NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Technical Report No. 32-945

Filtering Techniques for Noise Suppression in Quasi-Balanced Circuits

W. R. Johnson

JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA, CALIFORNIA

June 15, 1966

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Technical Report No. 32-945

Filtering Techniques for Noise Suppression in Quasi-Balanced Circuits

W. R. Johnson

W. Shipley, *Manager*
Environmental Requirements Section

JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA, CALIFORNIA

June 15, 1966

Prepared Under Contract No. NAS 7-100
National Aeronautics & Space Administration

FOREWORD

This Report has been prepared to acquaint the reader with the existence of common-mode noise since this is a prerequisite for intelligent circuit filtering, isolation, and grounding. Common-mode problems are quite well known to designers of differential amplifiers and general balanced circuits; however, the author has not seen material relating these problems to the higher frequency regions considered in electromagnetic interference analysis. It is hoped that this Report will contribute to a more effective and uniform approach to noise filtering problems in system design.

CONTENTS

TABLE

FIGURES

FIGURES (Cont'd)

ABSTRACT

29511

This Report describes common-mode noise voltages, which may be present in electrical power and signal circuits, and submits means of preventing such noise from interfering with electronic equipment through the proper selection of filters and/or electrostatically shielded isolation transformers. As will be shown, there is a distribution of solutions to the problem. However, if the problem is generally understood, a solution may be proposed on the basis of the information in this Report.

Filters offer the best means of noise suppression for balanced-mode noise voltages, particularly in the medium- and high-frequency region ($>$ 20 kc). They also yield some attenuation to common-mode noise voltages and may be used for this purpose at high frequencies ($>$ 10 Mc).

Isolation transformers with electrostatic shielding can be effective in eliminating the common-mode noise voltages in the low- and mid-frequency ranges ($\approx$ 0 to 10 Mc). This useful range may be extended by careful construction. The number of electrostatic shields required increases with the number of grounds seen by the circuits of either primary or secondary. Noise which is transmitted in a balanced mode, or has a net-balanced component, cannot be decreased by transformers in the transformer passband, but may be decreased by medium amounts in the transformer stop band where transformer action ceases and the transformer becomes a filter.

Balanced or ungrounded circuitry generally loses its identity at high frequencies. Occurrence of capacitive coupling to unwanted grounds results in loss of rejection to common-mode noise. Consequently, it is very desirable, cost and size permitting, to use a filter driving an isolation transformer.

An attempt has been made to define test methods for determining the type of mode present in a circuit. General application of filters and isolation transformers to balanced-mode and common-mode noise voltage problems appears in tabular form. The grounding philosophy for multishielded transformers is not considered here. AUTHOR

I. INTRODUCTION

The approach to the analysis of effective filtering techniques investigated in this Report is based on the philosophy that interference is ultimately a circuit problem. Systems are not interfered with, only the circuits within them, and system noise problems are ultimately attacked at the circuit level. Circuits presented herein may represent a complex series of circuits and are simplified to clarify the analysis.

Circuits are primarily classified in two categories: balanced and single ended. There are, however, various degrees of unbalance in balanced circuits. The maximum unbalance possible yields the single-ended circuits. (For the purpose of this Report, a balanced circuit will designate a circuit which is designed to be balanced, but has inherent unbalance which may or may not be recognized and which will probably be undesirable.) This Report analyzes the effects of the common-mode noise on the load.

A common problem is design based on area of interest: The circuit designer's area of interest may not always encompass the full scope of environmental requirements to which a circuit may be exposed. If a balanced circuit is desired to operate at 60 cps, it is generally not necessary to take many precautions. One end may be a form of center-tap grounding, and the other end floating. At high frequencies, however, the floating end will capacitively couple to other grounds or circuits. This coupling may furnish a path for undesired signals. The designer, therefore, must increase his *area of interest* to consider these effects. The electromagnetic interference (EMI) analysis generally takes into account the spectrum from low RF frequencies (and sometimes audio) to the high microwave region. The area of interest here is quite large and circuits must be analyzed not only as they exist at operational frequencies, but as they metamorphose at frequencies far removed from the operational range.

It might be added at this point that a picture of pessimism has been painted as far as the effect of common-mode voltage is concerned. It is not generally a problem. Circuits which are completely unbalanced (single ended), such as a generator and load combination where a ground plane or chassis furnish the return, are used extensively, and most work quite well. This Report indicates the existence of common-mode problems and potential solutions to these problems. Consequently, these points are emphasized, and a distorted perspective may be created.

II. BALANCED AND UNBALANCED CIRCUITS

A balanced circuit is one in which schematically there is symmetry about a horizontal axis. The impedance to the axis of symmetry at any point above the axis is identical to the impedance at the symmetrical point below the axis. This axis is normally at ground (or zero) potential. A circuit of this type is shown in Fig. 1.

Here:

$$R_{g1} = R_{g2},\ R_a = R_b, \text{ and } R_{L1} = R_{L2}$$

If the axis is moved vertically downward to the very bottom of the circuit, we have the equivalent circuit of Fig. 2. This is the unbalanced form, also referred to as *single ended.*

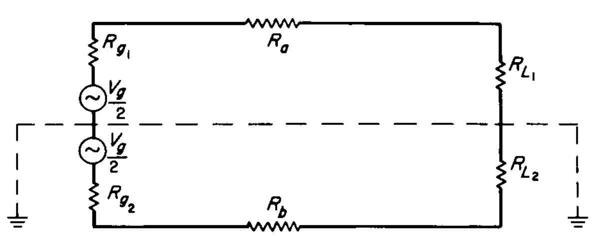

Fig. 1. Balanced circuit

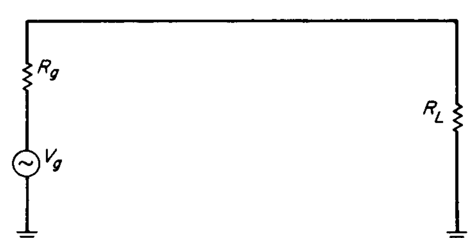

Fig. 2. Unbalanced circuit

A circuit which demonstrates an asymmetry (unbalance) between the above two extremes is shown in Fig. 3 when:

$$R_{L2} \neq R_{L1},\ R_a \neq R_b, \text{ or } R_{g1} \neq R_{g2}\,.$$

This is then referred to as a quasi-balanced circuit.

The total output voltage for Fig. 3 is:

$$V_o = \frac{V_g\,(R_{L1} + R_{L2})}{(R_{L1} + R_{L2}) + (R_a + R_b) + (R_{g1} + R_{g2})} \tag{1}$$

The grounds shown may be hard-wire connection or they may result from coupling or both.

Again it can be seen that the circuit is balanced if:

$$R_{g1} = R_{g2},\ R_{L1} = R_{L2} \text{ and } R_a = R_b\,.$$

If these conditions are not true, the circuit is asymmetrical or quasi-balanced.

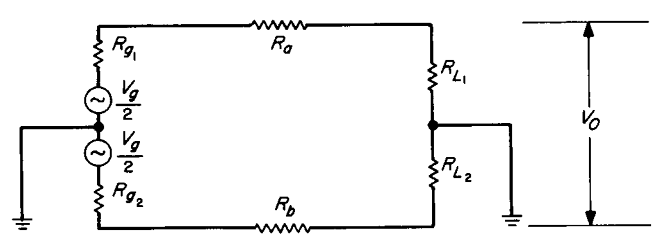

Fig. 3. Quasi-balanced circuit

III. BALANCED-MODE AND COMMON-MODE VOLTAGES

The balanced-mode signal (or noise) is applied to the circuit in a transverse fashion, i.e., schematically the signal generator voltage is applied normal to the direction of signal flow. The common-mode voltage (normally noise) is applied in a longitudinal direction. Examples of the common-mode and balanced-mode representation are given in Figs. 4 and 5, respectively.

