designing impedance-matching systems

A graphical method of designing impedance-matching networks for your favorite antenna

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There's a line from Porgy and Bess, "the things that you're liable to read in the Bible – they ain't necessarily so." It's also a fact that the things you read in a good antenna theory book ain't necessarily so when it comes to your particular antenna.

What is the impedance of a vertical antenna? Well, you can look up the impedance on carefully constructed charts with electrical height in one direction and ohms in the other and get some ball-park estimates for both resistance and reactance. But what is the impedance of *your* vertical? What is its electrical height and is it the same for a 3-inch pipe as it is for a piece of wire? Down at the bottom of the page containing the graph you may find a footnote that says, "over a perfect ground." (Sometimes this footnote appears 3 pages removed from the chart.) Now, do you have a perfect saltwater ground or do you have a piece of wire ten-feet long or do you have the body of a motor vehicle?

There are just too many variables to come up with an answer either by eye balling or by taking physical measurements. To really know, you need to take some electrical measurements. And, to get any kind of precision, you need a good rf bridge. A $1000 rf bridge is not available to everybody but I had the use of one for a short time and came up with some rather surprising results.

mobile-mounted vertical

This article will involve itself with a couple of outstanding examples, but to start with, I was motivated by the results I obtained from a vehicle-mounted vertical. I don't care much about mobiling but I do like to ham from a camp location once I get there. If there are trees around, a good dipole is hard to beat. I get mine up by shooting a fish sinker, attached to a spinning outfit, with a slingshot. These surgical rubber tubing slingshots (available in any sports store) will shoot a one-ounce sinker over a fifty-foot-high limb quite easily. Then you reel the fish line back with a nylon cord attached, and raise your antenna.

But in some places, like the seashore, trees are not handy. So, I wanted a good vertical whip, a full quarter-wavelength high on 20, 15 and 10 meters. This was made from telescoping aluminum tubing.

The time-honored method of grid dipping to achieve resonance was followed to get the required length on the three bands.

I have a Ford van station wagon which has quite an expanse of roof for a ground plane. I looked in the good book for an approximate resistance for a quarter-wave ground plane and came up with the magic number of 36 ohms. "Aha, two hunks of 72-ohm coax in parallel should yield 36 ohms." Well, maybe it does, but my swr was higher than a cat's back and adjusting the telescoping whip to some point off resonance didn't help at all.

Finally, I took off one of the pieces of coax and things were just as bad as before (this was on 20 meters). In desperation I got a piece of 50-ohm coax and everything was hunky-dory. Then, I went to 15 meters – with 50-ohm line the swr was way too high. I changed back to 72-ohm coax and got on board. I had the same experience on 10 meters.

impedance measurement

Well, I finally got everything working all right, but I wondered just what was really going on, anyway. So, I borrowed an rf bridge and made some measurements. The General Radio 1606A rf bridge has two dials that read out resistance and reactance. At resonance the so-called j-factor or reactive component should read zero. With the vertical adjusted to the proper height in the middle of the 20-meter phone band I obtained a readout of 52 ± j0. On 15 meters the reading was 70 ± j0, and on 10 meters, 75 ± j0. All of these measurements were for one-quarter wavelength height. The differences in R seems to be attributable to the mounting (one corner of the van) and the extent of the ground plane (vehicle body). They would, of course, differ for every installation and every vehicle. However, I suspect that a lot of installations would work best with a 50-ohm line on one band and a 72-ohm line on another.

Measurements were actually made at the end of an electrically measured half wavelength of line in each case, in order to remove the equipment from proximity to the vehicle.

vertical antenna

In the W7CSD part of the world, crops are irrigated, and a 40-foot length of aluminum irrigation pipe is pretty easy to come by. ($14.30 for 3-inch tubing.) I set a one-quart soft-drink bottle in concrete and mounted a 40-foot section of irrigation pipe on top of it guyed with polyurethane rope (the kind used for water skiing). I thought this would work pretty well on 20 meters and also 40 and 75. The big problem was building matching networks for each band.

Author W7CSD with his three-band 40-foot irrigation-pipe vertical.

First of all, I needed to make some impedance measurements to see what I had. The first thing that I determined was that long radials will work fine on 20 meters, but short radials will not work well on 75. So, I used three 75-foot radials (actually, not really radial, but following convenient fence lines). More would be better — the more the merrier. The same problems result as far as network design is concerned, whatever the ground system.

