Save Your Tuner for Two Pence

By Tony Preedy, G3LNP *

GIVEN THE CHOICE of circuits suitable for HF antenna tuning, would you sensibly choose a T network?

The T network is renowned for suffering from low power transfer efficiency when compared with typical tuned transformer circuits. As usually configured, with a shunt inductor, it also fails to provide protection against the harmonics that inevitably accompany the output of our transmitters. Arguably this is not a function of an ASTU, but a function of the transmitter, although in the past when TV used lower frequencies many amateurs relied on their tuner for the last 'ounce' of harmonic suppression. The T network does offer the ability to transform, to the usual 50Ω required by the transmitter, a wide range of impedances over a wide range of frequencies with a minimum number of components. It is this flexibility that makes it a popular choice for commercial and home-built tuners, regardless of its failings.

I became aware of the limitations of my T network tuner when I first used it to transform the impedance of a non-resonant antenna, as seen via open wire feeder, to the 50Ω required by my linear amplifier on the 12m band. As no sample settings were offered for this band in the instruction book, I otherwise followed the manufacturer's instructions to the letter, tuning on low power for minimum VSWR before introducing the amplifier. When I put the key down I was dismayed to see smoke leaking out of the cabinet of the tuner. I cannot recall what settings I used, but suspect now that I had obtained a high loaded Q, as distinct from component Q, because of too small capacitor values.

Inspection revealed that the contact wheel on the variable inductor had become so hot that the lubricant had vaporised. Some time later I experienced arcing on this same component and found that the turns of wire were loose on the former. As both ends were still attached I concluded that the plastic former on which the coil was wound had shrunk.

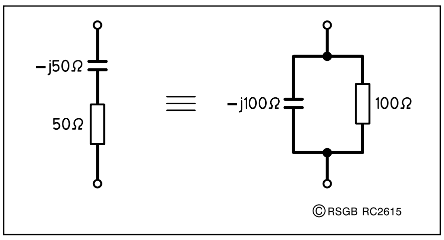


Fig 1: Equivalent parallel and series circuits.

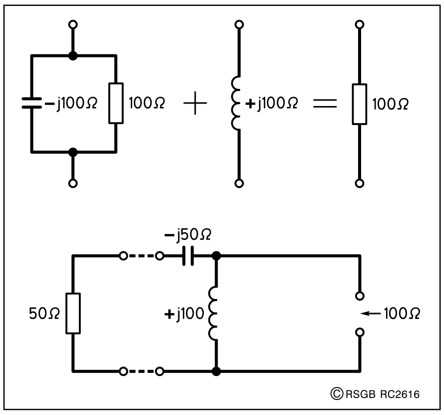


Fig 2: The L network used to transform 50Ω to 100Ω.

Presumably, like many plastics, it was hygroscopic and the heat generated by losses in the inductor had caused it to dry out! To restore the coil it was necessary to remove about 6 cm of wire.

I decided then that there was some discrepancy between my Watts and those used by the manufacturer when he rated this tuner at 3kW! Why did the integral power meter have a full-scale deflection of only 2kW? I concluded that the claimed power rating is most likely based on the system used by manufacturers of amateur antennas: *The peak DC input power to a typical transmitter's final stage having efficiency of 2/3 when using a two tone test signal.* Alternatively, perhaps the tuner will handle 2kW over a restricted range of impedances not specified by the manufacturer. If we take the power in an SSB speech signal to be 10dB below PEP, this equates to 200 real output Watts! This is also the average power in a 400 Watt CW signal having 50% duty cycle. This particular 3kW tuner may well have been suitable for 400 Watts CW or even RTTY, where the duty cycle is 100%, if more care had been taken when choosing initial settings for the controls. That is, settings which minimised the stress on the variable inductor. I was not surprised to learn that the manufacturer subsequently changed the variable inductor design after I bought my tuner.

These incidents caused me to investigate the requirements for the inductor in a T network tuner.

HOW THE 'T' WORKS.

TO UNDERSTAND the T network we must first appreciate how the L network functions.

The L network relies on a simple principle whereby complex impedances (those with resistance and reactance) in series circuits are represented as equivalent parallel circuits. A resistor of say 50Ω is without doubt the same in either parallel or series configuration, but a resistor of 50Ω in series with a reactance of 50Ω can also be represented by a resistor of 100Ω in parallel with a reactance of 100Ω (**Fig 1**).

