Optimal design of 400 Hz power filter for aircraft switching power supply

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Abstract: - This study aimed to develop a AC 115 V ± 10 %, 3-phase, 400 Hz, 4 A power filter with an attenuation efficiency of up to 70 dB and insulation resistance of below 0.5 Ω for application to the switching power supply of military aircraft. The 400 Hz power filter was designed and fabricated as an all-in-one structure with components that were minimized in terms of size and weight and a low pass filter for the switching noise. The test results showed that it had an excellent attenuation efficiency of up to 73.66 dB in the 100 kHz ~ 30 MHz band. Furthermore, a performance verification test was performed by applying the power filter to an aircraft switching power supply to check for the inhibition of electromagnetic interference in the power unit, and the results confirmed its reliability.


1 Introduction

Although electronic equipment for aircraft has become more lightweight with enhanced performance, output and precision, the increasing intensity of electromagnetic noise from electronic components due to the limited internal space has arisen as an important issue that must be dealt with. Thus, it has become fundamental to consider the aspect of removing electronic magnetic interference (EMI) noise during the design and fabrication processes, while maintaining the aircraft system functions at the same time.

Aircraft contains multiple power generation devices including the main and auxiliary power supplies in order to supply power to the essential equipment even in the event of emergency situations. The main power is supplied by the AC generator, which is usually driven by the engine, and because all AC generators use 400 Hz, the electrical and electronic components of aircraft are constantly exposed to electromagnetic waves. By applying an appropriate technology in filter design for noise removal that can inhibit the EMI, the electromagnetic compatibility (EMC) of the cable and internal interconnection can be improved.

This paper introduces the design method for a power filter, satisfying the 400 Hz requirement, that has been optimized to raise the reliability of aircraft switching power supply.

Section 2 explains the characteristics of aircraft switching power supply, which is EUT to which the power filter is applied, and its noise. In Section 3, the actual process of designing the filter for a switching power supply and the power filter that has been designed and developed as a result are explained. The results of the experiment, measuring the characteristics of the power filter and applying the developed power filter to an aircraft switching power supply, and the conclusions of the study are presented.

2 Switching Power Supply

Switching power supply is equipment that supplies low-voltage, high-current power to the radar processor unit of military aircraft. The design of EUT applied for the verification of the 400 Hz power filter will not be presented in this paper for security purposes due to its nature as a military device.

2.1 EUT description

Fig. 1 is a block diagram of the multi-output switching power supply [1-3]. The output power of the switching power supply is turned on and off by the control signal sent from the external system to the radar processor unit, and this is synchronized with the input frequency signal, causing the
switching frequency to vary. The 115 VAC, 3-phase, 400 Hz power of the aircraft passes generates 6 types of output power converted from the bus power generated through the 3-phase, full wave rectification and smoothing circuits, as well as 28 VDC and 5 VDC AUX power.

Fig.1 Switch Power supply block diagram.

2.2 Noise Characteristics of the EUT
In order to verify the optimal design of the 400 Hz AC power filter applied to the developed power supply, the noise in the power unit prior to the installation of the filter was measured. Based on the aircraft air force limit for the applied specification of MIL-STD-461F, an emission test was conducted.

Fig. 2 CE102 Set-up.

The result of measuring each phase in the CE102 set-up as shown in Fig. 2 showed that 400 Hz switching noise was produced in the entire 10 kHz ~ 10 MHz band, and that it was over the required limit, as shown in Fig. 3 [4].

Based on this result, the power filter was designed to inhibit the 400 Hz switching power noise and its performance was verified. These processes are explained in the following section.

Fig. 3 Measuring the power supply noise before the filter application, (a) Conducted noise of A Phase, (b) Conducted noise of B Phase, (c) Conducted noise of C Phase.

3 Power Filter Development
It is necessary to develop a power filter for noise removal in order to ensure the flight safety and the quality of the power supply. Unlike general forms of noise removal devices, it is essential that the components are compact and lightweight to keep the weight minimal for maximum performance in such a limited space [5].

In the case of aircraft using AC power, the size of the AC power unit is dependent on the frequency. Of particular note, magnetic components (various types of transformers, generators and filters, etc.) take up more than half of the equipment and the sizes of these components are dependent on the frequency. Increasing the frequency can minimize the equipment size, and this is why 400 Hz equipment is used. The reason for using 400 Hz, instead of a higher frequency, is that this is the design parameter that has been globally recognized, considering the overall constraints such as the frequency limitations of the applied components and the impact of the frequency on external electronic equipment, as well as the safety issues associated with long-term use.
Fig. 4 Power filter design stages.

Fig. 4 shows the design method implemented to develop the filter. Before designing a filter, it is important to separate the CM noise and the DM noise for noise flow and component analysis.

As shown in the graph in Fig. 3, DM noise in 400 Hz multiplication was confirmed in the frequency band below 150 kHz, and it was discovered that CM noise generated from DC-DC converter switching multiplied in the frequency band over 150 kHz.

Next, the cut off frequency \( F_0 \) for CM and DM was chosen as 10 kHz and Eq. 1 was used to obtain the component capacity values.

\[
L = \frac{R_d}{2\pi F_0}, \quad C = \frac{1}{2\pi F_0 R_d}
\]  

Eq. 1

Fig. 5 Circuit diagram of the power filter.

The circuit diagram of the developed power filter shown in Fig. 5 shows that MPP core was applied to the L2 component and film capacitor was applied to the C1 component for reduction of DM noise. In order to reduce the CM noise, ferrite core was applied to the L1 component and ceramic capacitor was applied to the C2 component as a means to minimize the distance with the filter case, which was the grounding point [6-9]. When the grounding wire of the filter is long, there is a coefficient of induction between the device frames, deteriorating the frequency characteristics of the filter. Thus, the grounding wire of the filter should be as thick and short as possible.