Forty feet on 20 meters is nearly 5/8 wavelength so you expect some kind of medium resistance value and capacitive reactance. 40 feet on 40 is more than 1/4 wavelength so you expect greater than quarter-wave resistance and inductive reactance. On 75 meters a 40-foot antenna is less than a quarter wavelength long so you would expect low resistance and a capacitive reactance. Actually, you need to know pretty close to the right values to be able to design the matching networks. With a ballpark estimate and a swr meter you might be able to get on board with some trial and error.

Taking advantage of the availability of the rf bridge again, I obtained the following measurements:

frequency	impedance
14.30 MHz	80 − j260 ohms
7.25 MHz	142 + j90 ohms
3.90 MHz	54 − j167 ohms

I wanted to match the above impedances to a 50-ohm line.

Matching a complex impedance to 50-ohm line with a T- or L-network by analytical methods is a lot of work. However, George Frese, A Consulting Radio Engineer in Wenatchee, Washington (ex W7FMI) came up with a fairly simple graphical solution to this type of problem.[1] Non-resonant vertical antennas are typical in a-m broadcasting.

Experimental loading system for using the 40-foot vertical on 75 meters.

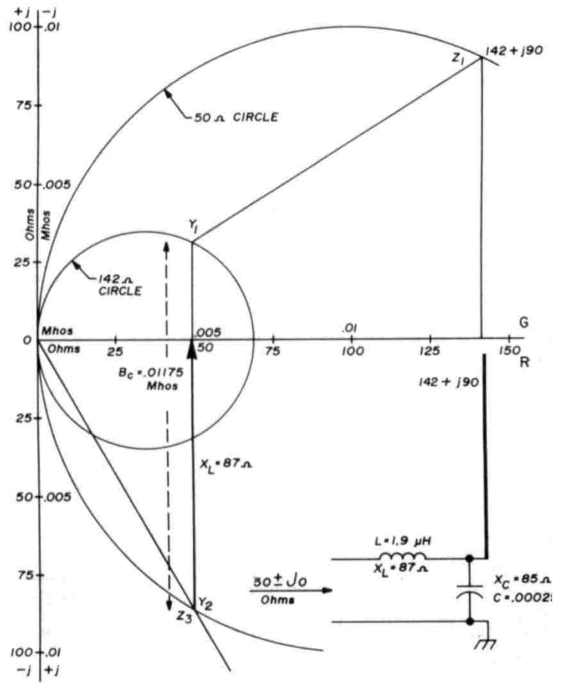

fig. 1. Graphical solution of an impedance-matching network for a 40-foot irrigation pipe vertical for operation on 7.25 MHz.

The graph has two calibrations, one for impedance in ohms and one for admittance in mhos. The two vertical calibrations have reversed signs; i.e., reactance going up is a +j, susceptance going up is − j (see **fig. 1**). Choice of scales is determined by the characteristics of the line and the antenna.

example 1

Let's take the 40-meter situation above as an example. I want to match 142 + j90 ohms to a 50 ± j0 transmission line. Since I have 142 ohms of resistance, the horizontal axis should go out to about 150 ohms. Likewise, the vertical should go to ± j100. The transmission line has an R of 50; 1/50 = 0.02 mhos = diameter of circle corresponding to 50 ohms. Therefore, 0.01 = radius of 50-ohm circle, needs to be on the paper, 20 squares = 0.01 seems appropriate, **fig. 1.**

1. With a good compass, draw the 50-ohm circle, radius = 0.01 mhos.

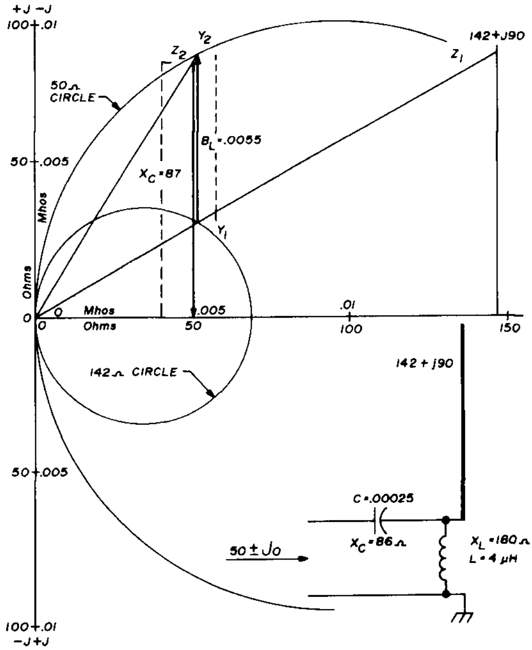

fig. 2. Another graphical solution for an impedance-matching network for a 40-foot irrigation pipe vertical for use on 7.25 MHz. Compare this network with the one shown in fig. 1.

