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MATCHING WITH INDUCTIVE COUPLING

The following material was extracted from earlier editions. Figure and Equation sequence references are those from the 21st edition of *The ARRL Antenna Book*

Inductively coupled matching circuits are shown in basic form in **Fig 2**. R1 is the actual load resistance to which the power is to be delivered, and R2 is the resistance seen by the power source. The objective is to make it R2 = 50 Ω. L1 and C1 form a resonant circuit capable of being tuned to the operating frequency. The coupling between L1 and L2 is adjustable.

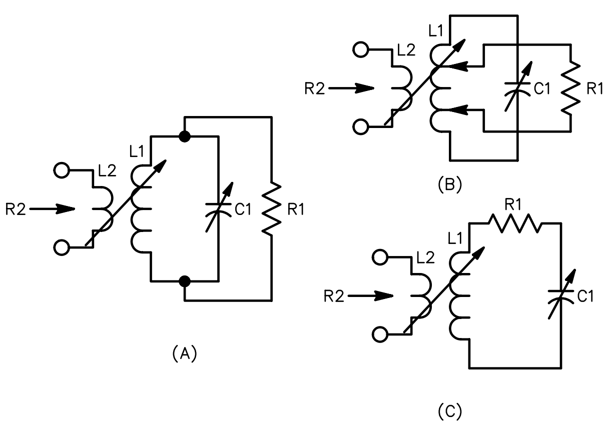

Fig 2—Circuit arrangements for inductively coupled impedance-matching circuit. A and B use a parallel-tuned coupling tank; B is equivalent to A when the taps are at the ends of L1. The series-tuned circuit at C is useful for very low values of load resistance, R1.

The circuit formed by C1, L1 and L2 is equivalent to a transformer having a primary-to-secondary impedance ratio adjustable over wide limits. The resistance coupled into L2 from L1 depends on the effective Q of the circuit L1-C1-R1, the reactance of L2 at the operating frequency, and the coefficient of coupling, k, between the two coils. The approximate relationship is (assuming C1 is properly tuned)

$$R2 = k^2 X_{L2} Q \qquad \text{(Eq 1)}$$

where X_{L2} is the reactance of L2 at the operating frequency. The value of L2 is optimum when X_{L2} = R2, in which case the desired value of R2 is obtained when

$$k = \frac{1}{\sqrt{Q}} \qquad \text{(Eq 2)}$$

This means that the desired value of R2 may be obtained by adjusting either the coupling, k, between the two coils, or by changing the Q of the circuit L1-C1-R1, or by doing both. If the coupling is fixed, as is often the case, Q must be adjusted to attain a match. Note that increasing the value of Q is equivalent to tightening the coupling, and vice versa.

If L2 does not have the optimum value, the match may still be obtained by adjusting k and Q, but one or the other—or both—must have a larger value than is needed when X_{L2} is equal to R2. In general, it is desirable to use as low a value of loaded Q as is practical. Low Q values mean that the circuit requires little or no readjustment when shifting frequency within a band (provided the antenna R1 does not vary appreciably with frequency). A low value of loaded Q also means that less loss occurs in the matching network itself.

Circuit Q

In Fig 2A, where a parallel-tuned network is used, Q_P is equal to

$$Q_P = \frac{R1}{X_{C1}} \qquad \text{(Eq 3)}$$

This assumes L1-C1 is tuned to the operating frequency. This circuit is suitable for comparatively high values of R1—from several hundred to several thousand ohms.

In Fig 2C, which is a series-tuned network, Q is equal to

$$Q_S = \frac{X_{C1}}{R1} \qquad \text{(Eq 4)}$$

Again, we assume that L1-C1 is tuned to the operating frequency. This circuit is suitable for low values of R1—from a few ohms up to a hundred or so ohms. In Fig 2B the Q depends on the placement of the taps on L1 as well as on the reactance of C1. This circuit is suitable for matching all values of R1 likely to be encountered in practice.

Note that to change Q in either Fig 2A or Fig 2C, it is necessary to change the reactance of C1. Since the circuit is tuned essentially to resonance at the operating frequency, this means that the L/C ratio must be varied in order to change Q. In Fig 2B a fixed L/C ratio may be used, since Q can be varied by changing the tap positions. The Q will increase as the taps are moved closer together, and will decrease as they are moved farther apart on L1.

