Tuning Algorithm for Pi and Tee Antenna Tuners Using Only SWR Meter

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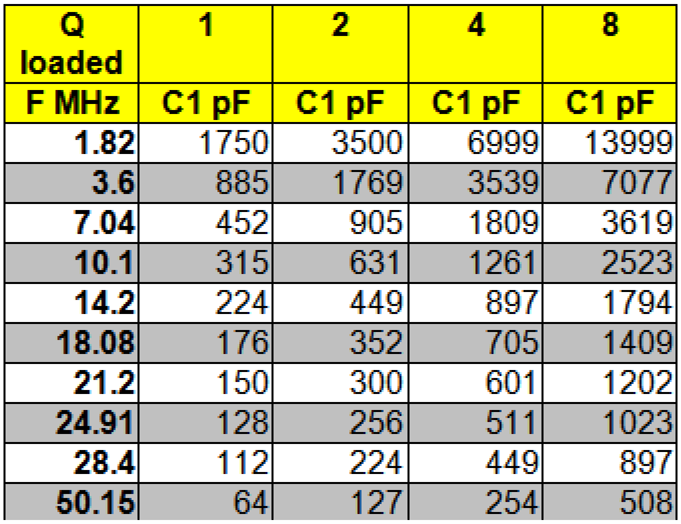
The problem is this: Simple *L*-match units have only a single tuning point for a given load *Z*. With successive approximations, by changing *L* and *C*, the desired minimum of SWR can be reached. Theoretically there is always a tuning point but the practical values of *L* and *C* limits it. These are the reason to use more complex matching units. With *Pi* and *Tee* units, there are multiple tuning points and it is desirable to find the best one - the one with the lowest losses in the tuner. The losses in these tuners are always larger that of the *L*-match unit, but we can come very close to these minimal losses with a proper algorithm. I will give one tuning algorithm that leads to finding this point.

1. Pi-match unit



Q loaded	1	2	4	8
F MHz	C1 pF	C1 pF	C1 pF	C1 pF
1.82	1750	3500	6999	13999
3.6	885	1769	3539	7077
7.04	452	905	1809	3619
10.1	315	631	1261	2523
14.2	224	449	897	1794
18.08	176	352	705	1409
21.2	150	300	601	1202
24.91	128	256	511	1023
28.4	112	224	449	897
50.15	64	127	254	508

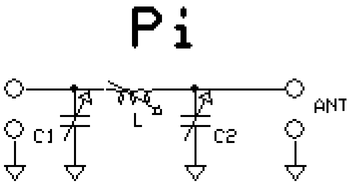


Table 1 *Pi-match initial values. Q is Q-factor of the Pi unit loaded with antenna impedance*

At the beginning we must set the first capacitor *C1* to the recommended value in ***Table 1*** from the column for *Q=1*. Then, with *C2* and the *L* , we tune for minimal SWR as is made for *L*-match unit. If a suitable setting is not found (SWR is high), we slightly <u>increase</u> the value of *C1* and repeat the procedure. The process is repeated until an acceptable SWR is obtained. If a suitable setting has been found for the first value of *C1 (Q=1)* , an attempt can be made further to reduce losses. Here, the opposite is done: we slightly reduce the value *C1* and repeat the matching procedure. A good setting, with the lowest losses, is the one for which the value of *C1* is minimal.

2. Tee-match unit

Q loaded	1	2	4	8
F MHz	**C1 pF**	**C1 pF**	**C1pF**	**C1 pF**
1.82	1750	875	437	219
3.6	885	442	221	111
7.04	452	226	113	57
10.1	315	158	79	39
14.2	224	112	56	28
18.08	176	88	44	22
21.2	150	75	38	19
24.91	128	64	32	16
28.4	112	56	28	14
50.15	64	32	16	8

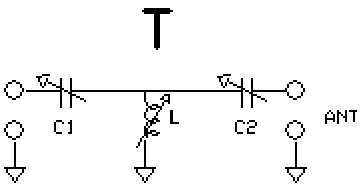


Table 2 *Tee-match initial values*

At the beginning we must set the first capacitor *C1* to the recommended value in ***Table 2*** from the column for *Q=1*. Then, with *C2* and the *L* , we tune for minimal SWR as is made for L-match unit. If a suitable setting is not found (SWR is high), we slightly decrease the value *C1* and repeat the procedure. The process is repeated until an acceptable SWR is obtained. If a suitable setting has been found for the first value of *C1 (Q=1)* , an attempt can be made further to reduce losses. Here, the opposite is done: we slightly increase the value *C1* and repeat the matching procedure. A good setting, with lower losses, is the one for which the value of *C1* is maximal.

