MAC'S SERVICE SHOP

SWR—FACTS AND FALLACIES

By John T. Frye, W9EGV

"MAC," Barney said, pulling a little notebook from his shirt pocket, "lay down your solder gun for a minute and bend an ear to these comments about SWR I've heard on the CB and ham bands recently. So help me, I'm quoting these gems verbatim! Just listen:

"'You've a strong carrier but low modulation—get your SWR down and the signal will be fine. . . . You can't get out unless your SWR is below 2:1. . . . If you have a high SWR, reflected power will go back into the tank circuit and burn out your final tubes or transistors. . . . This 75-meter mobile whip is a lot better than my old one because its SWR is lower. . . . A high SWR makes your feedline radiate and causes TVI. . . . Subtract your reflected power from your transmitter output power and what's left is all that's going into your antenna. . . . Reflected power is not power at all because the voltage and current are 90 degrees out of phase. . . . My signal should be much better now because I put a new balun in the middle of the antenna and it lowered the SWR here. . . . I can't put up an antenna for 80 meters because the lot is only 80' deep. . . . I'd like to work down around 3.5 MHz, but this antenna is cut for 3.75 MHz and the SWR is 'way too high down there for me to get out. . . . SWR readings don't mean anything unless you take them right at the antenna or a multiple of a half wavelength away from it.'

"Each one of those statements," Barney said to his employer, "displays ignorance of the true nature of SWR and its effects, but an amazing number of hams and CB operators believe at least some of them. More misconceptions about SWR are floating around than any other aspect of station operation. I get mad when I hear a guy smugly mouthing that drivel into a microphone because I know many listeners without a technical background will accept those fallacies as gospel and spread the same garbage."

"Ah, would that I were young enough again to become that indignant about ignorance," Mac said with a sigh as he leaned back against the wall and lighted his pipe. "But I can see you're about to lecture me on SWR, so get on with it. Let's see you shatter those clay pigeons you've tossed up."

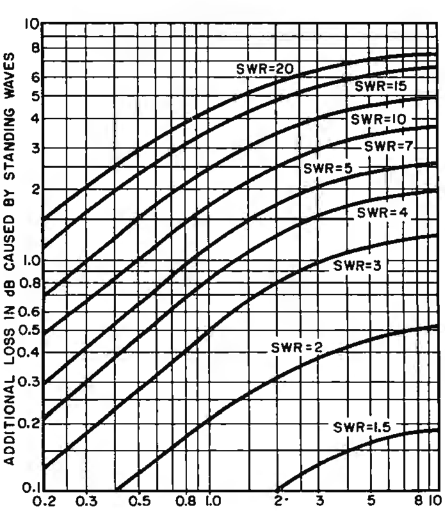
Theory Is Not Simple. "Delighted," Barney replied, "but it's only fair to admit many uttering those foolish things are only repeating what they've read. Their chief sin is gullibility, as they believe anything they read without regard for who wrote it. Ignorant, careless writers are the chief culprits. A writer should *know* his subject matter before he undertakes to instruct. Antenna and transmission line theory is not simple, and anyone who pretends otherwise is not being honest. Most of the half-baked articles I've read containing implicit or explicit errors about SWR usually carry titles like 'SWR Made Easy,' or 'All You Need to Know about SWR.' Other irresponsible writers, too lazy to dig out the facts for themselves, quote from these articles and so perpetuate the fallacies.

"Actually the truth about SWR is not difficult to find. *The Radio Amateur's Handbook* and *The ARRL Antenna Book* have presented it in time-tested edition after edition. So have such writers as George Grammer, retired technical editor of *QST*, and Dr. Yardley Beers, senior scientist of the Quantum Electronics Division of the National Bureau of Standards. But the most recent, lucid, and complete discussion of the subject is contained in an on-going nine-part series in *QST* called 'Another Look at Reflections' by M. Walter Maxwell, W2DU. He's the engineer in charge of the antenna laboratory and test range at RCA's Space Center in Princeton, NJ. More than 30 earth-orbiting spacecraft, including Echo I and all Tiros-ESSA weather satellites, carry antennas designed by Mr. Maxwell. If you think *I* get hot under the collar about published SWR fallacies, you should read his reaction! As of now, parts of the series appeared in the *QST* issues of April, June, August, and October, 1973, April and December, 1974, and August, 1976. Each part runs about 5,000 words and a 61-item bibliography is included."

"You're not going to cover all that, I hope!"

