Measurement Notes

Note 35

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Winding Bundles for Transformers

Carl E. Baum

Air Force Weapons Laboratory

Abstract

This note explores some new possibilities for transformer windings for fast transient pulses or for broadband CW performance. Besides using multiax cables one can use multiplet windings to give a variety of interesting cable topologies in constructing a winding bundle. This leads to various types of transformers for single-ended and differential signals. It also allows for multiple output signals (multiple secondaries) from a single input signal (primary), giving types of power dividers for fast pulses.

I. Introduction

As discussed in [3] one can use coaxial (and higher order multiaxial) cables as transformer windings. By bonding the outermost shields of the primary and secondary windings together, one can make these two windings act as a single conductor as far as external fields are concerned. Effectively the two windings act as one on the transformer core (including a possible air core). In particular this prevents magnetic flux from passing between two such windings, removing a term known as leakage inductance in the equivalent circuit of the transformer, leakage flux limits the high-frequency performance of a desired broad-band transformer.

Signals are introduced into the windings via gaps in the outer shields which are matched between primary and secondary windings, both in location and impedance. Impedance matching allows pulses to propagate from primary to secondary without reflection, except for the additional external impedance (ideally large) associated with the winding geometry and transformer core. By such concepts can a large high-frequency performance be achieved.

This note generalizes some of the concepts of [3]. Higher order winding bundles are introduced to allow for multiple secondary (or even primary) windings as desired. This allows for pulse splitters (or combiners) of various orders.

II. Concept of a Winding Bundle

Let us now consider a general winding bundle as illustrated in Figure 2.1A. Here both coaxial and higher order multiaxial cables are involved with outer shields bonded together as a single conductor. In this example we have 4 coaxial and 2 triaxial cables forming what we might term as a sextuplet cable or winding bundle. As far as external fields ar concerned this is a single conductor as long as the shields can be approximated as perfectly conducting.

Concerning nomenclature let us call the order of the winding bundle as:

monoplet ≡ 1 winding
dupletor or twin ≡ 2 windings
triplet ≡ 3 windings
quadruplet ≡ 4 windings
quintuplet ≡ 5 windings (2.1)
sextuplet ≡ 6 windings
etc.
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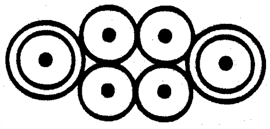
.
.
multiplet ≡ multiple (or arbitrary number of) windings

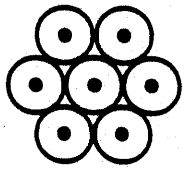
Note that in the discussion of the multiple Moebius strip loop [2] there can be a complex structure which can form a single winding. In this context a single winding can itself be multiplet. So let us admit the possibility that the order of the winding bundle may not equal the number of independent windings (primary plus secondary).

In a simpler case the windings might be coaxes, such as the twin coaxes discussed in [3]. As illustrated in Figure 2.1B coaxes can be bundled to an arbitrary order. For reasons, including mechanical flexibility to make it easier to wind the bundle on a magnetic core, one might bond the coaxes together in a flatpak form as illustrated in Figure 2.1C.

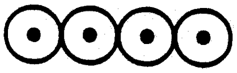
In each winding bundle there are one or more gap regions where signals are transferred from primary to secondary windings. At such gap regions outermost shields are cut so as to allow signals to propagate from the



A. General Case (e.g. Sextuplet)



B. Coax Bundle (e.g. Septuplet)



C. Coax Bundle in Flat Form
(Flatpak) (e.g. Quadruplet)

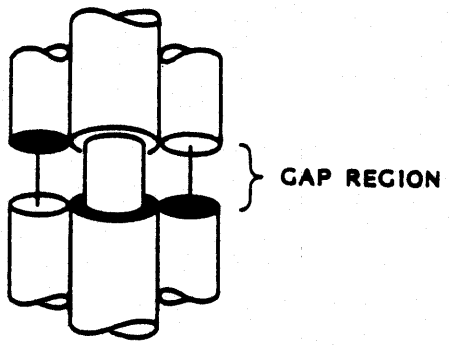
Figure 2.1. Winding Bundles

interior of one multiax (a winding) to another. As indicated in Figure 2.2A a signal might propagate from, say, between the outermost and next outermost shield of the multiax (the middle winding) into, say, two coaxes (effectively in parallel) which are appropriately impedance matched to the signal from the multiax. Note that there is an external signal on the outside of the shields, but the impedance here is approximated as very large.

