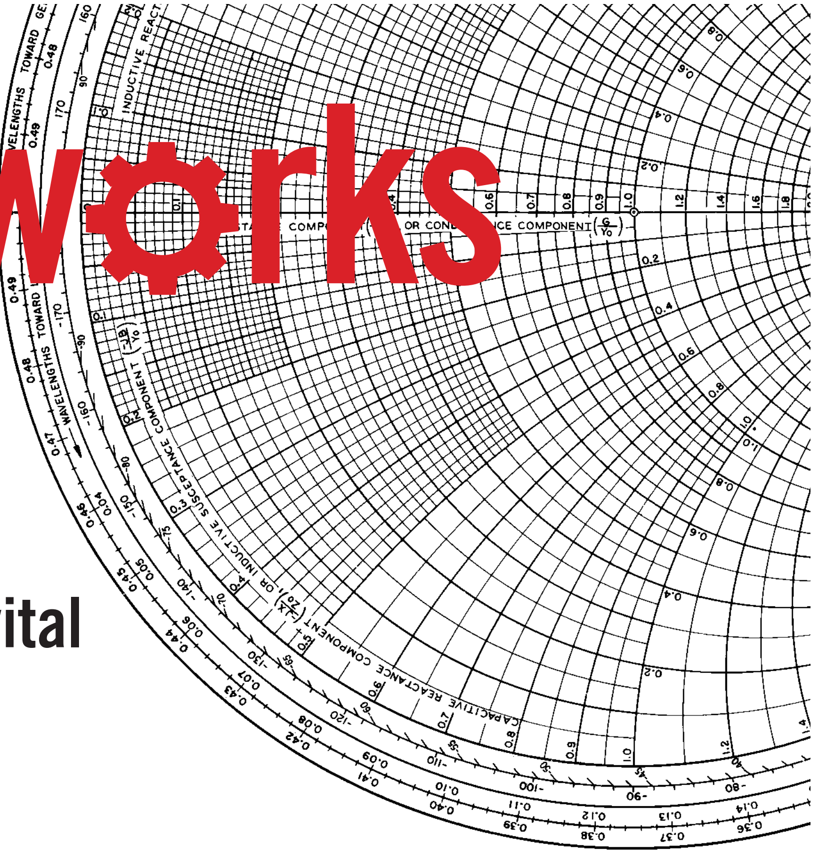
how it works



THE ORIGINAL SMITH CHART–60 YEARS AFTER ITS DEVELOPMENT–IS AN INCREASINGLY IMPORTANT TOOL FOR THE RF ASPECTS OF ANY DESIGN.

The Smith chart: more vital after all these years

Bill Schweber, Technical Editor

Few electronic-design tools and instruments are unchanged and remain in use many years after their invention. Vacuum-tube voltmeters were once as common as PCs but these days are pretty rare. But one tool–known universally as the "Smith chart," after its inventor Philip Hagar Smith–has survived virtually intact from its first days to the present (see **sidebar** "So those were the good old days?"). The Smith chart has not only survived, but also thrived: It applies to applications that didn't even exist when Smith developed it. For example, in data sheets from some high-speed processors that have clocks of several hundred megahertz, Smith charts define the RF characteristics of the processor IC pins. Similarly, state-of-the-art RF test equipment, such as network analyzers, traces a Smith chart on its display.

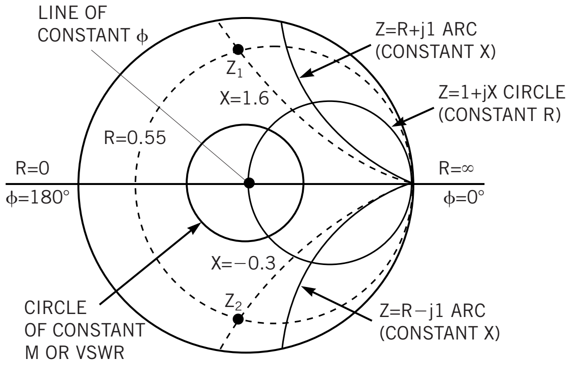
Using the Smith chart, you can graphically illustrate the complex impedance, Z=R+jX, of a transmission line, antenna, amplifier, or any signal point in the RF range at which the simple resistive approximation is not sufficiently valid. However, the ability to place the real and imaginary parts of Z on a 2-D graph instead of using numbers for R and X is not what makes the Smith chart significant.

The virtue of the Smith chart is its basic function: It lets you simultaneously see your present impedance and the impedance you are trying to match, and then it helps you solve the matching problem to ensure a minimum VSWR. It shows you your choices when you try to use various matching techniques, such as stubs, quarter-wavelength matching sections, or other techniques.

This function may not seem like a big deal to you today. After all, you have powerful calculators and computers that can easily solve almost any impedance equation in a fraction of a second. But this luxury did not always exist: Impedance-related calculations are often numerically intensive, and they were difficult to solve using precalculator tools, such as a slide rule or even a pencil and paper.

