Don't Blow Up Your Balun

Use these insights to improve your ARRL Field Day antennas.

R. Dean Straw, N6BV
Senior Assistant Technical Editor,
ARRL (Retired)

I'm doing well in the DX contest, picking up multipliers in Oceania on the low bands around the time of my sunrise. It's time for the higher bands to open up. I quickly switch to the five-element 10 meter Yagi, find a clear frequency, and push F1 to call "CQ Test."

I'm horrified to see that my transmitter is still on 40 meters, and so is the kilowatt amplifier. The SWR meter shows a high reading; it is almost pegged, in fact. I stop transmitting immediately, but it's too late — the balun on the 10 meter Yagi is fried.

In this article, I will examine the stresses placed on various components in your antenna system so you can avoid turning your antenna into a crispy critter [and get improved antenna performance for Field Day. — Ed].

Differential-Mode vs Common-Mode Currents

Figure 1 shows a simple half-wave dipole fed with a balanced two-wire transmission line. There are two kinds of RF currents in such an antenna system: differential-mode current and common-mode current. Differential-mode current flows in one direction on one conductor of the transmission line and in the opposite direction on the other conductor of that transmission line. Differential-mode current is what we want in an antenna system because it transports

power from the transmitter and antenna tuner down in the shack up to the antenna, where it is radiated.

The undesired RF current in Figure 1 is common-mode current, which flows in the same direction at any instant on both conductors of the transmission line. Common-mode current arises because of asymmetries in the dipole antenna itself, such as different lengths for each side of the dipole, or slight differences in the terrain under each half of the dipole. Common-mode

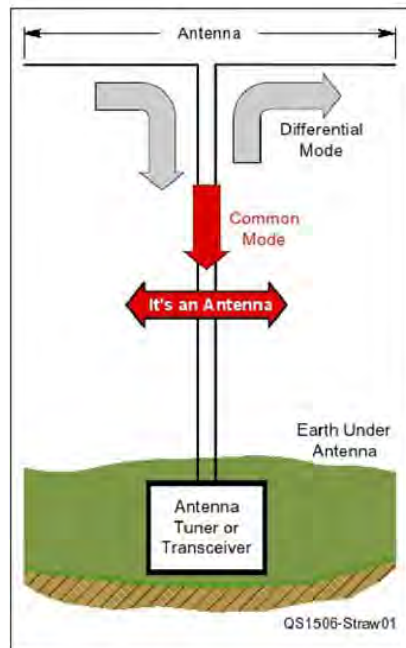Figure 2 — Some common-mode current chokes. [Jim Brown, K9YC, photos]

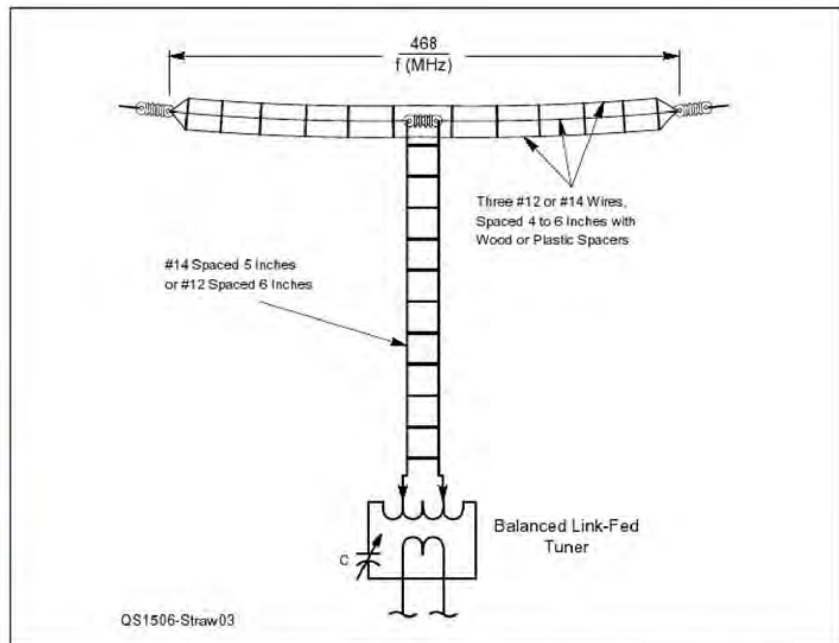Figure 1 — Common-Mode vs. Differential-Mode currents. [Image source courtesy of Jim Brown, K9YC]

Figure 3 — Back in the good old days, a flattop multi-wire dipole fed with homemade open-wire transmission line, using #12 AWG conductors separated by paraffin-coated insulators.

current can also arise from asymmetries in the manner in which the transmission line is dressed away from the antenna down to the antenna tuner in the shack.

When coaxial cable is used for the transmission line feeding an antenna rather than balanced two-wire line, common-mode currents flow on the outside surface of the coax shield. The desired differential-mode currents inside the coax flow in opposite directions on the outer surface of the center conductor and on the inner surface of the coax shield.

