Testability Modelling and Optimization Technology of Ship Electrical Equipment Based on Multi-Signal Flow Diagram

Peng Di\(^1\), Yang Cheng\(^1\), Sun Pan\(^2\), Fang Xiaotong\(^1\), Zhan Weiqiang\(^2\) and Yang Gang\(^2\)

\(^1\) China Institute of Marine Technology and Economy, Beijing, China
\(^2\) Naval University of Engineering, School of Electrical Engineering, Wuhan, China

E-mail: pengdi0321@163.com

Abstract. With the development of ship power systems, the degree of integration, complexity and automation of ship generators has increased significantly, which places higher requirements on its testability. The marine generator is a complex electromechanical system with multiple disciplines including electricity, magnetism, force, heat, and mechanics. Its main features include: various types of fault modes, a wide range of faults, and many types of fault features. Therefore, compared with electronic products, the testability modelling and optimization methods of marine generators are very different. First of all, this paper sorts out 11 typical failure modes of marine generators. Then, analyse the failure characteristics of each failure mode and set up 17 test points initially. Based on this, a multi-signal flow graph model is constructed, and the test point is optimized based on the correlation model. By comparing and analysing the test point optimization results, the feasibility and effectiveness of the proposed method are verified.

1. Introduction

With the development of ship power systems, the capacity and power density of ship generators have increased significantly [1][2]. Due to the increase in the installed capacity of marine generators and the increase in integration, complexity, and automation, it has set higher requirements for generator fault detection and isolation capabilities.

Since the 1980s, China has begun the research of test design analysis technology and achieved a series of research results. Testability modelling and analysis technology has been widely used in aviation and aerospace electronics. For example, Wei Qingxin proposed a method for fault diagnosis of missile equipment based on multi-signal flow graph model [3]. Xing He conducts test modelling for the Inertial Measurement Unit (IMU) [4]. Shi Junyou et al. proposed an improved test modelling method that considers multiple faults, and applied it to an inertial navigation system [5]. However, test modelling and analysis technology has yet to be developed for large and complex ship electromechanical products.

In this paper, a test-based modelling and optimization technology based on multi-signal flow diagrams is developed for marine generators. Firstly, the testability characteristics of the marine generator are analyzed, and the testability modelling and optimization process of the generator is proposed. Then, the typical fault modes and fault characteristics of the generator are sorted out, and
preliminary test points and test contents are proposed. Multi-signal flow graph model is built on this basis. After that, a multi-signal flow graph model is constructed, and the test points of the generator are optimized based on the correlation model. Finally, the results of test optimization are compared and analyzed.

2. Analysis of test characteristics of marine generators

The ship's generator is a complex system composed of mechanical, electronic, electrical and electromagnetic fields. Compared with electronic products, it has many unique characteristics, which leads to some difficulties in the application of testability modeling and optimization. The test characteristics of marine generators are as follows:

(1) There are various types of failure modes. For example, there are both electrical faults such as short circuit of electronic windings, mechanical faults such as bearing damage, and electronic faults such as open rectifier components.

(2) The fault affects a wide range. If the exciter loses magnetism, it will cause the excitation current to drop to 0, which will cause slippage between the stator and rotor of the engine. When the loss in the generator rotor circuit exceeds a certain value, the rotor will overheat. The differential current flowing on the surface of the rotor will also cause severe local overheating on the contact surface of the rotor body with the slot wedge and the grommet.

(3) There are many types of fault features. For example, an open-circuit fault in the stator winding not only causes a large temperature rise, but also changes in the voltage signal and changes in the characteristic frequency of the generator vibration.

