Research on Optimization of BIT Design Scheme for Digital NBC Protection System

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Abstract: BIT technology is an important means to detect, locate and isolate faults of system and equipment. In this paper, the digital NBC protection system is taken as the research object, and the on-line state detection method based on BIT technology is studied. The system structure division and analysis of typical fault mode have been done. The design flow of on-line state monitoring based on BIT technology is presented. A weighted cost indicator function is constructed. This paper also presents a selection method for selecting the optimal test set based on improved specially-stepwise optimal selection method for digital NBC protection system. From the theoretical point of view, the system typical fault mode is extracted and the BIT design objective is set, and finally, the optimal BIT design scheme is determined.

1. Introduction
BIT (built-in test) technology is a new on-line fault detection technology that can improve system reliability and reduce maintenance cost, which can realize the fault self-diagnosis of system circuits and key hardware units through the software and hardware testing unit attached in system [1]. The perfect BIT design can quickly and effectively detect, locate and isolate system faults, thereby reducing the duration of maintenance support and saving manpower and material resources. In the field of weapon equipment, there are many successful applications of BIT technology.

With the ever-increasing speed of digitalization and informatization process of armored equipment, the proportion of numerically-controlled subsystems in the electric systems of armored vehicle is becoming bigger and bigger, and the on-line state detection and fault diagnosis have gradually become the main research contents of on-line fault diagnosis technology of electric system as well. With the application of more and more new power electronic devices and integrated circuits, there are many new problems in fault detection and diagnosis of digital electric subsystems. Therefore, this paper
selects the NBC protection system as research object and combines the already-accomplished design of digital NBC controller to conduct the research on on-line fault diagnosis scheme based on BIT technology.

2. Overall BIT design flow of digital NBC protection system
With STM32 as the core control single-chip microcomputer (SCM), the digital NBC protection system is mainly composed of alarm unit, control mechanism, filter ventilation device and actuator and so on. In addition, the power amplifier and drive circuit can be supplemented to run the entire system, of which the unnecessary detailed descriptions are not presented here. The structure schematic diagram of digital NBC protection system is shown in Fig. 1.

![Fig. 1 Structure schematic diagram of digital NBC protection system](image)

As for the requirements of BIT technology, the testability factors should be considered in the initial stage of system or equipment function and structure design, so as that the automation of system fault detection, location and isolation can be stepwise achieved through good structuring. With the continuous development of power electronics and computer technologies, the system generally adopts the digital microprocessor as the core control unit, and modularly configures the architecture modes of peripheral functional circuits, so as to provide a good system platform for the system's BIT design and on-line fault diagnosis function development. At present, the electric and electronic equipment of armored vehicle in our army is undergoing rapid changes in the aspects of both signal mode and control mode. With the help of BIT design, on-line state monitoring and fault diagnosis of system can be realized and it's a way to improve the maintainability of electric and electronic equipment as well.

Combined with the control characteristics of digital NBC protection system, the BIT design flow is as shown in Fig. 2.

![Fig. 2 Design flow of on-line state monitoring of digital NBC protection system based on BIT](image)
3. System structure division and analysis of typical fault mode

System structure division and analysis of typical fault mode are the basic steps of BIT design of NBC protection system. Among them, system structure division is to reasonably decompose the system into multiple testable hardware units according to system control structure and hardware structure, so as to achieve the precise locating of system faults and targeted BIT design; Analysis of typical fault mode is used to extract and summarize the typical fault modes of system, and establish the fault causality between the typical fault mode and testability hardware in combination with system structure division.

The NBC protection system consists of atomic sensor, toxic agent sensor, control box and actuator, which is used to protect armored vehicles against NBC weapons attack so as to improve the protective performance of armored vehicles. According to the on-line testing requirements of NBC protection system, the digital NBC protection system takes the digital signal processor as the core control unit, the following tasks are accomplished through peripheral control circuit and driving circuit.

(1) To detect atomic and chemical agent signals; To sound alarming signal to enable the operation of actuator;
(2) To use the panel display to control the current state of panel system and receive panel control signal;
(3) To upload the current state of system and fault information in real time, and receive and execute control instructions;
(4) To achieve on-line monitoring of state and enable the diagnosis of system common faults based on system BIT design.

In this topic, the digital NBC protection system adopts a modular design scheme, of which the hardware schematic diagram is as shown in Fig. 3:

![Fig. 3 Hardware structure schematic diagram of digital NBC protection system](image)

As shown in Fig. 3, it can be clearly seen that the hardware structure of digital NBC protection system includes hardware such as the control system which takes STM32 control chip as the core unit, power supply module, signal processing module, power-driven module and BIT circuit and so on. Furthermore, the atomic and toxic agent signal sensors, and each actuator are also included in the system architecture. Obviously, this control system includes both digital and analog hybrid circuits with more complex functions and structures, and actuators of electromechanical equipment with higher power.