If we connect a reactance of opposite sign, but still 100Ω, across this parallel circuit we obtain a pure resistance once more, but now of 100Ω, because the reactances cancel each other. The pair of series and parallel reactive components in this case form an L network with an impedance transformation ratio of 2 (**Fig 2**). Higher ratios are achieved simply by choosing a smaller value of series capacitance. Lower ratios require quite large values of capacitance which make the L network impracticable as a regular ASTU circuit, where we are often attempting to make quite small impedance changes, such as reducing VSWRs of 2 to unity.

POWER DISSIPATION

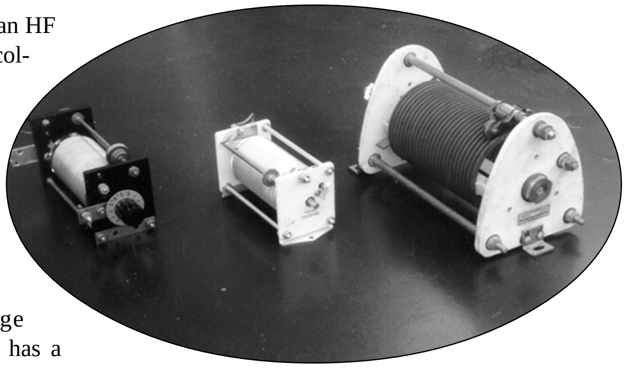
BECAUSE VARIABLE capacitors have much higher Q factors than inductors at HF, any losses, due to the inductor of the L network having a finite Q, can be represented by a parallel resistance equal to Q times the reactance of the inductor. By calculating the voltage across the inductor and hence across the loss resistance for a particular output power, we can obtain the power dissipated in the tuner. The calculations are straightforward. For example: an antenna impedance consists of 10Ω plus some series reactance, the transmitter requires a load of 50Ω, the required antenna power is 400 Watts and the tuner has an inductor with Q of 50. Provided the series capacitor has sufficient range of adjustment we can ignore any reactance component of the load: the power dissipated in this case works out to be only 16 Watts.

The simple L network as shown in Fig 2 has its limitations.

1. It can only transform impedances in which the resistance component is less than the resistance required by the transmitter.

2. For small impedance transformations, as would be the case when the load VSWR is low, the series capacitor values are unmanageably high.

**7 Station Road, Tring, Herts HP23 5NG.*



A selection of pre-1950 roller-coaster inductors.

To overcome these problems we have either to reverse the network and use large value capacitors, or use two L networks. In the latter case, one to bring the load resistance to a higher intermediate resistance, another to step the intermediate resistance down to the required transmitter resistance. Hence the T network!

The T network is therefore two L networks connected back to back. In the usual ASTU circuit the series arms are variable capacitors and the two shunt arms are then combined in a single variable inductor (**Fig 3**). As with the L network, almost all of the lost power is dissipated in the inductor, now with the losses of two inductors.

The build quality of the inductor is therefore the most significant factor when choosing or designing a T network ASTU. However, regardless of how good the inductor is, it can be degraded by too close proximity to lossy metalwork such as a steel screening box. These losses appear as additional series or parallel resistance at the inductor. The practical methods of minimising coupled losses are to place the inductor in the centre of a large cabinet, to use copper plating on the inside if using steel and/or to use aluminium construction (precautions which are all noticeably absent from many popular contemporary designs). I optimistically used a wooden cabinet in an ASTU built in the 1970s to minimise this problem.

VARIABLE INDUCTORS

DURING THE 1930s and 1940s a great deal of work apparently went into designing effective variable inductors suitable for HF transmitters. Of the various, sometimes ingenious, devices the two that proved most popular were the spiral and the cylindrical single layer solenoids, both using a contact wheel free to move along a rod to traverse the winding. The latter 'roller coaster' inductor is universally found in amateur radio equipment.

The photograph top right shows some representative pre-1950 roller coaster types. The smaller pair are by E F Johnson Company and the larger unit by Radio Development and Research Company. The small dark coloured inductor (1) consists of 37 turns of 18 AWG tin-plated copper wire on a 50mm diameter former of resin bonded fabric material. It has a maximum inductance of 30µH and came from the master oscillator of an HF Transmitter. The small light coloured 20µH inductor (2) designed for the output tank circuit of HF transmitters is wound with 14 AWG tinned copper wire, 27 turns on a 50mm diameter ceramic former with reduced pitch in the low inductance region. The large inductor (3) is of 50µH and has a coil of 25 turns of 6mm x 2 mm bare copper strip, edge wound on ceramic slats giving a diameter of 90mm. This robust item was salvaged from an RCA ET4336 500 Watt (real Watts!) marine transmitter. The initial Q of this item was disappointing until the inductor was dismantled and the parts treated to a session in the dishwasher. The main problem appeared to be old grease on the rotating contact surfaces. A later design, the inductor from the Heathkit SA2060 tuner (4) consists of 38 turns of 12 AWG wire on a 60mm diameter fibreglass former. The most recent (5) is from my MFJ 989C tuner and has 40µH inductance, 47 turns of 14 AWG tinned copper wire on a 50mm PTFE former.

