Reliability and Safety Analysis on Multi-state System of EMUs with Degraded Components

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Abstract. Aiming at the restrictions of the conventional reliability analysis based on binary logic on the systems with degraded components, a multi-state reliability analysis modeling method is proposed. The components and systems are classified into different states in this model according to different failure levels. Then a multi-state logic relation is established among units and systems as per the systematic block diagram, and the reliability analysis model for multi-state system is constructed, in which multi-level system reliability is realized and the major hazards resulted from neglecting potential faults in the binary system are avoided. Meanwhile, in line with the temporal distribution of system reaching ultimate limit state in safety, a system risk function is formulated. Therefore, the safety analysis model for a multi-state system is constructed. The examples of reliability analysis on EMU traction system indicate the effectiveness and advantages in evaluating reliability and safety of a complex system with multi-state reliability and safety analysis model.

1. Introduction

There are a lot of intermediate work states of many systems and their components between ideal work state and total failure mode in the engineering field. It is superficial to simply classify the reliability into "good" or "bad", which can hardly satisfy the high reliability requirements of complex systems. Meanwhile, the maintenance strategy of parts replacement based on "good" and "bad" has greatly increased the maintenance costs. Thus, the in-process time-dependent multi-state reliability research of systems is key to optimizing maintenance policy and reducing maintenance costs.

Currently, remarkable progresses have been made in the application of the reliability theory of the EMU binary system [1-3]. However, most components on EMUs degrade with time, which resulting in more than two states of the system. Hence, it is necessary to establish a multi-state system reliability analysis model, and the reliability prediction and safety assessment can be conducted more accurately.

2. Reliability Models for Degraded Components

2.1. Pattern Characters of Degraded Components

Failures of EMU components are mainly resulted from factors of heat, machinery, electricity and chemistry solely or jointly, and they are embodied in a various modes, such as fatigue failure, abrasion failure, corrosion failure and electrically induced failure. Each failure mode may lead to multi-state of
components with time, and this kind of components only getting worse gradually with time [4] are called degraded components. Transition process of reliability states of the degraded components are shown in Fig. 1.

2.2. Definition of Multi-state Pattern

It is assumed that there is a reliability state set \( \{0,1,\ldots,z\} \), where reliability are ranked from bad to good, and 0 is the worst state and \( z \) is the best state. \( T_i(u) \), standing for the time that reliability state of the component \( E_i \) in the subset \( \{u,u+1,\ldots,z\} \), is a random variable. When \( t=0 \), the reliability state of the component is \( z \). \( E_i(t) \) Stands for the reliability state of the certain moment \( t,t \in [0, \infty) \) of component \( E_i \).

Hence, for a system consisted of \( n \) components, the reliability state of it is degraded with time as well. \( T_i(u) \) Stands for the time of the reliability state of the system in the subset \( \{u,u+1,\ldots,z\} \). When \( t=0 \), the reliability state of the system is \( z \). \( S(t) \) Stands for the reliability state of the system \( S \) at the moment \( t,t \in [0, \infty) \).

2.3. Reliability Assessment for Degraded Components

Reliability, which is a key quantitative index to measure the reliability level of a product, can expressively indicate the reliability state of the product. So it is of the explicit engineering significance [5]. The multi-state reliability of the component is defined as the probability of a certain reliability state of the component \( E_i \) at the moment \( t \), the reliability function of degraded component is as follows [6]:

\[
R_i(t, \bullet) = [R_i(t,0), R_i(t,1), \ldots, R_i(t,z)]
\]

\( t \in [0, \infty), i = 1, 2, \ldots, n \)  

(1)

Where

\[
R_i(t,u) = P(E_i(t) \geq u | E_i(0) = z) = P(T_i(u) > t),
\]

\( t \in [0, \infty), u = 0,1,\ldots, z \)  

(2)