A point of clarification should be made here. It is assumed that the circuit under analysis should act like a

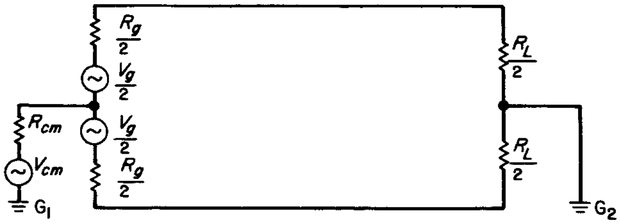

Fig. 4. Common-mode noise, V_{cm}

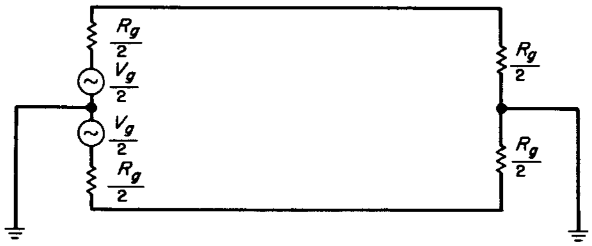

Fig. 5. Balanced mode, signal or noise

reasonably balanced circuit in that the signal voltage is always applied in a balanced-mode fashion. Throughout this Report the balanced-mode source will be titled V_n or V_g, depending on whether we are considering the balanced-mode noise or the balanced-mode signal, respectively. The common-mode generator will always be considered as a noise generator. It should be understood that while only V_n or V_g is considered at one time, in reality both generators exist simultaneously.

A. Common-Mode Sources

Any interference source can be represented by a common-mode and a balanced-mode noise generator. This is true regardless of the coupling means.

B. Radiated Fields

A radiated noise field may raise the ungrounded end of a circuit by some potential, causing longitudinal currents (common mode) to flow in both sides of the circuit. This same field may induce differing potentials to appear in each half of the circuit causing a balanced-mode noise current to flow around the circuit loop.

C. Ground-Plane Voltage Drop

If a balanced circuit is grounded to two different ground points (either directly by hard-wire connection or inadvertently by capacitive coupling) and there are currents flowing between these two ground points, a voltage will exist between them (Fig. 6). This voltage then appears as a generator between the two grounds and causes common-mode currents to flow in the balanced circuit. It can be seen here that there is a distinct advantage in having only one ground in the circuit. It is for this reason that single-point grounding is often specified. It must be recognized, however, that the integrity of the *singleness* of single-point ground philosophy can be maintained over only that frequency range where the common-mode coupling impedance is large.

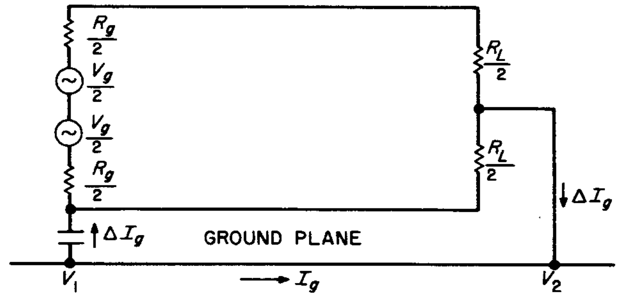

Fig. 6. Asymmetrical capacitive coupled circuit

D. Inductive Coupling

One solution to the problem of asymmetrical capacitive coupling, as shown in Fig. 6, is seen almost immediately to be a hard-wire connection from each end of the balanced circuit to one single physical ground point. Obviously, this would eliminate the voltage drop between two separate ground points. The configuration is shown in Fig. 7.

This technique, however, is often difficult to implement, due to physical separation of source and load and does not eliminate the *ground loop* through the balanced circuit. If there are circuits in the vicinity of the circuit under analysis, they will create magnetic fields which

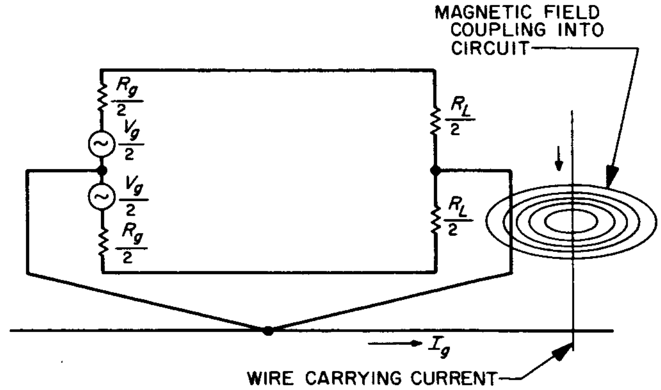

Fig. 7. Single-point grounding

will couple into the balanced circuit as shown in Fig. 7. This means of coupling is of the form:

$$E_{\text{coupled}} = A\,(dB/dt)$$

where A is the area of the ground loop normal to the magnetic field, and B is the magnetic flux density created by circuits in proximity. Note also that this coupling increases with frequency.

E. Effect of Common-Mode Voltage

Consider the operation of a simple balanced system with common-mode voltage present and no system unbalance. Let the common-mode generator be specified by V_{cm} and R_{cm} (Fig. 8).

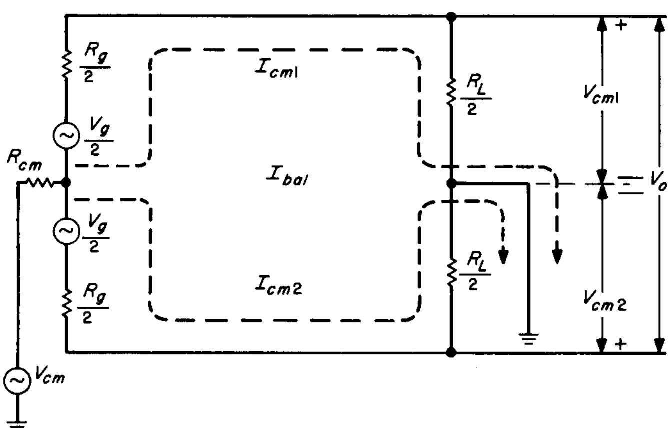

Fig. 8. Balanced circuit with common-mode voltage

If the system is completely balanced, then the common-mode currents will divide equally, half flowing in the upper side of the circuit, and half in the lower. These currents will cause a voltage drop across the load as shown in Fig. 8. Note that the polarity of V_{cm1} and V_{cm2} is such that the two signals cancel. From this explanation, the usefulness of the balanced circuit can be seen. If it is desirable to operate a low-level circuit in a very noisy environment (where the noise voltage has one side common to ground), the balanced circuit can be used and the noise voltage partially cancelled out, yielding much higher signal-to-noise ratios than would be possible for an unbalanced system. The disadvantages of the balanced form arise from extra weight (there must be at least two wires per circuit) and complex shielding and guarding circuits to maintain the balance integrity.

Consider the circuit shown in Fig. 9, where unbalance has been created by adding a resistance to one line and not the other. Note the effect this has on the common-mode rejection displayed by the balanced circuit of Fig. 8.

