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TECHNICAL CORRESPONDENCE

ON TUNING, MATCHING AND MEASURING ANTENNA SYSTEM IMPEDANCE USING A HAND HELD SWR ANALYZER

◊I was interested to read the product review on antenna analyzers by Joel Hallas, W1ZR, in the May 2005 issue of *QST*. I have an MFJ 259B analyzer, and find it a useful device for tuning HF mobile and camp portable antennas and base station antennas, providing the "antenna analyzer" is on the tuned side of the antenna system tuning unit (ASTU).

A problem not discussed in the *QST* Product Review concerns measuring the impedance of base station antenna systems, since unless one is in a remote area the amplitude of powerful local signals (particularly 50 kW broadcast stations) usually exceeds the amplitude of the analyzer's reference signal. The MFJ analyzer can be used (apparently) with an optional tunable measurement filter, which according to advertisements can be used "to accurately measure SWR and impedance in the frequency range 1.8 to 30 MHz in the presence of strong RF fields." This accessory does not help much [Michael Tracy, KC1SX, private communications, May 2005], and in any case, if we connect a tunable filter between the antenna and the analyzer, we are not connected directly to the terminals of the antenna system.

This technical correspondence describes how we can use an antenna analyzer together with a homebrew ASTU to measure the impedance of base station antennas.

On ASTUs

In my *QST* article on ASTUs I concluded that a simple L-network could be used to match any antenna system impedance.[1] The first sentence of that article reads: "The function of an antenna system tuning unit (ASTU) is to transform the impedance at the input end of the transmission line to the 50 Ω impedance required by the transmitter, and so establish a conjugate match for maximum power transfer to the antenna system." We are concerned here with matching the antenna system for maximum power transfer.

Suppose we wish to match an antenna system load impedance of $Z_{as} = 100 - j\,300\ \Omega$, at a frequency of 3.75 MHz, using a simple L-network. See Figure 1. The ARRL *TLA* program by Dean Straw, N6BV (a later version, *TLW*, is available for Windows) gives me a network comprising a series inductor equal to 9.1 µH (j 215.545 Ω), and a shunt capacitor equal to 59.9 pF ($-j$ 708.170 Ω). The Q factors are the default values for *TLA* (but default values can be changed): Q_L = 200, Q_C = 1000.

This circuit, looking back from the output terminals, with the input terminal shunted by 50 Ω, is a simple parallel LC network. Terman gives the equation for this parallel impedance (his Equation 11, p 141).[2]

$$\text{Parallel Impedance} = Z_{as}{}^* = \frac{Z_C Z_L}{Z_C + Z_L} \quad \text{(Eq 1)}$$

Z_{as}* since I expect to see the complex conjugate of the load Impedance, Z_{as}.

For the purpose of determining Z_{as}*

$$Z_C = R_C - jX_C$$

$$Z_L = 50 + R_L + jX_L$$

$$R_C = \frac{X_C}{Q_C}$$

$$R_L = \frac{X_L}{Q_L}$$

Inserting these values for our L-network in Equation 1, the parallel impedance of the L-network looking back from the output terminals is 104 + j 297 Ω, which is the complex conjugate of the load impedance.

On Measuring Base Station Antenna System Impedance

I have used antenna analyzers to tune antennas for a decade or more. The ASTU provides the required selectivity so that one can tune accurately for a 50 Ω impedance and zero reactance measured at the input terminals of the ASTU. If the ASTU is a homebrew L-network (preferred), provided with accurate read-out dials, which can be calibrated (dial setting corresponding to component values in µH and pF), and for accurate reset, we can use this ASTU to measure any antenna system impedance. Proceed as follows:

1) Tune the ASTU for a match to 50 Ω;

2) Connect a 50Ω termination resistance to the input terminals of the ASTU; and

3) Measure (or calculate using Equation 1) the impedance looking back into the output terminals of the ASTU. The antenna impedance is the complex conjugate of the measured impedance.

The complex conjugate impedance can easily be measured by a commercial laboratory impedance meter. For use in the field, with no ac power available, and particularly to measure the impedance of antenna systems with no ground connection, our calibrated ASTU and a hand-held, battery operated SWR analyzer is a great device for Amateur Radio operators. Knowing component values (dial setting of our calibrated L-Network) the complex conjugate impedance is calculated using Equation 1. This is a bit tedious, and some readers may not care what the antenna impedance is, as long as the SWR is reasonable, and the antenna system can be tuned by an ASTU without excess loss. The impedance of antennas is an important parameter for me. The impedance of electrically short antennas (mobile whips, and electrically small loop antennas) gives us a measure of the radiation efficiency; and the impedance of full size antennas is a valuable parameter for checking (validating) NEC analysis. In fact, the antenna impedance is a useful parameter needed to design a suitable high-power base-station ASTU.

