Short Papers

Diagnosis and Reduction of Conducted Noise Emissions

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Abstract—**A systematic method for the diagnosis and reduction of conducted noise emissions is described. The method consists of a device for determining whether the differential- or common-mode component of conducted noise is dominant along with a simplified equivalent circuit of the power supply filter for each component. The procedure consists of first using the device to determine which noise component is dominant in a particular frequency range and then using the simplified equivalent circuits to determine whether an anticipated change in value of an element in the power supply filter will be effective.**

I. Introduction

Most electronic products that are intended to be marketed in the U.S. must satisfy the Federal Communications Commission (FCC) limits on conducted and radiated emissions [1]. All products that use digital techniques and clock frequencies in excess of 10 kHz (virtually all digital electronic products today) are subject to this rule. Products that are intended to be marketed in other countries must satisfy similar and no less stringent requirements. See [1] for a complete discussion of these limits and the required test procedures. This paper deals with the subject of satisfying the limits imposed on noise signals conducted into the power mains (conducted emissions). The frequency range for the FCC conducted emissions limits (class A and class B) extends from 450 kHz to 30 MHz. Products intended to be marketed in countries outside the U.S. are often designed to satisfy the VDE conducted emissions limits for West Germany, which extend from 10 kHz to 30 MHz [1]. The problem to be addressed in this paper is the modification of the power supply filter in order for the conducted emissions of the product to satisfy the relevant regulatory limit.

Testing for compliance to conducted emission limits utilizes a Line Impedance Stabilization Network (LISN) as shown in Fig. 1 [1]. There are two purposes of the LISN. The first is to prevent noise from the ac power mains from contaminating the measurement, and the second is to present a (relatively) constant impedance (50 Ω) to the product instead of the variable impedance one sees looking back into the power mains. The power mains supply ac power to the product via three wires. In the U.S., these are referred to as Phase, Neutral, and Green Wire (or safety ground). The noise currents exiting the power supply consist of two components. Differential-mode noise current I_D flows out phase (neutral) and returns via neutral (phase). Common-mode noise current I_C flows out phase and neutral and returns via the green wire. In a two-wire system where the green wire is not attached to the product, common-mode current also exists and its return path appears to be via parasitic capacitance between the phase/neutral wires and the product frame. The differential-mode currents in the phase and neutral wires are equal and oppositely directed, whereas the common-mode currents are equal and directed in the same direction. Thus the green wire returns twice the common-mode current.

An ideal LISN (as we will assume) presents constant 50 Ω impedances (purely resistive) between phase and green wire and between neutral and green wire. These are represented by resistors R in Fig. 1. The voltages measured by the LISN are

$$V_{\text{phase}} = V_{CM} + V_{DM} = R(I_{CM} + I_{DM}) \tag{1a}$$

$$V_{\text{neutral}} = V_{CM} - V_{DM} = R(I_{CM} - I_{DM}). \tag{1b}$$

These voltages must satisfy the regulatory limit at every frequency of that limit. Note that the measured voltages are a combination of contributions from the common-mode currents I_{CM} and the differential-mode currents I_{DM}. *The key to modifying the power supply filter to satisfy the regulatory limits is in determining at the frequency where the emission exceeds the limit, which component of the total current is dominant.*

In order to illustrate this important point, a generic topology of a power supply filter is also shown in Fig. 1. The inductances L and M are associated with a common-mode choke that is normally found in all power supply filters. Ideally, this device presents no impedance to the differential-mode current and places an inductance in each line with regard to the common-mode current. The primary advantage of this device is that because magnetic fluxes due to differential-mode currents cancel in the core, the core is not saturated by the high-level, fundamental power frequency differential-mode current. The capacitances C_p represent the parasitic capacitances of the windings of the choke. These parasitic elements can be quite important elements but are frequently not included in other analyses. The line-to-ground capacitances C_{GL} and C_{GR} are included to divert the common-mode currents. (Subscripts L and R denote left and right, respectively.) The line-to-line or bulk capacitances C_{BL} and C_{BR} are included to divert differential-mode currents. Ideally they should have no effect on common-mode currents. The line-to-ground capacitors also have an effect on the differential-mode current as will be shown. However, this effect on the differential-mode component is typically much smaller than the effect of the line-to-line capacitors. In a typical power supply filter some of these capacitances may be absent. For example, it is common to place the line-to-ground capacitances only on the power supply side of the filter and for this application, $C_{GL} = 0$. Similarly, if all the line-to-line capacitance is placed on the power cord side of the filter, then $C_{BR} = 0$. So this generic power supply filter can be used to represent a wide class of filter topologies. In addition, we will assume the filter is symmetric with respect to phase/neutral as shown in Fig. 1. This is common practice, and there appears to be no advantage in using an asymmetric filter. An inductor L_{GW} is commonly placed in the green wire to block common-mode currents.

This shows that some elements of the filter ideally affect only one component of the total current, either common-mode or differential-mode. Suppose that at a certain frequency, the common-mode

Manuscript received December 21, 1987; revised June 16, 1988.

