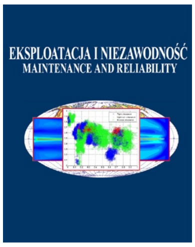


Eksploatacja i Niezawodnosc – Maintenance and Reliability

Volume 24 (2022), Issue 4

journal homepage: http://www.ein.org.pl

Article citation info:
Jiang X, Wang Y, Li J, Ye L. Comprehensive importance analysis for repairable system components based on the GO method. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2022; 24 (4): 785–794, http://doi.org/10.17531/ein.2022.4.18

Indexed by: Web of Science Group

Comprehensive importance analysis for repairable system components based on the GO method

Xiuhong Jiang[a,b,*], Yuying Wang[a], Jiaxin Li[c], Linlin Ye[a]

[a] Shenyang Aerospace University, Department of Electronic Information Engineering, Shenyang 110000, Liaoning, China
[b] Liaoning General Aviation Academy, Shenyang 110000, Liaoning, China
[c] Aero Engine Corporation of China, Shenyang 110000, Liaoning, China

Highlights

- A method for evaluating the importance of components is proposed for repairable systems.
- Use CRITIC to determine weights of steady-state availability and failure importance.
- The method is verified using a PMSM drive system based on the GO method.

Abstract

In order to effectively improve the reliability level of the permanent magnet synchronous motor (PMSM) drive system of electric aircraft, a component importance analysis based on the GO method for the repairable systems is proposed. Firstly, the system reliability model GO diagram is established according to the hardware schematic diagram of the PMSM drive system. Secondly, the steady-state availability and failure importance of the components are calculated. In addition, the criteria importance through intercriteria correlation (CRITIC) is adopted to determine the objective weights of steady-state availability and failure importance. The combined weighting is employed to obtain the importance of key components. Meanwhile, a system redundancy design based on the importance of components is proposed to provide data support for the design of the system. Finally, the feasibility and effectiveness of the proposed method are evaluated by an example of an electric aircraft PMSM drive system. This method provides a supporting basis for the optimization design of the entire system.

Keywords

component importance, electric aircraft, GO method, reliability analysis, permanent magnet synchronous motor.

1. Introduction

Electric drive system provides power for the electric aircraft, which is generally composed of the power source, controller, driver board, permanent magnet synchronous motor (PMSM), etc. [7, 8, 18]. The performance of the electric drive system directly affects flight quality and flight safety, especially its reliability. If a failure is not eliminated in time, it can lead to serious accidents such as air distress or even a crash. Hence, in order to avoid such catastrophic events, it is of utmost importance to conduct appropriate importance analysis of the components of the drive system.

Component importance is an elementary part of the system and is determined by system structure, quality of manufacturing, and environmental conditions, etc. Assessment of component importance is one of the key tasks in system reliability analysis [12, 28]. Importance analysis combines the knowledge of sensitivity, risk, hazard and importance, and is a powerful tool for determining system weaknesses and improving system reliability design. Component importance evaluation is the influence of the change of component reliability parameters on the success probability of the system output. By improving the reliability of components that have a greater impact on the success state of the system, the purpose is to considerably improve the reliability of the system in a simple way and at a lower cost and achieve maximum benefits. The importance analysis of each component in the electric drive system can provide strong data support for the improvement of system reliability, safety and system failure diagnosis [16, 22].

At present, traditional component importance analysis methods include structural importance, probability importance and critical importance, etc. [1, 17, 19]. In recent years, quite a few new analysis methods have also emerged. For example, Cai [2] used GO calculation to calculate the reliability of the logistics service supply chain system accurately and found the weak links affecting the reliability of the system by analysing the minimal cut set. Yang [26] judged the influence of the change of failure probability on the average failure-free working time by increasing the failure probability of some components by five times and keeping the failure probability of other components unchanged. Ma [14], Luo [11], and Chen [3] used the failure-tree reliability analysis method to comprehensively consider the importance analysis results of the three dimensions including probability

(*) Corresponding author.

E-mail addresses: X. Jiang (ORCID: 0000-0002-2560-9336): jxh_mt@163.com, Y. Wang (ORCID: 0000-0003-1072-6633): wyy0801999@163.com, J. Li (ORCID: 0000-0002-2989-8913): ljx_4256@163.com, L. Ye (ORCID: 0000-0003-4065-9304): ye_linlin@163.com

importance, critical importance and structural importance to judge the importance of components comprehensively. Jia [10] adopted the method of failure mode effects and criticality analysis (FMECA) to obtain the importance of civil aircraft components. Scherb [20] combined the relevant structural specifications and the observed failure rate in the entire system network to determine the impact of individual components on system reliability impact is sorted to assess the importance of components. Miziuła [15] and Xue [25] adopted Birnbaum's importance, comparing the availability before and after optimization of the constructed system can effectively reduce the maintenance cost of the system and enhance its availability. Fu [5] utilized a multi-layer network parsing method to evaluate component importance.

All the above studies assume that the object is a non-repairable system and the influence of the maintenance rate parameters of the components in the repairable system is not considered, which will lead to the inaccuracy of component importance analysis results. As a typical repairable electronic system, the electric drive system needs to consider the repair and update of the components during the importance analysis.

The PMSM drive system for electric aircraft is a repairable system. In order to effectively enhance the reliability level of the PMSM drive system of electric aircraft and identify the weakness of system design, a comprehensive component importance analytical method for repairable systems based on the GO method is proposed. According to the GO diagram of the reliability simulation model of electric aircraft drive system, the system steady-state availability and failure importance of key components are calculated by using parameters such as the maintenance rate and failure rate of components, and the objective weights of the system steady-state availability and failure importance are determined by CRITIC. The comprehensive importance of key components is obtained by weighted summation. Finally, the criticality of system components is identified through the case verification and analysis results of an electric aircraft PMSM drive system. Meanwhile, an idea of system redundancy design based on the importance of components is proposed to provide data support for the early design of the system. It can be verified that the proposed method can comprehensively evaluate the vulnerabilities of the PMSM drive system, which provides an important basis for the reliability design of the electric aircraft drive system.

2. Materials and Methods

2.1. Importance calculation of key components

The PMSM drive system of a general electric aircraft is principally composed of a power source (battery pack), TMS320F28335 DSP as the core controller, an IGBT drive board composed of 2SP0115T, an IGBT three-phase bridge inverter composed of FF600R07ME4, voltage sensor, current sensor, filter, bus transceiver, amplifier, 60kW PMSM and other repairable components, all components are industrial standards. Fig. 1 shows the basic structure schematic diagram of the system.