In my case, I have access to a laboratory impedance meter. Okay, so why not just use this meter? Such a devise is not very portable, and is not very useful to measure the impedance of antenna systems isolated from ground (mobile whips and antenna systems that should be operated isolated from a ground connection, such as ground-plane-type antennas with elevated radials).

I remember struggling to measure the impedance of mobile whips, many years ago, using an impedance meter. The HP meter I used had a balun at the input, but I wonder if this really isolated the impedance meter, which was connected to the ac mains, and so effectively connected to the ac mains ground. I inserted a United Transformer Company isolation transformer between the impedance meter and the ac line — but did this do the job? I have one, but most of you who read this may not even have heard of UTC transformers, and you will certainly not have one of their isolation transformers. It was said that the UTC isolation transformer really did simulate battery operation (it had a triple Faraday shield, and coupling between windings was said to be only a few picofarads) — but it is easier to use a battery-operated SWR analyzer to measure the resonant impedance of a tuned antenna system.

[This technique assumes the ASTU acts as an appropriate filter. If the design engineer has properly designed the network to filter

[1] J. S. Belrose, "On the Quest for an Ideal Antenna Tuner," *QST*, Oct 2004, pp 35-39.

[2] F. E. Terman, *Radio Engineers' Handbook*, McGraw-Hill, 1943.

out the unwanted signal, the measurement technique will be reliable. It is quite possible for someone not as technically astute to use the wrong network configuration, however. I suggest that most hams would want to perform one additional step. With the calculated impedance values, cobble up a test load to simulate the antenna. Connect the test load across the antenna terminal of the ASTU and verify that the SWR is 1:1, as expected. A significant difference may indicate inadequate filtering or an error in the calculations. — *Zack Lau, W1VT, ARRL Lab Engineer*]

Determining the Radiation Efficiency of a Center-Loaded Mobile Whip

We can measure the radiation efficiency by measuring ground wave field strength E (dB referenced to microvolts per meter).[3] For the average radio amateur, a field strength meter is not a part of his ham shack gear. We can predict performance using a readily available computational EM program, such as *NEC-2* (in the public domain), or *NEC-4*, provided we have a measure of actual losses. I use *EZNEC Pro*, by Roy Lewallen, W7EL.

There are a number of loss parameters we do not know. We do not know the Q factor for the center loading coil (R_L), and we do not know the ground induced loss resistance (R_g). In fact we do not know with certainty the radiation resistance (R_r), since the antenna sees an image of itself in the ground. *NEC* only gives us the sum of the various resistances.

$$R_{as} = R_r + R_C + R_g + R_L \qquad \text{(Eq 2)}$$

R_C, the only parameter not discussed above, is the conductor loss resistance.

We need to know R_r if we are going to compute radiation efficiency, since radiation efficiency is given by:

$$\eta = \frac{R_r}{R_{as}} \qquad \text{(Eq 3)}$$

So what do we do? We can measure R_{as} using the SWR analyzer, by adjusting the tuning so the reactance at the base of the antenna is equal to zero. We can then use *NEC* to predict the base impedance (resistive component), by changing the Q factor of the inductor so that R_{as} predicted equals R_{as} measured. We can then predict the ground field strength (dBμV/m) at say 100 meters for a transmitter power of 1 kW. We then reference this predicted field strength to that for an electrically small lossless vertical antenna (129.54 dBμV/m at 100 meters for 1 kW transmitter power — which corresponds to the commonly quoted value of 300 mVm at 1 km). This gives us a pretty good estimate of the radiation efficiency of our mobile whip.

On Electrically Small Loops

We cannot directly measure the antenna system resistance, since the resistance we measure is this impedance (resistive component) transformed to the desired transmitter load impedance (50 Ω). I am thinking here of a one turn loop, tuned at the top by a low loss tuning capacitor, and coupled to the feeder by means of a small coupling loop, such as the AMA loops.[4]

So, to estimate the radiation efficiency we proceed as follows. Using our SWR Analyzer we measure the bandwidth of the electrically small loop at the frequencies of interest.

The antenna system Q factor for the loop in its operational environment can be measured since:

$$Q = \frac{2\sqrt{\beta}}{FBWv} \qquad \text{(Eq 4)}$$

where:

$$\sqrt{\beta} = \frac{s-1}{2\sqrt{s}}$$

FBWv is the fractional match VSWR bandwidth (which can be determined using our antenna analyzer), and s is the arbitrary choice of VSWR about the matched resonant frequency. If the VSWR is 2.618:1, then

$$Q = \frac{1}{FBWv} = \frac{f_O}{BW} \qquad \text{(Eq 5)}$$

where BW is the bandwidth, and the Q factor determined for this BW is consistent with the Q factor used in the equation below.

$$R_{as} = \frac{X_a}{Q} \qquad \text{(Eq 6)}$$

Since $X_a > R_{as}$

Q is a measured value, and so R_{as} is a measured value.