Since taking the photographs I found another variable inductor (6). This consisted of 20 turns of silver plated copper strip, 6mm x 0.5 mm edge wound on a diameter of 90mm, with variable pitch and having a maximum inductance of 40µH. The coil was wound inside a skeleton former consisting of four fibreglass slats. The moving contact was uniquely inside the coil. This item came from a Gates broadcast transmitter.

I was intrigued to learn how the Q of the inductor in my tuner compared with the others, particularly those using pre-war materials.

Q, the ratio of inductive reactance to loss resistance, was obtained by measuring the equivalent parallel resistance with a Wayne Kerr B801B bridge. For inductors of good to moderate Q, the relationship between the parallel equivalent and series loss resistances is simply that the latter is Q squared times the former. It was not possible to measure the Q throughout the range of inductance at a single frequency because of both stray reactance effects and the limited measuring range of the bridge.

The measurements were therefore taken such that the section of inductor in circuit was representative of that which would be found, with typical load impedances at the measuring frequency, when the inductor was used in a T antenna system tuning network. The results are shown in **Fig 4**.

The Heath and MFJ inductors were first measured *in situ*, whilst the others were in the open. The general trend can be seen, whereby an initial high Q deteriorates as soon as turns are shorted and then it continues to fall gradually as minimum inductance is approached. As one might expect, the Q also degrades with frequency for a given inductance value, presumably because of both increased skin effect at the windings and increased dielectric loss in the former. A major factor at the higher measuring frequency of 29MHz is the former material. The Q of the last few percent of turns is most important, because this is the normal working region when tuning on the upper HF amateur bands.

The large RCA inductor (c) and the Johnson (b) with their ceramic insulation were very good at the lower frequencies. However, when I obtained the Gates unit (f) I discovered that it was even better, being outside my measuring capability at 4MHz. Although using less copper than the Radio Developments unit, it apparently benefitted from both the construction method and silver plating. The RCA unit might have also been best at higher frequencies, because of its thick conductor and skeleton former, but its high stray reactance prevented reliable measurements from being taken at 29MHz. On the higher frequencies the MFJ inductor was, despite my experience, less lossy than the pre-war inductors of comparable size.

The thicker wire and greater diameter of former used in the Heath inductor (d) gave disappointing results at first. However, this tuner had not been used for a decade so I decided to strip the inductor down and gently clean all the parts with a *Brillo* soap pad and warm water, before baking the coil in the oven for about 5 minutes. The moving parts were given a fine coat of contact lubricant before rebuilding. The reassembled inductor was unbelievably good, particularly at 29MHz when measured on the bench. The rapid improvement in Q below 3% of turns is due to the silver plated connection tapes for the bridge. These increasingly provided the most significant reactance when below one turn.

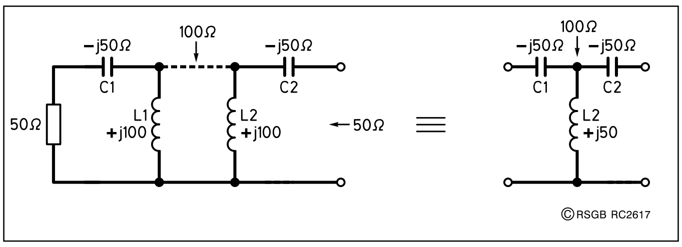


Fig 3: Derivation of the T network from two L networks (in this case transforming between a 50Ω load and source, via an intermediate resistance of 100Ω).