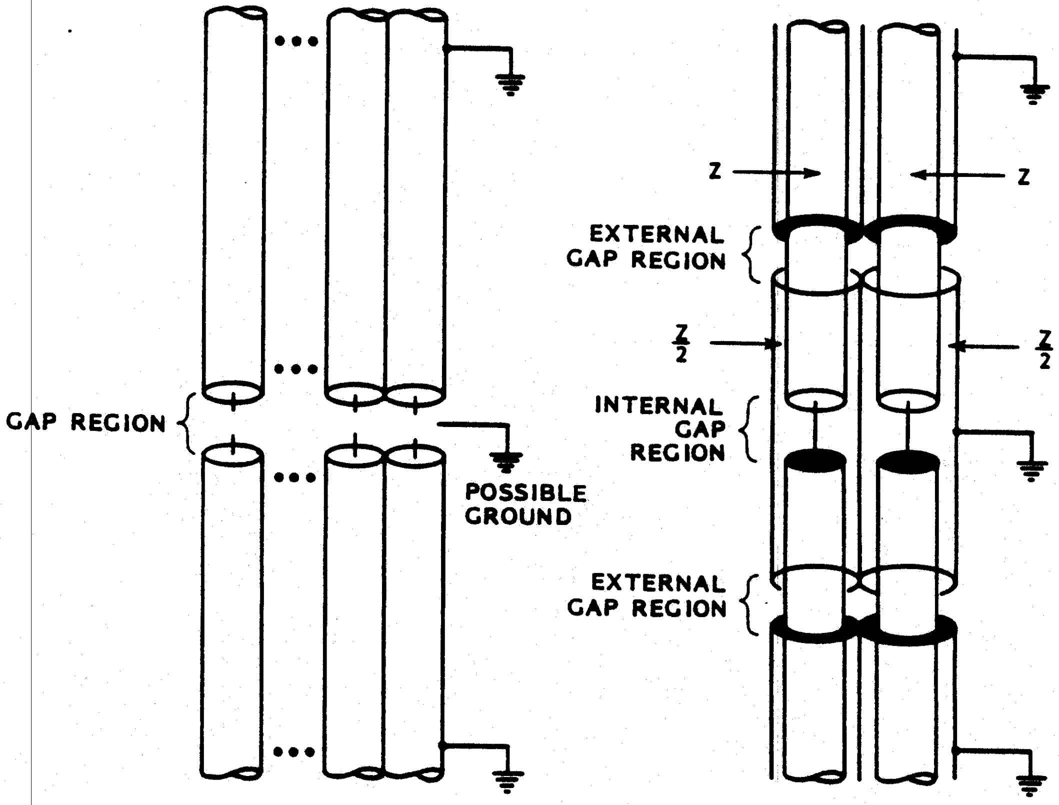
A coax multiplet as illustrated in Figure 2.2B forms a winding bundle with only one gap region. The gaps in the individual coaxes can be of a few types as considered in the next section. Note that at the two ends of the winding bundle the shields are connected to close the loop through some common reference conductor (e.g. the box containing the transformer core). Also, the signals enter and leave the winding at these two ends (see, for example, [4 (Figure 8)]. If there are any split-shield gaps the center conductor may also be connected to the common reference (local "ground").

A twin triaxial winding is illustrated in Figure 2.2C. Now we can have two gap regions for the outermost shields. This is accompanied by a single internal gap in the inner shield of each winding to send the signal out to (or receive the signal from) the gaps in the outermost shield. As discussed in [1] the inner coax impedances are Z where the impedances between the two shields of the triaxes are Z/2 for the case of symmetrical coax gaps. (For Moebius gaps here the ratio is 1/4 instead.) Note that while the winding shields at the ends are connected to a common reference, one can also connect the center sections of the outermost shields (otherwise floating) to this same reference (which may itself be a transformer shield). Generalizing Figure 2.2C to higher-order multiax cables of order N_a (the number of conductors) there are N_a-1 outermost gap regions if only unsymmetrical gaps are used.

The examples illustrated in Figure 2.2 use multiax cables as in [1]. One can also use the multiple Moebius winding discussed in [2]. In this case the situation is more complex in that only some of the outermost shields are split at a gap region. Referring to [2] one can construct windings (including multiple turns) which can be added to the present examples giving various possibilities in addition to those discussed here.