Common-mode currents can give rise to stray noise during receive, and a degradation of directional patterns on both receive and transmit. How do we get rid of such undesired common-mode currents on either coax or balanced two-wire transmission line? We insert a high-impedance common-mode current choke in series with the transmission line. This choke attenuates undesired common-mode currents, but doesn't affect the desired differential-mode currents. Radio amateurs often call such a current-choking device a "balun" (standing for "balanced to unbalanced"), but it is more instructive to think of these devices as common-mode chokes.

Figure 2 shows three common-mode chokes made of RG-213 or RG-8X coax wound through high-permeability ferrite cores. The choke on the right was made using bifilar #14 AWG enameled wires. The chokes using RG-213 coax are capable of handling 1.5 kW at a maximum SWR of about 10:1. All the chokes exhibit an impedance in excess of 5000 Ω resistive over a three octave frequency range. Thus, the common-mode choke impedance is high enough to "choke off" common-mode currents.

In the analyses that follow, I assume that common-mode current is reduced to inconsequential levels by the common-mode choke — the stress on antenna components just gets worse if the choke impedance is insufficient to suppress common-mode currents.

What about differential-mode stresses, especially under conditions of high SWR? The length of coax used for the larger chokes in Figure 2 is about 2 feet for each turn through the stack of toroidal cores. This gives a total length of about 10 feet for five turns of RG-213 coax threaded through the center of the ferrite toroids.

Table 1

Feed-point Impedances for a 66-foot-long, Center-fed Inverted V Dipole, Apex 50 Feet High Over Ground with Dielectric Constant of 13, Conductivity of 0.005 S/m

Frequency	Feed-Point Impedance
1.83 MHz	$1.6 - j2257\ \Omega$
3.8 MHz	$10.3 - j879\ \Omega$
7.1 MHz	$64.8 - j40.6\ \Omega$
10.1 MHz	$21.6 + j648\ \Omega$
14.1 MHz	$5287 - j1310\ \Omega$
18.1 MHz	$198 - j820\ \Omega$
21.1 MHz	$103 - j181\ \Omega$
24.9 MHz	$269 + j570\ \Omega$
28.4 MHz	$3089 + j774\ \Omega$

However, the size and shape of the K9YC larger common-mode chokes do not lend themselves well to baluns built inside typical antenna tuners, so I decided to model a more compact sort of choke balun that employs RG-303 coax made using high-temperature Teflon® insulation. RG-303 can be wound more tightly on a toroid than RG-213, whose center conductor is insulated with relatively soft polyethylene plastic that melts when overheated. This causes the center conductor to short out to the braid at high insulation temperatures when there is a tight bend radius. For my stress analyses in this article, I assumed a total length of 6 feet of RG-303 for a choke balun with five turns through a stack of three Type 31 ferrite cores, 2.4 inches in outside diameter.

The Quest for a Simple Multiband Antenna

Many hams want to get on all the HF bands with a simple multiband antenna that won't draw undue attention from their neighbors. A dipole fed with low-loss transmission line, such as open-wire balanced line or low-loss coax, seems very attractive, at least at first glance. The problem with a simple dipole is that the feed-point impedance varies all over the place as the frequency is changed.

Table 1 shows the variation with frequency of the feed-point impedance for a typical 66-foot-long 40-meter dipole installed as an inverted V, 50 feet high at the apex. The ground parameters are for average ground, with a dielectric constant of 13 and a conductivity of 5 mS/m. Note how the antenna is close to resonance at 7.1 MHz, just as you'd expect for a 66-foot-long dipole. At the second and third harmonics of the fundamental frequency, namely 14.1 and 28.4 MHz, the feed-point impedance rises to impressively high values. The impedance at the "half-harmonic" frequency on 80 meters is also very challenging, as will be shown later.

### Example 1: Back in the Good Old Days...

Figure 3 shows a multi-wire flat top dipole, fed with a homemade balanced #12 AWG open-wire feeder. This was a common antenna configuration back in the 1930s. A balanced link-fed antenna tuner is connected to the feeder down in the shack. Figure 4 shows a typical commercial link-fed tuner. This is the famous E.F. Johnson Matchbox, much beloved by several generations of hams after World War II. The beauty of this balanced design was that there was no lossy balun inside the spacious cabinet and the tuning components were beefy and low loss. The drawback to this design is the limited range of impedances that it could match, compared to modern high-pass T tuner topologies. Still, the Johnson Matchbox could match an impressive range of impedances fed to it.
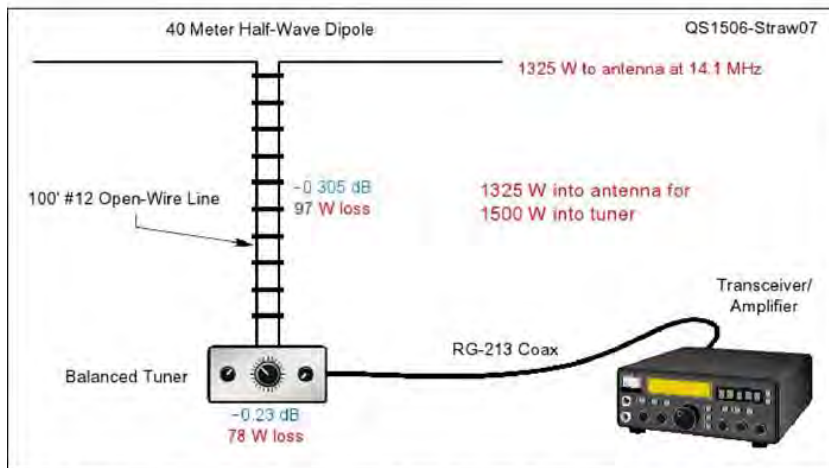