In this control system, the types and characteristics of faults caused by the defects of hardware circuits and execution components, and external environment and other factors are more complicated: They can be divided into local and global faults from the extent of influence; from the angle of actuating duration, they can be classified as permanent and temporary faults. Therefore, for better analysis, the following assumptions and explanations can be made [2]:

- Assumption 1: Each hardware unit can operate independently;
- Assumption 2: Each software module can function independently;
- Assumption 3: Each actuator can operate independently;
- Assumption 4: Each sensor can detect independently;
- Assumption 5: Each control module can perform its function independently.

With these assumptions, the causes and effects of faults can be analyzed more accurately and comprehensively.
(1) To grasp the main factors and ignore the secondary ones, only choose the typical faults that belong to the key hardware units in the system and have high fault rate and high harmfulness as the objects of BIT research, and do not consider the fault isolation function in the BIT design.

(2) To store (have the memory of) BIT system on-line fault diagnosis needs to use the test circuit to extract test signals and implement information processing, mechanism analysis and fault identification functions through control chip. Hence, the fault probabilities of core control chip (STM32) and BIT test circuit are assumed to be 0 when conducting research.

Since it is impossible to judge the duration of system faults, it can only be assumed that the faults are permanent ones, and the probability of occurrence of each fault mode is the same.

Based on the above-mentioned assumptions and combined with the system structure division, the typical fault modes of digital NBC protection system are summarized as shown in Table 1:

| Mode No. | Fault statement                                      | Mode No. | Fault statement                                      |
|----------|------------------------------------------------------|----------|------------------------------------------------------|
| $f_1$    | Open-circuit fault of detonating circuit of electric detonator | $f_7$    | Abnormal functioning of external D/A chip            |
| $f_2$    | Functional fault of fan operating circuit            | $f_8$    | Chip link fault                                      |
| $f_3$    | Abnormal functioning of atomic signal processing circuit | $f_9$    | Open or short circuit fault of toxic agent sensor    |
| $f_4$    | Open or short circuit fault of atomic signal sensor  | $f_{10}$ | Abnormal functioning of toxic agent signal processing circuit |
| $f_5$    | Drive circuit fault of electric detonator            | $f_{11}$ | Parameter fault of fan operating circuit             |
| $f_6$    | Excessive voltage of power supply system             | $f_{12}$ | Alarm circuit fault                                  |

Table 1 Typical fault modes of digital NBC protection system

4. Design scheme of digital NBC protection system

It is assumed that the typical fault mode set of NBC protection system is $F$, so,

$$F = \{f_1, f_2, f_3, \ldots, f_n\}$$  \hspace{1cm} (1)

In this formula, $N$ is the number of typical fault modes of system. In the system BIT design, for any typical fault mode $f_i$, $n_i$ kinds of BIT design method can be used to detect and diagnose this fault mode. It is assumed that the corresponding test set of fault mode $f_i$ is

$$T_{f_i} = \{t_{f_{i1}}, t_{f_{i2}}, \ldots, t_{f_{im}}\}$$  \hspace{1cm} (2)

The alternate test set $T$ of $F$ is formed from the union set of corresponding test sets of all fault modes in $F$.

$$T = T_{f_1} \cup T_{f_2} \ldots \cup T_{f_n}$$  \hspace{1cm} (3)

In accordance with formula (2) and (3), $T$ is one redundant complete test set of $F$. In this BIT design of NBC protection system, in view of the known typical fault mode set $F$, how to comprehensively consider the system test index, cost and resource cost and other factors, obtain the optimal test set $T$,
from reserve test set \( T \), are the key contents and the main difficulties of the optimization research on BIT design scheme of NBC protection system \([3]\).

Then, the problem of test set optimal selection is analyzed. Problem description: The system BIT design is only for fault detection and diagnosis without considering the design of fault isolation function. Therefore, the fault detection rate (FDR) will be the main testability index of system BIT design. Under the condition of meeting the requirements of preset FDR index, the main factors considered in the BIT design of numerically-controlled electric subsystems of armored vehicle include two aspects: test cost and test resources. Before the specific analysis is carried out, the definitions of related concepts should be given first.

(1) Fault detection rate (FDR): Under the prescribed condition, the test set can correctly detect the percentage between total probability sum of system faults and total fault probability of system. The fault detection rate index of test set \( T \) is expressed as \( T_{FDR} \), of which the calculation formula is expressed as follow:

\[
T_{FDR} = \left( \frac{\sum_{i=1}^{N} \lambda_i}{\sum_{i=1}^{N} \lambda_i} \right) \times 100\%
\]

(4)

In this formula, \( N \) is the dimension of total fault mode sets of system, \( N_D \) is the dimension of detectable fault mode set of test set \( T \). \( \lambda_i \) is the probability of system faults, which stipulates the occurrence of equal probability.