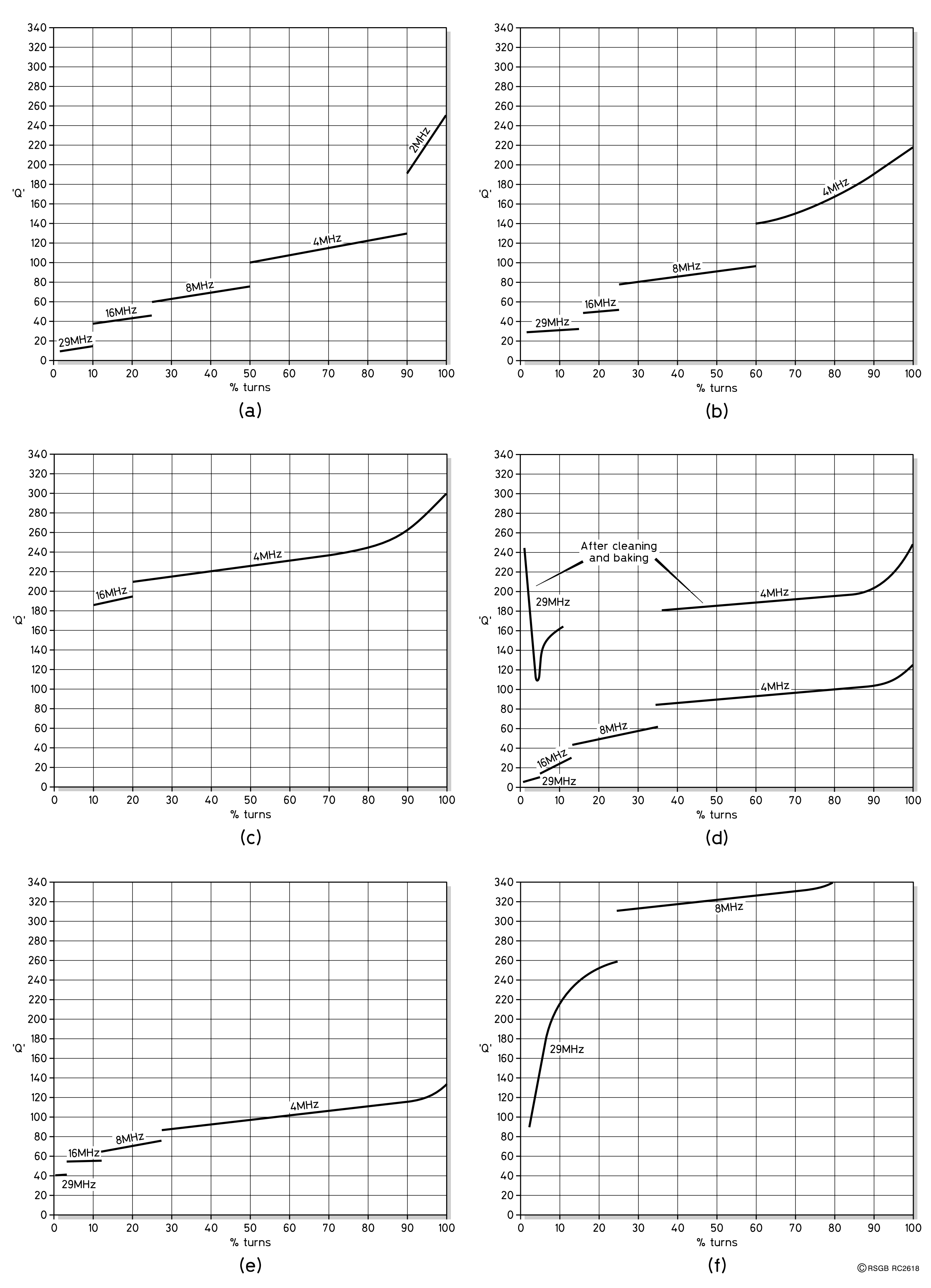


Fig 4: The Q of various variable inductors at a variety of frequencies.

COMPARING NETWORKS.

WE SAW EARLIER how much power was dissipated in the inductor of a typical L network. Now let's see how the T network compares: for example, let's make the intermediate resistance in a T network, as seen across the inductor, 200Ω. This is a value that can normally be achieved over most of the higher frequency range with component values in a typical T network ASTU. We therefore have an L network, C1 and L1, which transforms our 10Ω load to 200Ω.

The second half of the network, L2 and C2, transforms 200Ω to 50Ω. In this case the power dissipated in the loss resistance of the equivalent single inductor has increased to 49 Watts. To obtain 400 Watts in the load our transmitter must supply 449 Watts! Although quite a lot more power is lost than in the simple L network, one can argue that the difference in radiated power will never be noticed on the HF bands. This is probably true, but think of the life expectancy of the inductor in the ASTU and how this will be reduced by unnecessary heat dissipation.

