The analysis of the power factor of the capacitive pulse load in the aviation variable frequency power supply system

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Abstract. "More electric/all electrical aircraft" become the development trend in modern aviation, which leads a large increase of nonlinear devices. A capacitive load is formed when uses a capacitor filter to improve the quality of DC power supply. Coupled with the using of 360~800Hz power supply system, the impedance characteristics of the system will become complex. This paper consider the general situation, deduces the parameter calculation expressions of the equivalent exchange RC series-parallel load. Then, combined with the example, the impact of of the impedance characteristics for changing frequency is analysed under aviation VF system (360~800Hz).

1. Introduction

"More electric/all electrical aircraft" become the development trend in modern aviation[1,2], which uses electric energy for replace most or all the power source of the aircraft (electricity, liquid, gas). This leads a large increase of the motor and power electronic devices in the aircraft power supply system. Thus, this kind of equipment tends to show nonlinear load characteristic for power grid, and leads to power waveform distortion, damages the power quality of the power grid. Capacitor filter is one of common methods to improve the quality of DC power supply for the power supply system, meanwhile, the capacitive load of the power grid is formed.

On the other hand, the innovation of power supply system in aircraft performance in the system of power supply: 360~800Hz large capacity variable frequency AC power system is using gradually instead of the constant frequency of 400Hz power supply on most of the aircraft[3,4]. The impedance characteristics of the load under Aviation VF power supply system (360~800Hz) is different from that under the system of constant frequency (400Hz) for the changing frequency of power supply.

This paper consider the general situation, deduces the parameter calculation expressions of the equivalent exchange RC series-parallel load. Then, combined with the example, the impact of of the impedance characteristics for changing frequency is analysed under aviation VF system (360~800Hz).

2. Capacitive load of Aircraft AC power supply system

2.1 AC filter problem of AC/DC converter

Auto Transformer Rectifier Units (ATRU) is used as the AC/DC converter in Power electronic load of aircraft power supply system, which is shown in Fig. 1. This converter alters 115V AC into 270V DC and powers for different electronic load. In order to guarantee the power quality of the AC power grid, ATRU is required to adopt the structure of multi pulse such as 12 pulse ATRU, 18 pulse ATRU and 24 pulse ATRU. Fig. 1 illustrates the 18 pulse ATRU.

Fig. 1 the structure of 18 pulse ATRU

When the DC side is connected with the switching pulse load, even the multi pulse structure can not ensure the load characteristics. For example, voltage and current waveform of AC side is shown in Fig. 2 (a), while using 18 pulse ATRU as AC/DC converter and DC side connecting 1kHz pulse load. Obviously, the current waveform appears distortion. In this case, a capacitor filter in Fig. 1 is added in the AC input side in order to improve the effect of load to the power grid. The result is shown in Fig. 2 (b) that the current waveform is improved significantly.

(a) the waveform before increasing

(b) the waveform after increasing

Fig. 2 the comparison charts before and after increasing

Due to the addition of the capacitor filter, the whole equipment turns into a capacitive characteristic load to the power grid.

2.2 Simplified model of power supply system with capacitive load

A simplified model of a single phase power supply circuit with capacitive load is shown in Fig. 3 (a). The ATRU and DC load are equivalent to be a load resistance R_{LP} , which is parallel with a filter capacitor C_p in the model. e_a is the back EMF of generator's A phase, and internal resistance, inductance are described as r_a , L_a . In order to analyze the power factor of the circuit, the structure of the load is transformed from partial to serial which is illustrated in Fig. 3(b). The parallel load R_{LP} , C_p is equivalent to series load R_{LS} , C_S .

(a) Parallel load

(b) Equivalent series load

Fig. 3 Simplified model of power supply system with capacitive load

The impedance of parallel and series load will be:

$$\begin{aligned}
R_{LS} &= \frac{R_{LP}}{(\omega C_p R_{LP})^2 + 1} \\
X_{CS} &= \frac{\omega C_p R_{LP}^2}{(\omega C_p R_{LP})^2 + 1}
\end{aligned} \tag{1}$$

The power factor of the load is:

$$PF = \frac{1}{\sqrt{1 + (\omega C_p R_{LP})^2}} \tag{2}$$

By the formula (1,2), the impedance and power factor of the load are determined by the effect of the phase load resistance R_{LP} and the phase filter capacitance C_p , and is the function of the power supply electric angular velocity ω . Besides, they are nonlinear.

