Design and Verification of 400Hz Power Filter for Aircraft Switching Power Supply

Ju-Min Lee, Heon-Wook Seo, Sung-Su Ahn, Jin-Dae Kim, Woo-Hyun Kim and Ki-Jin Kwon

Abstract**—**This paper introduces power filter developed for application to the switching power supply of military aircraft. 400 Hz power filter specification includes rated voltage of AC 115 V ± 10 %, 3-phase, 400 Hz and 4 A of rated current and is designed to an all-in-one structure with insulation resistance of below 0.5 Ω. The filter characteristics 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.

Keywords**—**Electromagnetic Interference (EMI) Filter, Electromagnetic Compatibility (EMC), Insertion loss, Attenuation factor, RLC circuits, Power filters, Switching noise.

I. INTRODUCTION

AVIATION electronic devices has made technical progress and they tend to have higher output, better performance, lighter weight and smaller size, while the aircraft's internal space is limited. Therefore, it became essential in the knowledge-based industry to remove electromagnetic noise from aviation electronic components. Accordingly, design and construction issue to remove the noise source, Electromagnetic Interference (EMI) became critical, while maintaining the whole aircraft system functions.

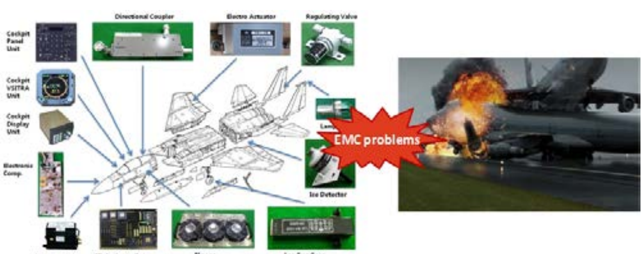


Fig. 1 potential risk by aircraft is electronic devices and EMI

J.M. Lee is with the Daegu Mechatronics & Materials Institute, Dalseo-gu, Daegu REPUBLIC OF KOREA (phone: +82-53-608-2054; fax: +82-53-608-2119; e-mail: jmlee@dmi.re.kr).

H.W. Seo is with the Daegu Mechatronics & Materials Institute, Dalseo-gu, Daegu REPUBLIC OF KOREA (e-mail: seo7712@dmi.re.kr).

S.S. Ahn is with the Daegu Mechatronics & Materials Institute, Dalseo-gu, Daegu REPUBLIC OF KOREA (e-mail: zecks@dmi.re.kr).

J.D. Kim is with the Daegu Mechatronics & Materials Institute, Dalseo-gu, Daegu REPUBLIC OF KOREA (e-mail: jdkim@dmi.re.kr).

W. H. Kim is with Yeungnam College of Science & Technology, Nam-gu, Daegu REPUBLIC OF KOREA (e-mail: whkim@ync.ac.kr).

K. J. Kwon is with Yeungnam College of Science & Technology, Nam-gu, Daegu REPUBLIC OF KOREA (e-mail: kjkwon@ync.ac.kr).

Aircrafts are equipped with several power supplies including main and auxiliary power supply to provide uninterrupted power to essential equipments even in the emergency state. Main power is usually supplied by AC generator which is mainly driven directly by engine. Aircraft's electric and electronic devices are always exposed to EMI since they all use 400 Hz frequency. It is able to enhance EMC compliance for interconnection between cable and inner part of the device by applying appropriate noise removal filter design technology that can suppress EMI.

Accordingly, this paper aims to introduce a power filter design technology which satisfies 400 Hz requirements and is optimized to realize high reliability of aircraft switching power supply.

Basic contents of initial development for this design technology is introduced at 3rd International Conference On Circuits, Systems, Communications, Computers and Applications (CSCCA '14) in Nov. 2014 [1].

This paper is organized as follows: Chapter 2 describes about our EUT (Equipment under test), aircraft switching power supply and its noise characteristics which is subject to be applied to our power filter design. Chapter 3 explains filter design process for actual switching power supply, and its developed power filter. Finally, we present the measurement results of power filter characteristics, along with experiment results after application of developed power filter to aircraft switching power supply, and thereby draw a conclusion.

II. AIRCRAFT SWITCHING POWER SUPPLY

Switching power supply is the device to supply low voltage and high current power to military aircraft radar processor unit. EUT's shape, which is applied to verified the 400 Hz optimized filter, is not presented in this paper due to the security issue of military product.

