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Proposal For The Construction Of An Antenna Impedance Matching Unit Giving An Optimized Match

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Table of Contents

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I. Introduction

During the past year the [redacted] 25X1
[redacted] has been engaged in the development of an automatically tuned transmitter operating in conjunction with an automatic antenna impedance matching network. The problems associated with the design of a suitable antenna matching network are considerable. Although the requirement for automatic adjustment adds circuit complexity, the major difficulties arise in the design of the matching network itself regardless of whether it is for manual or automatic adjustment. 25X1

The transmitter which is being developed during the present program will match to the range of antenna impedances agreed upon with the Contracting Agency. However, it is apparent that, using physically realizable components, the power transfer efficiency of a network even under matched conditions can still be quite low. This proposal describes a method whereby the consequences of the losses inherent in any practical reactances may be largely avoided. The system requires the adjustment of three variables, which in a manual system, would make matching an extremely laborious process. However, with automatic adjustment, a reasonable amount of control circuitry would enable an optimum matched condition to be achieved. By an optimum matched condition is meant that state of adjustment at which the antenna is matched to the transmitter in such a manner that the effects of the finite values of Q associated with the reactances are reduced to a minimum.

The proposed equipment would consist of an automatic impedance matching unit suitable for use with a low power transmitter having a specified output impedance. The unit would be provided with input, output and 12 v. dc power supply terminals, the necessary potentials being derived from a self contained converter.

It is appreciated that physical size is of extreme importance. Efforts will consequently be made to keep the dimensions to a minimum. However, the size of the individual components from which the unit will be built is a function of the amount of effort to be expended on their development. At the present state of the art, electrically variable reactances for operation at power levels of 10 watts are not available. It will consequently be necessary to use motor driven components. With sufficient effort variable reactances having very little mechanical friction could be developed. These, in turn, would permit operation from smaller motors than are currently available. However, since a major program of motor and component development is not being proposed, the design of the antenna matching network will have to rely on components which are available or may be adapted for this application. These items impose a rigorous limitation on the degree to which the equipment may be miniaturized. At the present time a volume of approximately 170 cubic inches is visualized.

II. Statement Of The Problem

In order to transfer RF energy from a transmitter to an antenna in an efficient manner it is usually desirable to place an impedance transformation network between them. The purpose of the network is to ensure that the transmitter always sees a load impedance which is the same as its own internal impedance. With ideal components in the matching network maximum power will be transferred to the antenna with such an arrangement. In any physically realizable system, components which are less than ideal have to be used. This is a particularly severe handicap in the case of inductances, where a Q of 200 is considered to be very good.

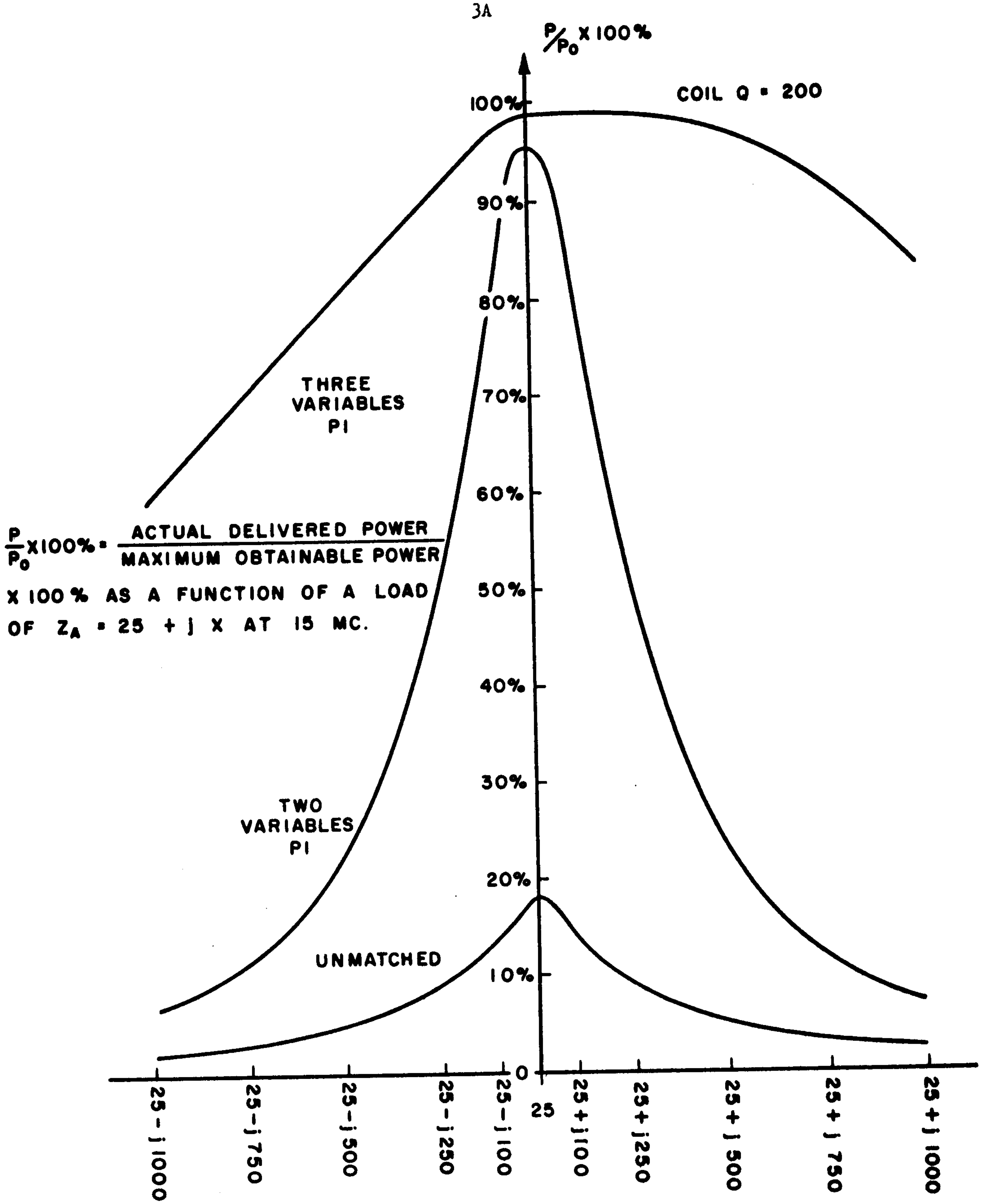
As an indication of the extent to which the finite losses in the components of a matching network become significant, the middle curve in Figure 1 shows a plot of the percentage of the available power from a transmitter which is actually transferred to the antenna assuming a two variable π matching network with a coil Q of 200 for different antenna reactances. The bottom curve in this figure shows the amount of RF energy fed into the antenna if no matching network is used. Figure 2 shows plots of power transferred to the antenna, for different values of resistive antenna, in the unmatched and two variable matched case, again with a coil of 200.