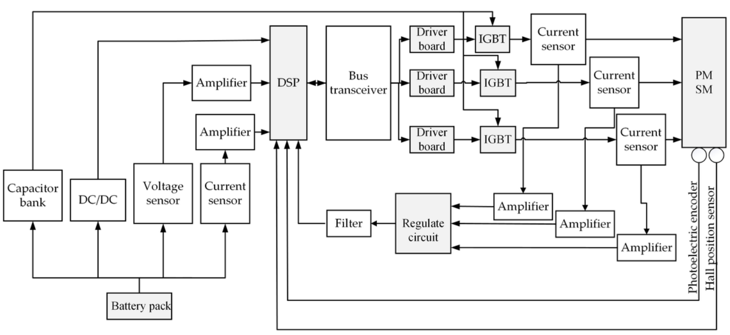


Fig. 1. The schematic diagram of the basic structure of the electric aircraft PMSM system

DC/DC converts battery pack energy and supplies power to DSP. As the control core, DSP has the advantage of realizing complex control algorithms and outputting high-precision pulse width modulation (PWM) through the corresponding algorithm. The PWM is connected with the external IGBT driver board through the bus transceiver to change the output power of the inverter, to achieve the purpose of PMSM control. The bus voltage is output by the voltage sensor as a differential signal and then transmitted to the DSP through the amplifier. The three-phase output current is transmitted to the DSP after amplification, conditioning and filtering. The bus current is also collected by the sensor and sent to the DSP for processing. The photoelectric encoder obtains the motor speed, rotation direction and absolute zero position, and the Hall sensor transmits the differential mode signal to the DSP for processing.

The GO method is a reliability analysis method of a success-oriented system that analyzes multi-state, time-series and process systems [4, 6, 13, 27]. The electric aircraft drive system is extremely suitable for reliability analysis using the GO method as a system with the current flow.

The basic idea of the GO method is to depict the operation, mutual relationship and logical relationship of specific units through operators (representing specific units or logical relationships) and signal flows (representing specific logistics or logical processes), and it directly translates system schematics, flowcharts, or engineering drawings into GO diagrams. The GO operation can be performed according to the operation rules of the operators and the signal flow direction after the GO map is established, and the quantitative analysis of the system's reliability can be completed.

The GO method defines 17 standard operators, which can simulate almost all combinations of component states and signal flows. Different operators correspond to different functions and simulate different components. For example, two-state unit operators can be used to model electronic components, alarms, amplifiers, batteries, safety valves, etc. Each operator has specified input and output data requirements and specified operation rules. The GO model of the PMSM drive system is established according to the basic structure schematic diagram of the system as shown in Fig. 2. Fig. 2 is equivalent to a translation of Fig. 1 using GO operators. The circles and triangles in the figure represent different types of GO operators. The number before "-" in the operator indicates the operator type, and the number after "-" indicates the operator number. Operators represent specific components or logical relationships. In Fig. 1, the power supply is used as the driving force for the entire system and is the system input, so it is represented by a single-signal generator (type 5 of GO operators). Owing to the disconnection of feedback, three-phase output current sensors, Hall sensors, and photoelectric encoders are also directly input as type 5 of GO operators. DC/DC converter, bus voltage sensor, bus current sensor, filter, conditioning circuit, DSP, bus transceiver, driver board, IGBT and PMSM only have two states of success and failure, so it is represented by a two-state unit (type 1 of GO operators). If one of the Hall sensors and the photoelectric encoder fails, the system can also work safely, accordingly, the OR gate (type 2 of GO operators) is used to indicate the relationship between the two. The signals collected to the DSP control board are indispensable, accordingly, an AND gate (type 10 of GO operators) is used to represent the logical relationship between the signals. In the same way, the relationship between the three IGBT is also AND. In this way, different components are simulated with different GO operators, and Fig. 2 is retrieved. The operation rules of specific operators are illustrated in the literature [21].

The arrow lines represent signal flows, representing specific logistics or logical processes.

When only one component fails, the equivalent failure rate λ_{ri} of different operators can be calculated according to the operator operation rules. The calculation methods of several common operators are provided below (assuming that the failure rate follows exponential distribution):

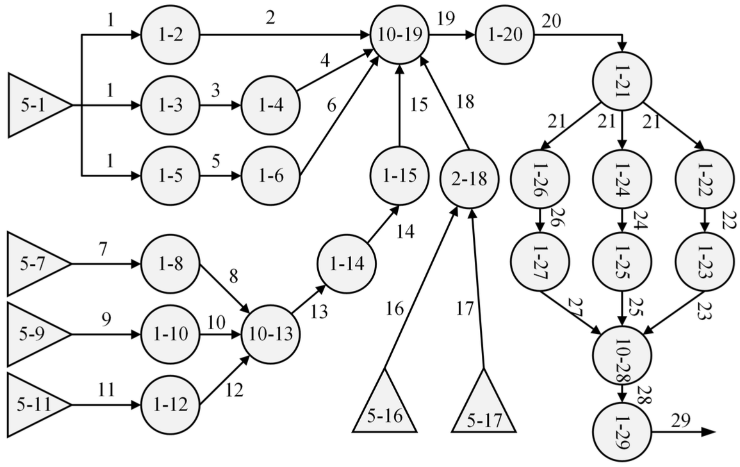


Fig. 2. GO diagram of PMSM drive system

(1) Two-state unit: a unit component with only one input signal and one output signal, and it has two states itself. When operating normally, the signal can pass, otherwise, the signal cannot pass:

$$\lambda_{ri}=\lambda_{si}+\lambda_{ci} \tag{1}$$

In the formula, λ_{ri} is the equivalent failure rate of the output signal of the λ_{si} is the equivalent failure rate of the input signal, and λ_{ci} is the failure rate of the operator itself.

