The EZ-Tuner - Part I

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Although antenna tuners have always been important station accessories, their popularity has soared in recent years thanks to the development of automatic tuners. In fact, convenient, limited-range autotuners are now standard features of most h.f. transceivers and are a blessing for amateurs who live in antenna-restricted neighborhoods.

Unfortunately, amateurs who use linear amplifiers, who prefer antennas with open-wire feedlines, and who need to match a wide-range of VWSRs, have until now been stuck with decidedly not-so-convenient manual tuners. The EZ-Tuner is designed to meet their needs. It is just the ticket for contesters, DXers, vintage radio collectors with multiple stations, and lazybones like myself who want a hassle-free way to change bands and antennas.

Figure1— The EZ-Tuner uses a T-network to match a wide range of transmission line impedances on all h.f. amateur bands.

The "EZ-Tuner" is an advanced, wide range memory tuner that covers all the amateur bands from 1.8-30 MHz. The EZ-tuner automatically tracks band-to-band frequency excursions, matches high or low antenna impedances up to at least a 16:1 VSWR, and handles the full power of a legal-limit amplifier. Furthermore, the EZ-tuner is expandable, so that new features and software upgrades can be downloaded from the internet and programmed into it through an ordinary serial port.

The EZ-Tuner is described in a three-part series. In this part, we take the mystery out of the versatile T-network (Figure 3a) and show how its most important properties can be distilled into two easy-to-use graphs. Armed with these graphs, we then walk through the design of the EZ-Tuner's matching network. Part I should be of interest to anyone who wants to learn about or build an antenna tuner.

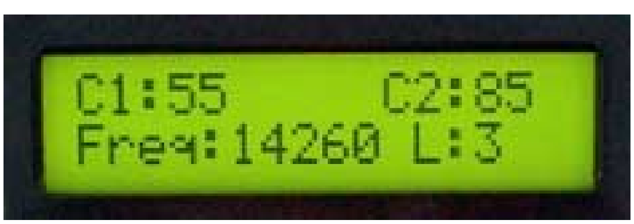

Figure 2— A front panel LCD "turns counter" shows the capacitor and inductor settings as well as the operating frequency.

Part II gets down to the nitty-gritty of the EZ-Tuner's design and circuitry. This part describes the r.f. matching network and also the microcontroller circuitry, which is based on the powerful new BASIC Stamp BS2sx.

We will also provide an overview of the software logic and tuner's operation and performance. Readers will be referred to a website where they can download complete circuit diagrams and software listings.

Part III discusses the EZ-Tuner's construction, with lots of practical details and homebrewer hints. Although the EZ-Tuner is an advanced project, intended for experienced builders (the EZ-Tuner is EZ to use, not EZ to build!), we will show how it can be built as a stand-alone manual tuner. The manual version would be a good stopping point for those who lack the time or experience to tackle the full-blown automatic version, but who want a versatile, easy to adjust high power antenna tuner.

<u>The Heritage of the Ultimate Transmatch</u>: The quest for the "ideal" antenna tuner dates back to the early days of radio communication. The earliest tuners were often single-band breadboarded contraptions with link-coupled inductors intended for end-fed wire antennas or open-wire transmission lines. The mid-fifties saw the development of general purpose, multiband desktop tuners, the best known being the famous E.F. Johnson "Matchbox," today greatly prized by collectors and still considered a top performer.

The ARRL technical staff has a long history of advancing the state of the art of antenna tuners. A case in point is the "Ultimate Transmatch," designed by the late Lew McCoy, W1ICP, and introduced to QST readers in July, 1970. So-called because it could match the proverbial wet noodle, the Ultimate Transmatch was subsequently featured in ARRL Handbooks of the 1970's and over the years became a favorite of builders.

