Universal output characteristics of the two-coils resonant inductive powering unit for implantable devices

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Introduction

Energy transfer stability is one of the primary concerns in resonant inductive powering units (IPUs) for implantable medical devices [1–5]. Low stability is primarily caused by misalignment of the transmitting and receiving coils and postoperative tissue swelling, and can lead to undesirable ripple of output voltage and low efficiency of the energy transfer. A number of scientific works are dedicated to techniques aimed for compensation of the effect of misalignments in IPU [6–9]. Besides mentioned practices the problem of evaluating IPU characteristics in terms of stability exists [10, 11]. Solution of this problem will ensure better understanding of the principal limitations of inductive powering and will enhance future design and optimization procedures of IPUs.

The main objective of the study was evaluation of the coils coupling effect on the two-coils IPU output. Systems operating at fixed frequency and based on resonant frequency tracking were considered. Derived universal output of the IPU was analyzed in the scope of the work.

Materials and Methods

Inductive powering unit equivalent circuit was analyzed (fig. 1). DC from the power supply is converted to AC by the inverter circuit. Resulting AC is driving primary (transmitting) coil. Alternating magnetic field generated by the primary coil induces AC current in the receiving coil. After that, rectifier converts AC to DC that flows into the load. However, simplified circuit shown in figure 1 will be used for the further analysis. Here, power supply and inverter are combined and represented by AC voltage source V_S. In its turn, rectifier is not included in the circuit. Resistor R_T represents combined losses in the transmitter, R_R represents losses in the receiver (usually caused by rectifier and regulator circuits). L_T, C_T and L_R, C_R are inductances and capacitances of the transmitter and receiver. M is mutual inductance of the transmitting and receiving coils. It is key parameter to describe effect of misalignment between the coils on the system output. Sometimes, another parameter, so-called coupling coefficient, is used for this purpose. Coupling coefficient can be described as the fraction of the flux generated by the primary coil which is captured by the secondary coil (and vice versa) and can be calculated as follows:

$$k = \frac{M}{\sqrt{L_T L_R}} \qquad (1)$$

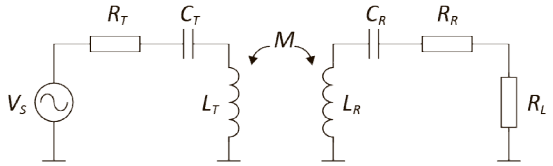


Figure 1: Basic equivalent circuit of the inductive powering unit

Coupling coefficient value can vary in range from zero to unity. Zero coupling coefficient corresponds to two distant coils that do not share any common magnetic flux. In its turn, coupling equals unity when transmitting and receiving coils are perfectly aligned and located very close. In the case of implantable devices coupling coefficient value is changes. This changes mainly caused by recipient activity and postoperative tissue swelling.

For the circuit shown in figure 1 equations for voltage gain, output power and total energy transfer efficiency of the system were derived. Voltage gain G_V can be calculated as:

$$G_V = \frac{\omega M R_L}{Z_T Z_R + \omega^2 M^2} \qquad (2)$$

here Z_T is impedance of the transmitter, Z_R is impedance of the receiver, ω is angular operating frequency of the IPU. The impedances are calculated as:

$$Z_T = R_T + j\left(\omega L_T - \frac{1}{\omega C_T}\right) \qquad (3)$$

$$Z_T = R_R + R_L + j\left(\omega L_R - \frac{1}{\omega C_R}\right) \qquad (4)$$

Output power of the system PL can be found as:

$$P_L = \frac{\omega^2 M^2 V_S^2 R_L}{(Z_T Z_R + \omega^2 M^2)^2} \qquad (5)$$

Finally, total energy transfer efficiency is calculated as:

$$\eta = \frac{\omega^2 M^2 R_L}{Z_R (Z_T Z_R + \omega^2 M^2)} \qquad (6)$$

Frequency response of the inductive powering unit output (voltage gain, output power and energy transfer efficiency) is a function of coils mutual orientation. The mutual orientation of the coils couple can be described using either mutual inductance or coupling coefficient. Figure 2 illustrates output power of inductive powering unit as a function of operating frequency of the system and coupling coefficient. Three distinctive operating areas can be distinguished: undercoupling, critical coupling and overcoupling.

