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A Research on Cascade Five-level Aeronautical Active Power Filter

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Abstract—**With the advance of "More Electric Aircraft", power capacity of the aircraft electrical power system and number of the nonlinear avionic devices get increased. Power quality problems including the harmonic issues effect the safe operation and flying qualities of the aircraft. Introducing active power filter (APF) techniques to solve the harmonic and reactive problems of the aircraft electrical power system is of high research values. For aircraft electrical power system, a cascade five-level topology based aeronautical active power filter (AAPF) is proposed and studied. Mathematical model, control strategy, key parameters and operation principle of the novel AAPF are presented. Experimental results obtained from a prototype show that harmonic and reactive components of the typical nonlinear load could be compensated effectively by the novel AAPF. A good compensation performance of the novel AAPF is achieved.**

Keywords-aeronautical active power filter; cascade multilevel; closed-loop control; hybrid carrier PWM modulation

I. INTRODUCTION

With the process of "More Electric Aircraft" and "All Electric Aircraft", the type and number of airborne electrical equipments are increasing [1][2]. However, more and more power electronics equipments will introduce harmonic pollutions into the aircraft electrical power system. It will be harmful to the safe operation of aircraft if the harmonic problem isn't solved [3][4].

The variable frequency AC power system is the trend of the power system of large aircraft in the future. Compared with traditional constant frequency power system, variable frequency system has higher reliability and capacity. For example, the main generators capacity Boeing 787 is 4×250 kVA. The challenges of improving power quality are also brought by variable frequency AC power system. Tuned filter is a kind of filter widely used in constant frequency system. But to variable frequency system, the filtering effect will be reduced to a discount because the frequency is variable.

The concept of active power filter (APF) is proposed in 1970s [5] and attracts more and more attentions and researchers [6]-[9]. It has the advantages of fast transient response, high compensation accuracy and ability to eliminate possible parallel resonance so that it is considered as the best method to improve power quality of low voltage stage power system. Introducing APF techniques into modern aircraft power system, plays an important role in improving generation efficiency, ensuring power supply quality and other aspects of aircraft. In [10], a fast and accurate harmonic algorithm based APF is proposed for the aircraft grid and achieves a good performance. [11] builds a variable-speed constant-frequency aircraft power system model and employs the perfect harmonic cancellation to eliminate the harmonics. [12] presents an aeronautical APF (AAPF) using an accurate wide-band current control method based on iterative learning control. [13] shows an improved dead beat digital control based APF for aircraft power system. In all, study of AAPF has an important theoretical significance and realistic values.

An AAPF based on cascade five-level converter is studied in this paper. The mathematical model is built and the control strategy is given. The influence of low pass filter (LPF) in control circuit on system performance is analyzed by simulation. At last, an experimental prototype is designed to verify the validity of theoretical analysis and the feasibility of proposed cascade five-level aeronautical active power filter.

