Modeling and Prediction of the Reliability Analysis of an 18-Pulse Rectifier Power Supply for Aircraft Based Applications

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This work was supported in part by the Fundamental Research Funds for the Central Universities of China, in part by the National Natural Science Foundation of China under Grant 51577046, in part by the State Key Program of National Natural Science Foundation of China under Grant 51637004, in part by the National Key Research and Development Plan (Important Scientific Instruments and Equipment Development) under Grant 2016YFF0102200, and in part by the Equipment Research Project in Advance under Grant 41402040301.

\textbf{ABSTRACT} Due to its advantages of small size and light weight, multi-pulse rectifier has a broad application prospect in the field of aviation. The 18-pulse rectifier is more popular in practical engineering application because of its better rectifier characteristics than 12-pulse, its simpler structure process and easier to realize than 24-pulse. The theoretical research and engineering application of the 18-pulse rectifier have achieved some success. However, whether the reliability of the system can be satisfied has always been one of the key problems to be solved in practical engineering. The aim of this work is to study the reliability modeling and prediction of the 18-pulse rectifier power supply. Its reliability block diagram and mathematical model are established. According to US Military handbook MIL-HDBK-217F, the most authoritative and widely used in the world, the two most commonly used methods for reliability prediction are parts count method and part stress analysis method. The reliability data are estimated by these two methods. It is concluded that the value of mean time between failures in airborne environment is 23326 h, which meets the requirement of 1.5 times of 15000 h. According to the reliability data, the failure mode and effect analysis of its weak links are carried out, and the improvement measures are proposed. This will promote and guide the reliability growth and engineering popularization of the 18-pulse rectifier power supply. At the same time, the reliability of the actual project can be extended to other related engineering applications to ensure the reliable operation of the system.

\textbf{INDEX TERMS} 18-pulse, rectifier power supply, reliability engineering, aircraft.

I. INTRODUCTION

Reliability prediction is a method used to evaluate whether the designed products meet the specified reliability requirements. In each stage of product design and development, through reliability modeling and prediction, can we determine whether the product, the system and the whole machine design meet the requirements of reliability index? Does it meet the requirements of users for product reliability and safety? Is the manufacturing process engineering of the product reliable? Are potential quality risks assessed? Are effective measures taken to control and prevent the weak links as early as possible? Is an optimization plan provided? Is the safety analysis of the product confirmed? [1], [2].

In the process of reliability growth from the beginning of the development to the maturity of the new product, no matter whether the expected value of the reliability reaches the requirement, the weak link of the reliability of the equipment should be analyzed according to the situation of the reliability prediction. The necessary design or process improvement
measures are adopted to increase the reliability of the weak links, and the growth measures are analyzed and explained in detail.

At the different product levels and at the different stages of development, the different methods of reliability prediction are used [3]–[6]. At present, the most commonly used reliability estimation methods for electronic equipment are parts count method and part stress analysis method [7]–[9]. Non-electronic devices can be expected using similar product methods and statistics data method. The reliability estimation for the system and machine level are predicted by equipment failure efficiency. Similar product method can be used in the absence of specific data.

There are lots of reliability prediction handbooks with many standards and methods [10], [11]. In 1956, Reliability Analysis Center (RCA) released TR-1100, “Reliability Stress Analysis for Electronic Equipment”, which presented mathematical models for estimating component failure rates. In 1962, the first version of US Military Handbook MIL-HDBK-217 was published by the US Navy [12].

While MIL-HDBK-217 has been updated several times, other organizations are developing reliability prediction models unique to their industries. For example, the SAE reliability estimation method of the American association of automation engineers. Telcordia SR-332 [13], CNET RDF-93 [14] and CNET RDF-2000 [15] of France national telecom research center, HRD-5 [16] of British telecom, SN29500 [17] of Siemens, GJB/Z-299C [18] of China, NTT procedure of Nippon telegraph [19], PRISM of the center for reliability analysis [20], DERA transport reliability assessment and calculation system (TRACS) of British defense education and research office, etc. It has been over a decade since the reliability prediction handbook MIL-HDBK-217 was last updated, yet it remains the most widely used reliability prediction method for electronic equipment.