3. Testability modeling and optimization process of naval generator

![Figure 1. Testability modeling and optimization process of naval generator.](image-url)
The general idea of selecting and optimizing the physical quantity test set for marine generators is shown in the figure below. First, the system composition and failure mode are used as top-level inputs to analyze the failure characteristics and influence of each failure mode. Then, a preliminary set of test points is set up to build a test multi-signal flow graph model of the marine generator. Based on the analysis of the multi-signal flow graph model, the correlation model (D matrix model) of the marine generator is obtained. Secondly, through the application of the test optimization theory method based on the correlation model, a preliminary set of test points for fault detection and fault isolation is obtained. By merging the two sets, an optimized set of test points can be obtained. Carry out testability evaluation for the optimized test points to verify whether the testability level of the current test point layout scheme meets the requirements. If the current design cannot meet the testability requirements, the preliminary test point set needs to be modified. Then the testability modeling, optimization, feasibility analysis and verification are carried out until the testability requirements are met.

4. Construction of multi-signal flow diagram for naval generator

4.1. The overview of multi-signal flow graph model

Multi-signal flow graph model is a hierarchical modeling method, from which we can directly see the propagation path of a failure mode affecting other modules [5]. The model composition can be described as: module node, test node, "AND" node, switch node. These nodes are connected to each other by wires. For a given model and system state, the graph can be transformed into a single global fault correlation matrix by the propagation algorithm. The correlation matrix contains some basic information of the system, which can be used to interpret test results and diagnose faults, as well as produce the optimal sequential test plan in the shortest time [6].

The four types of nodes of the multi-model model are specifically:

1) Module node
   It represents a piece of hardware with a specific set of functions (divided according to signals). Components allow hierarchical modeling, that is, components in a model graph can be described in detail with another graph containing its subcomponents and other nodes.

2) Test point node
   It represents the physical or logical measurement operation position. A test point allows multiple tests.

3) AND node
   It represents redundant connections and is used in modeling fault-tolerant systems. For example, if both A and B fail, C is affected. The connection between A, B, and C indicates that a voting node is required.

4) Switch node
   It represents the changing relationship of internal connections and can be used to model the different working states of the system.

4.2. Sorting out the failure modes of naval generator

Ship generators mainly include: stator winding, rotor winding, rotor guard ring, bearing, rotating rectifier, exciter, cooler, etc. This article analyzes the failure mode of the above components. Analysis results are shown in Table 1.
Table 1. Typical failure modes of marine generators.

| No. | Component        | Features                                         | Failure mode(FM)        |
|-----|------------------|--------------------------------------------------|-------------------------|
| 1-1 | Stator winding   | Cutting magnetic field generates electromotive force | Short circuit           |
| 1-2 | Stator winding   |                                                  | Interturn short circuit |
| 1-3 | Stator winding   |                                                  | Open circuit            |
| 2-1 | Rotor winding    | Generate a magnetic field                        | Interturn short circuit |
| 3-1 | Rotor guard ring | Fixed winding end position                       | Crack                   |
| 4-1 | Bearing          | Support rotating parts                           | Local injury            |
| 4-2 | Bearing          |                                                  | Oil spill               |
| 5-1 | Rotating rectifier | Convert the AC excitation current output by the AC exciter to DC | Open circuit |
| 5-2 | Rotating rectifier |                                                  | Component short circuit |
| 6-1 | Exciter          | Provide working magnetic field for generator     | Demagnetization         |
| 7-1 | Cooler           | Generator cooling                                | Poor cooling effect     |

4.3. Failure feature analysis

4.3.1. Analysis of stator winding fault characteristics
Stator faults account for 30% to 40% of all generator faults. The most common stator faults include stator winding phase-to-phase short-circuit, stator winding inter-turn short-circuit, and stator winding open circuit [7]. After the stator winding has an interphase short-circuit fault, the stator winding is no longer symmetrical, and even-numbered and fractional harmonic magnetic fields that do not exist during normal operation will appear in the air gap magnetic field. Generally, the internal voltage of the stator can be determined by detecting the open-circuit voltage signal of the detection coil whether a short-circuit fault occurs. The detection method of the stator winding inter-turn fault detection is similar to the phase-to-phase short-circuit fault. The detection coil can be used to detect whether there is an odd harmonic in the open circuit voltage for fault detection. After an open-circuit fault occurs in the stator winding, the phase current output is zero, and even-numbered harmonics with large amplitude appear in the frequency spectrum of the output voltage. Fault detection can be achieved by detecting the phase current and voltage [8].