II. TOPOLOGY AND MATHEMATICAL MODEL OF CASCADE FIVE-LEVEL AAPF

A. Topology Configuration

Fig. 1 shows the cascade five-level aeronautical active

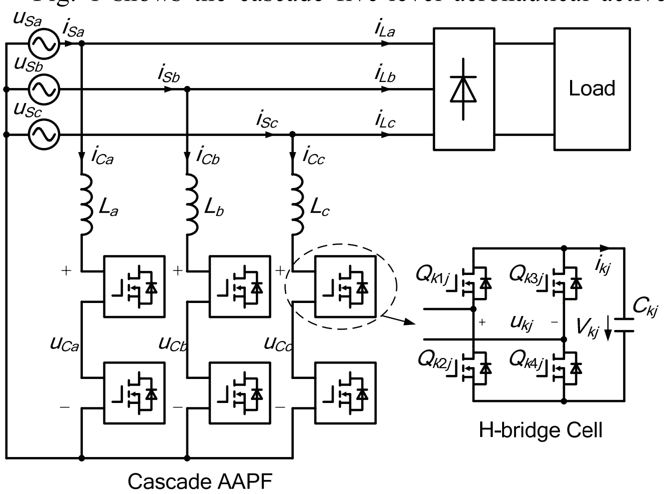


Figure 1. The AAPF based on cascade five-level converter

power filter. The cascade h-bridge converter is in parallel with the nonlinear load. The main circuit consists of three two-cell cascade h-bridge converters with the Y connection. In the figure, u_{Sk}(k = a, b, c), i_{Sk}, i_{Lk} and i_{Ck} represent the source voltage, source current, load current and compensating current separately, u_{Ck} is the compensating voltage, L_k is the coupling inductor. Variables u_{kj}(j=1, 2), C_{kj}, i_{kj} and V_{kj} are output voltage, DC capacitor, capacitor current and capacitor voltage of cell j in phase k. The first switch of cell j in phase k is named Q_{k1j} and so are other switches.

The advantages of employing cascade topology are listed as follows: It can meet the requirement of high bandwidth of aircraft grid with a low switching frequency; the voltages of each DC-link capacitor are low so that the voltage stress of the power switch gets decreased; the modular design makes the system simple and reliable.

B. Mathematical model

By supposing that $V_{k1}=V_{k2}=V_{dc}$, each cell produces three distinct voltage levels: 0, $\pm V_{dc}$. When $u_{kj}=+V_{dc}$, Q_{k1j} and Q_{k4j} are on; When $u_{kj}=-V_{dc}$, Q_{k2j} and Q_{k3j} are on; When u_{kj}=0, Q_{k1j} and Q_{k3j} or Q_{k2j} and Q_{k4j} are on. According to switches on and off, the switching function of each cell can be defined as follows:

$$P_{kj} = Q_{k1j} - Q_{k3j} \tag{1}$$

Here, Q=1 means switch on, Q=0 means off.

Output voltage of each cell is shown:

$$\begin{aligned} u_{k1} &= \left(Q_{k11} - Q_{k31}\right) \times V_{dc} = P_{k1} \times V_{dc} \\ u_{k2} &= \left(Q_{k12} - Q_{k32}\right) \times V_{dc} = P_{k2} \times V_{dc} \end{aligned} \tag{2}$$

Assuming that the loop impedance of each phase is R_k, the compensating currents yield the expressions:

$$\begin{aligned} \frac{di_{Ca}}{dt} &= \frac{1}{L}\left(u_{Sa} - i_{Ca} \times R_a - u_{a1} - u_{a2}\right) \\ \frac{di_{Cb}}{dt} &= \frac{1}{L}\left(u_{Sb} - i_{Cb} \times R_b - u_{b1} - u_{b2}\right) \\ \frac{di_{Cc}}{dt} &= \frac{1}{L}\left(u_{Sc} - i_{Cc} \times R_c - u_{c1} - u_{c2}\right) \end{aligned} \tag{3}$$

Substitute (2) into (3), model of AC side can be written as:

$$\begin{aligned} \frac{di_{Ca}}{dt} &= \frac{1}{L}\left(u_{Sa} - i_{Ca} \times R_a - P_{a1} \times V_{dc} - P_{a2} \times V_{dc}\right) \\ \frac{di_{Cb}}{dt} &= \frac{1}{L}\left(u_{Sb} - i_{Cb} \times R_b - P_{b1} \times V_{dc} - P_{b2} \times V_{dc}\right) \\ \frac{di_{Cc}}{dt} &= \frac{1}{L}\left(u_{Sc} - i_{Cc} \times R_c - P_{c1} \times V_{dc} - P_{c2} \times V_{dc}\right) \end{aligned} \tag{4}$$

Capacitor currents can be written as:

$$\begin{aligned} i_{k1} &= \left(Q_{k11} - Q_{k31}\right) \times i_{Ck} = P_{k1} \times i_{Ck} \\ i_{k2} &= \left(Q_{k12} - Q_{k32}\right) \times i_{Ck} = P_{k2} \times i_{Ck} \end{aligned} \tag{5}$$

Relationship between Capacitor voltages and currents are illustrated:

$$\begin{aligned} \frac{dV_{k1}}{dt} &= \frac{1}{C_{k1}} i_{k1} \\ \frac{dV_{k2}}{dt} &= \frac{1}{C_{k2}} i_{k2} \end{aligned} \tag{6}$$

