Operational Amplifier Gain-Bandwidth Product Enhancement Technique for Common-mode Active EMI Filter Compensation Circuits

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ABSTRACT

In this paper, the operational amplifier (op-amp) gain-bandwidth product (GBP) enhancement technique for common-mode (CM) active EMI filter compensation circuits is proposed. To evaluate the proposed concept, the CM reduction performance of active EMI filters with: voltage canceling, current canceling, and closed-loop techniques, is chosen to be verified. The design procedures of enhanced op-amp GBP of CM active EMI filters are also provided. Finally, the CM reduction performances of the proposed approach are compared and verified experimentally. From the experimental results, it can be concluded that the proposed approach can improve the CM reduction performance of conventional active EMI filters from about 5 dBuV up to 20 dBuV at a certain frequency range.

Keywords: Active EMI Filters, Common-Mode Emission, EMC, EMI, EMI Filters, GBP, Op-amps

1. INTRODUCTION

In modern days, power electronics are extensively embedded into a variety of applications from small products e.g. consumer products, electrical and electronic appliances, etc. up to large systems like transportations e.g. electric cars, electric trains, and power systems e.g. smart grids, HVDC and flexible ac transmission lines. However, one of the major side effects, when the power electronic systems are embedded, are the electromagnetic interference (EMI) generated by their switching operations [1]. In order to suppress such generating EMI, there are many possible ways to do so, but the most popular choice is still by use of EMI filters [2]. Typically, there are three types of EMI filters: passive, active, and the integration between passive and active EMI filters called "hybrid" one. Although, a passive EMI filter is a classical approach, it is still widely used in electrical/electronic industries. However, the main disadvantages of a passive type are bulky and heavy [1]-[2]. To solve such a drawback, an active EMI filter is proposed [3]-[5]. The large size of passive components, such as common mode chokes, is replaced by the smaller size of passive components together with some active control circuitry [3]. Nevertheless, by using the active control circuitry, it has some critical constraints i.e. limitation of gain-bandwidth product (GBP) of an operational amplifier (op-amp) which affects to filter performance degradation especially at a high frequency range [3], [6]. In order to improve EMI reduction performance of active EMI filters, the method to enhance the op-amp gain-bandwidth product is presented in this paper. Three compensation techniques, i.e. voltage canceling technique [5], current canceling technique [5], and closed-loop technique [13], are chosen to be studied. It should be noted that, although this method could be adapted for both differential (DM) - and common-mode (CM) active EMI filter compensation circuits, this paper focuses only on the CM reduction circuit.

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2. OP-AMPS GAIN-BANDWIDTH PRODUCT ENHANCEMENT CIRCUIT FOR ACTIVE EMI FILTERS

In [7], the approach to enhance the GBP of an op-amp is proposed as shown the circuitry in Fig. 1. It should be noted that this approach, composed of two conventional op-amps, is suitable for discrete type applications [8].

For sake of simplicity, assuming that the GBP of op-amp A_1 is much larger than that of A_2($GBP_1 \gg GBP_2$), so that gain of each op-amp can be expressed by:

$$A_{OL_i}(s) = \frac{(GBP_i/\omega_{ti})}{s+\omega_{ti}}, \quad (1)$$

where $i = 1{,}2$ and ω is the op-amp low frequency pole.

Since the bandwidth of two op-amps is separated widely, it avoids the stability problem, and yields

$$V_0(s) = V_x(s)\frac{(GBP_2)}{2}, \quad (2)$$

and

$$V_x(s) = -\frac{R_L}{R_i}V_{in}(s) - \frac{R_L}{R_f}V_o(s), \quad (3)$$

As a result, the closed-loop gain for inverting config-

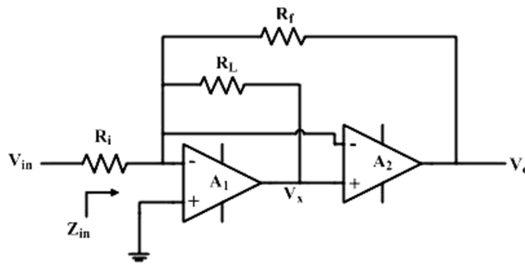


Fig.1: *Constant-bandwidth inverting amplifier [7].*

uration can be determined as:

$$\frac{V_o(s)}{V_{in}(s)} \simeq -G\left[\frac{\frac{GBP_2}{\alpha}}{s+\frac{GBP_2}{\alpha}}\right], \quad (4)$$

where $G = R_f/R_i$, $\alpha = R_f/R_L$ and must be greater than unity [8].

With this condition, the closed-loop gain is constant, and its cut-off frequency is located at

$$f_{-3dB} \simeq \frac{GBP_2}{2\pi\alpha}. \quad (5)$$

However, it is worth to note that in case of $\beta = (GBP_1/GBP_2) \geq 1$, the stability issue needs to be taken into account. To prevent such a problem, the and must be carefully chosen [7].

