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Energy Route Multi-Objective Optimization of Wireless Power Transfer Network: An Improved Cross-Entropy Method

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This paper identifies the Wireless Power Transfer Network (WPTN) as an ideal model for long-distance Wireless Power Transfer (WPT) in a certain region with multiple electrical equipment. The schematic circuit and design of each power node and the process of power transmission between the two power nodes are elaborated. The Improved Cross-Entropy (ICE) method is proposed as an algorithm to solve for optimal energy route. Non-dominated sorting is introduced for optimization. A demonstration of the optimization result of a 30-nodes WPTN system based on the proposed algorithm proves ICE method to be efficacious and efficiency.

Keywords: Wireless power transfer; Wireless power transfer network; Multi-objective optimization; Improved Cross-Entropy method; Non-domination sorting.

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1. Introduction

Through the years, Wireless Power Transfer (WPT) has been gradually recognized as a meritorious and future technology with irreplaceable application value. However, being at an emerging state of applications, such a technology is incapable of long-distance wireless power transfer. The power received by the device drops dramatically as the distance between transmitting and receiving coils increases, known as the exponentially decreasing power transfer efficiency. Overcoming such an obstacle can enormously expand the application scope of WPT. Recent attempts including magnetic coupler design, compensation topologies, and parameters optimization techniques have been made to improve the wireless power transfer efficiency between the primary and secondary coils [1-3]. Yet efficiency inevitably becomes unacceptable with a growing distance, for the compensations are insufficient compared to the huge energy loss during such a transfer. Relay resonators which transfer the power from the primary coil to the pick-up coil, have been recently proposed commonly to prolong the transmission distance. Compared to the conventional methods, relay resonators made it possible for the applications of mid-range WPT [4, 5]. However, when providing energy for multiple devices in real time, extra resonators could cause a waste in space utilization and made it difficult when a systemic maintaining or installation is required. Wireless Power Transfer Network (WPTN) is proposed to provide steady and high-efficient wireless power to all electronic equipment within a certain region.

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A WPTN is a wireless network made up of spatially distributed electrical devices, and the power transfers from one device to another through the entire network [6, 7]. What makes the WPTN unique is that any devices can supply power to the other if needed to maintain a network power equilibrium. In this paper, such a network aims to provide steady power to multi-devices while extending the transmission distance and keep the transmission efficiency.

The rest of this paper is organized as follows. Section 2 illustrates the WPTN and analyses the circuit configuration. Section 3 states the circuit modeling and objective functions of the energy route in detail. Section 4 provides a brief description of Cross-Entropy algorithm and the non-dominated sorting method as an improvement to CE, then detailed explains how to use the Improved Cross-Entropy (ICE) method to solve the energy route optimization problem. Section 5 discusses the simulation results on three cases. Finally, Section 6 draws the conclusions.

2. Wireless Power Transfer Network

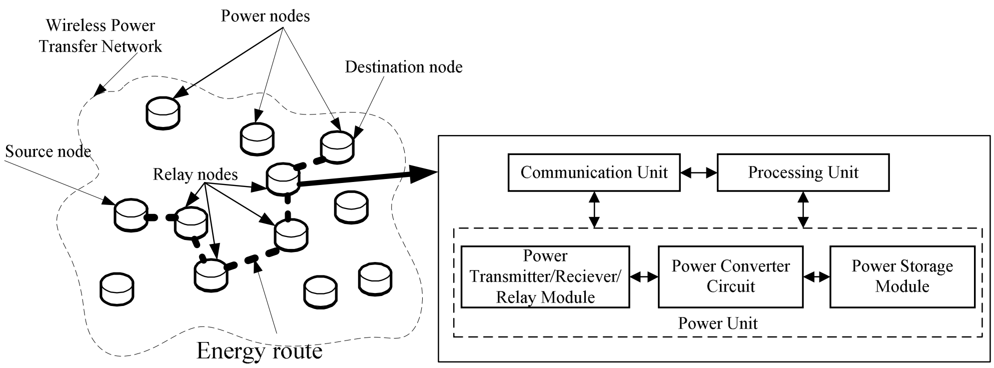
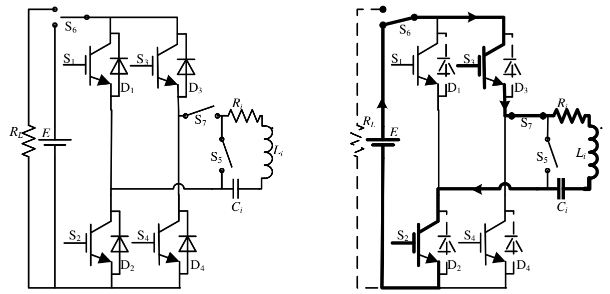