Substitute (5) into (6), the model of DC side is obtained:

$$\begin{aligned} \frac{dV_{k1}}{dt} &= \frac{1}{C_{k1}} P_{k1} \times i_{Ck} \\ \frac{dV_{k2}}{dt} &= \frac{1}{C_{k2}} P_{k2} \times i_{Ck} \end{aligned} \tag{7}$$

III. Control Strategy

A. System Control

The conventional control strategy of APF is detecting the harmonic and reactive components as the reference of compensating current and sending it to the current controller, making the practical compensating current tracking the reference. However, for source current, the conventional control strategy is open-loop. The compensation accuracy depends on the voltage and current sampling and harmonic detecting scheme to a great extent. But for the aircraft power system, of which the frequency is as high as 400Hz, the delay of the digital technique nowadays can not meet the demands. In order to meet the requirements of the aircraft power system, the source current direct control is employed in this paper and it is closed-loop to the source current.

Fig. 2 illustrates the control diagram of phase a. The overall control have two parts: source current direct control and DC-link voltage balance control.

In source current direct control, i_{Sa}^* is the reference of the source current. Its phase signal e_{Sa} is obtained by locking the phase of source voltage u_{Sa}. The amplitude of i_{Sa}^* has two components: fundamental of load current feedforward component I_{ffa} and APF DC-link voltage feedback component I_{fba}. The load current feedforward component is obtained by processing the load instantaneous power with a low pass filter (LPF) step and it is the majority of the amplitude of source current reference. APF DC-link voltage feedback component is the output of APF DC-link voltage loop and it is a relatively small active signal. The sum of the two components above is the amplitude of source current reference. The source current reference i_{Sa}^* minus the practical source current i_{Sa} is the control variable of source current vma.

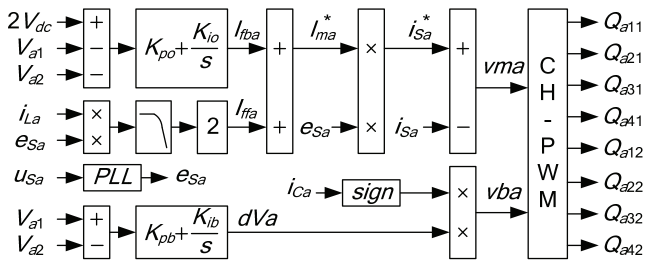


Figure 2. System control diagram of proposed AAPF

To guarantee the normal working of the cascade AAPF, the DC voltage balance control is required. The DC voltage balance control acts on the modulation process directly. The error between two capacitor voltages will be sent to the DC voltage balance regulator and dVa is got. The DC voltage balance control variable vba is the product of dVa and the polarity of compensating current. The nature of DC voltage balance control is regulating the active power of the different DC capacitors to make the capacitor voltages balance.

B. Modulation of Cascade Converter

The carrier hybrid pulse width modulation (CH-PWM) [14] is employed for the cascade five-level converter. Taking the converter in Fig. 3 for example, define the leg consisting of Q_{11} and Q_{21} as leg 1, of which the carrier is v_{C1}. So do other three legs. The operation of CH-PWM is shown in Fig. 4. In the figure, m is the modulation wave.

The CH-PWM for 5-level converter has 4 carriers. Two of them are above the zero-axis and their phase difference is 180°. The other two carriers are below the zero-axis and the phase difference is also 180°. All carriers have the same frequency and peak to peak value. The carriers for the legs of one h-bridge have the negative dispositions. So the CH-PWM is the combination of carrier disposition PWM (CD-PWM) and carrier phase shift PWM (CPS-PWM) in fact. The CH-PWM has the two characteristics of low practical switching times of CD-PWM and high equivalent switching frequency of CPS-PWM. In Fig. 4, when the modulation wave is positive, only 4 switches turn on and off with a high frequency and when the modulation wave is negative, the situation is similar. We can find that the equivalent switching frequency is 2 times as the practical carrier frequency. Totally, the using of CH-PWM in cascade 5-level AAPF can decrease the power loss effectively and make the AAPF have a high compensation performance as well.

