IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received January 4, 2019, accepted January 27, 2019, date of publication February 4, 2019, date of current version March 1, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2897125

Engineering Application Research of Aircraft Power Supply Characteristics Based on 18-Pulse Rectifier Power System

YINGYING ZHANG[1], (Member, IEEE), XIAOLI ZHANG[1], (Student Member, IEEE), ZHIWEI CHEN[1], (Member, IEEE), BING LI[1], (Member, IEEE), AND YIGANG HE[2], (Member, IEEE)

[1]School of Electrical Engineering and Automation, Hefei University of Technology, Hefei 230009, China
[2]School of Electrical Engineering, Wuhan University, Wuhan 430072, China

Corresponding authors: Yingying Zhang (zhangyy@hfut.edu.cn) and Yigang He (yghe1221@whu.edu.cn)

This work was supported in part by the National Natural Science Foundation of China under Grant 51577046, in part by the State Key Program of the 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.

ABSTRACT The low-harmonic and high-power density multi-pulse autotransformer has many advantages, such as simple structure, high reliability, high efficiency, strong overload ability, and so on. Therefore, it has a broad application prospect in aviation field. The multi-pulse rectifier power system is more and more widely used in aerospace. However, there are many practical engineering problems of the aircraft power supply characteristics that are difficult to predict. In this paper, the aircraft power supply characteristics of the rectified power system with 18-pulse autotransformer rectifier are simulated and investigated. According to the handbook MIL-HDBK-704-3, the performance of the power supply in the normal, abnormal, and fault state is verified and tested in detail. The research and discussion are carried out from six aspects: the load measurement, the steady-state limits, the voltage phase difference, the voltage transient, the frequency transient, and the power failure. The system can meet the requirements of the U.S. military standard MIL-STD-704A for the aircraft power supply characteristics. It has been applied to the radar power supply system of a large transporter, and the conformance verification test of the aircraft power supply characteristics has been completed, which provides the practical application basis for the engineering realization of the multi-pulse rectifier power supply in the radar power supply system. It also provides a reference for the development of the power supply system for other aircraft.

INDEX TERMS Power supplies, power system, reliability engineering, radar.

I. INTRODUCTION

Among the majority of the current popular switching power supply, its front input rectifier part can be seen to be frequently using the traditional uncontrolled diode rectifier circuit. Because of its non-linear characteristics, the input current on the network side will be distorted and the harmonic content is large, which will reduce the electromagnetic compatibility of the equipment and bring harm to the power grid and other power equipment. As the power of the switching power supply equipment increases, the harmonics produced by the uncontrolled rectifier are more serious. For example, the output voltage of a three-phase uncontrolled rectifier circuit has six wave heads in a single alternating current (AC) cycle. The output voltage is rich in low-order harmonics, which is not easy to filter, and the input current also injects abundant current harmonics into the public power network. It also pollutes the public grid. In the field of high-power rectifier, multi-pulse rectifier technology is generally used to reduce harmonic content [1], [2].

Due to its small size and light weight, multi-pulse rectifier has become a constant choice of on-board equipment for multi-power aircraft and all-electric aircraft. And with the increasing demand for equipment, the research on multi-pulse

The associate editor coordinating the review of this manuscript and approving it for publication was Tariq Masood.

rectifier is of practical value and practical significance [3]–[5]. Multi-pulse rectifier is constructed by phase-shifting transformer with different turn-to-turn ratio transform and winding connection to obtain voltage vectors with different phases. Different voltage vectors get current vectors of different phases via the rectifier bridge, and they are superimposed on the network side so that the current on the grid side becomes a step-wave current in phase with the corresponding voltage, which realized the function of power factor correction and harmonic suppression. When the number of steps of the synthesized current waveform increases, that is, the number of voltage vectors with different phases increases, and the number of current steps on the network side increases, the more sinusoidal the current waveform tends to be, the smaller the total harmonic distortion (THD) is.

Multi-pulse rectifiers are usually composed of phase-shifting transformers and multiple rectifying bridges. Three-phase input and multi-phase output to several three-phase rectifier bridges are realized by transformer phase shift. The combination of three-phase rectifier circuits makes the harmonics generated by one three-phase rectifier circuit counteract the harmonics generated by other three-phase rectifier circuits. The multi-pulse rectifier has two advantages: one is to reduce the harmonic content in the AC input current, the other is to reduce the ripple in the direct current (DC) output voltage [6].

The multi-pulse rectifiers can be divided into 6-pulse, 12-pulse, 18-pulse, and 24-pulse rectifier according to the number of rectified pulses. The more pulse number, the better the input current and output voltage characteristics of the rectifier, the more complex the rectifier's coefficient, and the more rectifying units required. The theoretical calculation of current harmonics for multi-pulse rectifiers has been extensively studied [7]–[14]. The theoretical values of current harmonics of the 6-pulse, the 12-pulse, the 18-pulse and the 24-pulse rectifiers are 31.1%, 15.2%, 10.1% and 6.8%, respectively. The military standard MIL-STD-704A requires a harmonic index of less than 8%. It can be seen that although the 24-pulse rectifier meets the requirements of the military standard, its structure is more complex than that of the 18-pulse, the process is difficult to realize, and its reliability of practical application is not high compared with that of the 18-pulse. The 18-pulse rectifier has better rectifying characteristic than the 12-pulse rectifier, the harmonic theory value is closer to the requirement of military standard, the structure process is simpler and easier to realize than the 24-pulse rectifier, and the cost is relatively low. Therefore, the 18-pulse rectifier has been widely used at present in aviation industry. However, some practical engineering application problems still exist and need to be solved.