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IEEE Log Number 8823333.

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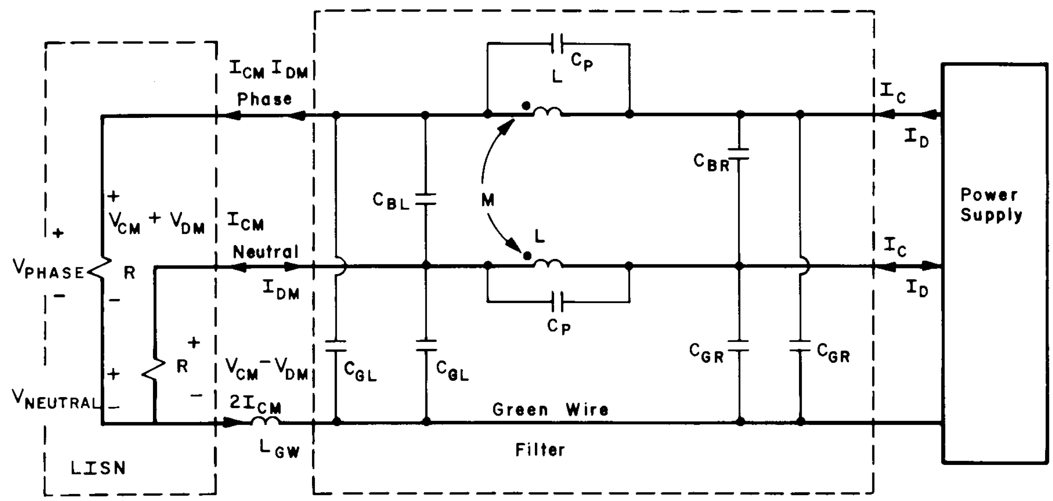


Fig. 1. A generic power supply filter topology.

component in (1) is dominant. The total measured voltage is

$$V_{\text{phase}} \doteq V_{CM} = RI_{CM}$$

$$V_{\text{neutral}} \doteq V_{CM} = RI_{CM}.$$

In this case, changing the value of the line-to-line capacitors, C_{BL} or C_{BR}, would effect *no change* in the total measured voltage. Conversely, if differential-mode current is dominant

$$V_{\text{phase}} \doteq V_{DM} = RI_{DM}$$

$$V_{\text{neutral}} \doteq V_{DM} = -RI_{DM}.$$

Changing the value of the green wire inductor L_{GW} would bring about no change in the total measured voltage. *Therefore, one must know whether differential- or common-mode noise is dominant in order to know which element of the filter must be changed in order to effect a reduction in total measured voltage.*

In the next section we will describe a device that can be used to determine which component of the conducted noise (common- or differential-mode) is dominant so that an intelligent modification of the filter can be made. This technique and device have been used in product development and have proven to be useful aids. In a latter section of this paper we will show simplified equivalent circuits of the power supply filter. One circuit will be shown for common-mode currents and another will be shown for differential-mode currents. These simple circuits show how to change element values to effect a change in that component of the noise current and are suitable for hand calculation.

II. A Device for Diagnosing Which Noise Current Component is Dominant

As pointed out above, the key to effecting a reduction in a conducted emission at a certain frequency is to determine which noise component, differential- or common-mode noise, is dominant at that frequency. There have been various suggestions for doing this [2]–[5]. The device we will describe is simple to construct and to implement in a conducted emissions test setup. The key to this device is to recognize, as shown by (1), that the conducted emission voltages measured by the LISN are the sum and difference of the common- and differential-mode noise contributions. The sum and difference of the phase and neutral voltages yield

$$V_{\text{phase}} + V_{\text{neutral}} = 2V_{CM} \tag{2a}$$

$$V_{\text{phase}} - V_{\text{neutral}} = 2V_{DM}. \tag{2b}$$

So, in order to determine which component is dominant, we must add and subtract the two voltages measured by the LISN. Most spectrum analyzers have a difference function but this unfortunately ignores phase angles and only subtracts magnitudes.

A device for adding and subtracting V_{phase} and V_{neutral} is shown in Fig. 2. A photograph of the device is shown in Fig. 3. Both V_{phase} and V_{neutral} outputs of the LISN are connected to the device. A pair of high-quality, 1:1 transformers are used to add or subtract (via a switch) these voltages. The transformers used are manufactured by VARI-L Co. in Denver, CO and the model numbers are LF 428. These transformers are specified to have an essentially flat frequency response from 10 kHz to 50 MHz, have center-tapped (not used) secondaries and are dc isolated. It is important to remember that the absolute accuracy of the circuit is not important; we are only interested in determining the common- and differential-mode levels *relative to each other*. Resistors (82 Ω) are placed across the inputs of the device so that the impedance seen by the LISN is 50 Ω. In a normal measurement, the phase/neutral outputs of the LISN would be externally terminated in 50 Ω.