Modern warfare is the information warfare in the complex environment. As the eye of the information warfare, the effectiveness of the radar directly determines the outcome of the war. In the dense, complex and changeable signal environment, it not only requires our “eyes” to be able to see far, clear, accurate and fast, but also to protect the “eyes” from deception and injury, which has become an eternal topic in the radar field.

In order to reduce the harmonic in the radar power grid and improve its power supply quality, the main methods are multi-pulse rectifier technology [21], [22], pulse width modulation technology (PWM) [23] and so on. The multi-pulse rectifier has been generally used in the aviation power systems because of its simple structure, high reliability and strong overload capacity. In particular, the variable voltage rectifier used as a secondary power supply has been used in large civil aircraft, and the 12-pulse voltage-changing rectifier has also been adopted. Additionally, a large number of multi-pulse rectifiers have been used in B787 and A380 aircraft. For example, a multi-pulse variable voltage rectifier and a multi-pulse autotransformer are used in the B787 power system. Multi-pulse rectifier has the advantages of small size and light weight. It is the airborne equipment for multi-electric aircraft and all-electric aircraft. It has a broad application prospect in the aviation field. With the increasing demands on the equipment, the research on multi-pulse rectifier is of practical value and practical significance.

The multi-pulse rectifier can be divided into 12-pulse, 18-pulse, 24-pulse and 30-pulse rectifier, etc. The higher the number of pulses, the better the rectifier’s input current and output voltage characteristics, however the more complex the rectifier structure, the more difficult the process implementation, and the higher the cost. Because the 18-pulse rectifier has better rectification characteristics than the 12-pulse rectifier, and the 18-pulse structure is simpler than the 24-pulse and 30-pulse rectifiers, the process is relatively easy and the cost is lower. Therefore, the 18-pulse rectifier has been widely studied and applied in practical aviation industry, and some achievements have been made. B. Singh et al. studied and simulated the AC-DC converter model based on the 18-pulse autotransformer, and improved its harmonic index [24]. J. Chen et al. investigated six types of autotransformers for an 18-pulse autotransformer rectifier units (ATRUs), aiming to provide an optimal selection guideline for a proper structure [25]. Y. Zhang et al. applied the 18-pulse rectifier power supply to the radar power system of a large airborne transport aircraft, making the harmonics below 7% and meeting the requirements of its environmental test [26].

Although the theoretical simulation and the engineering application of the 18-pulse rectifier power supply have achieved some success, but whether its reliability parameters meet the optimal requirements of the system? How can these requirements be ensured concurrently both in development and production processes? Can it ensure the best reliable operation of the system? These are very important issues in the practical engineering application. In this paper, the reliability block diagram (RBD) of the 18-pulse rectifier power supply is established based on the engineering practice. The general process and operation flow of two reliability prediction methods commonly used in electronic equipment, that is parts count method and part stress analysis method, are summarized. This product is a repairable system, failure rate, λ(t), and mean time between failures (MTBF) are selected to measure its reliability. The MTBF values according to the US military standard MIL-HDBK-217F [27] was calculated to meet the system requirements of 15000 h. The failure mode and effect analysis (FMEA) of weak links are carried out and the improvement measures are proposed. This will promote and guide the reliability and engineering popularization of the 18-pulse rectifier power supply. At the same time, the reliability workflow is simple and feasible, which can be extended to other related engineering applications.

II. RELIABILITY MODELING OF 18-PULSE RECTIFIER POWER SUPPLY
The 18-pulse rectifier power supply adopts a modular design, as shown in Fig. 1, it consists of six parts: the input filter
The 18-pulse rectifier power supply is made up of six parts: circuit P1, the soft-start circuit P2, the 18-pulse rectifier circuit P3, the output filter circuit P4, the auxiliary power supply P5, and the fault detection circuit P6. The output fault monitoring includes open phase fault detection, input overcurrent fault detection and output undervoltage fault detection.