The aircraft power supply characteristic standard is not only essential for aircraft electrical system design, but also an interface standard for aircraft power supply system and electrical equipment. It is the norm to be implemented in the process of development, production, procurement, acceptance, use, maintenance and repair. It is the basis for the inspection and acceptance of technical coordination at home and abroad and the introduction of equipment. Regards to the standard of aircraft power supply characteristic, many countries have issued standards, such as Russia standard ΓOCT19705-89 ''the general requirements for planes and helicopters power supply system and power quality regulations'' [15], China military standard GJB181-86 ''the aircraft power supply characteristics and the requirements of electrical equipment'' [16] and the United States (U.S.) military standard MIL-STD-704 ''characteristics and utilization of electric, power, aircraft'' [17]. Among these standards, the U.S. military standard MIL-STD-704 has the most international universality and authority.

The MIL-HDBK-704 series manual, ''guidance for test procedures for demonstration of utilization equipment compliance to aircraft electrical power characteristics'' [18], is a guided technical manual issued by the U.S. Department of Defense in April 2004. The purpose of the manual deals with the provisions of this series of manuals before the electrical equipment is installed, to verify the conformance of electrical equipment with MIL-STD-704 standard, so as to coordinate the work between the equipment and the aircraft power supply system. The MIL-HDBK-704 series manual on the compliance verification of electrical equipment is discussed in accordance with seven types of power supply types specified in the MIL-STD-704 series standards. These seven types are the single-phase 115 V/400 Hz AC, the three-phase 115 V/400 Hz AC, the single-phase 115 V frequency conversion AC, the three-phase 115 V frequency conversion AC, the single-phase 115 V/60 Hz AC, the 270 VDC and the 28 VDC power supply types. The MIL-HDBK-704 series standards are discussed separately for the five operating states of the aircraft power supply system. These five working states are normal working state, abnormal working state, emergency working state, engine starting and fault working state.

The reliability and stability of aircraft power supply are directly related to the reliability of airborne electrical and electronic equipment, and even to flight safety [19], [20]. Especially, the multi-electric civil aviation aircraft, represented by B787, has been put into operation, and the pneumatic and partial hydraulic systems have been eliminated, which has greatly increased the power consumption and equipment used on board. It has become clear whether the characteristics of the aircraft's airborne power supply system meets the requirements is the key to ensure safe flight. Therefore, the design of the aircraft power system must conform to the standard at home and abroad.

The performance and quality of aircraft power supply system impact significantly on the overall performance of aircraft. In addition to the power capacity index, the aircraft power supply system should meet the requirements of the onboard electrical equipment, and it should also have the power supply characteristics which meet the prescribed requirements under various working conditions of the aircraft, including the steady-state, transient performance of the power supply, conversion performance and system compatibility. To conclude, the characteristics of the power supply system should not only provide strict regulations for the generation system and distribution system, but also have corresponding limitations on the power equipment.

With the development of aviation industry and the continuous improvement of aircraft performance, a large number of high performance power electronic equipment are installed and used one after another. The application of these power electronic loads puts forward new requirements for the power supply capacity and power supply quality of aircraft power supply system. Thus, in the development of new aircraft and the improvement of active aircraft, the power supply characteristics of aircraft grid must be strictly tested [21], [22].

There are many researches on the theoretical calculation and simulation model of 18-pulse rectifier power system, and certain achievements have been made [23]–[25]. P. S. Oliveira *et al.* presented a Web application proposal to simulate and design 18-pulses rectifiers, which uses Wye and Delta differentials autotransformer connections. B. Singh *et al.* studied and simulated the AC-DC converter model based on the 18-pulse autotransformer, and improved its harmonic index. Y. Zhang *et al.* applied the 18-pulse rectifier power system to the radar power system of a large airborne transport aircraft, making the harmonics below 7% and meeting the requirements of its environmental test. However, the practical engineering application of 18-pulse power supply is still a very important topic. Whether it can meet the requirements of aircraft power supply characteristic is also a key indicator. Under various working conditions, whether the requirements of the parameters of electrical energy parameters such as voltage, frequency, waveform, phase and so on are always within the prescribed range? Can this power supply withstand the limit requirements of transient and conversion of aircraft states? Under extreme conditions, does the power supply have no effect on other electrical equipment? These urgent engineering problems are of practical value to the engineering application of the multi-pulses, and can also be used for reference in the distribution systems of other systems.

In this paper, the aircraft power supply characteristics of the rectified power supply with 18-pulse autotransformer rectifier are investigated and discussed thoroughly. The performance of the power supply in normal, abnormal and fault state is verified and tested in detail. The results show that, the system meets the test conditions of MIL-HDBK-704. On top of that, the system has been applied to the radar power supply system of a large transporter, and the conformance verification test of the aircraft power supply characteristics has been completed, which provides the practical application basis for the engineering realization of the 18-pulse rectifier power system in the radar power supply system. It also provides reference for the development of power supply system for other aircraft.

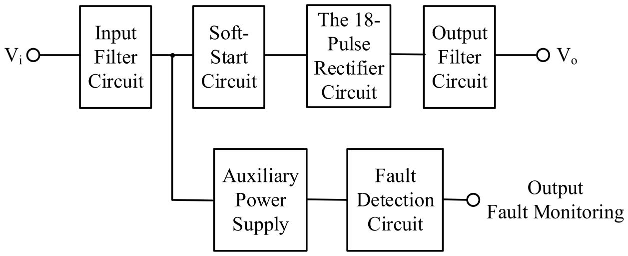


FIGURE 1. Circuit diagram of the 18-pulse rectifier power system. It adopts a modular design and consists of six parts.

II. EXPERIMENT CONDITION OF 18-PULSE RECTIFIER POWER SYSTEM

The 18-pulse rectifier power system adopts a modular design, as shown in Figure 1, it consists of six parts: the input filter circuit, the soft-start circuit, the 18-pulse rectifier circuit, the output filter circuit, the auxiliary power supply, and the fault detection circuit [25].