Suppose that we inadvertently tuned the network to obtain a transformation with a much higher value of intermediate resistance such as 600Ω, as I might have done on 12m. In this case, assuming the Q of the coil remains at 50, the loss is 88 Watts! We need to supply 488 Watts, a significant amount of which is dissipated in the inductor, and we have no indication other than our sense of smell to warn us of this fact!

The same comparison between L and T networks can be made when the load impedance contains a high resistance, say 600Ω. Assuming nothing else has changed, the L network loss = 26.5 Watts. For the T network case, assuming an intermediate resistance of 1200Ω, the loss increases to 46 Watts.

REDUCING LOSSES

THE Q VALUE used in the numerical examples above is typical of that measured at 16MHz. At higher frequencies the Q is less and consequently the T network losses can be greater. Generally there is an optimum ratio of winding length to diameter that results in the best Q for a particular inductor. Typically this ratio, or form factor, is 1.5. Measured at maximum inductance the Q value always appears to be maximum, even though the form factor would normally indicate a better Q at intermediate values of inductance, if these could be achieved without shorted turns.

Most often we will be using only a small proportion of the inductor, with most of the turns shorted out. Although they are shorted, these turns are still coupled to the active turns. Therefore they still contribute losses. The unused turns could be left open to prevent the rapid loss of Q in the top 20% of turns, but then, as we progressively reduce

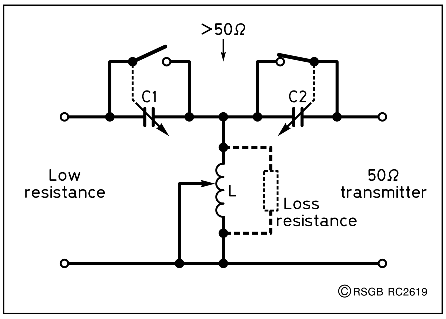


Fig 5: A T network adapted to function as an L network, by closing either switch. For a high resistance load, the switch states are reversed from those shown.

the number of active turns, we would couple a high voltage across the now greater number of unused turns with the possibility of both increased losses and voltage breakdown. If we could guarantee that more than half of the coil would always be in circuit it might be possible to leave the unused turns open circuited to achieve less loss.

Another approach might be to use a separate inductor for frequencies above say 10MHz, but both of these solutions would detract from the simplicity and flexibility of the T network.

Alternative techniques, more sophisticated than the roller coaster or spiral, are employed in some professional tuners where it is required to maintain the Q of the inductor throughout its range of adjustment. One method uses a conducting cylinder in which a thread has been cut which matches the pitch of the coil. The cylinder is screwed over the coil, thus enclosing and joining all the unused turns. Another removes all the unused turns, formed by flexible metal tape, from the inductor by transferring them to a storage drum where they cannot influence the working circuit.

Within the constraints of our roller coaster inductors we can minimise loss in the T network either by minimising the value of intermediate resistance or by optimising the Q of the inductor. We can do nothing to improve the latter except to keep the contact surfaces in a clean condition and generally keep the inductor free from contamination, whilst the former is very much under our control.

The unfortunate weakness that comes with the flexibility of the T network tuner has now been revealed! When we twiddle the controls for minimum VSWR we do not know what value of intermediate resistance we are achieving and if this resistance is not significantly less than the parallel aspect loss resistance we lose a lot of our valuable RF!

To avoid excessive dissipation it is obvious that we should aim for the lowest value of intermediate resistance consistent with obtaining unity VSWR at the transmitter. Unfortunately on the higher frequencies this condition can result in either insufficient turns to handle the voltage across the intermediate resistance, causing breakdown between turns, or excessive minimum inductance due to the residual inductance of the turn-shorting mechanism. To offset these tendencies we use more turns than are necessary for minimum dissipation. Some inductor designs like (2) and (6) increase the coil pitch, hence turn spacing, near minimum inductance to offset the first problem.

There will be instances, particularly on the lower frequencies, where the T network will only achieve the required transformation ratio with relatively high values of intermediate resistance. This is because the variable capacitors C1 and C2 are too small for efficient tuning at the lower frequencies. However, Q of the inductor is not such a problem on the lower bands where the voltage rating of the series capacitors tend to restrict the input power.

TUNING TECHNIQUE.

WHAT WE CAN show is that the lowest losses will occur when one of the capacitors C1 or C2 is at the highest value consistent with a correct transformation being achieved. This is the closest we can get to turning the network from a T to an L configuration with the adjustment range provided by the manufacturer. Under this condition we will normally have the greatest number of turns, across which the voltage is shared. From what we have seen above, and as you may already know, the minimum loss tuning technique for a T network ASTU is:

1. Start with both capacitors at maximum.
2. Then adjust the 'antenna' capacitor and inductor for minimum VSWR.
3. If the minimum VSWR is not unity, then progressively reduce the 'transmitter' capacitor and repeat the other adjustments.