The circuit on which the calculations for Figures 1 and 2 are based is shown in Figure 3. The following assumptions are made:

(a) Coil Q = 200

(b) Capacitor Q's = ∞ (Not true but a reasonable assumption.)

(c) The variable elements are adjusted for each antenna to present



P/Po X 100%
COIL Q = 200
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0
THREE VARIABLES PI
TWO VARIABLES PI
UNMATCHED
P/Po X100% = ACTUAL DELIVERED POWER / MAXIMUM OBTAINABLE POWER
X 100 % AS A FUNCTION OF A LOAD
OF ZA = 25 + j X AT 15 MC.
25 - j 1000
25 - j 750
25 - j 500
25 - j 250
25 - j 100
25
25 + j 100
25 + j 250
25 + j 500
25 + j 750
25 + j 1000

FIGURE 1

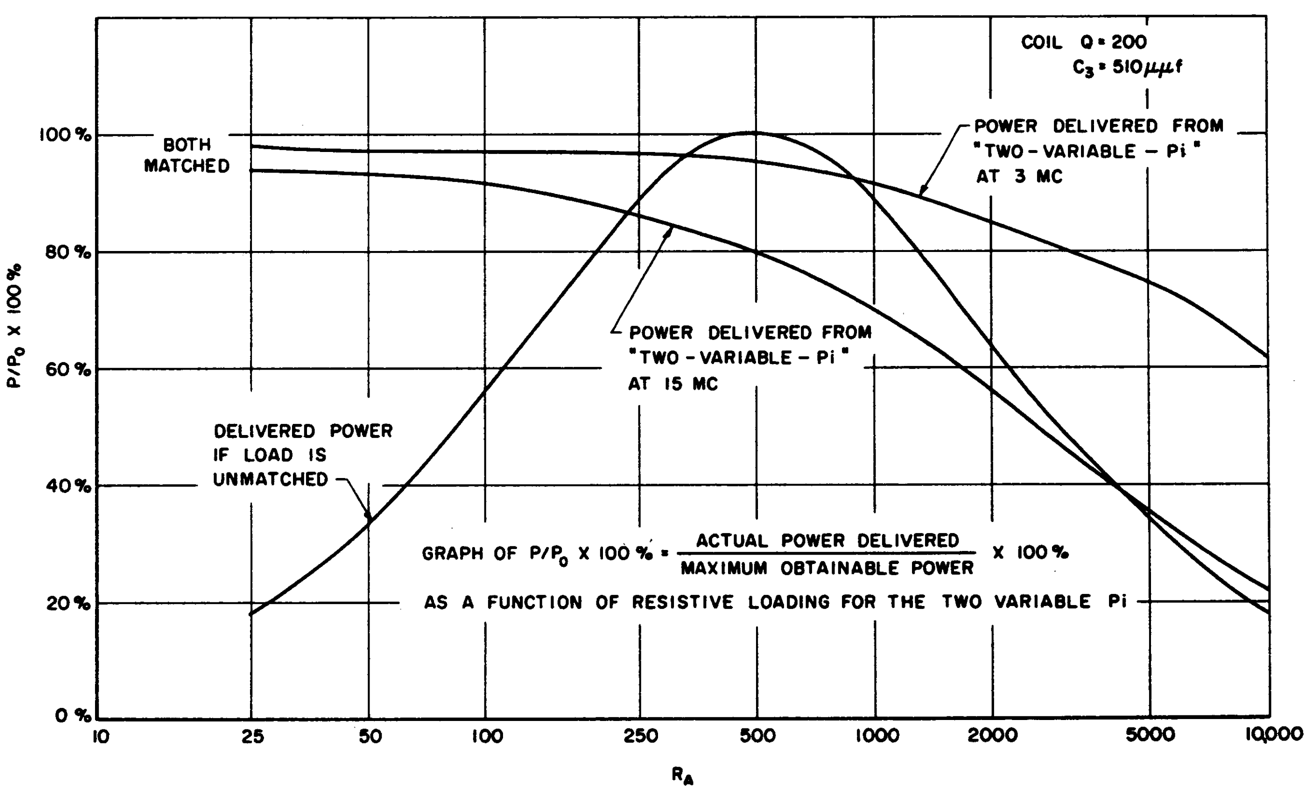