The device is placed at the LISN output and the device output is supplied to a spectrum analyzer. This is illustrated in Fig. 4. With the device switch in one position, the spectrum analyzer displays the common-mode (differential-mode) component. This can be placed in a storage register of the spectrum analyzer. With the switch placed in the other position, the spectrum analyzer displays the differential-mode (common mode) component. The contents of the storage register can then be recalled so that both measurements can be compared in order to determine which component of the noise is dominant at a particular frequency.

Measurements were made to determine the accuracy of the device. The results are documented in [2]. In order to determine the common-mode/differential-mode discrimination, a sinusoidal oscillator was applied to both inputs using equal-length cables. The voltage transfer ratios with the switch in each position were measured and show reasonable accuracy up to around 10 MHz. With the switch in the sum position the ratio of output and input voltages is approximately 6

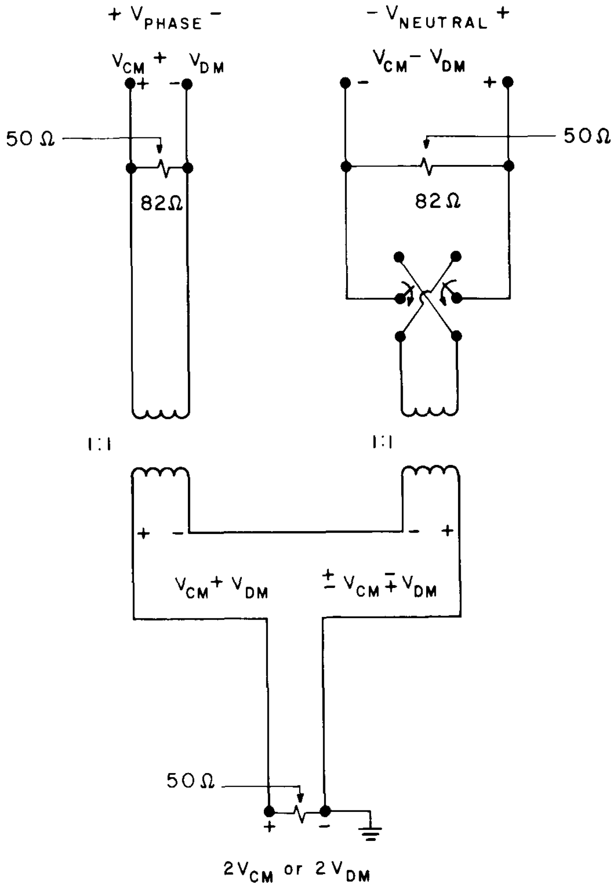


Fig. 2. Schematic of the device.

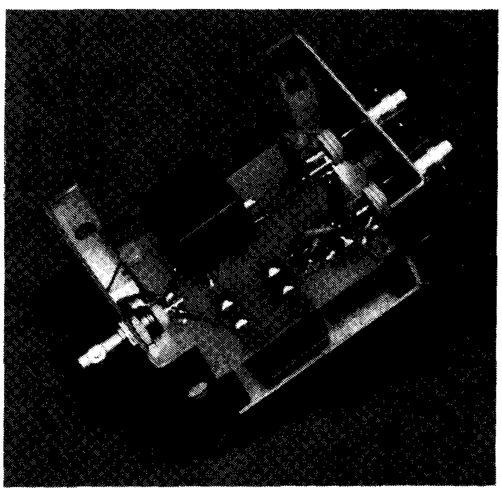


Fig. 3. Photograph of the device.

dB below 10 MHz. With the switch in the difference position, the ratio of output and input voltages is at least -50 dB below 10 MHz. In the authors' experience, the majority of the conducted noise emissions problems occur below 10 MHz so the accuracy of the device should be adequate.

An additional test was conducted to determine the frequency response of each input. The results of these tests are also documented in [2]. A sinusoidal generator was individually applied to each input and the voltage transfer function measured from 10 kHz to 30 MHz. The tests showed that the outputs for the signals applied to each input were within 0.5 dB of each other up to 10 MHz.

In order to illustrate the effectiveness of the device, a digital product having a primary-side switching power supply whose power supply filter components were removed was measured for its conducted emissions. The total voltages measured with the LISN (dB μV) are shown in Fig. 5. Only the neutral voltage is shown. The phase voltage was virtually identical to the neutral voltage. In addition, the differential- and common-mode components are measured with the device and shown on the plot. From this we see that the common-mode noise and differential-mode noise are approximately the same order of magnitude. Without a filter, the product fails the FCC conducted emission limit by some 30 dB.

A set of three 7-in lands, 125 mils in width, were etched on a glass epoxy board and inserted in the external ac power cord at a point some 6 in from the product. Various filter elements will be mounted on this board in order to see their effect on the common- and differential-mode noise components. The first set of elements will be two 3300-pF line-to-ground capacitors

$$C_{GR} = 3300 \text{ pF}.$$

The results are shown in Fig. 6. Note that both the common-mode and the differential-mode components have been reduced by the addition of these elements.