A. Triplet



B. Multiplet Coax

C. Twin Triax

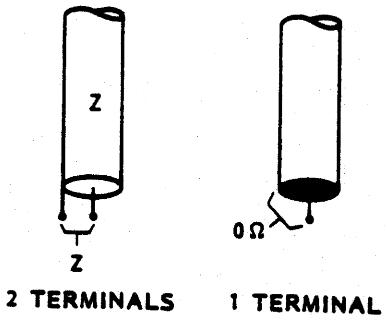
Figure 2.2. Gaps in Winding Bundles

III. Twin Coaxial Winding Bundles

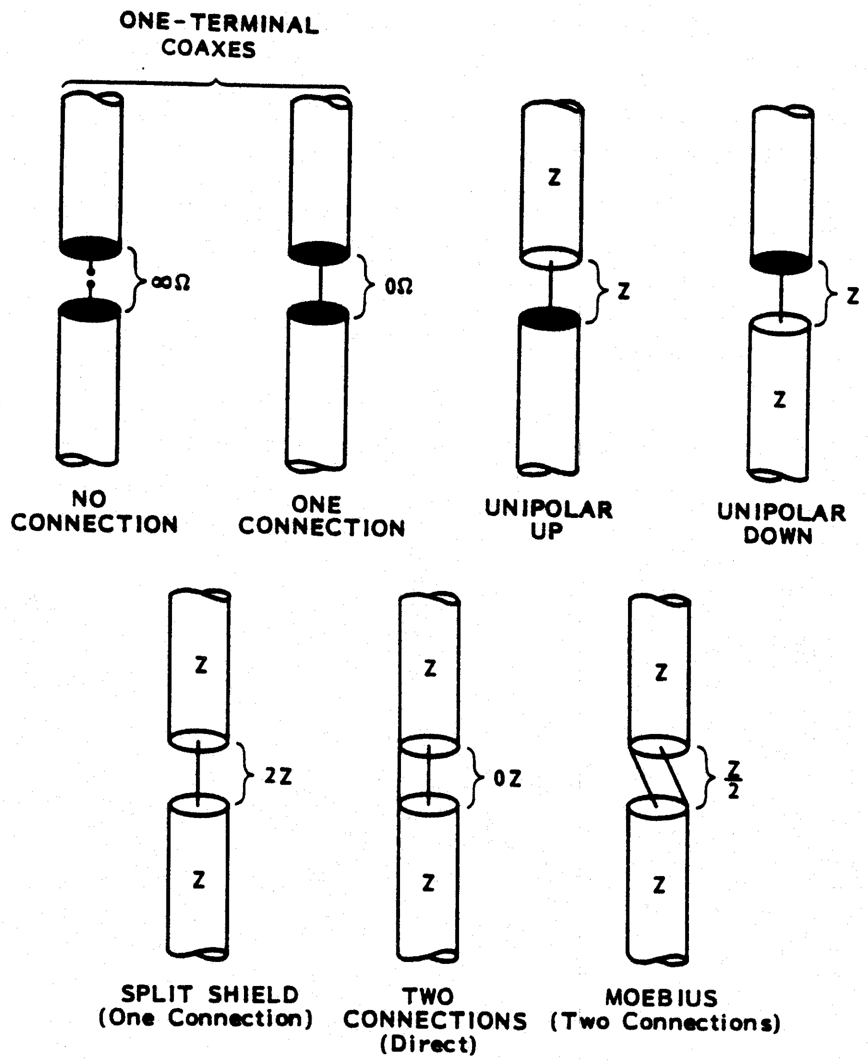
A previous note has considered twin coaxial winding bundles in some detail [3], leading to transformer designs involving various turns ratios (including inverting), single-ended signals, differential signals, and associated impedance ratios. The gap region for such a twin winding has a limited number of ways to make connections across the gap; let us consider these here.

First consider the gap possibilities for a single coax gap as in [1]. As indicated in Figure 3.1A there are two types of coax endings. In the two-terminal case separate connections can be made to both center conductor and shield; this allows a signal to propagate into (or out of) the coax. In the one-terminal case the center conductor is unaccessed allowing no signal to enter or leave the coax; this can be accomplished by shorting the center conductor (which now serves no separate purpose) to the shield (as indicated by the darkened region); in this configuration one can connect to either the center conductor or the shield and achieve the same electrical result.

Now combine these coax endings to form the coax gaps indicated in Figure 3.1B. Considering first the combination of two one-terminal cable ends, these single terminals are either connected or unconnected across the gap giving two possibilities, both of which admit no signals into either coax (a useless case which is included for completeness). Next consider combination of a two-terminal coax end with a one-terminal coax end. In this case the center conductor must connect across the gap and has only one terminal to which it can be connected (i.e. the shield); the shield of the two-terminal coax end cannot connect across the gap without connecting to the center conductor of the two-terminal end thereby making it a one-terminal end. There are two useful possibilities left for such unsymmetrical gaps depending on which of the two coaxes has an internal signal (designated as unipolar up and unipolar down). Finally, combine two two-terminal coax ends. There are three cases illustrated of which only two are useful. First, only the center conductors connect across the gap (a split-shield gap). Second, both conductors connect to their counterparts across the gap (useless as the shields are shorted across the gap, no signals going into or out of the coaxes from the exterior). Third, both conductors connect across the gap to their opposite



A. Coax Ends



B. Coax Gaps

Figure 3.1. Construction of Coax Gaps

counterparts, center conductor to opposite shield and conversely (a Moebius gap).

