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Review Article

Methods of Aircraft Grid Harmonic Reduction: A Review

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Abstract: We briefly introduce the source and harm of aircraft grid harmonic and summarise the common methods of harmonic reduction, such as passive filter, multi-pulse rectifier, power factor correction and active power filter. Then we introduce the disadvantages of the above methods, analyse the application status, advantages and deficiencies of active power filter in aircraft grid harmonic reduction, propose future research orientation of it. This paper is useful for relevant researchers who are engaged in airplane electric design.
Keywords: Aircraft grid, Harmonic, Harmonic reduction, PFC, APF

INTRODUCTION

With the development of more electric of aircraft, the aviation power capacity increasing. Meanwhile, power electronic devices have been more widely used in aircraft power system, which brought harmonic, reactive and imbalance problems to aircraft grid. These problems will seriously affect the quality of the aircraft power supply, degrade performance and service life of power generation equipment and electrical equipment, even threaten the safe operation of the entire aircraft electrical system. Therefore, to solve the aircraft grid harmonic, reactive and unbalanced problems, and ensure the quality of aircraft power supply system, maintain the stability and reliability of the power system has become a hot issue in aircraft power research.

Harmonic has the variety and complexity in advanced aircraft and current harmonic reduction methods are insufficient. We introduce the source and harm of aircraft grid harmonic, analyze the current common harmonic reduction methods and its problems. Then we discuss the application of active power filter in aircraft grid harmonic reduction, and prospect the development and research orientation of this new method.

BASIC CONCEPT OF GRID HARMONIC

The term of harmonic originated in acoustic. In acoustic, harmonic representation in a string or an air column vibrating in several times of the basic cycle (or fundamental) frequency of vibration. In electrical, harmonic is defined as a signal, actual frequency of the signal is an integer multiple of the actual system frequency(i.e. the frequency of the generator). Since the frequency of the harmonic components is an integer multiple of the fundamental frequency, we have often called higher harmonic. In addition, when the frequency of the harmonic components is non-integer multiples of the fundamental frequency, it is known as inter-harmonic, inter-harmonic is not in the traditional sense of harmonic, it represents the transient change of the electric system.

Voltage waveform of steady-state grid is a sine wave, its mathematical expression is:

$$u(t)=\sqrt{2}U\sin(\omega t+\alpha) \quad (1)$$

$$\omega = 2\pi f = \frac{2\pi}{T} \quad (2)$$

In the expression, U is voltage effective value, α is the initial phase angle, ω, f and T is respectively angular frequency, frequency and power frequency cycle.

In practice, we adopt effective value to measure current and voltage size, take $i(t)$ for example, its effective value is defined as:

$$I \square \sqrt{\frac{1}{T}\int_0^T i^2(t)dt} \quad (3)$$

For the transient value of non sinusoidal current and voltage, can be expressed by trigonometric series, that is:

$$u(t)=U_0+\sum_{n=1}^{\infty}\sqrt{2}U_n\sin(n\omega_1 t+\alpha_n) \quad (4)$$

$$i(t) = I_0 + \sum_{n=1}^{\infty} \sqrt{2} I_n \sin(n\omega_1 t + \beta_n) \quad (5)$$

In this expression n is harmonic order, n=1,2, 3, ……

In order to express the waveform distortion degree deviated from sine wave, we can use the following characteristic, such as harmonic content, total harmonic distortion and Nth harmonic content.

The harmonic voltage content is:

$$U_H = \sqrt{\sum_{n=2}^{\infty} U_n^2} \quad (6)$$

The definition HR (Harmonic Ratio) can describe the size of one harmonic component. For example, the Nth harmonic ratio of voltage(HRU_n) is

$$HRU_n = \frac{U_n}{U_1} \times 100\% \quad (7)$$

The definition THD (Total Harmonic Distortion) can describe the degree that waveform distortion deviation from sine waveform, its mathematical expression is:

$$THD_U = \frac{U_H}{U_1} \times 100\% \quad (8)$$

In order to prevent the harm and influence of harmonic in aircraft grid, there are many international standards for aircraft electrical power quality, such as RTCA DO-160, EUROCAE ED-14F, ISO 1540-2006, as well as the standard of many aircraft manufacturing enterprises, such as Boeing D6-44588 and Airbus ABD-0100. All the standards, above has put forward demands for aircraft power and harmonic content, typically require the harmonic distortion rate below 3%. But in fact, even if the power supply system and electrical equipments have taken measures to meet the requirements of technical specification, when all power electronic devices work together, by comprehensive in its characteristic, the harmonic still may have a significant impact on the quality of power supply system, and even beyond the requirements of steady state of the aircraft power supply characteristics. Therefore, besides the harmonic reduction of single equipment, we should resolve the harmonic problems systematically.

SOURCE AND HARM OF AIRCRAFT GRID HARMONIC

Source of Aircraft Grid Harmonic

1.Power generation system

The main harmonic source of power system is the generator and inverter. In actual operation of brushless alternator, magnetic field distribution is not exactly sinusoidal, thus the induced electromotive force is not an ideal sine wave, the output voltage contains a certain content of harmonic. The frequency and amplitude of this harmonic depends only on the structure and operation of the generator itself, substantially independent of the external load, and can be seen as a harmonic voltage source[1].

VSCF power system adopts inverter to convert variable frequency AC into constant frequency AC. There are two kinds of the inverter: AC-AC inverter and AC-DC-AC inverter. Because the AC-AC inverter adopts phase control, so its harmonic component is very complex. In addition to containing the integer harmonic content, but also contains inter-harmonics[2]. AC-DC-AC inverter converts DC power into AC power first and then reverse, the process of rectification and inversion will produce a lot of harmonic.

2.Power distribution system

The main harmonic source in power distribution systems is the vertoro. A typical vertoro consists of three-phase step-down transformer and diode rectifier bridge. With the development of power electronic technology, now we take a large number of electronic vertoro. Electronic vertoro is actually a DC converter isolated, and there is a rectifier circuit at its input end.

For transformer, due to its saturation of iron core, the nonlinear magnetization curve, combined with the transformer design consideration of economy, the choice of work flux density is in nearly saturated magnetization curve segment, thus make the magnetization current into a sharp waveform and contain harmonic. The higher iron core saturation degree, the farther working point deviation from the linear, the amount of 3th harmonic content can reach to 0.5% of rated current[1].

There are two kinds of rectifying device:single-phase and three-phase. If it is single-phase rectifier, when connecting inductive load it will contain odd harmonic current, and the 3th harmonic content can be up to 30% of the fundamental wave; when connecting capacitive load, it will contain odd harmonic voltage, and the harmonic content increases with the increase of capacitance.

If the rectifier circuit is 6 pulse rectifier, the transformer primary side and the grid will contain 5th or more odd harmonic current; if it is twelve pulse rectifier, will contain 11th or more odd harmonic current. The study shows that harmonic content of the rectification device accounts for nearly 40% of all harmonic content and is the greatest harmonic source.

3.Electric equipment

Harmonic source of electric equipment is mainly the lighting and heating equipment and equipment based on pulse power energy storage. Etc. Electrical deicing system is the main electric equipment in aircraft power supply system. When it working, the ice thickness is different, thus the heating temperature would be dissimilar, that may cause unbalanced three-phase loads, produce harmonic current. The energy storage system of airborne radar equipment is based on the capacitance charging circuit form of the rectifier, and also can produce harmonic current.

Harm of Aircraft Grid Harmonic

- If there is too many harmonic component in the aircraft grid, will cause a lot of adverse effects on the system[3].
- When there is harmonic component in the system, may lead to partial parallel or series resonance, magnify harmonic component, and therefore increase additional loss and heating due to the harmonic, make the electric power equipment overheating due to additional losses.
- The harmonic can interfere communication system near the dc transmission line, In severe cases, it will threat the security of communication equipments;
- The existence of harmonic may increase the surplus harmonic loss in the system, reduce the efficiency of power generation, transmission and use of electrical equipment. Harmonic may cause the error of the measuring instrument and mis-operation of some electric power protection equipment;
- The harmonic power can make the equipment components accelerated aging, shorten the service life, etc.

