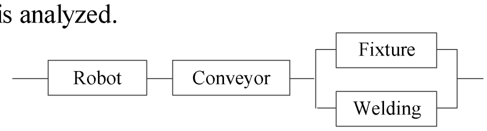

Fig. 4. The influence relationship diagram for splice assembly production line.

Fig. 4 shows that the equipment influence relationship diagram of the splice assembly production line which is based on the summary of topological structure relationship and function influence relationship.

B. Case application and analysis

According to the key equipment analysis of fault tree and failure mode, effect analysis of the splice assembly production line, combining with the technical specification documents, expert experience and statistical process control to analyze the actual historical failure data of the system, to confirm the fault characteristic parameters and failure threshold.

In order to validate our proposed method, 150 groups of the same kind of equipment recession signal from running to failure are applied to the experiment, where 100 groups are the reference samples, and 50 groups are the testing samples. The condition monitoring sampling interval for 1 hour and deadline for 50 hours is set. Predicted residual life time of each set of equipment can be calculated at any time, then the life time margin is obtained by formula (1). Table 1 shows the results.

TABLE I. LIFE TIME MARGIN OF EQUIPMENT.

Equipment	Life time margin
Robot	20.6
Welding device	18.4
Fixture	15.3
Conveyor	19.6

TABLE II. THE IMPLEMENTATION RESULTS OF MAINTENANCE SEQUENCE FOR CONVEYOR.

t	*ARUL(t)*	*PRUL(t)*	$T_{next}(t)$	*t*	*ARUL(t)*	*PRUL(t)*	$T_{next}(t)$
1	35	125.9	/	26	31	44.3	/
2	34	121.7	/	27	30	38.9	/
3	33	88.5	/	28	29	40.2	/
4	32	38.2	/	29	28	38.5	/
5	31	44.3	/	30	27	36.1	/
6	30	38.9	/	31	26	32.3	/
7	29	40.2	/	32	25	32.3	/
8	28	38.5	/	33	24	25.4	/
9	27	36.1	/	34	23	23.2	/
10	26	32.3	/	35	22	23.5	/
11	25	32.3	/	36	21	24.6	/
12	24	25.4	/	37	20	20.7	/
13	23	23.2	/	38	19	14.1<19.6	
14	22	23.5	/	39	18		
15	21	24.6	/	40	17		
16	20	20.7	/	41	16		
17	19	14.1<19.6	25	42	15		
18	18		27	43	14		
19	17		29	44	13		
20	16		32	45	12		
21	15		21(MAINTAIN)	46	11		
22	35	125.9	/	47	10		
23	34	121.7	/	48	9		
24	33	88.5	/	49	8		
25	32	38.2	/	50	7		

Similarly, the appropriate maintenance planning model to determine the maintenance schedule of the equipment is selected. The results of maintenance sequence are shown as Table 2.

With the above methods, the maintenance sequence of single set of equipment of robots, welding equipment and fixtures can be calculated. The maintenance sequence results of each single set of equipment are shown in Table 3.

TABLE III. THE MAINTENANCE SEQUENCE OF EACH SINGLE EQUIPMENT.

Equipment	Maintenance Sequence
Robot	18,36
Welding	33
Fixture	36
Conveyor	21,42

According to the influence relationship diagram of the splice assembly production line, it needs to integrate the predictive maintenance sequence planning twice, the results of the first integration are shown in table 4.

TABLE IV. THE MAINTENANCE SEQUENCE PLANNING.

Equipment	The first round	The second round
Robot	18，36	18，33
Welding	33	33
Fixture	36	33
Conveyor	18，39	18，39

The whole maintenance sequence of the system can be divided into three stages, the maintenance for robot and conveyor should be implemented at 8th hours; The maintenance for robot, welding device and fixture should be implement at 33th hours; The maintenance for transportation equipment should be implemented at 39th hours.

As observed above, the average maintenance cost is 3346, which is calculated under the selected maintenance planning model. It is in accordance with the optimal maintenance sequence planning of each set of equipment to implement the shutdown maintenance. The method strikes a balance between the costs and reliability, and the equipment actual maintenance requirements is also considered. Moreover, the maintenance sequence planning shows the maintenance activities are more reasonable and economical.

IV. CONCLUSIONS

This paper aims at the series-parallel system, and fully combines condition monitoring, residual life time prediction and maintenance sequence planning. Firstly, the influence relationship diagram of the system was constructed which mainly referred to the topological structure relationship and function influence relationship. Secondly, the proper residual life time prediction method was chosen, and the residual life time of equipment at any time with real time monitoring data predicted to confirm the life time margin with the history information of similar equipment. Thirdly, maintenance sequence of each set of equipment was calculated by chosen the suitable maintenance sequence planning model, and then whether some equipment meets the starting condition of system maintenance sequence planning integration was judged. Finally, the splice assembly production line was taken as an example to verify the reasonable and economical characteristics of the proposed method.

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