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Self-Paced Essays – #18 Vector Network Analyzer

The VNA is a Very Nice Apparatus.

I was first exposed to the Vector Network Analyzer (VNA) when I began working at HIPAS Observatory in the Fall of 1994. This massive Hewlett-Packard instrument weighed in at about 45 pounds and about $1000 per pound. It greatly simplified a lot of the tasks that we had at the facility, especially when it came to tuning up a variety of antennas.

Before working at HIPAS, I worked with a number of AM broadcast antenna facilities for a couple of decades, where the instrument of choice was a combination of: a General Radio impedance bridge, an RF signal generator, and an HF receiver (in our case an R-390, which itself weighed about twice what the HP VNA did). So we had already made some progress by 1994.

Now we have the NanoVNA, which is no bigger than a smart phone, and does about 99% of what the Hewlett-Packard did at about 0.1% of the cost. Some things have gotten a lot better, even with significant inflation.

The NanoVNA — and its various clones — are so good and so cheap that there's no excuse for any ham, or other RF person, not to have one. Besides the mere convenience of the instrument, the learning one derives from its use is of inestimable value. The only downside is that there is no single authoritative operating manual for the VNA, so one must glean most of it from the Web, which really isn't a bad source. Regardless of your particular "flavor" of VNA, most of the important functions are common to them all.

Three Points, One Port

You can learn a lot about transmission line theory just in the standard calibration process of the VNA. The following discussion addresses only the more common single-port calibration. We will discuss the two-port measurements in a subsequent essay. The process is commonly called the "three-point calibration" the purpose of which is to "calibrate out" the transmission line between your VNA and the device under test (DUT). The nice thing about the three-point procedure is that it doesn't matter how long, or how lousy, the transmission line is. When you perform the calibration at the far end, the VNA will accurately display the impedance of any DUT at the far end. This is one point you can completely miss if you go strictly by the "free floating" instructions out there in cyberspace, which tell you to perform the calibration right at the output terminals of the VNA. If you're using a very short test lead, this will usually do, but it is not the proper way to perform the calibration. You will definitely want to get a nice selection of RF adapters for your VNA, especially some SMA to BNC adapters, so you can conveniently perform the far-end OPEN, SHORT, and LOAD tests. The test loads supplied with the NanoVNA all have SMA connectors.

When you perform the three-point calibration, your VNA then knows what the characteristic impedance, length, and loss of the line are. There's actually a lot of rather sophisticated number crunching that goes on in the VNA that allows these factors to be determined by the three different terminations. We might go into some of this later on. The nice thing about the calibration procedure is, once you've performed it, you don't have to know any of this. All you need to know is that your VNA will now tell you the truth about what's at the far end of the cable. By the way, this was extremely important when network analyzers were the size and weight of refrigerators and you needed to find the impedance of an antenna at the top of a tower. Nowadays, you can just carry a NanoVNA up the tower with you.

With all this in mind, what does a VNA tell you that an old-school impedance (RX) bridge doesn't? Technically, not much. Except that it's a whole lot more convenient. First of all, it performs an automatic frequency sweep of the impedance in question. Second, and perhaps more importantly, it instantly plots the result on a convenient Smith Chart.

Now, if you're an old timer like some of us, you may be shocked and astounded with disbelief to see 'convenient' and 'Smith Chart' in the same sentence, or even in the same paragraph. But not to worry. We will soon prove that the Smith Chart is your friend!

Why Be Normal?

Before we get started, please print out half a dozen copies of a good Smith Chart. Here is my favorite link for printable Smith Charts: **https://www.acs.psu.edu/drussell/Demos/SWR/SmithChart.pdf**.