COIL Q = 200
C_3 = 510 μμf
POWER DELIVERED FROM "TWO-VARIABLE – Pi" AT 3 MC
BOTH MATCHED
POWER DELIVERED FROM "TWO-VARIABLE – Pi" AT 15 MC
DELIVERED POWER IF LOAD IS UNMATCHED
GRAPH OF $P/P_0 \times 100\% = \frac{\text{ACTUAL POWER DELIVERED}}{\text{MAXIMUM OBTAINABLE POWER}} \times 100\%$
AS A FUNCTION OF RESISTIVE LOADING FOR THE TWO VARIABLE Pi
$P/P_0 \times 100\%$
100 %
80 %
60 %
40 %
20 %
0 %
10
25
50
100
250
500
1000
2000
5000
10,000
R_A

FIGURE 2

3B

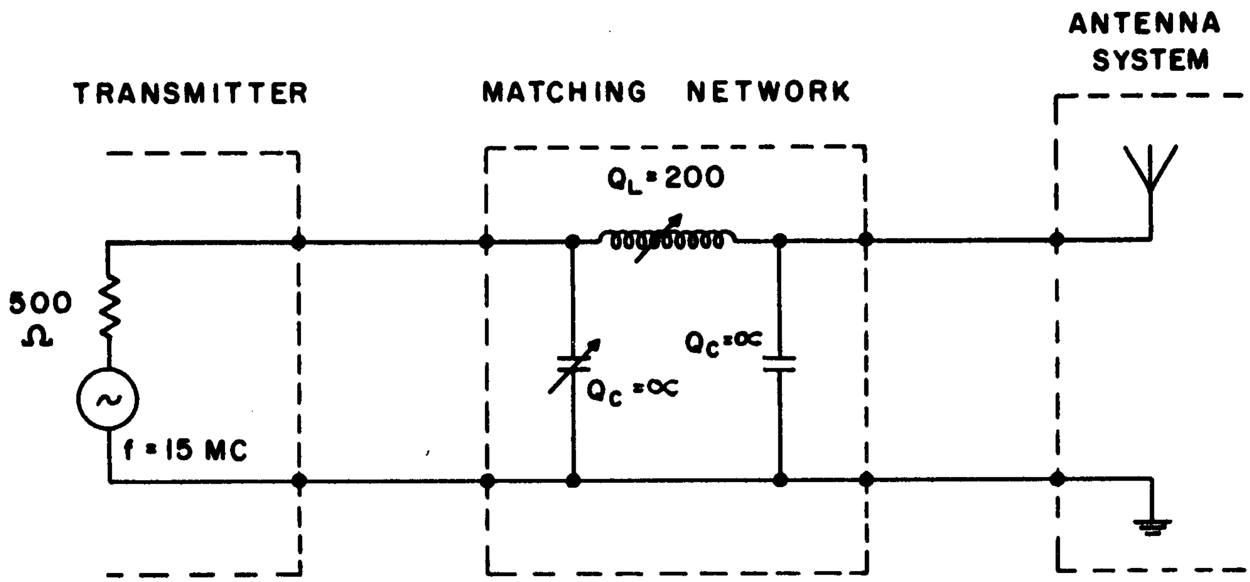

ANTENNA SYSTEM
TRANSMITTER
MATCHING NETWORK
Q_L = 200
500 Ω
Q_C = ∞
Q_C = ∞
f = 15 MC

FIGURE 3

a load of $500 \pm j\,0\,\Omega$ to the transmitter.