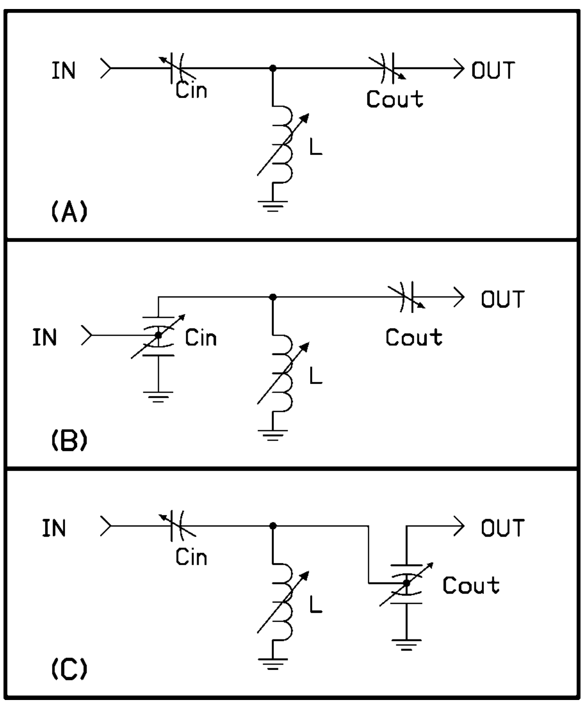

Figure 3— (a) basic T-network; (b) Ultimate Transmatch; (c) SPC tuner

The Ultimate Transmatch was a variation of the simple T-network (Figure 3b), with the transmitter r.f. fed to the mid-point of a split-stator capacitor. Subsequent experimentation showed that the split-stator capacitor was unneeded, and in later designs it was replaced by an ordinary single-stator capacitor.

In the 1980's, ARRL Handbooks rolled out another variation of the T-Match antenna tuner. Known as the "SPC" tuner (for series-parallel capacitance), this variation used a dual-section variable capacitor, one section of which was in series with the output, and the other in parallel with the inductor (Figure 3c). Initially, it seemed that the SPC tuner had great promise, notably good harmonic suppression and wide matching range, with modest-sized components. However, the SPC design was found to be excessively lossy, especially for low-Z loads, and despite its advantages it was abandoned after a few years.

The 1990's saw significant advances in antenna tuner design, with excellent theoretical treatments by Bill Sabin, W0IYH, and the development of sophisticated computer simulation programs by Dean Straw, N6BV, and others.[1] These programs made it possible for builders to estimate their tuner's matching range, internal losses, and peak r.f. voltages, before lifting a soldering iron. Furthermore, new diagnostic techniques also became available during the 90's, thanks primarily to Frank Witt, AI1H, and these techniques have allowed builders to evaluate the matching range and efficiency of their completed tuners.[2]

In spite of all this progress, the quest for the ideal antenna tuner continues. A recent QST review of several commercial, legal-limit antenna tuners[3] shows just how difficult it is to design an easy-to-use, low loss tuner with a wide matching range. More than any other piece of amateur equipment, antenna tuners inevitably reflect frustrating tradeoffs and compromises.

<u>The T-Network and the Quest for the Ideal Antenna Tuner:</u> Today, because of its impressive ability to match nearly any load, the basic T- network of Figure 3a remains the most popular choice for general purpose high-power antenna tuners.[4] However, as many of us have learned to our dismay, the T-network tuner can be finicky, and if improperly adjusted has an unfortunate tendency to self-destruct. All too often, melted components, scorched capacitor plates and vaporized switch contacts are the price one pays for the T-network's wide tuning range.

The T-network's greatest strength is also its greatest weakness. Simply put, the T-network is hard to tune because it is so versatile. Consider, for instance, the typical T-network antenna tuner, consisting of two variable capacitors, a roller inductor, and a VSWR or reflected power meter. (Often, a 4:1 toroidal transformer is also added to the input or output for matching balanced transmission lines.)

What makes this tuner difficult to adjust is that, for almost any load, there is a wide range of settings that yields a 1:1 VSWR. Unfortunately, many of these settings can result in excessive internal heating or damaging peak voltages. Because the VSWR or reflected power meter doesn't differentiate between "good" and "bad" settings, the first sign of impending disaster is often a flashover, a burning smell, or smoke. We know that somewhere, hidden in all those turns of the roller inductor, is just the right inductance needed for the perfect match. The rub is finding that one particular spot on the coil.