2. Draw the 142-ohm circle, diameter = 1/142 = 0.00705, radius = 0.00352.

3. Point Z1 = 142 + j90 = 142 to right and 90° up.

4. Draw line from Point Z1 to origin.

5. Transfer Z1 to Y1 along this line to the 142-ohm circle.

6. Draw vertical line from point Y1 down to Y2 on the 50-ohm circle. The distance Y1 to Y2 is the susceptance of Y_c = +jB = 0.01175 mhos or X_c = 85 ohms. C = 0.000256 µF at 7.25 MHz (use a 0.00025 mica).

7. Draw line from Y2 through origin.

8. From the origin go out 50 ohms on the horizontal and draw a vertical line to the intersection of the line drawn in **step 7.** (In this case it just happens to coincide with line drawn in **step 6.**) This vertical distance (actually from Z3 to the horizontal) is X_L = 87 ohms; L = 1.9 microhenries.

Now, in case you are suspicious of all this hocus-pocus, let's take the result and work it out to see if it is true. Looking into the network, we are supposed to see 50 ± j0 ohms. Going out to the far end, we have the antenna, 142 + j90 ohms in parallel with the capacitor, 0 − j85 ohms. Using the formula for parallel impedances,

$$Z_{combination} = \frac{Z1\ Z2}{Z1 + Z2}$$

$$Z = \frac{(-j85)\ (142 + j90)}{-j85 + 142 + j90}$$

Changing to the polar form,

$$Z = \frac{(85 \angle -90^\circ)\ (168 \angle 32.4^\circ)}{142 \angle 2^\circ}$$

$$= 101 \angle -59.6^\circ = 51 - j87 \text{ ohms}$$

Combining the series inductance, X_L = 87 ohms, we obtain 51 − j87 + j87 = 51 ± j0 ohms. Accuracy is as good as the graphical method. Greater accuracy can be obtained from a larger graph.

The above solution is the one you want for two reasons. First of all, the network should look like a low-pass filter which will discriminate against harmonics. Also, you can eyeball the 75-meter situation and see that all you need is a series inductance, X_L = j167 ohms – the 54 ohms R is close enough. Likewise, the same kind of network is desirable for 20 meters so that the same coil, tapped at the proper places, can be used for all three bands. However, there is another solution which, for another problem, might be more desirable.

example 2

Steps 1 through **5** same as in example 1.

6. Draw vertical line from point Y1 *up* to Y2 to the 50-ohm circle. This vertical distance (in the up direction = −jB, is the susceptance Y_L = −jB = 0.0055 mhos or K_L = 180 ohms; L = 4 microhenries (see **fig. 2**).

7. Draw line from Y2 through the origin.

8. From the origin go out 50 ohms horizontal and draw a vertical line to intersect the line drawn in **step 7.** (This line happens to nearly coincide with the line of **step 6.**) This vertical distance equals 87 ohms and is downward going so has capacitive reactance; C = .00025 μF, approximately.

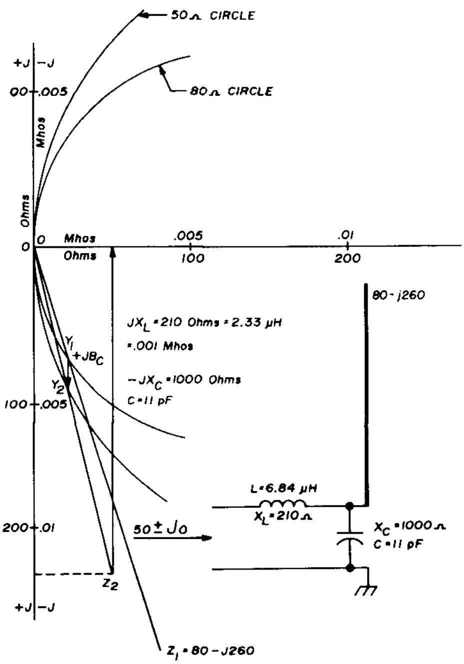

fig. 3. Graphical solution for an impedance matching network to the 40-foot vertical on 14.30 MHz. This network can be combined with the network in fig. 2 to provide the multiband system shown in fig. 4.

