An Effective Optimization of Reliability of Co-phase Power Supply Device

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Abstract— In this paper, the structure and principle of a kind of co-phase power supply system is proposed. The co-phase power supply devices based on two-level quadruple modular topology structure and three-level duplicate topology structure are studied and the former one is chosen as a computational example. According to the analysis of high power electronic elements in power system, a k/n(G) reliability model of the co-phase power supply device, based on two-level quadruple modular topology structure, is established. Then, the reliability of the co-phase power supply device is calculated. With the failure rate and Mean Time To Failures (MTTF) presented, the reliability of the co-phase power supply device is quantificationally evaluated. In order to promote the reliability of the device, two optimized schemes, which include increasing internal components of converter cells and increasing the standby branches of the device, are presented. Compared with the original scheme, the optimized schemes show the promotion of the reliability. Finally, to demonstrate, the computational method is adopted. The results agree well with the proposed schemes.

1. INTRODUCTION

There are many power quality problems existing in the traditional traction power supply system, such as unbalance, reactive power and harmonics to three-phase industrial grid [1, 2]. In [3, 4], the authors presented an advanced co-phase traction power supply system which can solve these power quality problems and improve the power quality greatly. [6] demonstrated the application of the back-to-back converter in active power compensation. The co-phase power supply device plays the key role of negative sequence compensation and harmonic suppression in the co-phase power supply system. As the core part of the system, its reliability index will directly affect the normal operation and application of the whole system. However, few studies have been done on the reliability of the co-phase power supply device or the whole system.

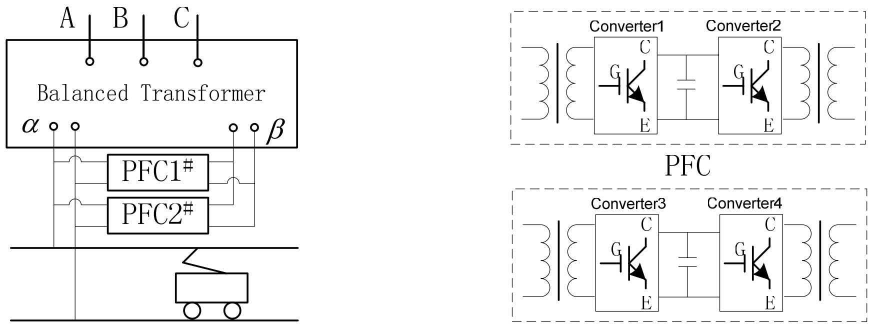
In this paper, the structure and principle of a kind of co-phase power supply system is proposed. A k/n(G) reliability model of the co-phase power supply device, based on two-level quadruple modular topology structure, is established. Then, the reliability of the co-phase power supply device is calculated. In order to promote the reliability of the device, two optimized schemes, which include increasing internal components of converter cells and increasing the standby branches of the device, are presented.

2. CO-PHASE POWER SUPPLY SYSTEM

Figure 1 shows the main structure of the co-phase power supply system. There are two co-phase power supply devices in this schemeand the capacity of each device is 5 MVA. When the traction load is under the traction condition, the port β of the traction transformer only output active power, which will flow into the contact line through the PFC1# and PFC2#, to supply power for the running electric train. The quantity of the active power output by port β is equal to half of the total traction load under the substation's power supply range. Meanwhile, in both co-phase power supply devices, the converters connected to the traction load will output reactive power to the load, which will make the power factor achieve the desired value. Then, the power needed in the hole feeding section of the traction substation will be supplied by port α, and the partition of the electrical phases in the traction substation exports can be canceled; As port α and port β only output active power equally, the high-voltage side of the traction transformer will be three-phase symmetrical, and the negative phase sequence current will be completely compensated. When the traction load is under the regenerative braking condition, the active power flows to the opposite direction, and the power fluxion of the other parts is similar to the traction condition.