Based on the volumes of the selected components, the case was designed and fabricated as shown in Fig. 6. For the case, metal with high permeability was used to increase the absorption loss and it was heat treated for a shielding effect.

Fig. 6 Shape and Dimensions, (a) Side view, (b) Top view.

4 Experiment results

A filter may satisfy the requirements based on a characteristics measurement test (CISPR17, MIL-STD-220B, etc.), but its characteristics tend to vary when they are used as a single unit and when they are applied to an actual device. Thus, an experiment was carried out to examine the attenuation characteristics when used alone and the conductivity noise characteristics when it is applied to an actual device.

4.1 Filter Characteristics Measurement

Fig. 7 shows the power filter that was actually developed in this study.

Fig. 7 External appearance (left) and internal appearance (right).
Table 1 Performance criteria.

<table>
<thead>
<tr>
<th>No.</th>
<th>Performance checklist</th>
<th>Criteria</th>
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<tbody>
<tr>
<td>1</td>
<td>Rated voltage/current</td>
<td>AC 115 V, 400 Hz, 4 A</td>
</tr>
<tr>
<td>2</td>
<td>Insulation resistance</td>
<td>Over 10 MΩ when applying 250 VDC between the terminal and the case. Perform conduction test according to the circuit diagram (below 0.5 Ω)</td>
</tr>
<tr>
<td>3</td>
<td>Attenuation factor</td>
<td>Equivalent or higher attenuation factor (Method: MIL-STD-220B)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Frequency (MHz)</th>
<th>Normal</th>
<th>Common</th>
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<tbody>
<tr>
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<tr>
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<td>30</td>
<td>5</td>
<td>20</td>
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</table>

Fig. 8 MIL-STD-220B : Concept for measuring the attenuation characteristics of the filter.

Table 1 shows the performance criteria for the developed filter, and the attenuation characteristics were measured using the MIL-STD-220B method, shown in Fig. 8 [10-11].

A test was conducted using a filter analyzer (Model FA-2100) and related measurement equipment (Model LSA 265). The measurement of the attenuation factor in each phase of the 400 Hz power filter from 100 kHz to 30 MHz showed that it was an excellent filter with attenuation factor of up to 70 dB, which was above the required level, as shown in Table 2 and Fig. 9.

Table 2 Input loss of EMI filter.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Normal Mode</th>
<th>Maximum value of Fig. 9 (a)–(c)</th>
<th>Common Mode</th>
<th>Maximum value of Fig. 9 (d)–(f)</th>
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</thead>
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<td>Frequency (MHz)</td>
<td>0.1</td>
<td>0.5</td>
<td>1</td>
<td>5</td>
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<tr>
<td>Attenuation (dB)</td>
<td>35</td>
<td>47</td>
<td>43</td>
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<table>
<thead>
<tr>
<th>Mode</th>
<th>Normal Mode</th>
<th>Maximum value of Fig. 9 (d)–(f)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (MHz)</td>
<td>0.1</td>
<td>0.5</td>
</tr>
<tr>
<td>Attenuation (dB)</td>
<td>11</td>
<td>32</td>
</tr>
</tbody>
</table>

An attenuation factor of 20 dB means that the noise level has been reduced by 1/10, while 40 dB means 1/100 reduction and 60 dB means 1/1,000 reduction. This relationship is shown in Eq. 2.

\[ \text{Attenuation(dB)} = 20 \log_{10} \frac{e_2}{e_1} \quad (2) \]

\(e_1\): The level reached with the noise filter
\(e_2\): The level reached without the noise filter

Fig. 9 Attenuation characteristics of the frequencies with respect to each line filter, (a) Attenuation of A Normal, (b) Attenuation of A, C Normal, (c) Attenuation of B, C Normal, (d) Attenuation of A Common, (e) Attenuation of B Common, (f) Attenuation of C Common.

4.2 Noise Characteristics of the EUT with power filter

The switching power supply supplies power to each of the internal elements through the EMI filter when it receives an input of 115 VAC from an external power source. The EMI filter blocks the noise from coming inside through the 115 VAC input and the internal noise from leaking to the outside.

Fig. 10 Block diagram of the switch power supply with EMI filter.
Fig. 10 shows an input EMI filter in the power input unit for the reduction of noise generated outside or inside the power supply unit. The filter should be mounted as closely as possible to the input/output ports of the equipment and the input/output cables of the filter should not be overlapped to allow maximum attenuation performance of the filter.

A conductivity test was conducted in accordance with the military specifications to check whether the power filter satisfied the reliability and filter characteristic criteria set forth for military equipment during actual application. As shown in Fig. 11, the test results showed that it conformed to all the criteria.

![Graphs showing conducted noise measurements](image1)

Fig. 11 Measuring the power supply noise after the filter application. (a) Conducted noise of A Phase, (b) Conducted noise of B Phase, (c) Conducted noise of C Phase.

5 Conclusion
In this study, a 400 Hz power filter was developed for application to 8 multi-output switching power supply units of military aircraft. The filter was designed to minimize the 400 Hz switching power noise and as an all-in-one structure to enhance the utility of the limited space. The structural design is characterized by a through pipe for the withdrawal of the wiring that is welded to the body, which helps maintain high shield effectiveness.

In an experiment, the power filter showed outstanding performance with an attenuation factor of up to 70 dB higher than the required value. On the other hand, a power unit EMC reliability test showed that the switching noise characteristics of the power supply improved when a model with enhanced capacity to block the DM noise was applied to an aircraft switching power supply.

6 Acknowledgement
This research was supported by Economic Region Collaborative Program through the Korea Institute for the Advancement of Technology (KIAT) funded by the Ministry of Trade, Industry and Energy (R0002611)

References:


