Med. & Biol. Eng. & Comput., 1977, 15, 634–640

Design of radio-frequency powered coils for implant instruments

Wen H. Ko **Sheau P. Liang** **Cliff D. F. Fung**

Engineering Design Centre, Case Western Reserve University, Cleveland, Ohio 44106, USA

Abstract—*Radio frequency (r.f.) has been investigated as a means of externally powering miniature and long term implant telemetry systems. Optimum power transfer from the transmitter to the receiving coil is desired for total system efficiency. A seven step design procedure for the transmitting and receiving coils is described based on r.f., coil diameter, coil spacing, load and the number of turns of the coil. An inductance tapping circuit and a voltage doubler circuit have been built in accordance with the design procedure. Experimental results were within the desired total system efficiency ranges of 18% and 23%, respectively.*

Keywords—*Radio frequency powering, Receiving coil, Transmitting coil, Power transfer efficiency, Inductance tapping, Voltage doubler, Implant telemetry*

1 Introduction

MINIATURISATION and long term use of implanted electronic systems for medical applications have resulted in a growing need for an external powering system. Investigation of r.f. powering to meet these needs has been undertaken at the Engineering Design Centre of Case Institute of Technology, Case Western Reserve University, Cleveland, Ohio.

The r.f. power output from an oscillator is amplified and is used to drive a transmitting (primary coil. A receiving (secondary) coil picks up the transmitted r.f. power, and a power receiving circuit rectifies the induced r.f. and converts it into a regulated d.c. supply for the implanted electronic system. Maximisation of the power transfer from the transmitting coil to the receiving coil is desired for system efficiency. A design procedure for the transmitting and receiving coil has been determined based on load, coil spacing and radio frequency.

2 Theory

The basic r.f. powering circuit is shown in Fig. 1· The diode efficiency is defined to be $A = V_0/V_{pk}$' where V_{pk} is the peak a.c. voltage across the tank circuit L_2C_2 and $V_0 = V_{pk} - V_{diode}$. When a semiconductor diode (D1) is used, V_{pk} exceeds several volts, and $R_0C_0 \gg 1/f$, then $V_{diode} \ll V_{pk}$ and A is approximately unity. In this case V_{pk} equals V_0, and the equivalent a.c. load resistance R which will dissipate an amount of a.c. power equivalent to the d.c. power in R_0 is

$$R = R_0/2 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

The equivalent a.c. series resistance R_L due to the load R_0 or R is

$$R_L = \frac{(\omega L_2)^2}{R} = \frac{2(\omega L_2)^2}{R_0} \quad . \quad . \quad . \quad . \quad (2)$$

As shown in Fig. 2, the total equivalent series resistance in the secondary tank circuit is $R_2 + R_L$, where R_2 is the series resistance of the unloaded secondary tank circuit.

The equivalent resistance R_e, reflected back into the primary coil, is

$$R_e = \frac{(\omega M)^2}{R_2 + R_L} = \frac{Rk^2Q_1Q_2}{R + Q_2{}^2R_2}R_1 \quad . \quad . \quad . \quad (3)$$

where $M = k\sqrt{L_1L_2}$ is the mutual inductance of the coils and $Q_1 = \omega L_1/R_1$ and $Q_2 = \omega L_2/R_2$ are the unloaded Qs of the primary and secondary coils, respectively.