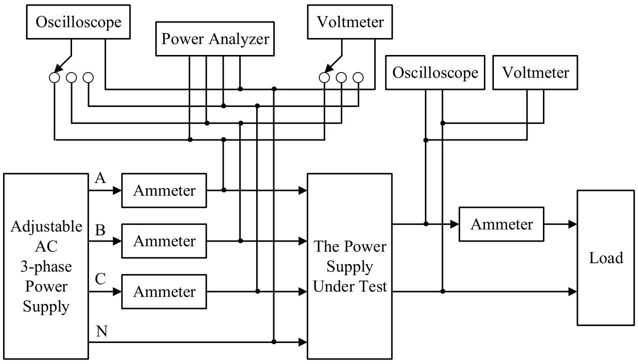


FIGURE 2. Experimental test block diagram of the 18-pulse rectifier power system for aircraft power supply characteristics.

Figure 2 shows the experimental test block diagram of the 18-pulse rectifier power system for aircraft power supply characteristics. The adjustable AC three-phase power supply is used to provide AC power. The voltmeter and ammeter are used to monitor the voltage and current, respectively. The power analyzer is used to measure the input voltage and current wave, power, power factor (PF), and other parameters. The oscilloscope is used to monitor the voltage and current wave. The experimental testing field, as shown in Figure 3, presented in this paper, consists of the power supply under test, the adjustable AC three-phase power supply, the power analyzer, the oscilloscope and the linear load. The voltmeter and ammeter are not shown.

Table 1 lists the experimental test items for aircraft power supply characteristics according to the handbook MIL-HDBK-704-3 [26]. It includes the load measurement, the steady-state limits for voltage and frequency, the voltage phase difference, the voltage transients, the frequency transients and the power failure.

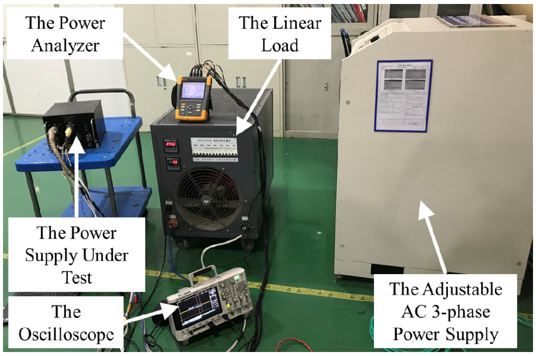


FIGURE 3. Photograph of the experimental testing filed. The linear load used here is a resistive load. The voltmeter and ammeter are not shown.

TABLE 1. Experimental test items for aircraft power supply characteristics.

Test Items	Description
1	Load Measurement
2	Steady State Limits
3	Voltage Phase Difference
4	Voltage Transients
5	Frequency Transients
6	Power Failure

III. SIMULATION AND EXPERIMENTAL RESULTS FOR AIRCRAFT POWER SUPPLY CHARACTERISTICS

The 18-pulse rectifier power system under test has been simulated in a MATLAB environment along with the Simulation toolbox according to Figure 1. The characteristics of aircraft power supply for the 18-pulse rectifier power system are simulated and experimented from six aspects according to Table 1.

A. LOAD MEASUREMENT

The load measurement is designed to verify whether the three-phase input power is balanced and is the power factor within the prescribed range in the case of the rated input voltage, the rated input frequency, and the rated output power. According to the requirement of MIL-STD-704A, when the output power of the system is 11 kW, the maximum unbalanced power is 650 VA, and the minimum power factor limit is 0.95.

The simulation results of the load measurement under the condition of the rated input phase voltage of AC 115 V, the rated input frequency of 400 Hz and the rated output power of 11 kW can be seen Figure 4. Figure 4(a) and (b) give the input phase voltage and current waveform, respectively. It is shown that the input voltage and the current are almost in phase, and the waveform is almost sinusoidal. The voltage and current of Phase A, Phase B, and Phase C are different in sequence by 120 degrees. Figure 4(c) shows the output voltage and current waveform. It can be seen that the output voltage and current are constant. The output voltage is about 275.50 V and the output current is 41.74 A, which is consistent with the rated output power of 11 kW.

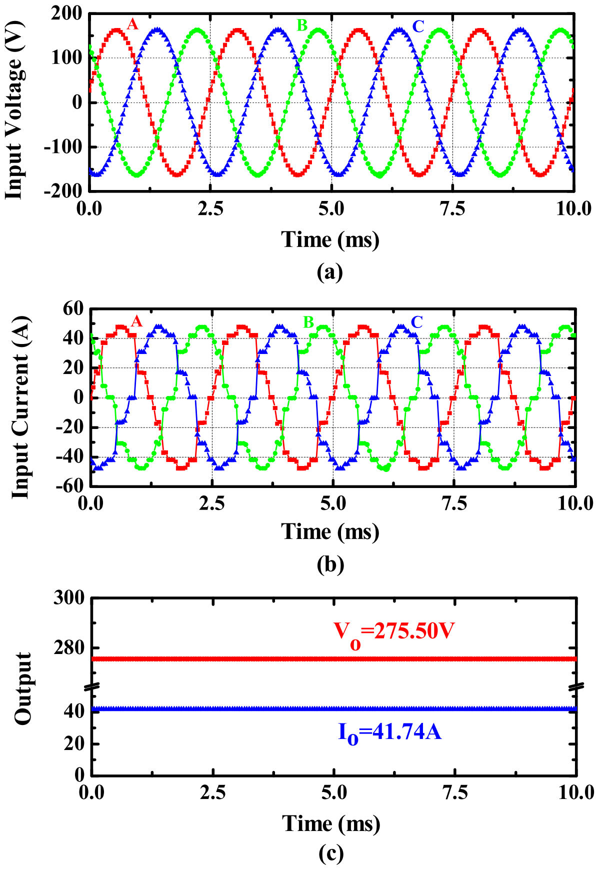


FIGURE 4. The simulation results of the load measurement at the rated input phase voltage of AC 115 V, input frequency of 400 Hz and output power of 11 kW. (a) Input phase voltage waveform. (b) Input phase current waveform. (c) Output voltage and current waveform.

TABLE 2. Summary of simulation and experimental results for balanced load and power factor.

