The Analysis of Power supply Characteristics of Aircraft Power supply System

Jieyan Xu¹, He Wang¹, Ziyun Su¹, Zheng Chen¹, Tianyi Hao¹*, Xiaobo Mao² and Shixian Bai³

¹State Grid Energy Conservation Design and Research Institute Co., Ltd, No 18, Heiyaochang Street, Xicheng District, Beijing, China
²State Grid Jiangsu Electric Power Co., Ltd, China
³Xi'an Action power Electric Co. Ltd, Xi'an Shannxi 710119, China

*Corresponding author e-mail: haotianyi5@163.com

Abstract. With the rapid development of multi-electric aircraft technology, the aircraft electrical power system is becoming more and more complex and significant. This paper analyzes power supply characteristics of aircraft power supply system. First, the Generalized State Space Averaging (GSSA) technique is adopted to realize the digital simulation of complex aircraft electrical system. Next, AC vector coordinate transformation, digital zero-crossing detection and least squares polynomial fitting are used to analyze power supply characteristics of aircraft power supply system. Finally, the power quality of the power supply system is analyzed in the time domain and the trend analysis diagram of these power quality parameters with the variation of time is given.

1. Introduction
More-electric aircraft has become an inevitable trend in the development of modern aircraft and will replace the commercial aircraft with mechanical energy structure. Developing next-generation aircraft electrical system construction design methods and power quality analysis methods are important to ensure reliable power for various loads under different flight conditions.

The aircraft power system model includes time domain model, small signal model, and generalized state space average model. At present, most of the researches on aircraft power system level are still based on time domain model and small signal model, and there are few studies based on generalized state space average model. In [1], the generalized state space averaging technique was applied to modelling PWM rectifier, and the correctness of the GSSA model was verified through a comparison with precise switching model. In [2], generalized state space averaging model and state space averaging model of Buck converter were established and the results of the two simulation models were compared, which illustrated the advantages of the GSSA model.

The Fourier transform method is widely used in the field of signal processing [3], and it is the basis of most current power quality parameter analysis methods. In [4], a fast Fourier transform method with windowed function was used to analyse the harmonic problem in power quality. The algorithm can accurately analyze the frequency and phase of harmonics. In [5], the d-q transformation was used to analyze the voltage sag phenomenon in the power grid. Other power quality analysis methods include...
neural network analysis method [6], prony analysis method [7], Kalman filtering method [8] and so on. However, these algorithms perform power quality analysis for specific parameters. Based on aforementioned discussion, this paper applies GSSA technique to model the aircraft electrical system. Using different power supply characteristic parameter design algorithms such as AC vector coordinate transformation, digital zero-crossing detection and least squares polynomial fitting, the power output of the system under different operating conditions is analysed and processed, and the power supply characteristics of the aircraft power system are obtained.

2. Aircraft power system modelling method

2.1. Generalized state space averaging technique

Generalized state space averaging (GSSA) is a frequency domain analysis technique. The GSSA technique ignores the unimportant higher harmonics and only considers the most important components so that the fast simulation and required accuracy of the model can be guaranteed. The accuracy and bandwidth of the model are determined by the width of the selected window function and the order of the harmonics [9]. The basic idea of GSSA modeling is to replace the real-time time domain variables with the Fourier coefficients of the time domain variables over a certain time interval. The more Fourier coefficients are used, the higher accuracy of the estimation model is established, and the complexity of the model will increase accordingly.

2.2. Advanced aircraft power system structure

A schematic diagram of the Boeing 787’s power system is shown in Fig. 1. As can be seen from this figure, the main power source of the single-channel model is a synchronous motor. The aircraft power system network consists of a power generation system, a rectifying unit, a DC/DC load, and an inverter.

![Figure 1. AAEPS diagram with APU](image-url)
2.3. GSSA model design of aircraft electrical system components

Take the Buck converter as an example to establish its GSSA model. The circuit topology is shown in Fig. 2.

![Buck Converter Diagram](image)

**Figure 2.** Buck converter

According to Kirchhoff’s theorem, we have:

\[
\begin{align*}
\frac{di_L}{dt} &= u(t) \ast \frac{V_{in}}{L} - \frac{V_o}{L} \\
\frac{dV_o}{dt} &= i_L \ast \frac{V_o}{C} - \frac{V_o}{CR}
\end{align*}
\]  

(1)

Where \( u(t) \) is the switching function of the switch, which is defined as follows:

\[
u(t) = \begin{cases} 
1 & 0 \leq t \leq d_s T_s \\
0 & d_s T_s < t \leq T_s
\end{cases}
\]

(2)

