Designing ATUs Using a Spreadsheet

By John Robinson, G3MPO*

I AM ONE OF those who does not have a 'classical' trapped dipole, a beam or any other recognised antenna. Rather, I use a short non-resonant doublet fed with low-loss twin feeder and a 1:1 balun which, after carefull trimming of the feder lengths, allows me to work all HF bands. The feedpoint impedance always includes reactive elements and the resistance varies widely. No 70Ω pure resistance here! Without an ATU, I would be unable to transmit significant power on any band, but my transceiver with its commercial T match ATU and home-brew linear with its pi output appear happy enough, although the settings often seem a bit strange. Whilst delighted at overcoming the limitations of my QTH, I have been aware that, despite all seeming to be well, I could be a prime candidate for the sort of ATU problems and losses that the books hint about but fail to clarify how much, under what circumstances or what to do about it. After many months of gentle rumination, I decided to bite on the bullet and work out the electrical design formulae for the two most common matching devices - the T and Pi networks - and in that way, try to answer some of the questions that have been worrying me.

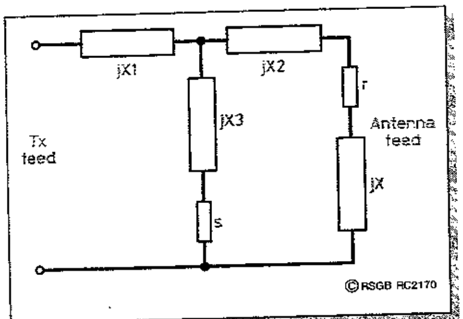

Fig 1: T match ATU. X1 is the variable 'tuning' capacitor reactance, X2 is the variable 'loading' capacitor reactance, X3 is the coil reactance, X is the antenna feedpoint reactance, r is the antenna feedpoint resistance, and s is the RF resistance of the coil.

For example:

- How big does an ATU inductance have to be in terms of coil diameter, wire thickness, wire spacing and inductance? Or, rather, how small can it be?
- What values of variable capacitor are required?
- Which is best - a T or pi match?
- What scale of losses can occur, under what circumstances, and what can you do about it?
- How does a reactive component in the antenna affect performance and design?

My end objective was to be able to design and size a network (ATU) to feed the sort of odd-ball antenna like mine that really does require one in order to work at all.

The result was two spreadsheet programmes that allow you to type in the characteristics of your transmitter and antenna system, and which then responds by calculating the values, characteristics and sizing of the ATU components required, together with the resulting ATU losses. The programme was written for Microsoft® Office and Works Excel spreadsheets, and instructions are given here on how to write your own version, even if you are a computer novice.

THE CALCULATIONS

CIRCUITS FOR T and pi networks are shown in **Fig 1** and **Fig 2** respectively. They differ from the normal simple 'L, C, R' representations only insofar as the RF resistance of the coil(s) and the reactance on the antenna feedpoint (X) have been added.

For those familiar with 'j' notation, the impedance of the antenna system feedpoint has been taken to be (r + jX), where r is the resistance and X is the reactance. (X is negative if the feedpoint reactance is capacitive and positive if it is inductive). Similarly, when both resistive and reactive elements are included, the impedance of the (ATU) coil becomes (s + jX3). (The coil resistance dissipates power which will show up as ATU losses). Finally, the variable capacitors have been assumed to have no resistive component and are therefore written simply as jX1 and jX2.

The mathematics turned out to be straightforward, if tedious, and I ended up quite quickly with equations which gave the following:-

(1) A useful rule which says that for the simple case of a non-reactive load and an inductance with zero resistance, there is a simple relationship for both types of ATU between the reactance of the inductance (X3) and the square root of the product of the PA output resistance, and the antenna feedpoint resistance (r).

Thus, in the case of the T network, (Fig 1), the reactance of the inductance must never be less than the square root of the product of the PA load and the antenna feedpoint resistance, and in the case of the pi network, (Fig 2), it must never be more.