4.3.2. Analysis of rotor winding fault characteristics
Rotor winding inter-turn short circuit fault is a common generator electrical fault. This fault will cause many serious problems, such as increased rotor current, increased winding temperature, reduced reactive power output, voltage waveform distortion and mechanical vibration [9]. The diagnosis of inter-turn short-circuit faults can be achieved by monitoring the harmonic amplitudes of all levels of the shaft voltage.

4.3.3. Analysis of fault characteristics of rotor guard ring
Rotor guard ring cracking means that the rotor guard ring has burst during operation, and the flying guard ring fragments will damage the stator or fly into the control room to damage the console, causing huge losses. This fault is difficult to detect by electrical means, usually using ultrasonic nondestructive testing methods.

4.3.4. Analysis of bearing fault characteristics
Bearing failures account for more than 40% of all motor failures. Bearings operate under non-ideal conditions and are often affected by fatigue, environmental mechanical vibration, overload, shaft misalignment, current fluting, etc. The conditions just cause edge defects at the beginning, and then...
these defects will propagate and spread in the bearing inner ring, outer ring and ball assembly. Bearing local damage can be divided into outer ring faults, inner ring faults, ball defects, cage defects, etc. The vibration diagnosis frequency can be extracted by monitoring the vibration signal to extract the characteristic frequency of the vibration at different faults. More than 90% of bearing oil leakage failures are caused by the corrosion and aging of oil seals. The failure detection is mainly achieved by monitoring the oil pressure.

4.3.5. Analysis of fault characteristics of rotating rectifier
The rotating rectifier is the core component of the brushless excitation system. Its short-circuit failure modes include one-tube short circuit and two-tube short circuit. The open circuit failure includes one-tube open circuit, two-tube open circuit, one-phase open circuit and two-phase open circuit. Both short-circuit and open-circuit faults of the rotating rectifier can be detected by extracting the harmonics of the exciter stator current.

4.3.6. Analysis of exciter fault characteristics
Among the generator excitation system failures, the demagnetization failure is a relatively common failure. That is, the excitation current disappears and the rotor magnetic field disappears during the generator operation process, causing a demagnetization failure. After the demagnetization of the generator, especially after the demagnetization causes the step loss, it will cause serious harm to the generator and the power system. At present, it can be judged whether the demagnetization fault occurs through three ways: low rotor voltage, low impedance at the machine end, and low system voltage.

4.3.7. Analysis of fault characteristics of cooler
Due to the large capacity and high load of naval generators, the heat and heat dissipation of generators during operation have become an important factor restricting the development of their larger capacity. As a heat dissipation device of the generator system, the cooler will cause the generator to be heated and cannot be discharged in time, and the temperature rise continues to increase, which limits the various performances of the motor. Usually, the fault of the cooler is detected by monitoring the bearing temperature of the end cover and the temperature of the cooling medium.