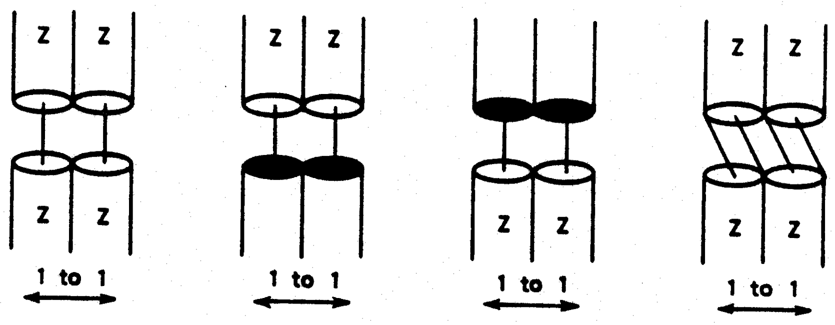
In all the cases in Figure 3.1B, the impedance driving into the coaxes as measured between the two coax shields (the gap impedance) is indicated in terms of the coax impedance Z. Note that currents on the shield exterior are assumed negligible for this purpose. The useless gaps have a gap impedance of 0 or ∞, indicating no signals entering the coaxes via the gap. This leaves four useful and interesting coax gaps: two unsymmetrical gaps (counting the two polarities or ways the signal can leave the gap via two different coaxes), and two symmetrical gaps (split-shield and Moebius). Ordering these in terms of gap admittance we have

$$Z \equiv \text{coax impedance}$$

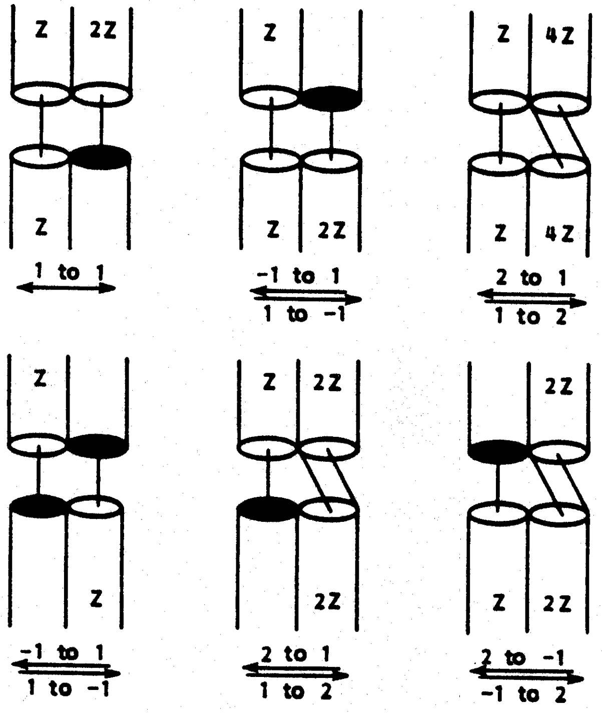
$$\begin{array}{lcl} \text{split-shield} & \Longleftrightarrow & Z_{gap} = 2Z \\ \text{unipolar up} & \Longleftrightarrow & Z_{gap} = Z \\ \text{unipolar down} & \Longleftrightarrow & Z_{gap} = Z \\ \text{Moebius} & \Longleftrightarrow & Z_{gap} = \frac{Z}{2} \end{array} \tag{3.1}$$

Now take these four types of coax gaps and combine them in a twin configuration to make the various twin coaxial winding bundles as indicated in Figure 3.2. As in Figure 3.2A twin each gap with itself giving 4 possibilities. As a transformer these configurations have 1 to 1 turns ratios. Since the two coax gaps are identical then Z_{gap} is matched from one to the other if the coax impedances are all Z (all the same). Furthermore, due to the symmetry it does not matter which winding is considered primary and which secondary; there are only 4 independent configurations here. Note that in two cases the signals are both differential, and in two cases are both single ended.

Going on to Figure 3.2B combine each of the 4 gap types in (3.1) with the remaining 3 gap types giving (3+2+1=6) twin coaxial gaps. Since these gaps use two different coaxial gaps it makes a difference which way the signal



A. Identical Twins



B. Other Twins

Figure 3.2. Twin Coaxial Gaps

propagates (i.e. which winding is primary and which secondary) so that one might wish to count these as 12 cases. Note now the turns ratios can be 1 to 1, 1 to -1, 1 to 2, 1 to -2, 2 to 1, and 2 to -1, with various combinations of single-ended and differential windings. Furthermore, the coax impedances are not necessarily the same due to the requirement of matching Z_{gap} for the two windings; so some coaxes are indicated as having a characteristic impedance as some multiple of Z. As a convention note that voltages in upper coaxes are positive and in lower coaxes are negative. For differential voltages this is given by upper voltage minus lower voltage. For turns ratios the arrows go from primaries to secondaries, so each example in Figure 3.2B can be considered as 2 cases if desired.

IV. Twin Multiaxial Winding Bundles

This concept of twinning applies not only to coaxial cables as in the previous section, but to more general multiaxial cables as well, Considering the number of possibilities, one has two multiax cables of various orders (coax, triax, etc.) which may be different or the same for the two cables. These are twinned such that the gaps in the outermost shields are matched in terms of gap impedance at every such gap. This leads to a large number of possibilities which do not fit so neatly on a single page as in Figure 3.2.

Examples of such twin multiaxial windings can be given. Figure 2.2C shows a twin triaxial winding of a simple variety with two matched gaps in the outermost shields, as well as gaps in the internal coax shields, with impedances matched here as well. In addition, transit times have to be matched between the external and internal gaps to perform the splitting and summing of the signals correctly.