The calculations, a sample of which is given in the Appendix, are for operation at 15 mc except for the top curve of Figure 2 which is for 3 mc operation. The frequency is significant in that the high losses occur mainly as a result of the high value of the fixed capacitor at the output of the network. This large capacitor is necessary in order to be able to accommodate certain antenna impedances at 3 mc with realizable maximum to minimum ratios for the variable elements. The losses could of course be reduced if a coil of higher Q could be used. However an increase in coil Q by a factor of 2 does not lead to a reduction of the losses in the network by a factor of 2. Furthermore, any improvement in coil Q above 200 would be quite marginal in an application where small physical size is of extreme importance. It is possible to wind relatively small coils on high frequency ferrite material and obtain Q's as high as 400 or even 500. However as soon as such a coil is placed in a metal case, the Q drops sharply. In applications where the coil has to be placed close to the sides of a metal case, as for instance in the RT21 transmitter where a total case thickness of 1 1/2" is specified, extremely high Q's are not possible. The situation can be improved by placing a ferrite strap around the coil but this procedure adds to the total volume of the coil. Consequently, although under ideal conditions Q's substantially in excess of 200 are obtainable, within the constraints of the particular application, such high Q's are not realizable.

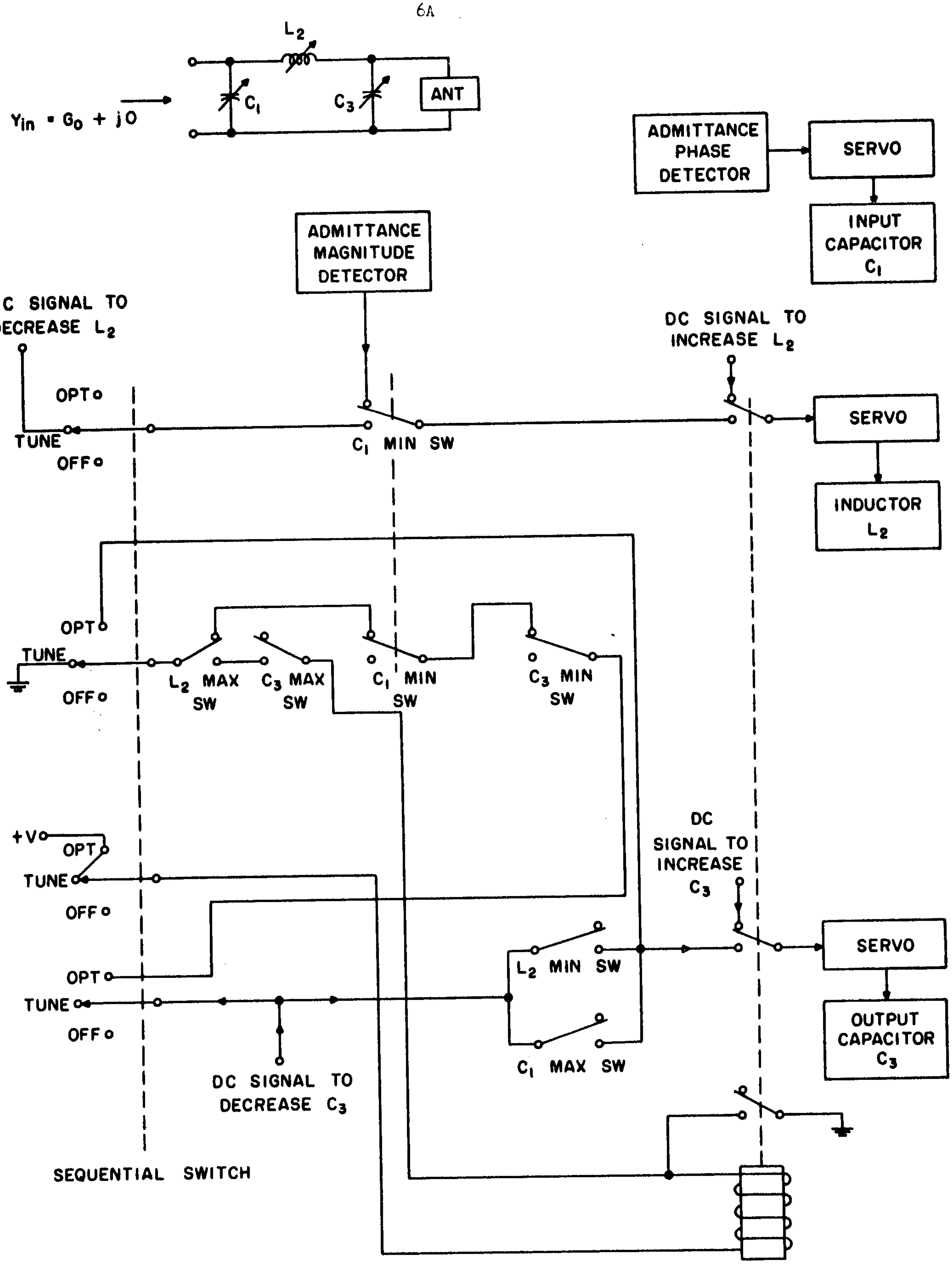
The situation which has been described above exists, it will be readily appreciated, regardless of the tuning method; i.e., in both manual and automatic systems. Fortunately a solution is available which lends itself to automatic adjustment more readily than to manual operation. A servo system can be designed in which three variable elements are used whereas the manual optimization of a three variable system would be extremely tedious. As will be described in this proposal, a three variable system largely overcomes the serious losses which can occur when a matched but non optimized matched condition is used.