Figure 4 — A Johnson Matchbox balanced-line antenna tuner from the 1950s. [Hank Garretson, W6SX, photo]
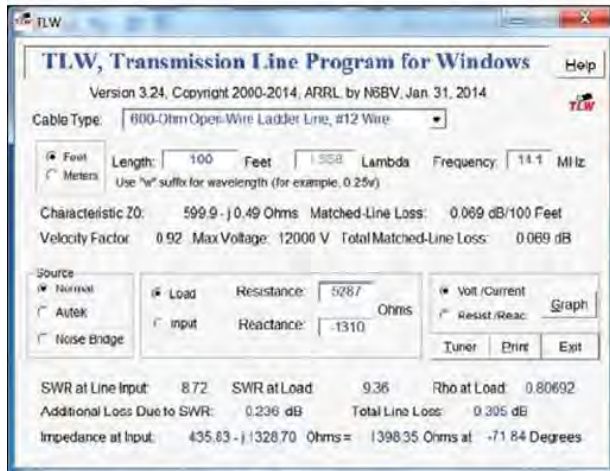
Figure 5 — *TLW* main window showing 100 feet of open-wire #12 AWG line feeding a 40 meter inverted V dipole at 14.1 MHz. The SWR at the antenna feed point is 9.36:1 and the impedance at the input of the transmission line is $435.83 - j1328.70\ \Omega$. The total line loss is 0.305 dB.
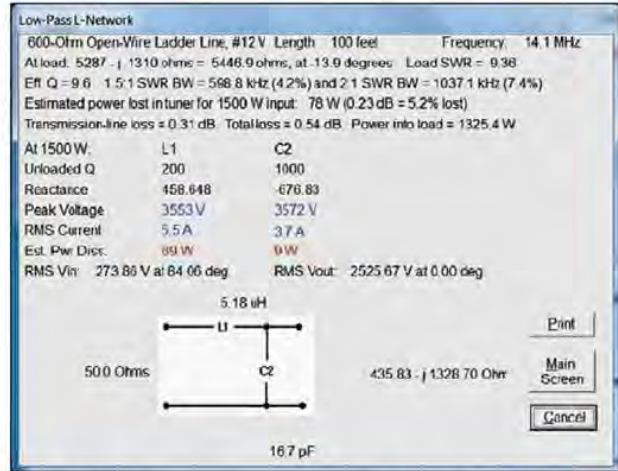
Figure 6 — Low-pass L network, modeled using *TLW*, simulates a Johnson Matchbox matching the $435.83 - j1328.70\ \Omega$ impedance to $50\ \Omega$. The loss in the tuner network is 0.23 dB, which is 78 W for 1500 W input to the tuner. The loss in the tuner's inductor is 69 W for an inductor unloaded Q of 200.

Figure 7 — Power losses in the antenna setup of Figure 5. The antenna receives 1325 W for 1500 W input to the balanced antenna tuner, such as a Johnson Matchbox.
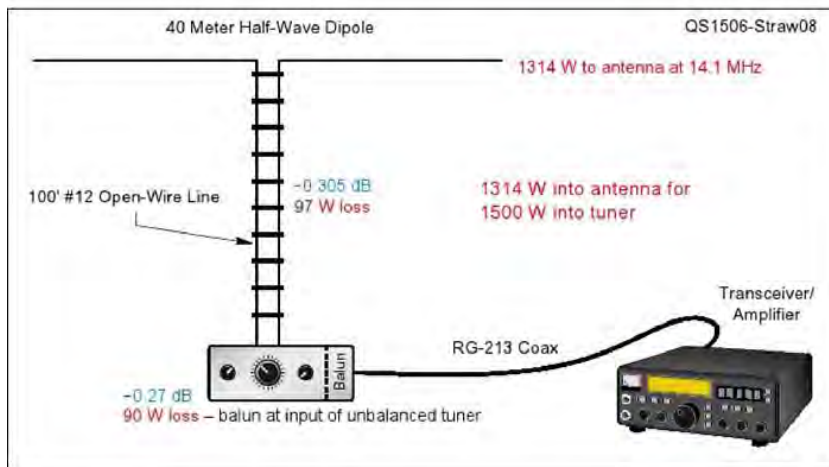

The loss analyses that follow were generated using the *TLW* (*Transmission Line for Windows*) program that is on the CD-ROM bundled with late editions of *The ARRL Antenna Book*.[1] *TLW* has been called the "Swiss Army Knife" of transmission line and tuner programs. Figure 5 shows a screenshot from *TLW* for 100 feet of #12 AWG open-wire transmission line feeding our 66-foot inverted V dipole at 14.1 MHz. Throughout this article, I'll use a length of 100 feet for the feed line. The characteristic impedance for this open-wire line is 600 Ω and the matched-line loss is 0.069 dB per 100 feet, very low indeed.