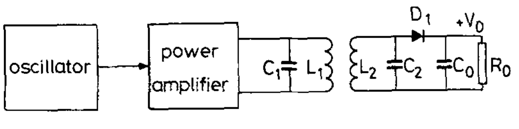

Fig. 1 Basic r.f. circuit

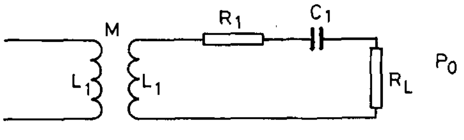

Fig. 2 Secondary equivalent circuit

Received 29th November 1976

From the primary equivalent circuit, shown in Fig. 3, the circuit efficiency at resonance can be determined:

$$P_i = \tfrac{1}{2}\left(\frac{|V_g|^2}{R_e+R_1}\right)$$

and

$$P_0 = \frac{R_L}{R_L+R_2}\ \frac{R_e}{R_1+R_e}\ P_i$$

and

$$\eta = \frac{P_0}{P_i}$$

$$= \frac{k^2Q_1Q_2{}^3R_2R}{(R+Q_2{}^2R_2)[(1+k^2Q_1Q_2)R+Q_2{}^2R_2]} \quad . \quad . \quad (4)$$

In r.f. powering, the maximum value of k is determined by coil size and spacing, and generally places an upper limit on the attainable efficiency. For maximum efficiency $d\eta/dR_2$ equals zero, thus

$$R_{2\,opt} = R\frac{(1+k^2Q_1Q_2)^{\frac{1}{2}}}{Q_2{}^2} \quad . \quad . \quad . \quad . \quad . \quad (5)$$

Substituting eqn. 5 into eqn. 4, the optimum efficiency of the circuit is given by

$$\eta_{opt} = \frac{k^2Q_1Q_2}{[1+(1+k^2Q_1Q_2)^{\frac{1}{2}}]^2} \quad . \quad . \quad . \quad . \quad (6)$$

Eqn. 6 indicates that optimum efficiency η_{opt}, increases as $k^2Q_1Q_2$ increases, and therefore the coils must be designed for the highest possible unloaded Q and k, which are functions of the shape, size and relative position of the coils. A typical coil configuration is shown in Fig. 4.

If M_0 is the mutual inductance between two coaxial single-turn coils of diameters d_1 and d_2 and the spacing D between the coils, then $M = n_1n_2M_0$, where n_1 and n_2 are the number of turns on the primary and secondary coils, respectively. From the definition of M, the coupling coefficient k^2 is given by

$$k^2 = \frac{M^2}{L_1L_2} = \frac{(n_1n_2M_0)^2}{L_1L_2} \quad . \quad . \quad . \quad . \quad . \quad (7)$$

The low frequency inductance of a single-layer solenoid is given by

$$L = dF \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (8)$$

where the shape factor F is a function of the diameter d and the length L of the coil. M_0 is given by

$$M_0 = 1{\cdot}27\,N\,(d_1d_2)^{\frac{1}{2}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (9)$$

where N is a function of r_2/r_1. From eqns. 7, 8 and 9, it follows that:

$$k^2 = \frac{(1{\cdot}27\,N)^2}{F_1F_2} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (10)$$

where F_1 and F_2 are the shape factors for the primary and secondary coils. It is noted that k is independent of the number of turns of the coils and that N* increases as r_2/r_1 decreases. It is determined by the shape factors of the coils and r_2/r_1.

The ratio r_2/r_1 can be determined as

$$r_2/r_1 = \sqrt{\left\{\frac{(d_1-d_2)^2+4D^2}{(d_1+d_2)^2+4D^2}\right\}} \quad . \quad . \quad . \quad (11)$$

For maximum N and k, minimum r_2/r_1 is desired. By setting $d(r_2/r_1)/d(d_1)$ to zero, it can be shown that,