Next we add a 0.1-μF line-to-line capacitor in addition to the existing 3300-pF line-to-ground capacitors of the previous test

$$C_{GR} = 3300 \text{ pF}$$

$$C_{BR} = 0.1\ \mu\text{F}.$$

The results are shown in Fig. 7. Note that the common-mode component, as expected, has not been affected by the addition of this line-to-line capacitor. However, again as expected, the differential-mode component has been substantially reduced. This illustrates, rather dramatically, the utility of being able to determine which component, differential- or common-mode, is dominant in a particular frequency range. If we are able only to observe the total voltage measured by the LISN, we might conclude that adding this line-to-line capacitor had only a minor effect and we might try increasing its value to no avail. What becomes clear with the device is that the line-to-line capacitor *did* reduce the differential-mode component but now the dominant common-mode component must be reduced in order to change the *total* measured voltage.

Next we add, in addition to the above components, a green wire inductor consisting of 25 turns of wire on a #77 ferrite toroid. This gives an inductance of $L_{GW} \doteq 1$ mH. The results are shown in Fig. 8. Note that the addition of the green wire inductor has drastically reduced the common-mode component but, as expected, has not substantially changed the differential-mode component.

Next we add a common-mode choke to these elements. The choke has

$$L = 22.94 \text{ mH}$$

$$M = 22.89 \text{ mH}$$

$$C_p = 33 \text{ pF}.$$

The results are shown in Fig. 9. Note that the addition of the common-mode choke has only slightly reduced the common-mode component above 10 MHz but has drastically reduced the differential-

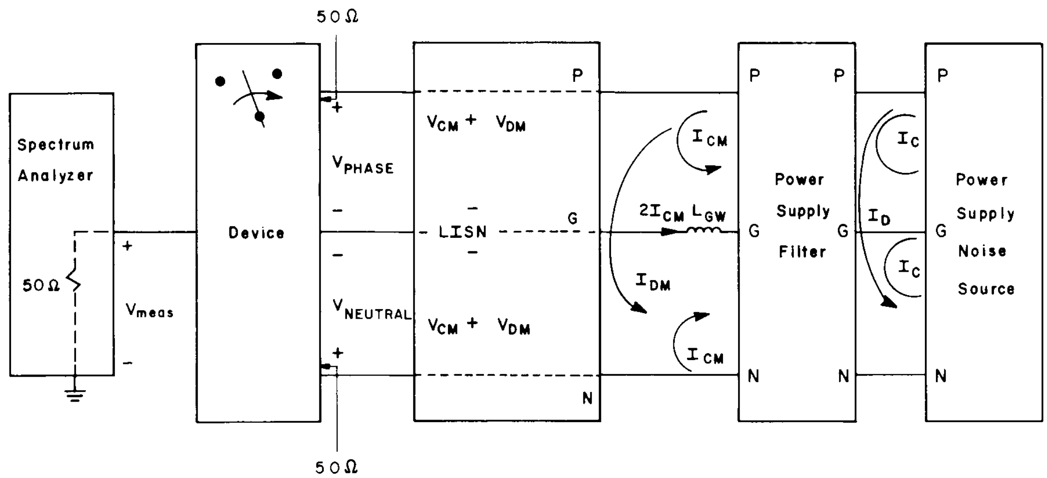


Fig. 4. Implementation of the device in a conducted emission test.

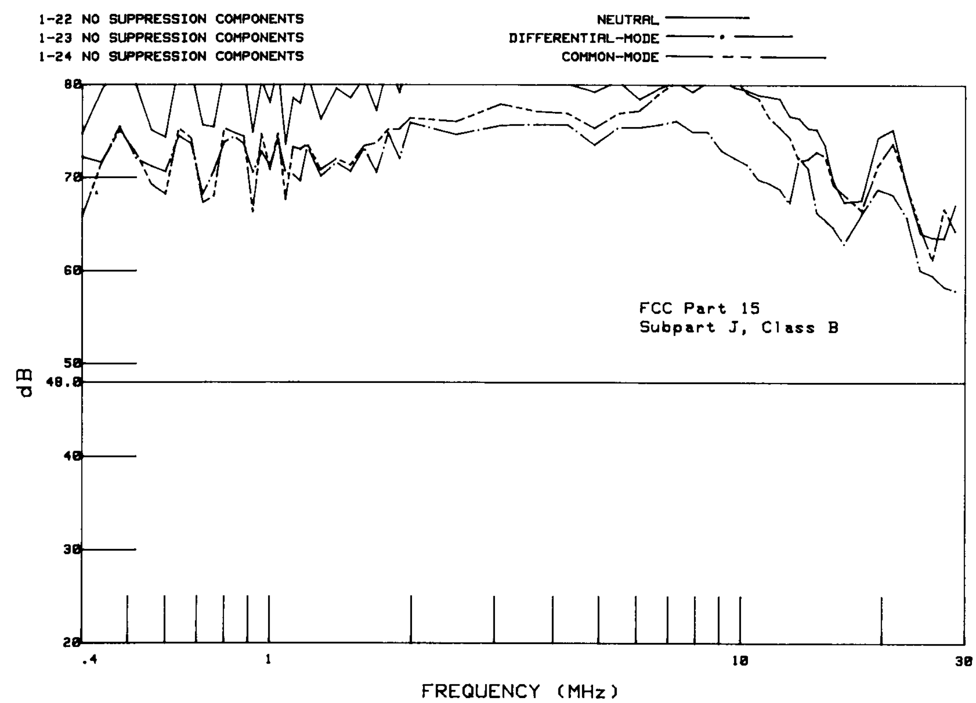


Fig. 5. Power supply filter with no suppression components.

mode component below 3 MHz. It is conjectured that the common-mode choke affects differential-mode current by the addition of its leakage inductances in the phase/neutral lines. The green wire inductor has already reduced the common-mode component substantially so no significant effect of the choke on common-mode current is observed.