Since the EMI reduction performance of an EMI filter is strongly dependent on the connecting impedances at input and output ports of an EMI filter [1]. As a result, to design an EMI filter optimally, the input impedance of an active EMI filter should be taken into consideration.

For the input impedance of inverting circuit of Fig. 1, it can be determined by:

$$Z_{input}(s) \cong \frac{s^2 R_f}{(\alpha+1)s^2 + (\alpha GBP_1 + GBP_2)s + (GBP_1 \cdot GBP_2)} \cong 0 \; (GBP_1 \gg GBP_2) \quad (6)$$

From Eq. (6), it shows that at low frequencies the input impedance is very small. As frequency increases, the input impedance increases up to the maximum value of $[R_f/(1+\alpha)]$ which is distinguish from the conventional circuit whose the maximum input impedance is equal to input resistance of the inverting terminal [7].

3. DESIGN PROCEDURES OF ENHANCED OP-AMP GAIN-BANDWIDTH PRODUCT OF COMMON-MODE ACTIVE EMI FILTERS

In order to evaluate the proposed concept, widely-used three compensation circuits of active EMI filters, i.e. voltage canceling technique [5], current canceling technique [5], and closed-loop technique [13], are chosen to be verified. The CM reduction performances of conventional (one op-amp) and proposed (two op-amps) circuits are compared.

3.1 Design of Enhanced Op-amp GBP of CM Active EMI Filters Using Current Canceling Technique

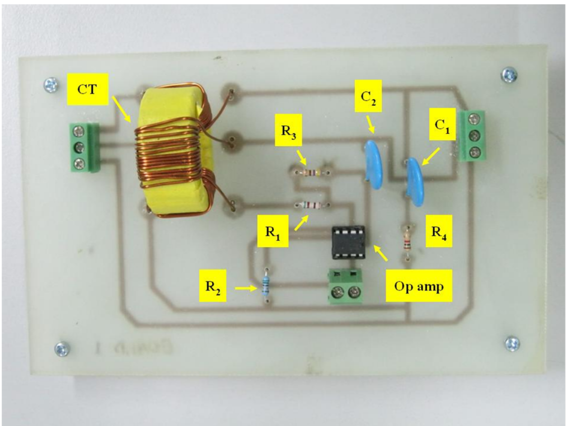
The photograph and schematic diagram of CM active EMI filters using current canceling technique are shown in Figs. 2 (a) and 6 (a) for conventional approach (one op-amp), and in Figs. 3 (a) and 6 (b) for proposed approach (two op-amps) respectively. It comprises: current transformer, op-amps, resistors and ceramic capacitors. In this paper, the op-amp AD811 was chosen. From Eq. (4) to achieve gain equal to 10, it yields R_5 (or R_f in Fig. 1) and R_1 (or R_i in Fig. 1) equal to 511 and 51 Ω, respectively, where R_2 and R_4 are chosen to be 50 and 1000 Ω. From the condition that the Îś must be greater than one, R_3 is selected to be equal to 50 Ω. Since capacitors C_1 and C_2 are used to inject the compensated current into the main ac lines, according to safety considerations, both capacitors are ceramic type and equal to 3300 pF/2kV. For the current transformer, the design procedure is referred to [3], and is not repeated here.

3.2 Design of Enhanced Op-amp GBP of CM Active EMI Filters using Voltage Canceling Technique

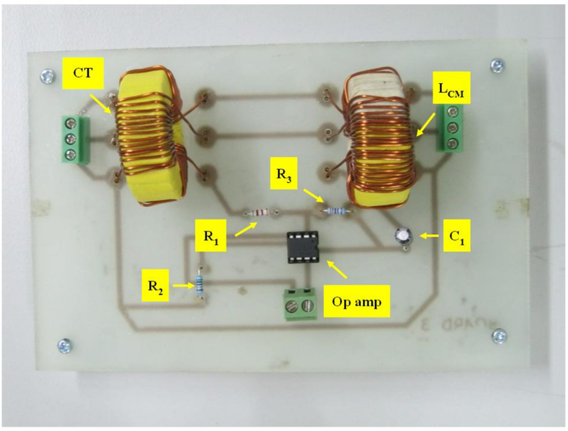
The photograph and schematic diagram of CM active EMI filters using voltage canceling technique is shown in Figs. 2 (b) and 10 (a) for conventional approach (one op-amp), and in Figs. 3 (b) and 10 (b) for proposed approach (two op-amps) respectively. Similarly, the components are the same as in case of current canceling technique except that this circuit uses two current transformers and C1, as shown in Fig. 2 (b), is the electrolytic type with the chosen value of 10 μF [5].