Even if you are not trying to match a signal source or generator to a load for maximum power transfer, the chart traces the locus of the source impedance versus frequency, the impact of frequency changes, and the dynamics of complex-impedance-related issues. Although you could make precise calculations within a few milliseconds, without the

Figure 1



This simplified Smith chart uses circles and arcs to plot critical RF parameters: R, X, SWR, ϕ, and M (courtesy Analog Instrument Co).

Smith chart you don't get the same sense of where you are, what choices you can consider in achieving your RF goal, or what the trade-offs may be.

GOING IN CIRCLES

Although the Smith chart has many circles, arcs, and gradations, it has a clever underlying structure that uses two basic sets of curves (**Figure 1**). All the circles on the right-hand side touch, and an increase in diameter represents an increase in the value of resistance (R). Any point on a circle has the same resistance as any other point on that circle.

Also emanating from the right-hand side are arcs of increasing radius, which represent reactances (X). Similar to the circles, any point on an arc has the same reactance as any other point on that arc. The upper half of the chart indicates inductive reactance (+jX), and the lower half indicates capacitive reactance (−jX). The horizontal line across the middle of the chart divides inductive reactance and capacitive reactance, and any point on this line is a pure resistance, with R=0 at the left side (a short circuit) and R= ∞ at the right side (an open circuit).

As you vary either the real component, R, or the imaginary component, X, of a complex impedance, the plotted point moves along its arc or circle, but not both. The **figure** shows two impedance examples: $Z_1=0.55+j1.6\Omega$, and $Z_2=0.55-j0.3\Omega$.

Another equally important way to present data using the chart is to draw concentric, centered circles (different from the circles of constant R that touch at the right-hand side). The circumferences of the circles represent points of equal VSWR; larger circles denote higher VSWRs. Any point on a straight line that originates at the center of the circle and radiates outward has a phase angle, ϕ, that corresponds to its polar plot angle. The distance from the center to the plotted point represents the magnitude, M, of the standard M/ϕ form.

Because real-world impedances span a range of values, the first step in using the chart is normalizing actual impedance values to your nominal impedance value, Z_0. For example, if you are in the standard 50Ω environment and your measured impedance value is 79.3+j22Ω, you divide this value by Z_0 and then use the chart with a normalized impedance result of 1.59+0.44Ω. Multiply your answers by Z_0 to get back to the actual values.

For all its power, the Smith chart is not easy or intuitive. But the chart is much better than the available alternatives for the insight it provides and its ability to show trade-offs and transitions. These features demonstrate why the chart has retained its usefulness for so many years. Once you learn how to use the Smith chart to plot impedances, match sources and loads, and determine admittance (the inverse of complex impedance, which is useful for stub tuning), it becomes a powerful tool. Books and videos can teach you the basics of using the Smith chart; they can also provide problems and the techniques for using the chart to solve those problems (**Reference 1**). □

Reference

1. Smith, Phillip, "Electronic Applications of the Smith Chart," Crestone Technical Books/Noble Publishing Co, second edition, 1995.

SO THOSE WERE THE GOOD OLD DAYS?

It's hard to imagine those precalculator, pre-PC days of electronics in the 1920s and 1930s. It's even more challenging to understand the difficulties of basic measurements that engineers endured. In 1928, Phillip Hagar Smith joined Bell Telephone Laboratories, where he worked on the design and installation of directional equipment for commercial AM-radio broadcasting (**Reference 1**). The link between the transmitter and the antenna was a two-wire transmission line, and the mathematical analysis of wave propagation on the line used standing-wave amplitude and wave position as its basic data.

This measurement was difficult to make. The engineers used a thermocouple sensor array coupled to two frequency-specific tuned coils. The output of the array and coils went to a microvoltmeter indicator, which showed the magnitude of the signal. One engineer would move the assembled instrument along the transmission line. (The transmission line was often high in the air, so the engineers attached the instrument to a long pole.) A second engineer read the microvoltmeter using a telescope. In this way, the engineers could determine the location and relative values of the maximum and minimum signals on the transmission line. Obviously, this process was time-consuming, awkward, and frustrating!

Smith sought to simplify the process by developing a graphical solution. At first, he used rectangular plots. However, the limited range of data that this type of coordinate frame could handle restricted the chart's application. Smith kept working on the problem, and by 1936 he developed a chart that used special polar coordinates, which could handle all impedance values. The impedance coordinates in this chart were not orthogonal and were not true circles, but the SWR scaling was linear.

Smith then worked with two Bell Labs co-workers who understood conformal mapping principles. By 1937, this collaboration allowed Smith to develop a version of the Smith chart that is very similar to the current chart. This chart could handle data from zero to infinity. Smith also added straight-line scales along the bottom of the chart to accommodate return loss and signal attenuation. After two years of trying to get his chart published (there weren't many electronics publications, especially for microwave and RF work), the chart and its description finally appeared in the January 1939 issue of *Electronics*. In addition to its use at Bell Labs, Smith's chart soon saw extensive application in microwave work at the radiation lab at the Massachusetts Institute of Technology. (That lab was formed in 1940, and researchers there were critical in developing radar and related topics during World War II.)

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