III. Proposed Solution

As described in the Statement Of The Problem the high losses inherent in a conventional matching network may be attributed largely to the high value required for the fixed capacitor at the output of the π network. This high capacitor value is, in turn necessary in order to make a match to some possible loads at low frequencies. The proposed system utilizes a variable capacitor at the output of the π network. This third capacitor is controlled by the portion of the other two variable elements. The basic operation of the system shown in block diagram form in Figure 4, may be described as follows.

The optimized admittance match is achieved by manually operating a sequential three position switch. The three positions are "Off", "Tune", and "Optimize". The desired value of input conductance is first achieved in the "Tune" position, and then improved efficiency may be achieved by switching to the "Optimize" position.

The manner in which the Three-Variable-Pi is driven to produce a purely conductive admittance of value G_o is as follows: The operation of the system requires that both L_2 and C_3 be at their maximum positions when the tuning cycle begins. This is accomplished automatically by means of a relay which, when unactuated, applies signals which drive both L_2 and C_3 to their maxima. When both L_2 and C_3 have been driven to their maxima, limit switches then actuate the relay and the tuning cycle begins. The output of the phase detector tends to drive C_1 to the position which cancels any phase angle associated with the input admittance. The output of the magnitude detector tends to drive L_2 to the position which produces the desired value of input conductance, provided that C_1 was not initially driven to its minimum position.



SCHEMATIC DIAGRAM OF SYSTEM

FIGURE 4

If C_1 is initially at its minimum position, a limit switch is actuated. This limit switch applies a signal which causes L_2 to decrease until C_1 leaves its minimum position. At this time the control of L_2 is returned to the magnitude detector. Under certain conditions, C_1 may be driven to its maximum or L_2 may be driven to its minimum before an admittance match is achieved. In these cases limit switches which cause C_3 to decrease are actuated. C_3 continues to decrease until the limit switches are released. This then completes the tuning cycle.

When the sequential switch is moved to the "Optimize" position, a signal which causes C_3 to decrease is applied. As C_3 decreases, C_1 and L_2 move to maintain the admittance match. C_3 continues to decrease until the limit switch at either L_2 maximum, C_1 minimum, or C_3 minimum is actuated. When any of these switches is actuated, C_3 stops and the "Optimized" admittance match has been achieved.

The reduction of the capacitor at the output of the π network to the lowest value consistent with the ranges of the other two variable elements improves the network efficiency for nearly all values of antenna impedance contained within the 25 to 1300 $\pm$ j 1000Ω impedance area originally specified. For the points where the adjustment of the output in this manner does not lead to an optimized match, with a coil Q of 200, the resultant non optimized match would still provide an efficiency in excess of 95%.

The improvement in power transfer efficiency which can be expected as a result of adjusting for an optimized match is represented by the upper curve in Figure 1 and by Figure 5. Figure 5 shows, for various values of resistive antenna load, the percentage of the available transmitter power