Reactive Loads—Series and Parallel Coupling

More often than not, the load represented by the input impedance of the transmission line is reactive as well as resistive. In such a case the load cannot be represented by a simple resistance, such as R1 in Fig 2. As stated in Chapter 24, for any one frequency we have the option of considering the load to be a resistance in parallel with a reactance, or as a resistance in series with a reactance. In Fig 2, at A and B, it is convenient to use the parallel equivalent of the line input impedance. The series equivalent is more suitable for Fig 2C.

Thus, in **Fig 3A** and 3B the load might be represented by R1 in parallel with the capacitive reactance C, and in Fig 3C by R1 in series with a capacitive reactance C. In Fig 3A, the capacitance C is in parallel with C1 and so the total capacitance is the sum of the two. This is the effective capacitance that, with L1, tunes to the operating frequency. Obviously the setting of C1 will be at a lower value of capacitance with such a load than it would with a purely resistive load such as in Fig 2A.

In Fig 3B the capacitance of C also increases the total capacitance effective in tuning the circuit. However, in this case the increase in effective tuning capacitance depends on the positions of the taps. If the taps are close together the effect of C on the tuning is relatively small, but it increases as the taps are moved farther apart.

In Fig 3C, the capacitance C is in series with C1 and so the total capacitance is less than either. Hence the capacitance of C1 must be increased in order to resonate the circuit, as compared with the purely resistive load shown in Fig 2C.

If the reactive component of the load impedance is inductive, similar considerations apply. In such case an inductance would be substituted for the capacitance C shown in Fig 3. The effect in Fig 3A and 3B would be to decrease the effective inductance in the circuit, so C1 would require a larger value of capacitance in order to resonate the circuit at the operating frequency. In Fig 3C the effective inductance would be increased, thus making it necessary to set C1 at a lower value of capacitance for resonating the circuit.

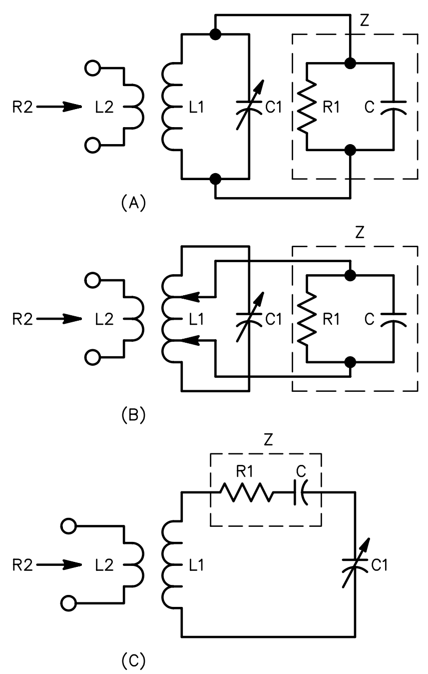

Fig 3—Line input impedances containing both resistance and reactance can be represented as shown enclosed in dashed lines, for capacitive reactance. If the reactance is inductive, a coil is substituted for the capacitance C.

Effect of Line Reactance on Circuit Q

The presence of reactance in the line input impedance presented to the matching network can affect the Q of the matching circuit. If the reactance is capacitive, the Q will not change if resonance can be maintained by adjustment of C1 without changing either the value of L1 or the position of the taps in Fig 3B (as compared with the Q when the load is purely resistive and has the same value of resistance, R1). If the load reactance is inductive, the L/C ratio changes because the effective inductance in the circuit is changed and, in the ordinary case, L1 is not adjustable. This increases the Q in all three circuits of Fig 3.

When the load has appreciable reactance, it is not always possible to adjust the circuit to resonance by readjusting C1, as compared with the setting it would have with a purely resistive load. Such a situation may occur when the load reactance is low compared with the resistance in the parallel-equivalent circuit, or when the reactance is high compared with the resistance in the series-equivalent circuit. The very considerable detuning of the circuit that results is often accompanied by an increase in Q, sometimes to values that lead to excessively high circulating currents in the circuit. This causes the efficiency to suffer. (Ordinarily the power loss in matching circuits of this type is inconsequential, if the loaded Q is below 10 and a good coil is used.) An unfavorable ratio of reactance to resistance in the input impedance of the line can exist if the SWR is high and the line length is near an odd multiple of $\lambda/8$ (45°).