4.4. Analysis of test points and test contents of naval generator
According to the typical failure modes of ship generators, as well as the failure characteristics of each failure mode, the test method for each failure mode is given, that is, the test points and test contents are clarified. Since most of the failure modes of the generator will cause the phenomenon of large temperature rise, temperature test points are set in each part of the generator. In addition to the temperature sensor, other test points and test contents are shown in the following table.
| No. | Component     | Failure mode | Test point                                      | Test content                                                                                        |
|-----|---------------|--------------|-------------------------------------------------|-------------------------------------------------------------------------------------------------------|
| 1-1 | Stator        | Short-to-phase | The test point of stator winding open circuit voltage | Test for the presence of even and fractional harmonic magnetic fields in the open circuit voltage     |
|     | winding       |              |                                                 |                                                                                                       |
| 1-2 | Interturn short |             | The test point of stator winding open circuit voltage | Test for open-circuit voltage for odd harmonics                                                       |
|     |                |              |                                                 |                                                                                                       |
| 1-3 | open circuit  |              | The test point of phase current                 | Test if phase current is 0                                                                            |
|     |                |              |                                                 | The test point of stator winding DC voltage                                                           |
|     |                |              |                                                 | Large amplitude even-numbered harmonics appear in the spectrum of the test output DC voltage           |
| 2-1 | Rotor         | Interturn short | The test point of rotor shaft voltage           | Detect whether the amplitude of the harmonics of the shaft voltage at all levels exceeds the specified threshold |
|     | winding       |              |                                                 |                                                                                                       |
| 3-1 | Rotor         | Crack        | The test point of ultrasonic nondestructive testing | Test the rotor retaining ring for cracks                                                              |
|     | guard         |              |                                                 |                                                                                                       |
| 4-1 | Bearing       | Local injury | The test point of bearing vibration signal      | Test for abnormal bearing vibration signals                                                          |
| 4-2 |                | Oil leak     | The test point of oil pressure                  | Test for abnormal oil pressure                                                                       |
| 5-1 | Rotary        | Open element | The test point of exciter stator current         | Harmonics of Exciter Stator Current                                                                  |
|     | rectifier     |              |                                                 |                                                                                                       |
| 5-2 | Component     | Component short | The test point of exciter stator current         | Harmonics of Exciter Stator Current                                                                  |
|     | short         |              |                                                 |                                                                                                       |
| 6-1 | Exciter       | Demagnetization | The test point of rotor voltage                 | Test if the rotor voltage is too low                                                                  |
|     |                |              |                                                 | The test point of rotor impedance                                                                     |
|     |                |              |                                                 | Test the generator rotor for low impedance                                                            |
|     |                |              |                                                 | The test point of generator rotor output voltage                                                      |
|     |                |              |                                                 | Test if the output voltage of the generator system is too low                                         |
| 7-1 | Cooler        | Poor cooling effect | The test point of end cap bearing temperature | Test whether the end cap bearing temperature exceeds the upper threshold                               |
|     |                |              |                                                 | The test point of cooling medium temperature                                                         |
|     |                |              |                                                 | Test whether the temperature of the cooling medium exceeds the upper threshold                        |

4.5. Multi-signal flow graph model establishment
Based on the combed ship generator failure modes, test points and fault propagation process, a multi-signal flow graph model of the generator is constructed. The multi-signal flow graph model has three
levels: system layer, LRU layer, and failure mode layer. It includes: 7 modules, 11 failure modes, 17 test points, the results are shown in the figure below.

![Multi-signal flow graph model of generator](image)

**Figure 2. Multi-signal flow graph model of generator.**

5. Test point optimization based on correlation model
Correlation model is a method of designing fault detection and isolation based on the process of how faults are discovered based on correlation reasoning. Correlation-based models include correlation graphical models and correlation mathematical models [12]. According to the constructed multi-signal flow graph model, the correlation mathematical model of the ship generator can be obtained. On this basis, the optimization of test points for fault detection and test points for fault isolation is carried out to form an optimized set of test points to achieve the least of test points to achieve the purpose of maximizing detection and isolation.

5.1. Correlation model of naval generator
The correlation model expresses the correlation between each failure mode of the marine generator and each test point. When the number in the matrix is 1, it means that the failure mode can be detected by the test point. If the number in the matrix is 0, it means that this failure mode cannot be detected by this test point. The correlation mathematical model obtained from the multi-signal flow graph model of naval generator in this paper is shown in the following table.

By analyzing the correlation model, it is found that there are currently redundant test points and fuzzy groups. On the one hand, the test points need to be optimized. On the other hand, in order to eliminate the fuzzy groups, test points or test contents need to be added.
Table 3. The correlation mathematical model of generator.

| Test point optimization for fault detection |
|---------------------------------------------|
| Assuming that the simplified D matrix model is \( D = [d_{ij}]_{m \times n} \), then consider the fault detection weight of the \( j \)-th test point of the reliability parameter (represents a relative measure of how much useful information is detected), \( W_{FDj} \) can be calculated by the following formula:

\[
W_{FDj} = \sum_{i=1}^{m} \alpha_i d_{ij}, \quad j = 1, 2, 3, \ldots, n
\]  

\[
\alpha_i = \lambda_i / \sum_{i=1}^{m} \lambda_i
\]

In the formula, \( W_{FDj} \) is the weight of the \( j \)-th test point. \( \alpha_i \) is the ratio of the frequency of failure of the \( i \)-th component unit. \( d_{ij} \) is the element in row \( i \) and column \( j \) of the D matrix model. \( \lambda_i \) is the failure rate of the \( i \)-th component unit. \( m \) is the number of correlation matrix rows to be analyzed.