Items	Simulation Results			Experimental Results		
	A	B	C	A	B	C
U (V_{rms})	115.5	115.5	115.5	113.1	112.8	113.5
I (A_{rms})	34.20	33.93	34.04	33.97	34.33	34.56
P (W)	3895	3868	3873	3819	3849	3895
S (VA)	3950	3919	3932	3842	3872	3923
PF	0.986	0.987	0.985	0.994	0.994	0.993
Maximum Unbalance (VA)		31			81	

Table 2 presents the summary of simulation and experimental results for the balanced load and power factor. The maximum unbalance power of simulation and experiment is 31 and 81 VA, respectively. The power factor of simulation and experiment is 0.986 and 0.994, respectively. Because the simulation components are more ideal than the actual ones, the simulation results are slightly smaller than the actual test results, but they all meet the maximum unbalanced 650 VA and the limit of 0.95 power factor required by the MIL-STD-704A standard.

B. STEADY STATE LIMITS FOR VOLTAGE AND FREQUENCY

The steady state limits for voltage and frequency is used to verify that the system operates and maintains specified performance when the input voltage and input frequency vary within a specified limit. According to the requirement of MIL-STD-704A, the steady state input voltage range is 108 V ∼ 118 V, and the steady state input frequency range is 380 Hz ∼ 420 Hz. During the test, the system can continuously work for no less than thirty minutes.

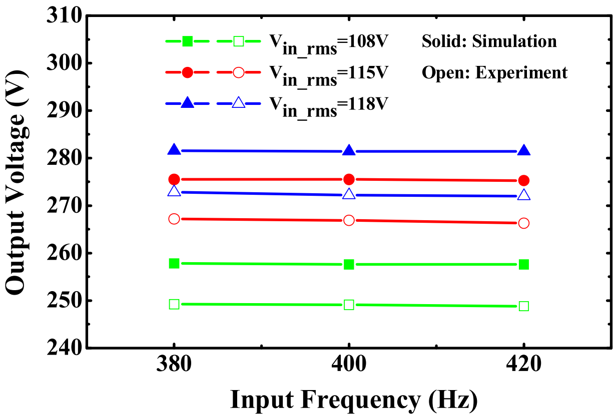
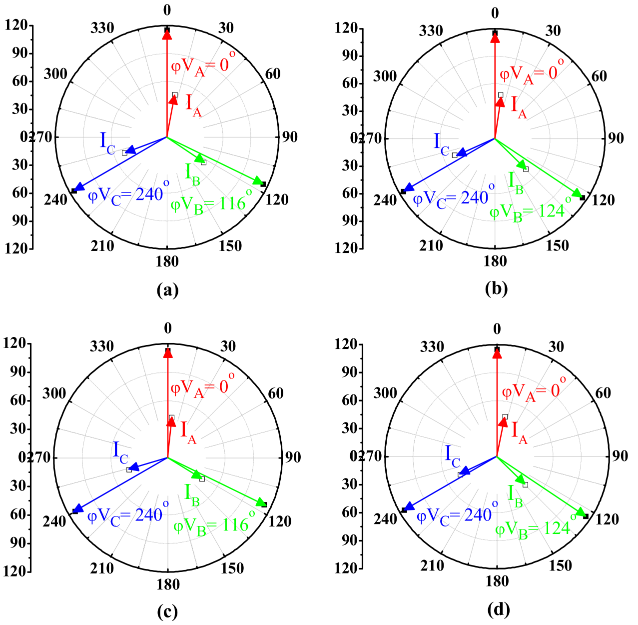


FIGURE 5. **The simulation and experimental results of the output voltage within the limits of steady-state input voltage and input frequency.**

Figure 5 shows the simulation and experimental results of the output voltage within the limits of steady state input voltage and input frequency. It can be seen that the simulation results are consistent with the experimental results. The system can still work stably within the specified performance by varying the input voltage and frequency. When the input frequency is constant, the higher the input voltage, the higher the output voltage through the rectifier. When the input voltage is constant, the output voltage does not change obviously with the input frequency. The output voltage of the experimental results is a little lower than that of the simulation because of the imperfect voltage drop of the components in the actual circuit.

C. VOLTAGE PHASE DIFFERENCE

The voltage phase difference is designed to verify whether the system will work properly when the phase angle of the input voltage changes within the limits. According to the requirements of MIL-STD-704A, the phase angle of input voltage ranges from 116° to 124°. When the phase angle of the input voltage changes, the system can continuously work for no less than thirty minutes.



(a)

(b)

(c)

(d)

FIGURE 6. **The simulation and experimental results of input voltage phase difference. (a) Simulation: V_{an} 0°, V_{bn} 116°, V_{cn} 240°. (b) Simulation: V_{an} 0°, V_{bn} 124°, V_{cn} 240°. (c) Experiment: V_{an} 0°, V_{bn} 116°, V_{cn} 240°. (d) Experiment: V_{an} 0°, V_{bn} 124°, V_{cn} 240°.**

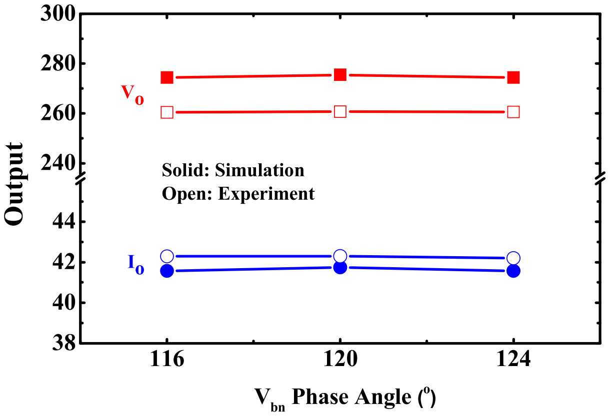


FIGURE 7. **The simulation and experimental results of output voltage and current for the input voltage phase difference when the phase B angle of input voltage ranges from 116° to 124°.**

The simulation and experimental results of the voltage phase difference at the rated input phase voltage of AC 115 V, input frequency of 400 Hz and output power of 11 kW are shown in Figure 6. Figure 6(a) and (b) show the simulation results of input voltage and current when phase B is 116° and 124°, respectively. Figure 6(c) and (d) show the experimental results of input voltage and current when phase B is 116° and 124°, respectively. The simulation and experimental results of output voltage and current for voltage phase difference are shown in Figure 7. It can be seen that the simulation results are consistent with the experimental results. When the phase shifts, the input current lags several degrees of the input voltage, which is related to the load in the system. And the output voltage and the output current are almost unchanged. That is to say, when the phase angle of the input voltage changes within the limits, the output of the system is almost invariable, and it can run normally for no less than thirty minutes, which can meet the requirement of MIL-STD-704A.