However, in Figure 5 the feed line is not being used with a 600 Ω matched load; it is seeing the antenna feed-point impedance of $5287 - j1310\ \Omega$ at 14.1 MHz. The SWR at the antenna is 9.36:1, which raises the total loss in the transmission line to 0.305 dB because of the additional loss due to SWR. The impedance seen at the bottom of the 100-foot feed line is $435.8 - j328.7\ \Omega$.

To gauge the approximate loss in the tuner, we'll use a simple L network model in *TLW*. Figure 6 shows an L network that matches

Figure 8 — Power losses when an unbalanced antenna tuner network is isolated from ground using a common-mode choke balun at its input. The efficiency of the input balun is high because it is being operated into the 50 Ω for which it is designed. The net power reaching the antenna is 1314 W, compared to the 1325 W for the Johnson Matchbox used in Figure 7.
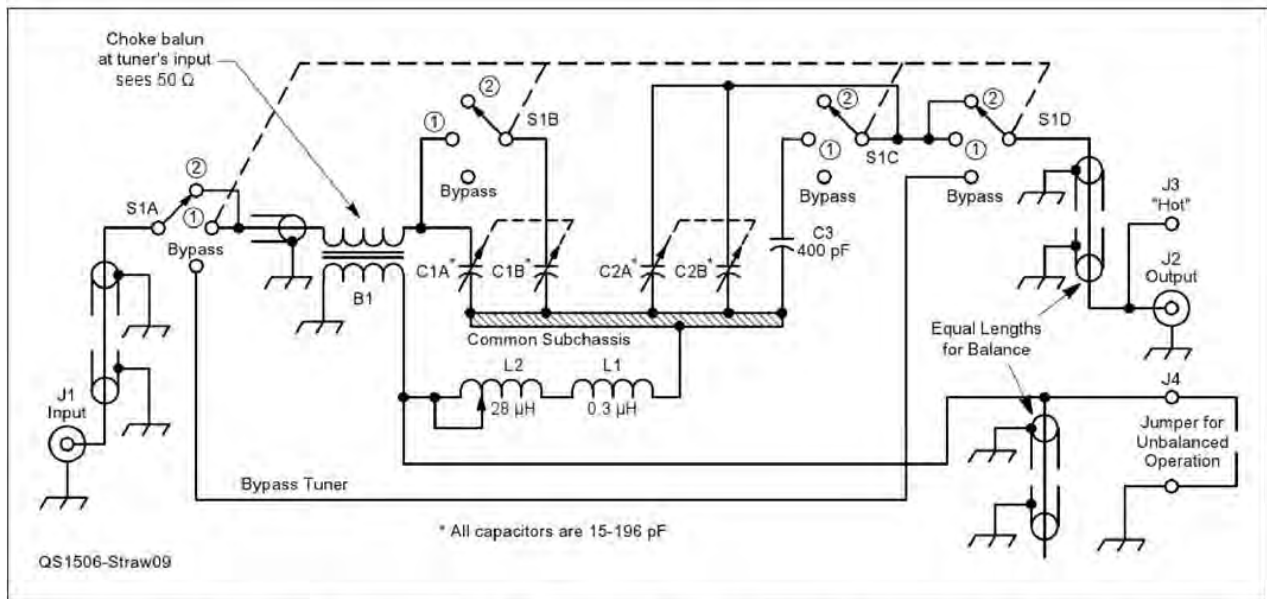
Figure 9 — Schematic for the high-power antenna tuner in *The ARRL Antenna Book*, which uses an unbalanced high-pass T network with a current-mode choke balun B1 at its input.
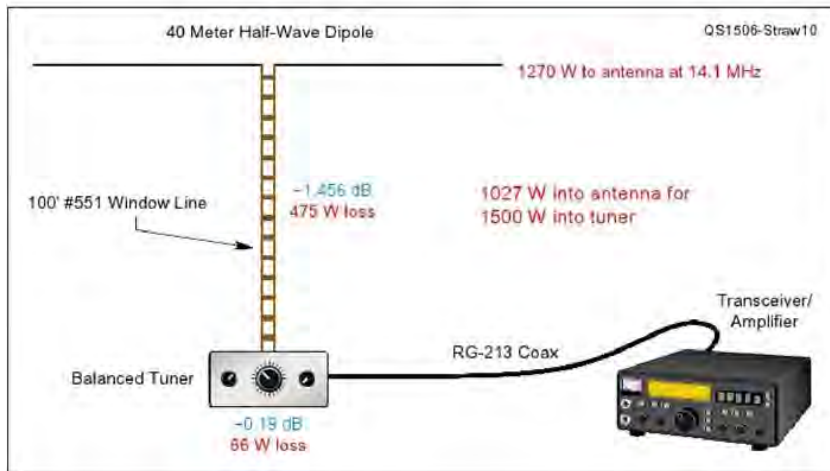
Figure 10 — Power losses for Johnson Matchbox feeding 100 feet of "window ladder line" instead of #12 AWG wire open-wire line. The net power reaching the antenna is 1027 W, with 475 W lost in the window ladder line, which uses #18 AWG copper-clad wire.

the 435.8 $-j$ 328.7 Ω impedance to 50 Ω, losing an estimated 78 W in the tuner components. This is 0.23 dB loss: 69 W in the coil and 9 W in the capacitor. You might find it a little surprising that power is lost in a capacitor, but this is pretty typical for variable capacitors using mechanical wiping contacts.