This Q factor relates to the –3 dB BW used by radio engineers.[5] For practical interest from the point of view of transfer of power to antenna systems, typical bandwidths are measured for an SWR = 2:1, and this is the BW measured by Christian Käferlein, for the AMA loops manufactured by his company.[6] For this BW:

$$Q = \frac{0.707}{FBWv} \qquad \text{(Eq 7)}$$

If R_{as} computed (according to *NEC*) is not equal to R_{as} measured (Equation 6), the only parameter we have not taken into account is the Q factor of the tuning capacitor, and so we adjust the Q for this capacitor so that R_{as} computed equals R_{as} measured.

We can then compute the ground wave field strength for 1 kW transmitter power at, say, 100 m distance. We can then reference this field strength to that for an electrically small lossless antenna, as we did above for the mobile whip, to realistically estimate the radiation efficiency.

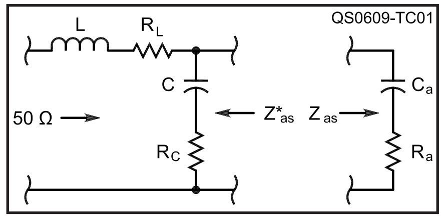

Figure 1 — An L Network, series L, shunt C. Analysis of this network tuned to match a load impedance as shown provides a case study to demonstrate the function of the network, which establishes a conjugate match for maximum power transfer to the load (see text for details).

Concluding Remarks

Let me close by making a few remarks as a follow-on to my article on ASTUs.[7] I received many e-mails and letters complimenting me and questioning remarks made (two score and more). A number of correspondents questioned network requirements and configurations needed for component switching. I thank those who wrote, since this resulted in my rethinking the circuit. The basic network shown in my referenced article (Figure 1 of that article) is a reversible series inductor, and a shunt capacitor. With this switch arrangement we can reverse input and output terminals. Its origin is based on my early experience. Intuitively, when computing component values manually, if the antenna system impedance is capacitive, the simplest procedure is to resonate the antenna system first (switch position B for this example), and this configuration is right for $R_{as} < 50\ \Omega$ (electrically short monopoles). When $R_{as} > 50\ \Omega$ we need to reverse the L-network.

The more versatile circuit described in that article is perhaps an overkill. Certainly this complicated switch arrangement does work, since it changes the network into the four possible component arrangements. Now

[3] J. S. Belrose and L. Parker, "A Tunable All-Bands HF Camp/Mobile Antenna," *Communications Quarterly*, Fall 1998, pp 47-57.

[4] J. S. Belrose, "Electrically Small Transmitting Loops — Part 1," *RadCom*, Jun 2004, pp 65-67; Part 2, Jul 2004, pp 88-90; and Technical Feedback, Jun 2005, p 78.

[5] See Note 2.

[6] See Note 4.

[7] See Note 1.

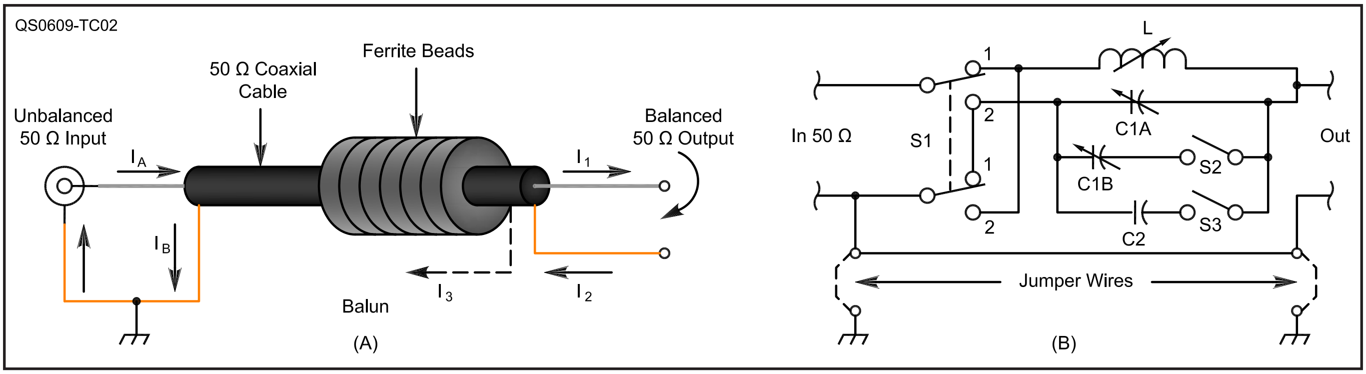

Figure 2 — An L network ASTU, switch arrangement (S1) to change configuration from series L, shunt C to series C, shunt L. Suggested component values: L — Rotary inductor, 28 µH inductance, Cardwell E. F. Johnson 229-203, with steatite coil form (or equivalent); C1 — dual 15-196 pF variable with voltage rating 3000 V peak, such as E. F. Johnson 154-507-1, arranged so that one section is used or two sections in parallel; C2 — 400 pF, 3000 V peak; S1 — quality switch to carry RF currents; S2 and S3 — high voltage switches. Remove jumper wires to feed a balanced antenna system.