(2) Single signal generator: The operator's data is the output signal's data:

$$\lambda_{ri}=\lambda_{ci} \tag{2}$$

(3) AND gate: There are two or more signals in a parallel input signal for AND logic operation, and one signal is output. The operator itself has no data, and the output signal can succeed only when all input signals succeed. Consequently, its equivalent failure rate is the sum of all input signal failure rates:

$$\lambda_{ri}=\sum_{i=1}^{n}\lambda_{si} \tag{3}$$

(4) OR gate: If the input signals are independent of each other, as long as one of the input signals succeeds, the output will succeed. The operator itself has no data, and its equivalent failure rate is the product of the failure rates of all input signals:

$$\lambda_{ri}=\prod_{i=1}^{n}\lambda_{si} \tag{4}$$

2.2. Critical component importance calculation

In this paper, a component importance analysis method is proposed for the repairable PMSM drive system that integrates the steady-state availability and failure importance. The component steady-state availability is calculated by reliability parameters such as component maintenance rate and failure rate. The failure importance is calculated by the influence of the component from success state to failure state on the success probability of the system. Combined with the two to obtain the key components of importance Y_i, the computation formula is as follows:

$$Y_i=\omega_1 A_i+\omega_2 I_g(i) \tag{5}$$

In the formula, A_i is the steady-state availability of component *i*; $I_g(i)$ is the failure importance of component *i*; ω_1 is the weight of steady-state availability; ω_2 is the weight of failure importance. The weight coefficient can be determined based on the CRITIC method. The calculation method of each quantity is explained below.

2.2.1. Component steady-state availability

Electric aircraft drive systems are repairable systems. Availability is a measure of the probability that a device is in a normal working or usable state when it begins to execute a work task at any time. Steady-state availability is one of the important reliability indicators for measuring repairable systems. It is related to the failure rate and repair rate of components, and it can provide important data for the detection of large-scale equipment and the formulation of repair strategies.

Assuming that the PMSM drive system is alternating between normal operation and downtime for maintenance, and the failure rate λ_i and maintenance rate μ_i of each component, as well as the failure time and the completion time of maintenance, all follow the exponential distribution [23]. The electric drive system is scheduled for regular maintenance by staff, as well as emergency repairs in the event of a failure to restore its performance. The mean time between failures (MTBF) of component *i* can be expressed as:

$$MTBF_i=\frac{1}{\lambda_i} \tag{6}$$

The mean time to repair (MTTR) of component *i* is:

$$MTTR_i=\frac{1}{\mu_i} \tag{7}$$

The mean cycle time (MCT) of component *i* is:

$$MCT_i=MTBF_i+MTTR_i \tag{8}$$

Then the steady-state availability of component *i*, namely the average working probability, can be expressed as:

$$A_i=\frac{MTBF_i}{MCT_i}=\frac{\mu_i}{\lambda_i+\mu_i} \tag{9}$$

In the formula, $MTBF_i, MTTR_i, MCT_i$ are in units of h.

2.2.2. Component failure importance

In order to identify the weak links in the electric aircraft drive system effectively, measuring the importance of each component of the system by failure importance is indispensable. The failure importance describes the influence to which the change in the failure rate of a single component of the system affects the overall reliability of the system and reflects the contribution of the component to the reliability of the system [24]. When the failure rate of component *i* is taken as λ_{ci} and $5\lambda_{ci}$, respectively, that is, when the failure rate of component *i* increases by five times, the influence of the change of the component failure rate on the system reliability is calculated.

The average number of repairable system failures caused by component *i* failures is N_{ci}. The calculation formula is as follows:

$$N_{ci}=P_{ci}(1)\cdot 5\lambda_{ci}\cdot(P_{ri}-P'_{ri}) \tag{10}$$

In the formula, $P_{ci}(1)$ is the probability of the ith component successful operation state; λ_{ci} is the failure rate of components; P_{ri} is the probability of successful operation of the system when the component failure rate is taken λ_{ci}; P'_{ri} is the probability of successful operation of the system when the component failure rate is taken $5\lambda_{ci}$.

The component failure importance $I_g(i)$ is the ratio of the average number of system failures caused by component *i* failures to the average number of system failures N_c. The calculation formula is as follows:

$$I_g(i)=\frac{N_{ci}}{N_c} \tag{11}$$

2.2.3. Evaluation index weight

The CRITIC method is an objective weight assignment method based on evaluation indicators. As the comparative strength of samples and the conflict between indicators are fully considered, the calculation results are more objective and reasonable [9]. Suppose a system has *m* samples and *n* indicators, x_{ij} represents the value of the *j*th evaluation index of the *i*th sample, and the evaluation matrix is shown in equation (12):

$$X=\begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & & \vdots \\ x_{m1} & x_{m1} & \cdots & x_{mn} \end{bmatrix} \tag{12}$$

The calculation steps of objective weighting are as follows:

Step1 Normalize x_{ij}, x'_{ij} represents the value of the *j*th evaluation index of the *i*th sample, and the standardized matrix X' is obtained. The calculation formula is as follows:

$$x'_{ij}=\frac{x_{ij}-\min_j(x_{ij})}{\max_j(x_{ij})-\min_j(x_{ij})} \tag{13}$$

In the formula, $\max_j(x_{ij})$ is the maximum value of x_{ij} in the *j*th evaluation index; $\min_j(x_{ij})$ is the minimum value of x_{ij} in the *j*th evaluation index.

Step2 Solve the index mean $\overline{x_j}$ and index standard deviation σ_j:

$$\overline{x_j}=\frac{1}{m}\sum_{i=1}^{m}x_{ij} \tag{14}$$

$$\sigma_j=\sqrt{\frac{1}{m}\sum_{i=1}^{m}(x_{ij}-\overline{x_j})^2} \tag{15}$$

Step3 Calculate the correlation coefficient ρ_{ij} and information quantity E_j:

$$\rho_{ij}=\frac{\text{cov}(x'_k, x'_l)}{\sigma_k\sigma_j},k=1,2,\ldots,n \tag{16}$$

$$E_j=\frac{\sigma_j}{\overline{x_j}}\sum_{k=1}^{n}(1-\rho_{ij}),j=1,2,\ldots,n \tag{17}$$

In the formula, ρ_{ij} is the correlation coefficient between the ith index and the *j*th index after the matrix standardization, $\text{cov}(x'_k, x'_l)$ represents the covariance between the *k*th index and the *l*th index after matrix normalization.

Step4 Calculate the objective weight:

$$\omega_j=\frac{E_j}{\sum_{i=1}^{n}E_j}, j=1,2,\cdots,n \tag{18}$$

In the formula, ω_j is the objective weight of the *j*th index.

3. Results

The component importance of a general electric aircraft drive system is analyzed, and a SIMULINK simulation model is established according to the GO diagram of the system. The electric drive system is composed of 15 repairable components. The success probability of *i*th component is $P_{ci}(1)$ and the failure rate is λ_{ci}. The probability of system success state is $P_r(1)$, and the equivalent failure rate is λ_r.

