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Efficiency Optimal of Inductive Power Transfer System Using the Genetic Algorithms

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Abstract. The Inductive power transfer (IPT) systems' efficiency is determined by kinds of parameters. Aim at maximum the power transfer efficiency for Inductive power transfer (IPT) system, the efficiency of four basic topology IPT systems is analyzed. Based on the analysis, genetic algorithms (GA) are used to optimize IPT systems parameters to achieve the maximum of the power transfer efficiency. Before the GA optimization process, the IPT systems are compensated in a resonance condition which can achieve to minimize VA rating of the power supply and maximum power transfer. In the process of GA optimization, to ensure the final solutions achieving bifurcation-free operation, the solutions that generate bifurcation phenomenon (multi zero phase angle frequency) are excluded. The simulation results verify that the GA can find the best optimal solutions for all topology IPT systems.

Introduction

Inductive power Transfer (IPT) has been used in many commercial and industrial applications due to its ability to transfer electrical power without and physical contact [1-2]. The IPT system includes two independent mutually coupled part called primary and secondary respectively [4]. The primary part generates an essentially current i_p in the primary coil L_p with a resonant high frequency switching power supply. The primary compensation is used to minimize the VA rating of the supply. On the secondary part, compensation is also required to enhance the power transfer. A switched mode controller is normally used to control the power flow from the secondary coil L_s to the load.

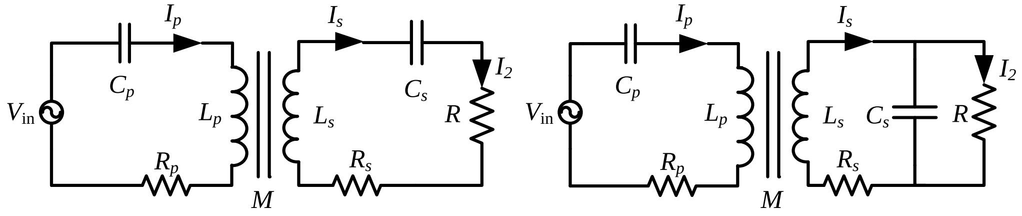
Because of large air gaps via magnetic coupling, the efficiency is a signification target that must be considered when design of the IPT systems [6,7]. However, the systems' efficiency is determined by not only one parameter, such as air gap, operating frequency, coupling coefficient and so on, which makes the efficiency optimal design difficult [9,10]. To date, some analysis and optimal have been undertake. The effects of load and air gap variations are studied for different topology IPT systems [11].

However, the operating frequency effect is not considered. The reference [12] designs the IPT system by using an optimization algorithm. But the algorithm ignores the effect of coupling coefficient. Reference [13] analyzed all the parameters that influence the efficiency and presented an optimal algorithms design method, however, the algorithms cannot ensure to find out the most optimal solution and the bifurcation phenomenon is ignored.

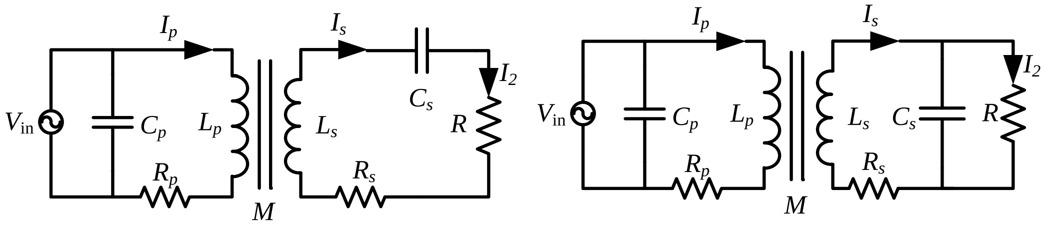
In this paper, the GA is selected to efficiency optimal design of the IPT system undertakes the resonance conditions. In the process of the GA optimization, the solutions that generate bifurcation phenomenon are excluded. The simulation verifies that the GA can find the best optimal solutions for all base topology IPT systems.