The total common-mode current that flows in the balanced circuit is:

$$I_{cmt} = I_{cm1} + I_{cm2} \tag{2}$$

Now the common-mode current is:

$$I_{cmt} = \frac{V_{cm}}{R_{cm} + \dfrac{(R_g/2 + R_u + R_L/2)\ (R_g/2 + R_L/2)}{R_g + R_L + R_u}} \tag{3}$$

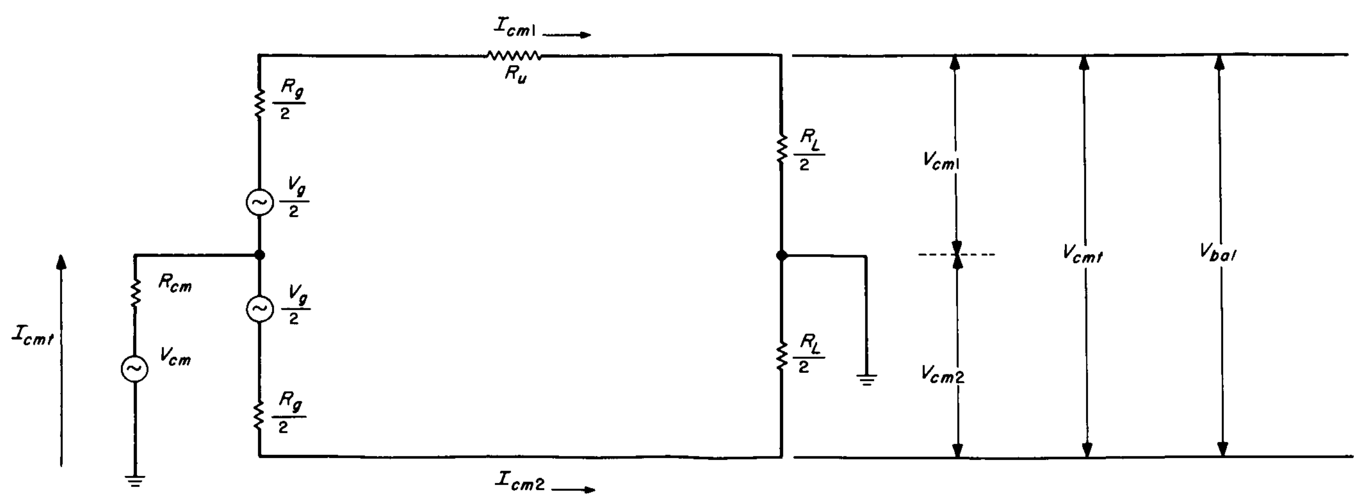

Fig. 9. Unbalanced circuit with common-mode voltage

and the branch currents are:

$$I_{cm1} = I_{cmt} \frac{(R_g/2 + R_L/2)}{(R_g + R_L + R_u)} \tag{4}$$

$$I_{cm2} = I_{cmt} \frac{(R_g/2 + R_L/2 + R_u)}{(R_g + R_L + R_u)} \tag{5}$$

The voltages due to I_{cm1} and I_{cm2} are out of phase and subtract across the load:

$$V_{cm2} - V_{cm1} = I_{cm2} \frac{R_L}{2} - I_{cm1} \frac{R_L}{2} = V_{cmt} \tag{6}$$

$$V_{cmt} = (R_L/2)\,(I_{cmt}) \left(\frac{R_g/2 + R_L/2 + R_u - R_g/2 - R_L/2}{R_g + R_L + R_u} \right) \tag{7}$$

$$V_{cmt} = I_{cmt} \frac{R_L}{2} \frac{R_u}{(R_g + R_L + R_u)} \tag{8}$$

The ratio of converted common-mode voltage across the load to the actual common-mode generator output is:

$$\frac{V_{cmt}}{V_{cm}} = \frac{(R_L/2) \quad (R_u)}{R_{cm}\,(R_g + R_L + R_u) + (R_g/2 + R_L/2 + R_u) \quad (R_g/2 + R_L/2)} \tag{9}$$

If there is an unbalance in the circuit, there will be a net voltage across the load due to the common-mode currents not being equal in the upper and lower half of the circuit and, therefore, not cancelling. The quantitative value of this net common-mode voltage is:

$$V_{cmt} = \frac{V_{cm}\, R_u\, R_L}{2\,[R_{cm}\,(R_g + R_L + R_u) + (R_g/2 + R_L/2 + R_u)\,(R_g/2 + R_L/2)]} \tag{10}$$

assuming $R_u << R_g$ or R_L:

$$V_{cmt} = \frac{2\, V_{cm}\, R_L\, R_u}{(R_g + R_L)^2 + (4\, R_{cm})\,(R_g + R_L)} \tag{11}$$

In practice at low frequencies, R_{cm} is usually a capacitive reactance due to capacitance coupling, and generally R_{cm} is large compared to R_g and R_L. On this basis, an approximation to Eq. (10) can be made.

Low-Frequency equivalent:

$$V_{cmt} = \frac{V_{cm}\, R_u\, R_L}{2\, R_{cm}\,(R_g + R_L)} \tag{12}$$

Here: R_u may be an impedance, rather than a pure resistance.

Mid-Frequency given by Eq. (11);

High-Frequency equivalent ($R_{cm} = 0$):

$$V_{cmt} = \frac{2\, V_{cm}\, R_u\, R_L}{(R_g + R_L)^2}$$

Generally, there is not a great unbalance in balanced systems due to difference of line impedance. The unbalances are commonly caused by one of the grounds being displaced from the center of the circuit. In a single-point ground system, only one of the grounds will be a hard-wire connection. The second ground will result from coupling and may not be at the symmetrical center of the circuit. Consequently, from the point of injection, there is asymmetry in the balanced circuit. An example of this is shown in Fig. 10. Note that the previous analysis was for a circuit with an unbalance in the line. The subsequent analysis will be for an asymmetrical ground connection.

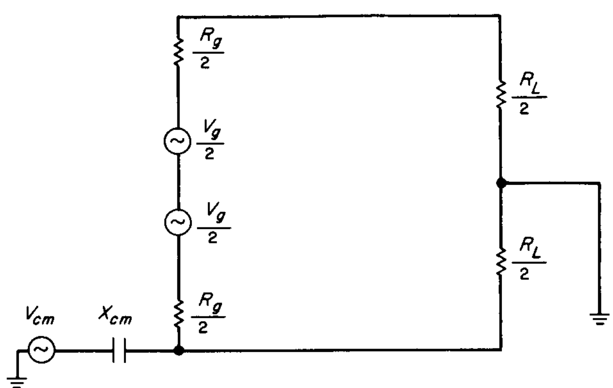

Fig. 10. Balanced circuit with asymmetrical common-mode noise

Here it can be seen that the amount of unbalance in the common-mode path is equal to R_g. The ratio of the balanced-signal voltage to the common-mode voltage, which represents the signal-to-noise ratio of the circuit, appearing at the load is:

Low Frequency:

$$\frac{V_{bal}}{V_{cm}} \approx \frac{2\,X_{cm}}{R_g}$$

(Note that $X_{cm} = 0$ here would give no signal. However, for low frequencies, X_{cm} is always very large.)