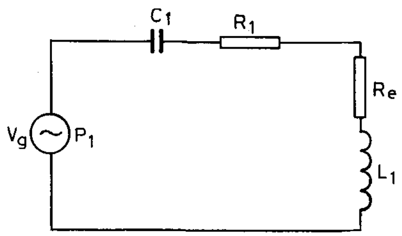

Fig. 3 Equivalent circuit of primary

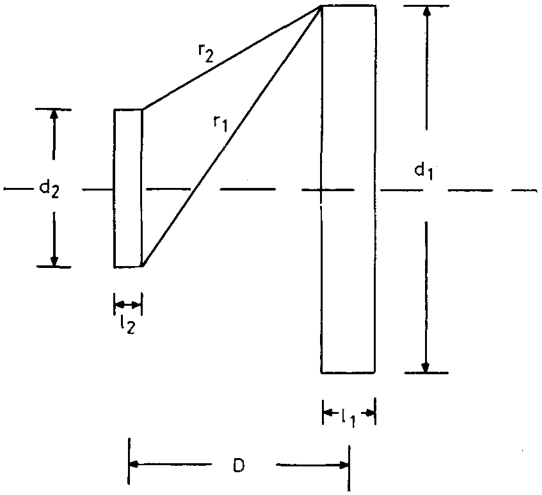

Fig. 4

Tables for values of F and N as a function of r_2/r_1 can be found in Frederick E. Terman · 'Radio Engineers' Handbook', McGraw Hill, New York, 1943, Tables 12 and 17, respectively for a given d_2 and D, r_2/r_1 is minimum when

$$d_1 = (d_2^2+4D^2)^{\frac{1}{2}} \quad . \; . \; . \; . \; . \; . \; . \; . \quad (12)$$

Hence, for a given d_2, D, d_1/l_1, and d_2/l_2; d_1 can be chosen to maximise k^2 using eqn. 12.

3 Design procedure

From the above theoretical analysis, a design procedure has been formulated as follows:

Given the following known or derived conditions:
(*a*) V_0, I_0, $R_0 = V_0/I_0$ and $R = R_0/2$ (d.c. output requirements)
(*b*) the spacing D between coils
(*c*) the secondary coil diameter d_2
(*d*) the diameter–length ratio of the two coils d_1/l_1 and d_2/l_2
(*e*) frequency of operation

The design procedure is outlined in the following steps:

(i) Calculate d_1 by eqn. 12, to maximise k^2

(ii) Calculate r_2/r_1 by eqn. 11, obtain the value for N and the values for F_1 and F_2, calculate k^2 from eqn. 10

(iii) Calculate η_{opt}. The unloaded Q_1 and Q_2 must first be selected. Although it is very difficult to perform the theoretical calculation of the unloaded Q of the coils, experimental measurement of the Q values usually yields a close approximation:

(*a*) For a coil diameter approximately equal to 2 inches (5·08cm), (d/l) approximately equals 8, and for a frequency of 3·5 MHz a Q of approximately 100 is obtained for a single-layer coil, with numbers 19 wire (American gauge), closely wound at 10–20 turns.

(*b*) For a coil diameter of approximately $\frac{1}{4}$ inch (1·27 cm), (d/l) approximately equals 4, and for a frequency of 3·5 MHz a Q of approximately 60 is obtained for a single-layer coil and a Q of 40 is obtained for a 2-layer coil.

Owing to the fact that increasing the parasitic capacitance decreases the Q value, it is not practical to wind a coil with more than two layers. Therefore, it is recommended that single-layer coils be used for r.f. powering unless special coil winding equipment for winding low-capacitance coils is available.

The efficiency η_{opt} varies slowly with $k^2Q_1Q_2$, and so a reasonable estimate of Q is sufficient. Such estimates can be based on measured values of Q for coils of the size and shape to be used at the frequency of interest. Furthermore, the efficiency attained will not be critically dependent on R_2 and so eqn. 5 can be used to find R_2 using estimated values of Q_1 and Q_2 and will usually lead to an acceptable design.

(iv) Determine L_2 and C_2. R_2 can be determined from eqn. 5 and is used to calculate L_2 and C_2 by

$$L_2 = \frac{Q_2R_2}{2\pi f} \quad \text{and} \quad C_2 = \frac{1}{(2\pi f)^2L_2}$$

(*a*) If L_2 is too small to obtain a high Q, then L_2 can be increased by inductance tapping. The circuit configuration for the inductance tapping method is shown in Fig. 5.