These results show the utility of being able to determine which component, common-mode or differential-mode, is dominant in a particular frequency range. For example, consider Fig. 8 where the filter includes a line-to-line capacitor, line-to-ground capacitors, and a green wire inductor. From 400 kHz to 3 MHz, the total noise current is predominantly differential mode. Therefore increasing the inductance of the green wire inductor (which would only affect common-mode current in this range) would produce no effect on the *total noise current* in this frequency range.

III. Simplified Equivalent Circuits

Once it has been determined which component of conducted noise is dominant at a certain frequency, it is important to ascertain how to change the values of the existing elements in the filter in order to reduce that component. Lumped circuit analysis codes can be used to analyze the filter circuit of Fig. 1 but such an analysis provides little insight into what values to choose in the filter in order to effect the desired change. The purpose of this section is to show simplified equivalent circuits that clearly illustrate the effect of the elements of the filter on each component of the conducted noise.

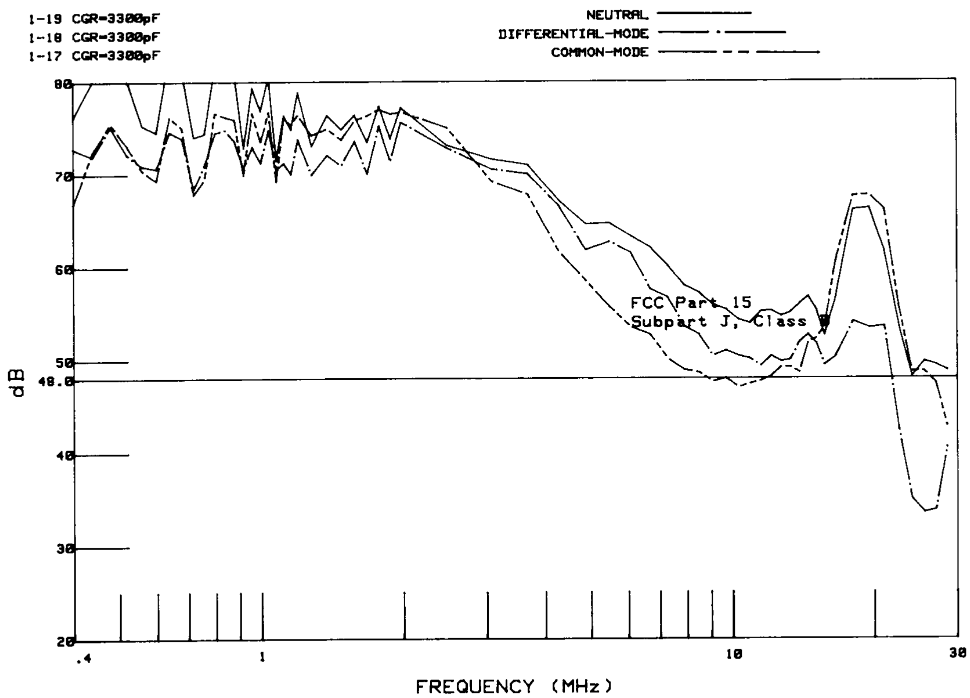


Fig. 6. Power supply filter with line-to-ground capacitors, C_{GR} = 3300 pF.