Usually, the setting obtained with values of the first capacitor close to those given in the Tables 1 and 2 for *Q 1* to 2, has low losses, very little differing from those obtained by this additional optimization.

Note that the recommended values of *C1* at *Q=1* for *Pi* and *Tee* are the same. Settings obtained at higher Q-factors, according to the table, are with increased losses. Especially, when using high power, one should always look for an optimal setting. Let there be two cases of settings - with losses of 1% and 10%, respectively. The reduction of the signal at the correspondent is practically imperceptible. But at a power of 1000 watts, the heating of the elements will be 10 or 100 watts, respectively. If it is assumed that the main losses are in the coil, then in the second case it is possible to melt the soldering of the coil! - i.e. from a constructive point of view the difference is significant. For work with QRP it does not matter much. If the tuner is used to match a receiving antenna, larger operating Q-factors can be used, in order to use the selective properties of the tuner.

This tuning algorithm is very simple and always works. There is a very nice program by W9CF [1] This is a Java applet of a virtual *Tee* tuner. You set the impedance for matching and turn the knobs until you set *SWR* to 1. If you do not have an algorithm in your head, and you turn the knobs randomly, it will be quite difficult to find the best setting. The program plays tricks on you and when you press the “auto” button, it immediately finds the setting. Since, as we said, the setting is not unique, the applet has a criterion for minimum losses, which is minimal inductance. Using the just described algorithm and the criterion of maximum value of *C1*, the setting is found very quickly and it is always better or equal in losses to the optimal setting selected by this program.

Remark: The *Pi* unit requires larger capacitor values than the *Tee* unit (see tables), but there *C1* always operates at a low voltage (approx. 100 V pv at 100 W) and the hardware design is simplified. Usually the most serious limitations in tuner design are the breakdown voltages of the capacitors. Large *C1* values in *Pi* are not a problem in automatic tuners but for manual ones Tee circuit is preferred since *C2* and *C2* are with smaller values.

How *Tables 1* and *2* were calculated?

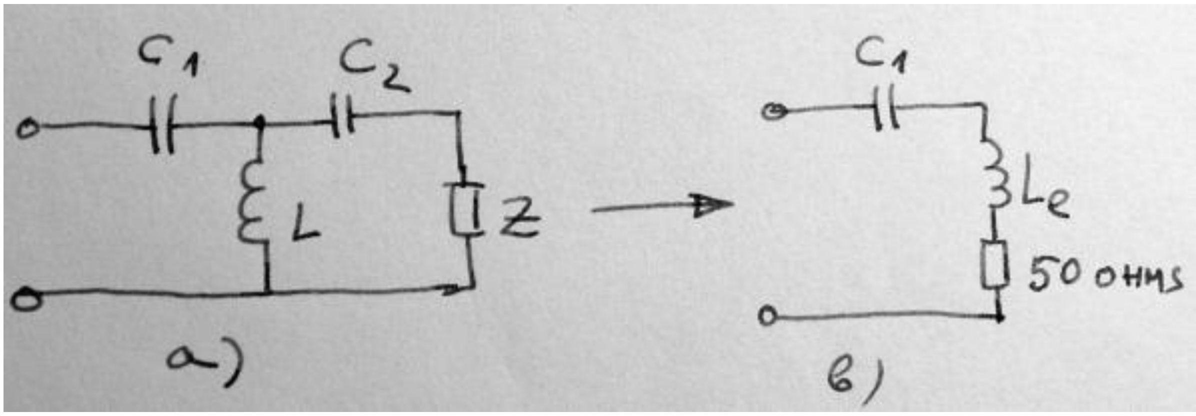


Fig.1

Let us have a *Tee* tuner loaded with some arbitrary impedance *Z*. In the tuned state, the circuit is transformed in all cases as shown in ***Fig. 1b.*** L_e is the transformed equivalent inductance (not to be confused with the inductance of the tuner in the tuned state). ***50*** ohms is the transformed equivalent resistance of antenna radiation resistance including all additional losses (feeder , tuner etc.) and ***f*** is the frequency. The tuning condition is at the serial resonance point:

$2\pi f L_e = 1/2\pi f C1$ (1)

When this condition is met, the equivalent resistive impedance at the tuner input will be 50 ohms. Here we can calculate the operating Q-factor of this equivalent circuit in tuned state:

$Q = X_{c1}/50$ (2)

Thus we can calculate *C1* values for different Q-factors at given frequency.

In *Pi* match case, in tuned state we have parallel *C1, L_e and R=50* ohms in parallel resonance and the Q-factor is calculated as:

$Q = 50/X_{C1}$ (3)

It is assumed that the lowest losses will be at a minimum operational *Q*-factor since in this case the currents in reactive elements of the matching circuit will be at minimum. In practice, it is good to work in the *Q* ranges from 1 to 2 if possible. As a rule, when the impedances to be matched are very different, the achievable minimum *Q*-factor is higher and the losses increase. It is obvious that the value of *C1* uniquely determines the operating *Q*-factor of the tuner.

An example can be given - the Kenwood AT120 tuner. It is based on the Pi-L circuit scheme where *C1* is fixed for every band, with the values almost coinciding with those in the *Table1* for the *Pi* circuit with *Q=1*.

There is a software that calculates the losses - the programs TLW *[2],* which is available as an application to every ARRL Antenna book. The W9CF *[1]* program also calculates the losses of a *Tee* tuner. I took the trouble to make a graph of the dependence of the operating *Q*-factor and the actual losses calculated with TLW (Loss%, ***Fig. 2***) for several different cases of impedances and losses. The relationship is almost linear.

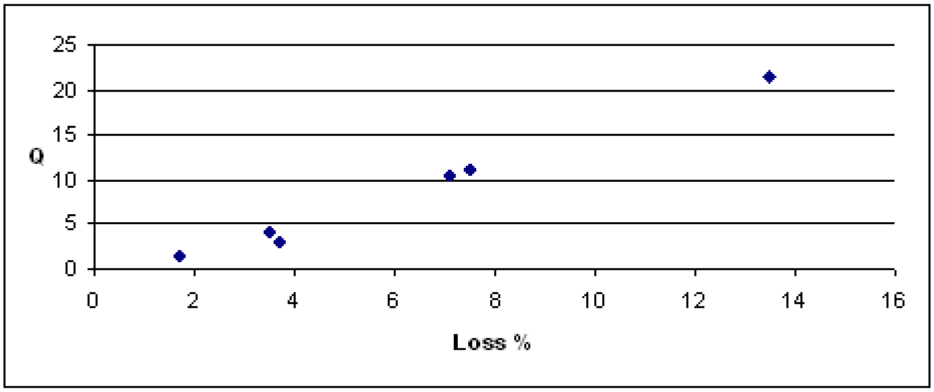


Fig.2 *Operational Q-factor versus losses calculated with TLW. The L and C Q-factors are Q_L =200 and Q_C=1000 (default values in the program), F=7 MHz.*

Note that the value of *C1* gives important information about the working Q-factor of the antenna tuner and we can estimate the probable losses.

Remark:

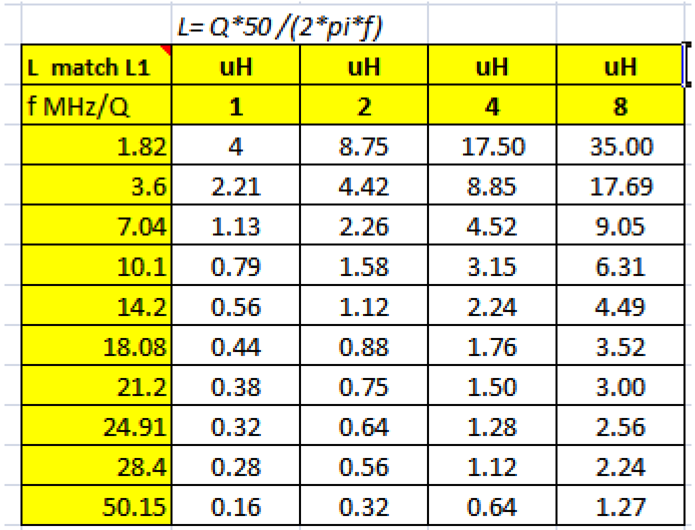
Real tuner losses depend on individual *Q*-factors of *L* and *C* used in the circuit. With ideal *L* & *C* there are no losses in the tuner. Do not mix the operating *Q* with *Q*-factors of *L* & *C* elements. Power losses are proportional to square of the current through the given element. Using low operational *Q*-factor means lower currents in the reactive elements. *Fig.2* tells us only that for fixed *Q*-factors of *L* and *C* elements the losses in the tuner are proportional to operating *Q*-factor. We cannot estimate actual losses if we do not know the real Q-factors of the reactive elements but in any case we can get a "sense" for probable loses. Here we do not take into account feeder losses due to high SWR.

Initial value of L-match unit

The same method can be applied to obtain the initial values of simple low-pass *L*-match unit (*Table 3*) . If we have unknown *Z*= *r*+*jx* it is always a question what must be the initial values from where to start the successive approximation procedure. For the case where *r* >50 *(Z)* the *C1* must be to TX side. In this case the values in Table 1 are valid. For *r*<50 the *C1* must be to antenna side and we must calculate this time the initial value of *L* in the similar manner:

$$Q = X_L/50 \qquad (4)$$

Here the *L* value determines the operating Q-factor*. Table 3* gives the initial values of *L* for this case. Unfortunately we do not know the *r* values of *Z* so we must try both cases in order to obtain matching.



*L= Q*50 /(2*pi*f)*

L match L1	**uH**	**uH**	**uH**	**uH**
f MHz/Q	**1**	**2**	**4**	**8**
1.82	4	8.75	17.50	35.00
3.6	2.21	4.42	8.85	17.69
7.04	1.13	2.26	4.52	9.05
10.1	0.79	1.58	3.15	6.31
14.2	0.56	1.12	2.24	4.49
18.08	0.44	0.88	1.76	3.52
21.2	0.38	0.75	1.50	3.00
24.91	0.32	0.64	1.28	2.56
28.4	0.28	0.56	1.12	2.24
50.15	0.16	0.32	0.64	1.27

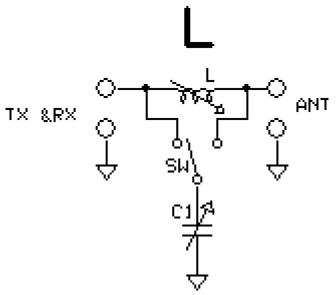


Table 3 *L-match initial values*

Examples

I can tune my 14 MHz delta loop (with 12 m open wire feeder) on 7 Mhz. The tuner is *L*-match and the *L* value in tuned position is 9 uH. *C1* is to the antenna side = 150 pF. From *Table 3* we can get the operating *Q*=8 and the probable losses are 7%. At 100 W there are 7 watts losses. The peak voltage at the tuner output is 750 V. Every 50 KHz we must tune again since the bandwidth is small due to the high operational Q-factor.

The same antenna tuned for 10 MHz band has C1 (now to TX side) value of 770 pF, *L*=3.5 uH. From *Table 1* we get *Q*=3 and losses of 3%. The peak voltage at the tuner output is now approximately 1200 V but my tuner is heavy duty - a modified automatic military tuner with 3500 V capacitors and at 100 W it does not have any problem. At 1000 W the losses are only 30 W but the voltage will be close to 4000 V and I am afraid to use such a power. A simple peak voltage detector at the tuner output is very useful device in order to obtain some additional information about the tuner stress which usually exists in highly reactive loads .

Links:

1. W9CF https://w9cf.github.io/tuner/tuner.html
2. https://www.arrl.org/files/file/Product%20Notes/Antenna%20Book/tlw.pdf
3. http://www.lz1aq.signacor.com/

This paper was first published in 2006 in Bulgarian language at http://www.lz1aq.signacor.com/docs/atuner/atuner.htm *and translated in English on March 2025 with some additions.*