The reliability function \( R_i(t,u) \) in equation (2) provides the coordinates for the multi-state reliability function \( R_i(t,\bullet) \) of component \( E_i \) in equation (1). Therefore, the relation among fault
distribution function $F_i(t,u)$ of component $E_i$, time function $T_i(u)$ of its reliability state in the subset \{u,u+1,...,z\} and the coordinates $R_i(t,u)$ of multi-state reliability function is as follows:

$$F_i(t,u) = P(T_i(u) \leq t) = 1 - P(T_i(u) > t) = 1 - R_i(t,u) \quad t \in [0, \infty), u = 0, 1, \ldots, z$$

(3)

From the above definitions, it can be identified that multi-state reliability function of degraded components has the following features:

$$R_i(t,0) \geq R_i(t,1) \geq \cdots \geq R_i(t,z), t \in [0, \infty), i = 1, 2 \ldots n$$

(4)

3. Multi-State Based System Reliability and Safety Assessment

3.1. Establishment of System Reliability Model

System reliability model is the basis of system reliability analysis. The same process as that for the binary system may be adopted to establish reliability block diagram or fault tree model for multi-state systems.

Reliability block diagram is a reliability model which can describe logical relation among all components of a system. The main steps to establish multi-state reliability block diagram include: firstly, to define the system state, the states of components forming the system and the logical and functional relations of components and system under different states; secondly, based on the functional relation of system, to describe the dependencies among all the components of the system using a continuous network structure.

Multi-state fault tree model is one of the most common method in reliability and safety analysis, which shows the logical relation among the states of system and sub-systems and states of components using graphical interpretation features such as “or” gate, “and” gate and multi-state events. The first step to establish the multi-state fault tree model is to define the system state as the top event and analyze the relation pattern of states of the subordinate subsystems and components which is descending by levels; the second step is to define the border conditions of the analyzed events, that is, to analyze and to define the physical border conditions, initial conditions and state levels. In addition, event marks in multi-state fault tree have the following meanings: “$E_i \leq u$” stands for the state of the component being in the subset \{0,1,..., u\}; “$S \leq u$” stands for the state of the system being in the subset \{0,1,..., u\}.

3.2. System Reliability Assessment

Generally, a system is a hybrid system consisted of several serial and parallel subsystems, so the reliability assessment on the whole system can be carried out by analyzing components, subsystems and systems level by level.

(1) Serial System

Fig 2. Reliability Structure Block Diagram of Serial System

Multi-state serial system is consisted of n components, and its system reliability structure block diagram is shown in Fig. 2. State function of serial system can be presented as follows:
\[
T(u) = \min_{1 \leq i \leq n} \{T_i(u)\}, u = 1, 2, \cdots, z
\]  

(5)

Reliability of serial system state larger than or equal to \( u \) is as follows:

\[
P\{S \geq k\} = P\{\min (E_i) \geq k\} = \prod_{i=1}^{n} P\{E_i \geq k\}
\]  

(6)

(2) Parallel System

\begin{center}
\includegraphics[width=0.5\textwidth]{parallel_system.png}
\end{center}

Fig 3. Reliability Structure of Parallel System

Multi-state parallel system is consisted of \( n \) components, and its reliability structure block diagram is shown in Fig. 3. State function of parallel system can be presented as follows:

\[
T(u) = \max_{1 \leq i \leq n} \{T_i(u)\}, u = 1, 2, \cdots, z
\]  

(7)

Reliability of parallel system state larger than or equal to \( u \) is as follows:

\[
P\{S \geq k\} = P\{\max (E_i) \geq k\} = 1 - \prod_{i=1}^{n} P\{E_i < k\}
\]  

(8)

3.3. System Safety Assessment

Safety is in close relation with reliability; generally, a reliable product is safe. If a system is consisted of the multi-state components whose safety changes with time, at first, the critical state of system safety shall be identified. This state may pose a threat to the environment, or it is unsatisfactory for reaching the level of efficiency during operation process. Secondly, the probability of system being in the reliability critical state that threatens safety shall be identified, namely the risk function for multi-state system [4]. Risk function is to describe the time and distribution of ultimate limit state of system safety, i.e.

\[
r(t) = P\{S(t) < r | S(0) = z\} = P\{T(r) \leq t\}
\]

\[
= 1 - R(t, r) \quad t \in [0, \infty)
\]  

(9)
This equation indicates that the probability of the system risk function with reliability state being under the critical state \( r \), on the premise of reliability state of system being \( z \) at \( t=0 \).