"No, but I want you to have reliable sources to check any statement that you question. All conclusions in the cited works are supported by quoted authority, sound logic, mathematical proofs, and laboratory experiments using top-notch equipment. There's *no* disagreement among these authors.

"But before we start pigeon-busting, I must define three terms: *source power* is the power a transmitter delivers to the input of the transmission line; *incident power* is power flowing up the transmission line towards the antenna; and *reflected power* is unabsorbed power appearing at the junction of the antenna and a mismatched line, power that flows in a separate wave back down the line towards the transmitter.



Increase in line loss due to standing waves (ARRL Antenna Book).

Reflected Power. "Reflected power isn't 'imaginary,' 'wattless,' or 'lost.' It's just as real as incident power, but the current direction reversal at the antenna mismatch causes a 180° phase shift between current and voltage in the reflected wave. This is in contrast to current and voltage in the incident wave, which, seeing only the resistive impedance of the line, are in phase with a 0° phase angle. For power in the reflected wave to be reduced to wattless, reactive volt-amperes, their phase difference would have to be 90°. Furthermore, if reflected power *were* wattless, it couldn't deflect a meter connected to the output of a directional coupler—as it certainly does.

"Neither is reflected power mysteriously 'lost,' breaking the law of the conservation of energy. When the down-going reflected wave encounters a conjugate match at the transmitter end of the line, it is again totally reflected and its voltage and current go through another 180° phase shift which brings them into step with the 0° phase angle of the incident waves continuously travelling up the line. The reflected power thus adds to the source power; and the fortified incident power combination is sufficient, with a lossless line, to override the mismatch at the top and deliver the full source power to the antenna. You might say the reflected power is salvaged and recycled!"

"What's a 'conjugate match'?" Mac asked.

"It's a condition of system resonance that establishes a unilateral match between the transmitter and the line. Such a match creates a "one-way mirror" at the bottom of the line. The transmitter sees only the resistive component of the line-input impedance, as it would if there were no reflected power. At the same time, the down-coming wave sees a perfectly reflecting mirror that again reverses its direction. The proper adjustment of the transmitter's ouput circuit will provide a conjugate match if the pi-network has sufficient range to cancel the reactive component of the line's input impedance produced by standing waves on the line. If not, an antenna tuner or "transmatch" can supplement the limited impedance matching range of the transmitter output circuit."

"Don't standing waves on the line waste power?"

"Yes, but not nearly so much as many believe. Remember a perfectly flat line suffers some signal-attenuating losses. The amount of attenuation depends on the type and length of the transmission line and on the operational frequency, as shown in the table giving loss per 100 feet in dB for popular transmission lines at selected frequencies. The 28-MHz figures can be applied to the CB 27-MHz band. When there are standing waves on the line caused by a mismatched load, there's an additional loss of reflected power during its round trip down to the transmitter and back again because the line attenuates the reflected wave to the same degree it attenuates the incident wave. The higher the line attenuation, the less reflected power reaches the source where it is turned around and added to the incident power. This simply means less reflected power is recycled and eventually radiated.

"Both the line attenuation and the SWR must be high, however, for this additional loss to be serious, as is shown in the diagram. For example, 100 feet of RG-8/U perfectly matched to an antenna resonant at 3.75 MHz would have a 0.32-dB loss. At either 3.5 or 4.0 MHz the SWR of such an antenna would rise to about 5:1, but the extra loss because of this high SWR at 4 MHz would only be 0.46 dB. Even a 1-dB drop in signal strength is barely noticeable, so the extra loss due to SWR would be insignificant; but use the chart and the graph to see how SWR-induced losses climb as you go up in frequency or use a higher-loss cable, such as RG58/A-AU.

"A lower SWR doesn't *always* mean a stronger radiated signal. If reactive currents saturate the core of an underrated balun when operating far from the antenna's resonant frequency, the SWR might read lower. But power heating the saturated core is subtracted from the radiated signal. A similar effect can be caused by a high-resistance connection in the antenna-feedline system. Be suspicious if a thin-wire 80-meter antenna fed with 50-ohm coax doesn't display an SWR of around 5:1 when tuning more than a few hundred kHz from the resonant frequency.

"A vertical antenna with lots of radials has a combined ground-and-radiation resistance that is considerably lower than the surge impedance of a 50-ohm line, as evidenced by a fairly high SWR. Reducing the number of radials increases the ground resistance in series with the radiation resistance, thus lowering the SWR, but power now heating the ground is subtracted from the radiated signal. A center-loaded whip for 80 meters has a radiation resistance of about one ohm and an average "ground" resistance of 7 ohms. The resistance of a high-Q loading coil is around 8 ohms, but this may go as high as 31 ohms for a lossy coil. The good coil will thus produce an SWR of about 3:1, while the worst coil will give an SWR of about 1.3:1. Power wasted in heating the lossy coil will far exceed the small loss caused by the higher SWR on the short length of RG8/U feeding the antenna."