3. Impedance characteristics of capacitive load in variable frequency power supply

The load impedance and power factor as shown in Fig. 3 will change for the altering angular velocity ω ($\omega = 2\pi f$) in the use of the aeronautic VF (360~800Hz) power supply.

3.1 The effect of power frequency on load impedance

By the formula (1), if R_{LP} and C_p are fixed, the changes of power frequency will lead to the changes of X_{CS} , and then trigger R_{LS} and X_{CS} changes. In this case, the formula (1) can be considered as a function of ω .

Ask about the partial guide of ω on formula (1), there are:

$$\begin{aligned}
\frac{dR_{LS}}{d\omega} &= \frac{-2\omega C_p^2 R_{LP}^3}{[(\omega C_p R_{LP})^2 + 1]^2} \\
\frac{dX_{CS}}{d\omega} &= \frac{C_p R_{LP}^2 - \omega^2 C_p^3 R_{LP}^4}{[(\omega C_p R_{LP})^2 + 1]^2}
\end{aligned} \tag{3}$$

By the formula (3) we can know that when ω changes, R_{LS} is monotonous decreasing, and X_{CS} has extreme value. This extreme value will arise when meet $\omega C_p R_{LP} = 1$, and $\frac{dX_{CS}}{d\omega} = 0$.

At this point, the maximum capacitive is shown as a fixed value $X_{CS} = \frac{1}{2} R_{LP}$. Meanwhile,

$R_{LS} = \frac{1}{2} R_{LP}$, and the power factor is $\frac{1}{\sqrt{2}} = 0.707$.

For example, the power supply phase voltage is 115V, the ATRU transform load power is 6kW, and the phase filter capacitor is 60μF. The power of each phase is 2kW when ignoring the power loss, and the equivalent phase load resistance R_{LP} is 6.6Ω. Thus, X_{CS} appear maximum value when the power frequency is 400Hz and $\omega = 2525 \text{ rad/s}$. Simulation results of different frequencies are shown in Fig. 4.

(a) the process of R_{LS} and X_{CS} change (b) the process of PF change

Fig. 4 Impedance characteristic change of VF power supply (R_{LS} , X_{CS} , PF)

3.2 Influence of load power varying

The variation of impedance and power factor is nonlinear when output DC power of ATRU changes. Three types of power are chosen to simulate: 6KW ($R_{LP}=6.6\ \Omega$), 9kW ($R_{LP}=4.4\ \Omega$), 4.5KW ($R_{LP}=8.82\ \Omega$). The phase filter capacitor is $60\mu F$. When f changes, the changing curve of R_{LS} and X_{CS} corresponding to different power load can be drawn according to the formula (1), which is shown in Fig. 5.

(a) the changing curve of R_{LS}

(b) the changing curve of X_{CS}

Fig. 5 the changing curve of R_{LS} and X_{CS} with f varying

3.3 Influence of filter parameters

The variation of impedance and power factor is also nonlinear when filter parameters of ATRU changes. Three kinds parameter of filter are chosen to simulate: $C_p = 30\mu F$, $C_p = 60\mu F$, and $C_p = 90\mu F$. The output DC power of ATRU is 9KW. When f changes, the changing curve of R_{LS} and X_{CS} corresponding to different filter parameter can be drawn according to the formula (1), which is shown in Fig. 6.

(a) the changing curve of R_{LS}

(b) the changing curve of X_{CS}

Fig. 6 the changing curve of R_{LS} and X_{CS} with f varying

4. Conclusion

This paper consider the general situation, deduces the parameter calculation expressions of the equivalent exchange RC series-parallel load in simplified model of aviation power system. Based on this, the impedance characteristics of the capacitive load under the aviation VF system (360~800Hz) are analyzed, and the effects of power frequency, load power and filter parameters to the impedance characteristics of capacitive load are pointed out.

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