Roller tuners have other disadvantages. Cranking a turns counter dial is tedious and slows down band-changing, quality roller inductors don't come cheap, and the rolling contact is a source of heating and intermittent contact. Given their druthers, most amateurs would prefer the convenience of a tuner with a bandswitched fixed inductor…*if* they could be assured that they wouldn't pay too high a price in loss of efficiency and matching range.

The EZ-Tuner probably comes as close to satisfying this desire as is currently possible. The secret to its design lies the particular choices of inductances, selected out of the T-network's infinity of possibilities. So how do we make those choices?

<u>Simplifying the T-Network</u>: It is not generally known that the T-network's matching combinations fall into simple patterns. Figure 4 illustrates these patterns for the 160 meter amateur band for resistive loads varying between 3.125Ω and 800Ω.[5] These loads correspond to VSWRs ranging up to 16:1, and the curves assume losses typical for transmitting capacitors and inductors.

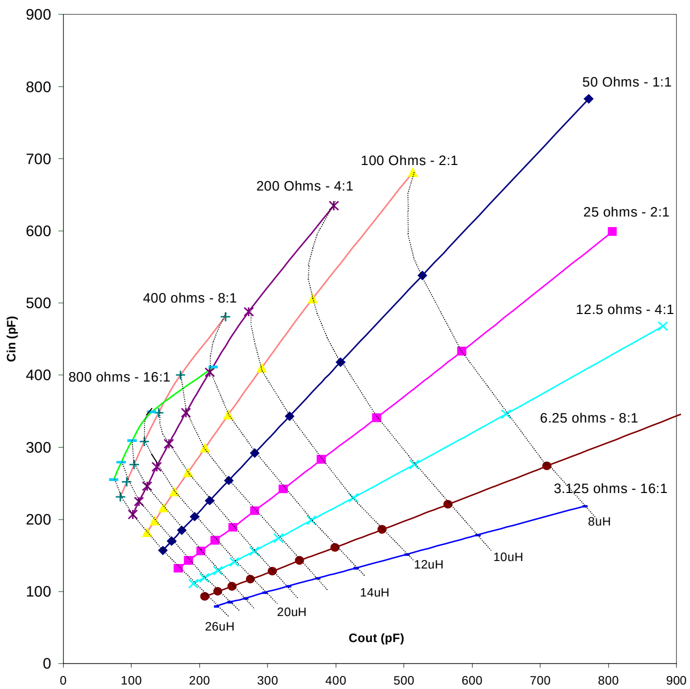

Figure 4—T-network constant VSWR curves for the 160 meter band and unbalanced resistive loads.

The axes of Figure 4 correspond to the values of Cin and Cout in the circuit of Figure 3a. Constant VSWR values (resistive load impedances) are shown as straight lines (except for some curvature at the highest impedances) which extrapolate to the origin. The 50Ω line corresponds to a 1:1 VSWR and has a slope of one (45 degrees). Also shown in the figure are curves of constant inductance spanning the range from 8-26 μH. These curves, in combination with the VSWR lines, show at a glance nearly the entire 1.8 MHz matching capability of the T-Network for resistive loads.[6]

To illustrate how to use the figure, suppose we have a 14 μH inductor and we want to know what capacitances will be required to match a low-impedance 6.25Ω load (8:1 VSWR) at 1.8 MHz. By noting where the 14 μH curve intersects the 6.25Ω line, we see that values of Cin =160 pF and Cout =400 pF are required to give a match. If we specify any one of the values of the three network components, the figure tells us the remaining two values.

But what if want to know the matching values on a different band? It turns out that Figure 4 can give the matching range at any frequency by simply multiplying the frequency and dividing the capacitances and inductances by the same factor. For instance, we can translate our 1.8 MHz example to 28.8 MHz by dividing the results by 16, since 28.8 MHz/1.8 MHz = 16. Thus we find that L = 14 μH /16 = 0.88 μH, Cin = 160 pF/16 = 10 pF, and Cout = 400 pF/16 = 25 pF. These values will match a 6.25Ω load at 28.8 MHz.