Another such example is given in [3 (Figure 4.4)]. This is a case of a twin coax/triax with two parallel signal inputs (single ended) and one signal output (single ended) giving a 1 to 2 turns ratio. By combining this twin winding with another similar winding differential signals and other turns ratios can be produced.

V. Multiplet Coaxial Winding Bundles

Now let us go to higher order multiplet winding bundles as in (2.1). Considering coaxial windings then one or more of these windings may be the primary and the remainder the secondary. Various possibilities involving single ended and differential signals, and parallel connections of coaxial inputs and/or outputs are possible. While one can imagine an enormous number of possibilities let us illustrate this class of winding bundles by a few simple examples.

Our first example, illustrated in Figure 5.1, is what might be termed a four-way single-ended power divider. It uses a triplet coaxial winding with all coaxes of the same characteristic impedance Z. The signal comes in one end of one coax (taken as the center coax for symmetry) and transitions from an unsymmetrical coax gap into the parallel combination of two split-shield gaps (each with $Z_{gap} = 2Z$, two in parallel giving an impedance of Z). As discussed in [3] this winding bundle is wound on a magnetic core with common local ground connections at winding positions as indicated in the figure. Note that in this example there are four outputs, two with $+V_{in}/2$, and two (inverting) with $-V_{in}/2$. If one were to merely use a resistive current divider where the input coax divided the signal to 4 output coaxes in an impedance-matched configuration, then the signal would be further reduced to $\pm V_{in}/4$. In this type of transformer all the input power appears equally divided to the 4 outputs. This example can also be considered as a two-way single-ended-to-differential power divider.

This special example is quite simple in that all the cables are of the same impedance. (Of course the two secondary-winding coaxes of characteristic impedance Z could be replaced by a single one of characteristic impedance Z/2 which could then be further divided into coaxes of characteristic impedance Z after leaving the transformer.) Having four signals of level $\pm V_{in}/2$ seems to be a very special case. Note that each output may be connected to the input of another such transformer giving 16 outputs with signal levels $\pm V_{in}/4$; this process may be continued indefinitely.

Our second example, illustrated in Figure 5.2, is a four-way differential power divider. It can also be considered as an eight-way differential-to-single-ended power divider. It uses a quintuplet coaxial winding, again with all coaxes of the same characteristic impedance Z. Note the Moebius gap