A. EUT Description

Figure 2 is the block diagram of multiple output switching power supply [2]-[4]. Switching power supply turns on/off the output power according to the control signal applied from external system to military aviation radar processor unit. It has variable switching frequency that is synchronized to external input frequency signal. Aircrafts power with 115 VAC, 3-phase, 400 Hz generates 6 output power which converts the bus power through 3-phase full-wave rectifier/smoothing circuit, in addition to

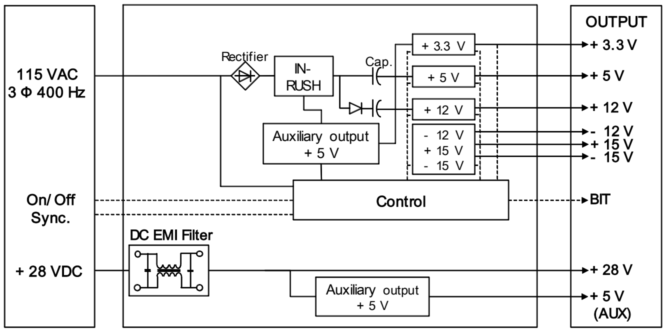


Fig. 2 switch power supply block diagram

B. *Noise Characteristics of the EUT*

First, we measured noise at the power terminal before installing the filter to verify whether the design is optimized for 400 Hz AC power filter application. Applied specification was aircraft air force limit criteria in MIL-STD-461F and conducted emission test. As shown in Figure 3, we prepared CE102 test configuration and measured for each phase.

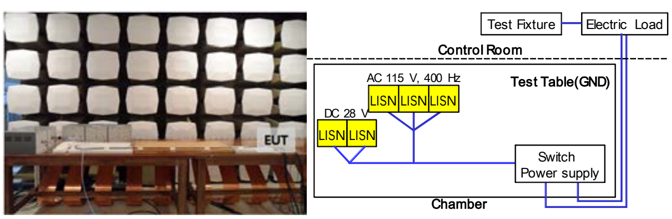
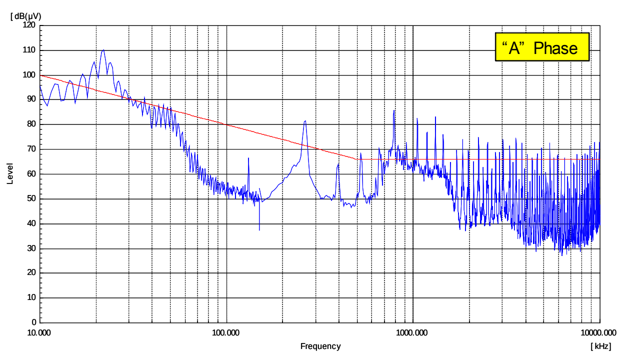
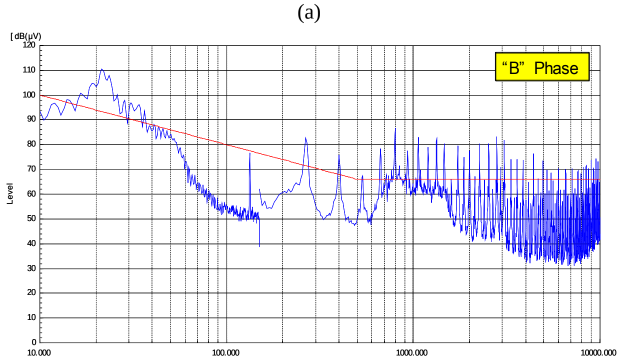


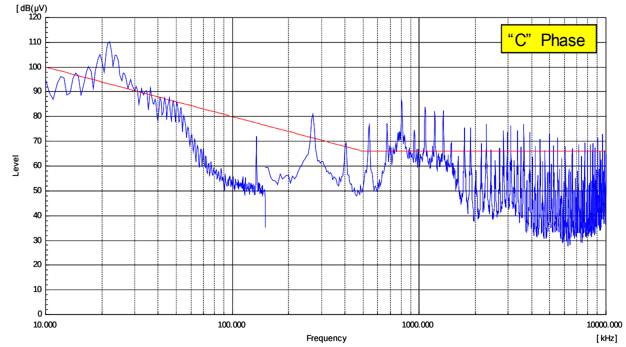
Fig. 3 CE102 Set-up



(a)



(b)



(c)

Fig. 4 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

The result shows that it has 400 Hz switching noise from entire bandwidth between 10 kHz ~ 10 MHz, and it is above the required limit as shown in Figure 4 [5].