After calculating the \( W_{FD} \) of a test point, the one with the largest \( W_{FD} \) value is selected as the first test point for detection, and the corresponding column matrix is:

\[
T_j = [d_{1j}, d_{2j}, \ldots, d_{mj}]^T
\]

Use \( T_j \) to divide the matrix D into two, it can get two sub-matrices:

\[
D^0_p = [d]_{\alpha \times j}
\]

\[
D^1_p = [d]_{(m-\alpha) \times j}
\]
of ‘0’ means that its corresponding UUT component unit (or fault type) has not been detected. If there is no element with a value of 0, it indicates that all constituent units can be detected, and the selection process of the test point for fault detection is completed.

If in the process of selecting test points for detection, there is a maximum value of $W_{FD}$ corresponding to multiple test points, you can choose an easy-to-implement test point. The test points for the fault detection of the ship generator and their priority order are obtained through calculation as shown in the table below.

### Table 4. Test point of fault detection.

| NO. | Test point of fault detection               |
|-----|-------------------------------------------|
| 1   | T3_temperature                            |
| 2   | T4_temperature                            |
| 3   | T_exciter stator current                  |
| 4   | T_generator rotor impedance               |
| 5   | T_stator winding voltage                  |

5.3. Test point optimization for fault isolation

Calculate the fault isolation weight of each test point, and select the point to be tested according to the calculated isolation weight.

$$W_{Fij} = \sum_{k=1}^{Z} \left( \left[ \sum_{i=1}^{m} \alpha_i d_{ij} \right] \cdot \left[ \sum_{i=1}^{m} \alpha_i (1-d_{ij}) \right] \right)$$

(6)

In the formula: $W_{Fij}$ is the isolation weight of the $j$-th test point; $Z$ is the number of the analyzed matrix.

Determine the test point with the largest weight $W_{Fij}$ as the first fault isolation test point, and use $T_j$ to divide the matrix $D$ into two to obtain two sub-matrices:

$$D^0_p = [d]_{\alpha \times j}$$

(7)

$$D^1_p = [d]_{(m-\alpha) \times j}$$

(8)

In the formula: $D^0_p$ is a sub-matrix composed of rows corresponding to elements equal to 0 in $T_j$. $D^1_p$ is a sub-matrix composed of rows corresponding to elements equal to 1 in $T_j$; $\alpha$ is the number of elements equal to 0 in $T_j$; $p$ is subscript, it is the serial number of the selected test point.

Calculate and add the fault isolation weights of the two sub-matrices separately, compare the weights of all test points, and select the test point corresponding to the largest weight as the second fault isolation test point. And so on, until all fault isolation test points are found.

The test points for fault isolation of ship generators and their priority order are obtained through calculation as shown in the table below.
Table 5. Test point of fault isolation.

| No. | Test Point                                      |
|-----|-----------------------------------------------|
| 1   | T3_temperature                               |
| 2   | T7_temperature                               |
| 3   | T4_temperature                               |
| 4   | T_generator output voltage 1                 |
| 5   | T_ultrasonic nondestructive                  |
| 6   | T_ultrasonic nondestructive                  |
| 7   | T_oil pressure                               |
| 8   | T_exciter stator current                     |
| 9   | T_stator winding voltage                     |
| 10  | T5_temperature                               |
| 11  | T_stator winding open circuit voltage         |
| 12  | T_generator rotor impedance                  |

5.4. Fuzzy group elimination

According to the test analysis results, it is found that there are currently two fuzzy groups: Stator winding#Short to phase & Stator winding#Interturn short, Rotary rectifier#Open element & Rotary rectifier#Component short.

