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Reactive Component Selection for TET Powered Medical Devices

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***Abstract*—Transcutaneous energy transfer (TET) is capable of supplying power across the skin to implantable devices and avoids the risk of infection associated with wires passing through the skin. These systems rely on a high frequency magnetic field to overcome the relatively low coupling between a coil located outside the body, and a coil implanted within the body. This paper introduces a new optimisation procedure to choose tuning capacitors that minimises the amount of power dissipated in the power transfer coils of an implantable TET system. The frequency of operation is determined by the selection of the resonant reactive components. By analysing the overall circuit impedance it is possible to observe that a Zero Voltage Switched TET system may dissipate different amounts of power in the power transfer coils while delivering the same amount of power. In this study an objective function was developed to determine the best configuration of resonant capacitors for any particular set of TET coils in order to minimize power loss. The method is used to find the value of the resonant capacitors for a system delivering 15W over a coupling range of *k*=0.1 to 0.55 (corresponding to a separation of up to 20mm).**

***Index Terms*—Magnetic coupling, transcutaneous energy transfer (TET), implantable biomedical devices.**

I. INTRODUCTION

Implantable heart pump technology has been shown to be reliable in terms of moving blood effectively without causing damage to the blood cells or clotting [1],[2]. The greatest cause of serious adverse events is associated with infection, and this is dominated by the need to have a wire penetrating through the skin to provide power [3] to meet the continuous high power needs of 5-15W. Transcutaneous Energy Transfer (TET) eliminates percutaneous wires through the use of magnetic fields to transfer power across the skin. This is achieved by generating fluctuating magnetic fields with a primary coil outside the body and with the magnetic flux passing through the skin and interacting with a secondary coil implanted inside the body. At the secondary, voltage is induced and is used to power the device. A TET system aimed at delivering power to artificial hearts using thin and compact air-cored coils 50 mm in diameter has been developed by Dissanyake et. al. [4].

With the presence of resonant circuits, different amounts of power may be dissipated in the TET coils although the same amount of power is being delivered to the load. The resonant current and frequency is not just dependent on the load but also significantly dependent on the equivalent impedances reflected onto the system. Here we analyse the primary and secondary side impedance to determine these resonant currents inorder to find the optimal resonant tank tuning capacitor values that minimise the power loss in anyparticular set of TET coils over a specified coupling range.

II. SYSTEM ARCHITECTURE

A TET system for delivering power to high power implantable devices is shown in Fig. 1. It consists of a zero voltage switched push-pull parallel resonant converter and a parallel tuned resonant pickup with a resistive AC load. The circuit is soft switched via a Phase Lock Loop (PLL) control circuit which is triggered by the zero crossing of the primary side resonant voltage. More information regarding the push-pull converter used here is found in [5].

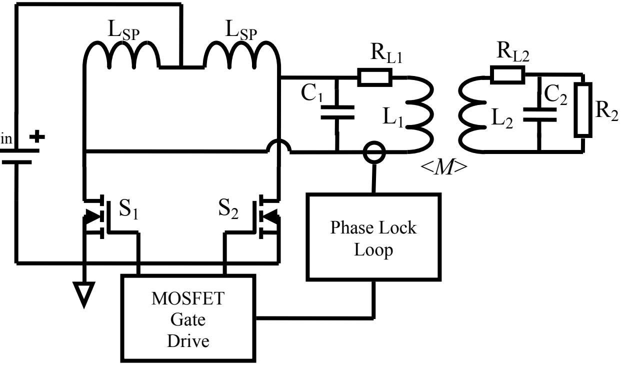

Fig. 1 Push-pull parallel resonant converter with parallel resonant pickup

L_1 and L_2 are the self inductance of the primary and secondary energy transfer coils respectively and are coupled together with a mutual inductance *M*. R_{L1} and R_{L2} are the frequency dependent equivalent series resistance (ESR) of the primary and secondary coils respectively. C_1 and C_2 are the primary and secondary tuning capacitors respectively and are in place to form a parallel resonant circuit with the energy transfer coils. R_2 represents the implantable load. Adding a rectification circuit provides power for a medical device.

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Energy transfer coils L_1 and L_2 as shown in Fig. 2 are air-cored coils made with 1.8mm diameter Litz wire consisting of 405 strands. The coils are designed with a low profile and are embedded in biocompatible silicon making them suitable for implantable devices. The spiral winding of the coils provides good tolerance to displacement of the coils while maintaining an acceptable level of coupling [6]. The self inductances of the primary and secondary coils are approximately 12µH and 3µH respectively.