In next chapter, we describe the power filter design and performance verification process to suppress 400 Hz switching power noise based on these results.

III. Power Filter Design and Manufacturing

To secure flight safety and to realize high power quality, power supply's noise removal filter development is required, and it is essential to make it compact size and lightweight, different from other general noise removal device [6].

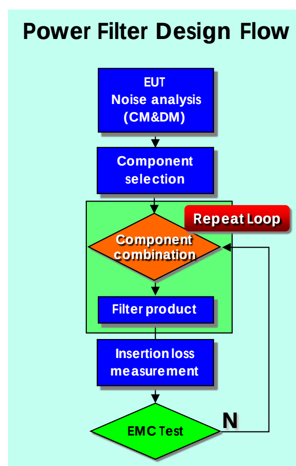


Fig. 5 Power filter design flow diagram

For aircraft using AC power, the size of AC power generator depends on frequency. Magnetic components (e.g., transformers, generators and filters), in particular account for more than half of the device, and the frequency determines the size of these components. The size of device can be smaller as you use higher frequency, and that is the reason to use 400 Hz. 400 Hz is selected instead of higher frequency because it is globally approved design variable considering all related conditions including the frequency limit of the components used for the device, the effect of external electronic devices by the selected frequency, and also the longer period of safe use.

Figure 5 shows the block diagram of design process to develop filter. First, before designing filter, it is important to separate CM noise and DM noise to analyze noise flow and its component analysis.

From the graph in Figure 4, DM component noise is multiplied as 400 Hz under 150 kHz frequency band, and CM component noise from DC-DC converter switching is multiplied above 150 kHz frequency band.

Next, the cut off frequency (F_0) for CM and DM is set to 10 kHz and Equation 1 was used to obtain the component capacity values.

$$L = \frac{R_d}{2\pi F_0}, \quad C = \frac{1}{2\pi F_0 R_d}. \tag{1}$$

From the circuit diagram for the filter developed according to Figure 6, it uses MPP core for L2, and film capacitor for C1 to reduce DM component noise. Also, it uses ferrite core for L1, and ceramic capacitor for C2 to reduce CM component noise, and it minimizes the distance from filter case which is the grounding point [7]-[10]. If filter's ground wire is long, then there appears induction coefficient, and it deteriorates filter is high frequency characteristics.

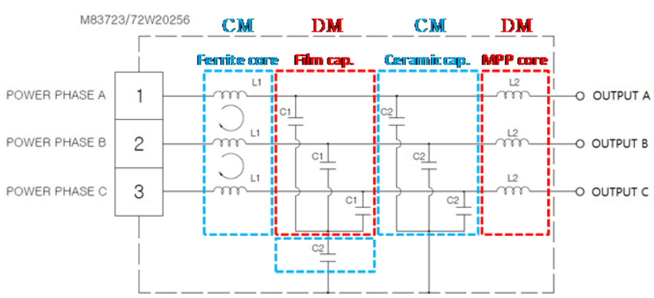
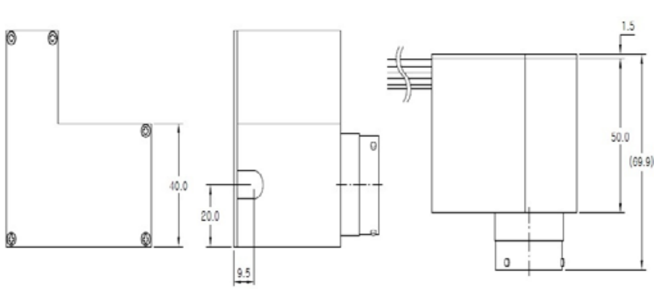


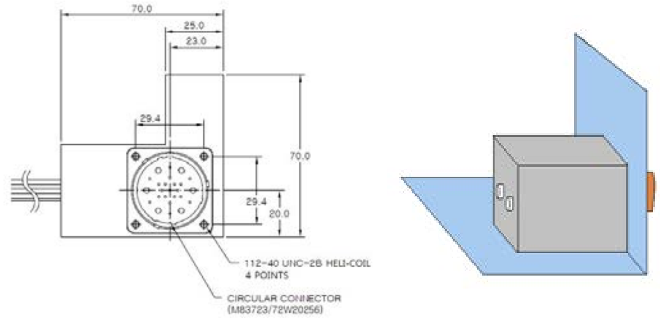
Fig. 6 Power filter circuit diagram

Therefore, filter is ground wire should be thick and short, if possible.

