Analysis of the reliabilities of maglev train power system with DFTA method

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ABSTRACT: For a higher reliability of the Maglev Train, we are considering a redundant scheme in the designing of the train. In this paper, we first introduced the Maglev Train and its safety requirements, then analyzed its power structure and introduced the theory of Dynamic Fault Tree Analysis (DFTA). Based on the principle of the Dynamic Fault Tree, we made the model and analyzed the faults of the power supply system as well as calculated the effect of the critical parts. Finally, a thorough comparison between the redundant scheme and the normal scheme was given, demonstrating the advantage and disadvantage of the redundant scheme.

Keywords: DFTA, power supply system of the Maglev Suspend Train, redundant, Markov chain

1 INSTRUCTIONS

The magnetic suspension train is a new type of railroad traffic tool, which runs encircling the railroad but does not have mechanical contacts with it. Its supporting and guiding functions are finished by the active –controlled electromagnet, and pushed by the linear motor. It runs with high speed. Its shape is shown as in Figure 1. The maglev train has two types, high speed one and middle or low speed one. The speed of the latter is normally within 120km/h. So, it is proper for near –distance incity traffic or touring regions. The Japanese middle and low speed magnetic suspension train (HSST series) and the CMS series of the National University of Defense Technology of China (NUDT) belong to this type. They are seen in Figure 1, Figure 2, Figure 3 and Figure 4.

The basic principle to guarantee the high safeties and reliabilities of the magnetic suspension under disturbances, faults, and other urgent conditions, and whenever, the running train can stop at any given point, where all the passengers can get off the train completely and find a safe place. The object studied in this paper is the CMS-3 type electromagnetic suspension sample train developed in the National University of Defense Technology. Based on the method of dynamic fault tree analysis, the safeties and the reliabilities of the key part (the power system) of the train are analyzed systematically. And the instructive viewpoints and the improving measures are put forward.

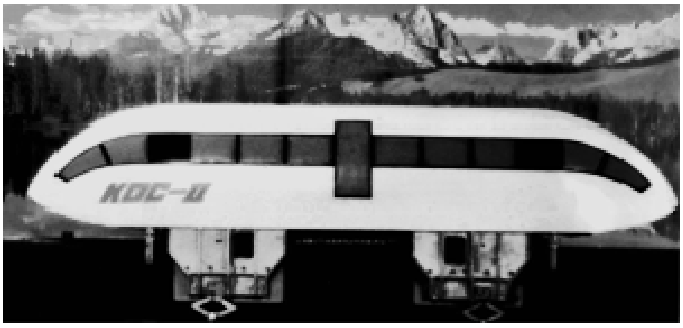

Figure1: the CMS-01 type magnetic suspension train in1989

Figure2: the experimental line in the National University of Defense Technology

Figure3: the CMS-03 type magnetic suspension train developed in 2001 is running on the experimental line

Figure4: the CMS-03A type magnetic suspension train developed in 2005

2 POWER STRUCTURE OF THE MAGNETIC SUSPENSION TRAIN

10KV ground, high-pressure alternating current is transformed into 750V direct current, which then becomes the power supply of the train by the third and the fourth current-accepting rails of the line and the train-borne current acceptor .The 750V power in the train is distributed as in Figure 5.

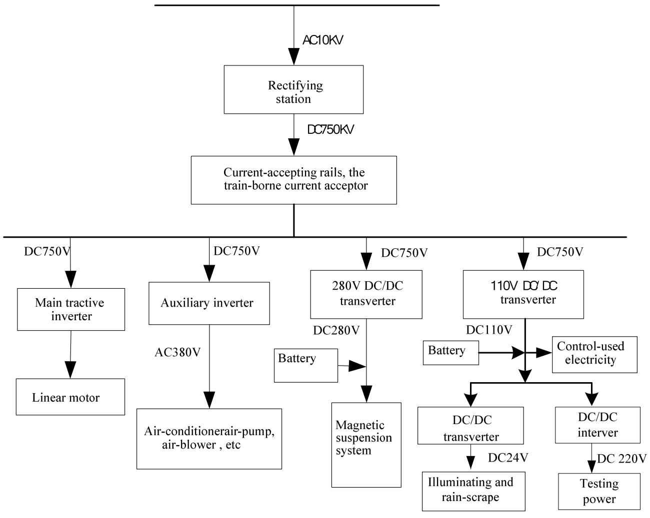

Figure 5: The diagrammatic sketch for the total power supplies of the CMS-03 system

What Figure 5 gives is the topological diagram [1] of the power system for only one train. Then, a gang-up of three trains has three sets of power system as shown in Figure 5. The 3 sets of independent train-borne powers supply power separately to the electrical facilities of their responding train. Different from the high-speed magnetic suspension train, no matter this type of train is under static suspension or is running; the power required by the train is all supplied by the current-accepting rail installed on the track beam. If the power system has any faults, the train will be powered by batteries. Therefore, the safety requires that only after the batteries are fully charged, can the train start from a stopping point. The design principle of the batteries is that even if a fault takes place when the train has just started running, can the batteries supply power for suspension and urgent braking, until the train stops at the next point.

3 THE THEORY OF DFTA

The method of FTA (fault tree analysis) is often used to analyze the reliability of the system. But for systems containing dynamic fault tolerance, redundant repairable devices, or sequence dependant behaviors, it is really hard to analyze the dynamic behavior with the traditional fault tree model.

DFT (Dynamic fault tree) is a superset of traditional (static) fault tree in that additional gates are used to model sequential behavior, and its analysis method-DFTA, has been shown particularly useful for reliability analysis of systems discussed above.

The fault tree of a complex system is often large and complex in itself. In order to solve such a fault tree efficiently, DFTA uses a divide-and-conquer [2][5] method by which independent sub-trees are identified and solved by suitable solvers. Sub-trees comprised of only AND, OR and K-of-M gates are solved by conversion to the equivalent BDD [3], while dynamic sub-trees are solved by Markov models [4]. Using the concept of coverage incorporated into Markov models, replacing each subtree by a node with responding result, the tree can be simplified and the fault rate of the system can be calculated.

4 FAULT ANALYSIS OF THE POWER SUPPLY SYTEM WITH REDUNTANT SCHEME

4.1 DFT modeling on power supply system

For higher reliabilities of the Maglev Suspend Train, many important devices of the power supply system have used redundant scheme, for which the traditional FTA method is no longer fit for the modeling. Here, we use the method of DFTA mentioned above.

According to the power supply structure shown in Figure 5, we build its DFTA model on the assumption that the Maglev Suspend Train is organized into two groups, as shown in Figure 6.

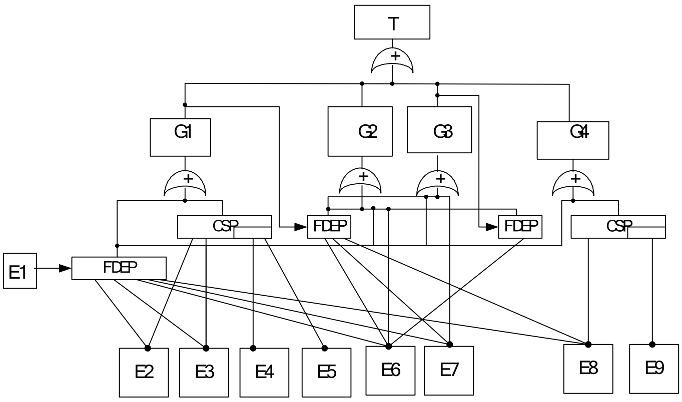

Figure 6: Dynamic Fault Tree of power supply system.

The symbol meanings in Figure 6 are: T: power supply system fault; G1: DC110V power supply fault; G2: the tractive system fault; G3: power supply of auxiliary system fault; G4: DC280V power supply fault; E1:DC750V ground power supply fault; E2: 110VDC/DC transverter of local train fault; E3:110VDC/DC transverter of other trains fault; E4: 110V battery of other train fault; E5: 110V battery fault; E6: main tractive inverter fault; E7: auxiliary inverter fault; E8: 280VDC/DC transverter fault; E9: 280V battery fault.

4.2 Analysis process

According to the process expatiated in section 3, we analyze the model shown in Figure 6.