Q of Line Input Impedance

The ratio between reactance and resistance in the equivalent input circuit—that is, the Q of the impedance at the line's input—is a function of line length and SWR. There is no specific value of this Q of which it can be said that lower values are satisfactory while higher values are not. In part, the maximum tolerable value depends on the tuning range available in the matching circuit. If the tuning range is restricted (as it will be if the variable capacitor has relatively low maximum capacitance), compensating for the line input reactance by absorbing it in the matching circuit—that is, by retuning C1 in Fig 3—may not be possible. Also, if the Q of the matching circuit is low, the effect of the line input reactance will be greater than it will when the matching-circuit Q is high.

As stated earlier, the optimum matching-circuit design is one in which the Q is low, that is, a low reactance-to-resistance ratio.

Compensating for Input Reactance

When the reactance/resistance ratio in the line input impedance is unfavorable, it is advisable to take special steps to compensate for it. This can be done as shown in **Fig 4**. Compensation consists of supplying external reactance of the same numerical value as the line reactance, but of the opposite kind. Thus in Fig 4A, where the line input impedance is represented by resistance and capacitance in parallel, an inductance L having the same numerical value of reactance as C can be connected across the line terminals to cancel out the line reactance. (This is actually the same thing as tuning the line to resonance at the operating frequency.) Since the parallel combination of L and C is equivalent to an extremely high resistance at resonance, the input impedance of the line becomes a pure resistance having essentially the same resistance as R1 alone.

The case of an inductive line impedance is shown in Fig 4B. In this case the external reactance required is capacitive, of the same numerical value as the reactance of L. Where the series equivalent of the line input impedance is used, the external reactance is connected in series, as shown at C and D in Fig 4.

In general, these methods are not needed unless the matching circuit has insufficient range of adjustment to provide compensation for the line reactance as described earlier, or when such a large readjustment is required that the matching-circuit Q becomes undesirably high. The latter condition usually is accompanied by heating of the coil used in the matching network.

Methods for Variable Coupling

The coupling between L1 and L2, Figs 2 and 3, preferably should be adjustable. If the coupling is fixed, such as with a fixed-position link, the placement of the taps on L1 for proper matching becomes rather critical. The additional matching adjustment afforded by adjustable coupling between the coils facilitates the matching procedure considerably. L2 should be coupled to the center of L1 for the sake of maintaining balance, since the circuit is used with balanced lines.

If adjustable inductive coupling such as a *swinging link* is not feasible for mechanical reasons, an alternative is to use a variable capacitor in series with L2. This is shown in **Fig 5**. Varying C2 changes the total reactance of the circuit formed by L2-C2, with much the same effect as varying the actual mutual inductance between L1 and

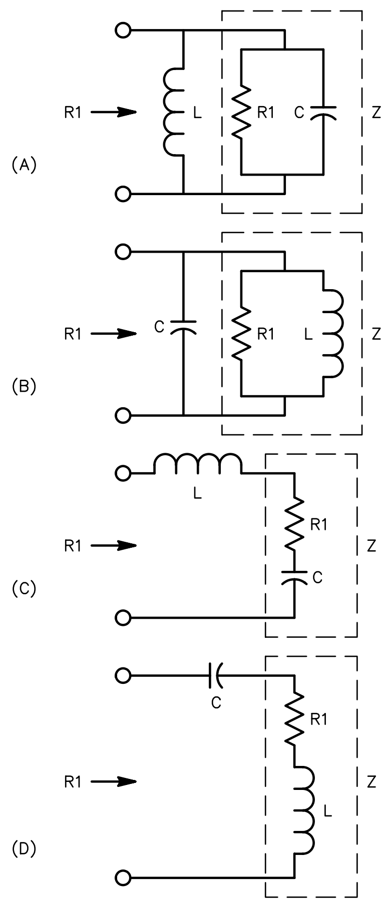

Fig 4—Compensating for reactance present in the line input impedance.