COMMON METHODS OF HARMONIC REDUCTION

There are two main ideas to solve the problem of harmonic, one is active treatment, and the other is passive treatment.

Active treatment is starting from the device itself, makes it does not generate harmonic current and does not absorb reactive power. By using multi-pulse rectifier technology to achieve reduction of harmonic output is a relatively common method. For example, by changing the control circuit topology and multi-pulse rectifier ways to reduce the harmonic content when the transformer rectifier design[4]. In addition we can also through the use of advanced power output control strategy to achieve lower harmonic content, such as the use of selective harmonic elimination pulse width modulation (SHE-PWM) technology in the design of aircraft seat power supply to make the output power harmonic characteristics meet the requirements[5].

Passive treatment is by adding filter to prevent harmonic into the power grid, the conventional method is passive filter and power factor correction technology. Passive filter is mainly through the LC passive filter circuit to filter low-order harmonic. For some scattered AC/DC power supply, we can add a power factor correction device in the first grade in order to decrease the harmonic, and can achieve good compensation effect[6].

There are many research attempts by adding active power filter(APF) to achieve the comprehensive compensation of harmonic, reactive power and unbalance, and it is currently the key areas of aircraft grid harmonic suppression research [7-8]. In practice, the harmonic suppression usually requires comprehensive of the above methods to obtain good effect.

Passive Filtering Technology

Passive filter is the traditional method of harmonic reduction, it is generally composed of capacitance, inductance, and resistance, also known as the LC filter. Along with harmonic suppression, LC filter can both reactive power compensation and improve power factor. This method is simple in structure and less investment in equipment. Besides it is mature technology and convenient for maintenance. So passive filter plays a key role in aircraft grid harmonic reduction.

Multiple Pulse Rectifier Technology

In the field of high-power and aviation, we often use multiple pulse rectifier transformer to realize power factor correction[9]. Take 12 pulse rectifier circuit as an example, the structure is shown in figure 1.

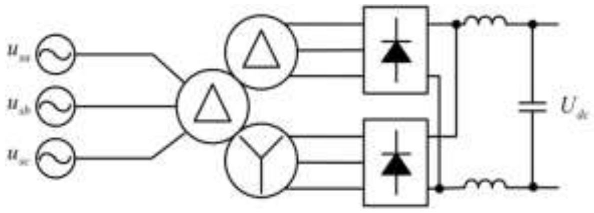

Fig.1. Structure of 12 pulse rectifier circuit

Three-phase input voltage through a particular Y-∆ connection transformer connects to two uncontrolled diode bridge rectifiers, the bridge rectifier DC output side through balancing inductance in parallel to provide the DC power supply for electrical equipment. Primary side of transformer using ∆ connection, in the secondary side, a winding uses a ∆ connection and another one uses a Y connection. Because the structure of two secondary windings are different, can make the input voltage phase of two rectifier bridge 30 degrees difference.

The above structure can make the 5th, 7th, 11th, 17th and 19th harmonic cancel each other out, only $12K\pm1$(K is positive integer) harmonic can into the power grid, such as 11th, 13th, 23th, 25th and so on. So as to reduce the influence of the harmonic current to the power grid. Multiple pulse rectifier is generally use transformer, thus can realize electrical isolation of the input and output, but the volume and weight of the transformer are larger.

Power Factor Correction Technology

With the development of power electronic technology, more and more electronic equipment power supply on the aircraft using AC/DC power switch circuit, so we can use power factor correction(PFC) before the AC/DC converter[10], Through the control of power switching device, to make the input current waveform track the input voltage, so as to realize the power factor is close to 1 and the total harmonic content of input power flow (Total HarmonicDistortion, THD) is relatively small, then achieve the goal of improving the power factor of the system and harmonic reduction.