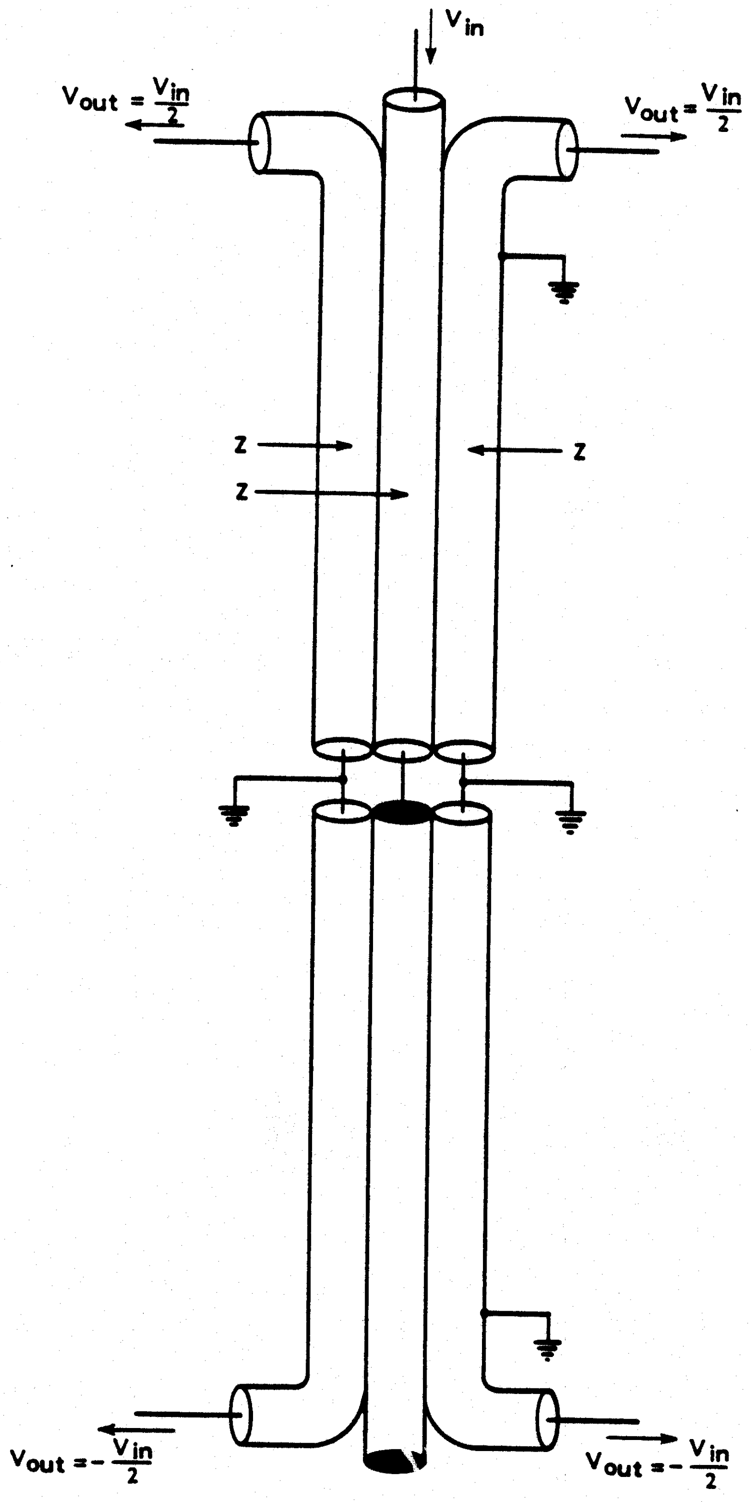


Figure 5.1. Four-Way Single-Ended Power Divider
(Triplet Coaxial Winding)

in the primary winding driving 4 parallel split-shield gaps in the secondary windings.

As one can see the use of multiplet coaxial windings can lead to a large number of possibilities for transformers which can be used as power dividers with broad-band characteristics suitable for pulses.

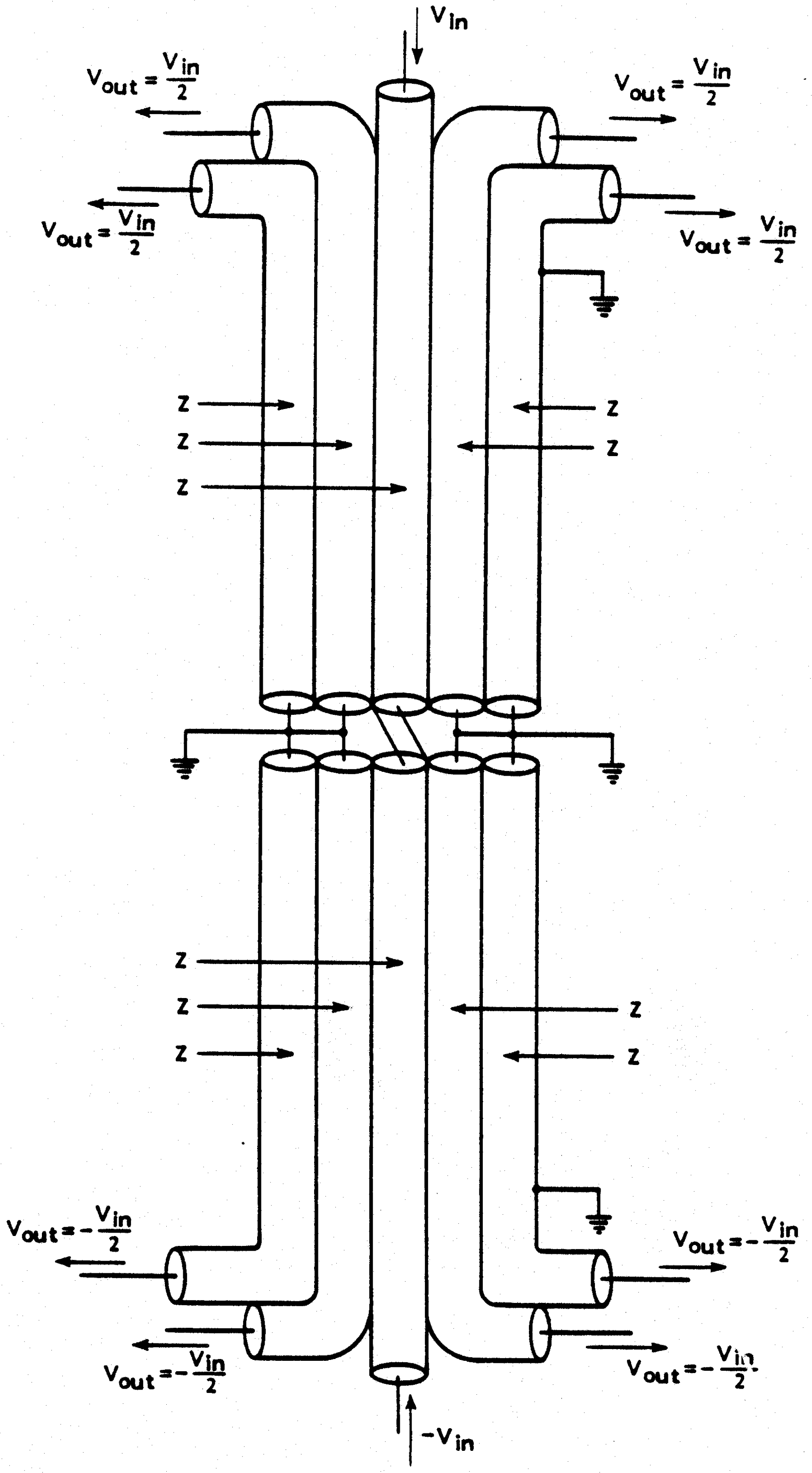


Figure 5.2. Four-Way Differential Power Divider (Quintuplet Coaxial Winding)

VI. Multiplet Multiaxial Winding Bundles

Combining the multiplet winding concept with multiaxial windings allows for even more possibilities. Here we just show two examples.