Component equivalent failure rate and maintenance rate are important parameters and calculation basis for component importance analysis. The failure rate is the change of component failure probability per unit time, and the main influencing element of maintenance rate is the component failure rate, which is crucial content for realizing specific system functions and ensuring system reliability. The equivalent failure rate can comprehensively measure the influence of all component states on the success probability of system output, it is an extension of component importance, which can provide a reference for system reliability analysis and improvement. The failure rate and maintenance rate of key components in the PMSM drive system are given according to the military standard (GJB/Z299C-2006), as shown in Table 1.

SIMULINK provides a comprehensive and efficient integrated environment, which can accomplish the modelling and simulation functions of a dynamic system for users. It is widely used in the complex simulation and design of automatic control principles and signal processing technology.

The package design of several common operators in SIMULINK is as below:

(1) Signal generator

The signal generator has no input, only output, so it can be simulated with Constant.

(2) Two-state unit

The operator has only two states, success or failure. The system model of the two-state unit is shown in Fig. 3 (a).

The embedded M-file of the Embedded MATLAB Fcn block is

```
function y=fcn(u)
    A=u(1,:)'*u(2,:);
    y=A(:,2)'
```

In the formula, u is the input of the GO operator, y is the output of the GO operator, and the middle operation expression is written according to the operation rules of the two-state unit.

(3) AND gate

The output signal state of AND gate is the maximum state value of the input signal flow. And gate modeling is shown in Fig. 3 (b).

The embedded M-file of the Embedded MATLAB Fcn block is

```
function y=fcn(u)
    A=u(1,:)'*u(2,:);
    y=[A(1) sum(sum(A))-A(1)]
```

(4) OR gate

The output signal state of OR gate is the minimum state value of the input signal flow. Or gate is shown in Fig. 3 (c):

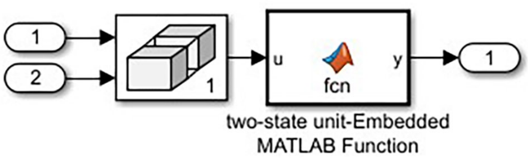
The embedded M-file of the Embedded MATLAB Fcn block is

Table 1. Failure rate and maintenance rate of key components

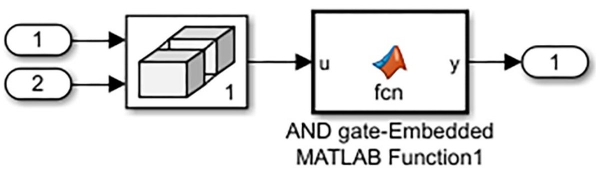
Component Name	Failure rate / *h*	Maintenance rate / *h*
Power source	0.0000486	0.0001220
DC/DC Converter	0.0000700	0.0003860
Voltage sensor	0.0000390	0.0002130
Amplifier	0.0000032	0.0000206
Bus current sensor	0.0000420	0.0001880
Three-phase output current sensor	0.0000420	0.0001880
Conditioning circuit	0.0000059	0.0000202
Filter	0.0000170	0.0001010
Hall sensor	0.0000230	0.0001860
Photoelectric encoder	0.0000580	0.0003020
DSP	0.0000703	0.0003880
Bus transceiver	0.0000119	0.0001080
Driver board	0.0000210	0.0001980
IGBT（Contain the capacitance plate）	0.0000414	0.0003220
PMSM	0.0000150	0.0001090
AND gate	---	---
OR gate	---	---

```
function y=fcn(u)
u=[u(3) 1-u(1)-u(3);u(4) 1-u(2)-u(4)];
A=u(1,:)'*u(2,:);
y=[1-sum(sum(A));sum(sum(A))-A(4)]'
```

a)



b)



c)

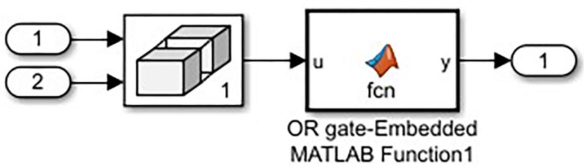


Fig. 3. Encapsulation model. (a) is two-state unit-Embedded MATLAB Function. (b) is AND gate-Embedded MATLAB Function. (c) is OR gate-Embedded MATLAB Function

Fig. 4 replaces the GO operators in Fig. 2 directly with the simulation model. According to the GO diagram of the electric aircraft drive system in Fig. 2, each operator in the GO diagram is encapsulated according to the packaging model. The state probability matrix of each operator is input through the Constant module in SIMULINK Library Browser. Finally, the SIMULINK reliability analysis simulation model of the electric aircraft drive system is shown in Fig. 4. The operation rules of these operators are described above in the article. The reliability data of components in Table 1 is input into the Constant module, and the reliability output data at each signal flow can be obtained by running the simulation.

Step1 Calculate the steady-state availability of system components:

Substitute the reliability data of system components in Table 1 into Equations (6) ~ (9), and the calculated steady-state availability is shown in Table 2.

Table 2. Steady-state availability of key components.

Number	Type	Component Name	Steady-state Availability
1	5	Power source	0.7151231
2	1	DC/DC Converter	0.8464912
3	1	Voltage sensor	0.8452381
4,6,8,10,12	1	Amplifier	0.8655462
5	1	Bus current sensor	0.8173913
7,9,11	5	Three-phase output current sensor	0.8173913
14	1	Conditioning circuit	0.7739464
15	1	Filter	0.8559322
16	1	Hall sensor	0.8899522
17	1	Photoelectric encoder	0.8388889
20	1	DSP	0.8466070
21	1	Bus transceiver	0.9007506
22,24,26	1	Driver board	0.9041096
23,25,27	1	IGBT（Contain the capacitance plate）	0.8860759
29	1	PMSM	0.8790323
13,19,28	10	AND gate	
18	2	OR gate	

Step2 Calculate the component failure importance:

Bring reliability data into SIMULINK simulation models, and the probability of system success state $P_r(1)$ is calculated to be 0.99816610, so the equivalent failure rate λ_r is 0.00183390. Substituting in equations (10) and (11), the failure importance of each component can be obtained in Table 3.

Step3 Calculate the weight of indicators

The electric drive system has a total of 15 components and 2 evaluation indexes. x_{ij} represents the value of the *j*th evaluation index of the *i*th sample. The evaluation matrix can be obtained from equation (12).