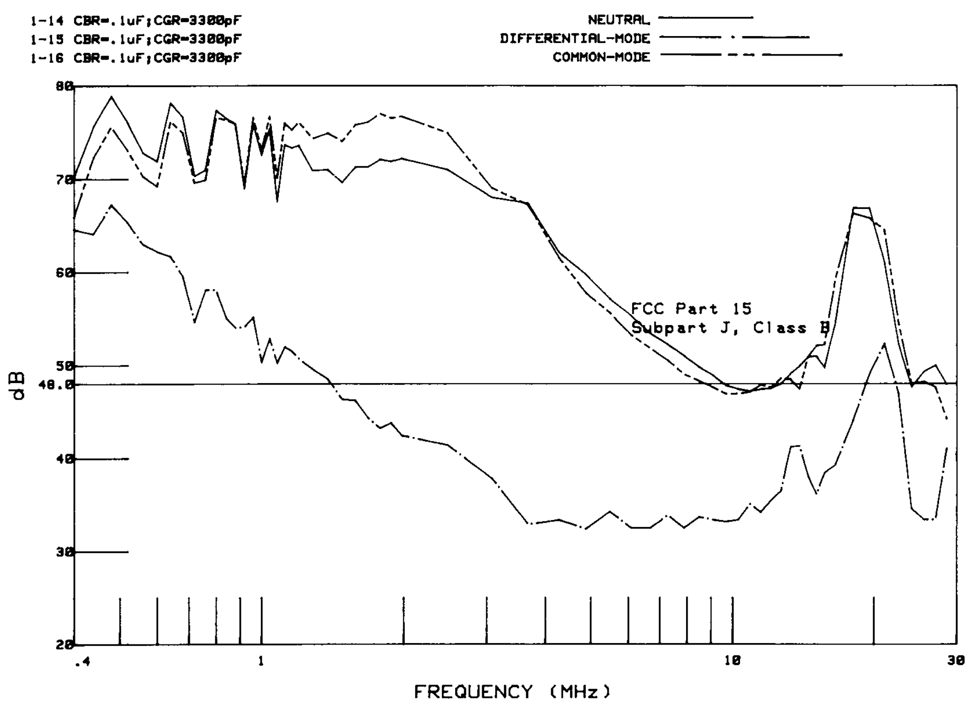


Fig. 7. Power supply filter with line-to-ground and line-to-line capacitors, C_{GR} = 3300 pF and C_{BR} = 0.1 μF.

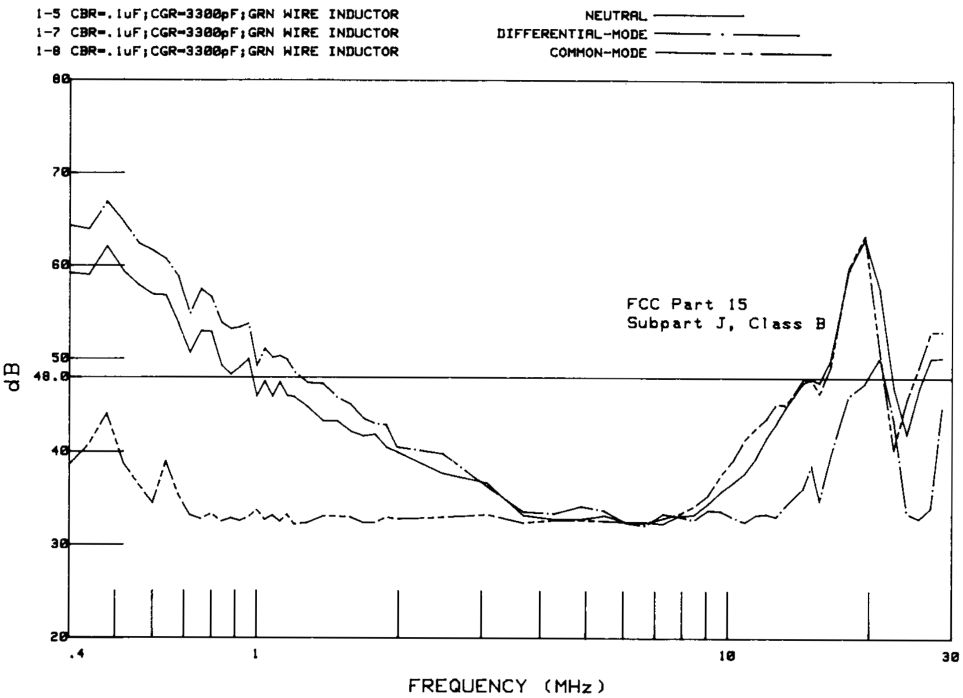


Fig. 8. Power supply filter with C_{GR} = 3300 pF, C_{BR} = 0.1 μF and green-wire inductor, L_{GW} = 1 mH.