Figure 7 shows the losses and impedance levels in the complete system. There is 97 W lost in the transmission line. For 1500 W of RF applied to the antenna tuner,

1325 W makes it all the way to the antenna feed point to be radiated.

### Example 2: An Unbalanced Tuner with Balun at Input

Figure 8 shows the setup for a #12 AWG open-wire line, 100 feet long, connected to an unbalanced high-pass network tuner with a 50 Ω common-mode choke at the input of the tuner. (Note: this is different from most tuner designs, which place the common-mode choke balun at the output of the tuner, where the impedance level that

the choke sees can vary dramatically, depending on the antenna itself, on the length of transmission line, and the frequency in use.)

Figure 9 shows the schematic for the ARRL high-power antenna tuner that has been in *The ARRL Antenna Book* for about 15 years.[1] The common-mode current choke/balun is B1 in the left-hand side of the schematic. The use of an unbalanced tuning network isolated from chassis ground with the choke balun makes the mechanical construction more complex than a tuner design having the choke balun at the output side of the tuner. But keeping the common-mode choke B1 working into the impedance (50 Ω) for which it was designed is a worthy thing to do.

The common-mode input choke has an estimated loss of 15 W, for a total loss in the tuner and input choke of 90 W. This is only slightly worse than the Johnson Matchbox in Example 1, which has 75 W of estimated loss. The net power into the antenna for the tuner with input choke balun is 1314 W for 1500 W into the tuner input.

Conceptually, a common-mode choke used in conjunction with an antenna tuner can be envisioned as though it were a giant ferrite toroid that is large enough to slide sideways left-to-right over the antenna tuner. When the giant toroid is slid all the way to the right, the common-mode choke
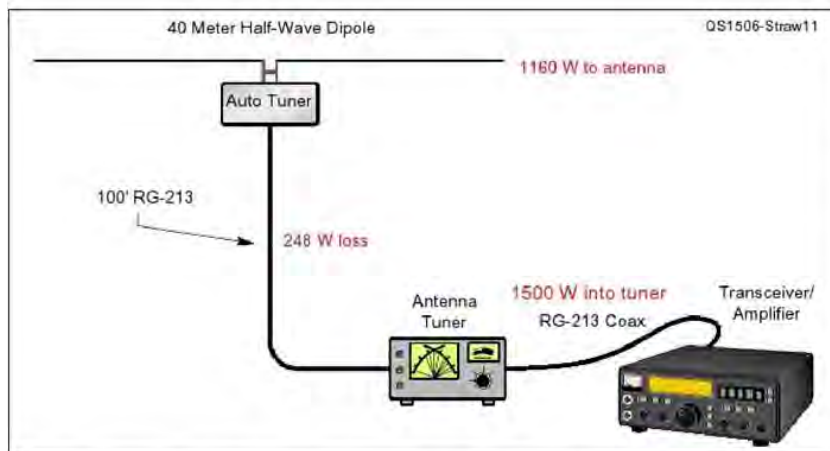
Figure 11 — Setup for feeding a 40 meter inverted V dipole at 14.1 MHz, with an automatically tuned antenna tuner located up at the antenna feed point.
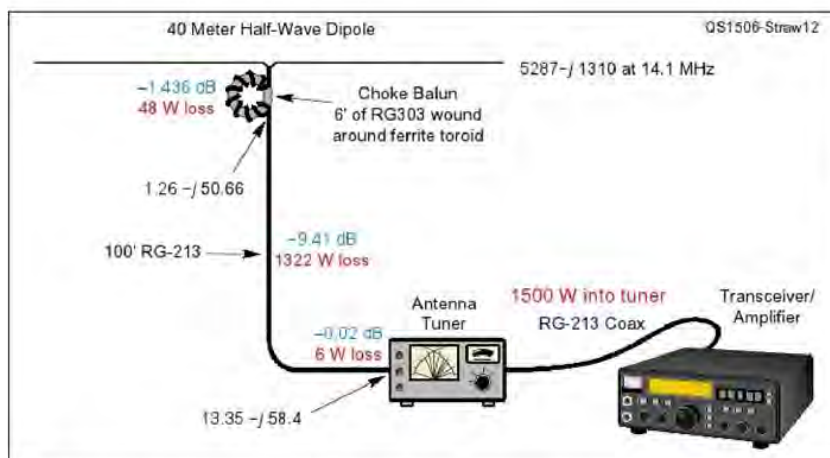
Figure 12 — Setup for "N6BV's Train Wreck," where common-mode current choke is placed at antenna feed point. The choke is made up of 6 feet of RG-303 Teflon-insulated coax threaded through ferrite toroids. The loss in the 100 feet of RG-213 feed line is 9.41 dB, very high indeed.
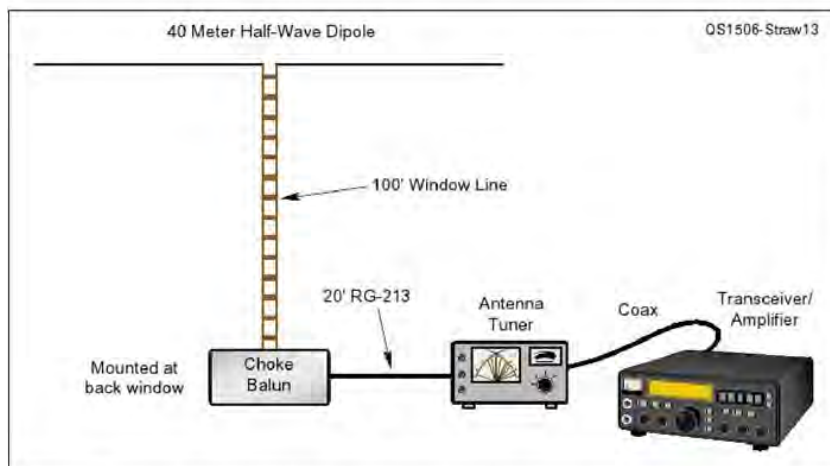
Figure 13 — A popular method for feeding a multiband dipole, where the common-mode choke balun is placed at a rear window in the shack and a jumper of RG-213 coax connects the choke to an antenna tuner located at the operating position. I assumed in this example that the jumper coax is 20 feet long.