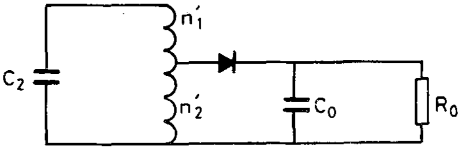

Fig. 5 Inductance tapping

(*b*) If L_2 is too high, then R is too high; a voltage doubler can be used to decrease R. The circuit configuration for the voltage doubler is shown in Fig. 6.

From this circuit one can see that

$$\frac{V_0^2}{R_0} = \frac{V_p^2}{2R} \quad \text{and} \quad V_0 = 2V_p$$

Hence

$$R = R_0/8$$

(v) Calculate the impedance of the primary circuit R_p. $P_0 = V_0I_0$ and $P_i = V_0I_0/\eta_{opt}$, therefore

$$R_p = \frac{V_{CC}}{2P_i} = \frac{V_{CC}\eta_{opt}}{2V_0I_0}$$

where V_{CC} is the d.c. collector voltage for the class C r.f. amplifier used to drive the primary coil. It is assumed that sufficient base drive is used so as to develop a peak r.f. voltage equal to V_{CC} across the primary input.

(iv) In order to determine L_1 and C_1, Q_{L1} (the loaded Q of the primary circuit) must be determined:

$$Q_{L1} = \frac{Q_1R_1}{R_1+R_e} = \frac{Q_1}{1+\dfrac{k^2Q_1Q_2R}{R+Q_2^2R_2}}$$

By definition

$$L_1 = \frac{R_p}{\omega Q_{L1}} = \frac{R_p}{(2\pi f)Q_{L1}}$$

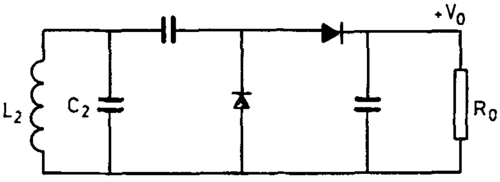

Fig. 6 Voltage doubler

and

$$C_1 = \frac{1}{(2\pi f)^2 L_1}$$

If L_1 is too small to obtain a high Q, then L_1 must be increased by tapping, and the equation for L_1 would then be

$$L_1 = \left(\frac{n'_1 + n'_2}{n_1}\right)^2 \left(\frac{R_p}{2\pi f Q_{L1}}\right) \quad . \quad . \quad . \quad (13)$$

(vii) Calculate the number of turns of the two coils. From steps (iv) and (vi) the values for L_1 and L_2 were determined. Rearrangement of eqn. 8 yields the following equations, which are used for calculation of the number of turns of the coils:

$$n_1 = \left(\frac{L_1}{F_1 d_1}\right)^{\frac{1}{2}} \quad \text{and} \quad n_2 = \left(\frac{L_2}{F_2 d_2}\right)^{\frac{1}{2}}$$

The wire diameter of the primary coil is equal to $(l_1 \times 0{\cdot}8)/(n_1/m_1)$ and the wire diameter of the secondary coil is equal to $(l_2 \times 0{\cdot}8)/(n_2/m_2)$, where m_1 and m_2 are the number of layers of the coils.

4 Design examples and results

The following Section contains two examples of the implemented design procedure and tested results. The format follows that given in Section 3.

Given the following parameters:

(*a*) $V_0 = 4V$, $R_0 = 15\text{k}\,\Omega$ and $R = 7{\cdot}5\,\text{k}\Omega$

$$P_0 = \frac{V_0^2}{R_0} = 1{\cdot}05\,\text{mW}$$

(*b*) $D \leqslant 1$ inch (2·54 cm)

(*c*) $d_2 = \frac{1}{2}$ inch (1·27 cm)

(*d*) $d_1/l_1 = 10$ and $d_2/l_2 = 4$

(*e*) $f = 3{\cdot}5$ MHz.

and then following the design procedure described in the previous section:

(i) Calculate d_1:

$$d_1 = (d_2^2 + 4D^2)^{\frac{1}{2}} = 2{\cdot}06 \text{ inches } (5{\cdot}23\,\text{cm})$$

(ii) Calculate r_2/r_1:

$$r_2/r_1 = \sqrt{\frac{(d_1 - d_2)^2 + 4D^2}{(d_1 + d_2)^2 + 4D^2}} = 0{\cdot}78$$

From the Radio Engineers' Handbook, $F_1 = 0{\cdot}051$ and $F_2 = 0{\cdot}0367$ and $N = 0{\cdot}000863$. Hence

$$k^2 = \frac{(1{\cdot}27N)^2}{F_1 F_2} = 6{\cdot}5 \times 10^{-4}$$

(iii) Calculate η_{opt}:

Set the unloaded Q, $Q_1 = 100$ and $Q_2 = 40$.

$$\eta_{opt} = \frac{k^2 Q_1 Q_2}{\{1 + (1 + k^2 Q_1 Q_2)^{\frac{1}{2}}\}^2} = 30{\cdot}97\%$$

(iv) Determine L_2 and C_2:

$$R_2 = R\frac{(1 + k^2 Q_1 Q_2)^{\frac{1}{2}}}{Q_2^2} = 9\Omega$$

Hence

$$L_2 = \frac{Q_2 R_2}{2\pi f} = 18\,\mu\text{H and } C_2 = 115\,\text{pF}$$

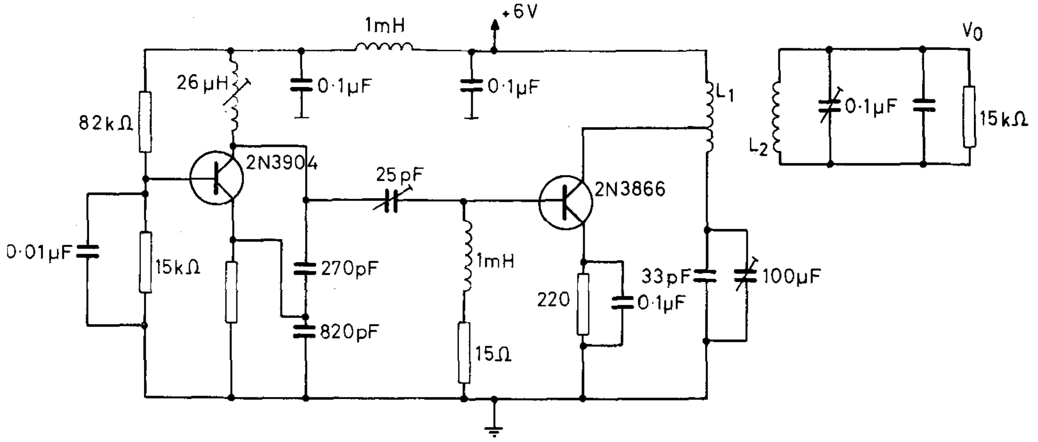

Fig. 7 R.F. powering circuit diagram

(v) Calculate the impedance of the primary circuit R_p:

$$P_0 = V_0^2/R_0 = 1\,\text{mW}$$

$$P_i = P_0/\eta_{opt} = 3{\cdot}6\,\text{mW}$$

$$R_p = V_{CC}/2P_i = 5\,\text{k}\Omega, \text{ where } V_{CC} = 6\,\text{V}$$

(vi) Calculate L_1 and C_1:

$$R_e = \frac{k^2 Q_1 Q_2 R}{R + Q_2^2 R_2} R_1 = 0{\cdot}89\,R_1$$

$$Q_{L1} = \frac{Q_1 R_1}{R_1 + R_2} = \frac{100}{1{\cdot}89} = 53$$

$$L_1 = \frac{R_p}{2\pi f Q_{L1}} = 4{\cdot}3\,\mu\text{H}$$

$$C_1 = \frac{1}{(2\pi f)^2 L_1} = 480\,\text{pF}$$

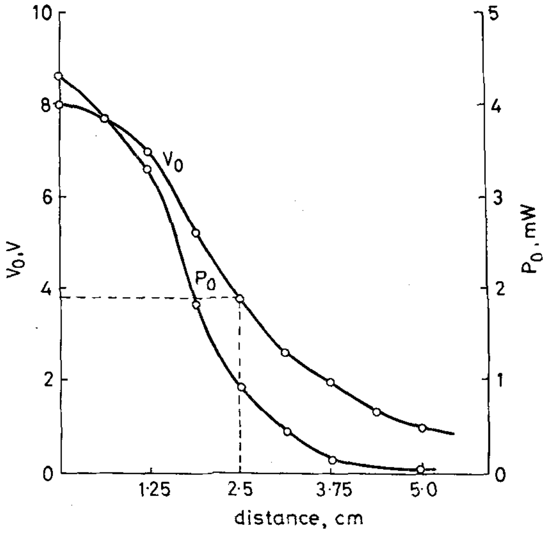

Fig. 8 V_0 and P_0 against distance characteristics

If L_1 is too small and inductance central tapping is employed, then $L_1 = 4 \times 4{\cdot}3 = 17{\cdot}3\,\mu\text{H}$ and $C_1 = 120\,\text{pF}$.

(vii) Calculate the number of turns of the two coils.

$$n_1 = \left(\frac{L_1}{F_1 d_1}\right)^{\frac{1}{2}} = 13 \text{ (single layer)}$$

$$n_2 = \left(\frac{L_2}{F_2 d_2}\right)^{\frac{1}{2}} = 32 \text{ (two- layer, 16 turns per layer)}$$

The wire diameter of the primary coil equals:

$$d_1 = \frac{l_1 \times 0{\cdot}8}{n_1} = 0{\cdot}012 \text{ inches } (0{\cdot}3\,\text{mm}),$$

number 29 wire (American gauge)

$$d_2 = \frac{l_2 \times 0{\cdot}8}{n_2} = 0{\cdot}006 \text{ inches } (0{\cdot}15\,\text{mm}),$$

number 34 wire (American gauge)

5 Experimental results

The completed r.f. powering circuit is shown in Fig. 7, where $L_1 = L_2 = 20\,\mu\text{H}$, $d_1 = 2$ inches (5·08 cm), $d_2 = 1/2$ inches (1·27 cm), $n_1 = 12$ (number 28 wire), $n_2 = 30$ (two layer, number 34 wire), $Q_1 = 100$, $Q_2 = 35$ and $f = 3{\cdot}5$ MHz.

The distance D between L_1 and L_2 was varied from 0 to 2 inches (5·08 cm). The power amplitude, output voltage V_0, output power P_0, and total efficiency η_T were measured at ¼ inch (6·35 mm) intervals. The results of V_0 and P_0 against distance is plotted in Fig. 8.

The total system efficiency η_T is determined by the ratio of the output power and the input d.c. power. The product of the power amplifier efficiency and the coil efficiency is represented by η_T ($\eta_{coil} = \eta_{opt}$ for an optimum design):

$$\eta_T = \frac{V_0^2/R_0}{V_{CC} I_{dc}} = \eta_{power\ amplifier} \times \eta_{coil}$$

A plot of η_T against distance is given in Fig. 9.

In step (iii) of the design procedure, η_{opt} was calculated as 30·97% at a spacing of 1 inch (2·5 cm). At this distance η_T equals 18%. Hence, $\eta_{power\ amplifier}$ equals 58%, which is an acceptable and obtainable efficiency.