D. VOLTAGE TRANSIENTS

The voltage transient is to verify whether the system can meet the requirements when the input voltage of the system changes normally or abnormally. According to the requirements of MIL-STD-704A, the voltage transients include normal voltage transients and abnormal voltage transients. The transients include the over-voltage and the under-voltage. The test conditions for voltage transients are shown in Table 3. The items 1-2 are for over-voltage transients and the items 3-4 are for under-voltage transients. The items 1 and 3 are for normal voltage transients, the items 2 and 4 are for abnormal voltage transients. When the input voltage of the system is transient, the system can not only damage itself, but also can not affect other equipment.

TABLE 3. **Test conditions for voltage transients.**

Items	T_1	V_T	T_D	T_2
1	<1.25 msec	160 Vrms	50 msec	<1.25 msec
2	<1.25 msec	180 Vrms	100 msec	<1.25 msec
3	<1.25 msec	58 Vrms	50 msec	<1.25 msec
4	<1.25 msec	45 Vrms	100 msec	<1.25 msec

Note: T_1 is the time from the steady state voltage to the voltage transient level; V_T is the voltage transient level; T_D is the duration time at the voltage transient level; T_2 is the time from the voltage transient level to the steady state voltage.

In order to ensure the normal operation of the system during the voltage transient, the system should consider broadening the input voltage range of the DC/DC converter circuit at the back of the rectifier circuit, that is, the fluctuation of the output of the rectifier power supply is still within the range of the input voltage required by the later stage, so that the output of the whole system can be kept stable.

Figure 8 and 9 show the simulation and experiment results for normal and abnormal voltage transients at the rated input phase voltage of AC 115 V and output power of 11 kW, respectively. The duration time at normal and abnormal voltage transient level is 50 and 100 msec, respectively. It can be seen that there is also a transient in the output voltage during the input voltage transient, but when the transient voltage returns to normal, the output voltage can also recover the normal output.

E. FREQUENCY TRANSIENTS

The frequency transient is to verify whether the system can meet the requirements when the input frequency of the system changes normally or abnormally. According to the requirements of MIL-STD-704A, the frequency transients include normal frequency transients and abnormal frequency transients. The transients include the over-frequency and the under-frequency. The test conditions for frequency transients are shown in Table 4. The items 1-2 are for over-frequency transients and the items 3-4 are for under-frequency transients. When the input frequency of the system is transient, the system can not only damage itself, but also can not affect other equipment.

In order to make the system meet the requirements of operation in the case of frequency transient, the design allowance of the 18-pulse transformer at low frequency should be fully considered in the design to avoid saturation of the transformer at low frequency. Figure 10 shows the simulation and experiment results of the input and output voltage for the frequency transient under item 1, and the results of the

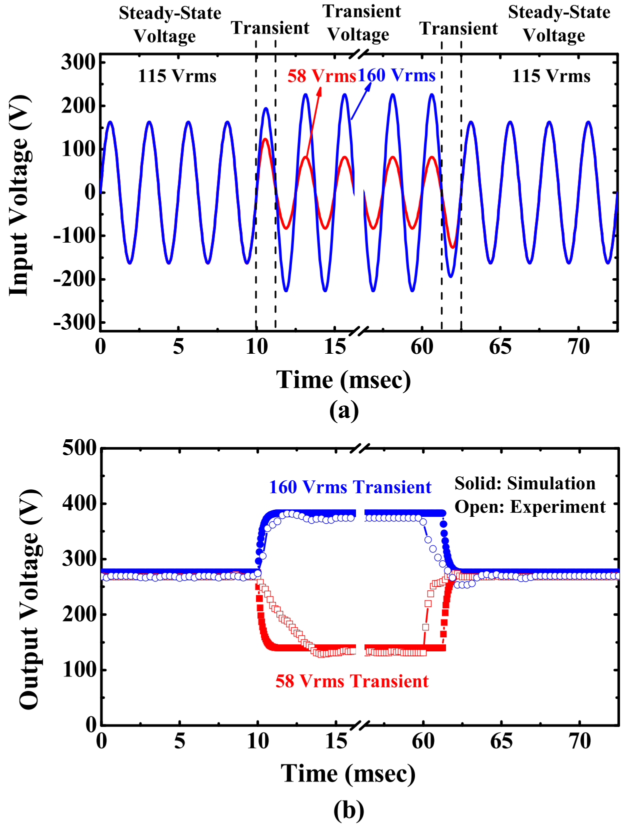
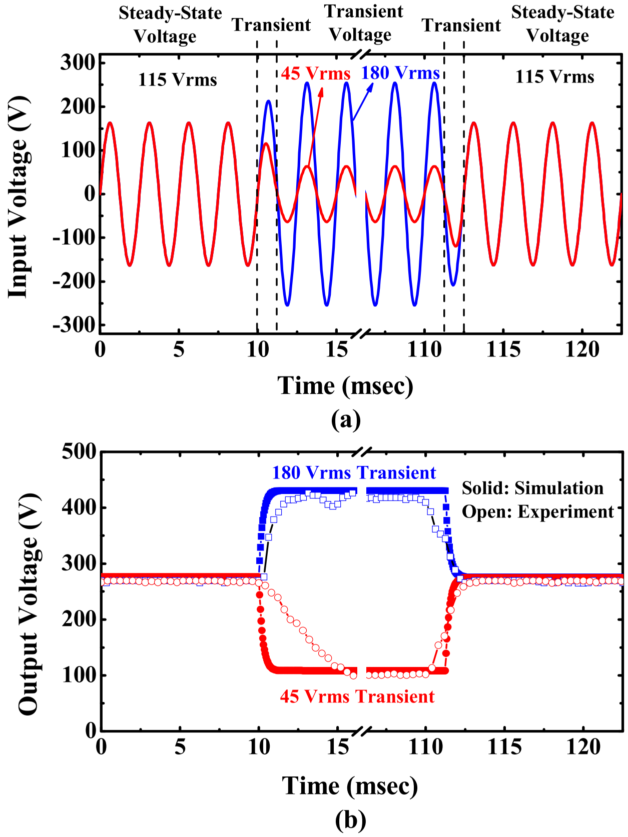