The actual state space variable of the Buck converter system is obtained from the circuit state variable, the inductor current \( i_L \) given by equation (1), and the Fourier coefficient of the capacitor voltage \( V_o \). Using the first-order approximation of the Fourier coefficients, \( i_L \) and \( V_o \) can be represented by the following state variables:

\[
\begin{align*}
\langle i_L \rangle_0 &= x_5 \\
\langle V_o \rangle_0 &= x_6 \\
\langle i_L \rangle_1 &= x_1 + jx_2 \\
\langle V_o \rangle_1 &= x_3 + jx_4
\end{align*}
\]

(3)

Applying the differential properties, convolution properties and additive properties of the Fourier coefficients into equations (1), and separating the real and imaginary parts of the first-order signal, the mathematical model of the Buck converter GSSA can be obtained as follows:
In the above formula, \( w = 2\pi/T_s \) represents the switching angular frequency, where \( T_s \) is the switching period. According to the definition of signal reconstruction in the GSSA concept, the expressions of the inductor current \( i_L \) and the capacitor voltage \( V_o \) are given as follows:

\[
\begin{align*}
    i_L &= 2x_1 \cos(wt) + x_5 - 2x_2 \sin(wt) \\
    V_O &= 2x_3 \cos(wt) + x_6 - 2x_4 \sin(wt)
\end{align*}
\]  

\[ \tag{5} \]

3. **Principle of power quality test algorithm**

3.1. *Test content defined by relevant standards*

This chapter follows the relevant definitions of the US military standard MIL-STD-704F [10], and carries out algorithm research and program design on the aircraft power supply characteristics.

3.2. *Determination of voltage parameters*

3.2.1. *AC voltage.* The instantaneous value of each phase voltage is obtained using the sampling frequency specified by the standard. The rms value is calculated for each half wave of the phase voltage and the AC voltage is obtained as follows:

\[
    V_{rms} = \sqrt{\frac{1}{m} \sum_{i=1}^{m} u_i^2}
\]  

\[ \tag{6} \]

Where \( m \) is the number of samples per half wave and \( u_i \) is the voltage sample value. In actual operation, the instantaneous AC voltage value corresponding to each sampling point in the time domain is required, so for each time point, the calculation range of half a cycle should be determined. According to the instantaneous frequency, the signal period can be obtained, and the calculated starting and ending time points \( t_{s1}, t_{e1} \) can be defined. As shown in equation (7), the visible time range is half a cycle.

\[
\begin{align*}
    t_{s1} &= t - 1/(4f(t)) \\
    t_{e1} &= t + 1/(4f(t))
\end{align*}
\]  

\[ \tag{7} \]

3.2.2. *Voltage modulation amplitude.* In the power quality analysis, the voltage modulation amplitude is defined as the difference between the maximum value and the minimum value of the measured signal voltage for a given period of time, which can be given as follows:
\[ v_{TZ} = \max[v_{A_{\text{max}}}, v_{A_{\text{min}}}, v_{B_{\text{max}}}, v_{B_{\text{min}}}, v_{C_{\text{max}}}, v_{C_{\text{min}}}] \] (8)

Where \( v_{A_{\text{max}}}, v_{A_{\text{min}}}, v_{B_{\text{max}}}, v_{B_{\text{min}}}, v_{C_{\text{max}}}, v_{C_{\text{min}}} \) are the maximum value and the minimum value of each phase voltage, respectively.

The start and end time of the window \( t_{s2}, t_{e2} \) are defined as follows:

\[
\begin{aligned}
    t_{s2} &= t - t_w / 2 \\
    t_{e2} &= t + t_w / 2
\end{aligned}
\] (9)

Where \( t_w \) is a fixed window width.

### 3.2.3. AC voltage DC component

The DC component of the AC voltage refers to the average of the voltages. When calculating the characteristic parameter, the actual value of each phase AC voltage in a whole cycle is calculated for each time point, so the starting and ending time point’s \( t_{s2}, t_{e2} \) defined by (9) are used. At this time, the fixed window width \( t_w \) takes the instantaneous period \( 1/f(t) \), and the calculation method is similar to the calculation of the instantaneous AC voltage rms value. The calculation result is:

\[ k_{\text{JZ}} = \frac{\sum_{i=1}^{m} v_i}{n} \] (10)

Where \( v_i \) is the instantaneous value of the phase voltage at the sampling point, and \( n \) is the number of sampling times in the corresponding time range.