3.3 Design of Enhanced Op-amp GBP of CM Active EMI Filters using Closed-Loop Technique

The advantage of closed-loop technique is that it can reduce the CM emission without the use of a current transformer. Although, this invention was first designed for motor drive applications, it applies to SMPS applications in this paper. By this technique, the differential signal is amplified which resulted as error signal in a closed loop control to reduce CM emissions [13]. The photograph and schematic diagram of CM active EMI filters using closed-loop technique is shown in Figs. 2 (c) and 14 (a) for conventional approach (one op-amp), and in Figs. 3 (c) and 14 (b) for proposed approach (two op-amps) respectively. From Eq. (4) to achieve gain equal to 10, it



(a)



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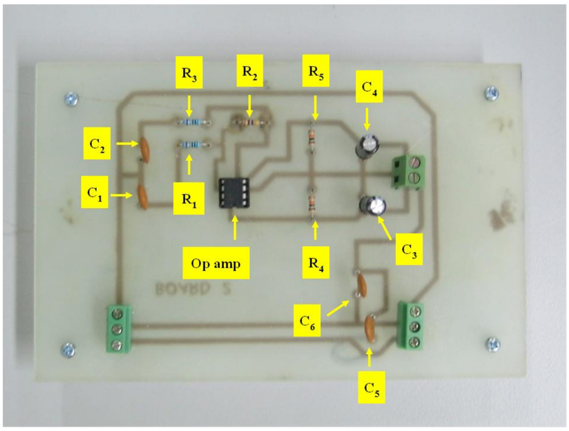
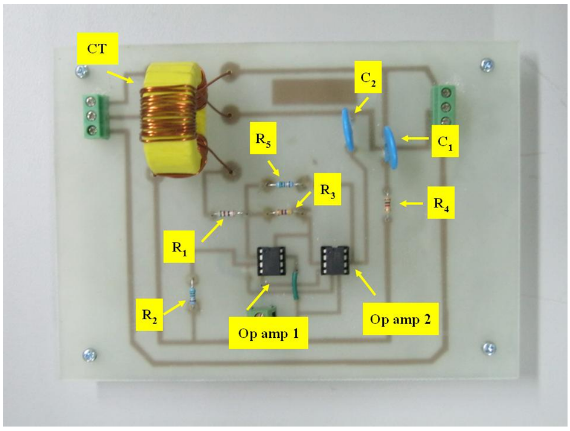
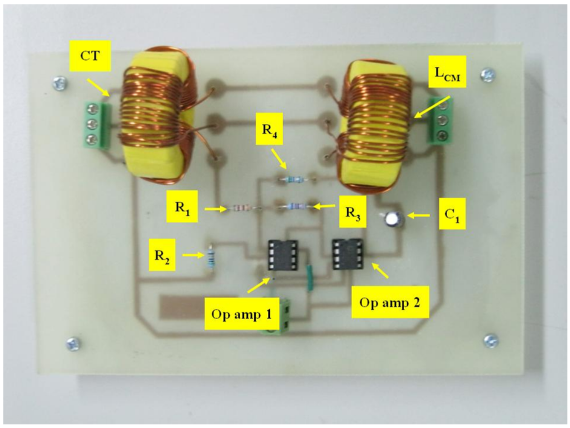


(c)

Fig. 2: *Photograph of conventional approach: (a) current- (b) voltage- canceling compensation circuits and (c) closed-loop techniques that used as active EMI filters for CM EMI reduction.*



(a)



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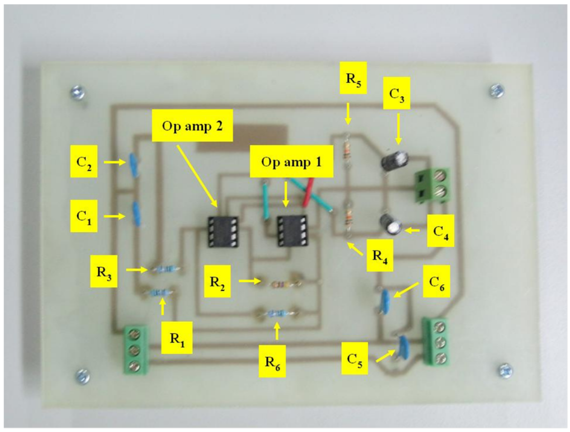


(c)

Fig. 3: *Photograph of proposed approach: (a) current- (b) voltage- canceling compensation circuits and (c) closed-loop techniques that used as active EMI filters for CM EMI reduction.*

yields R_2 (or R_f in Fig. 1) and $R_1 = R_3$ (or R_i in Fig. 1) equal to 511 and 51 Ω, respectively.

