Optimizing Transcutaneous Energy Transmitter using Game Theory

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Over the past recent years, several researches, seeking reliable Transcutaneous Energy Transmitters (TET), have used different type of optimization techniques with different objectives. Algorithms with multiple objectives and constraints resulted in different configurations in the Pareto front, making the decision of the final configuration harder. Moreover, the game theory has been gaining a lot of ground in the engineering design, mainly in decision-making in optimization problems. This research uses the advantage of the game theory together with genetic algorithm to find one final configuration of TET, which fulfills the specified constraints while optimizing different objective functions. It uses three players playing with six different variables which were assigned to each player in a strategic manner according to each player's target.

Index Terms— Game theory, Optimal design, Inductive power transmission

I. Introduction

TRANSCUTANEOUS Energy Transmitters (TET) are systems widely studied by several researchers with the aim of transferring energy inside the body without percutaneous electrical leads that can cause infection due to wires passing through the skin. TETs normally use an inductive link between a primary coil external to the body and a secondary coil underneath the skin, similar to a coreless transformer [1]-[3]. Since they perform such an important task, seeking the smallest coils that transfer the necessary power at the maximum efficiency has attracted attention over recent years. This search was the goal of [4], which used multiobjective genetic algorithm (MGA) optimization, having 7 final different configurations in the Pareto front (PF). The problem has become to decide which of the configurations from the PF should be used. In recent years, new kinds of optimization methods have been investigated and among them the game theory. In actuality, the game theory is not categorized into an optimization method in an engineering field but into a decision-making method in economics. Nevertheless, it was used in multiobjective optimal design problems of electromagnetic apparatus [5], [6].

For more practical use of an optimization shape design method, it is necessary to optimize several objectives, and the result to be obtained has to be rational from the viewpoints of engineering, robustness, and productivity. In this paper, a method utilizing the game theory is proposed for obtaining the smallest TET coils with the maximum transmission efficiency and the least coil heating possible that supply the necessary power at the required voltage ranges.

II. Transcutaneous Energy Transmitter Optimization

A. Transcutaneous Energy Transmitter

Fig. 1 shows the TET system to be optimized. It is composed of two coils: one that transmits the power (primary coil) with N_1 turns of gauge AWG_1, and another that receives the power (secondary coil) with N_2 turns of gauge AWG_2. The primary coil is supplied with voltage V_1 at frequency *Freq* from a switching control system. The secondary coil uses the received power to feed a rectifier with a controller that supplies power to an artificial organ. The system composed of the rectifier, controller and artificial organ consumes constant power P_2 when the received voltage V_2 is within some specified limits.

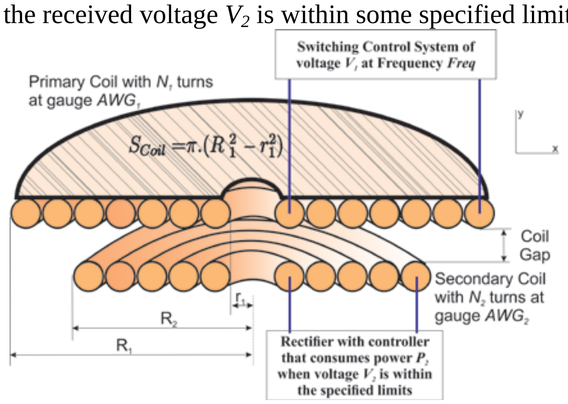

Fig. 1. Representation of the TET system.

B. Parameters of the optimization

Similarly to [4], in this paper, the increase of temperature is indirectly accounted for by the relation of the dissipated power ($P_{dissipated}$) in W to the coil area (S_{Coil}, see Fig.1) in m^2, denominated "thermo factor" (λ) in W/m^2:

$$\lambda = \mathrm{P_{dissipated}} / \mathrm{S_{Coil}} \tag{1}$$

Finding the smallest TET coils with the smallest "thermo factor" is desired to supply the required power at the required voltage limits for a range of specified coupling situations. Moreover, the efficiency of the transmission (η) should also be consider to avoid unnecessary losses during the transmission and to allow more efficient electronic circuits to supply and to receive power to and from the TET coils. However, the "thermo factor" and the transmission efficiency depend on the coil gap (see Fig. 1). This would make an extremely large number of objective functions unless these objective functions are grouped together, such as:

$$\begin{cases} f_1 = \sqrt{\sum_i \left(\lambda_{1,i}^2\right)} \quad ; \quad f_2 = Vol_1 \\ f_3 = \sqrt{\sum_i \left(\lambda_{2,i}^2\right)} \quad ; \quad f_4 = Vol_2 \\ \quad f_5 = 100 - mean(\eta_i) \end{cases} \tag{2}$$

In (2), *Vol* is the coil volume in cm^3, λ is the coil "thermo factor" in W/m^2, η is the efficiency in %, the subscripts 1 and 2 respectively represent the primary and secondary coils and the subscript i is the coil gap index at which the TET was simulated (4, 8, 12, 16, 20 and 25 mm).