(2) Correlation matrix: The dependency matrix between fault mode set \( F \) of system and test set \( T \) is usually expressed as \( F - T \). In \( F - T \), if element \( d_{ij} = 1 \), then it means that there is a dependency relationship between the test set \( t_i \) and fault mode \( f_j \), that is to say, when fault mode \( f_j \) exists, the test results of \( t_i \) will be abnormal; if element \( d_{ij} = 0 \), it means that there is no dependency relationship between fault mode \( f_j \) and test set \( t_i \).

(3) Test cost: The sum of economic, time and manpower costs and so on required for the implementation of test set \( t_i \) in BIT test set is called as test cost, which is expressed by \( C_{p_i} \).

(4) Test resource cost: It can be defined as the cost taking up the cost of main control chip when system implements test set \( t_i \), which is usually measured by system cycle \( C_{S_i} \).

Based on above definitions, in the system BIT design, the known fault mode set \( F \) and fault detection rate index is between one, and based on BIT alternate test set \( T \), the problem of test set \( T_S \) optimal selection can be converted into the following mathematical problem: Based on correlation matrix \( F - T \), the test subset \( T_S \) can be quested from alternate test set \( T \), which should meet following requirements:

\[
\begin{align*}
\min & \quad f \left( \sum C_{p_i}, \sum C_{S_i} \right) \\
T_S & \subseteq T, \quad FDR \geq S
\end{align*}
\]

(5)

The above formula is the optimal solution problem with constraints, among which, \( f \left( \sum C_{p_i}, \sum C_{S_i} \right) \) is the function of test cost and test resource cost, and called as cost index function of optimal solution. Through the document research, the direct accumulation method is usually used to construct the cost index function, which is described by mathematical formula
as \( f(\sum C_{P_1}, \sum C_{S_i}) = \sum C_{P_1} + \alpha \sum C_{S_i} \).

For the numerically-controlled electrical subsystems of armored vehicle, there are large differences in function, control and structure between various systems. Different electric subsystems have different concerns about test cost and test resource cost in system BIT design. For instance, the example of digital voltage regulation system has been studied before. The digital voltage regulation system needs to complete the control function of high real-time requirement/performance, so its BIT design has a higher level of concern about test resource cost \( \sum C_s \) of test set. Considering above practical factors of NBC protection system, this paper proposes a weighted cost indicator function from the practical application point of view. The expression is:

\[
f(\sum C_{P_1}, \sum C_{S_i}) = \sum C_{P_1} + \alpha \sum C_{S_i} \tag{6}
\]

In this formula, weight value parameter \( \alpha \) is more than zero, which is used to weigh the concern of system BIT design on test cost and test resource cost, and the greater the \( \alpha \), the higher the level of concern about the test resource cost in this system BIT design\(^{[4]}\). Now bring it into the constraints to get the final mathematics description of NBC protection system as follow:

\[
\left\{ \begin{array}{l}
\min f(\sum C_{P_1}, \alpha \sum C_{S_i}) \\
T_s \subseteq T, \ FDR \geq S
\end{array} \right. \tag{7}
\]

5. Selection of optimal test set based on improved specially-stepwise optimal selection method

Formula (7) gives the mathematical description of optimal selection problem of fault diagnosis test set in system BIT design, but the direct solution based on this formula has the problems of multiple parameters and large calculations, etc., and blindly pursuing the minimization of index function may lead to the deviation of optimization result from the practical application. For this reason, this paper introduces the concept of minimum test set, and proposes a selection method of fault test set based on specially-stepwise optimal selection method. While simplifying the calculation process, the optimal results of test set can better meet the actual demand.

Each element \( t \) in the complete system alternate test set \( T \) can detect one or more faults, so the test subset in \( T \), which meets the requirements of FDR index, is not unique. In system BIT design, in order to improve test efficiency and reduce the number of test, the minimum test set is usually chosen as the key analysis object. The definition of minimum test set is as follow:

The test set in alternate test set \( T \), which meets the requirements of FDR index and has the minimum dimension of test set, is called as minimum test set \( T_m \).

The concrete ideas of selection method of fault test set based on specially-stepwise optimal selection method for digital NBC protection system are as follows: Under the condition that the known system fault mode set \( F \) and test set \( T \) meet the fault detection rate index \( S \), the union \( A(T_m) \) of minimum test set should be determined first; and then, among \( A(T_m) \), the optimal test set \( T_S \) should be selected based on the index function shown in formula (7). In order to achieve a better global optimization, in optimal selection design, the number of minimum test set \( N[A(T_m)] \) included in \( A(T_m) \) should be no less than the set value \( N_{\text{min}} \). When \( N[A(T_m)] < N_{\text{min}} \), a new union will be constructed by introducing the relaxation factor \( \eta \) for the global optimal test set.

