More on Transmission Lines and SWR – Part II

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This is the second of a multipart article dealing with transmission lines and SWR. This article defines and explains many of the terms that are essential to understanding transmission lines and SWR.

Transmission Line – The physical wire or cable that connects the transmitter or receiver or antenna tuner to the antenna. The transmission line might be coaxial cable, open-wire line, twinlead, or just a wire. We like to think of the transmission line as a simple hose where what goes into one end comes out the other, unchanged. Reality is, the transmission line almost always acts as a transformer and the impedance looking into the transmission line at the transmitter is not the impedance seen at the end of the transmission line connected to the antenna. This being the case, the SWR at the transmitter is not the same as the SWR at the antenna.

Characteristic Impedance (Zo) – The transmission line is an RLC network with a characteristic impedance Zo, also known as the surge impedance. Zo is a function of the per-unit-of-length parameters of resistance R, conductance G, inductance L and capacitance C. The characteristic impedance of a specific type of line is a function of the conductor size, the conductor spacing, the conductor geometry, and the dielectric constant of the insulating material used between the conductors. (Practical Antenna Handbook, Fourth Edition, page 64).

Standing Wave Ratio (SWR) - A measure of the power delivered to the antenna vs. the power reflected back toward the transmitter from the antenna due to an impedance mismatch between the antenna and the transmission line. The difference is the power delivered into the antenna. The SWR seen at the transmitter end of the transmission line is almost never the SWR seen at the antenna because losses in the transmission line make the return loss appear higher than it really is, making the SWR appear lower than it really is. Textbooks may claim that the SWR is the same everywhere on the transmission line. That’s only true if there is no loss in the transmission line. There is always some loss in the transmission line although it might be insignificant, or it might be not. In general, the SWR measured at the sending end of the transmission line will appear lower (better) than it actually is at the antenna. SWR is a ratio that can be based on measurements of voltage (VSWR), current or power.

Forward (Incident) Power (P_F) – The power sent down the transmission line to the antenna from the transmitter. Also called incident power. Losses in the transmission line result in less power delivered to the antenna than was input into the transmission line.

Reflected Power (P_R) – The power sent back to the transmitter (reflected) from the antenna due to an impedance mismatch at the antenna. If the impedance of the antenna where the transmission line is connected is exactly equal to the characteristic impedance of the transmission line, all of the power is accepted by the antenna and none is reflected back to the source. In that case the reflected power is zero and the SWR is 1.

Reflection Coefficient (ρ) – The ratio of the reflected voltage (or current) at a given point on the transmission line to the incident voltage (or current) at the same point on the transmission line. It's also the square root of the ratio of the reflected power to the incident power at the same points on the transmission line. The reflection coefficient is usually represented by the Greek letter rho, ρ.

Return Loss (RL) – The difference between the incident power to the antenna and the reflected power from the antenna. If all of the power delivered to the antenna was accepted by the antenna, there would be no power reflected back to the source, the return loss would be infinite, and the SWR would be 1. The return loss is also expressed as the absolute magnitude of the reflection coefficient expressed in dB, or $RL=-20 \log|\rho|$.

Matched-Line Loss – The power lost in the transmission line when the load impedance is equal to the characteristic impedance of the line. The manufacturer usually specifies this in dB/100 ft. It's directly related to the matched-line attenuation and the two terms are often used interchangeably. The manufacturer has no clue as to how you are using the transmission line, so it simply gives you the matched-line loss and you can calculate the rest for yourself.

Wavelength (λ) – The distance between two like points on a waveform, such as the distance between successive positive peaks or between zero-crossings. The wavelength is equal to the velocity of propagation (the speed of light) divided by the frequency.

Velocity Factor (VF) – An electromagnetic wave, or radio wave, in free space, travels at the speed of light or 299,792,458 meters per second or approximately 300,000,000 meters per second. At that speed, we say the velocity factor (VF) is equal to 1. The wave travels slower in a transmission line and the VF is less than 1. The manufacturer usually specifies a nominal VF. There are times when the exact VF for a given piece of coax needs to be determined, and that can be done experimentally. The VF for coax cable typically ranges from 0.66 to 0.86.

Reactance (±jX) – The opposition to the flow of alternating current. Capacitors and inductors exhibit reactance. Reactance, like resistance, is measured in ohms. The reactance of a capacitor decreases with frequency. The reactance of an inductor increases with frequency.