Fig. 1 WPTN and essential components of a power node

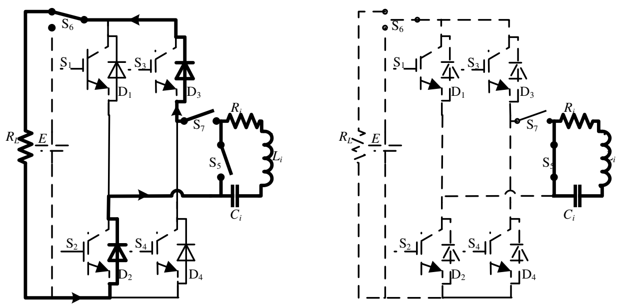
In the Wireless Power Transfer Network (WPTN), power is transferred through devices embedded with a special circuit namely the power node. A power node is the smallest structure which can perform a complete wireless power transfer. To achieve the goal of providing steady and abundant power energy in real time along the network, we designed the power unit to form each power node. Each power node consists of three different units, which are the processing unit handling messages and status, the communication unit transferring and receiving the node status, and the power unit storing the power energy and the place for power transmission. The power unit is the core in the power node and it also consists of three modules: the power transmitter-receptor-relay module; power converter circuit; and power storage module. These units collaborate and enable the power node to work under three modes: the transmitter supplying power energy to other nodes, the receptor receiving energy from other nodes, and relay relaying power for a steady remote power transfer.

Fig.2 describes the design of the power node circuit. In Fig. 2 (a), the power node circuit is made up of the load R_L, the battery E, two switch pairs, (S_1, S_4) and (S_2, S_3), inverse parallel diodes (D_1-D_4), the inductance of coil L_i, resonant capacitor C_i and the equivalent resistance R_i. Different modes are determined by the ON-OFF states of the switches S_5-S_7. Fig.2 (b) to Fig.2 (d) shows the circuits status under the three working modes respectively:

In Fig. 2 (b), when the position of S_6 is down, S_5 is OFF state, and S_7 is ON state, the power node is working in the power transmitter mode. The two switch pairs operate complementarily and transfer the DC current input from the battery *E* to high-frequency current and produce alternating magnetic field through *LC* resonant network. In Fig. 2 (c), when the position of S_6 is up, S_5 is OFF state, and S_7 is ON state, the power node is working in the power receiver mode. The power node picks up the power from the alternating magnetic field through *LC* resonant network and then transfers the power to DC output to the load R_L. In Fig. 2 (d), when S_6, S_7 are OFF states and S_5 is ON state. The power node is working in the power relay mode. The power unit only comprises *LC* resonant network and performs similarly to the conventional relay resonator.



(a)The circuit configuration (b) power transmitter mode



(c) power receptor mode (d) power relay mode

Fig. 2 Circuit configuration and three modes explanations of a power node

3. Energy route in WPTN

3.1. Description of WPTN topology

In a WPTN topology:

Let the all working electric devices, considered as nodes, be the elements of a non-empty set $V = \{v_1, v_2, \ldots, v_{n-1}, v_n\}$ that contains at least two elements.

For a better demonstration and a simpler topology structure, suppose the power transfers from a node, namely, the source node v_s to the remote node, namely, the destination node v_d through some relay nodes. Notably, by the definition of the WPTN, $s \in$ n, $d \in$ n, $s \neq d$, which means any pair of nodes a be a pair of allocation (v_s, v_d).

Say (v_i, v_j) is connected, the path of two nodes is a distance $d(v_i, v_j)$. Then the path of WPTN can be defined as a set of all pair of nodes involved in the power transfer, $E = \{(v_i, v_j), i \neq j, v_i, v_j \in V\}$.

Say (v_i, v_j) is reachable if and only if $d(v_i, v_j) \leq D_{max}$, where D_{max} is the distance with the least acceptable efficiency.

Say (v_i, v_j) is single-directional if and only if $d(v_j, v_d) < d(v_i, v_d)$.

Then, $(v_i, v_j) \in E$ if and only if (v_i, v_j) is both reachable and single-directional.

Thus, the energy route can be defined as the set $R = \{((v_s, v_i), \ldots, (v_j, v_d)), (v_i, v_j) \in E\}$.

Then, a general form of an entire WPTN can be defined as $G = <V, E, R>$.

In this paper, assume that the position of each node is determined and there are only one source node and one destination node. Each node is stationary, and there is no cyclic directed graph in any energy route.