IV. Simulation Analysis of AAPF

A. Influence of Low Pass Filter on System Performance

With the employment of source current closed-loop control, the system performance reflects as the accuracy of the amplitude of source current reference I_{mk}^*. The majority of I_{mk}^* is the fundamental of load current feedforward component I_{ffk},

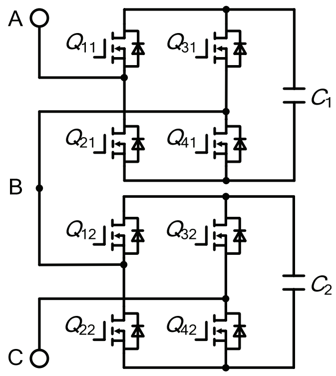


Figure 3. Cascade five-level converter

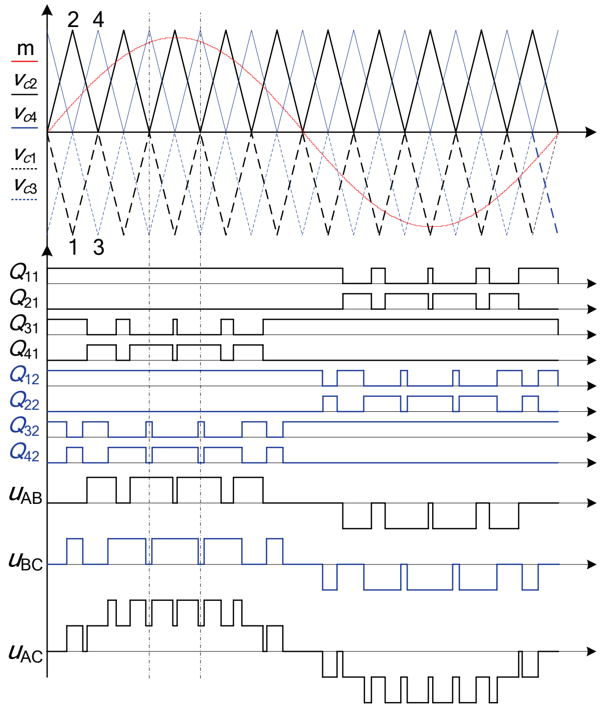


Figure 4. Operation of CH-PWM control cascade converter

so the parameters of the LPF in the process of I_{ffk} obtaining have the key effect on the system performance.

Simulation by Matlab/Simulink is down to study the influence of LPF on the system. The system parameters are: aircraft grid 115V/400Hz, DC-voltage of each capacitor 120V, APF capacitor 680μF, APF coupling inductor 500μH, and carrier frequency 20 kHz.

Fig. 5 illustrates the influence of cut-off frequency f_c on the system performance. The waveforms are load current i_{La}, source current i_{Sa}, load current feedforward component I_{ffa}, APF DC-link voltage feedback component I_{fba} and amplitude of source current reference I_{ma}^*. The load is cut off at the time of 0.4s and up again at 0.5s. It can be find that when f_c is low, the transient state lasts for a long time, but the steady state performance is good because the ripple of amplitude of source current reference is small. With the increasing of f_c, the dynamic performance is better but the steady performance is worse.

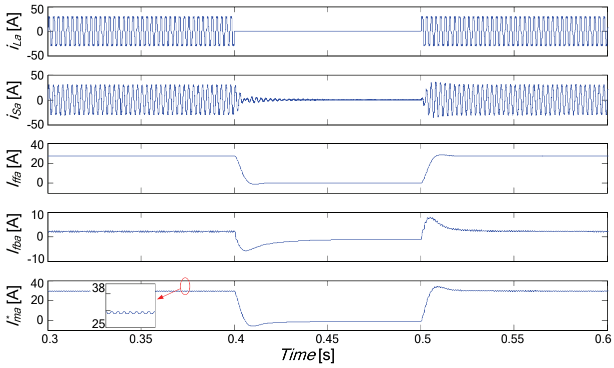
The order of LPF also has an effect on the system performance. Fig. 6 gives the influence of LPF order on the system. With a higher order, the current tracking accuracy is better. However, the transient response will be slower. In general, a second order LPF can meet the demands.