Mid Frequency:

$$\frac{V_{bal}}{V_{cm}} = \frac{R_L\left(\frac{2\,R_g + R_L}{R_g + R_L}\right) + 4\,X_{cm}}{2\,R_g}$$

High Frequency:

$$\frac{V_{bal}}{V_{cm}} \approx \frac{R_L}{R_g}\left(\frac{2\,R_g + R_L}{R_g + R_L}\right)$$

IV. SUPPRESSION OF UNDESIRED SIGNALS

Undesired signals may be significantly reduced in magnitude by use of filters and/or isolation transformers. Each of these suppression devices has its own characteristics and uses. A transformer will reject the common-mode signals in the low-frequency range (0 to $\approx$ 5 Mc), and the filter may be small, yet quite effective, in the 1 Mc to 1 Gc range. The transformer cannot reject unwanted signals in the low- or high-frequency ranges, which are balanced and appear across the transformer winding. Filtering is not efficient in the low-frequency range due to difficulty of design, weight, and price. A more thorough analysis of each of these types of suppression devices follows.

A. Filters

In the absence of common-mode voltage, the asymmetrical filter (Fig. 11) works as well as a balanced filter. If, however, there are common-mode voltages, then the inductance being in only one line causes an unbalance to exist and generally this is detrimental. This case can

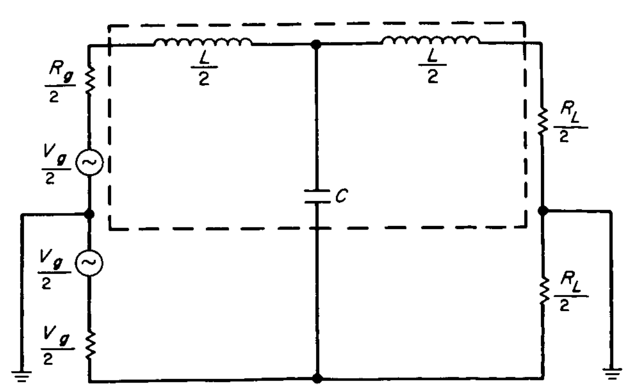

Fig. 11. Balanced circuit with asymmetrical filter

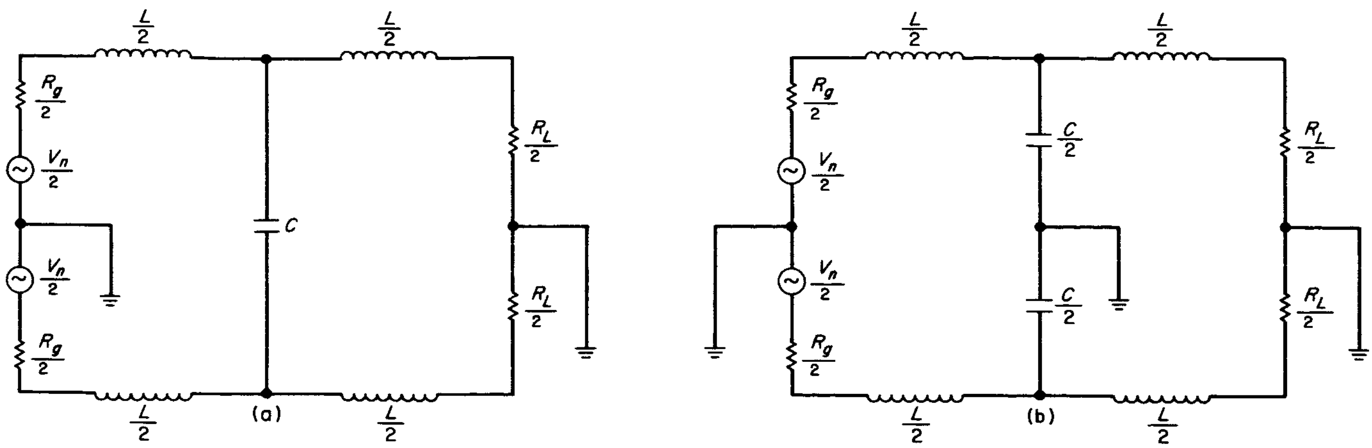

Fig. 12. Balanced circuits with symmetrical filters

be helpful if it recreates balance in a system already unbalanced. Normally, however, the circuits shown in Fig. 12 are used.

Consider the circuit in Fig. 12a with common-mode voltage injected. This is shown in Fig. 13.

Note that the current flowing through the top half of the load is $I_{cm1} + \Delta I_{cm2}$. The current flowing in the bottom half of the load is $I_{cm2} - \Delta I_{cm2}$. The total net current through the load is then:

$$I_{net} = (I_{cm2} - \Delta I_{cm2}) - (I_{cm1} + \Delta I_{cm2})$$

$$I_{net} = I_{cm2} - I_{cm1} - 2\Delta I_{cm2}$$

This is less than:

$$I_{net} = I_{cm2} - I_{cm1}$$

which would be the value of the net current if the capacitor were not installed.

A balanced filter which is grounded is shown in Fig. 14. In addition to performing the balancing action of Fig. 13, some of the common-mode current is dumped to ground and is not available to flow through the load.

On this basis, it might be assumed that this configuration would always be better than the ungrounded filter. However, there is a possible undesirable effect which may be present. If V_{cm} is due to voltage difference between G_1 and G_3 or a loop created by them, then there is the possibility of creating a common-mode voltage between G_2 and G_3 which would not exist in the ungrounded filter. A simplified version of this condition is shown in Fig. 15.

Only those currents which flow through the load are shown. These currents generally are of different frequencies and phase relationship; thus showing that all currents in phase in each half of the load is a realistic