Working the problem again, the 142 + j90-ohm antenna is in parallel with the inductor X_L = j180 ohms

$$Z = \frac{(j180)\,(142 + j90)}{j180 + 142 + j90}$$

$$= \frac{(180\,\angle 90^\circ)\,(168.5\,\angle 32.4^\circ)}{305\,\angle 62.3^\circ}$$

$$= 99.5\,\angle 60^\circ = 49.8 + j86.2 \text{ ohms}$$

Combining with the series capacitor

$$Z_{in} = 49.8 + j86.2 - j87 = 49.8 - j0.8 \text{ ohms}$$

Both answers should be 50 ± j0, but due to the inaccuracies of graphic construction, X_L in **example 1** appears to be a little to the right of where it should be, and X_c in **example 2** seems to be to the left of where it should be. Either way, you are within ±2%. It is doubtful that you will be able to get a capacitor or wind an inductor within this tolerance.

example 3

Now, let's look at 20 meters (14.3 MHz). You can use the same admittance scale but the impedance scale will have to be one square = 10 ohms to get everything on the graph **(fig. 3)**. Since you want capacitance to ground and a series inductor, raise the horizontal axis and work below the line only. The distance Y1 to Y2 is very short and, hence, of questionable accuracy. If you had used the other solution and gone up instead of down, Y1 to Y2 would have been much greater and much more accurately measurable. But, for the reasons mentioned before you do not want this solution.

So, as closely as you can measure, Y1 to Y2 = 0.001 mhos or X_C = 1000 ohms and C = 11 pF. Locating Z2 is a little uncertain on this graph, too, but it comes out with X_L = 210 ohms and L = 2.33 microhenries. If you care to work out the problem again you will get Z = 48 + j8. This is still pretty close to 50 ohms.

proof of the pudding

Two months transpired between making the measurements and building the matching networks, and the commercial rf impedance bridge had been returned. With the aid of an L/C meter I wound and tapped a coil at 1.9, 2.33 and 6.84 microhenries. This could be done by any other method, including grid dipping using a known capacitor in a resonant circuit and solving for L. A 0.00025-μF mica capacitor was readily available. I used a small variable for the 11-pF capacitor.

On 75 and 40 meters I had an swr of

1.0:1 on the first trial. The swr on 20 meters was up near 1.5:1 and minimum was with the little 11-pF variable wide open. Removal of the variable capacitor and moving the inductor tap one-half turn yielded an swr of 1.0:1. Apparently, the capacitance of the coil to the aluminum box housing the network was very close to the required 11-pF. The final circuit of the network is shown in **fig. 4.**

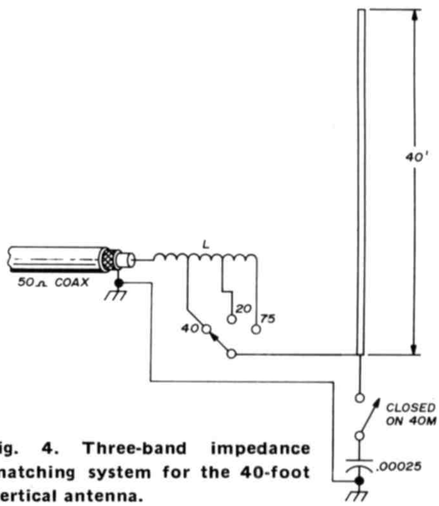

fig. 4. Three-band impedance matching system for the 40-foot vertical antenna.

summary

I have received excellent reports on all bands. I have no comparison on 75 and 40. On 20 the vertical cannot compete with a cubical quad, but this is not surprising. However, on DX contacts it is only down about 1 S-unit.

The big problem is how to measure the impedance of the antenna without a $1000 bridge. I think I may have some answers for this which I will verify when antenna weather comes again. There are several possibilities that are close enough that little trial and error would be necessary to get everything tuned up.

reference

1. George Frese, "Graphical Solutions to RF Networks," *Broadcast Engineering,* January, 1964, page 12.

ham radio