DYNAMIC PERFORMANCE ANALYSIS AND WEIGHTED-BASED FAULT DIAGNOSIS SCHEME FOR AIRCRAFT ELECTRIC POWER SYSTEM

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Abstract

The electric power system is an important part of the aircraft, which plays the role of providing electrical energy for integrated electrical equipment. The quality of the aircraft power system directly affects the reliability of the electrical equipment and flight safety. In this paper, the dynamic performance analysis of electric power system under disturbances of generators is considered. In addition, a weighted-based fault diagnosis strategy is presented to achieve accurate fault locating for the aircraft. Finally, extensive simulation and experimental results are further provided to confirm the validity and effectiveness of the proposed dynamic performance analysis and fault diagnosis scheme for the aircraft electric power system.
Keywords: Dynamic performance, Fault diagnosis, Aircraft electric power system, Generator.

1. Introduction

Over the past 20 years, the development of high power electronic technology and high power density electronic machinery bring a great change in aerospace [1-3]. Advanced electric power systems can be used to replace complex mechanical systems, which greatly improve performance and maintainability and simultaneously reduce weight and cost of the aircraft [4-6]. In addition, in order to overcome environmental concerns and reduce aircraft operating cost, the concept of More Electric Aircraft (MEA) has been presented to increase the use of electrical power [7-9]. In a MEA, mechanical transmission systems include air starting system, environmental control system, wing anti-icing system, braking system and flight control system are replaced by electrically driven system, which further improve the maintainability and reliability of the aircraft and decrease operation and maintenance costs [7-12].

Low voltage DC power supply system and constant frequency AC power supply system have been widely used in Aircraft Electric Power System (AEPS). With the increase of load power demand, the high voltage direct current (HVDC) power supply system has been widely accepted [10-15]. HVDC power supply system has the advantages of large capacity, light weight, high efficiency, simplified ground maintenance, high reliability and favorable electromagnetic compatibility performance. The HVDC power supply system has been used in advanced military aircrafts, such as F-22, F-35 and RAH-66 [10-15]. Although 230V wide frequency AC voltage is used in Boeing B787, amounts of Auto Transformer Rectifier Units (ATRU) are needed to convert AC voltage to 270V HVDC [10-17]. HVDC power supply has become the main direction of more electric aircraft power system development. In a MEA, the higher electrical power is required and HVDC power supply system can provide greater power capacity to meet the increasing load power demand.

In addition, the HVDC power supply system simplifies the difficulty in designing the speed-regulating motor, Electro-Mechanical Actuator (EMA) and Electro-Hydrostatic Actuator (EHA) [7-12]. Furthermore, the higher efficiency and lighter weight of the HVDC power supply system can reduce energy consumption and pollution emissions. Moreover, aircrafts are usually equipped with multiple engines, generators and auxiliary power unit (APU), which makes it possible to increase the power capacity of the power system to meet the demand of high power loads, such as laser weapon.
With the increase of aircraft electrical equipment, the power quality of HVDC needs to be improved and the output power of the generator needs to be increased to meet the power supply demand of the electrical equipment [13-15]. Therefore, it is crucial to analyze dynamic performance of the aircraft electric power system and further ensure the flight safety.
In this paper, the dynamic performance analysis and weighted-based fault diagnosis scheme for aircraft electric power system is proposed in this paper. The rest of this paper is organized as follows. In Section 2, the review of the typical structure of aircraft power system is presented. The dynamic performance analysis and weighted-based fault diagnosis strategy of the aircraft is proposed in Section 3. In section 4 and 5, the simulation and experimental results are presented, which verifies the correctness and effectiveness of the proposed fault diagnosis scheme for the aircraft. Finally, the concluding remarks are given in Section 6.

2. Review of Aircraft Power System

The power system is an important part of the aircraft electric power system, which consists of power generation, power conversion and power distribution, as shown in Fig. 1. The aircraft power supply system can start the engine on the ground, provide power for the various electrical loads, manage the power supply of the electrical equipment and provide emergency power for the aircraft, etc. [10-15]. Therefore, the reliability of aircraft power supply system is directly related to the stability of the electrical equipment and flight safety.