4. Engineering Example of EMU Traction Drive System

4.1. System Composition
Traction drive system is a vital composition of EMU, and its reliability directly affects the normal and stable operation and safety of EMUs. Normally, EMU is marshaled as 4M4T, with 2 motor cars and 2 trailers as a basic power unit. Traction drive system of each power unit is consisted of 1 traction transformer, 2 traction converters and 8 traction motors, and the system structure diagram is shown below.

![Structure Diagram of Traction System](image)

Fig 4. Structure Diagram of Traction System

4.2. System Reliability Model
During normal operations, power is supplied from OCS through pantograph and to EMUs via the transformer/converter, so that all traction drive devices on EMUs can function well. Hence, this system is consisted of the transformer/converter subsystem and traction drive subsystem in serial connection. When the primarily selected transformer/converter system is in normal operation, the other transformer/converter system is in standby, or the standby transformer/converter system is put in normal service, namely, the transformer/converter subsystems are in the logical function of parallel relation. However, any fault in any traction motor and gear drive device in traction drive subsystem will lead to emergency brake on running EMUs. Thus, the traction drive subsystems are in the functional logic of serial relation. According to logic function relation of each component of EMU traction drive system, the reliability model of traction drive system is established. As shown in Fig. 5, the reliability block diagram of this system is generated by simplification.
Fig 5. Reliability Diagram of Traction Drive System

The three reliability states \((z=3)\) for system, subsystem and each component are defined as:

1. Reliability state \(3\) -- System and components are intact and sound, operating in maximum efficiency;
2. Reliability state \(2\) -- System and components have potential faults;
3. Reliability state \(1\) -- System operates in low efficiency, due to increased danger level of component degradation;
4. Reliability state \(0\) -- System and component fail.

4.3. System Reliability and Safety Analysis

The initial state of traction drive system is intact and the probability of each component of traction system in different state for operating a million kilometers \([3]\) based on comprehensive rating method is shown in Table 1.

| Component Name | State 1 | State 2 | State 3 |
|----------------|--------|--------|--------|
| Transformer    | 0.0022 | 0.1600 | 0.8378 |
| Converter      | 0.0093 | 0.4800 | 0.5107 |
| Traction Drive | 0.0001 | 0.0010 | 0.9989 |

Components of traction system have an exponential type reliability function. Thus, according to Table 1, the coordinates of reliability function of each component can be generated, as shown in Table 2.

| Component | \(R(t,1)\) | \(R(t,2)\) | \(R(t,3)\) |
|-----------|-----------|-----------|-----------|
| \(E_{1j}\) | \(R_{1j}(t,0)=\exp[-0.0022t]\) | \(R_{1j}(t,1)=\exp[-0.0600t]\) | \(R_{1j}(t,1)=\exp[-0.1000t]\) |
| \(E_{2j}\) | \(R_{2j}(t,0)=\exp[-0.0093t]\) | \(R_{2j}(t,1)=\exp[-0.0800t]\) | \(R_{2j}(t,1)=\exp[-0.4000t]\) |
| \(E_{3j}\) | \(R_{3j}(t,0)=\exp[-0.0001t]\) | \(R_{3j}(t,1)=\exp[-0.0005t]\) | \(R_{3j}(t,1)=\exp[-0.0005t]\) |

Note: Unit for operation kilometrage \(t\) is million km.