Active Power Filter Technology

Since 1983, the instantaneous reactive power theory is proposed by Japanese scholar H.Akagi[11], APF has become one of the advanced methods to adjust and control the quality of electric energy. APF can realize comprehensive compensation of harmonics, reactive and unbalanced. Then we will take the shunt active power filter as an example to introduce the working principle of APF.

The structure of shunt active power filter is as shown in figure 2. load current i_L is real-time calculated, extract the harmonic components i_{LH}, and then by the high performance control technology of current, to make the converter output same size and opposite direction compensation current i_C, for $i_S=i_L+i_C=i_{LH}+i_{LF}+i_C$, i_S is equal to the fundamental component of the load current i_{LF}, we will reach the purpose of compensating harmonic.

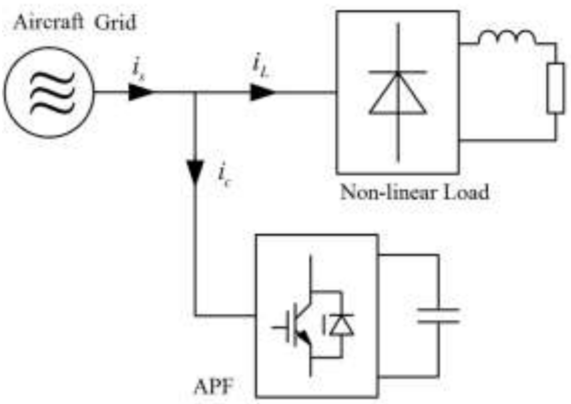

Fig.2. Structure of shunt active power filter

APF is less affected by the grid parameters, can adapt to the variable frequency AC power system compared with the passive filter. At the same time, APF only deal with harmonic power load (also contain reactive power) compared with the PFC handling all load power. Therefore under the same technical indicators, the volume, weight and capacity of APF are relatively small.

THE APPLICATION OF APF IN AVIATION

In the year of 2006, Milijana Odavic et al at the University of Nottingham had successfully applied multilevel shunt APF to aircraft variable frequency AC power system. After that, study on the application of APF in aviation becoming hotter, research of representative are as follows:

- For application background of aerospace, proposes a series APF, and make a detailed analysis on the system, then gives the simulation waveforms and experimental prototype photos, but lack of the related experimental waveform[12].
- For aircraft AC power system, proposes a new digital wave detection algorithm, and gives a detailed theoretical analysis, simulation and experimental results to verify the feasibility of the algorithm[13].
- For aircraft AC power system, proposes a low switching frequency and high bandwidth active filter system, the system uses strategy of predictive current control, the main circuit adopts the cascade multilevel topology, simulation results are given for harmonic current tracking effect of different grid frequency,but lack of the experimental verification [14].
- A method is presented for the 400Hz aircraft power supply system and variable frequency AC power system with shunt APF, by using the perfect harmonic cancellation of harmonic detection method, to realize greatly improve on the aircraft power system power quality. In the same way, conclusions in this paper are built on the simulation, also lack of the corresponding experimental waveforms[15].
- Set up a complete model of different loads in aircraft electrical power system, by comparing the differences of aviation power system power quality before and after the introduction of APF, verify the feasibility of APF in the traditional and advanced aircraft[16].
- By summing up the work of predecessors, we can find that at present the study of APF in aviation has the following features:
- Adopt new main circuit topology and control strategy of aviation APF.
- For the aviation network features, proposes the corresponding current detection strategy, or improves the existing current detection method in aerospace application.
- Research on the main circuit topology which can make the equivalent switching frequency increased, and the corresponding current control strategy.
- Building aircraft grid modeling, verifies the feasibility of APF in application.
- Generally lack of the persuasive experimental waveform, or just the small power experiment.
- Most of the studies are three-phase three-wire system or a single-phase system, although considering the high frequency demand for the quickness of algorithm, but the harmonic algorithm in three-wire system is not applicable in a four-wire system.

- Nearly all of the aviation shunt active filter system is based on conventional control strategy that by detecting the load current to control compensation current.