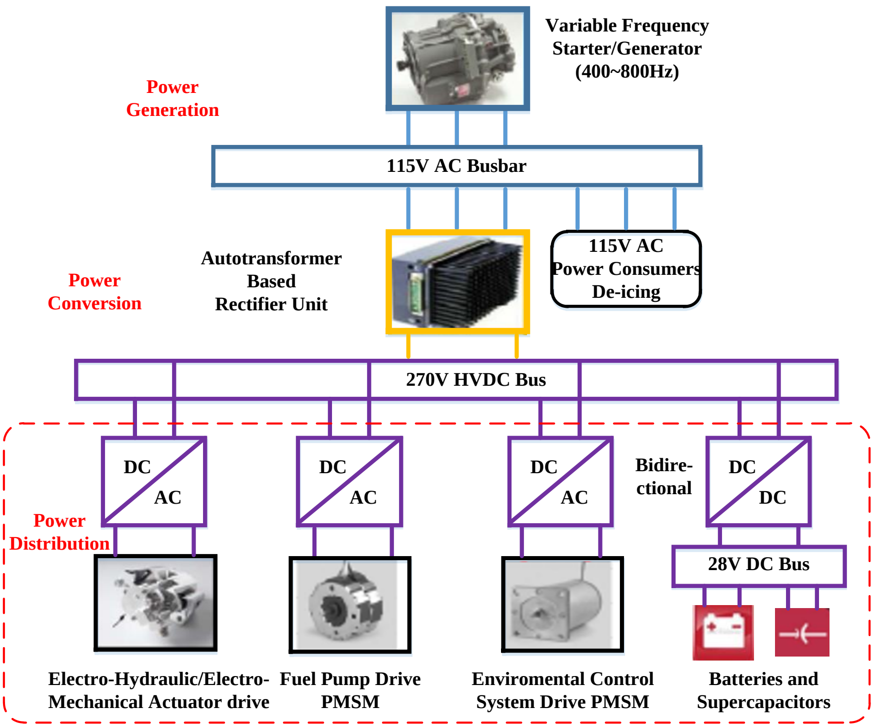


Figure1–Typical structure of an aircraft power system.

As shown in Fig.1，the distributed DC voltage in this architecture is provided by the ATRU that convert the variable frequency voltage of the generator output to 270V DC voltage, and the 28V DC voltage is provided through DC/DC converters. Making coupling between the main source and the storage devices is easier in this architecture. Moreover, a dc system needs only two cables to transport power, which decreases the number of power converters and the required cable insulation. Note that the most important problems in this architecture are safety and system failures, which can be caused by corona effects and insulation breakdown. Therefore, the power quality and stability issues must be considered of the aircraft power system.

3. Dynamic Performance Analysis and Fault Diagnosis Scheme for AEPS

This section presents the dynamic performance analysis and weighted-based fault diagnosis scheme for aircraft electric power system. It is crucial to analyze the output voltage under the steady state, transfer operation and transient of aircraft electric power system.

The dynamic performance analysis method of aircraft power system mainly includes data receiving, signal conditioning, data acquisition and analysis of voltage and current signals, and the accurate numerical signal of the measured physical quantity can be obtained. The detailed dynamic analysis algorithm can be divided into the root mean square, steady-state amplitude, voltage unbalance, modulation amplitude and voltage distortion factor. And then the calculated data can be further used in the weighted-based fault diagnosis scheme to analyze the reliability and stability of the aircraft power supply system in this paper.

3. 1 Root Mean Square Calculation

The root mean square (RMS) value of a set of values (or a continuous-time waveform) is the square root of the arithmetic mean (average) of the squares of the original values (or the square of the function that defines the continuous waveform), which is a statistical measure of the magnitude of a varying quantity in mathematics. The RMS of the voltage can be obtained as follows:

$$U_i = \sqrt{\frac{1}{m}\sum_{j=1}^{m} u_j^2} \tag{1}$$

where m is the total number of samples; j is the sampling sequence; u_j is the voltage transient value of the sampling point.

3.2 Steady-state AC Voltage Calculation

The sampling time is chosen the time including the maximum voltage cycles but less than 1s, and the steady-state AC voltage U_{ss} can be calculated as follows.

$$U_{ss} = \sqrt{\frac{1}{T_w}\sum_{i=1}^{m} u_i^2 \Delta t} \tag{2}$$

where T_w is the sampling time; m is the total number of samples; i is the sampling sequence; u_i is the voltage transient value of the sampling point; Δt is the sampling time interval.

3.3 Voltage Unbalance Calculation

Voltage unbalance is defined as the maximum difference between RMS phase voltage amplitudes at the utilization equipment terminals. The three-phase voltage unbalance value ΔU_{ABC} can be written as follows:

$$\Delta U_{ABC} = \max\left[\left|U_A - U_B\right|, \left|U_B - U_C\right|, \left|U_A - U_C\right|\right] \tag{3}$$

where U_A, U_B, U_C are the steady-state voltage of each phase of U_{ss}.