Now, these are the full-fledged, fully

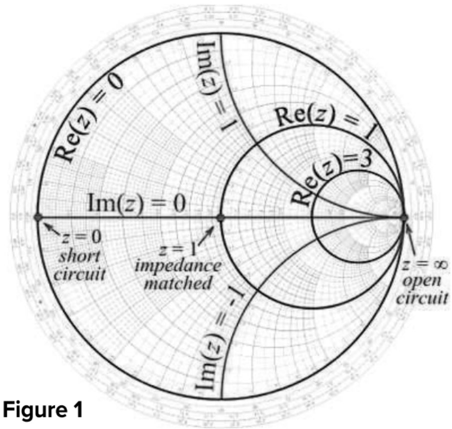

Figure 1

daunting Smith Charts. **Figure 1** shows an undaunting version. I sometimes refer to this as the "fat purple crayon" (FPC) version because I draw it with an actual fat purple crayon — or dry erase marker — in my brick-and-mortar electronics classes.

There are two general forms of Smith Chart, the non-normalized, universal version (as in **Figure 1**), and the normalized version, which is what your VNA displays. The non-normalized version works with any impedance transmission line, while the normalized version is geared around a fixed impedance, normally 50 Ω transmission line, as in the case of your NanoVNA.

I normally (pun intended) taught the non-normalized version first, since it's more general, but since the advent of the NanoVNA, I start out with the 50 Ω normalized version. Nowadays, this is the style most folks first encounter with Mr. Smith. Once we have that nailed down, we will show you how to normalize any Smith Chart with just a couple of extra steps.

The Same but Different

Like the familiar complex impedance graph we explored many essays back, the Smith Chart has both a real and imaginary axis. Like the standard complex impedance graph, up is inductive reactance (+*j*), and down is capacitive reactance (–*j*). The horizontal axis is the real (resistive) axis. No surprises here.

One readily apparent thing that is different is that, while the normal impedance plot has zero ohms (both resistive and reactive) at the origin, the Smith Chart has zero resistance at the far left, and infinite resistance at the far right. The reactance is expressed by a family of arcs, all converging at infinity at the far right, which represent the loci of all possible reactance values. Remember from your ancient geometry classes that a locus is a set of all points that satisfy some condition, a very important concept as we explore the Smith Chart.

Any complex impedance we plot on the Smith Chart will fall on the intersection of two loci: a resistance circle, and a reactance arc.

The center of the chart (origin) is the characteristic impedance of any transmission line we're using. We assume that the transmission line is ideal, exhibiting a pure real value, while in reality any transmission line has some minute value of reactance.

Taking Laps

Now, we get to the salient point of distributed versus lumped constant behavior. While the impedance at any given frequency is plotted at a single point of intersection between resistance and reactance, we find that this impedance will change depending on where it is located; in this case, where it is located along a transmission line.

To show this, we now need to look at a fully daunting Smith Chart, which we trust you have printed out. If you take a look at the far left of the chart, just above 0 Ω resistance, you see the nomenclature "wavelengths toward generator." This means exactly what it says. For any complex impedance at the end of a transmission line, we can find out what the impedance is at the input of a transmission line — or at any point in between. Now, we need to know that one complete lap around the Smith Chart is one-half wavelength at whatever frequency we're working with. We will find that any half wave or multiple thereof of transmission line will repeat the impedance at the starting point — most commonly the "load" end. Similarly, if we move a quarter wave along the line, we find our impedance is diametrically opposite the starting point.

Handy Special Case

The quarter wave transmission line is a particularly interesting case, and an extremely useful device. If a load impedance is a pure resistance, the input impedance Z_S of a quarter-wave section is the geometric mean of the characteristic impedance Z_0 and the load impedance Z_L:

$$Z_0^2 = Z_S \cdot Z_L$$

This is one of those formulas you'll want engraved on the inside of your eyelids.

Let's say you have a quarter-wave 50-Ω transmission line with a 150-Ω resistor at the end. What will the impedance be at the input? We rearrange to get Z_S, so,

$$Z_s = Z_0^2/Z_L$$

which gives us 2500/150 or 16.6 Ω. Again, this works only for resistive loads, which is actually quite common. In the next issue, we'll actually work this out with the Smith Chart. In the meantime, please inspect the daunting Smith Chart for a while, and see what great insights you acquire. — *73, Eric*