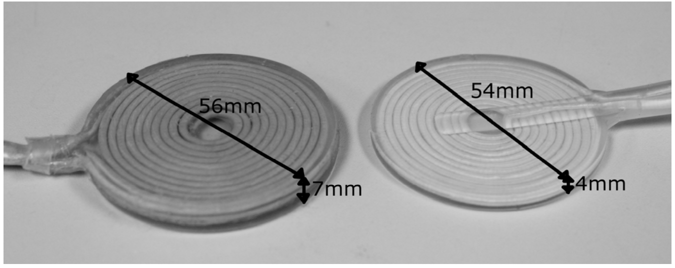

Fig. 2 TET coils. Left, primary coil; right, secondary coil

Operating displacement range is considered to be either a separation of 20mm vertically or 25mm laterally, both cases corresponds to the minimum operating coupling factor of approximately k=0.1. This low coupling condition is expected to cover reasonable changes in coupling due to surgical placement, posture, patient alignment and differences in body shape. Maximum coupling is achieved when the coils are right on top of each other and corresponds to a coupling factor of approximately k=0.55. Thus the operating coupling range for our energy transfer coils is k=0.1 to 0.55.

The ESRs of the energy transfer coils were measured with a FLUKE PM6360 RCL meter at frequencies starting from 50 kHz to 400 kHz at 10 kHz intervals. A plot of the ESR of L_1 and L_2 are shown in Fig. 3.

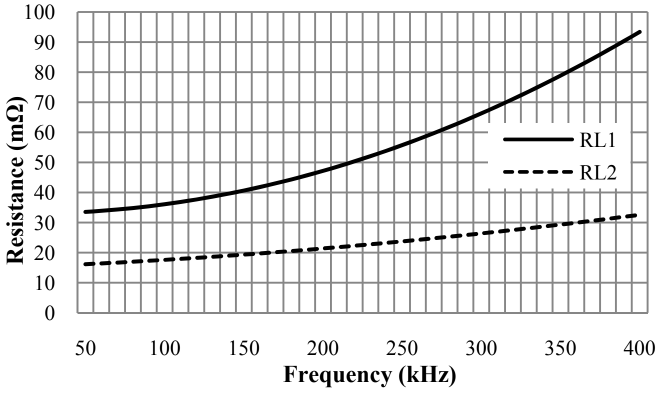

Fig. 3 ESR of primary and secondary TET coils

III. SYSTEM IMPEDANCE ANALYSIS

For efficient operation of a TET system, it is important to implement soft switching techniques such as zero voltage switching (ZVS) or zero current switching (ZCS). The operating frequency of the system discussed in this paper will be the ZVS frequency of the system.

The resonant part of the TET system consists of four reactive components they are L_1 (with R_{L1}), L_2 (with R_{L2}), C_1, C_2 and R_2 as defined previously. The effect of the coupling between L_1 and L_2 can be represented as a current dependent voltage source [7] as shown in Fig. 4(a). Due to the coupling k between the primary and secondary the total impedance seen by the converter is 4th order impedance [5]. The secondary circuit can be reflected onto the primary as an impedance Z_R as illustrated in Fig. 4(b).

The impedance of the reactive components are expressed in terms of angular frequency ω as given in Eq. 1 and the relationship between coupling k and mutual inductance M is given in Eq. 2.

$$\omega = 2\pi f \tag{1}$$

$$M = k\sqrt{L_1 L_2} \tag{2}$$

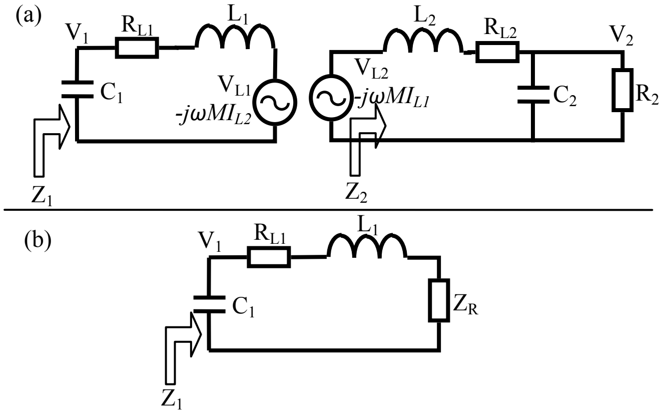

Fig. 4 (a) Effect of coupling reflected as voltage sources. (b) Secondary impedance reflected onto the primary.