The Boolean formula for traction system with comprehensive state larger than or equal to \(k\) is as follows:
\{S \geq k\} = \{S_1 \geq k\} \cap \{S_2 \geq k\} = \{S_{11} \geq k\} \cup \{S_{12} \geq k\} \cap \{S_2 \geq k\} \\
= \{(E_{11} \geq k) \cap [(E_{21} \geq k) \cup (E_{22} \geq k)]\} \cup \\
\{(E_{12} \geq k) \cap [(E_{23} \geq k) \cup (E_{24} \geq k)]\} \cap \\
\{(E_{31} \geq k) \cap (E_{302} \geq k) \cap \cdots \cap (E_{316} \geq k)\}

(10)

Accordingly, the reliability prediction is as follows:

\[ P\{S \geq k\} = P\{S_1 \geq k\} \cdot P\{S_2 \geq k\} \tag{11} \]

Where:

\[ P\{S_1 \geq k\} = 1 - \left[1 - P(E_{11} \geq k) \cdot \left[1 - (1 - P(E_{21} \geq k))(1 - P(E_{22} \geq k))\right]\right] \cdot \\
1 - P(E_{12} \geq k) \cdot \left[1 - (1 - P(E_{23} \geq k))(1 - P(E_{24} \geq k))\right] \tag{12} \]

\[ P\{S_2 \geq k\} = \prod_{i=1}^{16} P(E_{3i} \geq k) \tag{13} \]

Based on the coordinates of reliability function of each component, the reliability function of traction system in different state can be formulated, as shown in Table 3.

| State | Reliability Function | Reliability of Million km |
|-------|----------------------|---------------------------|
| \( P\{S \geq 1\} \) | \( R(t,1) = e^{-0.016t} \left[ 2 \left(2e^{-0.0115t} - e^{-0.0208t}\right) - \left(2e^{-0.0115t} - e^{-0.0208t}\right)^2 \right] \) | 0.9984 |
| \( P\{S \geq 2\} \) | \( R(t,2) = e^{-0.008t} \left[ 2 \left(2e^{-0.14t} - e^{-0.22t}\right) - \left(2e^{-0.14t} - e^{-0.22t}\right)^2 \right] \) | 0.9880 |
| \( P\{S \geq 3\} \) | \( R(t,3) = e^{-0.088t} \left[ 2 \left(2e^{-0.5t} - e^{-0.9t}\right) - \left(2e^{-0.5t} - e^{-0.9t}\right)^2 \right] \) | 0.9548 |

From Table 3, it can be known that operating for a million kilometer, the reliability of traction system without potential fault is \( P\{S \geq 1\} = 0.9984 \), the reliability of system operating with potential fault is \( P\{S \geq 2\} = 0.9880 \), and the reliability of degraded system is \( P\{S \geq 3\} = 0.9548 \). As for the binary system, the system reliability is \( P\{S \geq 1\} = 0.9984 \), which is actually the reliability for system faults in degraded mode. \( P\{S \geq 1\} > P\{S \geq 3\} \), it indicates that binary system neglected the states for function degradation and potential fault, which shows an insufficient estimation on the system reliability, leading to frequent faults and reduced availability in operation.

Since the reliability critical state of system is \( r = 2 \), the risk function of traction system is as follows:
\[ r(t) = 1 - R(t, 2) = 1 - e^{-0.008t} \left[ 2 \left( 2e^{-0.14t} - e^{-0.22t} \right) - \left( 2e^{-0.14t} - e^{-0.22t} \right)^2 \right] \] (14)

If the acceptable risk level of the system is 0.02, the traction system is in operation

\[ \tau = r^{-1}(0.02) \approx 1.44 \text{(Million km)} \] (15)

From the maintenance process of EMUs, it is known that the daily operation kilometrage of EMUs in China does not exceed 4000km. Hence, this system must receive a preventive overall inspection and repair annually, so as to control the risk level for system operation in an acceptable range.

5. Conclusion

(1) The relation between system multi-state and degraded component multi-state is established with the help of multi-state logic functional diagram, fulfilling the predictions on system multi-state reliability.

(2) In the reliability analysis of EMU traction system, four states, namely intact, potential faults, function degradation and failure, are considered to prevent hazards due to the neglect of potential faults and function degradation in the conventional binary system.

(3) Based on the temporal distribution of system reaching ultimate limit safety state, the system risk function is formulated and the operation duration (or kilometrage) within acceptable risk level of system are proposed, paving the way to optimizing the maintenance procedure.

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