<u>Example: a 160 meter Antenna Tuner:</u> Now let us introduce some other design considerations with a practical example. Suppose we wish to build a 160 meter legal-limit antenna tuner that uses a fixed inductor and a bandswitch. We want to use as few taps as possible on the inductor and keep losses in the network components below about 25% (corresponding roughly to a 1 dB loss). We have two variable capacitors, each tuning 36-496 pF and rated at 3.5 kV.[7] Our goal is to find the optimum inductances for our tuner.

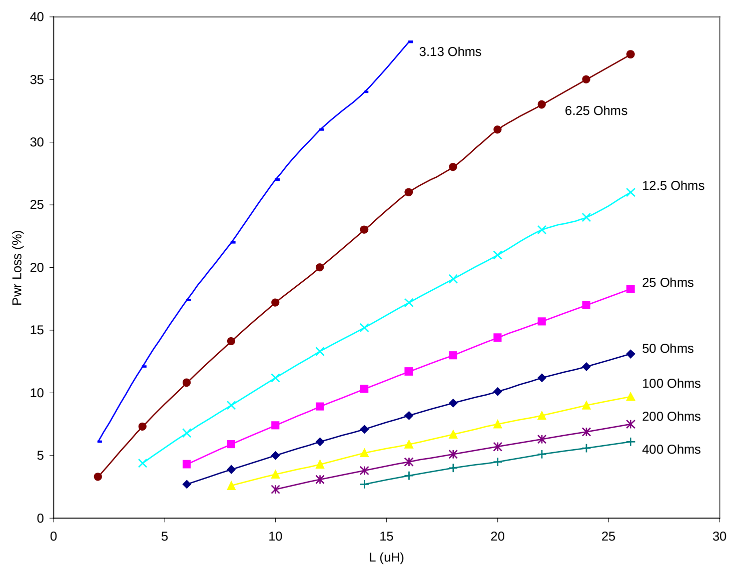

Figure 5—T-network power loss as a function of network inductance on the 160 meter band, for resistive unbalanced loads and typical component losses. As described in the text, the curves can be used on other amateur bands by scaling the inductances.

To begin, we draw horizontal lines corresponding to the minimum and maximum values of Cin on the vertical axis of Figure 4, and the corresponding (vertical) lines for Cout on the horizontal axis. These four lines intersect to form a rectangle, the interior of which defines the possible matching range of our hypothetical tuner. Since all of the inductance curves between 12 μH - 26 μH intersect all of the VSWR curves within this rectangle, we know that any inductance between 12 μH and 26 μH will provide a match to a 50Ω transmitter.

Before we choose one of these inductances, however, we need to remember that Figure 4 says nothing about network losses. For this information, we turn to Figure 5, which plots the power loss in a T-network as a function of inductance. The power loss is shown as the percentage of transmitter power dissipated as heat in the network components. Each curve in Figure 5 corresponds to a different load, and the curves span the full range of low and high resistances, up to a 16:1 VSWR mismatch. For example, the figure tells us that a T-network matching a 6.25Ω load with a 14 μH inductance at 1.80 MHz will absorb about 23% of the transmitter power.

Note that the power loss percentages depend on the properties of our actual inductor and capacitors. The curves of Figures 4 and 5 assume typical values for transmitting-type components: Q=200 for L, and Q= 1000 for Cin and Cout. (These are the default choices used in the simulation software TLA.exe, which was used to generate the data on which these curves are based.) Most of this power loss occurs in the inductor, so if our analysis shows excessive loss, we can always compensate by using heavier wire or copper tubing.

Note also that the 1.80 MHz curves of Figure 5 can be scaled with frequency, just as we did for the curves of Figure 4. For instance, by multiplying the frequency and dividing the inductance by 16, we see that that at 28.8 MHz, a network with a 0.88 uH inductance will also dissipate 23% when matching 6.25Ω.

As we inspect Figure 5, we see that for loads greater than 12.5Ω any inductance in the range of 12-26 μH will result in power loss well below 25%. However, low impedance loads below 12.5Ω can create significant problems. In fact, we need an inductance of no more than 10 μH to hold the power loss below our 25% goal. Unfortunately, we have already learned from Figure 4 that an inductance of 12 -26 μH is needed to provide a match. A 10 μH inductance will not let us match these small resistances, because our variable capacitors don't have enough maximum capacitance.