According to above ideas, the optimal selection steps of BIT fault test set of numerically-controlled electrical subsystems of armored vehicle based on specially-stepwise optimal selection method are as follows:

(1) To determine system typical fault mode set \( F \) through system structure division and analysis of fault mode.
(2) To construct the alternate test set $T$ of typical fault mode set $F$ and get the correlation matrix $F - T$ based on common BIT design methods.

(3) To calculate $A(T_m)$ and judge whether $N[A(T_m)] \geq N_{\min}$ is true or not based on matrix $F - T$ when FDR index $S$, lower limit of number of minimum test set $N_{\min}$ and relaxation factor $\eta$ are given; and to introduce $\eta$ so as to solve the union of $A(T_m)$ if $N[A(T_m)] \geq N_{\min}$ is not true$^{[6]}$.

(4) To set weight value parameter $\alpha$ as per system characteristics, and select the optimal test set $T_s$ from $A(T_m)$ or $A(T_m^*)$ based on weighted cost indicator function shown in formula (7), so as to accomplish system BIT optimal design.

The solution of minimum test set $A(T_m)$ based on correlation matrix $F - T$ is the key step to realize the specially-stepwise optimal selection method of system BIT fault test set. The specific solution method of minimum test set is given below:

The correlation matrix between the known system typical fault mode set $F$ and alternate test set $T$ is expressed as:

$$F - T = \begin{bmatrix}
d_{i,1} & d_{i,2} & \ldots & d_{i,x-1} & d_{i,x} \\
d_{x,1} & d_{x,2} & \ldots & d_{x,x-1} & d_{x,x} \\
\vdots & \vdots & \ddots & \vdots & \vdots \\
d_{m,1} & d_{m,2} & \ldots & d_{m,x-1} & d_{m,x}
\end{bmatrix}$$

(8)

$F - T$ is Boolean matrix, among which, each element in row vector $d_i = (d_{i,1}, d_{i,2}, \ldots d_{i,x})$ indicates the detectable state of each fault mode in system fault mode set $F = \{f_1, f_2, \ldots, f_m\}$. In the optimal selection of test set, each row vector $d_i$ corresponds to a Boolean parameter $a_i$. When $a_i = 1$, it indicates that the corresponding test set $t_i$ of row vector $d_i$ is included in optimal test set. The corresponding Boolean parameters of all row vectors in matrix $F - T$ form the vector quantity $A = (a_1, a_2, \ldots, a_m)^{[7]}$.

In the actual BIT design of NBC protection system, for the typical fault mode set $F$, the FDR index of test set $T$ is usually set to 100%. At this moment, corresponding Boolean vector quantity $A$ of $T_m$ should meet the following requirement:

$$f = \prod_{j=1}^{n} \sum_{i=1}^{m} a_{i,j} = 1$$

(9)

Under the condition of meeting the requirement of above formula, if the number of non-zero element in the corresponding Boolean vector quantity $A$ in test set $T_m$ is the minimum, then $T_m$ is the minimum test set. From above problem analysis, it can be known that, based on Boolean algebra method, the minimum test set can be obtained through simplifying the expression $f$. Its constraint expression is as follow:

$$\begin{align*}
a_j + a_j \sum_{i=1}^{m} a_{i,j} = a_j, f_{\text{max}} = \min(m, n) \\
\sum_{j=1}^{m} a_j (\sum_{i=1}^{m} a_{i,j} + \sum_{j=1}^{m} a_i) = \sum_{i=1}^{m} a_i
\end{align*}$$

(10)

In terms of above two expressions, it can be expressed as:
\[
\begin{align*}
\left\{ \begin{array}{l}
\quad \quad f = \sum_{k=1}^{N_m} f_k(a_1, a_2, \ldots, a_m) \\
\quad f_k(a_1, a_2, \ldots, a_m) = \prod_{l=1}^{N_m} a_{kl}
\end{array} \right.
\end{align*}
\]

In the product term \( f'_k \) of expression \( f \), \( N_m \) is the number of included minimum test set \( T_m \) in alternate test set \( T \); while in the product function \( f_k \), the corresponding test set \( t_{kl} \) of each product term parameter \( a_{kl} \) forms the minimum test set[8].

6. Conclusion
In this paper, for the digital NBC protection system, the on-line state detection method based on BIT is studied. The system structure division and analysis of typical fault mode have been done. The design flow of on-line state monitoring circuit of digital NBC protection system based on BIT is presented. A weighted cost indicator function is constructed. This paper also presents a selection method for selecting the optimal test set based on improved specially-step wise optimal selection method for digital NBC protection system. In the mean time, from the theoretical point of view, the system typical fault mode is extracted and the BIT design objective is set, and finally, the optimal BIT design scheme is selected.

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