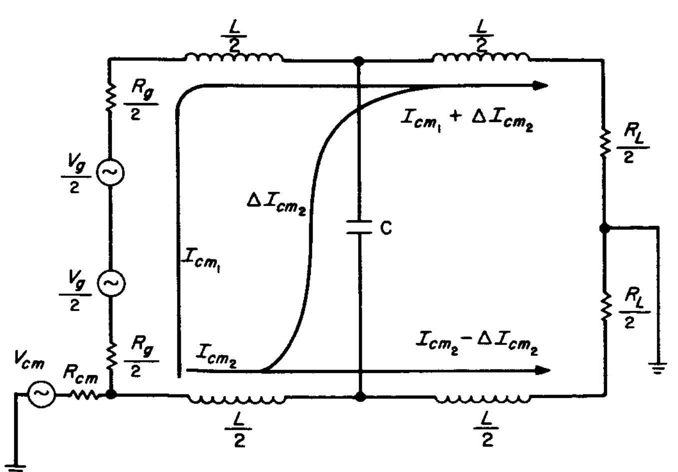

Fig. 13. Balanced filter circuit with asymmetrical common-mode noise

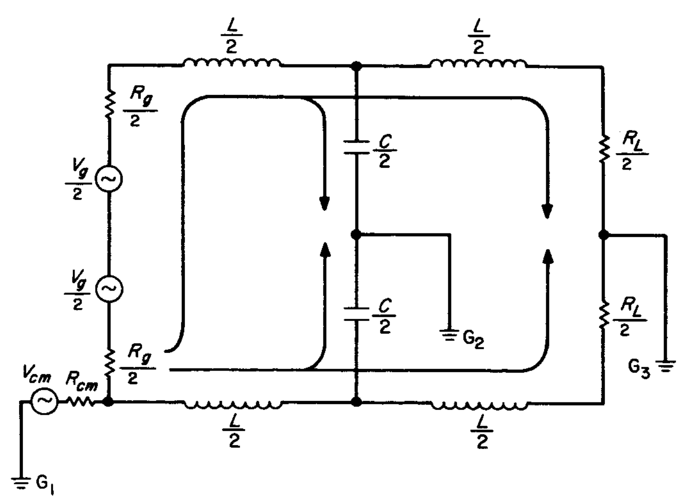

Fig. 14. Circuit with a balanced grounded filter

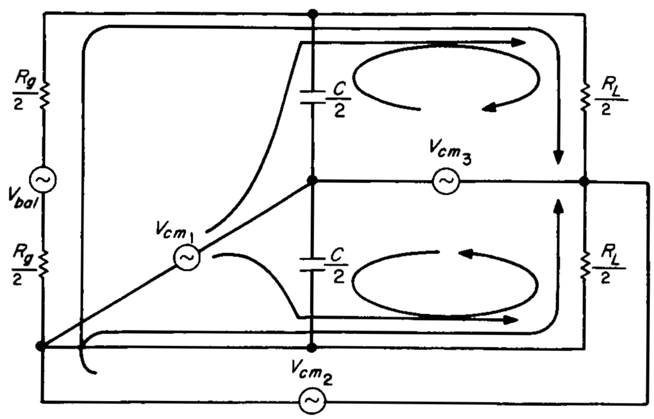

Fig. 15. Ground loops created by unequal ground potentials

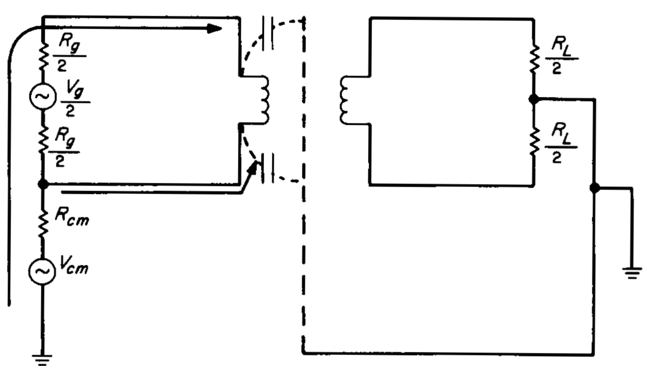

Fig. 16. Balanced circuit with a single-shielded isolation transformer

picture for peak values. From Fig. 15, it can be seen that the insertion of a ground-referenced filter has the potential of being detrimental. In the major portion of the cases, this form of filtering does not create nearly the number of problems that it solves. However, it does have the ability to cause problems and this fact should be considered in special low-level balanced instrumentation circuitry. If the ground-referenced filter does not create a common-mode problem, it is quite effective for common-mode rejection.

B. Isolation Transformers

One technique to reduce common-mode voltage effects without disturbing the operation of the balanced circuitry is shown in Fig. 16.

Disregarding momentarily the electrostatic shield, the transformer is used to couple magnetically the balanced-mode signals. Since a transformer can couple only those voltages which appear between the two ends of a winding, and the V_{cm} shown does not exist across any one winding but between windings, the transformer should cure the common-mode problem. This is normally true for very low frequencies; however, there is capacitance existing between windings, and this becomes the coupling element at higher frequencies. Now, considering the electrostatic shield, it is seen that this shield forms a capacitively-coupled circuit which shorts the common-mode current around the secondary. The circuit will develop a balanced-mode signal due to V_{cm} and unbalances in the primary, but unbalances in the secondary

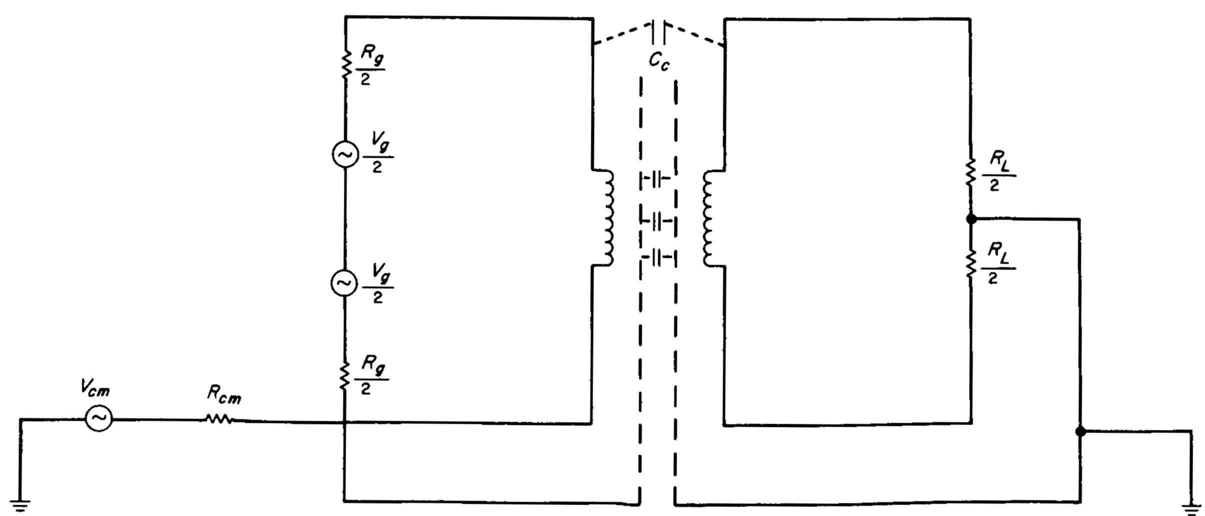

Fig. 17. Balanced circuit with a double-shielded isolation transformer

are immaterial since no common-mode current flows here. This will be fundamentally true for frequencies where the impedance of the shield grounding lead is low compared to the interwinding capacitive reactance. An improvement may be made on this circuit by the addition of a second shield as shown in Fig. 17. In this circuit, the common-mode current flows primarily between the shields and unbalances in either primary or secondary are of smaller consequence.

Proper construction of transformer shields can reduce the effective capacitance between primary and secondary windings to the order of 1.0 pf. This represents a relatively high impedance to common-mode voltages in the low and middle frequencies (100 kΩ at 1.6 Mc) and can give reasonable attenuation in this range. Any voltage which appears across the balanced circuit, however (whether noise or signal), will be transformed to the secondary. Therefore, there is no filtering effect to any balanced voltage or net common-mode current in the passband of the transformer. The filtering effect, offered by a transformer, is due to parasitic elements which become dominant at higher frequencies, and transformer action ceases to exist; however, the filtering effect of the transformer decreases at higher frequencies.

A simplified equivalent circuit for a 1:1 transformer at higher frequencies is given in Fig. 18.

Here $\mathcal{L}$ is the sum of the primary and secondary leakage inductances, and C is the sum of the primary and secondary distributed capacities. If this equivalent circuit maintained its form, the result would be the action of a 2-pole low-pass filter. However, at some frequency still higher, the distributed interwinding leakage capacitance will become dominant and negate the effect of the low-pass filter (Fig. 19).

The transformer then will be a capacitive divider having approximately 20 log C_p/C_d dB of attenuation. In practice, this may be in the order of 10 to 30 dB depending on the quality of electrostatic shield material and construction.