we have computer programs to aid network design. *TLA* (for example) can be used to calculate component values for two L-network arrangements: 1) a series L and a shunt C; and 2) a series C and a shunt L. Try your hand at using this program. One can in fact match almost any impedance. Clearly a basic requirement for the network is by switch arrangement to be able to reverse L and C, rather than reversing input and output terminals. A switch arrangement for this requirement is shown in Figure 2. This is certainly a simpler network switch arrangement, compared with the one shown in my referenced article.

Balun requirements were previously discussed. In Figure 2, I show again for clarity (based on readers' comments) a W2DU type balun: ferrite beads over coax. This is a convenient arrangement, since the beads can be on the connecting coax between the ASTU and the transceiver (beads as close as possible to the ASTU end of this coaxial cable).

Look again at Figure 1 of my earlier referenced article. *TLA* does not cater to the circuit arrangement with the switch in Position A (inductor on the antenna side). Practically, we may not need this configuration (see above), but for those interested in making case studies, to decide for themselves possible circuit re-arrangement, what can we do? We can simulate this circuit, at least for a range of impedances to be matched, by selecting the Pi-Network configuration in *TLA*. Change the default value for the output capacitor from 500 pF to a very low value (say 1 to 10 pF), and we now have an L-Network. I have commented before that by setting the input and output capacitors to minimum we in fact simulate a reversible L Network — but not quite, since practical minimum capacitance values are usually 10 pF.

— John S. "Jack" Belrose, VE2CV, 17 rue des Montagnais, Secteur Aylmer, Gatineau, QC 191 1G1, Canada; **john.belrose@crc.ca**.

FAST TR SWITCHES

Switching systems such as the one described in the article "A Fast TR Switch" should never be implemented in systems.[8] They are a disaster waiting to happen. While "A Fast TR Switch" is generally a very good article it has a serious safety flaw. The flaw is depending on a single PIN diode or reed relay to hold off the output of a transceiver to the input of a receiver. DPDT or SPDT switching systems are *much* more reliable. In other words, a fast single contact that has NO and NC connections could have been used. It could have been arranged to prevent the transceiver output from ever being connected to the receiver regardless of any failure mode.

Worse yet, nether system in the article has a series fuse (like a small light bulb). The only receiver safety device is a pair of very small diodes arranged as a clamp. This is a system that often adds IMD to receivers; small diodes actually start to turn on at voltages less than the 0.7 V or so clamping voltage.

If the keying line has a poor connection, if the reed relay sticks (a common failure mode), if Q1 shorts, or if the transceiver internal sequencing is incorrect the receiver has a strong possibility of damage or ruin. The simple addition of a low current lamp in series with the RF line between J1 and the diode clamp would greatly improve chances of receiver survival.

The same is true with the PIN diode switch. A small fuse lamp could be added on either side of C4 to protect the clamp diodes and the receiver for sequencing, connection or component failures. If you look at any commercial external PIN switch manufactured, they all include some sort of fuse lamp. This is the result of bench testing or field failure experience.

[8] J. Kuecken, "A Fast TR Switch," *QST*, Oct 2005 (Workbench), pp 56-57.

We can't always depend on a clamp diode to fail shorted and protect the receiver from direct application of 100 W (or more) to the RF connector.

— Tom Rauch, W8JI, 371 Dean Rd, Barnesville, GA, 30204; **w8ji@contesting.com**

In reply to Mr. Rauch's comments I would note that the military reliability guides list relays among the least reliable items used in electronic equipment. I do not agree that they are more reliable than a PIN diode or a transistor.

The point that the pair of diodes can lead to intermodulation distortion with large signal input is well taken. If you are often exposed to large signals, as with multiple radios on a naval vessel, the diodes can be a problem. Field Days can also pose this problem. On the other hand, for most common signal levels the diodes pose no problem.

On the subject of the inclusion of a small lamp to act as a fuse, this was a common practice for protection of the grid of the input amplifier tubes. The lamp would often fail before the tube. In the case of solid state front ends, I question whether a lamp would fail before the transistor or IC at the front end. I do not think that the inclusion of a lamp is common in modern transceivers to protect the front end from TR switch failure.

— Jack Kuecken, KE2QJ, 2 Round Trail Dr, Pittsford, NY 14534; **ke2qj@aol.com**

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