Figure 6.1 shows a four-way single-ended power divider. In comparison with Figure 5.1 this divider has all outputs of the same polarity $+V_{in}/2$. Note the triaxial primary with center-coax characteristic impedance Z and shield-to-shield characteristic impedance Z/2. The four outputs from the two coaxial secondary windings all have characteristic impedance Z. This transformer is made from a triplet triaxial/coaxial winding.

Figure 6.2 shows a sixteen-way single-ended to single-ended power divider. It could also be considered as an eight-way single-ended-to-differential power divider. The coaxial outputs give now signals $\pm V_{in}/4$. The primary is the same kind of triax as in the previous example. This transformer is made from a quintuplet triaxial/coaxial winding.

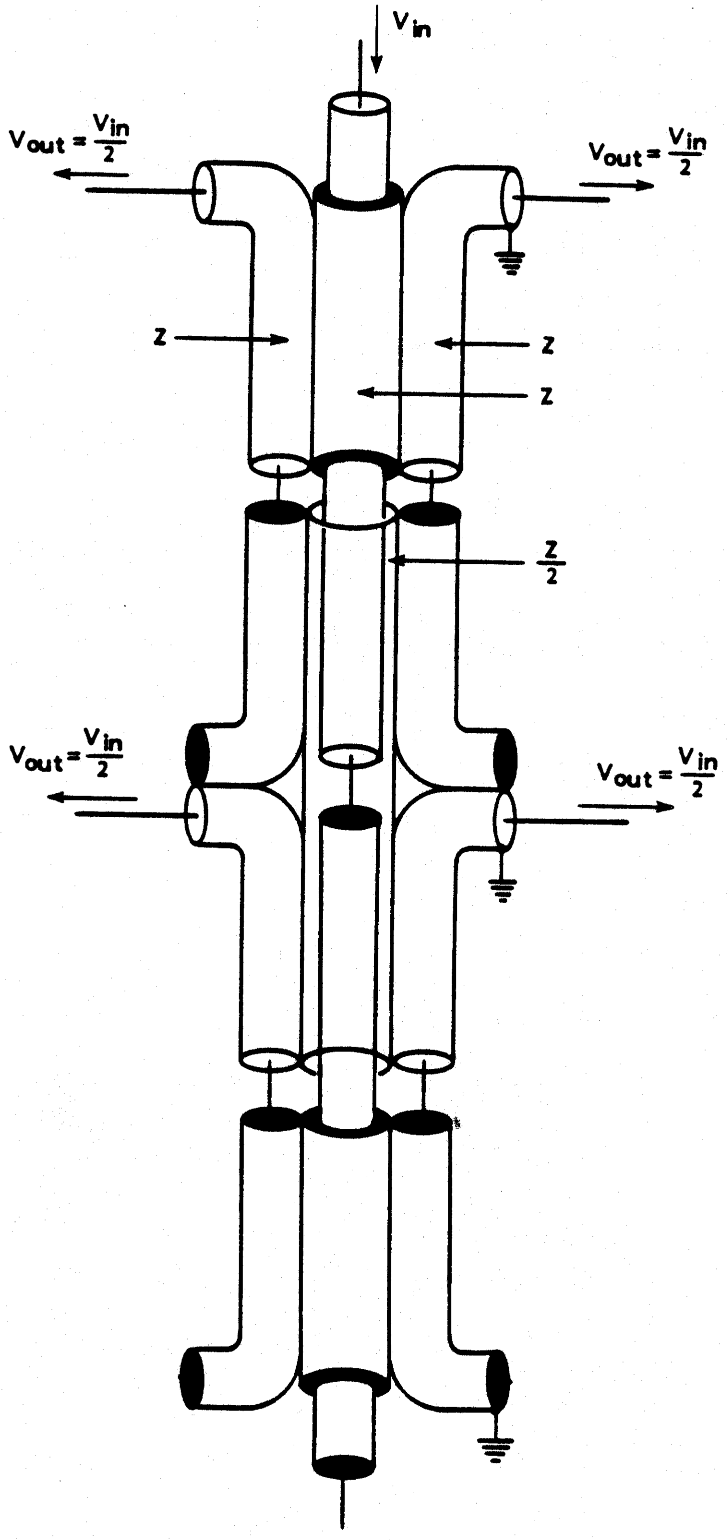


Figure 6.1. Four-Way Single-Ended Power Divider
(Triplet Triaxial/Coaxial Winding)