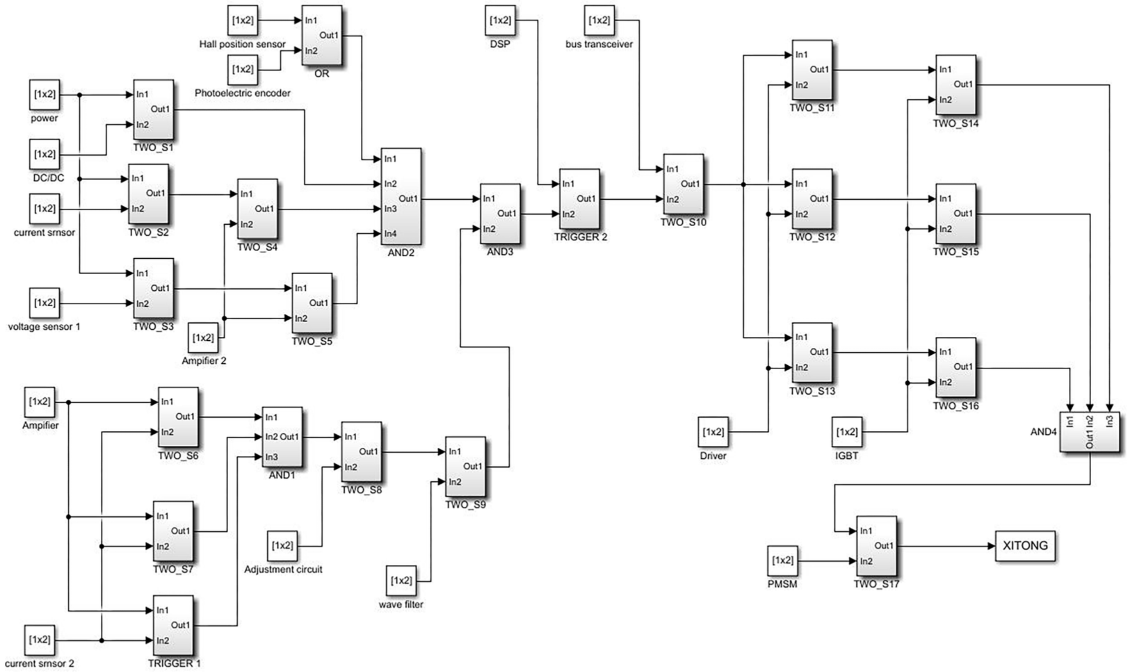


Fig. 4. Simulation Model for Simulink Reliability Analysis of Electric Aircraft Drive System

Table 3. Failure importance of the key components

Component Name	System success probability (failure rate is λ_{ci})	System success probability (failure rate is 5 λ_{ci})	Average number of system failures caused by component faults	Failure importance
Power source	0.9955	0.9890	0.0000016	0.0008617
DC/DC Converter	0.9948	0.9917	0.0000011	0.0005919
Voltage sensor	0.9945	0.9928	0.0000003	0.0001809
Amplifier	0.9943	0.9938	0.0000000	0.0000044
Bus current sensor	0.9946	0.9927	0.0000004	0.0002177
Three-phase output current sensor	0.9954	0.9892	0.0000013	0.0007103
Conditioning circuit	0.9944	0.9935	0.0000000	0.0000145
Filter	0.9947	0.9922	0.0000002	0.0001159
Hall sensor	0.9942	0.9942	0.0000000	0.0000000
Photoelectric encoder	0.9942	0.9942	0.0000000	0.0000000
DSP	0.9948	0.9917	0.0000011	0.0005944
Bus transceiver	0.9943	0.9938	0.0000000	0.0000162
Driver board	0.9944	0.9934	0.0000001	0.0000573
IGBT (Contain the capacitance plate)	0.9943	0.9937	0.0000001	0.0000678
PMSM	0.9942	0.9941	0.0000000	0.0000041
AND gate				
OR gate				

$$X=\begin{bmatrix} 0.7151231 & 0.0008617 \\ 0.8464912 & 0.0005919 \\ 0.8452381 & 0.0001809 \\ 0.8655462 & 0.0000044 \\ 0.8173913 & 0.0002177 \\ 0.8173913 & 0.0007103 \\ 0.7739464 & 0.0000145 \\ 0.8559322 & 0.0001159 \\ 0.8899522 & 0.0000000 \\ 0.8388889 & 0.0000000 \\ 0.8466070 & 0.0005944 \\ 0.9007506 & 0.0000162 \\ 0.9041096 & 0.0000573 \\ 0.8860759 & 0.0000678 \\ 0.8790323 & 0.0000041 \end{bmatrix}$$

Objective weighting calculation:

1. Normalized x_{ij}, and normalized matrix X' is obtained by calculation of equation (13).

$$X'=\begin{bmatrix} 0.0000000 & 1.0000000 \\ 0.6951192 & 0.6868527 \\ 0.6884884 & 0.2098866 \\ 0.7959464 & 0.0050660 \\ 0.5411403 & 0.2526199 \\ 0.5411403 & 0.8243387 \\ 0.3112564 & 0.0168127 \\ 0.7450750 & 0.1345575 \\ 0.9250876 & 0.0000000 \\ 0.6548923 & 0.0000000 \\ 0.6957319 & 0.6897953 \\ 0.9822264 & 0.0188385 \\ 1.0000000 & 0.0664859 \\ 0.9045771 & 0.0786353 \\ 0.8673062 & 0.0047491 \end{bmatrix}$$

2. The mean value of the index $\overline{x_j'}$ is calculated from equation (14), and the standard deviation is σ_j', which can be calculated from equation (15):

$$\overline{x_j'}=\frac{1}{15}\sum_{i=1}^{15}x_{ij}' \Rightarrow \overline{x_1'}=0.6898658$$

$$\overline{x_2'}=0.2659092$$

$$\sigma_j'=\sqrt{\frac{1}{15}\sum_{i=1}^{15}(x_{ij}'-\overline{x_j'})^2} \Rightarrow \sigma_1'=0.2573791$$

3. The correlation coefficient ρ_{ij}' is calculated from equation (16), and the information amount E_j' is calculated from equation (17).

$$\rho_{ij}'=-0.6127065$$

$$E_j'=\frac{\sigma_j'}{\overline{x_j'}}\sum_{k=1}^{15}(1-\rho_{ij}') \Rightarrow E_1'=2.0440027$$

$$E_2'=0.6016777$$

4. The objective weight ω_1 of steady-state availability and the objective weight ω_2 of failure importance are calculated from equation (18).

$$\omega_j=\frac{E_j'}{\sum_{j=1}^{2}E_j'} \Rightarrow \omega_1=0.2274189 \quad \omega_2=0.7725810$$

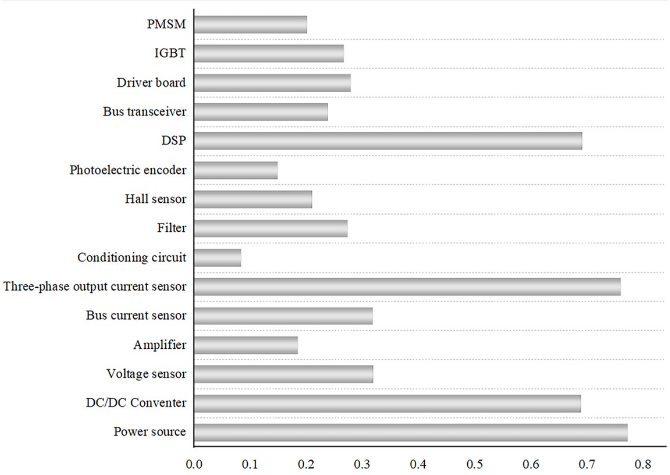


Fig. 5. Weighted importance of key components.

Table 4. Weighted importance of components

Component Name	Steady-state availability	Failure importance	Component importance
Power source	0.0000000	1.0000000	0.7725811
DC/DC Converter	0.6951192	0.6868527	0.6887327
Voltage sensor	0.6884884	0.2098866	0.3187297
Amplifier	0.7959464	0.0050660	0.1849272
Bus current sensor	0.5411403	0.2526199	0.3182349
Three-phase output current sensor	0.5411403	0.8243387	0.7599340
Conditioning circuit	0.3112564	0.0168127	0.0837748
Filter	0.7450750	0.1345575	0.2734007
Hall sensor	0.9250876	0.0000000	0.2103824
Photoelectric encoder	0.6548923	0.0000000	0.1489349
DSP	0.6957319	0.6897953	0.6911454
Bus transceiver	0.9822264	0.0188385	0.2379312
Driver board	1.0000000	0.0664859	0.2787847
IGBT (Contain the capacitance plate)	0.9045771	0.0786353	0.2664701
PMSM	0.8673062	0.0047491	0.2009109

Table 5. *Operator data of PMSM drive system after adding redundancy*

Number	Type	Component Name	Success rate (10^{-5} /h)	failure rate (10^{-5} /h)
1~*m*	5	Power source	1−λ	4.86
3~*n*	1	DC/DC Converter	1−λ	7.00
5	1	Voltage sensor	1−λ	3.90
6,8,10,12,14	1	Amplifier	1−λ	0.32
7	1	Bus current sensor	1−λ	4.20
9,11,13	5	Three-phase output current sensor	1−λ	4.20
16	1	Conditioning circuit	1−λ	0.59
17	1	Filter	1−λ	1.70
18	1	Hall sensor	1−λ	2.30
19~*p*	1	Photoelectric encoder	1−λ	5.80
23~*o*	1	DSP	1−λ	7.03
25	1	Bus transceiver	1−λ	1.19
26,28,30	1	Driver board	1−λ	2.10
27,29,31	1	IGBT（Contain the capacitance plate）	1−λ	4.14
33~*q*	1	PMSM	1−λ	1.50
15,22,32	10	AND gate	---	---
2,4,20,21,24,34	2	OR gate	---	---

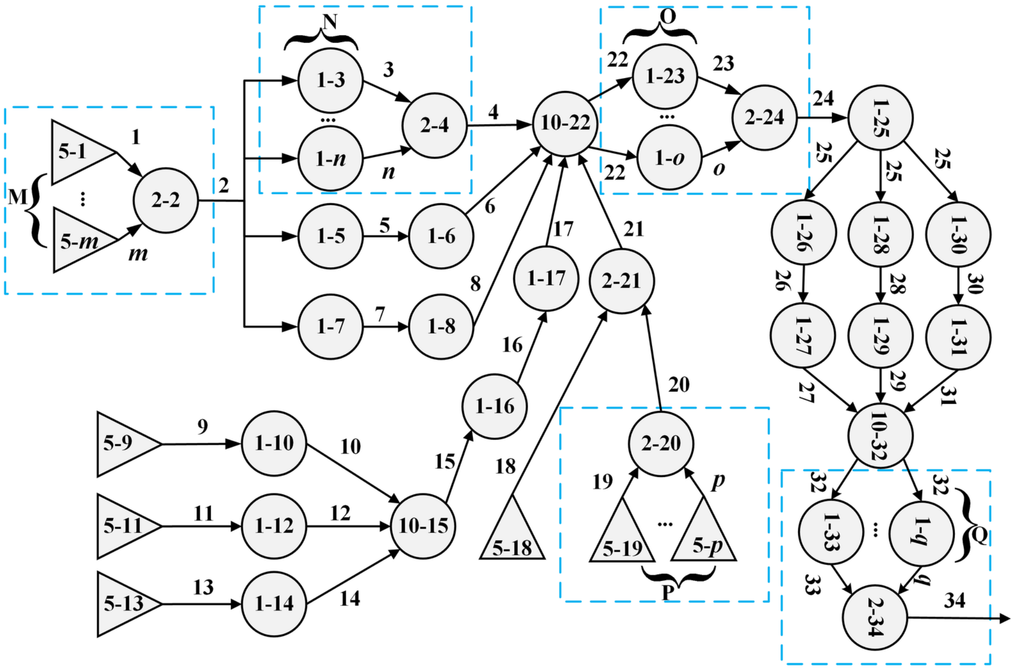


Fig. 6. GO diagram of PMSM system after adding redundancy

The objective weight of the steady-state availability of components is 0.2274189, and the objective weight of failure importance is 0.7725810. The importance of the key components obtained by comprehensive weighting is shown in Table 4. Drawing the importance of the components in Table 4 as a bar graph, the results can be analyzed more intuitively, as shown in Fig. 5.

4. Discussion

As we can see from Table 4 and Fig. 5, the failure of the power source, three-phase output current sensor, DSP and DC/DC converter will have a tremendous impact on the overall system. Accordingly, reliability optimization design should be carried out, such as increasing redundancy and selecting devices with higher reliability to enhance the reliability level of the electric aircraft drive system.