The resonant currents I_1 and I_2 that flow in L_1 and L_2 are defined in Eq. 3 and 4, together with R_{L1} and R_{L2} they determine the power dissipated in the primary and secondary energy transfer coils. The combined energy transfer coil loss is given in Eq. 5.

$$I_1 = \frac{V_1}{j\omega L_1 + R_{L1} + Z_r} \tag{3}$$

$$I_2 = \frac{j\omega M I_1}{Z_2} \tag{4}$$

$$Combined\ coil\ loss = {I_1}^2 R_{L1} + {I_2}^2 R_{L2} \tag{5}$$

Z_2 is the secondary side impedance and Z_R is the reflected secondary side steady-state impedance as given in Eq. 6 and Eq. 7 respectively. The combined steady-state impedance Z_1 seen by the primary converter for a parallel-parallel tuned TET system is given in Eq. 8. The RMS output voltage V_2 at the load R_2 is given in Eq. 9.

$$Z_2 = j\omega L_2 + R_{L2} + \frac{R_2}{1 + j\omega C_2 R_2} \tag{6}$$

$$Z_r = \frac{V_r}{I_{L1}} = \frac{(\omega M)^2}{Z_2} \tag{7}$$

$$Z_1 = \frac{j\omega L_1 + R_{L1} + Z_r}{1 + j\omega C_1 \cdot (j\omega L_1 + R_{L1} + Z_r)} \tag{8}$$

$$V_2 = j\omega M I_{L1} - (j\omega L_2 + R_{L2}) \cdot I_2 \tag{9}$$

IV. MINIMAL COIL LOSS OPTIMISATION PROCEDURE

A. Objective Function

The purpose of the proposed Minimal Coil Loss optimisation procedure is to acquire the values of the resonant tank capacitors such that there is minimum power loss in the TET coils across the specified operating coupling range. While output power regulation was performed via primary side magnitude control by varying the input voltage V_{in}. The objective function to be minimised is the total power being dissipated by the primary and secondary TET coils as represented in Eq. 5. Note that resistances R_{L1} and R_{L2} are frequency dependent terms.