The CM voltage is detected through C_1 - C_2 and C_5 - C_6 which are equal to 0.01 μF. To reduce the CM voltage of the input line, C_3 and C_4 equal to 10 μF are used where R_4 - R_5 are equal to 10 kΩ. For proposed circuits, from the condition that the α must be greater than one, R_6 is selected to be equal to 50 Ω.

4. EXPERIMENTAL VERIFICATIONS

The photographs of experimental setups to verify the CM reduction performance of conventional and proposed active EMI filters with current and voltage

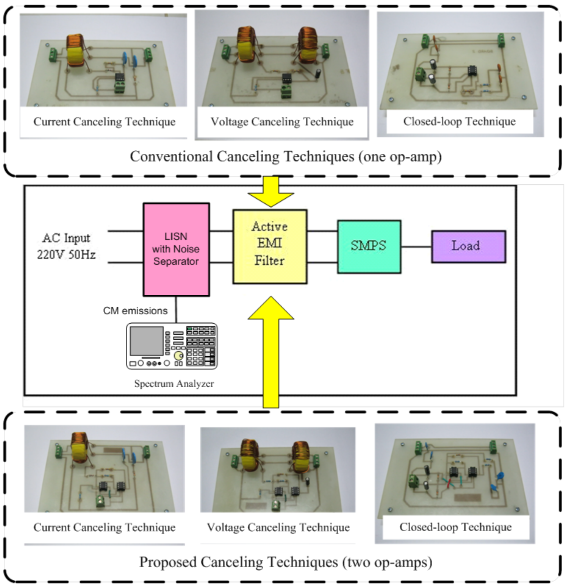


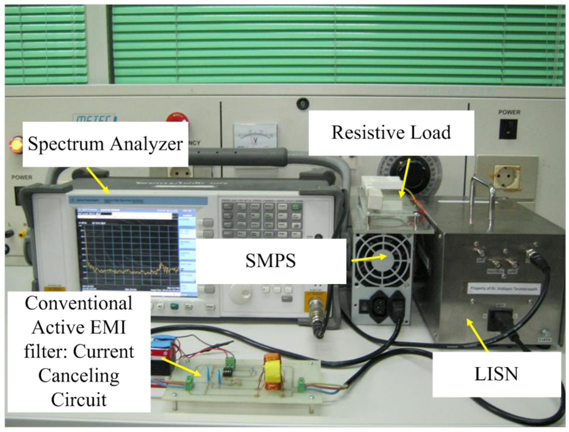
Fig.4: *The block diagram of experimental setup for CM emission measurements.*

canceling techniques as well as closed-loop technique are shown in Figs. 5, 9 and 13, respectively. A 250W switching power supply is used as a noise source where the CM EMI is measured through the LISN which is included the CM and DM noise separator network [12]. The block diagram of experimental setup for CM emission measurement is shown in Fig 4.

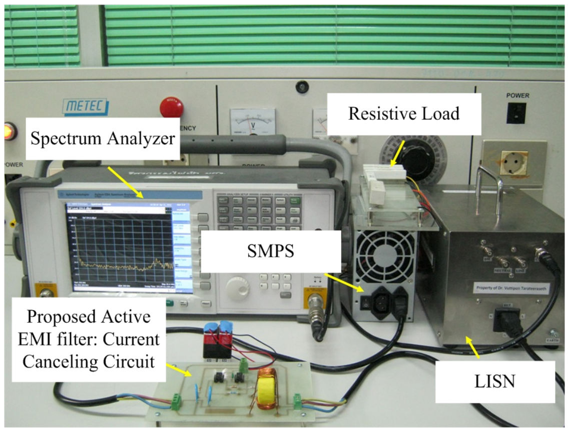
In order to verify the CM reduction performances of conventional and proposed circuits, two experiments are demonstrated. First experiment is to study the effect of gain on CM reduction performance by varying the gain of conventional circuit from 10, 50, and 100. This experiment is to assure that the improvement of CM reduction performance of proposed circuit is because of GBP enhancement, not by increasing gains. The second experiment is to compare the CM reduction performances of active EMI filters with conventional and proposed circuits. For comparison purposes, the gain of both conventional and proposed circuits is designed to be equal to 10.