PROBLEMS OF HARMONIC REDUCTION METHODS AT PRESENT

Problems of Traditional Harmonic Reduction Methods

Due to the principle and structure, there are many insurmountable difficulties of passive filter, because not only the harmonic current through the passive filter, but also fundamental wave current, so the filter have a larger capacity requirements, especially low harmonic filter; The volume and weight of the passive filter is larger; Compensation characteristic easily affected by power grid impedance and running state; the design of LC parameters are difficult; it easy occurs parallel resonance with system, makes filter overload even burned. In addition, it can only compensate for the fixed frequency of harmonic. The compensation effect is not very ideal.

For multiple pulse rectifier, the rectifier is generally adopt transformer, so can realize the electrical isolation in the input and output, but the volume and weight of the transformer will be larger, system efficiency loss is bigger, so it has low reliability and the match with generator is bad.

Problems of PFC Technology

For single-phase systems, at the zero crossing of input voltage, the inductor current rise rate of PFC converter is very small, so the inductor current is hard to track the reference current and the input current distortion will happen. As the aircraft AC power system which fundamental frequency is higher(400Hz), the phase of input current will be ahead of input voltage more, distortion of current zero crossing is more obvious, and will seriously affect the power factor of the system. For a three-phase system, using the PWM rectifier technology to improve the power factor of system, can get high power factor, and the load adaptability is strong, but the converter will deal with all of the load power, the capacity is large, the volume and weight can not effectively reduce. Once the facilities are breakdown, the load may not work properly, so the reliability is poor.

Problems of Aviation APF

Although most studies show that, APF is the best solution to harmonic, reactive power and unbalancing problem. But in fact, there are many difficulties to use APF in the aircraft AC power system. First of all, the aircraft AC power supply system is independent, the internal impedance of the power source is relatively large, the power is greatly influenced by load, and the nonlinear load is in a large proportion, which requires the APF with better dynamic compensation performance, in order to ensure the power supply quality of aircraft power system when load changes. Secondly, the frequency of aircraft AC power grid is 400Hz, and is eight times of power frequency. That means the frequency of same harmonic order in aircraft AC power grid is eight times of power frequency. Due to the limits of Digital Signal Processor(DSP) arithmetic speed and switching device, the switching frequency cannot be very high and the current bandwidth is limited. This increases the difficulty of using APF to compensate power grid harmonic in aircraft power system.

CONCLUSION

In this paper, we have reviewed the common methods of harmonic reduction in aircraft grid. Passive filter can only compensate the fixed frequency harmonic, its volume and weight is relatively large, and easy resonance with the aircraft power grid; power factor correction can achieve power factor close to 1 and make THD of the input current is relatively small, but the converter will deal with all of the load power, the whole capacity is larger, volume and weight can not be effectively reduced, and the reliability is poor. APF has good performance in dynamic compensation, small compensation capacity and high reliability. With the increasing of aircraft power capacity and reliability requirements, the study of aviation APF is of great significance.

In the future, research for harmonic suppression in aircraft grid should start from the following aspects.

A. The study of aviation APF: 1) research the current detection technology for three-phase four-wire independent small capacity power supply system, and through the research to find a suitable generation method of reference current for aviation APF; 2) for the high frequency of aircraft grid, after using MOSFET to improve switch frequency, we can get good current tracking effect and then improving the precision of current benchmark became a key to improve the performance of APF compensation. We can adopt high precision A/D, DSP and D/A chip to achieve; 3) should further study the different power circuit topology structure. We can consider to use multi-level inverter structure, such as the structure of the cascade system to reduce the switching frequency of the power tube, or to realize better compensation effect under the same switching frequency.

B. The reasonable combination of passive filter and active power filters. Mainly using APF to suppress large amplitude low-order harmonic, and using a passive filter to filter lower amplitude high-order harmonic.

C. Because the aircraft variable frequency power supply has been applied in many larger capacity plane, and become one of the trend of future aircraft power supply. Considering the frequency change of variable frequency power supply is generally 360~800HZ, due to the frequency range is wide, optimize design of passive filter mode is difficult, so the application of APF will have more application value. We can through the study of APF in aircraft variable frequency power supply to ensure the quality of power supply.

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