FIGURE 8. **The simulation and experiment results for normal voltage transients. (a) The input voltage waveform diagram for voltage transient. (b) The output voltage waveform.**

TABLE 4. **Test conditions for frequency transients.**

Items	T_1	F_T	T_D	T_2
1	200 msec	450 Hz	1/2 cycle	200 msec
2	333 msec	480 Hz	1/2 cycle	60 msec
3	200 msec	350 Hz	1/2 cycle	200 msec
4	333 msec	320 Hz	1/2 cycle	60 msec

Note: T_1 is the time from the steady state frequency to the frequency transient level; F_T is the frequency transient level; T_D is the duration time at the frequency transient level; T_2 is the time from the frequency transient level to the steady state frequency.



(a)

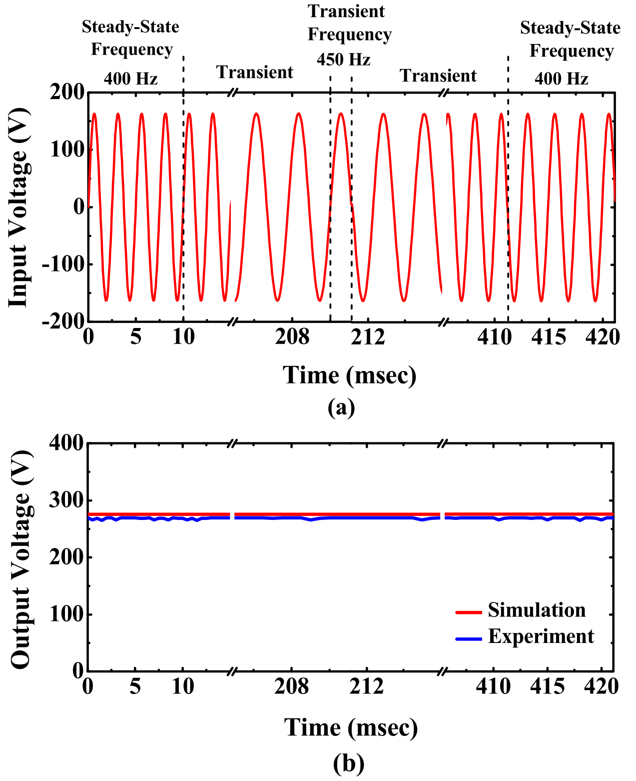
(b)

FIGURE 9. **The simulation and experiment results for abnormal voltage transients. (a) The input voltage waveform diagram for voltage transient. (b) The output voltage waveform.**

tests under other items are consistent. As can be seen from Figure 10(b), when the frequency changes, the output voltage hardly changes. This is because 18-pulse transformer has been fully considered in the design of the design allowance, the output voltage will not change, but when the frequency changes, the transformer noise will be affected. The higher the frequency, the greater the noise. However, the noise is within the scope of the system control, which can meet the use requirements.

F. POWER FAILURE

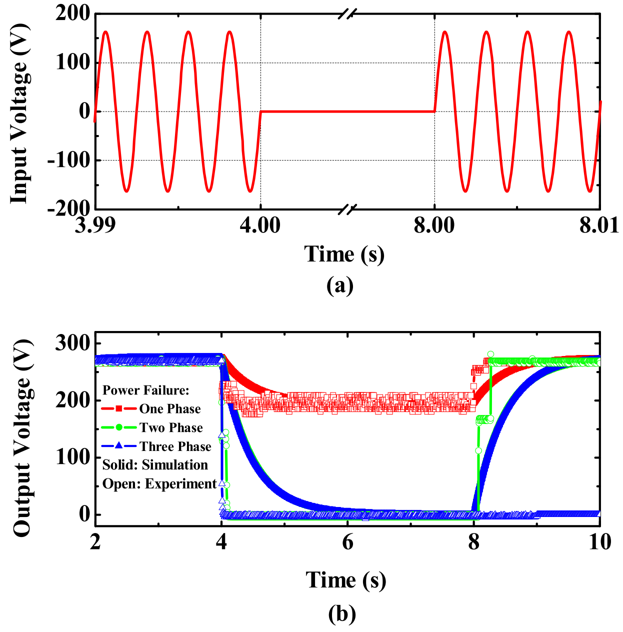
The power failure test is used to verify whether the system can meet the operational requirements when the input one phase, two phase or three phase failure. According to the requirements of MIL-STD-704A, the power failure includes one phase power failure, two phase power failure and three phase failure. When the power supply fails, the system not only can't damage itself, but also can't affect other equipment.