The TET parameters that could help meeting the demands of this project (variables of decision of the optimization) are described in II.A (N_1, N_2, AWG_1, AWG_2, V_1, and *Freq*).

Guaranteeing that the TET will always be able to supply the required power (P_2) at the right range of voltage to the internal system (V_2) at the specified distances is of extreme importance. Thus, the transfer power and voltage must be mandatory constraints at each distance between coils from 4 to 25 mm, totalizing 18 constraints. These non-linear constraints allow a more reliable TET operation.

Note that the objective functions f_2 and f_4 depend only on the variables N_1, AWG_1 and N_2, AWG_2, respectively. However, all other functions depend on all 6 variables of decision.

III. Game Theory applied in the optimization of TET

The objective of the game is to minimize "thermo factor" and volume simultaneously in both coils while maximizing efficiency in transmitting the required power.

According to [6], each objective function related to each player depends on all the variables of decision, i.e., it depends on the variable controlled by its player as well as on all the other variables controlled by the other players, which are fixed at the moment that the specific player plays.

At this point of view, f_2, for example, is not a good function to be adopted as an objective of a player because it does not depend on N_2, AWG_2, V_1 and *Freq*. The same applies for f_4. Hence, a game with 5 players, each with one objective function, would not work well.

For this reason, three players were considered in this game: i) Player 1 (P_1) deals with the primary coil, i.e., P_1 controls the variables of decision of the primary coil (N_1 and AWG_1) to minimize the progression of "thermo factor" and volume of the primary coil ($f_1 / f_{1old} + f_2 / f_{2old}$); ii) Player 2 ($P_2$) deals with the secondary coil. That means, P_2 controls the variables of decision of the secondary coil (N_2 and AWG_2) to minimize the progression of "thermo factor" and volume of the secondary coil ($f_3 / f_{3old} + f_4 / f_{4old}$); and iii) Player 3 ($P_3$) controls the TET power transmission capability, i.e., the general variables of decision (*Freq* and V_1) to maximize the efficiency (η) (minimizes f_5). The functions used by all players (f_1, f_2, f_3, f_4 and f_5) are defined in (2); f_{iold} is the value of the function i at the previous iteration.

In this paper, each player uses GA to minimize its objective function with the defined constraints. The game starts with an initial configuration, which is part of the initial population of the GA. Then, one by one, each player plays, optimizing its objective function by varying its controlled variables while the variables of the other players remain fixed at their previous values. In the case of P_1 and P_2, they also use the values of f_1, f_2 and f_3, f_4, respectively, from the configuration before they start their optimization (f_{1old}, f_{2old} and f_{3old}, f_{4old}).

IV. Results

The development of the game applied in this paper is shown in Table I. The game was composed of 4 rounds after the starting configuration (N_1 = 60 turns, N_2 = 23 turns, AWG_1 = 20, AWG_2 = 25, V_1 = 25 V, and *Freq* = 144 kHz). The configurations in all the tries do not violate any constraint. At each round, the target of each player either improved or worsened depending on who was playing. However, at the final round, each player could not find any other variables that could improve their targets, thus reaching equilibrium with the final configuration (N_1 = 61 turns, N_2 = 21 turns, AWG_1 = 32, AWG_2 = 28, V_1 = 27 V, and *Freq* = 205 kHz).

When increasing the coil gap, the configuration selected by the game decreases the load voltage from 28 to 8 V and the transmission efficiency from 72 to 62%, while supplying constant power of 19 W. These results show a reliable TET design.

TABLE I
Development of the Game

		Variables						Objective functions				
		N_1 turns	AWG_1	N_2 turns	AWG_2	*Freq* kHz	V_1 V	f_1 W/m^2	f_2 cm^3	f_3 W/m^2	f_4 cm^3	f_5 %
Start		60	20	23	25	144	25	279.02	8.53	52.33	0.41	57.75
1	P_1	66	24	23	25	144	25	207.40	2.99	57.26	0.41	44.23
	P_2	66	24	29	29	144	25	206.20	2.99	30.84	0.21	43.69
	P_3	66	24	29	29	237	30	149.62	2.99	88.75	0.21	33.22
2	P_1	66	24	29	29	237	30	149.62	2.99	88.75	0.21	33.22
	P_2	66	24	30	29	237	30	149.06	2.99	75.76	0.22	32.91
	P_3	66	24	30	29	237	30	149.06	2.99	75.76	0.22	32.91
3	P_1	61	21	30	29	237	30	139.26	6.45	88.68	0.22	37.98
	P_2	61	21	32	28	237	30	137.75	6.45	59.79	0.31	36.96
	P_3	61	21	32	28	205	27	100.74	6.45	79.24	0.31	32.00
4	P_1	61	21	32	28	205	27	100.74	6.45	79.24	0.31	32.00
	P_2	61	21	32	28	205	27	100.74	6.45	79.24	0.31	32.00
	P_3	61	21	32	28	205	27	100.74	6.45	79.24	0.31	32.00

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