4.1 Common-mode Active EMI filters with Current Canceling Technique

Figs. 5 - 6 (a) and (b) show the photograph of experimental setups and schematics of CM active EMI filter compensation circuits with current canceling technique of conventional circuit [5] and proposed circuit, respectively. As shown in Fig. 7, the measured CM emissions of the conventional active EMI filter with current canceling technique (one op-amp) when gain is varied from 10, 50, 100 are compared. It can be seen that the CM reduction performance is not always dependent on the gain. From frequency ranges 150 kHz - 400 kHz, the CM reduction performance is worst when gain is maximum (gain = 100), but it



(a)



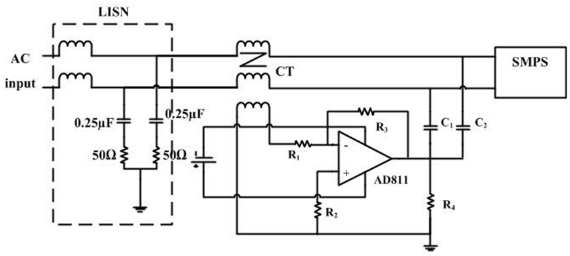
(b)

Fig.5: *Photograph of experimental setups for CM reduction performance testing of CM active EMI filter with current canceling technique.*

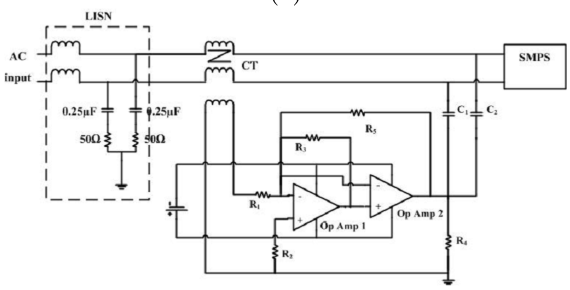
provides similar results when gain is equal to 10 and 50. However, for frequency range from 400 kHz - 30 MHz, the CM reduction performance is almost the same.

Next demonstration is to compare the CM reduction performances of active EMI filters with conventional and proposed circuits. The comparison of measured CM emissions among in case of without filter, with conventional active EMI filter using current canceling technique (one op-amp) [5], and with proposed active EMI filter using current canceling technique (two op-amps) is shown in Fig. 8. From the experimental results as shown in Fig. 8, it can be concluded that, with the proposed circuit, the CM reduction performance of active EMI filter is improved at frequency range: 400 kHz - 16 MHz, where the maximum reduction is about 10 dBuV comparing to the conventional circuit, and about 40 dBuV comparing to without any filter inserted.

With these experiments, it can be summarized that in order to improve the CM reduction performance of an active EMI filter with current canceling technique, the best way is to enhance the GBP of



(a)



(b)

Fig.6: *CM active EMI filter compensation circuit with current canceling technique (a) conventional circuit [5] (b) proposed circuit.*

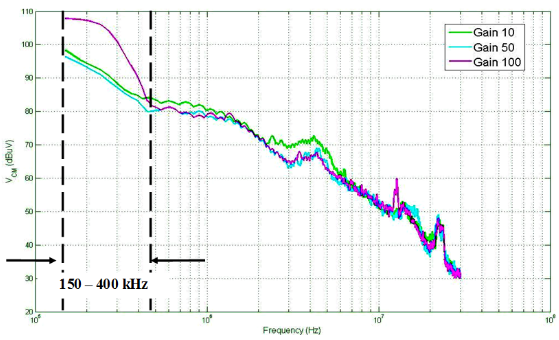


Fig.7: *Comparison of measured CM emissions when gain of conventional active EMI filter with current canceling technique is varied from 10, 50 and 100.*

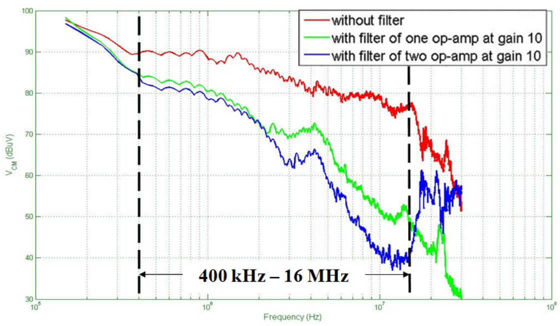
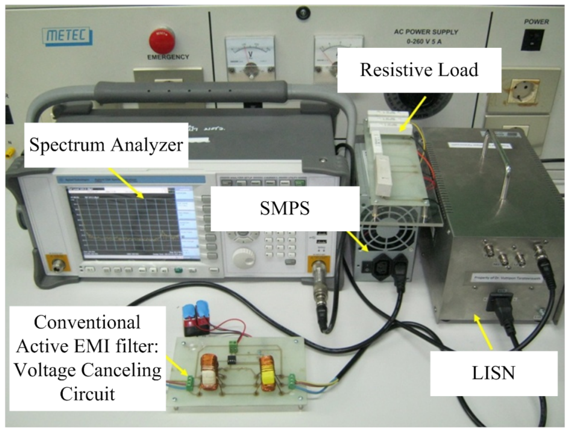
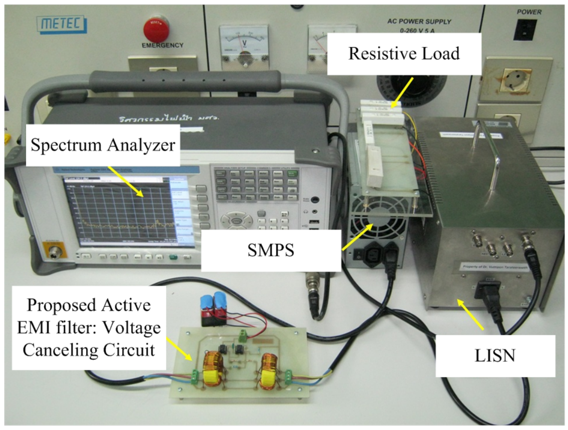