is positioned at the tuner's output terminals. When the giant toroid is slid all the way to the left, the common-mode choke is at the input terminals of the tuner. In both cases the choke works as it should by choking off the undesired common-mode currents, but the impedances it must work with are stabilized at 50 Ω when the choke is at the input of the tuner.

Example 3: A Balanced Tuner "Window-Line" Feeder

In Example 3, I assume that the 40 meter inverted V is now fed with 100 feet of open-wire "window ladder line" at 14.1 MHz. The window line is selected in *TLW* as Wireman #551, which uses copper cladding over steel wire for each #18 AWG conductor. The total line loss at 14.1 MHz is 1.456 dB, which is 475 W, compared to 0.305 dB matched-line loss for the balanced open-wire line constructed of #12 AWG copper cladding over steel wire in Example 1.

In Example 3, we'll again use a Johnson Matchbox, which has a loss of 0.19 dB, or 66 W of power loss. Figure 10 shows that the total RF power delivered to the antenna is 1027 W for 1500 W supplied to the antenna tuner. This is less than in Example 1, but is still quite efficient.

Example 4: An Autotuner at the Antenna Feed Point

Figure 11 shows the 40 meter inverted V dipole used at 14.1 MHz, but now with an automatic tuner up at the feed point, fed with the usual 100 feet of RG-213. The system delivers 1160 W of RF power to the antenna, with a matched-line loss in the 100 feet of RG-213 of 248 W. This is an efficient system, although there aren't many commercial 1.5 kW tuners that can be placed outside in the wind, snow, rain, and sun.
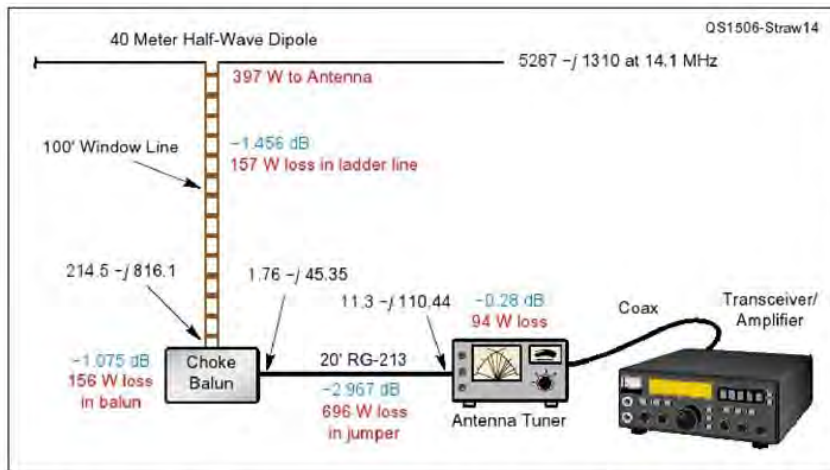
Example 5: A Common-Mode Current Choke at the Antenna Feed Point

Figure 12 shows what Jim Brown, K9YC, has dubbed "N6BV's Train-Wreck Scenario." It again uses the 40 meter inverted V dipole on its second harmonic at 14.1 MHz. The balun consists of 6 feet of Teflon-insulated RG-303 50 Ω coax, which in turn is fed with 100 feet of RG-213 feed line to the antenna tuner in the shack. *TLW* computes 1.436 dB of loss in the common-mode choke, with an SWR of 111.67:1 and an input impedance of $1.26 - j\,50.66$ Ω.