B. Global Simulation of the AAPF system

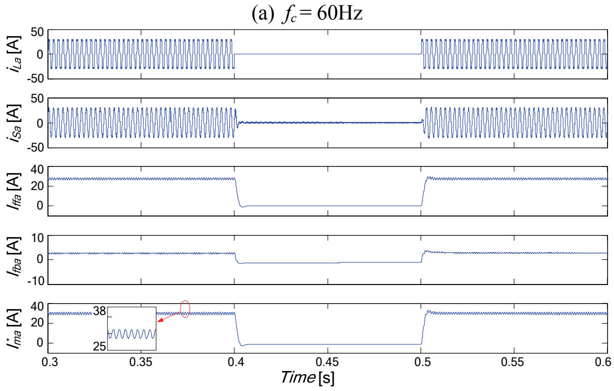
After consideration, a second order Butterworth low pass filter with cut-off frequency of 160Hz is used in the global simulation.

Fig. 7 shows the simulation results of source voltages, load currents, source currents of three phases and two DC-voltages in phase a. The harmonics of load currents are eliminated effectively by the AAPF. The DC-voltage of each capacitor is 120V and the voltage balance control has a good performance.

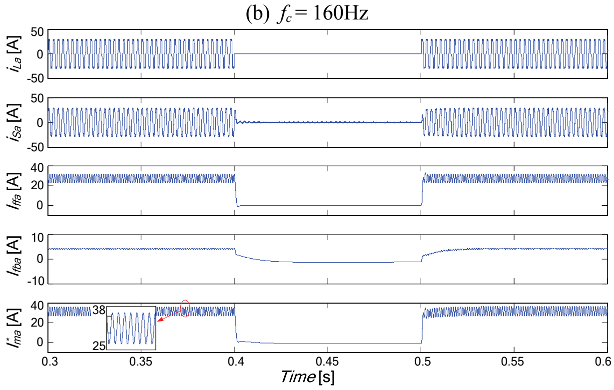
Fig. 8 gives the key waveforms of phase *a*. We can find that the compensating voltage is a five-level waveform.