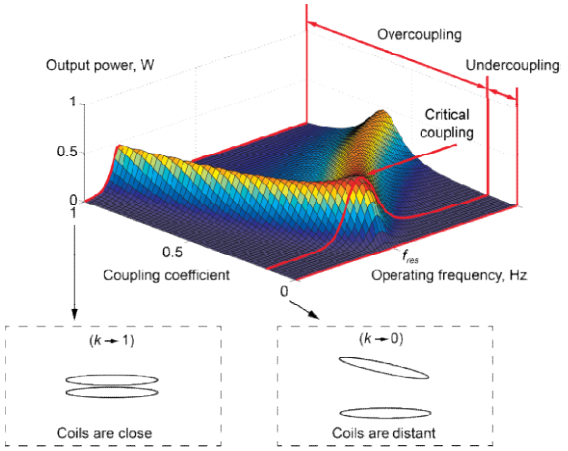


Figure 2: Output power of inductive powering unit as a function of operating frequency and coupling coefficient

In the undercoupling area decrease in coupling coefficient leads to decrease in the output power and energy transfer efficiency. Thus, system output is not stable and operation in this area should be avoided for the most applications. Critical coupling is very important concept in inductive power transfer [12]. Critical coupling value corresponds to the point of maximum output power for the given source and load. However, it restricts energy transfer efficiency in critical coupling point by 50%. Worth noticing, that it is very similar to maximum power transfer theorem. Critical coupling can be calculated as:

$$k_{crit} = \frac{1}{\sqrt{Q_T Q_R}} \qquad (7)$$

here, Q_T and Q_R quality factors of the transmitter and receiver.

Critical coupling is a function of circuit parameters only and is not affected by the misalignment of the coils. Design procedures targeting maximization of output power should be focused around operation at the critical coupling area.

In the overcoupling area, resonance frequency splits into two different frequencies. These two frequencies are called odd and even splitting frequencies and vary with changes in coupling coefficient. However, output parameters are perfectly stable in this area if operating frequency of the inductive powering unit corresponds to the odd or even frequency. Equations for these frequencies have been found to calculate output of the system in overcoupling area. However, resulting formulas are too bulky and not shown in the paper for this reason.

Results of the IPU output characteristics analysis at critical coupling and in overcoupling area are given in following section.

Results

Critical coupling point corresponds to the maximum voltage gain and output power. Exact value of these parameters in the point of critical coupling can be found by analyzing inductive powering unit operating on a fixed resonant frequency. To find the parameters coupling coefficient in equations (2), (5) and (6) must be substituted by critical coupling value from equation (7). Coupling coefficient need to be converted to mutual inductance using equation (1). By doing so equation for voltage gain in the point of critical coupling can be found:

$$G_{V_CC} = \frac{R_L}{2\sqrt{R_T(R_L + R_R)}} \qquad (8)$$

Similarly, equation for output power in the point of critical coupling:

$$P_{L_CC} = \frac{V_S^2 R_L}{4R_T(R_L + R_R)} \qquad (9)$$

It must be noticed, that in the case when resistance of the receiver is much smaller than load resistance voltage gain is defined only by voltage supply and transmitter resistance. Thus, voltage gain is independent from the parameters of the receiving part of the inductive powering system.

Total energy transfer efficiency of the system in the point of critical coupling:

$$\eta_{CC} = \frac{R_L}{2(R_L + R_R)} \qquad (10)$$

As we can see, energy transfer efficiency in the point of critical coupling is limited by 50%.

Oscillating LC-circuits parameters have no effect on the value of output parameters of the inductive powering unit in the critical coupling point. However, inductances and capacitances still define position of the critical coupling point on the axis of coupling coefficient.

Key finding of this paper is that universal output of the inductive powering unit can be found if coupling coefficient normalized by critical coupling value. Voltage gain and output power were normalized by their corresponding maximums for further generalization of obtained results. Figure 2 shows corresponding universal output for inductive powering unit operating on fixed resonant frequency.