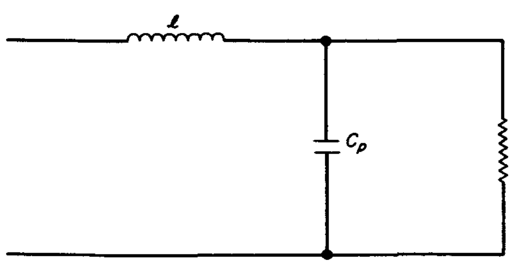

Fig. 18. Transformer high frequency equivalent circuit

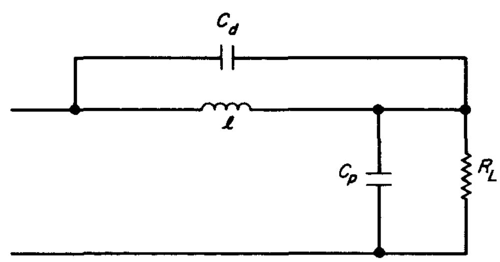

Fig. 19. Figure 18 circuit at higher frequencies

V. INSTALLATION OF SUPPRESSION DEVICE

The suppression device used should be as near the line entry point to a cabinet, rack, or room as possible. The input and output leads should be isolated from one another either via shielding, bulkhead mounting or spatial separation. Of these choices, bulkhead mounting is more effective if the enclosure is metal; shielding is the most effective if it is not. The device should be well bonded to a metallic enclosure. Examples of installation techniques are shown in Fig. 20.

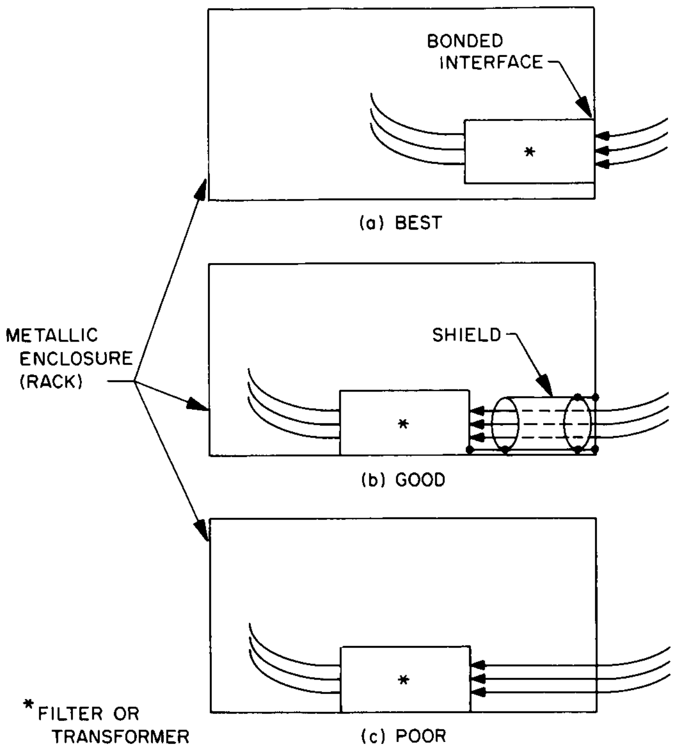

Fig. 20. Suppression filter installation techniques

In Fig. 20a, it can be seen that there is no radiation path around the filter. The only path available is through the filter. In Fig. 20b, there is a small area open to the leads at the shield termination, and in Fig. 20c, the input and output leads are exposed. Noise currents flowing on one side of the filter can couple to lines on the opposite side via the air path. Depending on frequency and geometry, this coupling-path attenuation may vary from approximately 80 to 15 *dB*.

Filters offer the best means for balanced-mode noise suppression. Isolation transformers with electrostatic shielding can be effective in eliminating the common-mode noise voltages. Balanced or ungrounded circuitry generally loses its identity at high frequencies. Because of capacitive coupling to unwanted grounds, a resultant loss of rejection to common-mode noise occurs. Consequently, it is very desirable to use a filter driving an isolation transformer (Fig. 21). Representative curves showing frequency vs attenuation for balanced and common-mode operations are given in Fig. 22. A graph showing typical insertion loss for a filter-transformer combination is shown in Fig. 23.

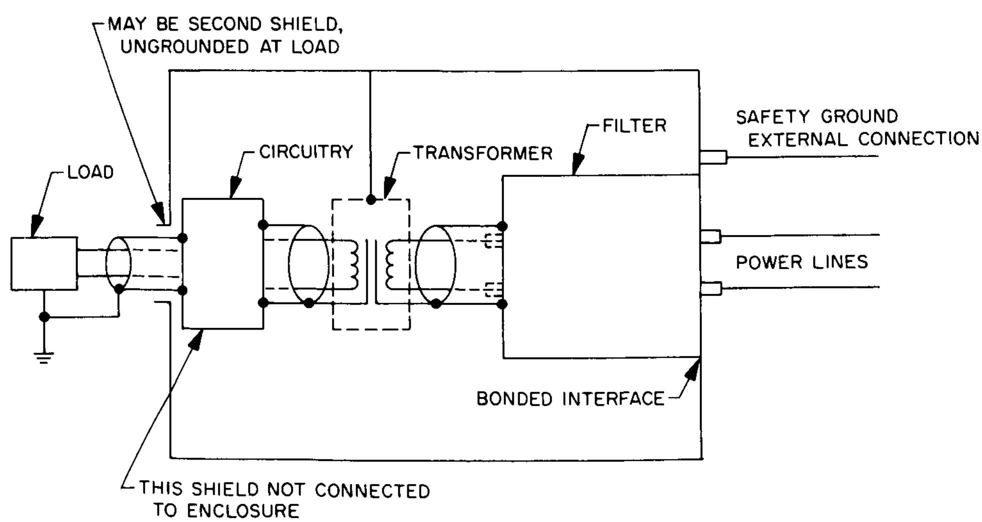

Fig. 21. Recommended suppression technique using both a filter and isolation transformer