For example, if your PA requires a load of 5000Ω and the lowest antenna feedpoint resistance you will have to deal with is 20Ω, then the inductive reactance of the pi network coil cannot be more than the square root of 5000 x 20, ie 316.2Ω. Similarly, for a T network with a PA load of 50W and a maximum antenna feedpoint resistance of 200Ω, then the inductive reactance cannot be less than the square root of 50 x 200, ie 100Ω.

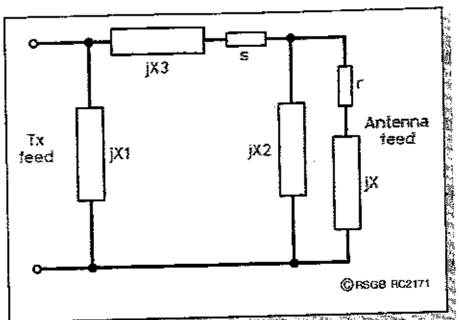

Fig 2: Pi match ATU. Component references are the same as Fig 1.

Once the load required by the transmitter and the minimum or maximum feedpoint resistance has been decided, this rule provides a clear mathematically justified starting point for the design by setting 'first shot' values for X3.

(2) With the coil reactance, diameter and wire gauge chosen, the turns required for the coil and its length follow automatically, together with an estimate of the consequential losses and, in turn, from these follow a consequential value for the (variable) 'loading' capacitor reactance (X2) for any value of loss resistance (s) and antenna feed point reactance (X).

(3) Finally, a value for the corresponding 'tuning' capacitor reactance (X1) emerges.

This was all very satisfactory, but the trouble was that the expressions were so lengthy that it was extremely time consuming and tedious to work out the results using a calculator and also virtually impossible to avoid casual mistakes. The result was that, invariably, different answers were obtained each time. It was then that I had the idea of putting the equations into a spreadsheet and letting the computer do the calculating. A major benefit was that if any parameter were changed, the consequent effect on all the other parameters could be seen in the blink of an eye and then, if necessary, the

*10 Greenways, Highcliffe, Christchurch, Dorset BH23 5AZ. E-mail: john.robinson5@virgin.net

AE11 3		
AF12 10	AG12 0.1539	AH12 =AE11*0.0251
AF13 12	AG13 0.1894	AH13 =AE11*0.0309
AF14 14	AG14 0.2463	AH14 =AE11*0.0402
AF15 16	AG15 0.3075	AH15 =AE11*0.0504
AF16 18	AG16 0.4099	AH16 =AE11*0.06
AF17 20	AG17 0.5470	AH17 =AE11*0.0893
AF18 22	AG18 0.7033	AH18 =AE11*0.115

Table 1: Put the following numbers and expressions into the cells numbered as shown.

results printed out. The spreadsheet had converted the mathematics into a very practical design tool.

THE SPREADSHEETS

THE VISIBLE PARTS of the spreadsheets are shown in **Fig 3**. They contain the columns you need to see and the ones you need to put values into. There are other columns, but these only hold intermediate calculations which are of no interest to us. There are two rows of values shown here for each type of ATU, but in fact there can be as many as you like, each perhaps set to a different situation. Or you can be satisfied with just one and set up different situations one after the other. The seven columns on the left are for typing in values representing the desired performance, whereas the eight columns on the right give 'consequential' values, ie they are the result of the computer's calculations.

In the first row, a typical linear pi output situation with a PA load of 5000Ω is shown, working at 2MHz. The value of the inductance reactance used has been set to 200Ω (at 2MHz) and the antenna load has been set to 20Ω resistance together with -100Ω (at 2MHz) of capacitive reactance. A coil of 50mm diameter made with 10SWG wire has been chosen. Note that in these spreadsheets and for all these calculations, single-spaced windings have been assumed.