Figure 2 demonstrates that twofold increase (or decrease) of the coupling coefficient from critical coupling will always lead to 38% decrease in output power, and 30% increase (or 30% decrease) in energy transfer efficiency. Another conclusion that can be made is that decrease of coils inductances leads to increase of critical coupling and, therefore, to decrease in the distance between the coils at which critical coupling is observed. At the same time the inductive powering unit tolerance to coils misalignment is enhanced. This is a trade-off that must be considered in the design procedure of inductive powering unit.

Analysis presented further is similar to the presented above. The only difference is that inductive powering unit tracks resonant frequency for the whole range of coupling coefficient. Thus, ideally stable output characteristics of the system are achieved in overcoupling area. It is important to be able to analytically find exact values of the output characteristics. To analyze operation of the system in overcoupling area parameter called splitting coupling must be introduced.

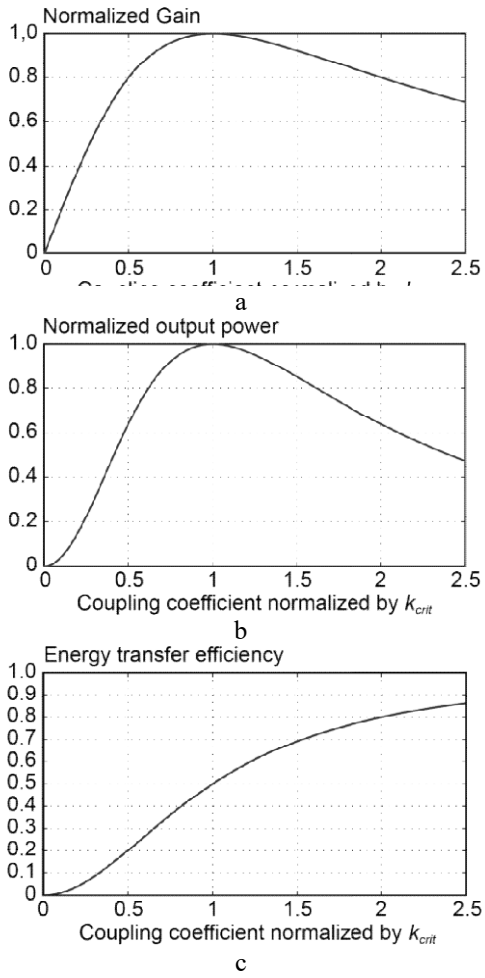


Figure 3: Voltage gain normalized by its maximum value (a), output power normalized by its maximum value (b) and energy transfer efficiency (c) as a function of coupling coefficient normalized by critical coupling for the system operating at fixed frequency

Splitting coupling defines the value of coupling coefficient that corresponds to transfer from single mode resonant frequency to odd and even coupling-dependent resonant frequencies (as can be seen on fig. 2). Splitting coupling is a function of receiving side parameters only and can be calculated as:

$$k_{split} = \frac{1}{Q_R} \qquad (11)$$

To find the output parameters of the IPU operating on the tracked resonant frequency coupling coefficient in equations (2), (5) and (6) must be substituted by splitting coupling value from equation (11). Coupling coefficient must be converted to mutual inductance using equation (1). By doing so voltage gain in the overcoupling area can be found:

$$G_{V_OC} = \frac{\sqrt[4]{\frac{L_T C_R}{L_R C_T}} R_L}{R_T + \sqrt{\frac{L_T C_R}{L_R C_T}}(R_L + R_R)} \qquad (12)$$

Similarly, equation for output power in overcoupling area:

$$P_{L_OC} = \frac{\sqrt[4]{\frac{L_T C_R}{L_R C_T}} V_S^2 R_L}{\left(R_T + \sqrt{\frac{L_T C_R}{L_R C_T}}(R_L + R_R)\right)^2} \qquad (13)$$

Equation for IPU efficiency in overcoupling area:

$$\eta_{OC} = \frac{\sqrt{\frac{L_T C_R}{L_R C_T}} R_L}{R_T + \sqrt{\frac{L_T C_R}{L_R C_T}}(R_L + R_R)} \qquad (14)$$

Figure 3 illustrates universal output for inductive powering unit operating on tracked resonant frequency.