According to the circuit diagram of the 18-pulse rectifier power supply, the RBD is adopted for reliability modeling of the system. When one of the six parts fails, the entire power supply fails, so it’s a typical series reliability model, which is the famous Lusser law. Its RBD is shown in Fig. 2. The RBD of each functional unit is also a series model. The RBD of the input filter circuit P1 is composed of one input connector X1, four inductors L101-L104, twelve capacitors C101-C112, and three resistors R101-R103 in series. The RBD of the soft-start circuit P2 consists of one contactor K201, one time-delay relay K202, one reverse parallel diode D201, and three current limiting resistors R201-R203 in series. The RBD of the 18-pulse rectifier circuit P3 is composed of one 18-pulse autotransformer T301 and three rectifier diodes D301-D303 in series.

The RBD of the output filter circuit P4 is composed of one output inductor L401, one output capacitor C401, one output leak resistor R401 and one output connector X2 in series. The RBD of the auxiliary power supply P5 consists of three transformers T501-D501-C501 in series.
one auxiliary transformer T501, one rectifier diode D501, and one output filter capacitor C501 in series. The RBD of the fault detection circuit P6 is composed of one transformer T601, seven capacitors C601-C607, twenty-three resistors R601-R623, eleven diodes D601-D611, five optical couplers N601-N605, one sensor S601, and one fault monitoring output connector X3 in series. The total failure rate of the power supply is the sum of the failure rates of each functional unit. The structure of the sensor is complex, which is not the main functional device of the system, and has little effect on the reliability of the whole system, which is ignored in the reliability prediction.

According to the RBD in series, if each unit is independent and the service life follows the exponential distribution, the mathematical model of the system reliability is as follows:

$$R_s(t) = \prod R_i(t) = \prod e^{-\lambda_i t}$$  \hspace{1cm} (1)

Each unit obeys the exponential distribution, and the system formed by its series connection still obeys the exponential distribution, and the system failure rate is the sum of all unit failure rates. The mathematical model of system failure rate is as follows:

$$\lambda_s = \sum \lambda_i$$  \hspace{1cm} (2)

The mathematical model of MTBF of the system is as follows:

$$MTBF = \frac{1}{\lambda_s}$$  \hspace{1cm} (3)

The function diagram of reliability index for the 18-pulse rectifier power supply is shown in Fig. 3.

III. RELIABILITY PREDICTION OF 18-PULSE RECTIFIER POWER SUPPLY

The system requirements of the reliability index for the 18-pulse rectifier power supply is the MTBF $\geq 15000$ h. The implementation process of reliability prediction for the 18-pulse rectifier power supply is performed “from down to up” step by step, as shown in Fig. 4. Firstly, the system structure of the power supply is analyzed and divided into six function units. Secondly, the component parameters of each functional unit, such as, component type, quantity, quality grade, environmental factor, stress coefficient, temperature coefficient, etc. are analyzed. Then, the formula of each component are determined and the operating failure rate of various components in the power supply is estimated according to the reliability formula of components. And then, the operating failure rate of all kinds of components in the unit is added to obtain the total operating failure rate of each functional unit. Finally, the total operating failure rate of each functional unit is added to obtain the reliability indexes of power supply, such as the total operating failure rate and the MTBF.

There are generally two methods to predict the reliability of electronic equipment, parts count method and part stress analysis method.

A. PARTS COUNT METHOD

The parts count method is mainly used in the initial design of the products. The information needed to apply the method is the generic part types and quantities, the part quality levels and the equipment environment. The equipment failure rate is obtained by looking up a generic failure rate in the tables, multiplying it by a quality factor, and then summing it with failure rates obtained for other components in the equipment. Its reliability prediction model is shown in (4).

$$\lambda_P = \sum_{i=1}^{n} N_i \left( \lambda_g \pi Q \right)_i$$  \hspace{1cm} (4)

FIGURE 3. The function diagram of reliability index for the 18-pulse rectifier power supply.

FIGURE 4. The implementation process of reliability prediction for the 18-pulse rectifier power supply.
where $\lambda_p$ is the operating failure rate of the equipment, $\lambda_y$ is the generic failure rate for the $i^{th}$ generic part, $\pi_Q$ is the quality factor for the $i^{th}$ generic part, $N_i$ is the quantity of $i^{th}$ generic part, $n$ is the number of different generic part categories in the equipment.

It can be seen that the failure rate of the parts count method is only related to its general failure rate and quality factor. The application environment is set as airborne, uninhabited, and cargo, that is $A_{UC}$. The general failure rate and quality coefficient of components can be obtained by checking MIL-HDBK-217F. According to formula (4), the failure rate of each component is calculated, as shown in Table 1. The electrolytic capacitors, contactors and relays have higher operating failure rates for components, reaching $6.3 \times 10^{-6}/h$ and $6.2 \times 10^{-6}/h$, respectively.

**TABLE 1. The operating failure rate of the components by using parts count method.**

| Component Name | $\lambda_y$ ($10^6/h$) | $\pi_Q$ | $\lambda_y$ ($10^6/h$) | Remarks |
|----------------|------------------------|--------|------------------------|---------|
| Inductor       | 0.016                  | 1.0    | 0.016                  | MIL-C-15305 |
| Ceramic Cap.   | 0.032                  | 3.0    | 0.096                  | MIL-C-11015 |
| Electrolytic Cap. | 2.1                | 3.0    | 6.3                    | MIL-C-39018 |
| Resistor       | 0.021                  | 3.0    | 0.063                  | MIL-R-10509 |
| Connector      | 0.23                   | 1.0    | 0.23                   | Circular |
| Contactor/Relay| 6.2                    | 1.0    | 6.2                    | High current |
| Diode          | 0.16                   | 2.4    | 0.384                  | JAN |
| Transformer    | 0.35                   | 1.0    | 0.35                   | MIL-T-27 |
| Optical Couple | 0.21                   | 2.4    | 0.504                  | JAN |

The total failure rate of the power supply can be obtained from the operating failure rates of the components in Table 1 and the number of components in each functional module in Fig. 2. The total failure rate for each functional module is summarized in Table 2. The failure rates of P1 to P6 modules are 1.635, 12.973, 1.502, 6.609, 0.83, and $9.445 \times 10^{-6}/h$, respectively. The reliability module of this power supply is a series model, so the total failure rate of the power supply is the sum of the failure rates of each functional module, that is, $32.994 \times 10^{-6}/h$. The MTBF value analyzed by parts count method is $1/\lambda_{p\text{-total}} = 30309$ h.

**TABLE 2. The reliability prediction of the 18-pulse rectifier power supply by using parts count method.**

| Functional Unit | Types          | $\lambda_y$ ($10^6/h$) | Quan. N | $N_{\lambda_y}$ ($10^3/h$) | $\lambda_{p\text{-total}}$ ($10^6/h$) |
|-----------------|----------------|------------------------|---------|-----------------------------|-------------------------------------|
| Input Filter Circuit P1 | Inductor       | 0.016                  | 4       | 0.064                       | 1.635                              |
| Capacitor       | 0.096          | 12                     | 1.152   |                            |                                     |
| Resistor        | 0.063          | 3                      | 0.189   |                            |                                     |
| Connector       | 0.23           | 1                      | 0.23    |                            |                                     |
| Soft-Start Circuit P2 | Contactor     | 6.2                    | 1       | 6.2                         | 12.973                             |
| Relay           | 6.2            | 1                      | 6.2     |                            |                                     |
| Diode           | 0.384          | 1                      | 0.384   |                            |                                     |
| Resistor        | 0.063          | 3                      | 0.189   |                            |                                     |
| Rectifier Circuit P3 | Transformer | 0.35                   | 1       | 0.35                        | 1.502                              |
| Diode           | 0.384          | 3                      | 1.152   |                            |                                     |
| Output Filter Circuit P4 | Inductor | 0.016                  | 1       | 0.016                       |                                     |
| Capacitor       | 6.3            | 1                      | 6.3     |                            |                                     |
| Resistor        | 0.063          | 1                      | 0.063   |                            |                                     |
| Connector       | 0.23           | 1                      | 0.23    |                            |                                     |
| Auxiliary Power Supply P5 | Transformer | 0.35                   | 1       | 0.35                        |                                     |
| Diode           | 0.384          | 1                      | 0.384   |                            | 0.83                                |
| Capacitor       | 0.096          | 1                      | 0.096   |                            |                                     |
| Fault Detection Circuit P6 | Transformer | 0.35                   | 1       | 0.35                        |                                     |
| Diode           | 0.384          | 1                      | 0.384   |                            | 9.445                               |
| Opt. couple     | 0.504          | 5                      | 2.52    |                            |                                     |
| Connector       | 0.23           | 1                      | 0.23    |                            |                                     |
| Total           |                |                        |         |                             | $32.994 \times 10^{-6}/h$          |