(a) f_c = 60Hz

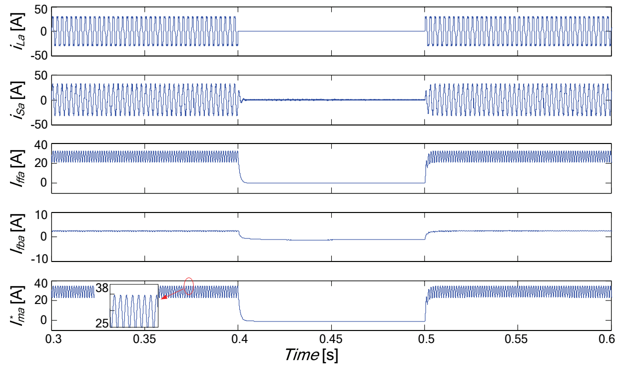


(b) f_c = 160Hz

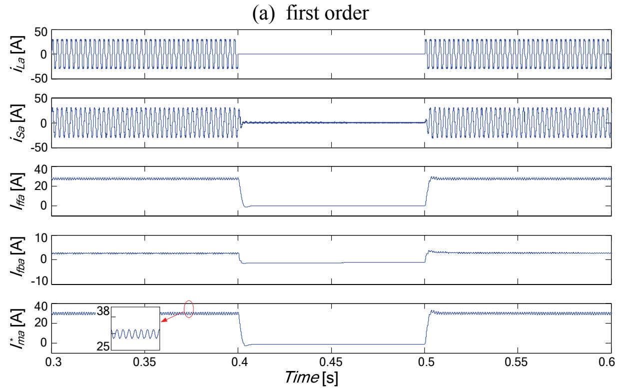


(c) f_c = 320Hz

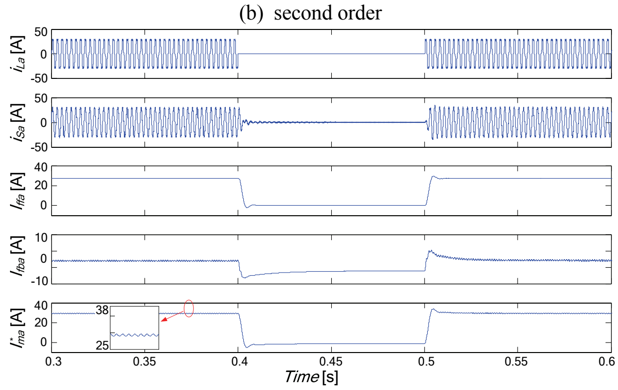
Figure 5. Influence of f_c on system performance



(a) first order



(b) second order



(c) third order

Figure 6. Influence of LPF order on system performance

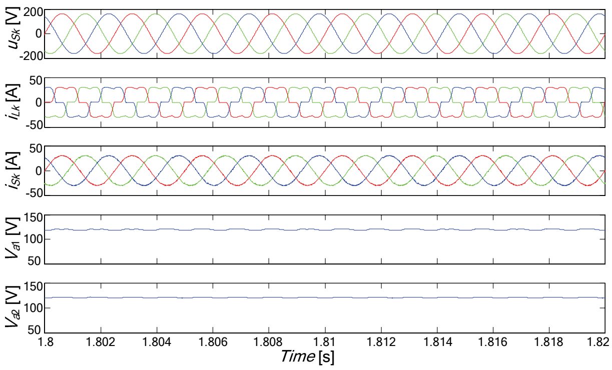


Figure 7. Simulation results of three phase

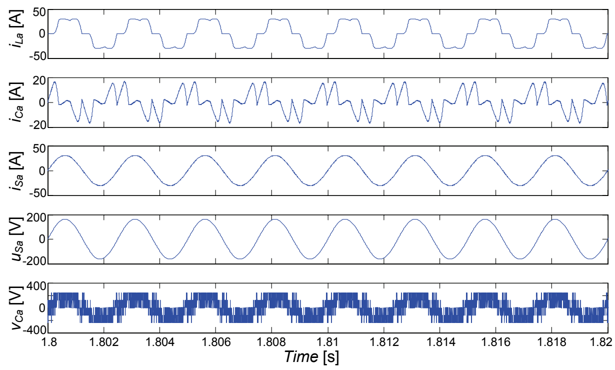


Figure 8. Simulation results of phase *a*

V. PROTOTYPE DESIGN AND EXPERIMENTAL RESULTS

A. Design of Power Switch Driver Module

With the requirement of isolated drives for 8 switches in each phase, a practical multiple isolated power supplies module is designed (as shown in Fig. 9).

The converter in the figure employs the pull-push DC/DC topology with several outputs. The input voltage is 10~20V. The power supply has five isolated outputs, four of which are used as supplies for drives with +15V/-8.5V output voltage and 100mA output current. The other one is the power supply of chips and hall devices with +15V/-15V output voltage and 200mA output current. The power stage of the module is 15.4W.

B. Experimental Results

A 3 kVA prototype is designed in the laboratory to verify the feasibility of the cascade five-level AAPF and the system setup is shown in Fig. 10. The type of the power switches selected is FQ24N60. Other key parameters of the prototype are following those of the simulation.

Fig. 11 shows the source currents of three phases before and after AAPF's compensation. Without AAPF, the source currents are distorted and contain rich harmonics. While after AAPF's compensation, the source currents are nearly sinusoidal. The THDs of the currents are listed in Tab. I.

Fig. 12 gives the experimental results of phase *a* and shows a good performance of the proposed cascade five-level AAPF. The waveforms are load current i_{La}, compensating current i_{Ca}, source current i_{Sa}, source voltage u_{Sa} and compensating voltage u_{Ca}. After compensation, the power factor of the grid side is nearly 1 and the compensating voltage is a five-level waveform.