Fig.8: *Comparison of measured CM emissions among in case of without filter, with conventional CM active EMI filter using current canceling technique (one op-amp) [5], and with proposed CM active EMI filter using current canceling technique (two op-amps).*



(a)



(b)

Fig.9: *Photograph of experimental setups for CM reduction performance testing of CM active EMI filter with voltage canceling technique.*

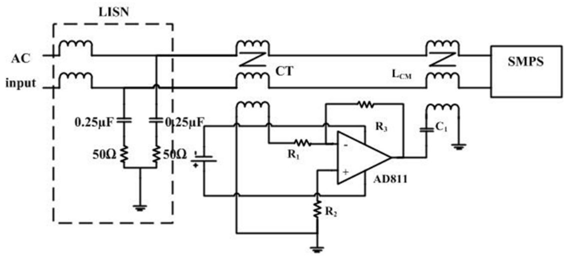
op-amps, not by increasing the gain of op-amps.

4.2 Common-mode Active EMI filters with Voltage Canceling Technique

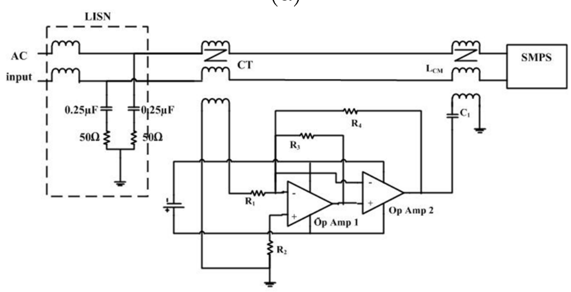
In the same manner as current canceling technique, Figs. 9-10 (a) and (b) show photograph of experimental setups and schematics of CM active EMI filter with voltage canceling technique of conventional circuit [5] and proposed circuit, respectively.

The relationship between varying gains and CM reduction performance of the conventional CM active EMI filters with voltage canceling technique is verified as shown in Fig. 11. The gain is varied from 10, 50 and 100, respectively. It can be seen that at frequency range from 150 kHz - 400 kHz, gain equal to 10 gives the best CM reduction performance while CM reduction performance is worst with gain equal to 50. On the other hand, at frequency range from 400 kHz - 5 MHz, CM reduction performance in case of gain equal to 10 is ruined. However, at frequency range from 5 MHz to 30 MHz, CM reduction performance is almost the same in any cases.

Fig. 12 shows the comparison of measured CM



(a)



(b)

Fig.10: *CM active EMI filters with voltage canceling technique (a) conventional circuit [5] (b) proposed circuit.*

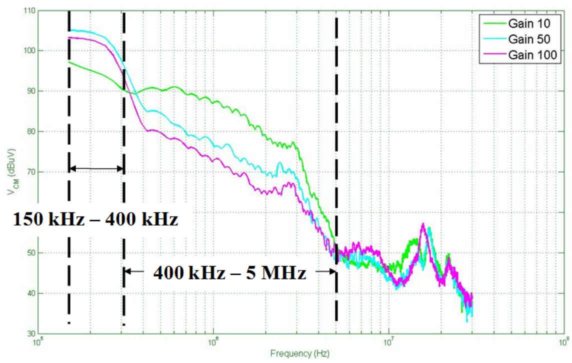


Fig.11: *Comparison of measured CM emissions when gain of conventional active EMI filter with voltage canceling technique is varied from 10, 50 and 100.*