3.2. Circuit Modeling of Energy Route

Fig. 3 is the overall equivalent circuit configuration of an energy route. A route with n+2 nodes has n relay nodes. I_S represents the AC excitation source, ω_i represents the angular frequency of v_i node and $M_{i,i+1}$ is mutual inductance between v_i and v_{i+1} node. Assuming all nodes have the same frequency, $\omega_i=2\pi f_i$, and ignores the couplings between non-adjacent nodes.

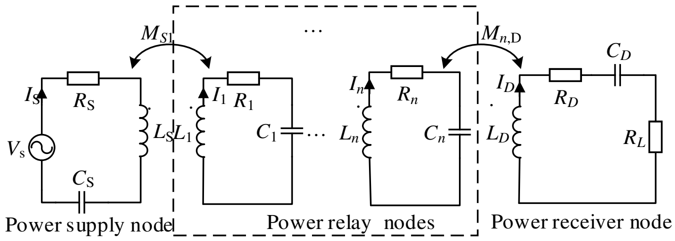


Fig. 3 Circuit model of an energy route

The circuit model using circuit theory can be derived as equation (1):

$$\begin{bmatrix} R_S + j(\omega L_S - \frac{1}{\omega C_S}) & j\omega M_{S1} & \cdots & j\omega M_{Sn} & j\omega M_{SD} \\ j\omega M_{S1} & R_1 + j(\omega L_1 - \frac{1}{\omega C_1}) & \cdots & j\omega M_{1n} & j\omega M_{1D} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ j\omega M_{Sn} & j\omega M_{1n} & \cdots & R_n + j(\omega L_n - \frac{1}{\omega C_n}) & j\omega M_{nD} \\ j\omega M_{SD} & j\omega M_{1D} & \cdots & j\omega M_{nD} & R_D + j(\omega L_D - \frac{1}{\omega C_D}) + R_L \end{bmatrix} \begin{bmatrix} I_S \\ I_1 \\ \vdots \\ I_n \\ I_D \end{bmatrix} = \begin{bmatrix} V_s \\ 0 \\ \vdots \\ 0 \\ 0 \end{bmatrix} \quad (1)$$

where $M_{i,i+1}$ can be calculated from:

$$M = \rho \times \sum_{i=1}^{i=n_p} \sum_{j=1}^{j=n_s} M_{ij} \ and$$

$$M_{ij} = \frac{\mu_0 \pi a_i^2 b_j^2}{2(a_i^2 + b_j^2 + z^2 + x^2)^{3/2}} \times \left[1 - \frac{3}{2}\delta_{ij} + \frac{15}{32}\gamma_{ij}^2 (1 - \frac{21}{2}\delta_{ij}) + \frac{15}{16}(\alpha_{ij}^2 + \beta_{ij}^2)(1 - \frac{7}{4}\delta_{ij}) \right] \quad (2)$$

In equation (2), the parameter ρ depends on the shape of the coil; n_p and n_s are the numbers of turns of the primary and secondary coils; a and b are the radius of coils; x is the lateral displacement symmetry; z is the distance between two concentric coils. Thus, we have:

$$\delta_{ij} = \frac{x^2}{a_i^2 + b_j^2 + z^2 + x^2}, \gamma_{ij} = \frac{2a_i b_j}{a_i^2 + b_j^2 + z^2 + x^2}, \\ \alpha_{ij} = \frac{2xa_i}{a_i^2 + b_j^2 + z^2 + x^2}, \beta_{ij} = \frac{2xb_j}{a_i^2 + b_j^2 + z^2 + x^2} \tag{3}$$

Notably, all three units in each node can cause energy consumption. As communication and processing consume negligible energy compared to the power unit consumes, we assume the energy consumed by communication and processing to be ignored. Then, the energy consumption of node i, which contributes to most of the energy loss, can be defined as:

$$P_{v_i\_loss} = I_{v_i}^2 R_i \tag{4}$$

where I_{vi} is the current and R_i is the equivalent resistance of the coil. The current I_{vi} can be derived from equation (1).