CONVERTING THE ASTU CIRCUIT

WE HAVE SEEN that we can further reduce losses, when the load resistance is known to be less than the required resistance at the transmitter, by converting the network into an L network. The simple way to do this is to short out the 'transmitter' capacitor C2. This is easily but inelegantly achieved by bending the corner of one moving plate, so that at maximum capacitance the fixed and moving plates touch each other (**Fig 5**). The L network that we have thus created will not provide unity VSWR for the wide range of antenna impedances previously covered by the T network but for those impedances and higher frequencies, where there is sufficient range of capacitor adjustment, also the frequencies where T network losses are highest, it will have benefits. The same technique can be applied when the load resistance is higher than that required at the transmitter, by shorting out the plates of the 'antenna' capacitor C1.

A SIMPLE MODIFICATION

YOU MAY NOT be keen to spoil either a good variable capacitor or the resale value of your tuner by bending the plates. In this case you can follow my example and add a contact which is closed by a cam that is fixed to the shaft of the capacitor. If, like on most T network HF ASTU capacitors, the shaft is free to rotate 360 degrees it is only necessary to arrange that the contacts close, joining the fixed plates to the shaft, when the control knob is off the normal 180 degree tuning range (**Fig 6**).

The tuner will still work as it was intended within the calibrated scale. This simple modification will:

1. Reduce tuner losses.
2. Allow higher power on the higher frequencies, by reducing both the volts per turn and current in the inductor.
3. Reduce the number of variables.
4. Extend the upper frequency tuning limits for a given range of load impedances - because the inductor does not then have to act as two inductors in parallel.

You can apply this modification to most of the popular T network tuners that incorporate a variable inductor for two pennies – literally! The photograph bottom right shows a modified capacitor as used in the Heathkit SA2060 tuner. I also added the modification to my MFJ-989C tuner and no doubt other manufacturers' products can be similarly modified.

MECHANICAL DETAILS

A PAIR OF CAMS are formed, one for each capacitor, as shown in **Fig 7**, by first taking a copper disc approximately 25mm diameter and drilling in the centre a 6.5mm hole. I used old type copper penny coins for my cams. It is illegal to mutilate current coinage of the realm, and besides the modern coins are not made of copper. Old sofas are a good source of old pennies, incidentally.

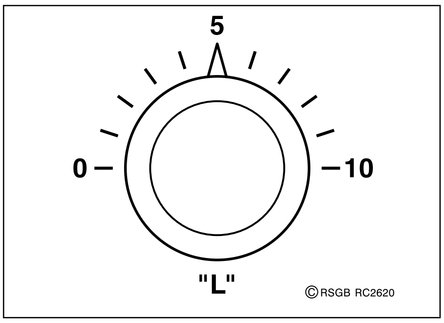


Fig 6: Control legend.

Over an arc of 270 degrees, the radius is reduced to 5mm using a hacksaw and file. A small vee shaped indent is made at the centre of the larger radius segment to locate the capacitor control. The corners of the cam are radiused with a fine file and the edge polished with fine abrasive paper.