3.4 Modulation Amplitude of Voltage

Voltage modulation is the variation voltage during steady state electric system operation. Sources of voltage modulation may include (but are not limited to) voltage regulation stability of the power source, generator speed variations and load variations within utilization equipment. Voltage modulation amplitude is the difference between the maximum and minimum voltage values that occur in a one second period during steady state operating conditions. As for a AC voltage, the sampling time is chosen the time including the maximum voltage cycles but less than 1s. $U_{Ai(\max)}$, $U_{Bi(\max)}$, $U_{Ci(\max)}$ are represented by the maximum values of phase A, phase B and phase C, respectively. $U_{Ai(\min)}$, $U_{Bi(\min)}$, $U_{Ci(\min)}$ are represented by the minimum values of phase A, phase B and phase C, respectively. The modulation amplitude of the voltage U_{tg} can be further calculated as follows:

$$U_{tg} = \max\left[U_{Ai(\max)} - U_{Ai(\min)}, U_{Bi(\max)} - U_{Bi(\min)}, U_{Ci(\max)} - U_{Ci(\min)}\right] \tag{4}$$

3.5 Voltage Distortion Factor Calculation

The AC distortion factor is the ratio of the AC distortion to the RMS value of the fundamental component. The DC distortion factor is the ratio of the DC distortion to the DC steady state voltage. The voltage distortion is calculated as follows:

$$U_j = \sqrt{\frac{1}{T_w}\sum_{i=1}^{n} u_{ji}^2 \Delta t}, \quad k_j = \frac{U_i}{U} \tag{5}$$

where U_j is the distortion voltage, k_j is the distortion factor, U_i is voltage transient value at the sampling point, n is the total sampling number.

3.6 Discrete Fourier Transform

In the discrete signal processing method, the signal must be discrete both in time/space domain and in frequency domain. Using Discrete Time Fourier Transform (DTFT), the discrete time signal can be transformed into continuous frequency signal in analysis domain. Therefore, the continuous periodic spectrum can be used by discrete signal processors directly.

For a complex periodic signal $x(t)$ can be decomposed into the sum of sine and cosine curves of different categories by DTFT as follows:

$$x(t) = a_0 + \sum_{n=1}^{\infty}\left(a_n \cos n\omega t + b_n \sin n\omega t\right) = a_0 + \sum_{n=1}^{\infty} A_n \sin\left(n\omega t + \Phi n\right) \tag{6}$$

where

$$A_n = \sqrt{a_n^2 + b_n^2}, \quad \Phi_n = tg^{-1}\frac{a_n}{b_n} \tag{7}$$

where A_n is the frequency spectrum in Fourier series and Φ_n is the phase Angle.

Considering $\omega t = x$ and $\omega T = 2\pi$, and the following equation can be obtained:

$$X(x) = a_0 + \sum_{n=1}^{\infty} (a_n \cos nx + b_n \sin nx) \tag{8}$$

where

$$a_n = \frac{1}{\pi} \int_0^{2\pi} X(x) \cos nx \,,\; b_n = \frac{1}{\pi} \int_0^{2\pi} X(x) \sin nx \tag{9}$$

Divide T into N equal parts, and set ΔT=T/N=1 and $t_k=k\Delta t$ (k=0,1,2...N), set ω_1T=2π=$\omega_1 N$, and the following equation can be obtained:

$$a_0 = \frac{1}{N} \sum_{k=0}^{N-1} x(t_k) = \overline{x} \,, a_n = \frac{2}{N} \sum_{k=0}^{N-1} \left(x(t_k) \left(\cos\left(\frac{2\pi nk}{N}\right)\right)\right) , b_n = \frac{2}{N} \sum_{k=0}^{N-1} \left(x(t_k) \left(\sin\left(\frac{2\pi nk}{N}\right)\right)\right) \tag{10}$$

where n= 1, 2, 3... N/2.

In addition, the RMS, Steady-state amplitude, voltage unbalance, modulation amplitude, voltage distortion factor can be further calculated and analyzed by the weighted-based fault diagnosis strategy.

3.7 Weighted-Based Fault Diagnosis Scheme

A weighted-based fault diagnosis algorithm is presented for the aircraft electric power system, as shown in Fig. 10. Hall sensors are used to collect voltage and current signals, and these continuous signals are transformed into discrete signals by DTFT. In addition, root mean square, steady-state amplitude, unbalance value, modulation amplitude and distortion factor of the voltage and current can be calculated.