	Freq MHz	PA load ohms	Ant load ohms	Inputs Ant react ohms	Coil diam mm	Wire swg	Coil react ohms	Coil induct mH	Turns per mm	Turns	Outputs Coil length mm	RF resist ohms	Tune capac pF	Load capac pF	Loss %
Pi	2	5000	20	-100	50	10	200	15.9	0.2	44.9	291.8	0.8	514.7	967.7	15.7
Pi	2	5000	20	60	50	10	200	15.9	0.2	44.9	291.8	0.8	470.6	3688.1	13.2

	Freq MHz	PA load ohms	Ant load ohms	Inputs Ant react ohms	Coil diam mm	Wire swg	Coil react ohms	Coil induct mH	Turns per mm	Turns	Outputs Coil length mm	RF resist ohms	Tune capac pF	Load capac pF	Loss %
T	2	50	20	-100	50	10	225	17.9	0.2	50.1	325.6	0.8	142.6	290.5	10.4
T	29	50	200	50	50	10	100	0.5	0.2	3.2	20.5	0.2	53.5	34.0	0.5

Fig 3: The spreadsheets, as they might appear on-screen.

On the right hand side, the spreadsheet has determined the resulting coil dimensions, together with the required input and output capacitances, and a prediction of 15.7% loss (in the ATU coil) has been made. By contrast, the second row shows a situation which is identical in all respects except for the fact that the antenna reactance has been changed to 60Ω inductive. Significantly, the required tuning and loading capacitances have changed substantially, to the extent that the loading capacitor is now so large that it is probably not viable. Note also that most of these inductances have turned out to be physically larger than would be acceptable.

LOSSES

YOU WILL probably be relieved to hear that I do not intend to bore you with pages of indigestible mathematics, but since attempts to deal with ATU losses quantitatively are rare, a word of justification and perhaps disclaimer is appropriate. It is traditional to talk in terms of loaded and unloaded Qs (notoriously difficult to measure) when discussing losses, but to an electronic engineer it is preferable to deal with tangible parameters such as resistance. My own experience in making coils (lossy and less lossy) is that providing air-spaced capacitors are used, you are not far out if you assume that the losses in an ATU are solely due to the resistance of the wire used to make the coil - 's' in Figs 1 and 2. The resistance of a length of wire is proportional to the length and inversely proportional to the cross-sectional area. In the case of DC currents, this area is simply the area of the wire cross section - the larger the gauge, the larger the area and the lower the resistance - but at RF the current becomes concentrated towards the wire surface - the so-called 'skin effect' - and the area through which the current flows is less than the actual area of conductor available and the resistance increases. The thickness of this 'skin' is inversely proportional to the square root of frequency, so the RF resistance of a straight length of wire is dependent on its length, gauge and frequency.

When wound into a coil, the RF resistance is increased several times, according to how closely the wire is wound turn to turn - the wider the turns are spaced, the lower the multiplying factor until the 'straight wire' value of 1 is reached. But as the spacing is increased, the length of wire required for a given inductance also increases, thereby increasing the 'straight wire' resistance, so in searching for a minimum resistance coil, a trade-off has to be made between the two effects. I have found that a good compromise is with turns spaced by one wire diameter - I call this 'single-spaced' - and in this configuration the multiplying factor over and above that of straight wire seems to be about 3.

In converting coil reactance, diameter and wire gauge to RF loss resistance, I have used the equations from G3BIK's article 'RF Coil Dimensions - The Easy Way' in *RadCom* December 1994, together with 'straight wire' RF resistance figures given in G6XN's book, *HF Antennas For All Locations*. Then I have applied my own empirical multiplying factor of three to determine the effective coil RF resistance. All this is included in the look-up table at AF12 to AH18 (see later). Thus, although the equations built in to the spreadsheet are (or should be) exact, the calculation of the resulting RF loss resistance is somewhat empirical and the accuracy of any parameters dependent on this cannot be taken as completely accurate. Fortunately, this will normally have little effect on any of the figures, other than the predicted loss, and even here I would expect the error to be no more than about 50% (which is still a big improvement on having no idea at all).

YOUR SPREADSHEET

FOR BOTH pi and T networks, to make your own spreadsheet follow the instructions given here using either Microsoft® Office or Works Excel. Remember to 'save' periodically, to avoid losing *all* your hard work by accident. Incidentally, to see columns which are off-screen to the right, click on the arrow at the bottom right hand corner.