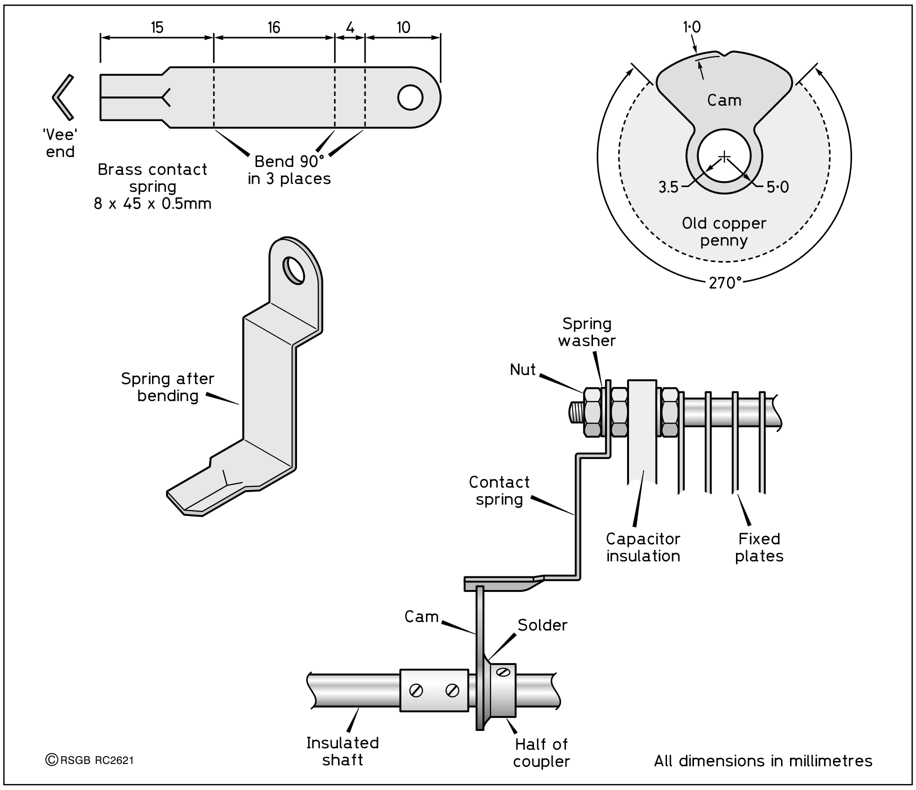
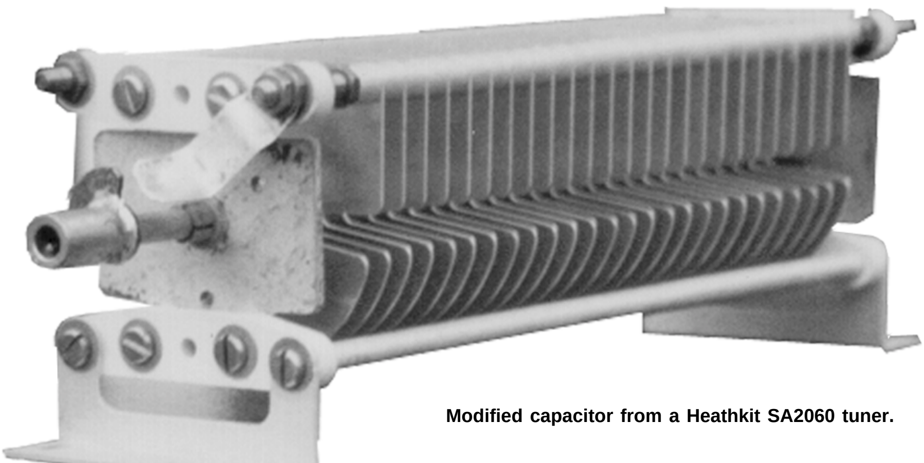


Fig 7: Mechanical details of the cam and contact, for shorting the capacitors in a T network ATU.

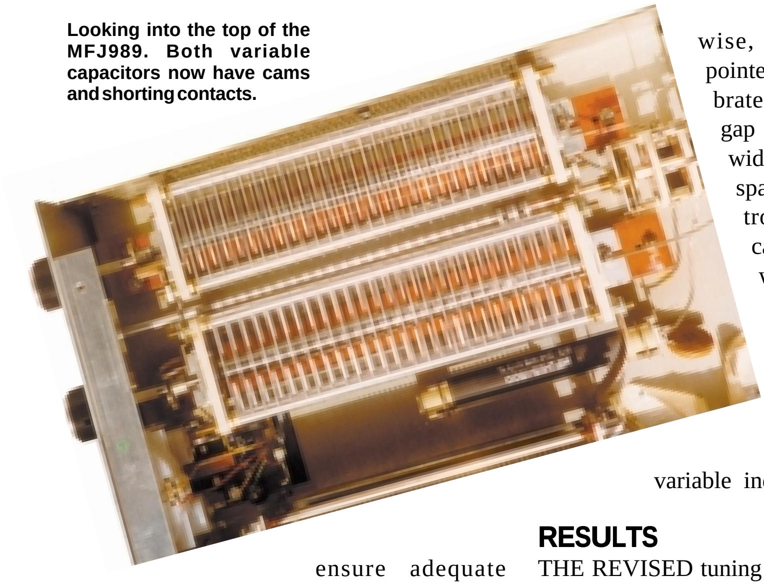
For A Heathkit SA2060 tuner, remove the shaft coupler from each capacitor by releasing the grub screws and pulling the knob and plastic shaft clear. Solder the cam to one end of the coupler. To ensure that the holes in the cam and coupler are coaxial it is best to check with the 6.5mm drill whilst soldering. If the coupler is made of steel it will be necessary to file away any plating material from the end before solder will adhere. After cooling, use the 6.5 mm drill bit to ream any excess solder from within the bore of the coupler.