Based on the volume of selected parts, we designed and manufactured the case as shown in Figure 7. We use metal with high permeability to increase absorption loss, and shield it through heat treatment. Also, it has high shield effectiveness due to its integrated structure characteristics.



(a)



(b) (c)

Fig. 7 Shape and dimensions, (a) Side view, (b) Top view, (c) Integrated structure

IV. Experiment Results

Even the filter satisfies required characteristics using characteristics test method (CISPR17, MIL-STD-220B, etc), its characteristics as a single item and when it is applied to actual product is different. Therefore, we perform experiment for filter is attenuation characteristic which is single item characteristic, and for filter is conductive noise characteristic which appears when it is applied to the product.

A. Filter Characteristics Measurement

Figure 8 shows the actual filter shape that is developed in this study.

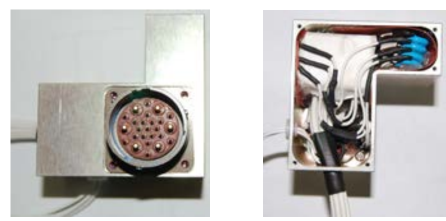

(a) (b)

Fig. 8 Actual filter shape, (a) External appearance, (b) Internal appearance

Single item power filter shall meet the requirements in Table 1, and we measured its attenuation ratio according to MIL-STD-220B shown in Figure 9 [11]-[12].

Table 1 Performance criteria

No.	Performance checklist	Criteria							
1	Rated voltage/current	AC 115 V, 400 Hz, 4 A							
2	Insulation resistance	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)							
3	Attenuation factor	Equivalent or higher attenuation factor (Method: MIL-STD-220B)							
		Frequency (MHz)	0.1	0.5	1	5	10	20	30
		Normal	20	30	30	20	10	5	5
		Common	5	10	10	30	20	20	20

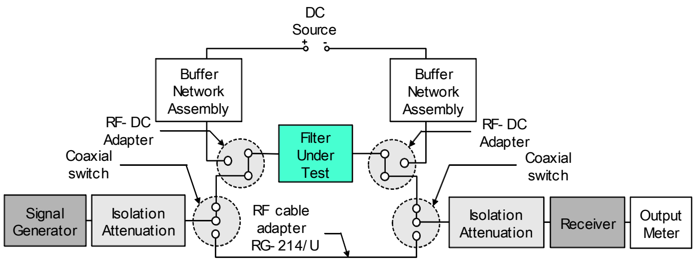


Fig. 9 MIL-STD-220B : Concept for measuring the attenuation characteristics of the filter

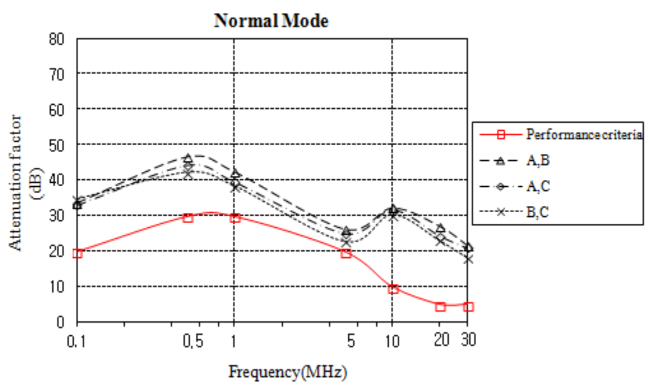
According to the test result using Filter Analyzer (Model FA-2100) and related measuring equipment (Model LSA 265), it is shown in the Table 2 and Figure 10 that filter is attenuation ratio of each phase is maximum 22 dB higher than requirement in Normal Mode, and maximum 44 dB higher than requirement in Common Mode.

Here, Equation 2 indicates that 20 dB of attenuation means 1/10 noise level reduction, 40 dB of attenuation means 1/100 noise level reduction, and 60 dB of attenuation means 1/1000 noise level reduction.