**TABLE 3. The reliability prediction modes of the components.**

| Component Name       | Reliability Prediction Mode | Formula Order Number |
|----------------------|-----------------------------|----------------------|
| Inductor             | $\lambda_p = \lambda_y \pi_Q \pi_r \pi_E$ | (5)                 |
| Capacitor            | $\lambda_p = \lambda_y \pi_Q \pi_r \pi_E$ | (6)                 |
| Resistor             | $\lambda_p = \lambda_y \pi_Q \pi_r \pi_E$ | (7)                 |
| Connector            | $\lambda_p = \lambda_y \pi_Q \pi_r \pi_E$ | (8)                 |
| Contactor/Relay      | $\lambda_p = \lambda_y \pi_Q \pi_r \pi_E$ | (9)                 |
| Diode                | $\lambda_p = \lambda_y \pi_Q \pi_r \pi_E$ | (10)                |
| Transformer          | $\lambda_p = \lambda_y \pi_Q \pi_r \pi_E$ | (11)                |
| Optical Couple       | $\lambda_p = \lambda_y \pi_Q \pi_r \pi_E$ | (12)                |

Note: $\lambda_p$ is the operating failure rate, $\lambda_y$ is the base failure rate, $\pi_Q$ is the quality factor, $\pi_r$ is the resistance factor, $\pi_c$ is the capacitance factor, $\pi_{E}$ is the environmental factor, $\pi_{C}$ is the construction factor, $\pi_E$ is the electrical stress factor, and $\pi_{C}$ is the contact construction factor.

**B. PART STRESS ANALYSIS METHOD**

The part stress analysis method is usually used in the detailed design phase. Its component reliability prediction modes are shown in Table 3. It can be seen that the part stress analysis method requires a great amount of detailed information of components, such as environmental requirements, quality coefficient, stress coefficient and temperature coefficient, and so on. The failure rate of components is the product of the basic failure rate and a series of coefficients, such as quality coefficient, environment coefficient, etc. The basic failure rate and some coefficients of the components can be obtained by checking MIL-HDBK-217F.

The working temperature of the 18-pulse rectifier power supply is set at $70^\circ$C, and the application environment is set as airborne, uninhabited, and cargo, that is $A_{UC}$. According to the formula (5) $\sim$ (12) in Table 3, the failure rate of each component in the application environment...
TABLE 4. The operating failure rate of the components by using part stress analysis method.