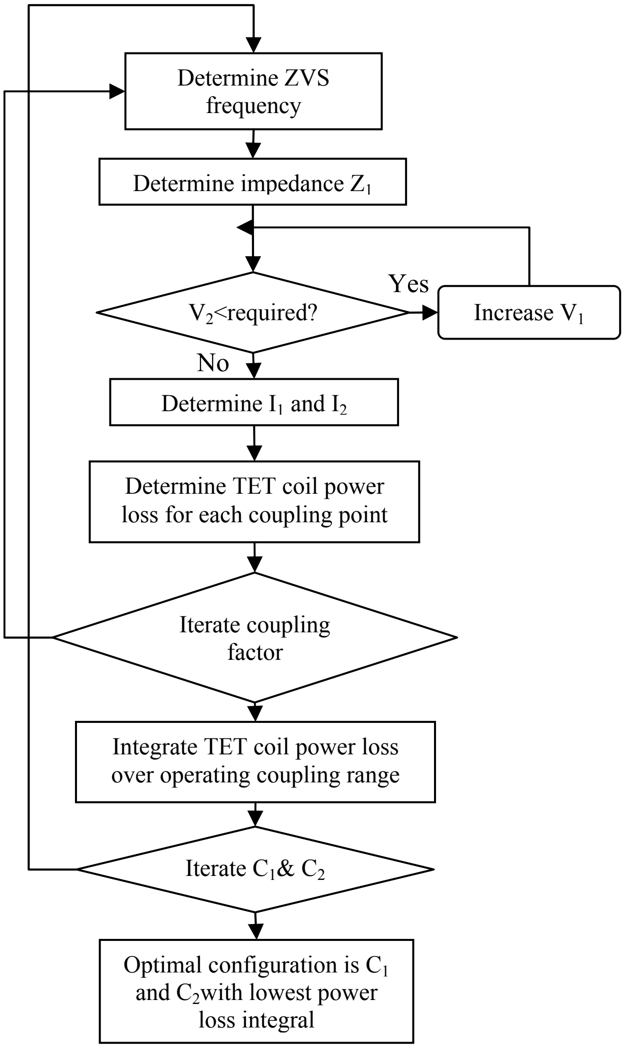

Fig. 5 Flowchart of Minimal Coil Loss optimisation procedure

B. Procedure

The procedure to determine the optimalvalues of C_1 and C_2 for minimum loss in the TET coils for the specified operating coupling range is summarised here. Each value of C_1 and C_2 is iterated and the ESR losses of the coils are calculated at each coupling factor. Then integral of the power loss over the desired operating coupling range is then calculated, the C_1 and C_2 pair with the lowest integral is the optimal pair, this procedure is shown in Fig. 5. The operating frequency of the circuit was determined using a method based on a stroboscopic mapping model [8] to accurately determine the ZVS frequencies of a push-pull converter.

V. RESULTS

A. Comparison of configurations

The optimal configuration for the coupling range of *k*=0.1 to 0.55 determined by the procedure was C_1 = 42nF and C_2 = 154nF.

It can be seen that the primary and secondary resonant capacitors with their respective coils do not tune to the same natural frequency. This is because as coupling increases, the natural resonant frequency begins to deviate from the unloaded tank frequency. Hence the traditional tuning method of tuning the primary and secondary tanks to the same nominal frequency is only suitable for loosely coupled TET systems. The power loss of the optimal configuration determined for the coupling range of *k*=0.1 to 0.55 and two traditionally tuned systems at 200 and 300 kHz nominal, are compared in Fig. 6 at each coupling point from *k*=0.1 to 0.55. In Fig. 6 it can be seen that the 200 kHz nominally tuned configuration bifurcates when coupling *k* exceeds 0.45 and losses in the TET coils increases significantly. The 300 kHz nominally tuned configuration also does not bifurcate in this coupling range but its losses are high at low coupling conditions.

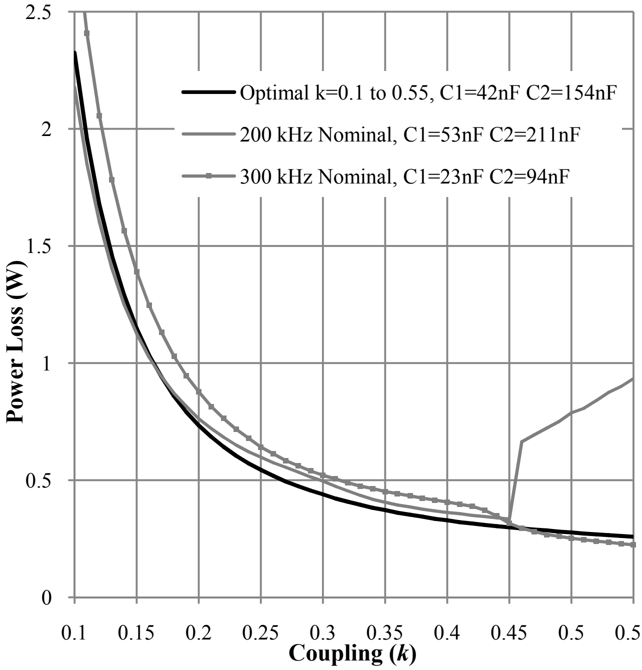

Fig. 6 Plot of power loss vs. coupling, for optimal configuration (*k*=0.1 to 0.55), 200 kHz and 300 kHz nominally tuned configurations.

In Fig. 7 the average TET coil's power loss over the coupling range of *k*=0.1 to 0.55 for nominally tuned configurations with a nominal frequency of 150 to 350 kHz is shown. Here we can see that the minimum loss for this set of TET coils and loading conditions is when the nominal frequency is approximately 250 kHz, but the optimal configuration determined by the Minimal Coil Loss procedure still gives a lower power loss.