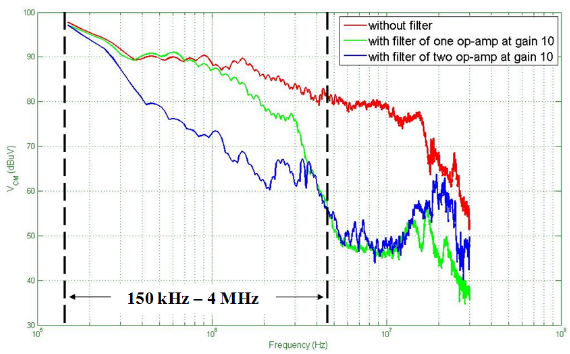
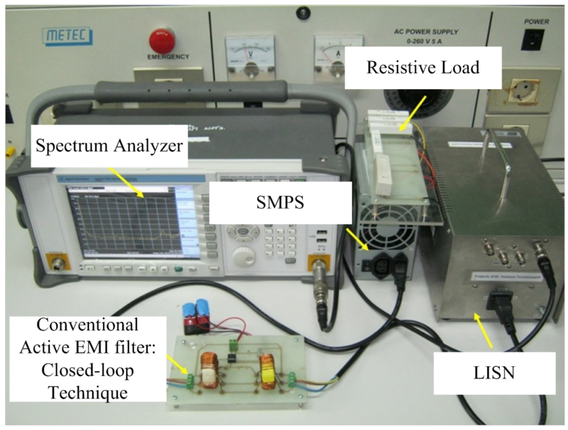
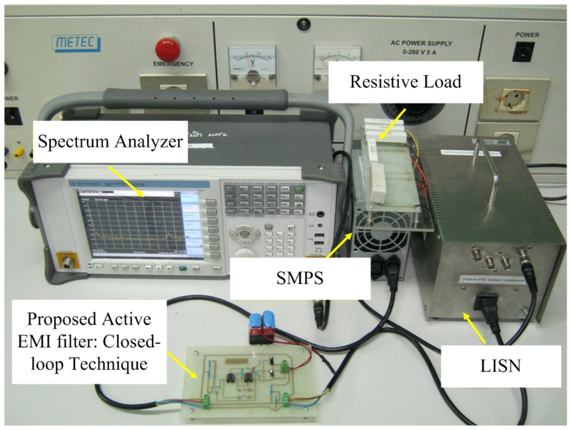


Fig.12: *Comparison of measured CM emissions among in case of without filter, with conventional CM active EMI filter using voltage canceling technique (one op-amp) [5], and with proposed CM active EMI filter using voltage canceling technique (two op-amps).*



(a)



(b)

Fig.13: *Photograph of experimental setups for conducted EMI performance testing of CM active EMI filter compensation circuit with closed-loop technique.*

emissions among in case of: without filter, with conventional active EMI filter using voltage canceling technique (one op-amp) [5], and with proposed active EMI filter using voltage canceling technique (two op-amps). From the experimental results as shown in Fig. 12, it is obvious that, with the proposed circuit, the CM reduction performance of active EMI filters is improved at frequency range: 150 kHz-4 MHz, where the maximum reduction is about 20 dBuV comparing to the conventional circuit, and about 30 dBuV comparing to without any filter inserted.

Again, these demonstrations confirm that the improvement of CM reduction performance of an active EMI filter with voltage canceling technique is due to GBP enhancement of an op-amp, not because of increasing its gain.

4.3 Common-mode Active EMI filters with Closed-loop Technique

Figs. 13-14 (a) and (b) show photograph of experimental setups and schematics of CM active EMI filter compensation circuits with closed-loop technique of conventional circuit [13] and proposed circuit, re-

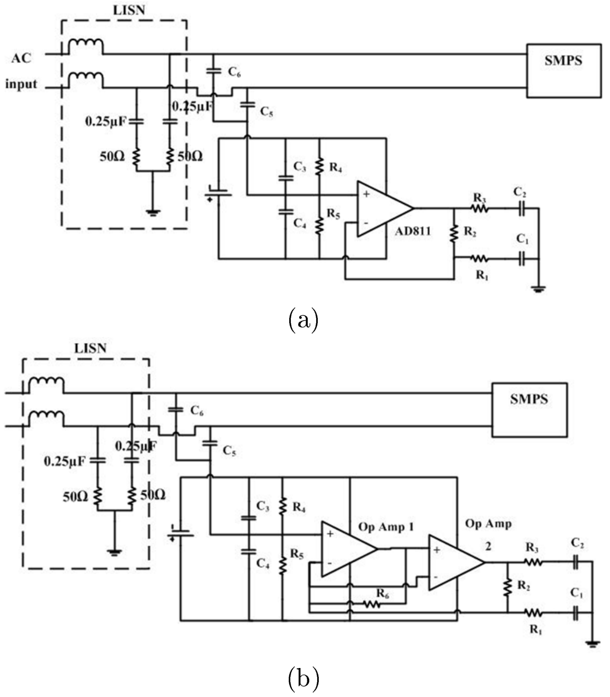


Fig. 14: *CM active EMI filter with closed-loop technique (a) conventional circuit [5] (b) proposed circuit.*