Refit the coupler to the capacitor and insulating shafts with the cam closest to the capacitor. Form a contact from springy conducting metal, such as a heavy duty relay contact strip or a piece of bronze draft excluder, and drill one end to fit the threaded connection at the fixed plates of the capacitor. I used some sheet bronze about 0.3mm thick. Shape the contact end into a shallow vee, to mate with the indent on the cam. In the case of the MFJ tuner, which has no couplers, it was necessary to acquire one and saw it in half. Each half is then soldered to a cam. A single grub screw is adequate to lock the cam to the metal shaft.

The easiest way to access the capacitor shafts in the 989C is to remove the front panel. This involves undoing the three lower front panel retaining screws, releasing the meter, disconnecting the counter drive belt and taking off all four control knobs. The contact, identical to that used in the Heath tuner and shown in Fig 7, is attached to the fixed plates of the capacitors using the nuts that are used for the inter-capacitor connection. The crank in the spring is required to



Modified capacitor from a Heathkit SA2060 tuner.



Looking into the top of the MFJ989. Both variable capacitors now have cams and shorting contacts.

ensure adequate clearance between the spring and the grounded end bearing plate of the capacitor.

The cams should be mounted on the metal shaft of the capacitors of the 989C as shown in Fig 7 and the grub screws tightened such that the contacts engage firmly, with the vee of the spring in the notch of the cam, only when the capacitor control is pointing downwards and the plates are half meshed, ie off the calibrated scale on the front panel. Otherwise, when the control pointer is within the calibrated scale, the contact gap should be at least as wide as the capacitor plate spacing. With the control knob of any one capacitor in the downwards position the tuner is obviously in the L network mode. With both capacitors in this condition the tuner circuit is simply a shunt variable inductor.

RESULTS

THE REVISED tuning technique, for an unknown antenna condition, requires that you initially attempt to obtain minimum VSWR with first one and then the other capacitor in the L network mode. If this fails, then resort to the normal T configuration. I found this modification to be always advantageous on the 18MHz band and above. On 14MHz and below, where the inductor is less vulnerable, there was sometimes not sufficient capacitance available to reduce the VSWR to unity when using the L configuration.

Some typical results are included below, where I have tabulated the inductor counter readings for alternative T and L configurations whilst driving a nominally 50Ω antenna with VSWR too high for my radio to deliver full power without an ASTU. These show that there is now much more inductor in circuit when using the L configuration. Note that these results are for the MFJ 989C tuner, which has 2.7 counts per turn of the inductor:

MHz band	'T' (counter)	'L'
18	5	9
21	2.5	10
24	4	10
29	2.5	9

The corresponding capacitor settings were always higher for the L condition, indicating that the single working capacitor was also less stressed, ie it had less voltage, in this configuration. Antenna results with typical VSWRs of 3 to 4 were more haphazard but, in my case, it was possible to use the same L circuit, with the antenna capacitor shorted, for all bands from 14 to 29MHz. A useful advantage, particularly if retuning after QSYing within a band, is that of now only having two controls with which to fiddle. ♦

RadCom Helplines FOR MEMBERS

- Bill, G4ZDF, is looking for information and advice on interfacing the **Kenwood TS-870S** with a computer. G4ZDF, QTHR. Tel: 0115 933 3313.
- Douglas, G3KPO, is looking for an ex-RAF **R1082** receiver and **T1083** transmitter for inclusion in his wireless museum on the Isle of Wight. G3KPO, QTHR. Tel: 01983 567665.
- G3NHU is looking for a copy of the circuit diagram for the **Yaesu FT-70GH** transceiver. All expenses reimbursed. G3NHU, QTHR. Tel: 01493 721173.
- Douglas, G0UYC, is looking for a copy of the operating and service manuals for the **HP-419A** DC null voltmeter, plus the **Rhode & Schwarz USWV** Selektomat measuring receiver. All costs reimbursed. G0UYC, QTHR. Tel: 01362 688142.
- Bill, GM0KMG, is looking for the source for a **2N3858** transistor (or equivalent), to repair his Drake R4 VFO. GM0KMG, QTHR. Tel: 0141 562 4571.
- Colin, GM3WKZ, would like to hear from anyone who has information on **CAT software products**, such as automatic log keeping, for the **Yaesu FT-100**. GM3WKZ, QTHR. E-mail: crbayliss@aol.com