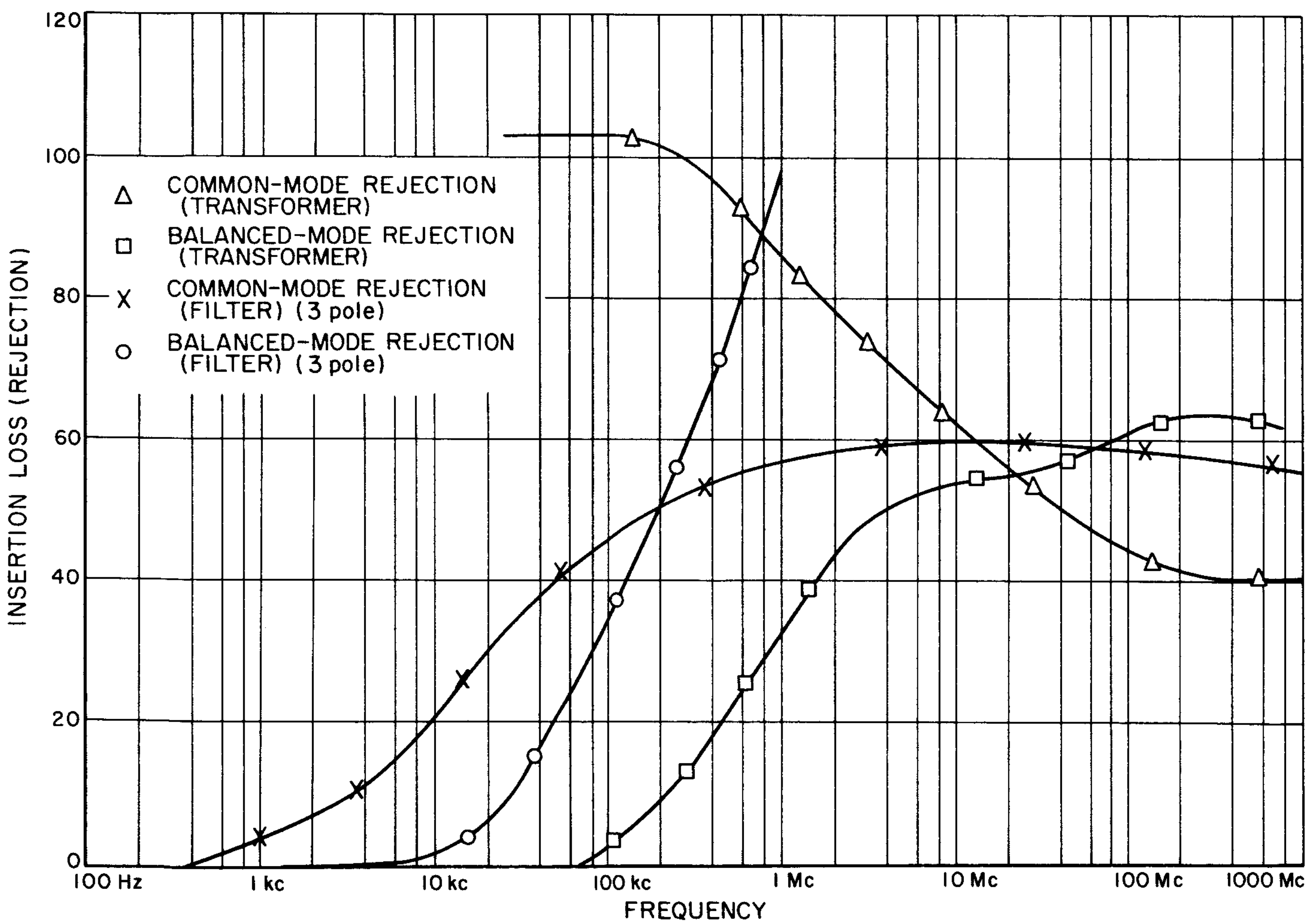

Fig. 22. Typical curves of balanced and common-mode noise rejection for filters and isolation transformers

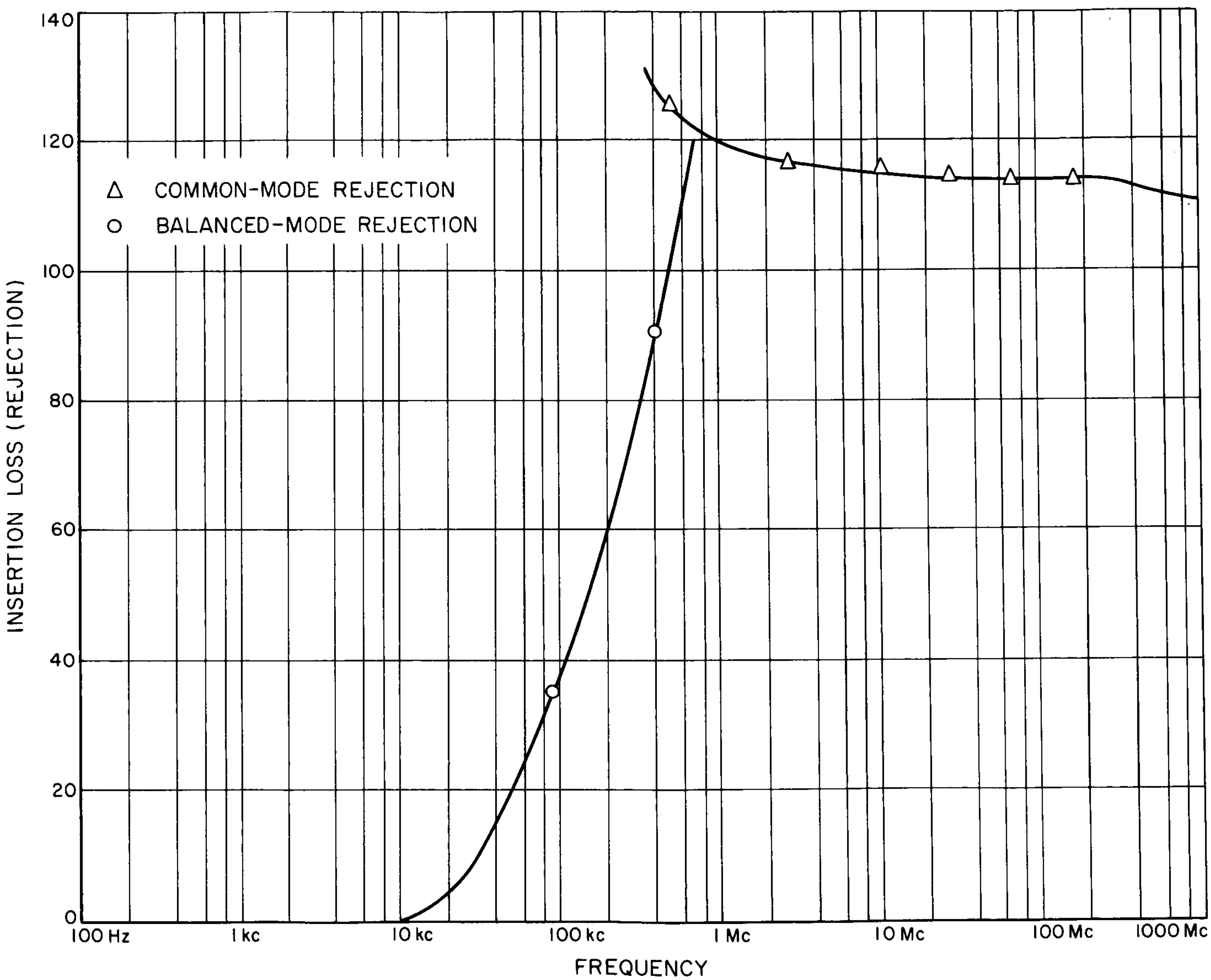

Fig. 23. Typical insertion loss for filter-transformer combination

In the application of noise filtering and the methods to be utilized, the first step is the determination of the source mode (i.e., is the problem due to common-mode noise in a reasonably well balanced circuit, or is it due to a noise generator which is itself fairly balanced). Section *VI* assists in determining the noise-source mode.

VI. NOISE-MODE IDENTIFICATION

Before it is possible to select the proper suppression device, it is necessary to determine whether the noise is due to a common-mode or balanced-mode source. This identification generally can be determined by making three current measurements over the frequency range of interest.

There are some ambiguous cases where a common-mode signal yielding certain values of I_{cm}/I_1 and I_{cm}/I_2 can be the same as a circuit with certain unbalances and no common mode present. These cases, however, generally resolve themselves since one combination of parameters are considerably more improbable than others.