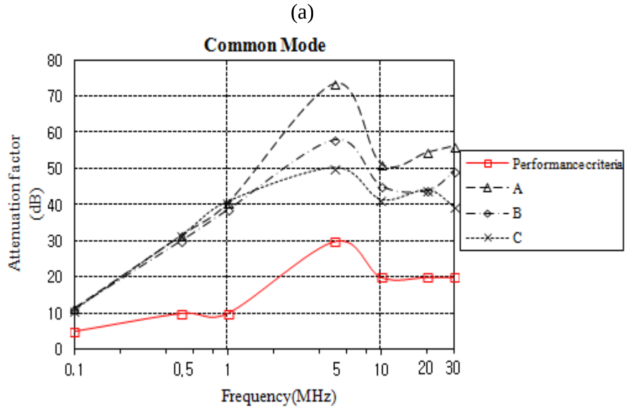
$$Attenuation(dB) = 20Log_{10}\frac{e_2}{e_1}. \quad (2)$$

e_1: The level reached with the noise filter

e_2: The level reached without the noise filter



(a)



(b)

Fig. 10 Frequency attenuation characteristic for each line filter per frequency band, (a) Normal mode, (b) Common mode

Table 2 Input loss of EMI filter

Mode	Normal Mode Maximum value of Fig. 10 (a)						
Frequency (MHz)	0.1	0.5	1	5	10	20	30
Attenuation (dB)	35	47	43	26	32	27	22
Mode	Common Mode Maximum value of Fig. 10 (b)						
Frequency (MHz)	0.1	0.5	1	5	10	20	30
Attenuation (dB)	11	32	41	74	51	55	56

B. *Noise Characteristics of the EUT with power filter*

Configure switching power supply so that it can supply power through EMI filter when there is 115 VAC external power supply. EMI filter for 115 V is connected to external power supply connector to prevent incoming of external noise, and to prevent outgoing of internal noise.

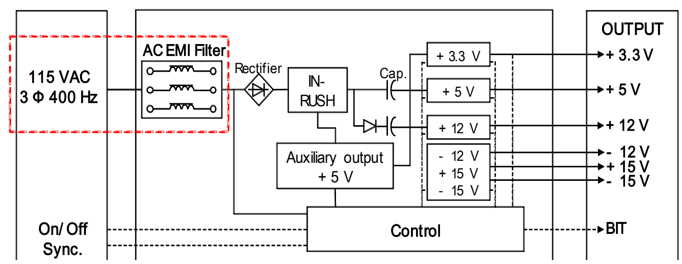
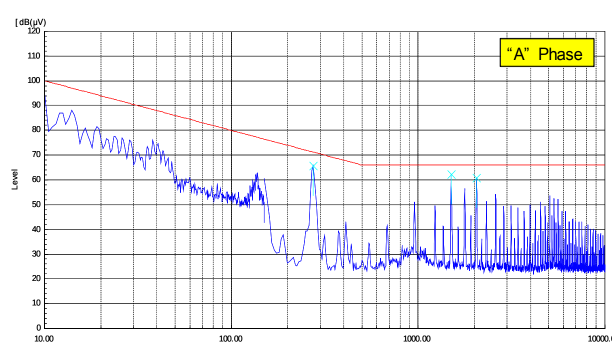


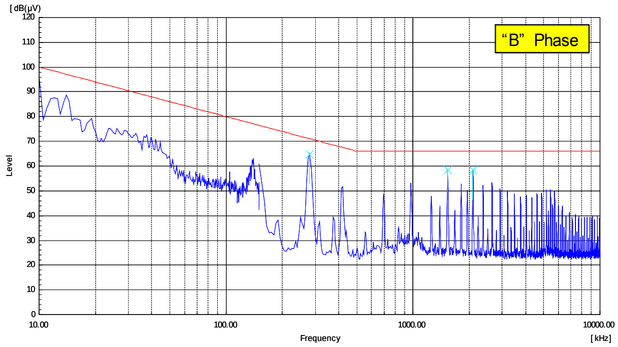
Fig. 11 Block diagram of the switch power supply with EMI filter

Figure 11 shows noise reducing EMI filter is located to reduce noise from external device or from internal circuit. Filter should be located as close to device is input/output port as possible, and filter is I/O wire should not be overlapped to maximize filter is attenuation characteristics.