(a)

(b)

FIGURE 10. **The simulation and experiment results of 450 Hz frequent transients at the rated input phase voltage of AC 115 V and output power of 11 kW. (a) The input voltage waveform diagram for frequency transient. (b) The output voltage waveform.**



(a)

(b)

FIGURE 11. **The simulation and experiment results of power failure. (a) The input voltage waveform for power failure (only one phase is shown). The failure time is set to 4 s. (b) The output voltage waveform for power failure.**

The simulation and experiment results are shown in Figure 11. Figure 11(a) shows the input voltage waveform when the power fails. The normal working state is at the rated input phase voltage of AC 115 V, input frequency of 400 Hz and output power of 11 kW. The power failure time is set to 4 s. From the output voltage waveform shown in Figure 11(b), it can be seen that the output voltage drops to about 193 V when a phase failure occurs. When two-phase or three-phase failure occurs, the output voltage drops to 0 V. This is because the 18-pulse autotransformer still has a coupled input voltage when one of the phases is not input. However, when two or three phases are not input, the coupling loop is absent. When the power failure time is shortened or extended, the simulation results are consistent.

In order to make the system meet the requirements of power failure, the output under-voltage protection circuit is generally designed in the system. The output under-voltage point is set according to the system requirements. When the output reaches the under-voltage point, the output enters into the protection state until the above fault disappears, and when the boot control instruction is re-sent, the system returns to normal output. When the input one or two phase failure, the input power recovery, the output can automatically return to normal. However, when the three phases fail at the same time, the rectifier power supply cannot automatically return to normal because it does not have an initial starting power supply, so the power supply needs to be re-turned on before the normal output can be achieved.

IV. CONCLUSION

It is crucial to ensure the overall performance of the aircraft whether the power supply system of the aircraft has the power supply characteristics satisfying all the requirements under various working conditions. In this paper, the aircraft power supply characteristics are simulated and verified for rectifier power supply with the 18-pulse autotransformer. According to the handbook MIL-HDBK-704-3, the research and discussion are carried out from six aspects of the load measurement, the steady state limits, the voltage phase difference, the voltage transient, the frequency transient and the power failure. The performance of the power supply under normal, abnormal and fault conditions is simulated and tested in detail. The system meets the criteria of MIL-STD-704A aircraft power supply characteristics. The conformance verification test of power supply characteristics has been completed on a large transport aircraft. The research results of this paper proves to promote the engineering application of 18-pulse rectifier technology in radar power system and provide reference for the development of other aircraft power supply systems. But at the same time, the reliability and electromagnetic compatibility of the whole machine are also very important, which is the next step of our work.

REFERENCES

[1] B. Singh, S. Gairola, B. N. Singh, A. Chandra, and K. Al-Haddad, "Multipulse AC–DC converters for improving power quality: A review," *IEEE Trans. Power Electron.*, vol. 23, no. 1, pp. 260–281, Jan. 2008.

[2] T. Yang, S. Bozhko, and G. Asher, "Functional modeling of symmetrical multipulse autotransformer rectifier units for aerospace applications," *IEEE Trans. Power Electron.*, vol. 30, no. 9, pp. 4704–4713, Sep. 2015.

[3] M. M. Swamy, "An electronically isolated 12-pulse autotransformer rectification scheme to improve input power factor and lower harmonic distortion in variable-frequency drives," *IEEE Trans. Ind. Electron.*, vol. 51, no. 5, pp. 3986–3994, Sep./Oct. 2015.

[4] S. Vidyasagar, R. Kalpana, B. Singh, and P. P. Saravana, "Improvement in harmonic reduction of a zigzag autoconnected transformer based 12-pulse diode bridge rectifier by current injection at DC side," *IEEE Trans. Ind. Appl.*, vol. 53, no. 6, pp. 5634–5644, Nov./Dec. 2017.

[5] R. C. Fernandes, P. da Silva Oliveira, and F. J. M. de Seixas, "A family of autoconnected transformers for 12- and 18-pulse converters–generalization for delta and wye topologies," *IEEE Trans. Power Electron.*, vol. 26, no. 7, pp. 2065–2078, Jul. 2011.

[6] D. A. Paice, *Power Electronic Converter Harmonics: Multipulse Methods for clean Power*. Hoboken, NJ, USA: Wiley, 1996.

[7] A. Panchbhai, Y. R. Patel, and N. Prajapati, "Simulation and hardware of multi-pulse rectifier for more electric aircraft," in *Proc. IEEE 7th Power India Int. Conf.*, Nov. 2016, pp. 1–6.

[8] A. Panchbhai, N. Prajapati, and S. Parmar, "Harmonic mitigation in AC motor using multi-pulse rectifier," in *Proc. IEEE Int. WIE Conf. Elect. Comput. Eng.*, Dec. 2016, pp. 1–4.

[9] H. S. Krishnamoorthy and S. Yerra, "Solid state auto-transformer concept for multi-pulse rectifiers," in *Proc. IEEE Appl. Power Electron. Conf. Expo.*, Mar. 2018, pp. 2362–2367.

[10] B. J. McRee, D. A. Wetz, D. A. Dodson, J. M. Heinzel, and Q. Dong, "Model validation of multi-pulse rectifiers for charging capacitors," in *Proc. IEEE Electr. Ship Technol. Symp.*, Aug. 2017, pp. 367–371.

[11] S. Khan *et al.*, "A novel 24-pulse rectification system," *IEEE Access*, vol. 6, pp. 59350–59361, Oct. 2018.

[12] R. Kalpana, K. S. Chethana, S. Prakash, and B. Singh, "Power quality enhancement using current injection technique in a Zigzag configured autotransformer-based 12-pulse rectifier," *IEEE Trans. Ind. Appl.*, vol. 54, no. 5, pp. 5267–5277, Sep./Oct. 2018.

[13] R. Abdollahi, "A simple harmonic reduction method in 20-pulse AC–DC converter," *J. Circuits Syst. Comput.*, vol. 28, no. 1, Jan. 2019, Art. no. 1950013.

[14] R. Abdollahi and G. B. Gharehpetian, "Inclusive design and implementation of novel 40-pulse AC–DC converter for retrofit applications and harmonic mitigation," *IEEE Trans. Ind. Electron.*, vol. 63, no. 2, pp. 667–677, Feb. 2016.

[15] *The General Requirements for Planes and Helicopters Power Supply System and Power Quality Regulations*, Russia Military, Standard 19705-89, 1989.