According to the previous analysis results, when the power source fails, it has the largest impact on the overall reliability of the system, so the redundant design of the power source is carried out. Since the system reliability is closely related to the component failure probability, the components with failure probability exceeding 5.0×10^{-5}/h, such as photoelectric encoder, DSP and DC/DC converter, are designed with redundancy to improve the system reliability. In addition, considering that PMSM plays a central role in the whole system as an executive component, redundant designed or replacement with a six-phase PMSM is required.

Table 6. Operator data of PMSM drive system after adding redundancy

System redundancy	1	2	3	4
System reliability	0.999351295	0.999555078797355	0.999555091221017	0.999555091221825

In summary, the redundant design of the power source, photoelectric encoder, DSP, DC/DC converter and PMSM is carried out to enhance the output success probability of the electric drive system. Assuming that the redundancies of the power source, DC/DC converter, photoelectric encoder, DSP and PMSM are M, N, P, O, and Q, respectively, the corresponding signal flow are $1 \sim m$, $3 \sim n$, $19 \sim p$, $23 \sim o$, $33 \sim q$. The operator data is shown in Table 5, and the system GO diagram after adding the margin is shown in Fig. 6.

When M=N=P=O=Q=1, the reliability data of the signal flow 34 represent the reliability characteristics of the electric aircraft drive system with single redundancy. Since modern aviation technology system components generally adopt dual-redundant, triple-redundant or even quad-redundant configurations, let M=N=P=O=Q=x take integers from 1 to 4, respectively, and obtain system reliability data as shown in Table 6.

The reliability of the electric aircraft drive system increases substantially when the redundancy of power source, photoelectric encoder, DSP, DC/DC converter and PMSM are increased from 1 to 2. The electric aircraft drive system reliability varies little when the redundancy is increased from 2 to 4. Therefore, considering factors such as cost, volume, and weight, dual redundancy is a better choice to enhance system reliability. It can increase system reliability by 0.0204%.

5. Conclusions

This paper presents new research results and methods. According to the working characteristics of the electric aircraft drive system, a method of importance analysis of the key components of a repairable system based on the GO method is proposed. Based on the reliability simulation model of the electric aircraft drive system, the steady-state availability and fault importance of key components of the system are calculated. The objective weights of steady-state availability and fault importance of the system are determined by the CRITIC method. The importance of the key components is obtained by the weighted summation. Meanwhile, an idea of system redundancy design based on the importance of components is proposed to provide data support for the early design of the system. In the system operation stage, this method can be used to reasonably allocate inspection and maintenance resources, so as to ensure that the most crucial system units can operate normally.

The case verification and analysis results illustrate that the proposed method can comprehensively evaluate the vulnerability of the electric drive system, and provide an important basis for improving the reliability of the electric aircraft drive system. The method is more comprehensive and more reasonable than the evaluation of a single index.

In the actual evaluation of the importance of components, there are many influencing factors, such as the environment in which the system is located, the cause and degree of failure, and the level of repair personnel. These factors will affect the evaluation of the importance of components. Therefore, it is necessary to establish a more comprehensive model to evaluate the importance of components. In addition, the research object is set as a two-state system, and the components in the system also have several degraded working states during the transition from the successful state to the fault state. Therefore, follow-up research can be continued on reliability analysis and component importance analysis of polymorphic electronic systems.

References

1. Chen DN, Wei X, Yao CY, Wang CL, Lv SJ. Continuous time T-S dynamic fault tree importance analysis method. Chinese Journal of Scientific Instrument 2020, 41(09): 232-241, http://doi.org/10.19650/j.cnki.cjsi.J2006516.
2. Cai C, Liu YQ, Zhang Y. Multi-level LSSC system reliability analysis based on go method. Statistics and Decision 2019, 35(12): 75-78, http://doi.org/10.13546/j.cnki.tjyjc.2019.12.018.
3. Chen YZ. Reliability analysis of vulnerable parts in scraper conveyor based on fault tree method. Coal Mining Machinery, 2019, 40(01): 144-145, http://doi.org/10.13436/j.mkjx.201901051.
4. Chen YQ, Xu TX, Li ZQ, Li HJ. Dynamic reliability analysis of complex polymorphic systems based on evidence go method. Systems engineering and electronics 2020, 42(01): 230-237, http://doi.org/10.3969/j.issn.1001-506X.2020.01.31.
5. Fu T, Wang D, Fan XY, Huang QH. Component Importance and Interdependence Analysis for Transmission, Distribution and Communication Systems. CSEE Journal of Power and Energy Systems, vol. 8, no. 2, 488-498, 2022, http://doi.org/10.17775/CSEEJPES.2020.05520.
6. Fan DM, Ren Y, Liu LL, et al. Algorithm based-on dynamic Bayesian networks for repairable GO methodology model. Journal of Beijing University of Aeronautics and Astronautics 2015, 41(11): 2166-2176, http://doi.org/10.13700/j.bh.1001-5965.2014.0767.
7. Gohardani AS, Doulgeris G, Singh R. Challenges of future aircraft propulsion: A review of distributed propulsion technology and its potential application for the all electric commercial aircraft. Progress in Aerospace Sciences 2011, 47(5): 369-391, https://doi.org/10.1016/j.paerosci.2010.09.001.
8. Huang J, Yang FT. Development and challenges of new energy electric aircraft. Acta Aeronautica et Astronautica Sinica 2016, 37 (01): 57-68, https://doi.org/10.7527/S1000-6893.2015.0274.
9. Hu T, Wang D, Sun Y, Huang ZY, Jiang LT. Air combat threat assessment based on improved CRITIC-LRA and grey approximation ideal solution sorting method. Acta Armamentarii 2020, 41(12): 2561-2569, https://doi.org/10.3969/j.issn.1000-1093.2020.12.022.
10. Jia BH, Guo T, Lu X, Li LY. Reliability analysis of typical components of civil aircraft. Aircraft Design 2020, 40(02): 64-68, https://doi.org/10.19555/j.cnki.1673-4599.2020.02.014.
11. Luo CK, Chen YX, He Z, Li Y, Zhang YM. Evaluation method of contribution rate of aviation equipment architecture based on fault tree analysis. Journal of National University of Defense Technology 2021, 43(01): 155-162, https://doi.org/10.11887/j.cn.202101020.
12. Li ZQ, Xu TX, Gu JY, An J, Liu YD. Reliability analysis method of a certain type of missile control system fused with uncertain information. System Engineering and Electronic Technology 2017, 39(12): 2869-2876, https://doi.org/10.3969/j.issn.1001-506X.2017.12.34.
13. Li JK, Wang Y, Wang BM. Reliability of spoiler system of an electric aircraft based on the moment go method. Acta Aeronautica Sinica 2021, 42(03): 62-70, https://doi.org/10.7527/S1000-6893.2020.23945.
14. Ma Z, Zhou HY, Li XQ, He XP. Research on the reliability of electric vehicle electric power steering system based on model-driven