Start with a clean (spread)sheet and set the font to Arial 10. Then use File/Page Setup/Margins to set left and right margins to 1.5 cm or thereabouts. Highlight the area bounded by cells AF12 and AH18 - (click on cell AF12 and 'drag' to cell AH18) - and click in the box just underneath the font name - it should say AF12 - and type Table (enter). This assumes that you are using Microsoft® Office. If you are using Works, see later. Highlight cells A8 to G8 inclusive then select Format/Column/Width/5/OK and with the cells still highlighted, select Format/Cells/Number/Number and set the decimal points to 0. Do the same with cells I8 toP8 and set the width to 7 and the decimal points to 1. Then highlight cell H8 and set the column width to 1. With the page now set up, type the entries into the cells as given in **Table 1** and **Table 2**. (Take care to type in the entries exactly as given, particularly the brackets). Use Symbol fonts for Greek characters or ignore them if you wish (μ is 'm' and Ω is 'W' in Windows '95 Symbol font).

A2	Pinetwork	D4	Inputs	L4	Outputs	X4	Intermediates
A5	Freq	B5	PA	C5	Ant	D5	Ant
E5	Coil	F5	Wire	G5	Coil	I5	Coil
J5	Turns	K5	Turns	L5	Coil	M5	RF
N5	Tune	O5	Load	P5	Loss	A6	MHz
B6	load	C6	load	D6	react	E6	diam
F6	swg	G6	react	I6	induct	J6	per
L6	length	M6	resist	N6	capac	O6	capac
P6	%	B7	ohms	C7	ohms	D7	ohms
E7	mm	G7	ohms	I7	µH	J7	mm
L7	mm	M7	ohms	N7	Pf	O7	Pf
A8	2	B8	5000	C8	20	D8	-100
E8	50	F8	10	G8	200		

Table 2: Then type the following texts into cells as shown.

Finally, the most error-prone part - the formulae, (**Table 3**). All entries are preceded by = and consist of cell addresses and brackets which are critical to the successful working of the spread sheet. Take your time and be very careful not to miss-type or omit anything. Don't worry if some of the cells begin to show strange entries, eg ########. This is because some large numbers are being generated and the column is not sufficiently wide to display them. This does not matter since you do not actually need to see these numbers, but should you want to, use Format/Column/Width/15/OK.

When all the entries have been made, columns I to P should show the values in the first row of Fig 3, and if any of the values in columns A to G are changed, then the values in columns I to P should automatically change correspondingly. If so, this shows that the spreadsheet is working and has been correctly filled in. If this is not the case, there must be a typing error in one or more of the cells. Check each one in turn carefully, by selecting the cell in question and then looking at the contents displayed in the box at the top of the sheet. To correct an error, click in the box and position the cursor at the point in the box where a change is required. Then use the keyboard and delete keys in the usual way, finishing with the usual 'enter'.

I8	=(G8/(2*3.142*A8))
J8	=VLOOKUP(F8,Table,2,TRUE)
K8	=((500*I8)/(J8*E8*E8))*(1+(SQRT(1+((J8 *J8*E8*E8*E8)/(500*I8)))))
L8	=K8/J8
S8	=VLOOKUP(F8,Table,3,TRUE)*SQRT(A8)
T8	=(3.142*E8*K8)/1000
M8	=S8*T8
R8	=C8*(B8-C8-2*M8)+M8*(B8-M8)-(G8+D8) *(G8+D8)
U8	=2*(D8*M8*(B8-M8)-(G8*C8*C8)-D8*G8* (G8+D8))
V8	=((C8*C8)+(D8*D8))*(M8*(B8-M8)- (G8*G8))
Z8	=(-U8-SQRT((U8*U8)-4*(R8*V8)))/(2*R8)
O8	=-1000000/(2*3.142*A8*Z8)
W8	=(C8*C8)+(Z8+D8)*(Z8+D8)
X8	=(C8*C8)+(D8*(Z8+D8))
Y8	=((Z8*Z8*C8)+(M8*W8))*((Z8*Z8*C8)+ (M8*W8))
AA8	=-(Y8/((W8*((Z8*X8)+G8*W8)))+ (Z8*X8/W8)+G8)
AB8	=M8*((C8*C8)+((Z8+D8)*(Z8+D8)))
AC8	=Z8*Z8*C8
N8	=-1000000/(2*3.142*A8*AA8)
P8	=100*AB8/(AB8+AC8)

Table 3: The formulae the spreadsheet uses to make its calculations for a pi network tuner.