Fig. 13 illustrates the dynamic performance of the AAPF system. We can find that the proposed AAPF in this paper has a fast dynamic response.

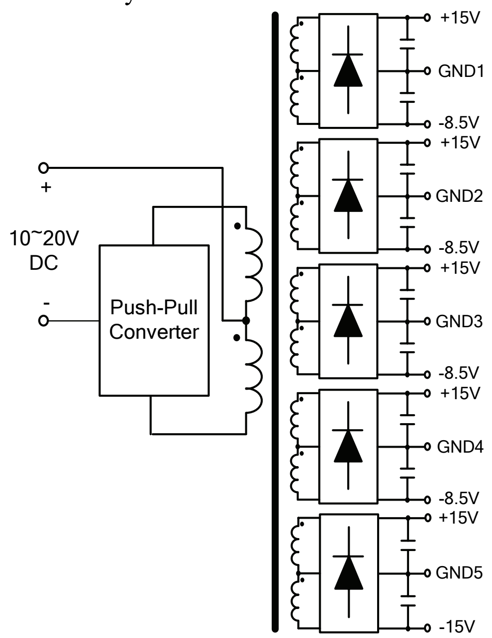


Figure 9. Multiple isolated power supplies module

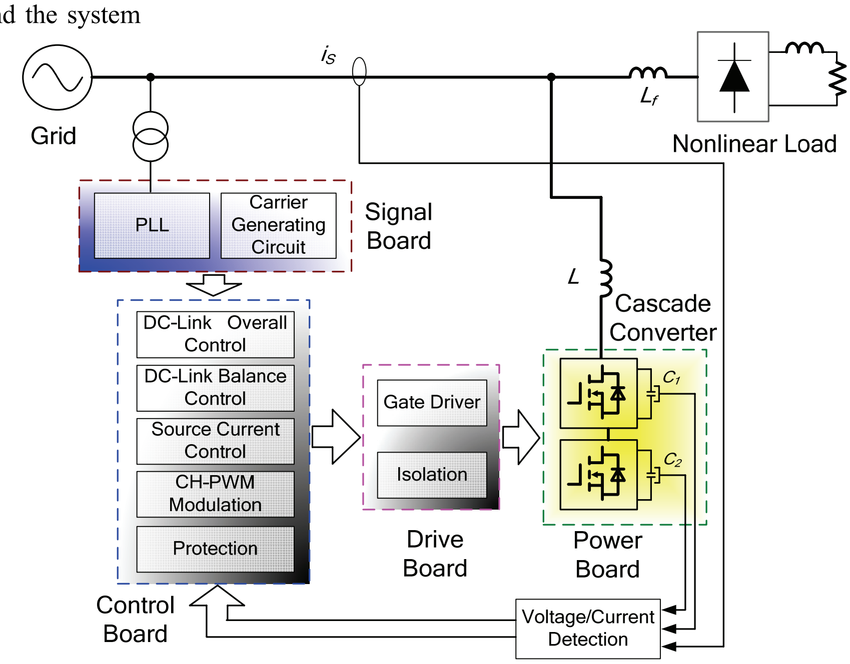
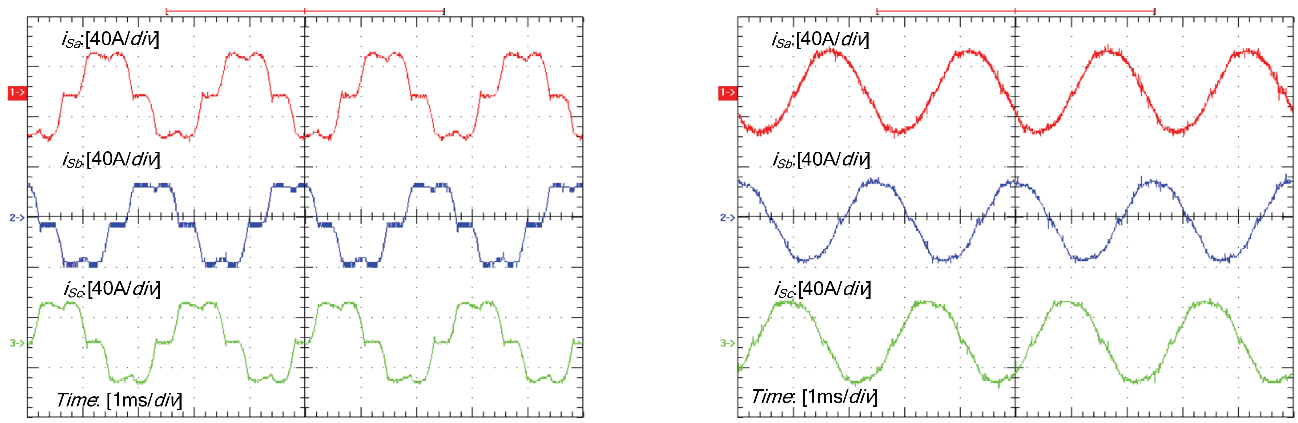