Impedance (Z) – The combined opposition to the flow of current in a circuit that contains both resistance and reactance. If the reactance is zero, the impedance is simply the resistance. If the reactance is not zero, the impedance is the vector sum of the resistance and reactance, usually expressed as a complex number (explained later) of the form $Z = R \pm jX$ where R is resistance in ohms and X is the reactance in ohms, positive for inductive reactance and negative for capacitive reactance. When we speak of impedance, we usually mean the magnitude of the impedance, such as 50 ohms, without regard to the individual resistive and reactive parts.

Conjugate match – Matching a source to a load such that the resistive terms are equal and the reactive terms cancel. For example, if the load impedance is R + jX, then the conjugate-matched source impedance would be R – jX.

Transmission line equation – The input impedance of a real, lossy transmission line can be computed if the following parameters are known:
- the complex load impedance at the end of the line
- the characteristic impedance of the line
- the physical length of the line
- the complex loss coefficient
- the matched-line loss attenuation constant
- the phase constant of the line

More about this later. The equation of interest can be found on page 24-12 of The ARRL Antenna Book 21st Edition, among other places. A similar equation for a lossless line is on page 31-8 of the Antenna Engineering Handbook (Henry Jasik, Editor, first edition, McGraw Hill Book Company).

Feed-point Impedance and Radiation Resistance – The impedance at the feed-point of the antenna appears as a resistance in series with a capacitive or inductive reactance. At resonance, the reactance is zero. The resistance is the radiation resistance of the antenna plus any (small) loss resistance in the antenna conductors. The radiation resistance is the part of the antenna impedance that can be thought of as actually radiating the power fed to the antenna. The reactive part of the impedance does not absorb or radiate any power, although it can result in high currents and voltages.

Antenna Tuner – A 'box' containing inductors and capacitors that can be configured to change the impedance looking into the transmission line toward the antenna to something that the transmitter is happy with (typically 50 ohms). It does not tune the antenna, it's simply a matching network.

Complex Numbers – If were going to be dealing with impedance, we need to get a handle on the so-called complex numbers. Let me be the first to assure you that Complex does not mean Complicated. Complex numbers consist of two components: a real part and an imaginary part. Imaginary numbers are just as real as real numbers, we just handle them differently. Dealing with complex numbers requires that we use a little basic trigonometry, or else graphically by drawing scaled drawings on paper – either way is fine.

Let's use the graphical approach and start with a piece of paper. Graph paper would be good. Make a mark near the center. Starting at that mark, draw a horizontal line to your right (the +X axis). Label that line R. We could also draw a line to the left of center (the –X axis) and label that –R, but since negative resistance isn't going to be showing up here we can forget about that. Next, draw a line vertically upward from the mark at the center. Label that line (the +Y axis) +jX. Finally, draw a line vertically downward from the mark at the center. Label that line (the –Y axis) –jX. We're going to use this graph to plot points of the form R + jX (or R – jX) where R is out along the horizontal axis and jX is on the vertical axis with +jX upward and –jX downward. Having plotted this particular point, the magnitude of the impedance is the length of the vector (another new word) from the origin (where the vertical and horizontal axes cross) to that point.

Maximum power transfer theorem – The essence of the theorem is that an equal amount of power will be dissipated in the load and the source if the load resistance is equal to the Thevenin/Norton resistance of the source. For alternating current the load impedance would need to be the complex-conjugate of the source impedance.
It's a common misconception that maximum power will be delivered from the transmitter if its Thevenin-equivalent output impedance matches the transmission line impedance. If that was the case, then your 100 watt transmitter would deliver 50 watts to the transmission line and burn up the other 50 watts in its internal circuitry. The output impedance of the transmitter, as designed, is much-much less than 50 ohms to deliver maximum power to the transmission line and dissipate minimum power internally. Consider your home stereo amplifier … it might be designed to use 8-ohm speakers, but its output impedance is a fraction of an ohm, not 8 ohms. Similarily, the electric company does not attempt to impedance-match your load. Here, the Thevenin impedance is very low and the load impedance (your toaster) is sized to extract the desired power. Be careful what you surmise from a name.

Next month's article will explore some practical examples using some of the information covered thus far.