| Components                                        | Items | Value | Remarks          | $\lambda_p (10^{-6}/h)$ |
|---------------------------------------------------|-------|-------|------------------|--------------------------|
| Inductor                                          | $\lambda_0$ | 0.0023 | 70°C             |                           |
|                                                   | $\pi_C$ | 1     | Fixed            |                           |
|                                                   | $\pi_Q$ | 4.0   | MIL-C-15305      | 0.0552                    |
|                                                   | $\pi_E$ | 6.0   | $\lambda_{AC}$   |                          |
| Ceramic Capacitor                                 | $\lambda_0$ | 0.0044 | 70°C             |                           |
|                                                   | $\pi_CV$ | 1.3   | 36000pF          | 0.13728                   |
|                                                   | $\pi_Q$ | 3.0   | MIL-C-11015      |                           |
|                                                   | $\pi_E$ | 8.0   | $\lambda_{AC}$   |                          |
| Electrolytic Capacitor                           | $\lambda_0$ | 0.31  | 70°C             |                           |
|                                                   | $\pi_CV$ | 1.3   | 1700µF           |                           |
|                                                   | $\pi_Q$ | 1.0   | MIL-C-39018      | 11.284                    |
|                                                   | $\pi_E$ | 28    | $\lambda_{AC}$   |                          |
| Resistor                                          | $\lambda_0$ | 0.0019 | 70°C             |                           |
|                                                   | $\pi_R$ | 1.0   | <0.1Ω            |                           |
|                                                   | $\pi_Q$ | 5.0   | MIL-R-10509      | 0.095                     |
|                                                   | $\pi_E$ | 10    | $\lambda_{AC}$   |                          |
| Connector                                         | $\lambda_0$ | 0.00032 | MIL-C-38999, 70°C |                           |
|                                                   | $\pi_K$ | 1.0   | 0 to 0.05        | 0.004352                  |
|                                                   | $\pi_T$ | 1.7   | 4                |                           |
|                                                   | $\pi_E$ | 8.0   | $\lambda_{AC}$   |                          |
| Contactant /Relay                                 | $\lambda_0$ | 0.50  | 70°C             |                           |
|                                                   | $\pi_Q$ | 1.0   | MIL-R-83726      | 10.5                      |
|                                                   | $\pi_E$ | 21    | $\lambda_{AC}$   |                          |
| Diode                                             | $\lambda_0$ | 0.0030 | Rectifier, MIL-S-19500 |                           |
|                                                   | $\pi_T$ | 3.9   | 70°C             |                           |
|                                                   | $\pi_C$ | 0.19  | $V_{C}<0.5$      | 0.106704                  |
|                                                   | $\pi_Q$ | 1.0   | Metallurgically bonded |                       |
|                                                   | $\pi_E$ | 2.4   | JAN              |                           |
|                                                   | $\pi_C$ | 20    | $\lambda_{AC}$   |                          |
| Transformer                                       | $\lambda_0$ | 0.012 | 70°C             | 0.672                     |
|                                                   | $\pi_Q$ | 8.0   | MIL-T-27         |                           |
|                                                   | $\pi_E$ | 7.0   | $\lambda_{AC}$   |                          |
| Optical Couple                                    | $\lambda_0$ | 0.0040 | MIL-S-19500       |                           |
|                                                   | $\pi_T$ | 3.4   | 70°C             | 0.19584                   |
|                                                   | $\pi_Q$ | 2.4   | JAN              |                           |
|                                                   | $\pi_E$ | 6.0   | $\lambda_{AC}$   |                          |

is calculated, as shown in Table 4. The Aluminum electrolytic capacitor is limited in airborne environment because of its sealing capacity, so its failure rate is higher, reaching $11.284 \times 10^{-6}/h$. And the contactor and relay device has a large environmental coefficient because of its mechanical structure, and the failure rate is as high as $10.5 \times 10^{-6}/h$.

In order to improve the reliability of each functional module and reduce the failure rate of each part, we should first consider reducing the number of these two kinds of components with high failure rate. In addition, because the environmental coefficient, $\lambda_{AC}$, of the Aluminum electrolytic capacitor is higher, up to 28, the Tantalum electrolytic capacitor is relatively low, which is 14, and the solid Tantalum electrolytic capacitor can be reduced to 12, but the cost of Tantalum is higher than that of Aluminum. Therefore, within the cost allowed, Aluminum electrolytic capacitor can be replaced by Tantalum electrolytic capacitor. In this way, the operating failure rate can be reduced by almost half.

The working principle of the contactor and the relay is the same, that is, the coil is electrified, the moving iron core moves under the action of the electromagnetic force, the moving contact is driven by the action of the moving contact, so that the normally closed contact is separated and the frequently opened contact is closed. The difference is that the contactor can pass through a relatively large current, mainly used to control the main circuit on and off. The relay can pass through a relatively small current, generally used to transmit signals, mostly used in the control circuit. They all belong to the mechanical class, the environment coefficient,

TABLE 5. The reliability prediction of the 18-pulse rectifier power supply by using part stress analysis method.