[16] *The Aircraft Power Supply Characteristics and the Requirements of Electrical Equipment*, China Military, Standard GJB181-86, 1986.

[17] *Characteristics and Utilization of Electric Power*, Aircraft, US Military Standard MIL-STD-704A, 1966.

[18] *Guidance for Test Procedures for Demonstration of Utilization Equipment Compliance to Aircraft Electrical Power Characteristics*, Standard MIL-HDBK-704, 2004.

[19] H. Nademi, R. Burgos, and Z. Soghomonian, "Power quality characteristics of a multilevel current source with optimal predictive scheme from more-electric-aircraft perspective," *IEEE Trans. Veh. Technol.*, vol. 67, no. 1, pp. 160–170, Jan. 2018.

[20] B. Sarlioglu and C. T. Morris, "More electric aircraft: Review, challenges, and opportunities for commercial transport aircraft," *IEEE Trans. Transp. Electrific.*, vol. 1, no. 1, pp. 54–64, Jun. 2015.

[21] B. Li *et al.*, "Modeling and simulation of aircraft power supply system based on Dymola and modelica," in *Proc. Int. Conf. Elect. Syst. Aircr., Railway, Ship Propuls. Road Vehicles Int. Transp. Electrific. Conf.*, Nov. 2016, pp. 1–6.

[22] J. Brombach, M. Jordan, F. Grumm, and D. Schulz, "Influence of small constant-power-loads on the power supply system of an aircraft," in *Proc. Int. Conf. Workshop Compat. Power Electron.*, Jun. 2013, pp. 97–102.

[23] P. S. Oliveira, S. C. L. Freitas, T. M. Silva, and F. J. M. Seixas, "Multitrafo-app: Web app for project of 18-pulses rectifiers with differential transformer connections," in *Proc. 17th Int. Conf. Harmon. Qual. Power (ICHQP)*, Oct. 2016, pp. 640–645.

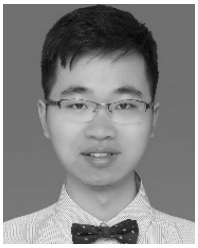
[24] B. Singh, G. Bhuvaneswari, and V. Garg, "A novel polygon based 18-pulse AC-DC converter for vector controlled induction motor drives," *IEEE Trans. Power Electron.*, vol. 22, no. 2, pp. 488–497, Mar. 2007.

[25] Y. Zhang, Z. Chen, B. Li, and Y. He, "Application of low harmonic 18-pulse rectifier power supply for radar power system," *IEEE Trans. Ind. Electron.*, vol. 66, no. 2, pp. 1080–1088, Feb. 2019.

[26] *Guidance for Test Procedures for Demonstration of Utilization Equipment Compliance to Aircraft Electrical Power Characteristics Three Phase, 400Hz, 115Volt (Part 3 of 8 Parts)*, Standard MIL-HDBK-704-3, 2004.

YINGYING ZHANG (M'07) was born in Hubei, China, in 1980. She received the B.S. degree in electronic information engineering from the Department of Electrical and Electronic Engineering, Hubei University of Technology, Wuhan, Hubei, in 2002, and the Ph.D. degree in semiconductors and circuits from the Department of Electronics Engineering, Chungnam National University, Daejeon, South Korea, in 2010.

From 2002 to 2004 and from 2011 to 2017, she was with ECU Electronics Industrial Company, Ltd., China. She is currently a Professor with the School of Electrical Engineering and Automation, Hefei University of Technology, China. Her main research interests include power supply and distribution systems, power quality analysis and control technology, harmonic detection and suppression technology, and reliability prediction and evaluation.



XIAOLI ZHANG was born in Henan, China, in 1989. He received the B.S. degree in agricultural electrification from the Agricultural Equipment Engineering College, Henan University of Science and Technology, Luoyang, Henan, in 2018. He is currently pursuing the master's degree with the School of Electrical and Automation Engineering, Hefei University of Technology, Hefei, China. His current research interests include energy system design of stratospheric airship, and stratospheric airship energy management and control.

ZHIWEI CHEN (M'14) was born in Anhui, China, in 1988. He received the B.S. degree in measurement and control technology and instrumentation from the Liaoning Institute of Science and Technology, in 2012, and the Ph.D. degree in electrical engineering from the Shenyang University of Technology, in 2017.

He is currently a Lecturer with the School of Electrical and Automation Engineering, Hefei University of Technology. His research interests include engineering electromagnetic field electromagnetic compatibility and permanent magnetic medical actuators.

BING LI (M'06) received the B.Eng. degree in automobile engineering from Chongqing Science and Technology University, Chongqing, China, in 1995, and the M.Sc. and Ph.D. degrees in electrical engineering from Hunan University, Changsha, China, in 2006 and 2011, respectively, where he has been a Postdoctoral Researcher and Visiting Scholar with the College of Electrical and Information Engineering, since 2011.

He has been an Associate Professor with the School of Electrical Engineering and Automation, Hefei University of Technology, Hefei, China, since 2013. His current research interests include smart grid, WSNs, and signal processing.

YIGANG HE (M'92) was born in Hunan, China, in 1966. He received the M.Sc. degree in electrical engineering from Hunan University, Changsha, China, in 1992, and the Ph.D. degree in electrical engineering from Xi'an Jiaotong University, Xi'an, China, in 1996.

In 1990, he joined the College of Electrical and Information Engineering, Hunan University, where he was the Director of the Institute of Testing Technology for Circuits and Systems, from 2006 to 2011. He was a Senior Visiting Scholar with the University of Hertfordshire, Hatfield, U.K., in 2002. From 2011 to 2017, he was the Head of the School of Electrical Engineering and Automation, Hefei University of Technology. He is currently the Vice-Head of the School of Electrical Engineering, Wuhan University. His current research interests include testing and fault diagnosis of analog and mixed-signal circuits, electrical signal detection, smart grids, satellite communication monitoring, and intelligent signal processing.

• • •