Efficiency analyses of base IPT systems

With different compensation, there are four basic topology IPT systems that called SS, SP, PP, and PS are shown in Fig.1, where the first S or P stands for series or parallel LC compensation of primary resonance and the second S or P stands for series or parallel LC compensation of secondary resonance. The inductor L_p and L_s represent the primary and secondary coil respectively. The resistance R represents the load on the secondary, while the resistance R_p and R_s represent the self-resistance of L_p and Ls respectively.



(a) SS (b) SP



(c) PS (d) PP

Fig.1 Four basic topologies of IPT system

The voltage V_{in} is the output voltage of the converter. The impedance of the secondary Z_s whose value depends on the secondary compensation as given by

$$Z_s = \begin{cases} j\omega L_s + \dfrac{1}{j\omega C_s} + R_L & \text{parallel secondary} \\ j\omega L_s + \dfrac{1}{j\omega C_s + 1/R_L} & \text{seris secondary} \end{cases} \tag{1}$$

The reflected impedance Z_p is dependent on the transformer coupling and operating frequency, which is given by

$$Z_p = \frac{\omega^2 M^2}{Z_s} \tag{2}$$

To achieve maximum power transfer, The capacitor C_s is chosen to compensate the large leakage inductances of the secondary coil L_s to achieve resonance conditions. Where, ω_0 is the inherent frequency of the secondary part.

$$C_s = \frac{1}{\omega_0{}^2 L_s} \tag{3}$$

The capacitor C_p is chosen to cancel the reactive part of the circuit seen by the source, to achieve maximum power transfer with minimum VA rating of the supply. With different topologies, the calculations of primary capacitor C_p for different topology IPT systems are shown in Table.1.

Table.1 Primary capacitor C_p

SS	$\dfrac{1}{\omega_0{}^2 L_p}$	PP	$\dfrac{L_p - M^2/L_s}{(\frac{M^2R}{L_s{}^2})^2 + \omega_0{}^2(L_p - M^2/L_s)^2}$
SP	$\dfrac{1}{\omega_0{}^2(L_p - M^2/L_s)}$	PS	$\dfrac{L_p}{(\frac{M^2R}{L_s{}^2})^2 + \omega_0{}^2 L_p{}^2}$

When operated at the secondary inherent frequency, the efficiency of the systems is given by [12]

$$\eta_s = \frac{R}{(R+R_s)(1+\dfrac{R_p(R_s+R)}{\omega_0 M^2})} \tag{4}$$

$$\eta_p = \frac{R}{R + R_s + \dfrac{R_s R^2}{\omega_0{}^2 L_s{}^2} + \dfrac{R_p R_s{}^2}{\omega_0{}^2 M^2} + \dfrac{R}{\omega_0{}^2 M^2 L_s}(\omega_0 L_s{}^2 + \dfrac{R_s R}{\omega_0{}^2})^2} \tag{5}$$

Where

$$M^2 = k^2 L_p L_s \tag{6}$$

Where *k* is coupling coefficient and subsistent (6) into (4) and (5), the systems efficiency can be given by

$$\eta_s = \frac{R\omega_0{}^2 k^2 L_p L_s}{(R+R_s)(\omega_0{}^2 k^2 L_p L_s + R_p R_s + R_p R)} \tag{7}$$

$$\eta_p = \frac{R}{R + R_s + \dfrac{R_s R^2}{\omega_0{}^2 L_s{}^2} + \dfrac{R_p R_s{}^2}{\omega_0{}^2 k^2 L_p L_s} + \dfrac{R}{\omega_0{}^2 k^2 L_p L_s{}^2}(\omega_0 L_s{}^2 + \dfrac{R_s R}{\omega_0})^2} \tag{8}$$

Efficiency optimal with genetic algorithms

When design the IPT systems, the efficiency usually is considered first. From (7) and (8), it can be seen that, four geometrical parameters, operate frequency ω_0, primary inductor Lp, secondary inductor L_s and coupling coefficient k need to be optimal to achieve maximum power transfer. Therefore, the efficiency optimal problem is a maximization of the objective function with four geometrical parameters, which can be given by

$$f_{obj} = \begin{cases} \eta_p(\omega_0, L_p, L_s, k) & \text{parallel secondary} \\ \eta_s(\omega_0, L_p, L_s, k) & \text{seris secondary} \end{cases} \tag{9}$$

However, it is difficult to find the optimal parameters with all of the four parameters with traditional numeric optimal algorithms. The genetic algorithms have become increasing important for this type of optimization problems by seeking the optimal solutions of the objective function with simulating the process of evolution and adaptation of living organisms.