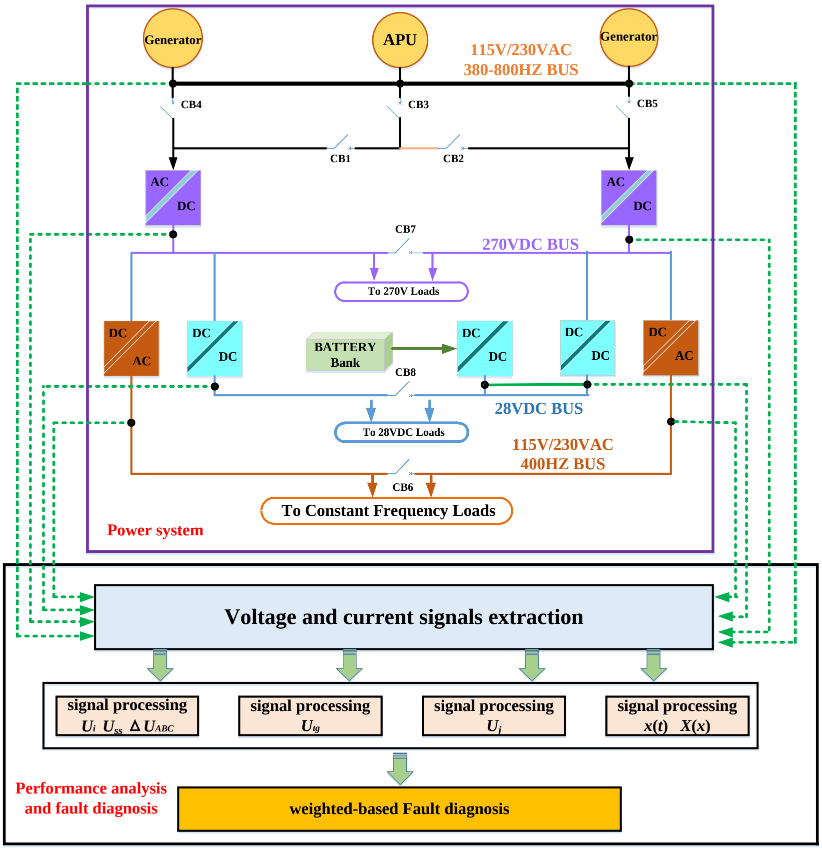


Figure2–Block diagram of the aircraft power system including the weighted-based fault diagnosis.

The weighted-based fault diagnosis algorithm can be used to analyze the dynamic performance of the power system, which can be written as follows:

$$F\left[f(t)\right]=\lambda\sum_{i=1}^{k}\omega_i f_{si}(t)+(1-\lambda)\sum_{j=k+1}^{n-k}\omega_j f_{tj}(t) \tag{11}$$

where $F[f(t)]$ is the objective function in the fault diagnosis algorithm, ω_i and ω_j are weight coefficients, voltage and current as real functions of time in steady-state and transient are represented by $f_{si}(t)$ and $f_{tj}(t)$, respectively.

In the steady-state, the following equation is used.

$$\sum_{i=1}^{k}\omega_i=1,\ \sum_{j=k+1}^{n-k}\omega_j=0 \tag{12}$$

In the transient, the following equations are considered in fault diagnosis algorithm.

$$\sum_{i=1}^{k}\omega_i+\sum_{j=k+1}^{n-k}\omega_j=1,\ \sum_{i=1}^{k}\omega_i>\sum_{j=k+1}^{n-k}\omega_j \tag{13}$$

To conclude, the dynamic performance analysis technology is mainly to convert analog voltage and current signals into digital signals by Discrete Fourier Transform, and calculate the root mean square, steady-state amplitude, voltage unbalance, modulation amplitude and voltage distortion factor. Moreover, the steady state, transfer operation and transient performance of aircraft power system is considered in the weighted-based fault diagnosis algorithm, which is more suitable to analyze the dynamic performance and achieve accurate fault diagnosis of the aircraft power system.