For a T network spreadsheet, select a new, clean sheet. If Microsoft Office Excel is being used and a pi network sheet already exists, there is no need to enter and name the table extending from AF12 to AH18 again or AE11 - just select a new sheet within the existing file. Otherwise, fill in cells AE11 and AF12 to AH18 as before. Put the following numbers in cells A8 - G8 respectively: 2, 50, 20, -100, 50, 10, 225 and for the rest, use the Tables 2 and 3 with the following (**Table 4**) substitutions/additions:

With these A8 - G8 entries, the figures in cells I8 to P8 should match those in row three of Fig 3.

For either spreadsheet, when it appears to be working satisfactorily, highlight cells A8 - AC8 inclusive, and Edit/Copy them. Then click in cell A9 and Edit/Paste/enter. A new row (9) is created which should look identical to row 8 but is quite independent from it. It can be used to feed in different parameters, perhaps for comparison with row 8, and as many rows as you require can be created in this way.

Once you have the spreadsheet as you want it, put columns R to AH out of sight by highlighting cells R8 to AH8 and selecting Format/Columns/Hide, and then, to prevent any of the formulae being changed by accident, highlight all the cells you have put data into in columns A - G, click on Format/Cells/Protection and click on the box labelled 'locked' so that the tick disappears, (ie set them to 'not locked'). Click 'OK', and then use Tools/Protection/Protect sheet/OK. All cells not unlocked will now be protected from change (until you choose to 'unprotect' them using Tools/Protection/Unprotect sheet). Save the file for the last time.

For Microsoft Works, use the instructions above but observe the following where appropriate:

1. Do not highlight AF12 to AH18 or name this area.

2. When inserting text, (table 2), precede each entry with ".

3. For VLOOKUP(F8,Table,2,TRUE) substitute VLOOKUP(F8,AF$12:AH$18,1).

4. For VLOOKUP(F8,Table,3,TRUE) substitute VLOOKUP(F8,AF$12:AH$18,2).

5. Use different files for different ATUs - Works does not have multiple sheets.

6. To hide columns, consult Help/Hide columns in spreadsheets. Before doing so, take a copy of the spreadsheet - to 'unhide' columns in Works appears to be difficult if not impossible.

7. To protect cells, unlock columns A to G using Format/Protection/Unlock cells, then Format/Protection/Protect data.

RESULTS

FROM ITS beginnings as the reluctant refuge of a mathematician who found the sums too intractable to handle, the spreadsheet has turned out to be a very versatile and convenient way of getting results that can be used in practical situations. It has for example warned me that, with my particular antenna system, up to 47% of my power could be lost in my linear pi network unless I take care with the characteristics I choose for the coil. The loss of half an S point in my reports does not concern me, but the possibility of overheating and failure of my linear does. At the same time, it has shown that no such concerns apply to my exciter's T network.

More generally, it was surprising to find that a pi network was more lossy than the T. For example, using representative pi and T ATU values and for nine different antenna impedances for each of the nine HF bands, the T network showed losses of less than 10% for 92% of the cases whereas, for the pi network, the corresponding figure was 76%. Increasing the pi coil reactance led to smaller losses whereas with the T network, the opposite was the case. Antenna reactance affected the settings of pi networks quite badly and tended to increase losses, but T networks were relatively immune, with no extra losses. Finally, it became clear why pi network high frequency coils are made from thick wire and copper tubing. By contrast, it would appear that T networks can use quite thin wire for the higher bands.

As far as using these spreadsheets is concerned, remember that they churn out a bewildering deluge of information and, if you are not careful, you will quickly lose track of what you are trying to do and what determines what. The secret of getting the results you are looking for is to be clear on what you are trying to do before you start. For example, do you want to design a general purpose network or just resolve a particular difficulty that occurs in just one situation? Or are you trying to make good use of some components that have been languishing in the junk box for years? How important is size and how much loss are you prepared to tolerate? That decided, here are a few do's and don'ts.