| Functional Unit | Types          | $\lambda_p (10^{-6}/h)$ | Quant. N | $N_{CA} (10^{5}/h)$ | $\lambda_{biox} (10^{-6}/h)$ |
|-----------------|----------------|--------------------------|----------|----------------------|-------------------------------|
| Inductor        | 0.0552         | 4                        | 0.2208   |                      |                               |
| Capacitor       | 0.13728        | 12                       | 1.64736  |                      |                               |
| Resistor        | 0.095          | 3                        | 0.285    |                      |                               |
| Contactant      | 0.004352       | 1                        | 0.004352 |                      |                               |
| Contactant      | 10.5           | 1                        | 10.5     |                      |                               |
| Relay           | 10.5           | 1                        | 10.5     |                      |                               |
| Diode           | 0.106704       | 1                        | 0.106704 |                      |                               |
| Resistor        | 0.095          | 3                        | 0.285    |                      |                               |
| Transformer     | 0.672          | 1                        | 0.672    |                      |                               |
| Diode           | 0.106704       | 3                        | 0.320112 |                      | 0.992112                     |
| Capacitor       | 0.13728        | 1                        | 0.13728  |                      |                               |
| Capacitor       | 11.284         | 1                        | 11.284   |                      |                               |
| Resistor        | 0.095          | 1                        | 0.095    |                      |                               |
| Connector       | 0.004352       | 1                        | 0.004352 |                      |                               |
| Transformer     | 0.672          | 1                        | 0.672    |                      |                               |
| Capacitor       | 0.13728        | 7                        | 0.96096  |                      |                               |
| Resistor        | 0.095          | 23                       | 2.185    |                      |                               |
| Fault Detection | 0.106704       | 11                       | 1.173744 | 5.975256             |
| Optical Couple  | 0.19584        | 5                        | 0.9792   |                      |                               |
| Connector       | 0.004352       | 1                        | 0.004352 |                      |                               |

Total operating failure rate (10^{-6}/h) 42.87112
TABLE 6. The failure mode and effect analysis of the several components.

| Types of Components | Failure Mode       | Failure Mode Freq, Ratio α (%) | Effect Analysis                                      | Effect on Rectifier Power Supply |
|---------------------|--------------------|-------------------------------|------------------------------------------------------|---------------------------------|
| Contactor K201 λ_p=10.5 | Contact broken     | 14.8                          | Contactor failure, abnormal input of rectifier circuit | No output                       |
|                     | Contact bonded     | 7.4                           |                                                      | No output                       |
|                     | Coil short or open | 22.2                          |                                                      | No output                       |
|                     | Lead wire broken   | 7.4                           |                                                      | No output                       |
|                     | Contactor bias     | 11.1                          | Contactor failure, parameter drift of rectifier circuit | No effect                       |
|                     | Parameter drift    | 37.1                          |                                                      | No effect                       |
| Relay K202 λ_p=10.5 | Contact broken     | 14.8                          |                                                      | No load                         |
|                     | Contact bonded     | 7.4                           |                                                      | No load                         |
|                     | Coil short or open | 22.2                          | Relay failure, loss of soft-start function           | No load                         |
|                     | Lead wire broken   | 7.4                           |                                                      | No load                         |
|                     | Contactor bias     | 11.1                          |                                                      | No load                         |
|                     | Parameter drift    | 37.1                          | Relay failure, parameter drift of soft-start circuit  | No effect                       |
| Capacitor C401 λ_p=11.284 | Short circuit     | 53.0                          | Capacitor failure, output short circuit              | No output                       |
|                     | Open circuit       | 35.0                          |                                                      | No effect                       |
|                     | Electrolyte leakage| 10.0                          | Capacitor failure, loss of output filter function    | No effect                       |
|                     | Capacity reduction | 2.0                           |                                                      | No effect                       |

AUC, is higher, up to 21. Consideration could be given to replacing contactors and relays with electronic switches with relatively small environmental coefficients.

The total failure rate for each functional module is summarized in Table 5. The failure rates of P1 to P6 modules are 2.157512, 21.391704, 0.992112, 11.438552, 0.915984, and 5.975256 × 10^{-6}/h, respectively. The total failure rate of the power supply is the sum of the failure rates of each functional module, that is, 42.87112 × 10^{-6}/h. The MTBF value analyzed by part stress analysis method is \( \frac{1}{\lambda_{p\text{--total}}} = 23326 \) h.

From the above calculation process, it can be seen that the parts count method takes less time, and the calculation method is simple but rough, which is used to judge whether the scheme meets the reliability index, to compare the optimal design scheme and to carry out reliability distribution. The part stress analysis method is quite complex, and it takes a long time to predict, which is closer to the actual situation of components. However, the reliability weakness of the power supply can be found out by stress analysis, so as to take corresponding measures to improve the design. The prediction process of the two methods is one thick and the other fine, so the calculation results may differ greatly.