First, find the independent subtree in it. We used the Depth-First algorithms to get the searching order of nodes: T G1 E1 E2 E3 E4 E5 G1 G2 G1 E1 E6 G3 G1 E1 E7 G3 G2 G3 G4 E1 E8 E9 G4 T, which lists in table 1,

Table 1: DFTA Depth-First search

	E1	E2	E3	E4	E5	E6	E7	E8	E9
M1	3	4	5	6	7	12	16	22	23
M2	11	4	5	6	7	12	16	22	23
M3	21	4	5	6	7	12	16	22	23
	T	G1	G2	G3	G4				
M1	1	2	9	13	20				
M2	25	8	18	17	24				
M3	25	14	18	19	24				
Min	2	3	2	2	3				
Max	24	21	21	21	23				
Y/N	Y	N	N	N	N				

In Table 1, Y/N shows whether the responding node is an independent subtree. From Table 1, we can see that there is no independent subtree on the fault tree. Convert the Dynamic tree to Markov chain, as shown in Figure 7, where the state meanings are: state 0 (system being OK), state 1 (E1 fault), state 2 (E1 or E2 fault), state 3 (E1 &E2 fault), state 4 (E4 or E5 fault), state 5 (E4 &E5 fault), state 6 (E6 fault), state 7 (E7 fault), state 8 (E8 fault), state 9 (E9 fault).

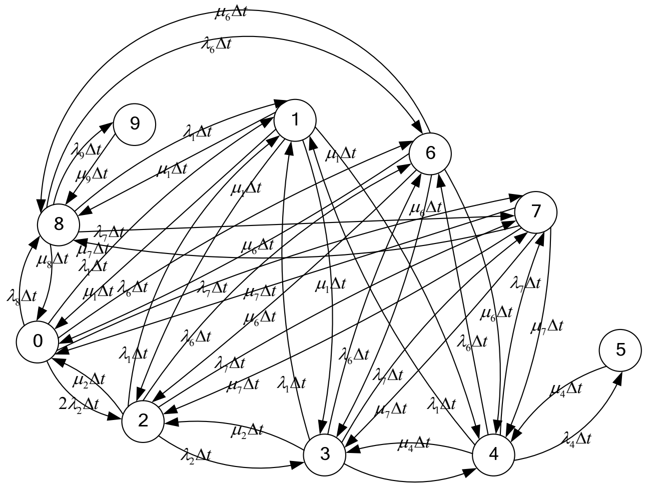

Figure 7: Markov chain

Based on Fokker-Planck Equations:

$$\dot{p}(t) = p(t)Q \qquad (1)$$

where row vector $p(t) = [p_0(t), p_1(t)...p_{Fa}(t)]$ denotes the possibilities of responding state, Q denotes the transfer matrix with. $\sum_j q_{ij} = 0$, system fault rate (SFR) can be calculated.

$$Q = \begin{bmatrix} \alpha_{00} & \lambda_1 & 2\lambda_2 & 0 & 0 & 0 & \lambda_6 & \lambda_7 & \lambda_8 & 0 \\ \mu_1 & -5\mu_1 & \mu_1 & \mu_1 & \mu_1 & 0 & 0 & 0 & \mu_1 & 0 \\ \mu_2 & \lambda_1 & \alpha_{22} & \lambda_2 & 0 & 0 & \lambda_6 & \lambda_7 & 0 & 0 \\ 0 & \lambda_1 & \mu_2 & \alpha_{33} & 2\lambda_4 & 0 & \lambda_6 & \lambda_7 & 0 & 0 \\ 0 & \lambda_1 & 0 & \mu_4 & \alpha_{44} & \lambda_4 & \lambda_6 & \lambda_7 & 0 & 0 \\ 0 & 0 & 0 & 0 & \mu_4 & -\mu_4 & 0 & 0 & 0 & 0 \\ \mu_6 & 0 & \mu_6 & \mu_6 & \mu_6 & 0 & -5\mu_6 & 0 & \mu_6 & 0 \\ \mu_7 & 0 & \mu_7 & \mu_7 & \mu_7 & 0 & 0 & -5\mu_7 & \mu_7 & 0 \\ \mu_8 & \lambda_1 & 0 & 0 & 0 & 0 & \lambda_6 & \lambda_7 & \alpha_{88} & \lambda_9 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \mu_9 & -\mu_9 \end{bmatrix}$$