### 3.2.4. Voltage phase difference

The voltage phase difference is defined as the electrical angle difference between two adjacent zero crossings of the fundamental component of any two-phase voltage from the negative to positive direction. In the actual test, for each sampling time point, the zero-crossing phase angle difference in a whole cycle range around it is calculated, and the definition of the starting and ending time point’s \( t_{s2}, t_{e2} \) in section 3.2.2 is used again. Take the phase difference of the A phase and B phase voltage as an example:

\[ \Delta \theta_{A-B}(t_x) = 2\pi f(t_x) \ast (\{z_2(t)\}_A - \{z_2(t)\}_B) \quad t \in (t_{s2}, t_{e2}) \] (11)

Where \( \{z_2(t)\}_A - \{z_2(t)\}_B \) represents all zero crossings of the A and B signals in a given time range, and \( \ast \) represents the average.

### 3.3. Frequency parameter determination

#### 3.3.1. Steady state frequency

The steady state frequency can be obtained by averaging the instantaneous frequencies that are collected within the time span not greater than and closest to 1 second as shown in equation (12).

\[ f_w = \frac{\sum_{i=1}^{n} f}{n} \] (12)
3.3.2. Frequency modulation amplitude. The frequency modulation amplitude is generally used to judge the frequency regulation stability of the power supply system. The test method is similar to the calculation of the voltage modulation amplitude in Section 3.2.2. A window can also be defined according to equations (9). The difference between the maximum frequency and the minimum frequency value is obtained in the range of \((t_{s2}, t_{e2})\), which is the frequency modulation amplitude:

\[
\hat{f}_{TZ} = \max_{t_{s2}, t_{e2}} f(t) - \min_{t_{s2}, t_{e2}} f(t)
\]  

(13)

4. GSSA model construction and simulation analysis

4.1. GSSA simulation model

According to the definition and related properties of generalized state space averaging technology (GSSA), the GSSA simulation model of more-electric aircraft electrical system is established on Matlab/Simulink platform. This system consists of a power generation system, a PWM rectifier, and a CV-Buck converter. The simulation results are shown in Fig. 3.

![Figure 3. Steady-state simulation results](image)

(b) CV-Buck converter output voltage

4.2. Power supply characteristics analysis

According to the algorithm presented in Chapter 3, the power supply characteristics of the model are obtained, as shown in Fig. 4.
5. Conclusion
This paper studies the typical structure of a more-electric aircraft electrical system. The simulation model of each component in the electrical system is established using GSSA technology. The accuracy of the model meets the requirements of the aircraft power system. Aimed at the characteristic parameters test of the aircraft power supply system, various algorithms for the power supply characteristic parameters are proposed. Simulation results show that the designed algorithm meets the requirements of MIL-STD-704F and can accurately collect, calculate and analyze the characteristic parameters of the aircraft power supply system.

Acknowledgments
This work was financially supported by 2017 State Grid Scientific Project “Research and application of typical scenario optimization interaction in electric energy substituting and power grid regulation and support technology” under Grant no 2017411000201030000050.
References
[1] J. You, S. B. Kang, Y. H. Luo. Generalized state space averaging based PWM rectifier modeling. Electrical Measurement & Instrumentation, 46 (2009) 67 - 70.
[2] Z. H. Gao, H. Lin, X. B. Zhang, et al. A comparison between the modeling of power converters using two kinds of state-space averaging approaches. Computer Simulation, 25 (2008), 241-244+248.
[3] Y. P. Hsu, S. Y. Lin. Implementation of low-memory reference FFT on digital signal processor. Journal of Computer Science, 4 (2008) 547 - 551.
[4] Y. C. Zhang, Y. Zhou. Application of windowed FFT in harmonic analysis. Journal of Nanjing University of Information Science & Technology (Natural Science Edition), 5 (2013) 544-547.
[5] S. Qu, C. Huang, Y. Q. Jiang, et al. A new detection method of voltage sag applied in DVR. Transactions of China Electrotechnical Society, 28 (2013) 234 - 239.
[6] L. Wang, X. H. Wang. Application of neural network in power system inter-harmonic detection. 2010 International Symposium on Information Science and Engineering (ISISE), 2010.
[7] L. Zhu, Y. J. Tang, Y. Q. Zhou, et al. Identification of power system low frequency oscillation mode based on improved Prony algorithm. Power System Technology, 33 (2009): 44-47+53.
[8] J. Li, Y. W. Wang, C. Wei, et al. A survey on the application of Kalman filtering method in power system. Power System Protection and Control, 42 (2014) 135 - 144.
[9] T. Krein, J. Bentsman, R. M. Bass, et al. On the use of averaging for the analysis of power electronic systems. 20th Annual IEEE Power Electronics Specialists Conference, 1989.
[10] "Military Standard", "MIL-STD-704 Aircraft Electric Power Characteristics", 2004.