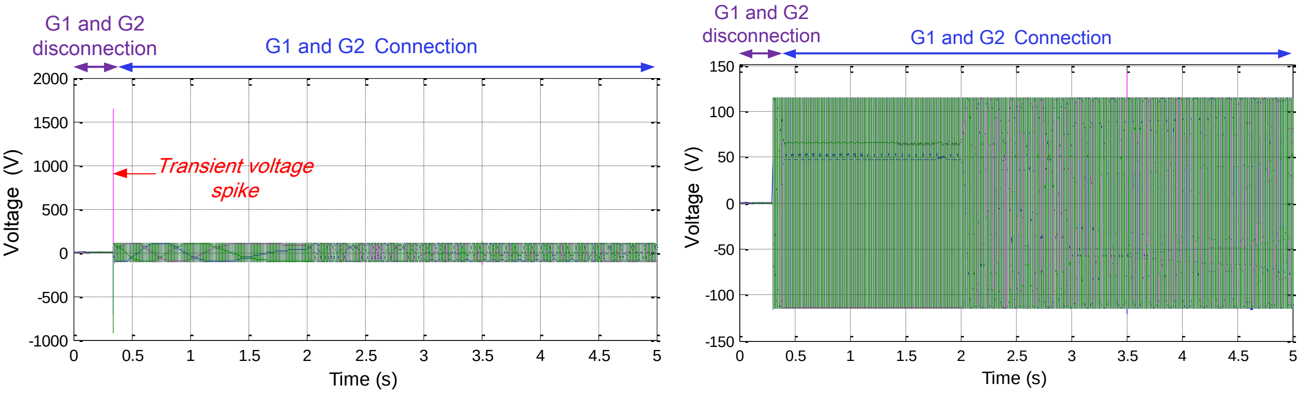
4. Simulation Results

This section presents the dynamic performance analysis and weighted-based fault diagnosis scheme for aircraft electric power system. It is crucial to analyze the output voltage under the steady state, transfer operation and transient of aircraft electric power system.

To verify the effectiveness of the proposed dynamic performance analysis and weighted-based fault diagnosis scheme of aircraft electric power system, a power supply system that consists of generators, ATRU, DC/DC converts and a battery is implemented in MATLAB/Simulink environment. The output voltage of generator 1 (G1) and generator 2 (G2) are represented by V_{G1} and V_{G2}, respectively. And the 28V DC bus voltage is represented by V_{DC}. Moreover, the rated voltage amplitude of G1 and G2 are 115V. ATRUs convert the G1 and G2 output to 270V DC, and the V_{DC} represents the voltage provided by DC/DC converters or the battery.

4.1 Dynamic Performance of the Output Voltage Considering Generators Connection

The dynamic performances of the output voltage of the G1 are shown in Fig. 3 (a) and Fig. 3 (b). In this scenario, the engine reaches to stable speed, the G1 and G2 connect to the system at t=0.3s and provide electrical power for the aircraft. As depicted in Fig.3 (a), it can be observed that the transient voltage spike of G1 reaches is over 1500V. The aircraft didn’t report an emergency about power supply system. However, it can be analyzed by the weighted-based fault diagnosis scheme. The transient voltage spikes of G1 instantaneous voltage is eliminated and the quality of the power system is improved significantly, as shown in Fig.3 (b).

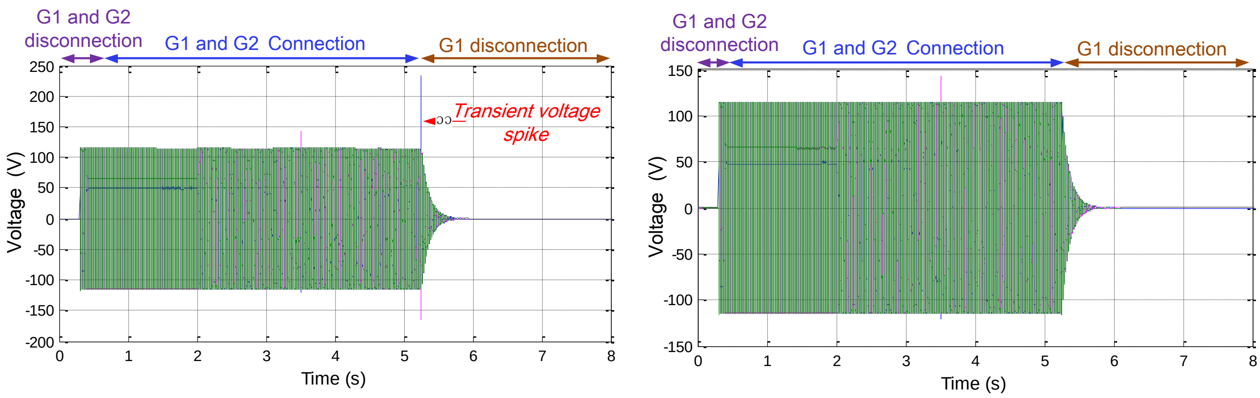


(a) (b)

Figure 3–Dynamic response of the output voltage of G1 considering generators connection. (a)V_{G1} without fault diagnosis analysis. (b) V_{G1} considering weight-based fault diagnosis scheme.