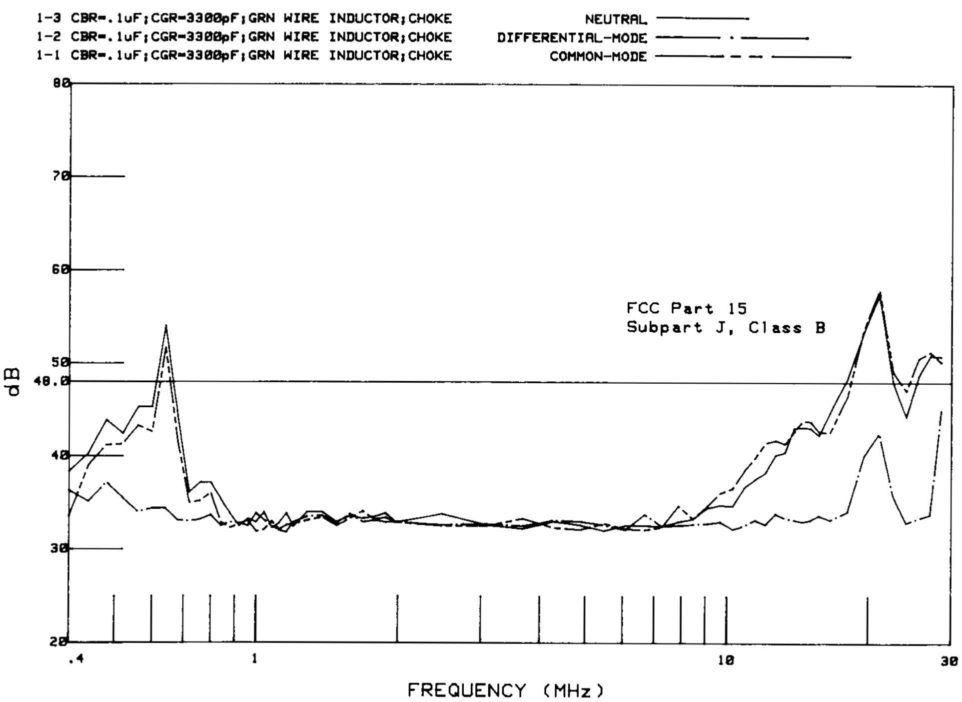
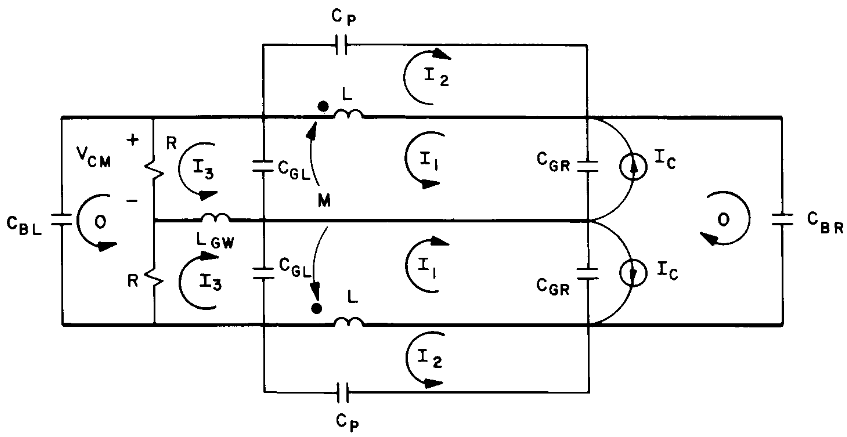
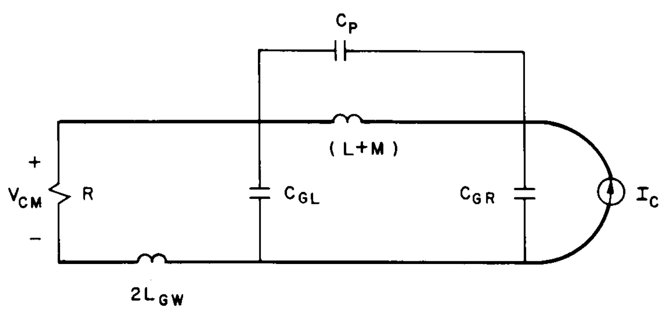


Fig. 9. Power supply filter with C_{GR} = 3300 pF, C_{BR} = 0.1 μF, L_{GW} = 1 mH and common-mode choke.



(a)



(b)

Fig. 10. Common-mode noise equivalent circuit for the power supply filter.

First consider common-mode noise. This will be simulated with current sources I_C as shown in Fig. 10(a). From the symmetry of this circuit, one can show that certain of the resulting mesh currents defined in Fig. 10(a) must be identical. The resulting voltages across the line-to-line capacitors are therefore zero and these may be removed from the circuit. One can write the resulting mesh-current equations and show that the circuit of Fig. 10(b) is equivalent with regard to computing V_{CM}. The green wire inductor will likely not be effective in reducing common-mode emissions for frequencies below which $2\omega L_{GW} < R = 50\ \Omega$ or

$$f = \frac{R}{4\pi L_{GW}}.$$

This occurs at 4 kHz for the above values of filter components. This illustrates the insight afforded by the simple equivalent circuit.

The effect of the filter on differential-mode noise currents is modeled in a similar fashion as shown in Fig. 11(a). Once again, because of symmetry (or asymmetry) one can show that mesh currents can be defined as shown. The net current through the green-wire inductor is zero and it can be removed from the circuit. Second, the total voltage across C_{BL} is twice the voltage across each R. Thus C_{BL} can be replaced with $2C_{BL}$ across each R. A similar reduction can be made with C_{BR}. Now, the only interaction between the neutral and phase circuits is via the mutual inductance of the common-mode choke. Because of the directions of I_1 and I_2 in the two circuits, the inductance in each phase can be replaced with one having a value of $L - M$. This gives the equivalent circuit for differential-mode currents shown in Fig. 11(b). Note that the line-to-ground capacitors C_{GL} and C_{GR} appear in this circuit and as such could affect differential-mode noise currents. This is evident from the results shown in Fig. 6 where the 3300-pF line-to-ground capacitors are present. However, the line-to-line capacitors C_{BL} and C_{BR} when present, are usually much larger in value so that when both C_{BL} and C_{BR} are present, the line-to-ground capacitors typically have little effect on the differential-mode noise emissions. If either of the line-to-line capacitors are not present, this is no longer true and the line-to-ground capacitances could also affect the differential-mode current. Other observations can be similarly made for this circuit. For example, $2C_{BL}$ and C_{GL} form an $R - C$ filter with the $R = 50\ \Omega$ of the LISN