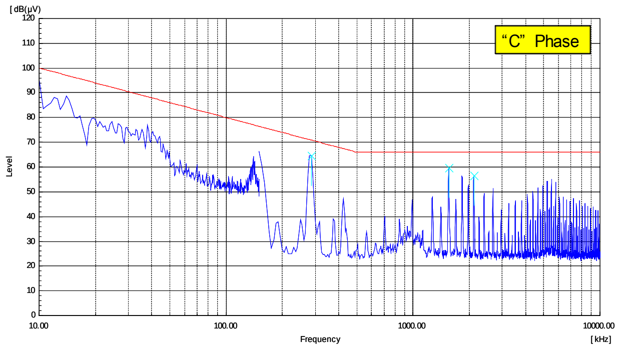
We performed conducted noise test after mounting the device based on military specification to verify whether it satisfies reliability and filter characteristics as a military equipment. Figure 12 shows that they all satisfy the required criteria.



(a)



(b)



(c)

Fig. 12 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

V. CONCLUSION

In this study, we developed 400Hz power filter that can be applied to 8 multiple output switching power supply for military aircraft. This device is designed as low pass filter type to minimize 400 Hz switching power supply is power noise, and is designed and manufactured as integrated structure to improve space utilization in the limited space, and minimized size and weight of components. Special feature of this structure is that the penetrating pipe for cables is welded to body to secure high shield effectiveness.

Attenuation ratio of the lab developed power filter itself is higher than the performance requirement for each mode, and indicated excellent characteristic with 70 dB above the requirement. For specific noise sources, EMC reliability test at the power terminal shows that DM shield characteristic enhanced model also indicated improved switching noise characteristic for corresponding power supply when it is applied to aircraft switching power supply that requires filter.

ACKNOWLEDGMENT

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

[1] J. M Lee, H. W. Seo, S. S. Ahn and J. D. Kim, "Optimal design of 400 Hz power filter for aircraft switching power supply," in *Proc. 3rd Int. Conf. on Circuits, Systems, Communications, Computers and Applications (CSCCA '14)*, Florence, Italy, pp. 73-78, Nov. 2014.

[2] S. J. Robert. Synchronous Rectification in High-Performance Power Converter Design. Texas Instruments Available: http://www.ti.com

[3] B. Keith and M. Taylor. *Switch mode Power Supply Handbook*, 3rd ed., McGraw Hill, 2011.

[4] S. Lopez Arevalo, "Control and Implementation of a Matrix-Converter-Based AC Ground Power-Supply Unit for Aircraft Servicing," *IEEE Trans. on Industrial Electronics*, vol. 57, issue 6, pp. 2076–2084.

[5] *Requirements for the Control of Electromagnetic Interference Characteristics of Subsystem and Equipment*, Department of Defense Interface Standard MIL-STD-461F, Dec. 2007.

[6] J. Milton and E. Greenwood, "Improving the Specifications For Power-Line Filters," *IEEE Trans. on Electromagnetic Compatibility*, vol. EMC-10, issue 2, pp. 264-268, Jun. 1968.

[7] H. M. Hoffart, "Electromagnetic Interference Reduction Filters," *IEEE Trans. on Electromagnetic Compatibility*, vol. EMC-10, issue 2, pp. 225-232, Jun. 1968.

[8] D. J. Jobe, "Selection and Test of Power Line Filters for Use in Equipment Designed to Meet Government Electromagnetic Compatibility Specifications," in *Proc. IEEE Electromagnetic Compatibility Symposium Record*, NJ, USA, pp. 283-289, 1969.

[9] H. M. Schlicke and H. Weidmann, "Compatible EMI Filters," *IEEE Spectrum*, vol. 4, issue 10, pp. 59-68, 1967.

[10] H. Weidmann and W. J. McMartin, "Two Worst-Case Insertion Loss Test Methods for Passive Power-Line Interference Filters," *IEEE Trans. on Electromagnetic Compatibility*, vol. EMC-10, issue 2, pp. 257-263, 1968.

[11] *Method of Insertion Loss Measurement*, Department of Defense Test Method Standard MIL-STD-220B, Jan. 2000.

[12] H. M. Schlicke, H. Weidmann, and H. S. Dudley, "The Controversial MIL STD 220A," in *Proc. IEEE Electromagnetic Compatibility Symposium Record*, NJ, USA, pp. 215-226, 1969.