3. CO-PHASE POWER SUPPLY DEVICE

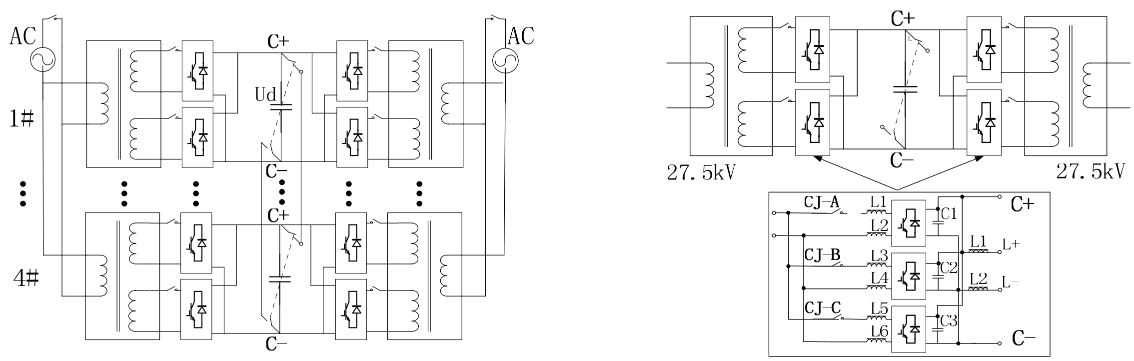
Figure 2(a) shows the inner structure of the co-phase power supply device based on two-level quadruple modular topology structure. This kind of device consists of four back-to-back converter



(a) (b)

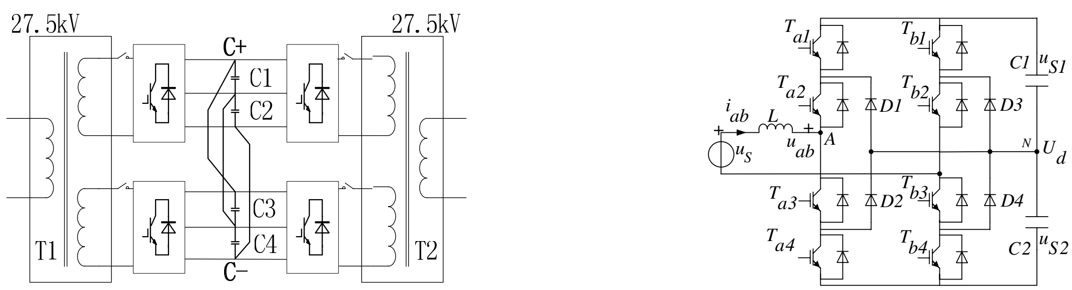
Figure 1: (a) Co-phase power supply system. (b) Co-phase power supply device.

branches which are connected to each other in parallel. Meanwhile, there are four converter cells in every back-to-back unit, and each converter cell consists of three single phase H bridges that are connected with each other in parallel. As the capacity of the whole device is 5 M·VA, every back-to-back converter branch's capacity will be 1.25 MV·A, and every converter's topology structure is shown in Figure 2(b).



(a) (b)

Figure 2: Co-phase power supply device based on two-level quadruple modular topology structure.



(a) (b)

Figure 3: Co-phase power supply device based on three-level duplicate modular topology structure.

The co-phase power supply device based on three-level duplicate topology structure is shown in Figure 3(a). In this scheme, there are two converter units and the capacity of each unit is 2.5 MV·A. Figure 3(b) shows the inner structure of each converter units.

4. RELIABILITY OF THE ORIGINAL SCHEME

The co-phase power supply device consists of many high power electronic elements, such as Insulated Gate Bipolar Transistor (IGBT), Freewheel Diode (D), The Secondary Filter Unit (LC), and Dc-link Capacity (C). According to the American military standard "MIL-HDBK-217F" and the Chinese military standard "GJB/Z 299C-2006", the failure rates and reliability of the high power electronic elements are estimated and their exact values are

$$\begin{cases} \lambda_{IGBT} = 187\,\mathrm{Fit} \\ \lambda_D = 128\,\mathrm{Fit} \\ \lambda_C = 295\,\mathrm{Fit} \\ \lambda_{LC} = 96\,\mathrm{Fit} \end{cases} \Rightarrow \begin{cases} R_{IGBT} = e^{-\lambda t} = e^{-187t} \\ R_D = e^{-\lambda t} = e^{-128t} \\ R_C = e^{-\lambda t} = e^{-295t} \\ R_{LC} = e^{-\lambda t} = e^{-96t} \end{cases} \tag{1}$$

Since many restricted factors such as engineering practice, capacity requirements and economic reasons exist, the IGBT's nominal parameter should be 3300 V/1600A, and the freewheel diode's nominal voltage should be 3000 V. As it is not allowed to make the reverse voltage of IGBT higher than the half of its nominal voltage, choose $U_d = 1800\,\mathrm{V}$ as the DC side voltage and $U_{N2} = 970\,\mathrm{V}$ as the low voltage winding nominal voltage. Then, the low voltage winding nominal current I_{N2}, the IGBT's maximum value current and the number of IGBT modules can be figured out:

$$I_{N2} = \frac{S_1}{U_{N2}} = \frac{1250}{0.97} = 1289A \quad I_1 = \frac{1600}{3} \approx 533A \quad I_{CJ} = \frac{1250}{U_d} = 694.4A \quad I_1 < I_{CJ} < 2I_1 \tag{2}$$

According to Figure 3 and the analysis above, the number of normal work IGBTs mustn't less than two in every three. Then, the 2/3(G) reliability model and the k/n(G) reliability model of the co-phase power supply device is built in Figure 4.

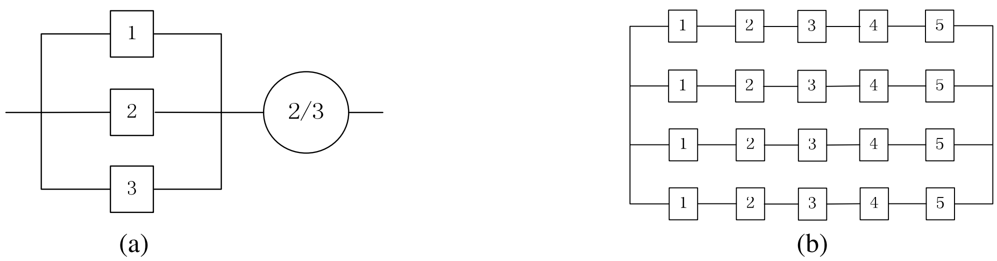


Figure 4: (a) 2/3(G) reliability model. (b) k/n(G) reliability model of the co-phase power supply device.

The reliability and MTTF of a converter unit are

$$R_1(2,3) = C_3^2 e^{-2\lambda t}\left(1 - e^{-\lambda t}\right) + C_3^3 e^{-3\lambda t} \quad T_{\mathrm{MTTF}_1} = \int_0^\infty R_1(t)\,dt \tag{3}$$

As Figure 4(b) shows, the four branches stand for the four converter branches, and every branch consists of four converter units and a DC capacitor.

The reliability and MTTF of a converter branch are

$$R_2 = \left[3e^{-2\lambda t}\left(1 - e^{-\lambda t}\right) + e^{-3\lambda t}\right]^4 \cdot e^{-\lambda_{\mathrm{C}} t} \quad T_{\mathrm{MTTF}_2} = \int_0^\infty R_2(t)\,dt \tag{4}$$

The reliability and MTTF of the device are

$$R_3 = \left[3e^{-2\lambda t}\left(1 - e^{-\lambda t}\right) + e^{-3\lambda t}\right]^{16} \cdot e^{-4\lambda_C t} \quad T_{\mathrm{MTTF}_3} = \int_0^\infty R_3(t)\,dt \tag{5}$$

5. RELIABILITY OF THE OPTIMIZED SCHEMES

Figure 5(a) shows the first optimized scheme based on increasing internal components of converter cells. Different with Figure 2(b), there are four converter cells in each converter unit, and the reliability model should be a 2/4(G) reliability model:

$$R_{11}(2,4) = C_4^2 e^{-2\lambda t}\left(1 - e^{-\lambda t}\right)^2 + C_4^3 e^{-3\lambda t}\left(1 - e^{-\lambda t}\right) + C_4^4 e^{-4\lambda t} \tag{6}$$

$$R_{31} = \left[6e^{-2\lambda t}\left(1 - e^{-\lambda t}\right)^2 + 4e^{-3\lambda t}\left(1 - e^{-\lambda t}\right) + e^{-4\lambda t}\right]^{16} \cdot e^{-4\lambda_{\mathrm{C}} t} \quad T_{\mathrm{MTTF}_{31}} = \int_0^\infty R_{31}(t)\,dt \tag{7}$$

Meanwhile, Figure 5(b) shows the second optimized scheme which is based on increasing the standby branches of the device. Compared with the original scheme shown in Figure 2(a), there are

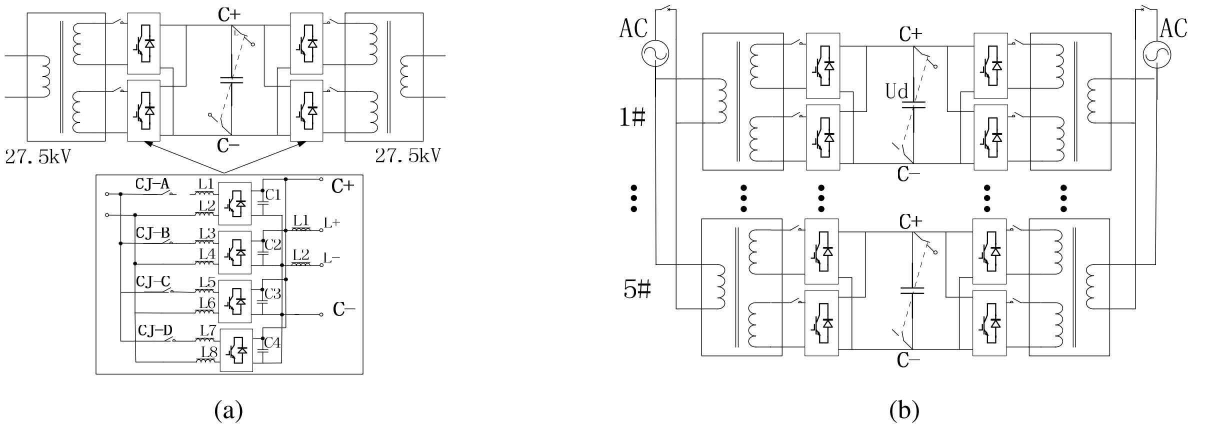


Figure 5: (a) The optimized scheme which is based on increasing internal components of converter cells. (b) The optimized scheme based on increasing the standby branches of the device.

five converter branches in the device. According to Eq. (4) the following equations can be achieved as

$$R_{32}(4,5) = C_5^4 R_2^4 (1 - R_2) + C_5^5 R_2^5 \tag{8}$$

$$R_{32}(4,5) = 5\left[3e^{-2\lambda t}\left(1 - e^{-\lambda t}\right) + e^{-3\lambda t}\right]^{16} \cdot e^{-4\lambda_{\mathrm{C}} t} - 4\left[3e^{-2\lambda t}\left(1 - e^{-\lambda t}\right) + e^{-3\lambda t}\right]^{20} \cdot e^{-5\lambda_{\mathrm{C}} t} \tag{9}$$

Substituting Eq. (1) into Eq. (5), Eq. (7) and Eq. (9), the MTTF of the devices with optimized schemes and the device with original scheme can be achieved. Table 1 shows the comparison of the MTTF between the three schemes and the comparison of the reliability curves is given in Figure 6.

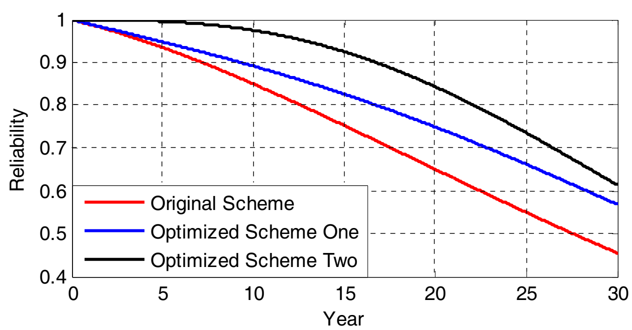


Figure 6: Reliability curves of three schemes.

Table 1: The MTTFs of different schemes.

Scheme	Original Scheme	The first Optimized Schemes	The second Optimized Scheme
MTTF/Year	23.8790	41.2477	36.6070

6. CONCLUSION

In this paper, the structure and principle of a kind of co-phase power supply system is proposed. Then, a k/n(G) reliability model of the co-phase power supply device, based on two-level quadruple modular topology structure, is established. Furthermore, two optimized schemes are proposed to promote the reliability of the device. Finally, the computational results are adopted to demonstrate the validity of the proposed optimized schemes.

ACKNOWLEDGMENT

This work is supported by the key Project supported by the Joint Funds of the National Natural Science Foundation of China (Grant No. U1134205), and the National Natural Science Foundation of China (Grant No. 51307143).

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