Where $\alpha_{00} = -\sum_{i=1,2,2,6,7,8} \lambda_i$, $\alpha_{22} = -\sum_{i=1,2,6,7} \lambda_i - \mu_2$,

$\alpha_{33} = -\sum_{i=1,4,4,6,7} \lambda_i - \mu_2$, $\alpha_{44} = -\sum_{i=1,4,6,7} \lambda_i - \mu_4$,

$\alpha_{88} = -\sum_{i=1,6,7,9} \lambda_i - \mu_8$

According to the data from electromagnetic suspension sample train developed in NUDT from 2001.11.25 to 2004.19.14, the statistic SFR are show in Table 2.

Table 2: The SFR and the maintenance rate (MR) (unit: 1/hour)

components	SFR λ_i	MR μ_i
E1	0.0021834	0.8
E2	0.005501	0.063492
E3	0.005501	0.063492
E4	0.0009250694	1
E5	0.0009250694	1
E6	0.0066287	0.6369427
E7	0.0008389262	∞
E8	0.0118064	0.6896552
E9	0.00092678406	1

According to the data in Table 2, Q is decided. Q together with the initial state $p(t)=[1,0...0]$ determines $p_{Fa}(t)$. The $p_{Fa}(t)$ curve in Matlab is show in Figure 8.

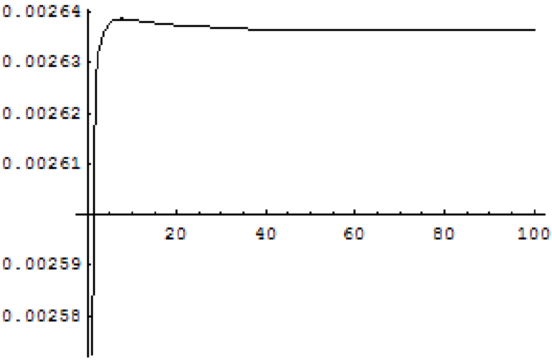

Figure 8: $p_{Fa}(t)$ curve

Define the component probability Importance:

$$I_{E_i}^{\Pr}(t)=\frac{\partial p_{Fa}(t)}{\partial p_{E_i}(t)} \tag{2}$$

thus,

$$I_{E_i}^{\Pr}(t)=\frac{\partial p_{Fa}(t)}{\partial p_{E_i}(t)}=\frac{\partial p_{Fa}(t)}{\partial(1-e^{-\lambda_i t})} \tag{3}$$

From (3), probability Importance of each component is calculated and shown in Figure 9. (Abscissa unit: day)

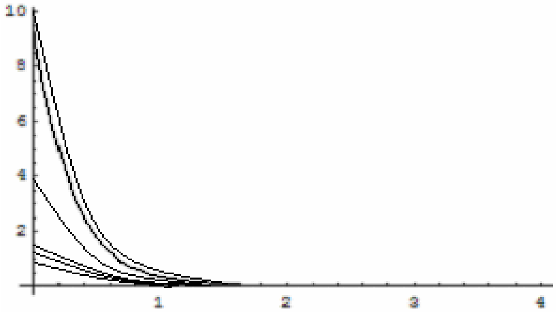

Figure 9: Probability Importance curves of components

5 COMPARISON BETWEEN REDUNDANT SCHEME AND NORMAL SCHEME WITH CONCLUSIONS

Compared with normal scheme, the advantages of the redundant scheme are：

1) The SFR decreased markedly. As time goes to infinite, the SFR goes to a constant with low value;
2) In redundant scheme, the probability importance of 110VDC/DC and 280VDC/DC convertor are much less than that of normal scheme;
3) The probability importance of different component in redundant are more balanced than that of normal scheme, thus there is no bottle-neck.

Of course, there are some limitations in redundant scheme:

1) The cost of whole system rises greatly;
2) There are so much relativity between components, it is hard to modularize and even harder to convert the DFT to Markov chain, therefore not so good for system design and analysis.

To summarize, redundant scheme intensifies greatly the reliabilities of the power systems and provides a safeguard for the running of Maglev Suspend Train.

6 REFERENCES

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