Figure 10. Experimental setup of cascade AAPF



(a) Without AAPF

(b) With AAPF

Figure 11. Experimental results of source currents

TABLE I. THE HARMONICS OF SOURCE CURRENTS

Orders	i_{Sk} no AAPF THD%			i_{Sk} with AAPF THD%		
	a	***b***	***c***	***a***	***b***	***c***
5	15.40	15.53	14.74	3.697	3.216	3.453
7	8.138	9.725	7.503	2.071	2.805	2.357
11	3.115	3.492	2.596	1.993	1.624	2.218
13	1.716	2.606	1.451	0.677	0.847	0.688
THD%	17.85	18.90	16.84	4.496	4.794	4.936

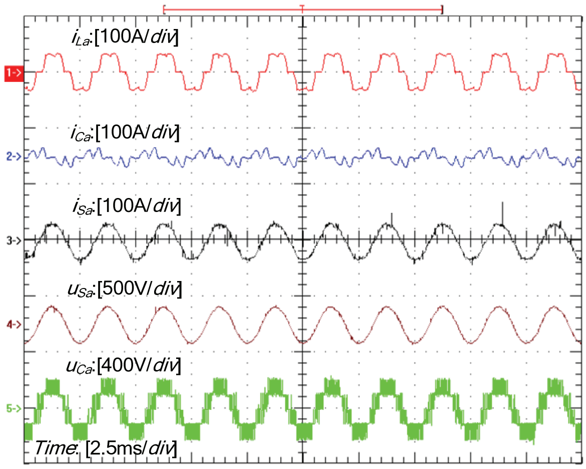


Figure 12. Experimental results of phase *a*

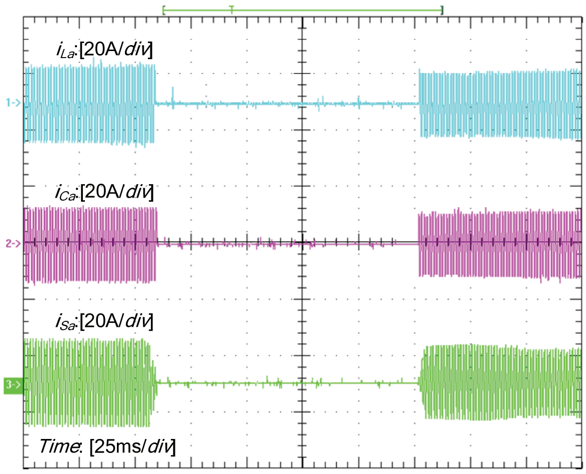


Figure 13. Waveforms of dynamic performance

VI. CONCLUSION

With the development of "More Electric Aircraft", the type and number of airborne electrical equipments are increasing. Power quality problems including the harmonic issues have attracted more and more attentions. Introducing APF, an advanced harmonic eliminating technique, into modern aircraft power system has an important theoretical significance and realistic values. A cascade five-level aeronautical active filter is studied in this paper. The source current closed-loop control and carrier hybrid PWM are employed in the AAPF. Simulation and experimentation show that the proposed AAPF can compensate the harmonics and reactive power produced by the nonlinear load effectively. It is obvious that the cascade five-level aeronautical active filter is feasible.

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