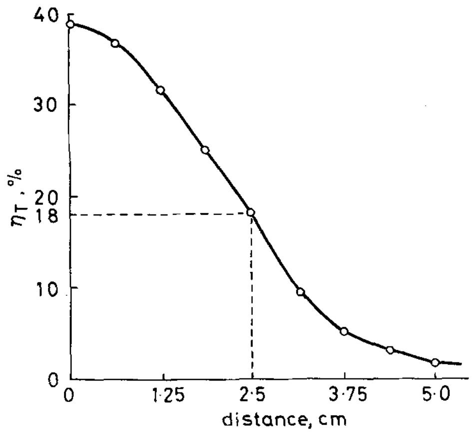

Fig. 9 η_T against distance

Example 2: In the case that L_2 is too large, a voltage doubler is used. The oscillator section of the circuit remains the same, with only slight modification of the component values in the power amplifier. The voltage doubler described previously is used. Using the same specifications outlined in the example above, with the exception that $R_0 = 30\,\mathrm{k\Omega}$, $L_1 = 22\,\mu\mathrm{H}$, $L_2 = 10\,\mu\mathrm{H}$, $d_1 = 2$ inches (5·08 cm), $d_2 = 1/2$ inches (1·27 cm), $Q_1 = 100$, $Q_2 = 65$, $n_1 = 15$, $(n_2 : n_1 = 10 : 5)$, $n_2 = 22$ and both coils are single-layer coils.

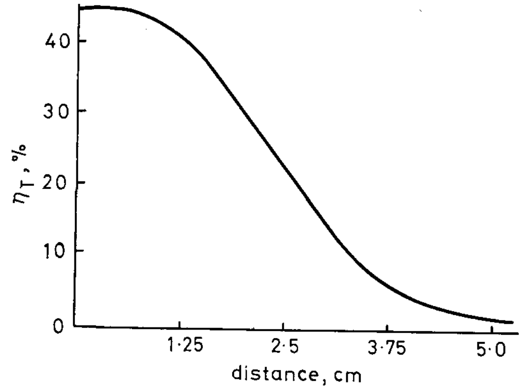

Fig. 10 η_T against distance

The value of η_{coil} is calculated to be 39% at a spacing of 1 inch (2·54 cm) and η_T equals 23%. Therefore, $\eta_{power\ amplifier}$ equals 60%. Fig. 10 shows a plot of η_T against distance.

The experimental results of V_0 and P_0 against distance is plotted in Fig. 11. A plot of V_0 against r_c, where r_c is the centre-to-centre distance of the coils, is shown in Fig. 12. As the spacing D increases, r_c of the null point ($V_0 = 0$) increases. Over-coupling occurs as the difference in size of the primary and the secondary coil is not large and the spacing is small. At $D = 1$ inch (2·54 cm) and $d_2 = \frac{1}{2}$ (1·27 cm), the specified design criteria, good results were obtained.

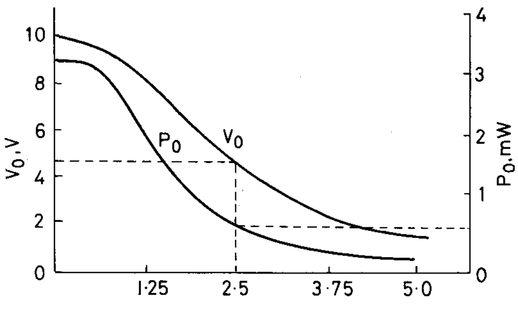

Fig. 11

6 Conclusion

A design procedure has been developed for use in the design of r.f. powering systems. The optimisation presented may not be unique, but it is relatively simple and offers practical application for r.f. powering.

Stated in a step-by-step outline, the procedure is flexible and can be used with various design conditions. The analysis and formulations can be used to design external r.f. powering systems for biomedical implant units or other applications; such as in the industrial control field to transmit power and signal through a barrier without wires or contacts.