architecture. Automotive Technology 2020(12): 36-42, https://doi.org/10.19620/j.cnki.1000-3703.20200057.
15. Miziuła P, Navarro J. Birnbaum Importance Measure for Reliability Systems With Dependent Components. IEEE Transactions on Reliability 2019, vol. 68, no. 2, 439-450, https://doi.org/10.1109/TR.2019.2895400.
16. Nguyen KA, Do P, Grall A. Condition-based maintenance for multi-component systems using importance measure and predictive information. International Journal of Systems Science: Operations& Logistics 2014, 1(4): 228-245, https://doi.org/10.1080/23302674.2014.983582.
17. Peng H, Coit DW, Feng Q. Component Reliability Criticality or Importance Measures for Systems With Degrading Components. IEEE Transactions on Reliability 2012, vol. 61, no. 1, 4-12, https://doi.org/10.1109/TR.2011.2182256.
18. Steiner HJ, Vratny PC, Gologan C, et al. Optimum number of engines for transport aircraft employing electrically powered distributed propulsion. CEAS Aeronautical Journa1 2015, 5(2): 157-170, https://doi.org/10.1007/s13272-013-0096-6.
19. Si SB, Yang L, Cai ZQ, Dui HY. Study on calculation method of comprehensive importance of two-state system components. Journal of Northwestern Polytechnical University 2011, 29(06): 939-947, https://doi.org/ 10.3969/j.issn.1000-2758.2011.06.021.
20. Scherb A, Garre L, Straub D. Evaluating component importance and reliability of power transmission networks subject to windstorms: methodology and application to the nordic grid. Reliability Engineering and System Safety 2019, 191: 106517-106517, https://doi.org/10.1016/j.ress.2019.106517.
21. Shen ZP, Huang XR. GO method principle and application: an analysis method of system reliability. Tsinghua University Press: Beijing, China.
22. Wang Y, Fu SS, Wu B, Huang JH, Wei XY. Towards optimal recovery scheduling for dynamic resilience of networked infrastructure. Journal of Systems Engineering and Electronics 2018, 29(05): 995-1008, https://doi.org/10.21629/JSEE.2018.05.11.
23. Wang XY, Fan QQ. Analysis of the importance of urban rail transit vehicle failure based on FMECA method. Urban Rail Transit Research 2020, 23(07): 121-124. https://doi.org/10.16037/j.1007-869x.2020.07.025.
24. Wang Z, Bao CY. The application of go method in the reliability analysis of YAG laser system. Journal of Tsinghua University (Natural Science Edition) 2007(03): 377-380, https://doi.org/10.3321/j.issn:1000-0054.2007.03.019.
25. Xue CG, Gu Y, Cao WJ, Cao HW. Optimization of opportunistic maintenance strategy for multi-component importance systems. Mechanical Design and Manufacturing 2022(02): 116-119+125, https://doi.org/10.19356/j.cnki.1001-3997.20211116.026.
26. Yang WS, Wang W, Mi GJ, Mao XJ, Yan JX, Zhong GS. Application of go method in reliability analysis of non-water-cooled all-solid-state laser system. Laser and Infrared 2010, 40(05): 479-483, https://doi.org/10.3969/j.issn.1001-5078.2010.05.007.
27. Yao AL, Huang LL, Xu TL. Reliability analysis of gas transmission station based on go method. Acta Petrolei Sinica 2016, 37(05): 688-694, https://doi.org/10.7623/syxb201605013.
28. Zhou K, Ding JY, Chen JY, Tao WW. Reliability and component importance analysis of substation automation system in multi-state mode. Electric Power Components and Systems 2019, 47(6-7): 589-604, https://doi.org/10.1080/15325008.2019.1602686.

Appendix A

Component Name	Failure rate / *h*	Maintenance rate / *h*	Steady-state availability	Failure importance	Weighted steady-state availability	Weighted failure importance	Weighted component importance
Power source	0.0000486	0.0001220	0.7151231	0.0008617	0.0000000	1.0000000	0.7725811
DC/DC Converter	0.0000700	0.0003860	0.8464912	0.0005919	0.6951192	0.6868527	0.6887327
Voltage sensor	0.0000390	0.0002130	0.8452381	0.0001809	0.6884884	0.2098866	0.3187297
Amplifier	0.0000032	0.0000206	0.8655462	0.0000044	0.7959464	0.0050660	0.1849272
Bus current sensor	0.0000420	0.0001880	0.8173913	0.0002177	0.5411403	0.2526199	0.3182349
Three-phase output current sensor	0.0000420	0.0001880	0.8173913	0.0007103	0.5411403	0.8243387	0.7599340
Conditioning circuit	0.0000059	0.0000202	0.7739464	0.0000145	0.3112564	0.0168127	0.0837748
Filter	0.0000170	0.0001010	0.8559322	0.0001159	0.7450750	0.1345575	0.2734007
Hall sensor	0.0000230	0.0001860	0.8899522	0.0000000	0.9250876	0.0000000	0.2103824
Photoelectric encoder	0.0000580	0.0003020	0.8388889	0.0000000	0.6548923	0.0000000	0.1489349
DSP	0.0000703	0.0003880	0.8466070	0.0005944	0.6957319	0.6897953	0.6911454
Bus transceiver	0.0000119	0.0001080	0.9007506	0.0000162	0.9822264	0.0188385	0.2379312
Driver board	0.0000210	0.0001980	0.9041096	0.0000573	1.0000000	0.0664859	0.2787847
IGBT (Contain the capacitance plate)	0.0000414	0.0003220	0.8860759	0.0000678	0.9045771	0.0786353	0.2664701
PMSM	0.0000150	0.0001090	0.8790323	0.0000041	0.8673062	0.0047491	0.2009109
AND gate	---	---					
OR gate	---	---					