Fig. 5 shows the comparison of the operating failure rates calculated by the parts count method and the part stress analysis method. It can be seen that the working failure rate calculated by the part stress analysis method is 42.87112/32.994 = 1.30 times that calculated by the parts count method. That is because the part stress analysis method provides more parameters of the influencing factors, while the parts count method requires fewer factors.

The MTBF values calculated by the two methods were 30309 h and 23326 h, respectively. Considering that there are some errors in the data sources used in the parameter estimation of the component prediction model in the MIL-HDBK-217F, according to the engineering experience, we set the design margin of MTBF to 1.5 times of the target, in order to ensure the accuracy of the reliability prediction. The MTBF of the power supply is \( \frac{23326}{1.5} = 15550 \) h > 15000 h, which meets the requirement of a MTBF ≥ 15000 h for the power supply system.
C. FAILURE MODE AND EFFECT ANALYSIS

From the above analysis, it can be seen that the whole working reliability of the rectifier power supply mainly depends on the soft-start circuit P2 and the output filter circuit P4. The components with higher failure rate in these two parts are the contactor K201 and the relay K202 for soft-start function, as well as the electrolytic capacitor C401 for output filtering. According to the probability importance of Birnbaum, the failure mode and effect of these parts with high failure rate are analyzed, as shown in Table 6. When improving the system, we should first consider these parts with greater importance to improve, so as to achieve the best effect with the minimum human, material and financial resources.

The main function of the rectifier power supply is to get DC output of 270V by rectifying AC 115V. From the analysis of failure mode, there are two main factors that lead to no output of the rectifier power supply. One is the contactor K201 failure, that is, contact broken, contact bonded, coil short or open, lead wire broken and so on. The sum of the frequency ratio of failure is 14.8% + 7.4% + 22.2% + 7.4% = 51.8%. The second is the failure of electrolytic capacitance C401, that is, short circuit mode. The frequency ratio of failure is 53.0%. Other failure modes have no effect on the output of the whole main circuit. The operating failure rate of the rectified power supply without output is 10.5 × 51.8% + 11.281 × 53.0% = 11.41793 × 10⁻⁶/h. The influence factors of other components with lower working failure rate are ignored here.

In addition, the relay K202 of contact broken, contact bonded, coil short or open, lead wire broken and contactor bias failure modes will lead to the loss of soft-start function, so that the rectifier power supply cannot work with normal load. The sum of the frequency ratio of failure is 14.8% + 7.4% + 22.2% + 7.4% + 11.1% = 62.9%. The operating failure rate of the rectified power supply that cannot be operated with the load is 10.5 × 62.9% = 6.6045 × 10⁻⁷/h. The FMEA is helpful for the later fault tree analysis (FTA) and importance analysis of the power supply.

IV. CONCLUSION

Due to the complexity of component types and operating environment, the current reliability prediction still has many shortcomings, such as not fully considering all factors affecting product reliability, not fully reflecting the impact of new devices and new processes on reliability. However, these shortcomings do not obliterate the importance of reliability prediction in evaluating the reliability level of products and in preventing, detecting and correcting defects in the design, manufacture and use of products. In this paper, the reliability model and prediction of the 18-pulse rectifier power supply are investigated. The reliability block diagram of the 18-pulse rectifier power supply is established, and its reliability data are predicted by parts count method and part stress analysis method. It is concluded that its MTBF value meets the requirement of 1.5 times of the reliability index, the failure mode and effect analysis of its weak links are carried out, and the corresponding improvement measures are put forward for the weak links, for example, selecting components with low environmental coefficient, selecting new electronic components with the same function, or using redundancy to improve the reliability of the system, etc. This is of guiding significance to the reliability growth of the 18-pulse rectifier power supply, and also has important theoretical and practical significance to the engineering application of multi-pulse rectifier power supply.

In addition, the FMEA of other components of the power supply need to be further studied in detail. According to these analysis, the failure mode and effect factors of the whole power supply are obtained, that is, FTA and importance analysis, is also of guiding significance to the risk management and control of the product.

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