Fortunately, we can solve this quandary by using *two* values of inductance to cover the range, and by padding the output capacitor with a small fixed capacitor. Referring again to Figure 4, we see that if we pad the output capacitor with 100 pF, so that it tunes 136 pF - 592 pF, we can use a 10 μH inductance to match loads of 50Ω and below. We can use a second inductance of, say, 20 μH to match loads greater than 50Ω, and in both cases we will have held the power loss below our specified limit. We can cover the 160 meter band with only two positions on our inductor switch. Success!

Now we still haven't dealt with the problem of high peak voltages. Although it would not be difficult to draw a third figure that shows peak r.f voltages in the T-network, we needn't bother. Instead, we will use the rule of thumb that peak voltages will be below 3.5 kV at the legal limit of 1500W, so long as we design for network losses below about 25%.

<u>The EZ-Tuner Inductances:</u> The 160 meter example illustrates the point that good T-network design involves the interplay between matching range and power loss. By extending these procedures to other bands, it is not hard to design a switched T-network antenna tuner that covers all nine amateur bands from 1.8 –30 MHz. Because the majority of amateur bands are harmonically related, most inductance choices are used on several bands, thus minimizing the required number of switch contacts.

Figure 6—The major components of the EZ-Tuner's T-network. From left to right are the dual-section input capacitor, the inductor switch, the tapped inductors and the output capacitor.

The design objective for the EZ-tuner was to use no more than eleven inductance values to match up to a 16:1 VSWR on all nine h.f. bands, while holding power loss to about 1 dB. (There are eleven positions on a 30 degree-indexed rotary switch.)

Table 1 shows the target values. The EZ-Tuner generally meets or exceeds these design goals. In fact, on most bands, it can match a 32:1 VSWR, and it also satisfactorily tunes the new 60 meter amateur band recently proposed by the ARRL. The capacitance ranges assumed in the computations are 19-402 pF for Cin, and 36-496 pF for Cout.

EZ-Tuner Inductances		
Tap No.	Inductance (µH)	Amateur Bands (meters)
1	0.3	10,12,15,17
2	0.4	10,12,15,17,20
3	0.7	15,17,20,30
4	1.0	17,20,30,40
5	1.3	20,30,40
6	1.7	30,40
7	2.4	30,40
8	3.1	40,80
9	4.6	80
10	10.0	80,160
11	20.5	160

Table 1—Nominal inductance values for the EZ-tuner's switched T-network. Most inductances can be used on more than one amateur band.

Parts II and III will cover the EZ-Tuner's r.f. and controller circuitry, as well as the tuner's software, construction, operation, and performance. Stay tuned!

References

[1] *The program TL ("Transmission Line"), or its successors TLA ("Transmission Line – Advanced") and TLW (Transmission Line – Windows) are provided with recent editions of the ARRL Antenna Book.*

[2] *See "How to Evaluate your Antenna Tuner" (in two parts) by Frank Witt, AI1H, QST, April and May 1995. These articles can be downloaded from the ARRL website at http://www.arrl.com*

[3] *See QST Product Review column, March, 1997: "QST Compares: Four High-Power Antenna Tuners."*

[4] *For tuners dedicated to specific antennas, many amateurs swear by the simple L-network. However, the L-network cannot match both high and low-impedance loads without changing its configuration, and this shortcoming makes it unwieldy for a general purpose antenna tuner.*

[5] *The program TLA.exe, by Dean Straw N6BV, was used to generate the data for Figures 4 and 5.*

[6] *Note that Figure 4 does not cover the extreme matching limits of the T-network. Instead it shows the practical range of importance to antenna tuner designers. Note also that the capacitance and inductance curves could be relabeled as reactances, rather than picofarads and microhenries. Doing so would make the curves frequency- independent, but at a sacrifice in intuitiveness and useability.*

[7] *These are the ratings of the Cardwell-Johnson 153-6-1 capacitor.*