"Don't you believe in baluns?" Mac asked.

"Certainly, but not for lowering SWR! A good balun eliminates current flowing on the outside of the coax, the result of directly feeding a balanced antenna with an unbalanced line. This current can cause feedline radiation and TVI, as can 'antenna current' induced onto a feedline that is brought away from the antenna at an acute angle. Keep in mind that voltages and currents produced by standing waves are confined to the inside of the coax, and cannot radiate.

TRANSMISSION LINE CHARACTERISTICS

Type of line	Zo ohms	Velocity %	Attenuation in dB per 100 ft 3.5 MHz	14 MHz	28 MHz	144 MHz
RG58/A-AU	53	66	0.68	1.5	2.2	5.7
RG58 Foam	50	79	0.52	1.1	1.7	4.1
RG8/A-AU	52	66	0.30	0.66	0.98	2.5
RG8 Foam	50	80	0.27	0.62	0.90	2.2
RG59/A-AU	73	66	0.64	1.3	1.8	4.2
RG59 Foam	75	79	0.48	1.0	1.4	3.4
#12 Open wire line, ignoring radiation		97	0.03	0.07	0.10	0.25

"Antenna current flowing on the outside of the coax makes it impossible to measure the true SWR. So does leakage between the forward and reflected circuits of a directional coupler, or use of an instrument not accurately matched to the impedance of the line. If these conditions exist, alone or in concert, SWR readings may change significantly when adding or subtracting a few feet of transmission line; but this *does not* mean the SWR is changing with line length. With a reliable instrument and no current on the outside of the coax, the SWR reading will be virtually the same anywhere in the line except for a gradual small decrease as you move away from the antenna, which is caused by attenuation of the reflected wave as it moves down the line."

"Aren't there any valid reasons for keeping the SWR down?"

"Of course there are, but they're chiefly concerned with the effect of SWR on line input impedance and not on lost power or TVI. For example, solid-state CB transceivers have very limited antenna matching ranges; so you can't obtain a conjugate match with their unaided output circuits if the SWR is much greater than 2:1. With a high SWR on the line, the transceiver's final amplifier may be grossly over- or under-loaded when working into a complex line input impedance whose value is dependent on line length. This can easily blow the transistors, but note the damage is not done 'by reflected power backing up into the rig.'"

"How about voltage breakdown on the line with high SWR?"

"The flat-line rms voltage equals the square root of line impedance times power. This would be $\sqrt{50 \times 100}$ or 70.7 volts for 100 watts into a 50-ohm line. With standing waves, the voltage maximum becomes the flat-line voltage times the square root of the SWR. With a 5:1 SWR this would be $\sqrt{5} \times 70.7$ or 158 volts. At 4.0 MHz, RG8/U will handle 700 watts CW continuously within ratings even when an SWR of 5:1 exists on the line. With the duty cycle of SSB, you'll be well below the maximum ratings at 2000 watts PEP. But this kind of power is not recommended for the closer-spaced RG58/U or RG59/U."

"As I get it," Mac interrupted, ticking the points off on his fingers, "you're saying many operators restrict their activities unnecessarily because of unwarranted fear of misunderstood SWR. An antenna doesn't have to be resonant to radiate all the power delivered to it, and with a conjugate match, a high SWR will not prevent all real power available at the feed point from being absorbed by the radiator. With the aid of a transmatch you can work the full width of the 3.5-4.0-MHz band without any significant loss of power from resulting SWR on an RG8/U line. Much higher values of SWR on an open wire line will cause no appreciable loss of radiated power. Mismatch-produced SWR does not cause TVI. You don't have to measure SWR at a multiple of a half wavelength from the antenna if you have a quality instrument. Reflected power is not irretrievably "lost". Lower SWR doesn't necessarily mean a more efficient antenna or a stronger signal, and reflected power doesn't flow backwards into a pi-network-coupled transmitter."

"You're a good listener," Barney said, clapping his hands, "and I hope you'll spread the gospel. It would be nice if the truth could just be stated once and that would be the end of misunderstanding, but that's not the way it is. Fallacies, like dandelions, keep sprouting up, going to seed, and blowing in the wind. They must be sprayed repeatedly with the truth to keep them from taking root and multiplying." ◇