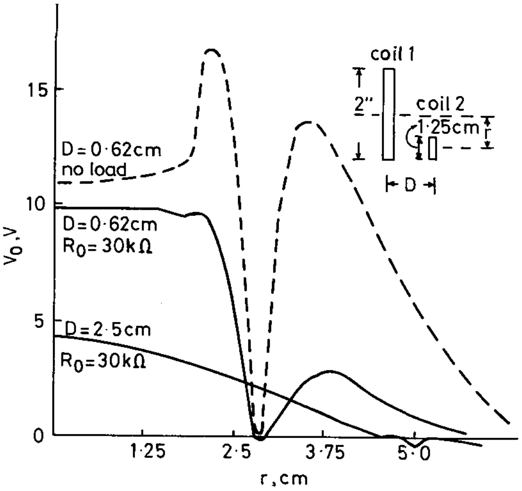

Fig. 12

Several designs utilising the procedure have been evaluated in our laboratory. The experimental results were in good agreement with predicted values. Two examples covering single-layer coils, and inductance tapping and voltage doublers, were described to illustrate the implementation of the design procedure.

Acknowledgments—Jointly supported by: NIGMS GM-14267-11 and NASA NGR-36-027-053 and Dr. Robert Collin's many contributions.

References

TERMAN, F. E. (1943). *Radio engineers handbook*. McGraw-Hill, New York.

SMYTHE, W. R. (1968) *Static and dynamic electricity*. McGraw-Hill.

HARNWELL, G. P. (1949) *Principles of electricity and electromagnetism*. McGraw-Hill

Bibliography

ADAMS, R. M., FROMME, G. L., DIZON, D. and ANSTADT, G. L. 'A Microwatt VHF Telemetry system for implantation in small animals' In : *Proceedings of the National Telemetering Conference*, 1963.

MACKAY, R. S., 'Telemetering from within the body of animals and man : Endoradiosondes." In: *Biomedical Telemetry*, C. A. Caceres, ed. Academic Press, 1965.

DOUGLAS, D. W. and SEAL, H. R., 'Internalized animal telemetry systems: Electronic considerations' In: *32nd Annual Meeting of Aerospace Medical Association*, Chicago, April 21, 1961.

KAVANAGH, D. A., 'Development of miniature telemetry system' R. F. Communication, Inc. Rochester, N. Y., Report SAMJ-TDR-63-80, 1963

Bobines f.r. concues pour les appareils d'implants

Sommaire—On a étudié la fréquence radio (f.r.) en tant que source extérieure permettant de faire fonctionner les systèmes télémétriques d'implants miniatures à long terme. Afin d'assurer une efficacité totale au système, il est nécessaire d'obtenir un transfert de puissance optimum de l'émetteur à la bobine réceptrice. On donne la description d'une technique de conception en sept temps, fondée sur la fréquence radio, le diamètre de la bobine, l'espacement des spires, la charge et le nombre de tours de la bobine. Un circuit de captage de tension par induction et un circuit doubleur de tension ont été construits conformément à la méthode de conception. Les résultats expérimentaux étaient compris dans les limites d'efficacité totale souhaitable pour le système, soit 18% à 23%, respectivement.

Konstruktionsprinzipien für Hochfrequenzspulen für Implantatinstrumente

Zusammenfassung—Hochfrequenz wurde als Mittel zur externen Energieversorgung von Miniatur und langfristigen Implantat-Telemetriesystemen untersucht. Zur Verwirklichung der höchsten Leistungsfähigkeit braucht das System optimale Energieübertragung von Sendegerät zu Empfangsspule. Ein auf Hochfrequenz beruhendes siebenstufiges Konstruktionssystem für Sende- und Empfangsspulen wird beschrieben, mit Hinweisen über Spulendurchmesser, Spulenanordnung, Ladung und die Anzahl der Wicklungen. Ein Induktionsanzapfstromkreis und ein Spannungsverdoppler wurden dem Konstruktionsverfahren entsprechend gebaut. Versuchsergebnisse lagen im Bereich des gewünschten Systemleistungsgrades von 18% und 23%.