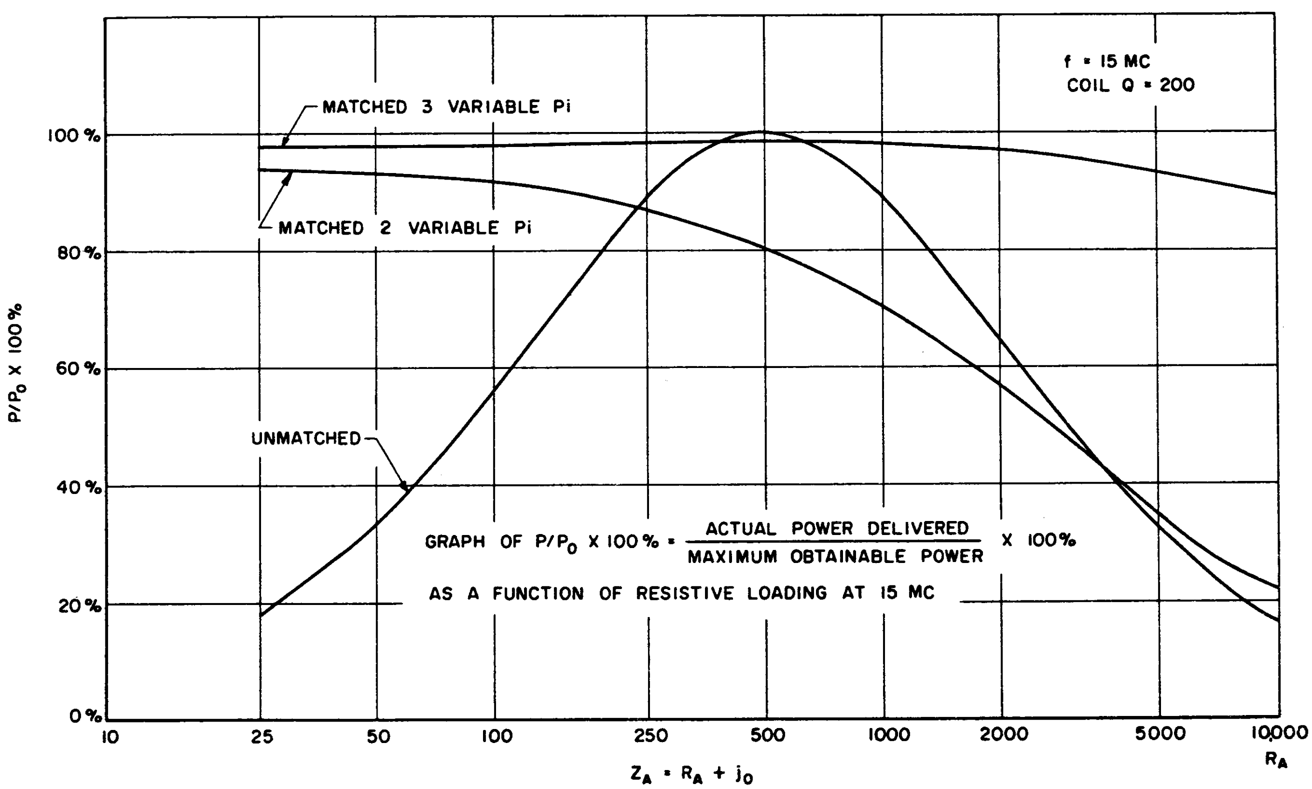


FIGURE 5

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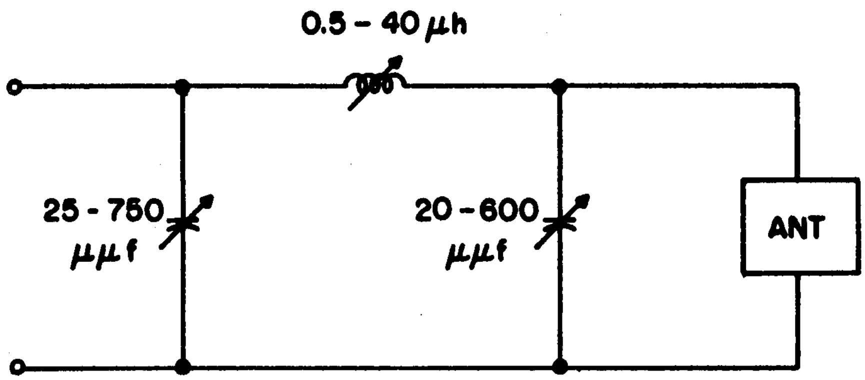
which is transferred to the antenna for both a two variable network giving a non optimized match and a three variable optimized matching network. The top curve in Figure 1 is for an optimized match using a three variable network and indicates, for certain values of antenna reactance, an increase in efficiency from less than 10% to over 80% compared with the non optimized matched condition. By going to a three variable network in order to obtain an optimized match, the requirements placed on the maximum to minimum ratios of the components are also eased. Consequently with the network shown in Figure 6 it is possible to match to the complete rectangle originally specified i.e., 25 to 1300 ± j 1000 ohms from 3-30 MC. It will be seen that the values required of the variable reactances are quite realizable, if not readily available.



3-30 MC MATCHING NETWORK
FOR ORIGINAL Z AREA

FIGURE 6

IV. Manpower Requirements and Time Schedule

The manpower effort required to implement the program described above is estimated to be as follows:

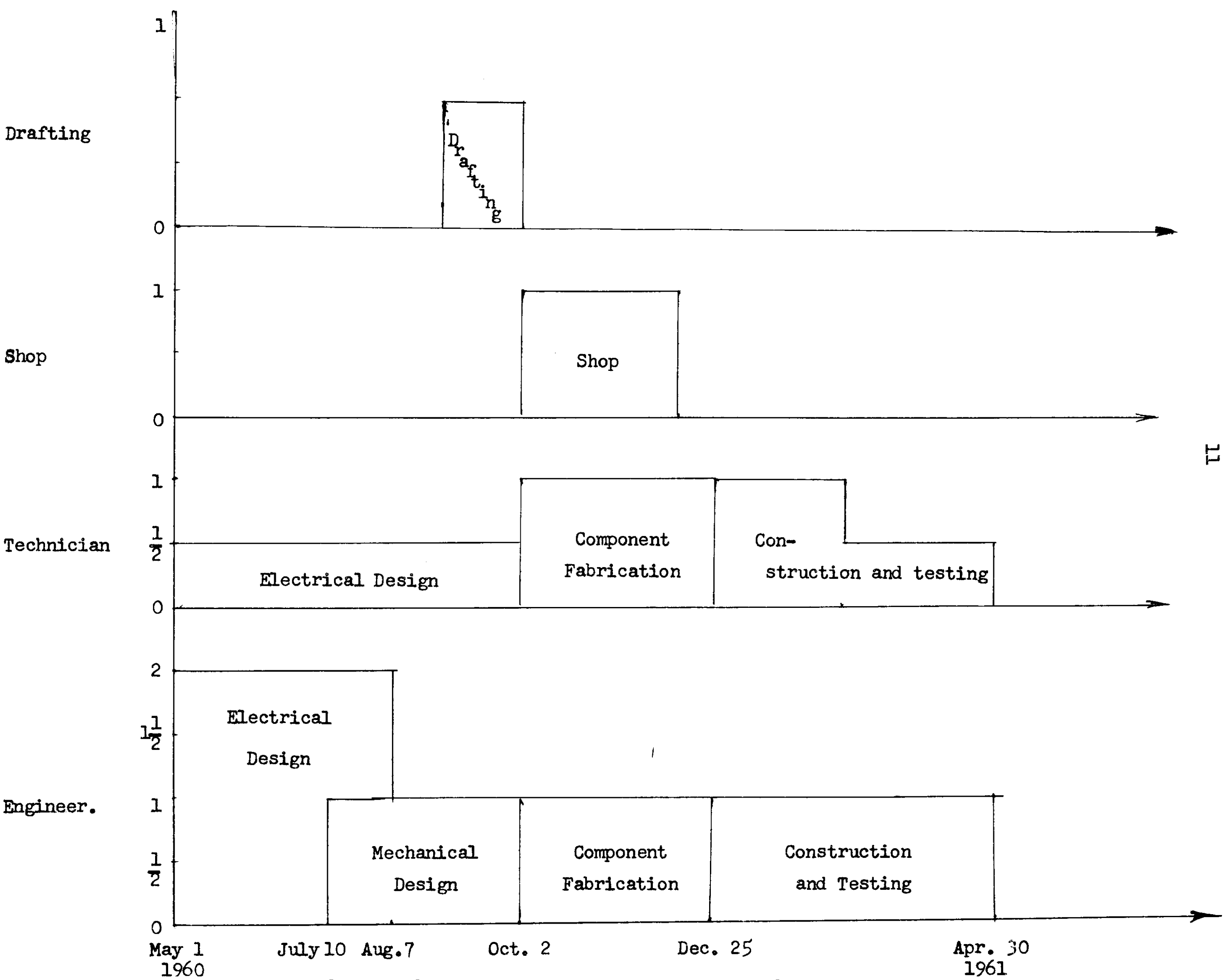
		Man Weeks
Electrical Design of System		
Engineering		24
Technician		11
Mechanical Design		
Engineering		12
Technician		0
Fabrication of Components		
Engineering		12
Technician		12
Construction and Testing		
Engineering		18
Technician		13
Total:	Engineering	66
	Technician	36

The proposed time schedule for implementing this program, which, it is anticipated will be iniated on May 1st, 1960 is as follows:

Electrical Design of System	May 1 - Oct. 2, 1960
Mechanical Design	July 10 - Oct. 2, 1960
Fabrication of Components	Oct. 2 - Dec. 25, 1960
Construction and Testing	Dec. 25 - Apr. 30, 1961

The above dates are based on a starting date of May 1st, 1960. If the starting date is postponed, all subsequent dates shown will be postponed by a similar amount.

A chart of engineering manpower is shown on the following page.


Drafting
Shop
Technician
Engineer.
Drafting
Shop
Electrical Design
Component Fabrication
Con- struction and testing
Electrical Design
Mechanical Design
Component Fabrication
Construction and Testing
May 1 1960
July 10
Aug.7
Oct. 2
Dec. 25
Apr. 30 1961

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VII. Appendix

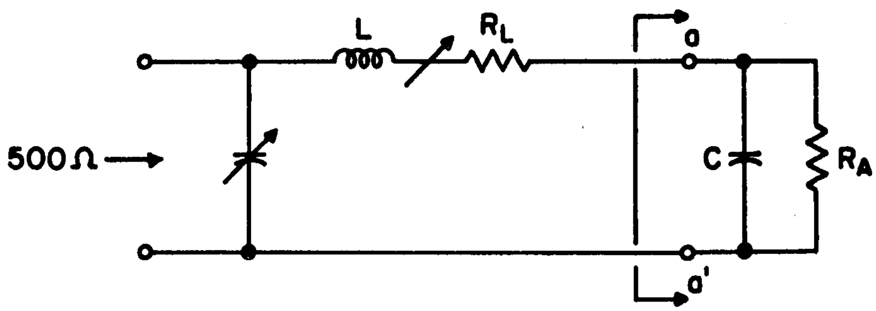
It has been previously stated that because of the loss resistance associated with the coil, the losses in the two-variable π network become appreciable under certain conditions. The reason for this may be seen by examining, as an example, the two-variable π with resistive terminations (shown in Figure 7). The impedance looking into the terminals a - a' may be represented as an equivalent series R - C. The π network in this equivalent form is shown in Figure 8. If the efficiency of the π is defined as the ratio of output power to input power, this efficiency, η, is then