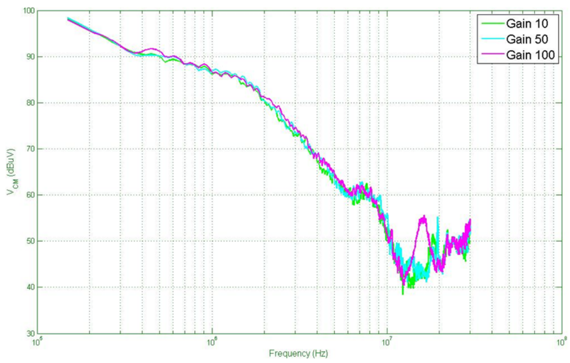


Fig. 15: *Comparison of measured CM emissions when gain of conventional CM active EMI filter with closed-loop technique is varied from 1, 50 and 100.*

spectively. Similarly, Fig. 15 show the CM reduction performance of conventional active EMI filters with closed-loop technique when its gain is varied from 10, 50, and 100. From experimental result, it shows that, with the closed-loop technique, a gain has a little effect to the CM reduction performance. The CM reduction performance is almost unchanged when gain is varied. Fig. 16 shows the comparison of measured CM emissions among in case of without filter, with conventional active EMI filter using closed-loop technique (one op-amp) [13], and with proposed active EMI filter using closed-loop technique (two op-amps). As shown in Fig. 16, the proposed circuit can improve the CM reduction performance by 5 dBuV comparing to the conventional circuit at frequency range from

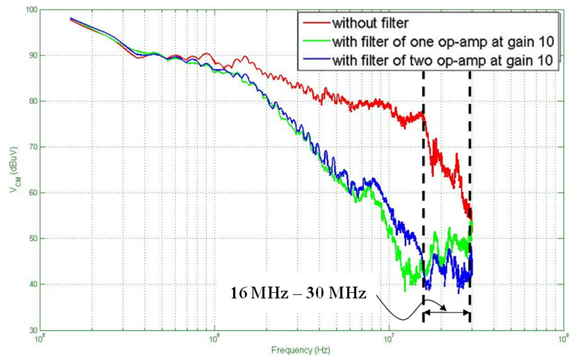


Fig. 16: *Comparison of measured CM emissions among in case of: without filter, with conventional CM active EMI filter using closed-loop technique (one op-amp) [5], and with proposed CM active EMI filter using closed-loop (two op-amps).*

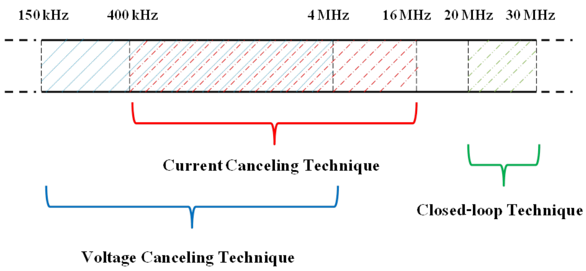


Fig. 17: *Useful frequency range of proposed active EMI filters (two op-amps) with voltage canceling technique, with current canceling technique, and with closed-loop technique.*

16 MHz-30 MHz, and about 30 dBuV comparing to without any filter inserted.

From these demonstrations, it shows that the proposed circuit helps to improve the CM reduction performance of active EMI filter using closed-loop technique especially at high frequency range from 16 MHz-30 MHz. Once again, these demonstrations assure that the improvement of CM reduction performance of active EMI filter with closed technique is not by boost its gain, but by enhancing GBP of an op-amp.

5. CONCLUSIONS

To improve the CM reduction performance of active EMI filters used in power electronic applications e.g. switching power supplies, the GBP limitation of op-amps is solved by being applied the concept of op-amp GBP enhancement proposed by [7]. Although, this technique could be adapted for both DM and CM active EMI filters, only CM active EMI filters are demonstrated. From the experimental results, it can be concluded that in order to improve the CM reduction performances of active EMI filters, the best way is to enhance the GBP of an op-amp, not by increasing the gain of an op-amp. By enhancing the op-amp GBP, the CM reduction performances of CM active EMI filters can be significantly improved at a certain frequency range, where the useful frequency range of proposed CM active EMI filters (two op-amps) with voltage canceling technique, with current canceling technique, and with closed-loop technique is summarized in Fig. 17. As shown in Fig. 17, it can be seen that the CM reduction performance of proposed CM active EMI filter with voltage canceling technique is good at frequency range from 150 kHz up to about 4 MHz, and from 400 kHz-16 MHz in case of with current canceling technique; moreover, the maximum CM reduction performances of CM active EMI filters with proposed circuits are 10 dBuV and 20 dBuV higher than that of CM active EMI filters with conventional circuits, and about 30 dBuV and 40 dBuV comparing to without any filter inserted, respectively. For an CM active EMI filter with closed-loop technique, it is good to used only at a high frequency range from about 20 MHz-30 MHz where the CM reduction performance is about 5 dBuV and 30 dBuV higher than that of active EMI filters with conventional circuits and without any filter inserted, respectively.

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