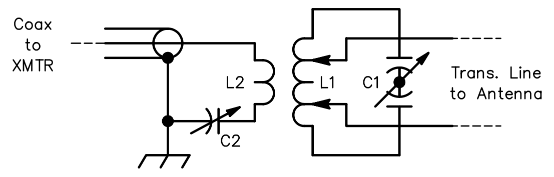

Fig 5—Using a variable capacitance, C2, as an alternative to variable mutual inductance between L1 and L2.

L2. The capacitance of C2 should resonate with L2 at the lowest frequency in the band of operation. This calls for a fairly large value of capacitance at low frequencies (about 1000 pF at 3.5 MHz for 50-Ω line) if the reactance of L2 is equal to the line Z_0. To utilize a capacitor of more convenient size—maximum capacitance of perhaps 250 to 300 pF—a value of inductance may be used for L2 that will resonate at the lowest frequency with the maximum capacitance available.

On the higher frequency bands the problem of variable capacitors does not arise since a reactance of 50 to 75 Ω is within the range of conventional components.

Circuit Balance

Fig 5 shows C1 as a balanced or split-stator capacitor. This type of capacitor is desirable in a practical matching circuit to be used with a balanced line, since the two sections are symmetrical. The rotor assembly of the balanced capacitor may be grounded, if desired, or it may be left *floating* and the center of L1 may be grounded; or both may float. Which method to use depends on considerations discussed later in connection with antenna currents on transmission lines. As an alternative to using a split-stator type of capacitor, a single-section capacitor may be used.

Measurement of Line Input Current

The RF ammeters shown in **Fig 6** are not essential to the adjustment procedure but they, or some other form of output indicator, are useful accessories. In most cases the circuit adjustments that lead to a match as shown by the SWR indicator will also result in the most efficient power transfer to the transmission line. However, it is possible that a good match will be accompanied by excessive loss in the matching circuit. This is unlikely to happen if the steps described for obtaining a low Q are taken. If the settings are highly critical or it is impossible to obtain a match, the use of additional reactance compensation as described earlier is indicated.

RF ammeters are useful for showing the comparative output obtained with various matching-network settings, and also for showing the improvement in output resulting from the use of reactance compensation when it seems to be required. Providing no basic circuit changes (such as grounding or ungrounding some part of the matching circuit) are made during such comparisons, the current shown by the ammeters will increase whenever the power put into the line is increased. Thus, the highest reading indicates the greatest transfer efficiency, assuming that the power input to the transmitter is kept constant.

Two ammeters, one in each line conductor, are shown in Fig 6. The use of two instruments gives a check on the line balance, since the currents should be the same. However, a single meter can be switched from one conductor to the other. If only one instrument is used, it is preferably left out of the circuit except when adjustments are being made, since it will add capacitance to the side in which it is inserted and thus cause some unbalance. This is particularly important when the instrument is mounted on a metal panel.

Since the resistive component of the input impedance of a line operating with an appreciable SWR is seldom known accurately (and since the impedance varies with frequency), the RF current is of little value as a check on the exact power input to such a line. However, it shows in a relative way the efficiency of the system as a whole. The set of coupling adjustments that results in the largest line current with the least final-amplifier input power is the most desirable—and most efficient. Just remember that the amount of current into a multiband wire may vary dramatically from one frequency band to the next, since the impedance at the input of the line varies greatly. See Chapter 2.

For adjustment purposes, it is possible to substitute small flashlight lamps, shunted across a few inches of the line wires, for the RF ammeters. Their relative brightness shows when the current increases or decreases. They have the advantage of being inexpensive and of such small physical size that they do not unbalance the circuit. Another method to measure RF current is to use a toroidal core with a single-turn primary. See the section at the end of Chapter 6 on "lowfer" antenna techniques.

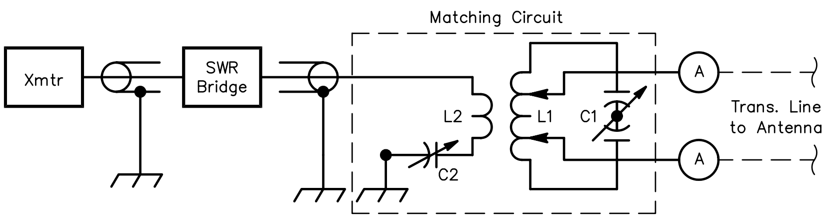

Fig 6—Adjustment setup using SWR indicator. A — RF ammeter (see text).