$$\eta = \frac{P_{out}}{P_{in}} = \frac{|I|^2 R'}{|I|^2 (R_L + R')}$$

$$= \frac{1}{1 + R_L/R'} \; . \tag{1}$$

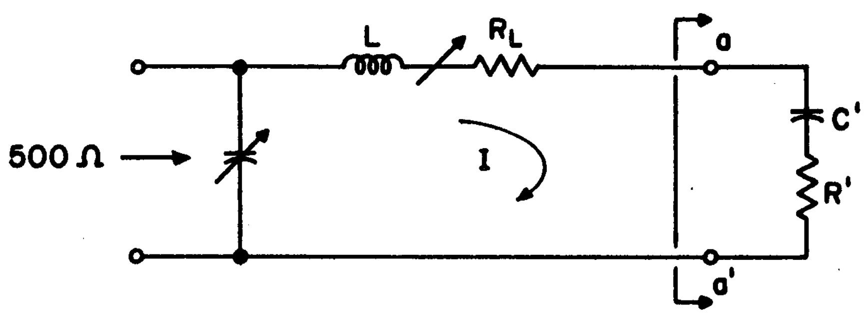
Since it is desired to have the efficiency near unity, the loss resistance of the coil should be kept small in comparison to the reflected load resistance, R'. Unfortunately, this can not always be done in the two-variable π system. The significance of this situation may be illustrated by the following calculations.

In order to match certain impedances at 3 mc, it is necessary to fix C at a value of not less than 510 μμf. If, as an example, the input impedance looking into a - a' is then evaluated at 15 mc with $R_A = 1300\,\Omega$,



TWO-VARIABLE Pi WITH RESISTIVE TERMINATIONS

FIGURE 7



EQUIVALENT REPRESENTATION OF THE TWO-VARIABLE Pi WITH RESISTIVE TERMINATIONS

FIGURE 8

$$Z_a = \frac{1}{\frac{1}{R_A} + \frac{j}{\omega C}}$$

$$= \frac{1}{\frac{1}{1300} + \frac{j}{(2\pi \times 15 \times 10^6)(510 \times 10^{-12})}}$$

$$= 0.333 - j\,20.6$$

Thus, in terms of the circuit of Figure 8,

$$R' = 0.33 \text{ ohm}$$

$$\frac{1}{\omega C'} = 20.6$$

In order to see how R' compares with R_L, it is necessary to find what value of L (along with its loss resistance, $R_L = \omega L/Q$) will result in a 500 ohm input. At resonance, the circuit of Figure 8 has an input resistance of

$$R_{in} = \frac{\omega L}{Q} + R' + \frac{(\omega L - 1/\omega C')^2}{R' + \frac{\omega L}{Q}} \quad .$$

Solving this equation for ωL,

$$\omega L = \frac{R_{in} - 2R'}{2\,Q} + \frac{1}{\omega C'} + \sqrt{\left[\frac{R_{in} - R'}{2Q}\right]^2 + \frac{R_{in} - 2R'}{\omega C' Q} + R'\,(R_{in} - R')} \qquad (2)$$

Evaluating the above for $R_{in} = 500$, $R' = 0.333$, $1/\omega C' = 20.6$, and $Q = 200$

$$\omega L = \frac{500 - 0.666}{2(200)} + 20.6 + \sqrt{\left[\frac{500 - 0.333}{2(200)}\right]^2 + \left[\frac{500 - 0.666}{200}\right](20.6) + (0.333)(500 - 0.333)}$$

$$= 36.7$$

Therefore,

$$R_L = \frac{\omega L}{Q} = \frac{36.7}{200} = 0.1835,$$

and

$$\eta = \frac{P_{out}}{P_{in}} = \frac{1}{1+R_L/R'} = \frac{1}{1 + \frac{0.1835}{0.333}} = 0.643.$$

This indicates that more than one-third of the power into the π is lost in the coil. This relatively poor efficiency is primarily due to the small value of the reflected load resistance, R'. Straight forward circuit analysis shows that R' can be made larger if C is reduced. (It is only for certain impedance at 3 mc that C must be 510 μμf.) With C decreased to 20 μμf,

$$Z_a = \frac{1}{\frac{1}{1300} + j\,(2\pi \times 15 \times 10^6)\,(20 \times 10^{-12})}$$

$$= 186 - j\,445$$

$$= R' - j/\omega C'.$$

Evaluating Equation (2) in terms of these parameters,

$$\omega L = \frac{500 - 2(186)}{2(200)} + 455 + \sqrt{\left[\frac{500 - 186}{2(200)}\right]^2 + \left[\frac{500 - 2(186)}{200}\right](445) + 186\,(500 - 186)}$$

$$= 699$$

$$R_L = \frac{\omega L}{Q} = \frac{699}{200} = 3.5\,\Omega$$

$$\eta = \frac{P_{out}}{P_{in}} = \frac{1}{1 + R_L/R'} = 0.975$$

Thus, instead of losing 35% of the input power in the coil, the loss has been reduced to 2.5% .

The conclusions which follow from analysis of the π are that R' must be much greater than R_L if the network is to transfer power efficiently to the load. This can be achieved by reducing the output capacitor when the termination does not actually require a large capacitance.