$$f = \frac{1}{2\pi R(2C_{BL} + C_{GL})}.$$

For the circuit tested this occurs at $f = 15.7$ kHz. If the line-to-line capacitor $C_{BL} = 0.1\ \mu$F is removed, but $C_{GL} = 3300$ pF remains, this frequency shifts to $f = 965$ kHz. Thus a filter using only line-to-ground capacitors of 3300 pF should affect *both* common-mode *and* differential-mode currents above 1 MHz. This is evident in the data of Fig. 6.

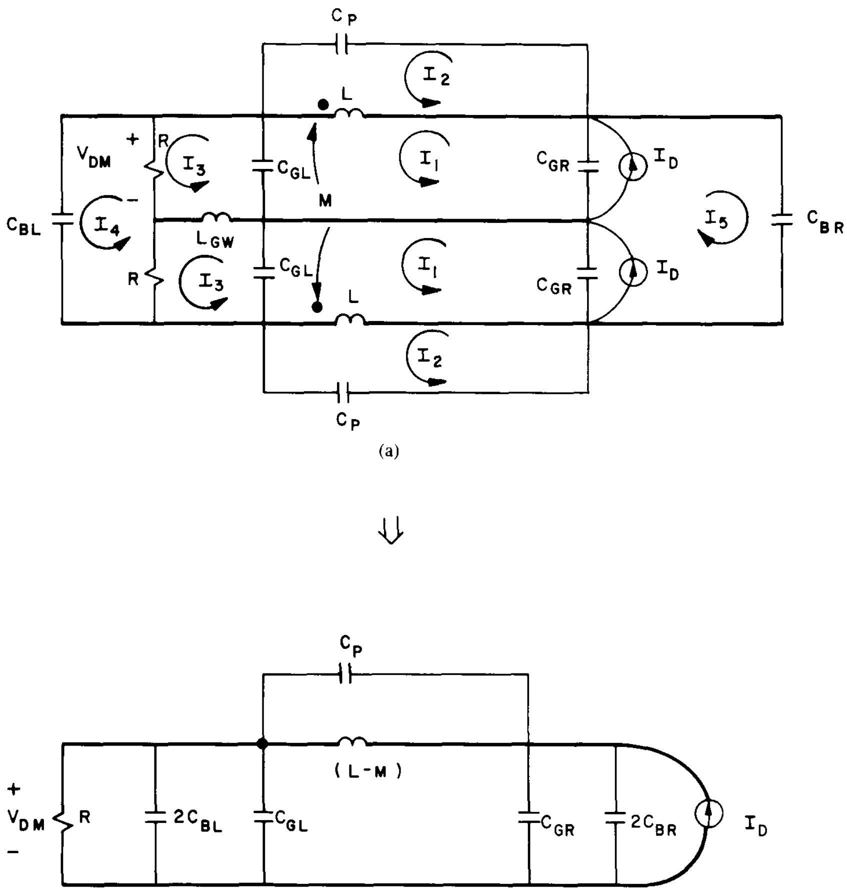


Fig. 11. Differential-mode noise equivalent circuit for the power supply filter.

Both of the equivalent circuits can be easily modified to account for nonideal component behavior. For example, nonideal capacitors may be modeled by adding their equivalent series resistance (ESR) and lead inductances in series with the ideal capacitors in the above models [1]. However, this affects the simplicity of the circuits.

IV. Summary and Conclusions

A diagnostic technique for the modification of power supply filters to reduce conducted noise emissions was described. The key to an efficient modification of the filter as opposed to trial and error changes in element values is to identify which component of the conducted emission, common-mode or differential-mode, is dominant at the frequency of interest. A simple device for doing this was described. Once the dominant component is identified one can then modify only those elements of the filter that effect that component. Quite often the authors have changed an element value in a power supply filter and observed no change in the total conducted emission. Although the change in that element value results in a change in one component of the conducted emission, if that component was not dominant, this will not change the total conducted emission. So an efficient identification of which element values to modify to effect a change can be made with this technique.

Two simplified equivalent circuits, one for common-mode emissions and one for differential-mode emissions, were obtained. Even though it may be clear which component of the total conducted emission must be reduced, it is not immediately clear how to select element values to accomplish this reduction. For example, simply increasing the values of the line-to-line capacitances will not always bring about a reduction in differential-mode conducted emissions particularly if the corresponding line-to-ground capacitance is much larger. The simplified equivalent circuits give insight into this problem.

Acknowledgment

The precise construction of the device in order to minimize imbalance is critical to its proper operation. For this aspect of the work, the authors acknowledge the talents of S. G. Parker, who constructed the device.

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