4.2 Dynamic Performance of the Output Voltage Considering One Generator Loss

The performances of the output voltage of the generator under G1 disturbance condition are shown in Fig. 4 (a) and Fig. 4 (b). In this scenario, the G1 is disconnection to the system at *t*=5.2s. The transient voltage spike of G1 reaches over 230V. The aircraft didn't send warning signs about power supply system either. It can be analyzed by the weight-based fault diagnosis scheme, and the transient voltage spikes of G1 instantaneous voltage is eliminated, as shown in Fig.4 (b).

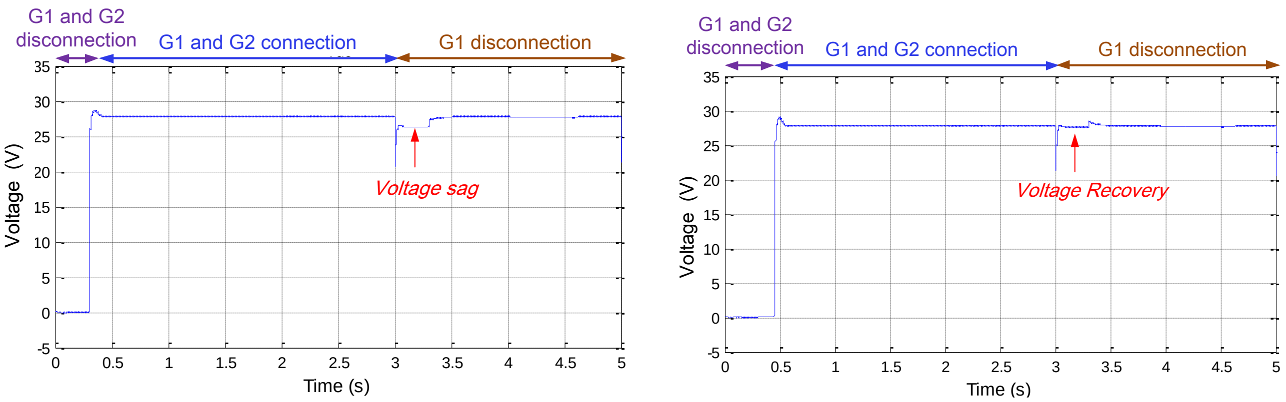


(a) (b)

Figure 4–Dynamic response of the output voltage of G1 considering one generator loss. (a)V_{G1} without fault diagnosis analysis. (b) V_{G1} considering weight-based fault diagnosis scheme.

4.3 Dynamic Performance of the Output Voltage Considering Emergency Operation

The performances of the 28V bus voltage are shown in Fig. 5. In this scenario, The DC/DC converts provide 28V DC voltage for the aircraft before *t*=3s the G1 and G2 are disconnection to the system at *t*=3s. The aircraft electric power system is in emergency operation and the battery provides electrical power for the aircraft. The simulation results of the V_{DC} are represented by Fig. 5 (a) and Fig. 5 (b). It can be observed that the voltage sage of the bus voltage over 10% in Fig. 5 (a). The aircraft didn't send warning signs about power supply system. However, it can be discussed by the weighted-based fault diagnosis scheme, and the voltage sage can be eliminated and the quality of the power system is improved significantly, as shown in Fig.5 (b).



(a) (b)