The GA that presented by Holland is a computational optimization paradigm modeled on the concept of biological evolution [14]. It operates a population of random solutions to an optimization problem. A fitness function is used to evaluate the quality of all possible solutions. The solutions with high quality are selected to create the next generations.Therefore, the GA can be used to optimal the IPT systems by not using any complex mathematical information in the searching process.

During the optimal process of the IPT system, to ensure the zero phase angle frequency is equal to the resonance frequency, bifurcation phenomenal must be avoided. The necessary criteria is tabulated in Table.2.[5]

Table.2 Necessary criteria for bifurcation-free operation

SS Topology	$\frac{\omega_0 L_s}{R} < \sqrt{\frac{1}{2(1-\sqrt{1-k^2})}}$
SP and PP Topologies	$\frac{R}{\omega_0 L_s} < \frac{1}{k}\sqrt{1-k^2}$
PS Topology	$\frac{\omega_0 L_s}{R} < \frac{1}{k}$

The solutions that dissatisfy the necessary criteria should be eliminated. Moreover, the four dimensions ω_0、L_p、L_s and k also has max and minimize value, and are given by

$$\left\{ \begin{array}{c} k_{\_\min} \le k \le k_{\_\max} \\ \omega_{0\_\min} \le \omega_0 \le \omega_{0\_\max} \\ L_{p\_\min} \le L_p \le L_{p\_\max} \\ L_{s\_\min} \le L_s \le L_{s\_\max} \end{array} \right\} \tag{10}$$

The Process of GA optimal can be denotated as fllow.

Step1: Chromosone coding

In this paper, static binary string is used to code the four dimensions. Assuming that the length of one dimension is *m*, the total length of the chromosome is 4*m*. The chromosome can be given by

$$X = [x_4, x_3, x_2, x_1] = [\omega_0, L_p, L_s, k] \tag{11}$$

$$x_i = b_{i*m-1} b_{i*m-2} \cdots b_{i*m-m} \tag{12}$$

The decimal value can be calculated by

$$x_{id} = x_{i\_\min} + \left(\sum_{j=i*m-m}^{i*m-1} b_{i*m-j} 2^{j-1}\right) \frac{x_{i\_\max} - x_{i\_\min}}{2^m - 1} \tag{13}$$

Step2: Fitness evaluate

Creating an initial population of N individuals for evolution after chromosome coding was done. Then calculate the objective function value for every individual. To ensure the systems which has multi zero phase angle are not selected to copy and exist in next generation, the objective function should be divided by

$$f'_{obj}(X_j) = \begin{cases} f_{obj}(X_j) & \text{one zero phase angle} \\ 0 & \text{multi zero phase angle} \end{cases} \tag{14}$$

Considering efficiency optimal is a maximization problem, the fitness function is equal to the objective function, and is give by

$$f_{\text{int}\,ss}(X_j) = f'_{obj}(X_j) \tag{15}$$

Step3: GA operator

The GA operator contains reproduction, crossover, and mutation operator. In this paper, roulette wheel selection is used in reproduction mechanism while single point crossover and single point mutation are used for crossover and mutation respectively. The efficiency optimal design of IPT system with GA is presented in Fig.2.