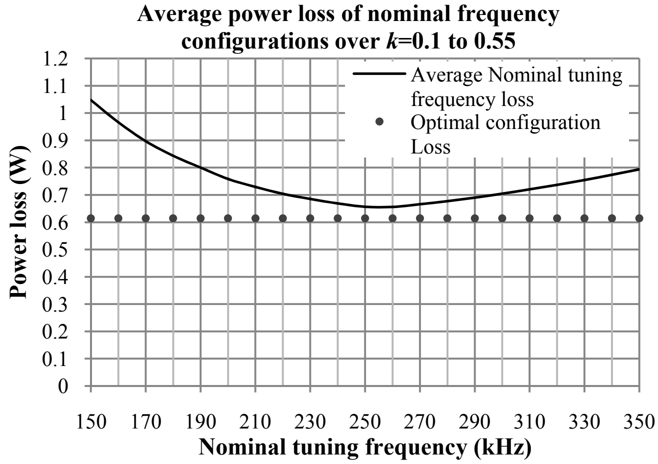

Fig. 7 Plot of average power loss of nominal frequency tuned configurations from 150 to 350 kHz; the power loss level of the k=0.1 to 0.55 optimal configuration is indicated by the dotted line.

B. *Advantages of the Minimal Coil Loss optimisation procedure*

The main purpose of the Minimal Coil Loss optimisation procedure is to determine the capacitor configuration that gives the lowest power loss in the TET coils. But it also implicitly determines a frequency stable capacitor configuration. As configurations with frequency instability would be rejected due to increased power losses in the TET coils. In addition optimisation procedure automatically penalises any capacitor configuration that bifurcates with the specified coupling range. Thus the optimal configuration will not bifurcate within the specified coupling range by shifting the bifurcation point beyond the specified coupling range. This is desired as bifurcation causes instability in system control and depending on the control scheme it may even collapse the circuit resonance.

C. *Practical Results*

Fig. 8 compares the ZVS frequency determined by the stroboscopic mapping model to the ZVS frequency found seen in practice.

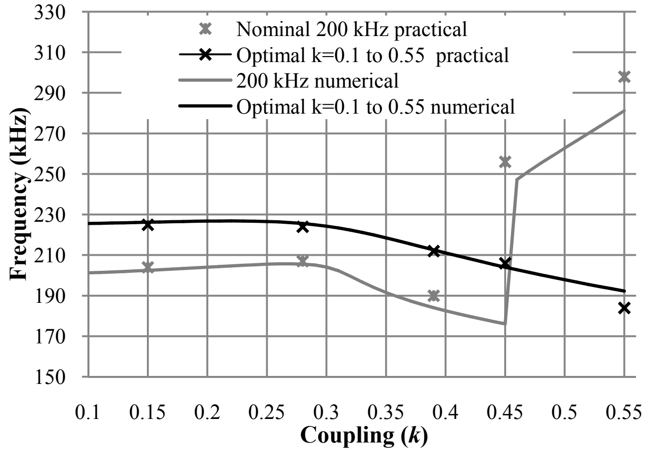

Fig. 8 Practical vs. numerical operating frequency

Fig. 9 compares the measured power loss in the TET coils compared to the simulation. The differences are expected to be due to parasitic properties in the system.

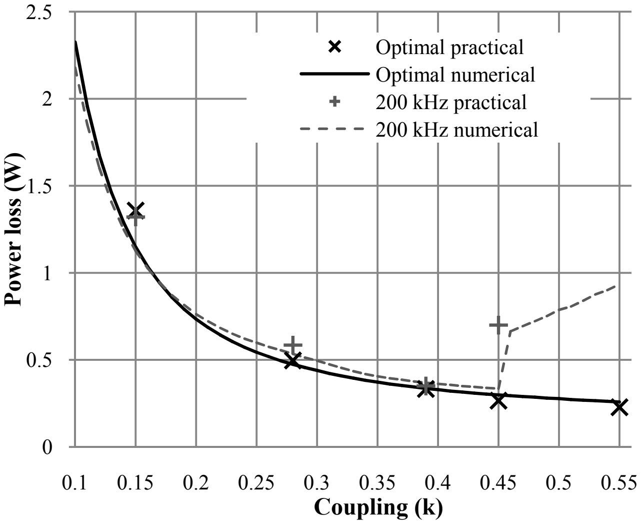

Fig. 9 Practical vs. numerical power loss

VI. CONCLUSION

TET systems rely on resonant circuits to transfer power under variable coupling and load conditions. We have presented a systematic method for selecting the resonant capacitors that minimises the power loss of the TET coils over an extensive variation in coupling. The process also provides an operating frequency stable configuration by avoiding bifurcation. Based on this method, TET systems can be designed to run with minimal heat generation in the TET coils and be highly tolerant to variations in coupling.

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