Figure 12 also shows the impedances and the power losses at each junction in this sys-

Figure 14 — Power loss in watts for system with choke balun placed at a rear window in the shack. A staggering 696 W is lost in the 20-foot-long jumper between the antenna tuner and the choke! The choke balun dissipates 156 W and it will probably become a "crispy critter" if the key is held down for long.
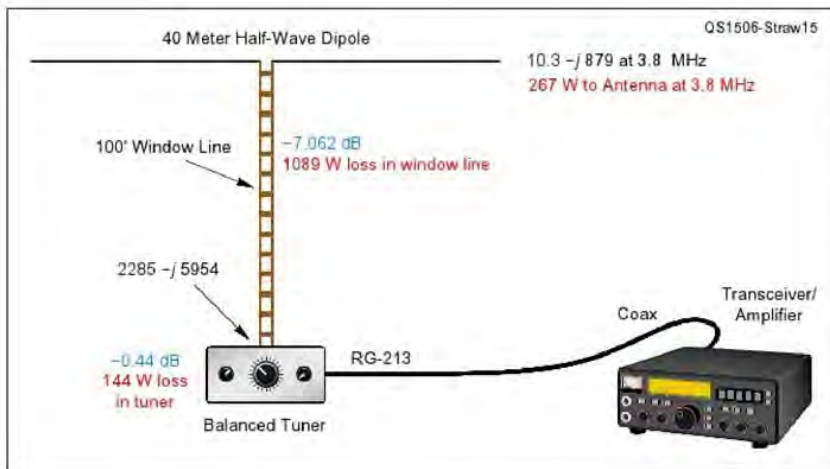
tem. The loss in the 100 feet of RG-213 is quite high, at 9.41 dB. Figure 12 also shows that 1322 W is burned up in the feed line when an efficient tuner is used with 0.02 dB (6 W) of loss. Thus, 171 W is presented to the input of the common-mode choke, and only 122 W makes it to the antenna. The net power dissipated by the differential-mode current inside the common-mode choke is 48 W, amounting to 8 W per foot of RG-303. This level of power shouldn't destroy the choke balun, provided that air can circulate to cool the choke balun.

I should note that the high loss in the 100 feet of RG-213 actually protects the choke balun from too much power at its input when operating into a high SWR. But what a waste of expensive RF this is: a train wreck indeed. Now please don't ask what kind of dimwit would actually try to feed a 40 meter dipole on 14.1 MHz.

Example 6: Open-Wire Feed line, with Common-Mode Choke in the Shack

This is probably the most common configuration that hams use — open-wire line with a common-mode choke balun. In a typical installation (Figure 13), 100 feet of ladder line goes from the antenna feed point to a choke balun placed at a back window in the shack. A typical jumper of 20 feet of RG-213 goes from the choke through the

Figure 15 — Setup for a 40 meter inverted V dipole fed on 80 meters, showing impedances and losses at each juncture. The antenna tuner is high efficiency, like a Johnson Matchbox. The window ladder line has a loss of 7.062 dB in this stressful condition.

window frame to the antenna tuner located at the operating position.

I've heard amateurs claim that this setup helps keep "RF out of the shack," since any common-mode current is choked off at the window by the choke balun. This is true — after all, the common-mode choke is doing what it was designed to do: choke off common-mode currents. However, if the antenna itself is located close to the shack, the desired differential-mode current in the feed system will radiate RF directly into the shack. The antenna is doing exactly what it was designed to do: radiate RF.

You must carefully observe the losses in such a setup. Figure 14 shows the impedances and losses at each point in the antenna feed system and translates the power loss from decibels to watts, given 1500 W input to the antenna tuner. What jumps out immediately from the setup in Example 6 is the 696 W lost in the 20-foot jumper between the choke balun at the rear window and the antenna tuner. This is 35 W per foot, a level that will probably melt the coax.

The power dissipated in the choke balun is 156 W, a level which puts quite a stress on the choke, especially for high duty-cycle modes like RTTY. The choke balun will definitely need air circulation for cooling. The net power making it to the antenna to be radiated is 397 W.

What happens if the 20-foot jumper coax is purposely made shorter? While less power will be dissipated by the shorter length of jumper, more power will be available to heat up the choke balun. Table 2 summarizes the six examples we've discussed.

Example 7: Operation of a Dipole on Frequencies Lower Than Resonance?

Figure 15 shows the impedance levels and power losses for a 40 meter inverted V dipole operated on its "half-harmonic" on 3.8 MHz. For 100 feet of window ladder line, fed with an efficient balanced antenna tuner such as a Johnson Matchbox, 267 W of RF makes it all the way to the antenna feed point. The voltages inside the tuner build up to some very impressive levels, close to 7000 V in this example. So the antenna tuner might arc over before its inductors melt due to overheating.

Another thing jumps out at you in Figure 15 — the loss in a low-loss transmission line, like window ladder line, is a staggering 1089 W out of the 1500 W applied to the antenna tuner.

What About an OCF Dipole?

Some hams are enthusiastic users of "Off-Center-Fed" (OCF) dipoles, since OCF antennas often allow relatively convenient multiband operation. However, common-mode currents are unavoidable due to the asymmetric feed, even with high values of common-mode choke resistance.

Radio amateurs often call the current-choking device a balun, but it is more instructive to think of these devices as common-mode chokes.

For a typical 80 meter OCF fed 37.5% from one end, *EZNEC* calculates a choke-balun loss of 326 W for a 5000 Ω choke resistance at the OCF feed point, at 7.1 MHz and 1500 W of input power to the antenna tuner. The common-mode choke balun is simply overwhelmed by common-mode current, and it will heat up quickly at a 1.5 kW power level.