After analysis, the stator-rotor phase-to-phase and inter-turn short-circuit faults can be detected by analyzing the voltage frequency, but the harmonic frequency is different. Based on the existing test points, the test content can be added to eliminate the fuzzy group.

The component short-circuit fault is also based on the exciter stator current test point, and the harmonic frequency of the exciter stator current is extracted to achieve fault isolation.

6. Comparative analysis of testability optimization results

Through the optimization of test points for fault detection and the optimization of test points for fault isolation, 4 and 12 test points were obtained respectively. Since the test points for fault detection are included in the test points for fault isolation, the optimized 12 test points.

Construct testable models for optimized test points. Carrying out test predictions, under ideal conditions, the fault detection rate and fault isolation rate indicators of ship generators are as follows:

Table 6. Comparison of test results.

| Test content                        | Before optimization | Optimized |
|-------------------------------------|---------------------|-----------|
| Number of test points               | 17                  | 12        |
| Failure detection rate              | 100%                | 100%      |
| Fault isolation rate (isolated to LRU) | 100%                | 100%      |
| Fault isolation rate (isolated to fault mode) | 63%             | 100%      |

It can be obtained from the analysis results that, after optimization, the ship generator have improved the fault isolation rate under the condition that the number of test points is reduced.

7. Conclusion

This paper analyzes the testability characteristics of naval generators, and gives testability modeling and optimization process. The failure modes and failure characteristics of typical component units of marine generators are studied, and 17 test points are preliminarily set. On this basis, a multi-signal flow graph model of marine generators is constructed and the optimization of test points is carried out. The feasibility and effectiveness of the method proposed in this paper are verified by testability index analysis.
8. References

[1] Ma Weiming, 2002 The development direction of ship power——Integrated power system J. Journal of Naval University of Engineering, 06 1–5 + 9

[2] Fu Lijun, Liu Lufeng, Wang Gang, Ma Fan, Ye Zhihao, Ji Feng and Liu Luhui, 2016 Research progress of China's ship medium voltage integrated power system, J. China Ship Research, 11 (01) 72–9

[3] Wei Qingxin, Wang Kunming and Sun Ping, 2017 Research on Missile System Level Fault Diagnosis Technology Based on Multi-Signal Flow Graph Model, J Computer Measurement & Control, 25(03) 109–11

[4] He Xing, Wang Hongli, Lu Jinghui and Jiang Wei, 2013 TEAMS-based inertial measurement combination testability modeling and analysis, J China Test, 39 (02) 121–4

[5] Shi Junyou, Gong Jingjing and Xu Qingbo, 2010 Improved testability modeling method considering multiple faults, J Journal of Beijing University of Aeronautics and Astronautics, 36 (03) 270–73 + 98

[6] Song Jianhong, 2018 Testability Modeling and Analysis of Doubly Fed Wind Turbine Based on TEAMS D.

[7] Sun Yuguang, Yu Xiwen, Wei Wei and et al, 2014 A new type of detection coil for interturn fault detection of generator windings, J Proceedings of the CSEE, 34 (6) 917–24

[8] Hao L , Wang S , Qiu A and et al, 2011 Exciter stator current harmonics of multi-phase brushless excitation system, J Journal of Tsinghua University (Natural Science), 051(001) 58–62

[9] Zhang Chao, Xia Li, Wu Zhenguo and et al, 2011 Characteristic transfer law of interturn short-circuit faults in rotor windings of synchronous generators, J Power System Protection and Control, 14 63–8

[10] Liu Miyue, Research on fault diagnosis method of motor bearing based on vibration signal D

[11] Hao L , Wang S , Qiu A and et al, 2012 Simulation and recognition for rotary rectifier fault of multi-phase brushless excitation system, J Diangong Jishu Xuebao/Transactions of China Electrotechnical Society, 27(4) 138–44

[12] Shi Junyou, 2011 Testability design analysis and verification, (National defense industry press)