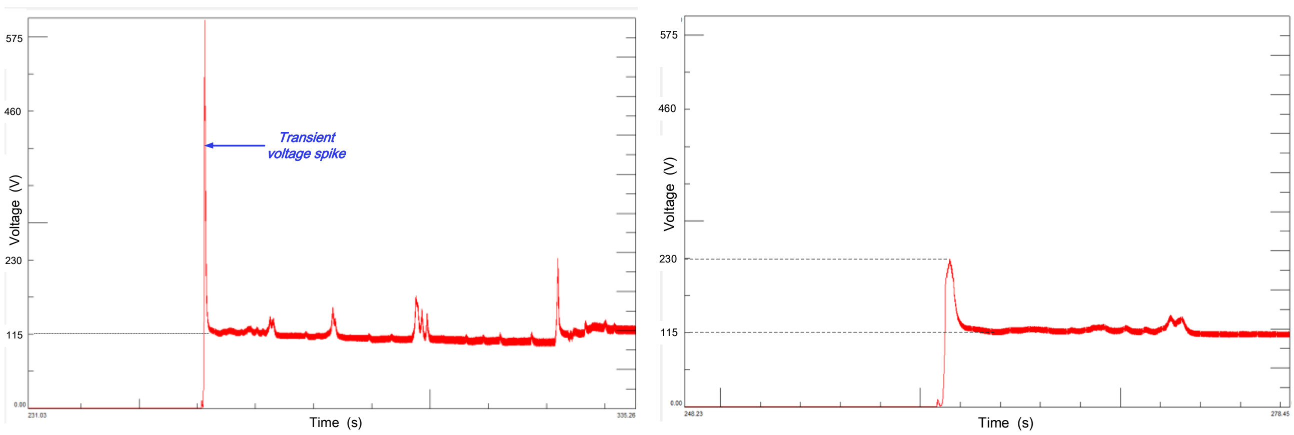
Figure 5–Dynamic response of the 28V DC bus voltage considering emergency operation. (a) V_{DC} without fault diagnosis analysis. (b) V_{DC} considering weight-based fault diagnosis scheme.

5. Experimental Results

To evaluate the effectiveness of the proposed dynamic analysis and weight-based fault diagnosis scheme, the experiments on the aircraft power system was established. And the dynamic performance of the output voltage of the generators and 28V DC bus voltage are analyzed in this section.

5.1 Dynamic Performance of the Output Voltage Considering Generators Connection

The output voltage of the G1 is shown in Fig.6(a) and Fig.6(b). It can be seen the instantaneous transient voltage spike is three times than the normal voltage and the steady-state voltage can maintain within the rated voltage range. Although the aircraft didn't send warning signs about power supply system, the performance needs to be improved, as depicted by the weight-based fault diagnosis scheme. The transient voltage spike is too high, which may cause differential protection of the generator in mistake and damage electric equipment. As shown in Fig.6, the normal voltage can be maintained at about 115V and instantaneous transient voltage spike is decreased significantly, which shows the dynamic performance of the output voltage is improved, and the safety of the aircraft power supply system can be further ensured.



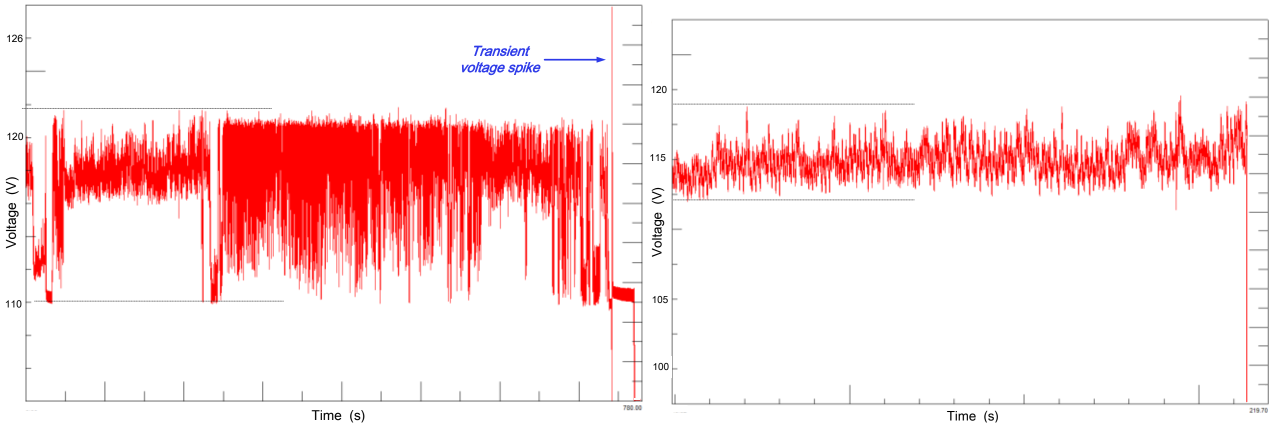
(a) (b)

Figure 6–Dynamic response of the output voltage of G1 considering generators connection. (a)V_{G1} without fault diagnosis analysis. (b) V_{G1} considering weight-based fault diagnosis scheme.