It can be noticed that resulting equation (12), (13), (14) for IPU output characterstics in overcoupling area are not very representative and not suitable for deriving analytical conclusions. Parameter β is introduced to solve this issue. Parameter β is defined as relation between splitting coupling and critical coupling:

$$\beta = \frac{k_{split}}{k_{crit}} = \sqrt{\frac{Q_T}{Q_R}} \qquad (15)$$

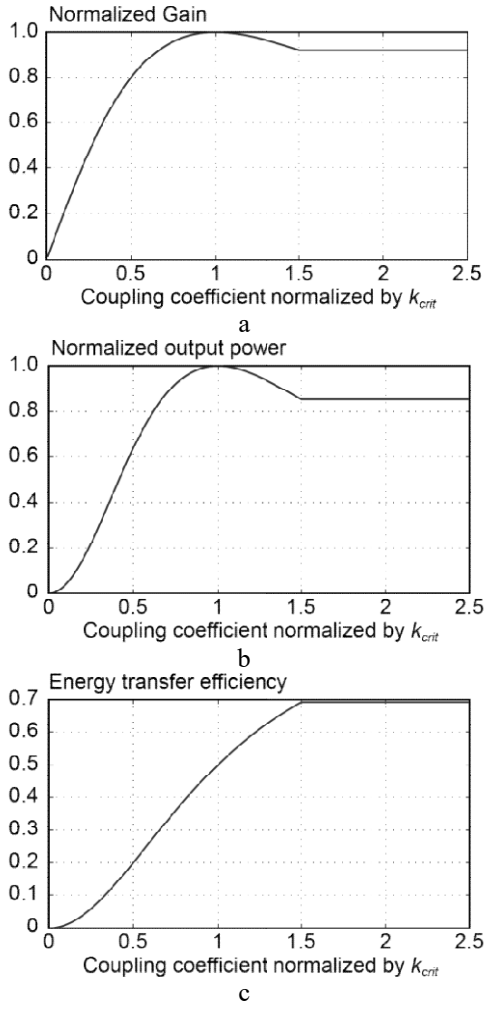


Figure 4: Voltage gain normalized by its maximum value (a), output power normalized by its maximum value (b) and energy transfer efficiency (c) as a function of coupling coefficient normalized by critical coupling for the IPU operating at tracking resonant frequency

Using equation (15) we can transform equation for the output parameters (12), (13), (14) to more representative form. Voltage gain in overcoupling area expressed in terms of parameter β:

$$G_{V_OC} = \frac{2\beta}{(1+\beta^2)} G_{V_CC} \qquad (16)$$

Output power in overcoupling area expressed in terms of parameter β:

$$P_{L_OC} = \frac{4\beta^2}{(1+\beta^2)} P_{L_CC} \qquad (17)$$

Efficiency in overcoupling area expressed in terms of parameter β:

$$\eta_{OC} = \frac{2\beta^2}{(1+\beta^2)} \eta_{CC} \qquad (18)$$

Output parameters in overcoupling area match output in point in critical coupling point if parameter β equals unity. Tradeoff between the output power/voltage gain and energy transfer efficiency can be observed. Inductive powering unit cannot simultaneously obtain high efficiency and high power output for the given source and load.Value of output parameters in overcoupling can be regulated by adjusting relation between the quality factors of the transmitter and receiver of inductive powering unit.

Conclusion

Universal output power and efficiency of the system operating at fixed frequency was found by normalizing coupling coefficient of two-coils wireless resonant power system by critical coupling. Deviation of the output characteristics as a function of coils coupling was found. Similar universal output was found for the two-coils wireless resonant system operating at tracked resonant frequency. In this case another parameter, so-called, splitting coupling must be considered to find the output parameters. At critical coupling maximum output power is a function of only the power source and resistances in the transmitter and the receiver. However, critical coupling position in space-frequency coordinates remains a function of the receiver resistance as well as inductances and capacitances of the system. It can be noted that in the case of the wireless system operating at fixed frequency the main tradeoff that must be considered is tradeoff of the distance between the coils and permissible misalignment of the coils. In the case of the system operating at self-resonant frequency the main tradeoff is tradeoff between output power level and energy transfer efficiency. Therefore, there is no single best operational mode of inductive powering unit. Benefits and drawbacks of operation in different coupling coefficient areas must be taken into account in regards to specific load. Achievable quality factors and critical coupling point are important parameters in the IPU design procedure. Worth mentioning, that both these parameters are heavily influenced by the geometry of the system

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