Beware, the common-mode current causes a power loss in the choke balun of 326 W. The total power loss would be greater than this because of the additional loss due to SWR acting on the differential-mode current, as we've been discussing so far in this article. No wonder the OCF dipole has a reputation for blowing baluns under high-power, high duty-cycle operation.

Summary

The old "Johnson Matchbox" tuners were inherently balanced and low loss. Modern designs, with choke baluns at the input of an unbalanced tuning network, can be almost as efficient and generally have wider impedance-matching capabilities.

There are a number of ways you can over-stress components in your antenna system. You should "run the numbers" before firing up that kilowatt amplifier, especially with non-resonant antennas.

[1]*The ARRL Antenna Book*, ARRL order no. 6948, available from your ARRL dealer, or from the ARRL Store, telephone toll-free in the US 888-277-5289, or 860-594-0355, fax 860-594-0303; www.arrl.org/shop/, pubsales@arrl.org.

R. Dean Straw, N6BV, has been licensed for 55 years, starting as WH6DKD in 1959, and has held four other call signs. He trained as an electronics engineer at Yale University, then joined National Radio Company, where he designed SSB and VHF radios. Dean was also in the marine electronics industry for 25 years, eventually joining technical marketing. He worked at ARRL Headquarters for 15 years, specializing in antennas, transmission lines, and propagation. Dean is the editor of five editions of *The ARRL Antenna Book*, and other books dealing with antennas. He retired from the ARRL in 2008, and admits to still having an absolute ball! "Few folks are so blessed by the Good Lord to combine their work and hobby together." You can reach Dean at n6bv@arrl.net.

For updates to this article, see the *QST* Feedback page at www.arrl.org/feedback.

New Products

Erico Grounding Products from DX Engineering

DX Engineering now carries accessories from Erico (**www.erico.com**) used to build a comprehensive and professional-quality tower and station ground system. Tying together a station using Erico's copper-bonded ground rods and ground bar ensures that all components remain at the same electrical potential. This limits possible damage from a lightning strike or voltage spike. Tying station equipment to the same single-point ground (SPG) can also reduce electrical noise in the transmission line and audio signal path. Additionally, Erico makes clamps and connectors to provide a solid mechanical junction between grounding components. The best way to secure a tower's grounding wire to its ground rod is by welding. Erico's CADWELD exothermic welding process makes copper-to-copper or copper-to-steel electrical connections without the need for outside heat or power sources. When installed properly, Erico's CADWELD system creates a permanent bond that won't loosen or corrode over time. For more information, or to order, visit **www.dxengineering.com**.

Add Full Break-in QSK Keying to Your Linear Amplifier

Modernize your homebrew or older amplifier with this high-speed switching circuit.

Printed circuit board of the QSK controller.

James C. Garland, W8ZR

QSK means "I can hear you between my signals." The notion of copying signals between transmitted Morse code characters, today called *full break-in keying*, was mostly wishful thinking and it remained so for many decades. The stumbling block was the early equipment's slow turnaround time between transmitting and receiving.

Modern transceivers, with their compact high-speed TR relays or solid state keying circuits, can now accommodate full break-in QSK keying. CW contesters and DX chasers recognize that full break-in keying is important for competitive operation. This QSK circuit guarantees smooth TR switching of a linear amplifier with properly sequenced relays.

QSK switching requires proper *timing* and *sequencing*. A single "dit" sent at 30 WPM has a key-down duration of 40 ms. To amplify this dit without appreciably shortening or distorting it, an amplifier must switch from bypass mode (RECEIVE) to TRANSMIT mode in approximately ¹⁄₁₀ this time, or 4 ms, then return to RECEIVE mode in a comparable time.

Sequencing requires that the transceiver must always be presented with a proper load, and the amplifier should never operate into a momentary open circuit. Adding to the challenge, there is no standardization in the interface between transceivers and amplifiers. Implementing QSK switching is possible only if the amplifier turnaround switching time can be made sufficiently brief.

QSK Design Objectives

First, we must ensure that the linear amplifier is brought online in such a manner that a live amplifier will never operate into an

open circuit while waiting for its output relay to close. To ensure this objective, the QSK circuitry closes the output relay, bias switch, and input relay in that order, allowing for relay closing times and contact bounce.

The second design objective is to protect relays from hot-switching of RF power. This might occur if RF is present at the amplifier input while the relays and bias switch are closing, or if the relays open

while RF is already being amplified. This QSK design also protects against the possibility that RF could be applied in the brief interval after the relay sequencing has begun but before it is completed. My QSK circuit also safeguards against switching transients caused by transceiver-amplifier timing mismatches.

Selecting a Vacuum Relay

I used this QSK circuit along with a home-made fixture to test several RF re-

Figure 1 — Timing comparison (0.5 ms per division horizontally) of a Jennings RJ1a (bottom curve) and a Gigavac G41c (top curve) vacuum relay. The RJ1a contact closes in 1.2 ms and shows no contact bounce. In contrast, the G41c contact closes in about 5.9 ms after appreciable contact bounce.