A. Measurement Techniques

Consider the circuit of Fig. 24

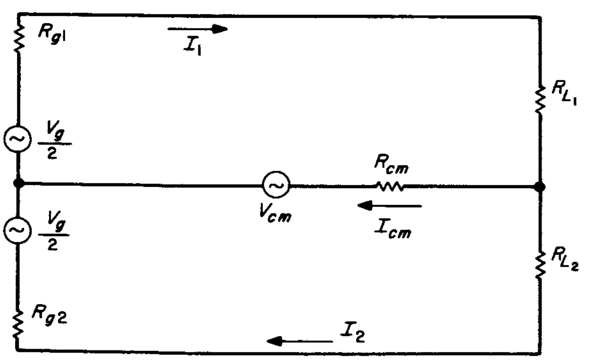

Fig. 24. Balanced circuit with unbalanced bridge current

In this circuit I_{cm} is that current which flows through the center (ground return) branch. It is due to the common-mode generator (when present) *and* a portion of the balanced-mode current arising

when:

$$\frac{R_{g1}}{R_{g2}} \neq \frac{R_{L1}}{R_{L2}}.$$

This is an unbalanced bridge current. The currents I_1 and I_2 are due to the normal balanced-mode current *plus* the common-mode current. The *plus* signifies the sum of the absolute magnitudes. This is chosen because a definitive phase relationship cannot be established between the common-mode and balanced-mode current.

B. Selection of Suppression Device

Table 1 is a guide to the selection of suppression devices based on the results of the I_{cm}/I tests which will be described below. It has been reduced to show only the probable combinations; as a result the table is not entirely rigorous. Some caution should be exercised in the selection of suppression components for those areas having limited frequency ranges in the table. The noise-source mode listed with frequency limitations is the most likely to occur. Note that I_{cm} and I do not have identifying subscripts in the table. This is because

$$\frac{R_{g1} + R_{L1}}{R_{g2} + R_{L2}} \gg 1$$

gives the same result

as:

$$\frac{R_{g2} + R_{L2}}{R_{g1} + R_{L1}} \gg 1$$

except that the I_{cm} and I subscripts are reversed. Both cases, however, identify the nature of the source.

An example of the use of the table is shown below (assume that noise measurements are made of the configurations shown by Fig. 25).

The ratio of I_{cm} to I in one case is $(1/5) = 0.2$ and in the second case $(1/50) = 0.02$. In both cases I_{cm}/I is

Table 1. Guide to selection of suppression devices

I_{cm}/I	Frequency range	Probable noise source mode	Suppression component, 1st choice	Suppression component, 2nd choice
≈ 1 and $>>1$	0–1 Mc	Common mode	Double shielded isolation transformer	Unbalanced filter
≈ 1 and $>>1$	1–20 Mc	Combination	Balanced filter and shielded transformer	Unbalanced filter or shielded transformer
≈ 1 and $>>1$	20–500 Mc	Balanced mode	Balanced filter	Shielded transformer
$<<1$ and $<<1$	All	Balanced mode	Balanced filter	Unbalanced filter
≈ 2 and ≈ 2	All	Common mode	Double shielded transformer	Unbalanced filter
≈ 0.5 and ≈ 1	All	Combination	Balanced filter and shielded transformer	Unbalanced filter or shielded transformer
≈ 0.5 and $>>1$	All	Balanced mode	Balanced filter	Isolation transformer
≈ 1 and ≈ 1	All	Combination	Balanced filter and shielded transformer	Unbalanced filter or shielded transformer

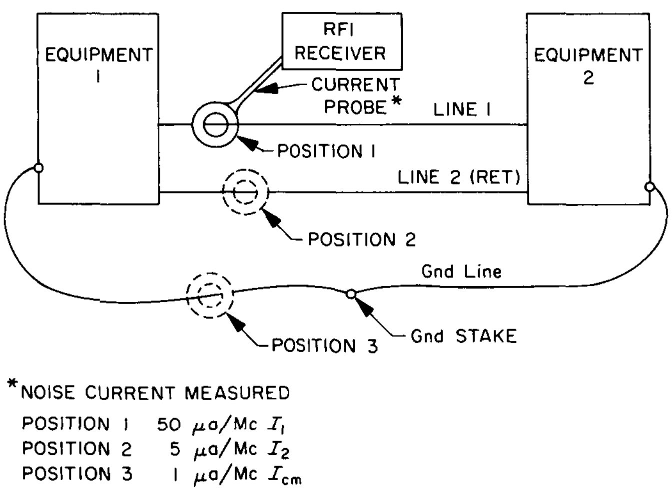

Fig. 25. Test setup illustrating use of Table 1

much less than 1. The two values of I_{cm}/I, both much less than 1, are found in the table. The noise source is seen to be primarily balanced mode, and a balanced filter is called out as the correction device. In the cases where unbalanced filters are called for, a trial method of inserting them in each line successively is required. The filter will act as a balancing device and it will be necessary to try the filter in each line to determine which side yields the maximum interference reduction.

The measurements necessary to determine the source-mode identification can be made using an RF current probe and standard RFI receiving instruments. These techniques can be used whenever a balanced or quasi-balanced circuit has at least one point tied to ground (since a ground line must be available for measurements); however, if no physical ground exists, some less significant information as to source-mode identification can sometimes be made. This can be done by measuring I_1, and I_2. A ratio of unity for these two measurements does not necessarily mean the absence of common-mode voltage, but a ratio reasonably far removed from unity does mean that a common-mode path is present and common-mode currents are likely.

APPENDIX A

Basis of Table 1

Taking the circuit of Fig. 24, the loop equations may be solved to yield expressions of I_{cm}/I_1 and I_{cm}/I_2

$$\frac{I_{cm}}{I_1} = \frac{V_{cm}(R_{g1} + R_{L1} + R_{g2} + R_{L2}) + V_g/2\,(R_{g2} + R_{L2} - R_{g1} - R_{L1})}{V_{cm}(R_{g2} + R_{L2}) + V_g/2\,(2\,R_{cm} + R_{g2} + R_{L2})}$$

$$\frac{I_{cm}}{I_2} = \frac{V_{cm}(R_{g1} + R_{L1} + R_{g2} + R_{L2}) + V_g/2\,(R_{g2} + R_{L2} - R_{g1} - R_{L1})}{V_g/2\,(2\,R_{cm} + R_{g1} + R_{L1}) - V_{cm}(R_{g1} + R_{L1})}$$

These are quantities which are measurable with a current probe. These equations were evaluated by letting each of three parameters vary over the range of 0, 1, and ∞.

The parameters were

$$\frac{V_g/2}{V_{cm}},\ \frac{R_{g1} + R_{L1}}{R_{g2} + R_{L2}}\ \text{and}\ \frac{R_{cm}}{R_g + R_L}.$$

The permutations of the three parameters over a range of three values each yield 27 solutions for the I_{cm}/I parameter. As might be obvious some values are redundant. For example the parameter

$$\frac{R_{g1} + R_{L1}}{R_{g2} + R_{L2}} = 0$$

yields the same solution

as:

$$\frac{R_{g2} + R_{L2}}{R_{g1} + R_{L1}} = 0$$

except the I subscripts are reversed. Other cases come to light which are trivial such as the combination

of:

$$\frac{V_g/2}{V_{cm}} = \infty$$

which says there is no common-mode voltage present so it hardly matters that the common-mode coupling impedance is zero, 1, or ∞. Table 1 represents simplification of the results of analyzing the various solutions and eliminating the redundant, the trivial and the improbable cases. This table lists several I_{cm}/I results and what these indicate as to the noise-source mode identification.

ACKNOWLEDGMENT

The author gratefully acknowledges the following personnel for their contributions in compiling the data for this Report: A. J. Nalbandian, for his help in organizing the presentation of the material and for his assistance in the publication; A. C. Whittlesey, for his many suggestions and assistance in the publication; and W. Shipley, Manager of the Environmental Requirements Section, for his guidance and helpful suggestions in the preparation of this Report.