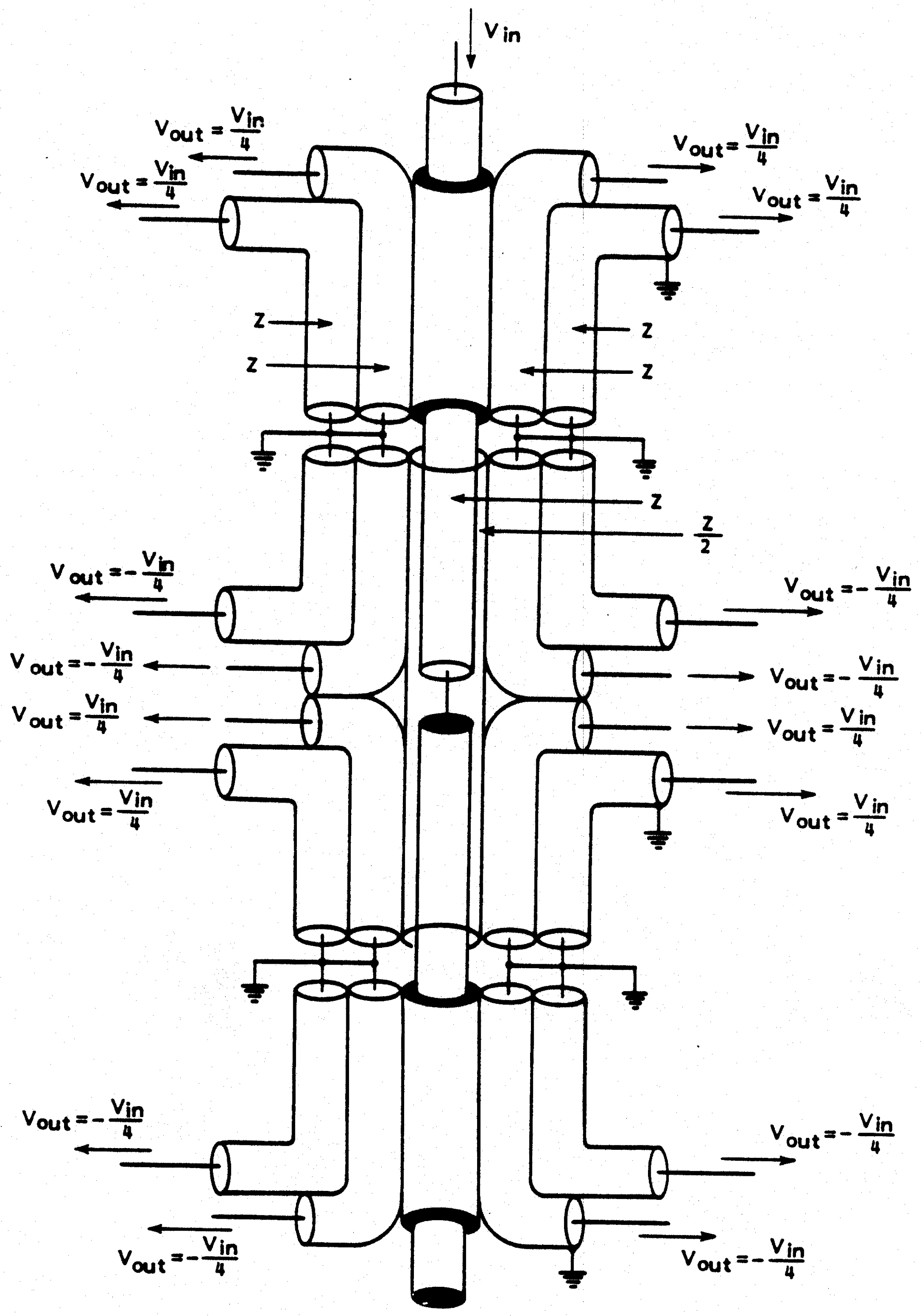


Figure 6.2. Sixteen-Way Single-Ended Power Divider
(Quintuplet Triaxial/Coaxial Winding)

VII. Summary

Looking back at the section titles we can now see that there are a set of concepts which can be used for the design of the windings of pulse (or broad-band) transformers. These concepts are all basically topological, involving ways that cables can be combined while behaving as a single conductor as far as external signals are concerned. The cables can be multiaxial, the windings can be multiplet, and single-ended and differential signals can be handled.

This paper has given examples of the various types of windings for various types of transformers. The types of twin-coaxial-winding gaps are of a small number with all being exhibited. As one goes to multiax and multiplet the possibilities are staggering. However, due to construction difficulties the number of practical permutations is more manageable. Note also that more than one winding bundle can be used on a transformer core.

Use of these techniques generalizes our concept of a transformer from a two-winding system (primary and secondary) to multiple secondaries. This allows for convenient, ideally lossless power dividers for fast transient pulses.

References

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3. C.E. Baum, Winding Topology for Transformers, Measurement Note 31, October 1986.
4. G.D. Sower and L.M. Atchley, Twin Coaxial Balun (TCB) Development, Measurement Note 34, June 1987.