5.2 Dynamic Performance of the Output Voltage Considering One Generator Loss

The output voltage of the generator considering G1 loss is shown in Fig.7(a) and Fig.7(b), respectively. The steady-state deviation of the output voltage and the transient voltage spike of the generator reach to about 18.5V and 20V during G1 loss, respectively. The aircraft didn't send warning signs about power supply system either. However, the poor dynamic performance affects the load operation, which can be observed by using the weight-based fault diagnosis scheme.

As shown in Fig.7, the steady-state deviation of the AC bus voltage can be decreased to about 2V and the transient voltage spike can be eliminated during G1 loss, which shows the dynamic performance of the AC bus voltage is improved significantly.

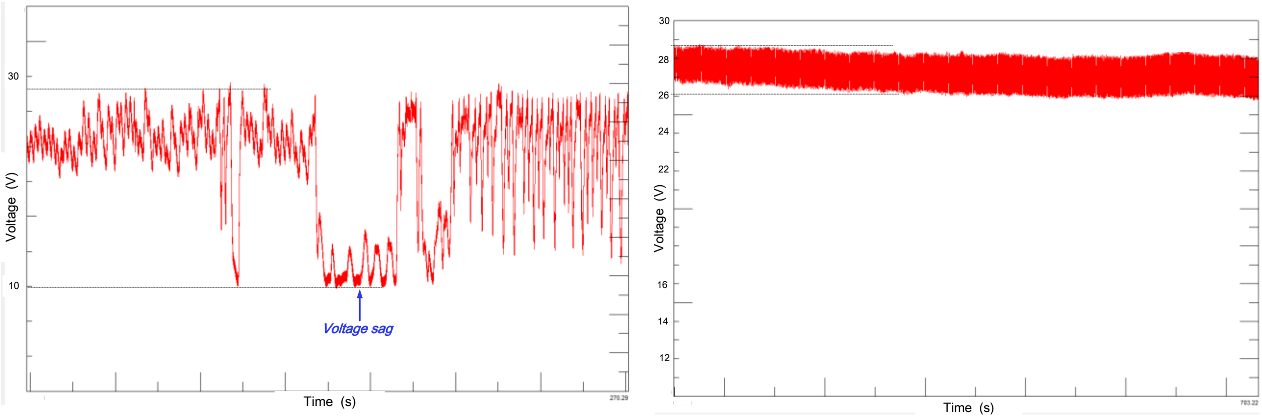


(a) (b)

Figure 7–Dynamic response of the output voltage of G1 considering one generator loss. (a)V_{G1} without fault diagnosis analysis. (b) V_{G1} considering weight-based fault diagnosis scheme.

5.3 Dynamic Performance of the Output Voltage Considering Emergency Operation

The output voltage of the 28V DC bus are shown in Fig.8(a) and Fig.8(b). The steady-state deviation of the 28V DC bus voltage reaches to about 5V when two generators loss. Then the battery provides the power for the aircraft. As shown in Fig.8, the steady-state deviation of the 28V DC bus voltage can be decreased to about 0.5V during two generators loss. Comparing with the bus voltage in Fig.8(a), the dynamic performance of the output voltage is improved significantly and the safety of the aircraft power supply system can be further ensured.



(a) (b)

Figure 8–Dynamic response of the 28V DC bus voltage considering emergency operation. (a) V_{DC} without fault diagnosis analysis. (b) V_{DC} considering weight-based fault diagnosis scheme.

To conclude, the experimental results of the dynamic response of the generator voltage and DC bus voltage further verify the effectiveness of the dynamic performance analysis and weight-based fault diagnosis of aircraft power system.

5. Conclusion

This paper proposes a dynamic performance analysis and weight-based fault diagnosis scheme to achieve accurate fault locating, improve the quality of the power system and ensure the safety for the aircraft electric power system. The typical structure of the power system of the aircraft is discussed. In addition, the complete dynamic performance analysis including root mean square, steady-state amplitude, voltage unbalance, modulation amplitude and voltage distortion factor are presented. And then the data in dynamic performance analysis method can be further used in the weighted-based fault diagnosis scheme, and the reliability and stability of the aircraft power system can be improved.

In addition, the Matlab/Simulink simulation results of the generator output voltage and DC bus voltage are given under generators connection, one generator loss and two generators loss disturbance conditions to show the effectiveness of the theoretical findings. Finally, the experimental results further validate that the proposed approach are capable to analyze the dynamic performance and achieve accurate fault diagnosis, which can be utilized to optimize the power system and ensure the high-quality and high-reliability power supply for electrical equipment of the aircraft.

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7. Copyright Statement

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