1. Don't waste time on impracticable combi-

A2	T network
As above	I8, J8, K8, L8, M8, N8, S8 and T8
R8	=B8*(C8+M8)*(C8+M8)-M8*C8* (C8+M8)+G8*G8*(B8-C8)
U8	=SQRT(B8*B8*G8*G8-(B8-M8)*R8)
Z8	=-((B8*G8+U8)/(B8-M8))
O8	=-1000000/(2*3.142*A8*(Z8-D8))
P8	=AB8
V8	=2*M8*G8*(C8+M8)+((G8*G8) -(M8*M8))*(Z8+G8)
W8	=((C8+M8)*(C8+M8))+((Z8+G8)* (Z8+G8))
X8	=(C8*C8)+(Z8*Z8)
Y8	=(C8*((M8*M8)+(G8*G8)))+(M8* ((C8*C8)+(Z8*Z8)))
AA8	=(V8/W8)-G8
AB8	=100*M8*X8/Y8

Table 4: The formulae the spreadsheet uses to make its calculations for a T network tuner.

nations. For example, remember that the coil reactance rule says that, in the absence of coil resistance or antenna reactance, a pi coil reactance *must* be *less* than the square root of the product of the PA load and the antenna feed resistance. This means that, for example, for a pi network, for each band, it is the *smallest* antenna resistance that determines the coil. For a T network, the coil reactance *must* be *greater* than this square root and therefore it is the *largest* antenna resistance that sets the coil for a given band (antenna reactance and coil resistance do affect this rule but usually, only slightly).

2. Pi network coil reactances can only go down from this 'square root value' and T network coil reactances, only up. But as frequency goes up, capacitor reactances fall and since coil and capacitor reactances need to keep broadly in step, (and since we can usually accept changing coils from band to band but not capacitors), the capacitor sizes (pF) are going to be determined:

a) For T networks, at the *highest* band frequency (as frequency decreases, capacitor reactances will increase and, for T networks, we are allowed to increase coil reactance in step), and

b) For pi networks, at the *lowest* frequency, reducing coil reactance as necessary at the higher frequencies.

Check out the necessary capacitor sizes at these points early on, to make sure they are in the right ball park.

3. Don't try to design a pi network to work with a solid state PA; the capacitor sizes will be too large for comfort. Similarly, a T network working with a valve PA will show impossibly small capacitors.

4. If designing a general-purpose network, check performance over a range of antenna situations. Surprisingly, the required settings do not in general change in a predictable way between the antenna resistance extremes. The highest (or lowest) capacitor values usually occur in mid antenna resistance range.

5. For a general-purpose network, you will find that each requirement you impose will carry some sort of penalty elsewhere. So when you are close to finishing, look to see what might be causing the least attractive feature of your design. You may find it has its roots in some early decision which is not so important and which can be changed to give a better overall result. All requirements interact, and this only becomes really apparent in the final stages of design.

6. For a multi-band network, you will probably want to use the high frequency coils as a component of the low frequency ones, ie coils will be connected in series for all but the highest band. Make sure that the high frequency coil losses when working at low frequency are acceptable. This can be checked by designing a configuration working at low frequency using a coil with the chosen high frequency diameter and wire gauge. The coil may turn out impossibly long, but the predicted low frequency losses can then be scaled according to the ratio of the lengths of this and the real (high frequency) coil.

FINALLY

THE STANDARD 'fit' of today's computers includes a lot of stuff that most people rarely use but which potentially could be very useful to them. Spreadsheets are one example which, with their comprehensive library of functions, have a multitude of uses. If this is your first brush with spreadsheets, why not look a little deeper into what they can do? You may well find that hidden within them, they contain the means of helping you out in several other aspects of your hobbies and daily routine. Try Insert/Function and see what there is. Log book statistics and antenna modelling come immediately to mind, or simply use it as an alternative to a calculator when a large number of computations is required..

Last but not least, this article would not have been possible without the hours of checking, advice and encouragement contributed by Brian, G4WEY. I am most grateful to him for his help, always so generously given. ♦