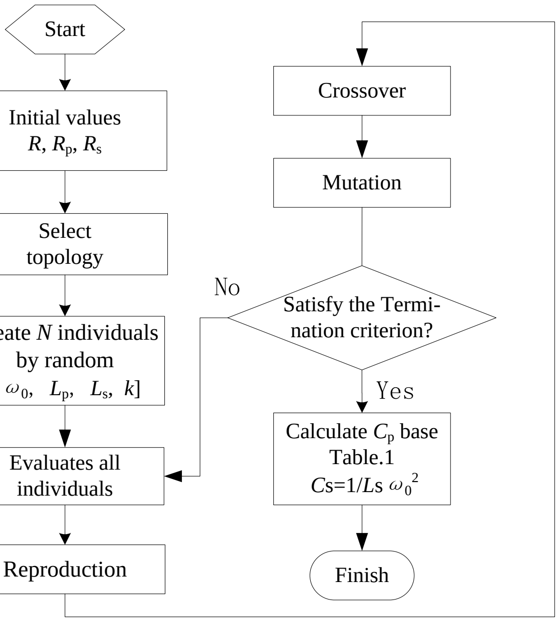


Fig.2 Efficiency optimal result with GA

In the GA parameters, set the maximum number of generations T=50, the number of individuals N=20, the crossover probability P_c=0.6, the mutation probability P_m=0.01, the length of the chromosome m=20, and the four dimension are given by

$$\left\{ \begin{array}{c} 0.1 \le k \le 0.6 \\ 30\mu\text{H} \le L_p \le 100\mu\text{H} \\ 30\mu\text{H} \le L_s \le 100\mu\text{H} \\ 2\pi \times 15\text{kHz} \le \omega_0 \le 2\pi \times 50\text{kHz} \end{array} \right\} \tag{16}$$

The GA optimal process is shown in Fig.3 and the final solutions are shown in Table.4

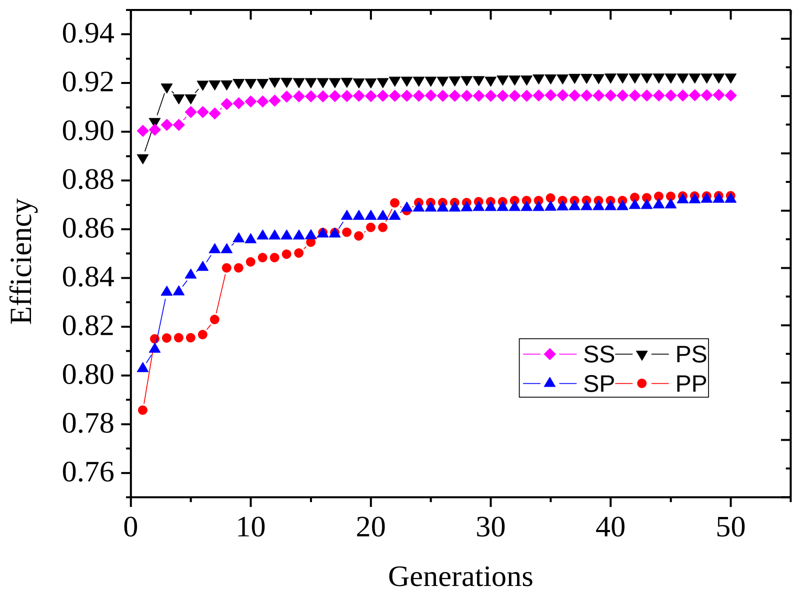


Fig.3 Efficiency optimal result with GA

Observation of Figure 3 reveals that the GA can find the best optimal solutions for all topology IPT systems. On the other hand, in the beginning of the process, not all the best solution in each population is being propagated to the subsequent generation. That's because the solutions with the highest efficiency may be not satisfy the necessary criteria of bifurcation-free.

Table.3 Optimized results of different topologies

Parameter	SS	SP	PS	PP
L_p(μH)	99.94	95.58	99.36	99.75
C_p(μF)	0.21	0.17	0.12	0.12
L_s(μH)	73.59	69.98	60.99	98.35
C_s(μF)	0.29	0.15	0.2	0.1
k	0.44	0.59	0.56	0.35
f(kHz)	34.74	48.86	45.38	49.83
η（%）	91.49	87.23	92.25	87.36

Conclusion

This paper has presented an optimization scheme based on the GA for the efficiency optimal design of the IPT system. Before the GA optimization process, the system is compensated in a resonance condition to minimize the VA rating of the power supply and achieve maximum power transfer. During the GA optimization process, the solutions that dissatisfy the necessary criteria should be eliminated to avoid bifurcation phenomenal occur in the finally solutions. The simulation verifies that the GA optimization can find the best optimal solutions for all topology IPT systems.

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