3.3. Energy Route Objective Functions

WPTN is a network which focuses on the performance of the transmission. In this paper, the performance is considered to be affected by three aspects, which are the power transfer efficiency, output power and network reliability. To solve optimal energy routes with the best performance is to optimize from these three aspects within the possible allowance. Then mathematically, we give three objective functions through a Nonlinear Problem (NLP) model:

$$f_1 = \frac{P_{in} - \sum_{v_i \in V} \sum_{v_j \in V} h_{v_i v_j} P_{v_i\_loss}}{P_{in}} \tag{5}$$

$$f_2 = \sum_{\forall v_i} k_{v_i} P_{v_i\_load} \tag{6}$$

$$f_3 = \min(I_i) \tag{7}$$

where $h_{vi} = 1$ when the node v_i is covered, otherwise $h_{vi} = 0$; $k_{vi} = 1$when the load of node v_i needs the power, otherwise $k_{vi} = 0$;

Equation (5) represents the objective function f_1, which means increase the efficiency based on minimizing the power loss during the transmission. Equation (6) focuses on the receiving power of the destination node v_d for setting up a high output power. Equation (7) improves the network reliability by minimizing current values in each single working node.

Our objective functions have following constraints:

$$P_{load} = I_{v_d}^2 R_L \geq P_0 \tag{8}$$

$$U_{load} = I_{v_d} R_L \leq U_0 \tag{9}$$

$$I_{v_i} \leq I_{\max} \quad , \forall v_i \in V \tag{10}$$

$$U_{v_i} \leq U_{\max} \quad , \forall v_i \in V \tag{11}$$

$$M_{\min} \leq M_{v_i v_{i+1}} \leq M_{\max} \quad , \forall v_i \in V / \{v_s\} \tag{12}$$

$$L_{v_i v_{i+1}} = \sqrt{\left(x_{v_i} - x_{v_{i+1}}\right)^2 + \left(y_{v_i} - y_{v_{i+1}}\right)^2} \leq L_{\max} \quad , \forall v_i \in V / \{v_s\} \tag{13}$$

where I_0 is the current threshold; I_{vi} is the current of the node v_i; U_0 is the voltage threshold; U_{vi} is the voltage of node v_i; I_{max} and U_{max} are the upper limits of current and voltage; P_0 is the power lower limit of the load.

The inequality in (8) shows that the power that the energy route can transfer should larger than the power lower limit. In a similar way, (9) to (13) show each condition objective functions should be satisfied.

The evolutionary algorithms have been the standard method for solving the Nonlinear Problem (NLP) of the energy route design for WPTN system. The CE algorithm, which is based on the information theory and entropy, can efficiently solve an optimization problem. Thus, an ICE method combined the two above algorithms is proposed and discussed in detail in next section.

4. Energy Routes Optimization using ICE Method

4.1. A Brief Introduction to CE Method

Rubinstein motivated the CE method as an adaptive algorithm for estimating probabilities of rare events in the stochastic network in 1997, which has been extended as a heuristic algorithm and wildly used in solving NP-hard problems in various research fields [8-12]. In this Section, the CE method for combinatorial optimization is briefly outlined, and details can be found on the Cross-Entropy website and the Annals of Operations Research in 2005.

Consider the following maximization problem, where χ is the space, let f be a family of probability density functions on χ. The probability can be expressed as:

$$l(\gamma) = \mathrm{P}_{\mu}(f(x) \geq \gamma)\mathrm{E}_{\mu} I_{\{S(x)\geq\gamma\}} \tag{14}$$

It can be estimated directly by using Crude Monte Carlo method. However, $f(x)\geq\gamma$ is called a rare event when l is significantly small and important sampling is introduced to improve the performance of the simulation. There exists another probability density function g(x), and (14) can be rewritten as:

$$l = \int I_{\{S(x)\geq\gamma\}} \frac{f(x;\mu)}{g(x)} g(x)dx = E_g I_{\{S(x)\geq\gamma\}} \frac{f(X;\mu)}{g(X)} \tag{15}$$

The best way to estimate l is to use the change of the measure with density g:

$$g^*(x) := \frac{I_{\{S(x)\geq\gamma\}} f(x;u)}{l} \tag{16}$$

And later a measure of distance between two densities g and h called Kullback-Leibler distance can be defined as:

$$D(g,h) = \mathrm{E}_g \ln \frac{g(\mathrm{X})}{h(\mathrm{X})} = \int g(x) \ln g(x)dx - \int g(x) \ln h(x)dx \tag{17}$$

The minimization of the Kullback-Leibler distance can be achieved by maximizing:

$$\begin{aligned} \max_{v} D(v) &= \max_{v} \int g^*(x) \ln f(x;v)dx \\ &= \max_{v} \int \frac{I_{\{S(x)\geq\gamma\}} f(x;u)}{l} \ln f(x;v)dx \end{aligned} \tag{18}$$

Thus, the optimal solution and estimation can be expressed as:

$$v^* = \underset{v}{\operatorname{argmax}} \mathrm{E}_u I_{\{S(x)\geq\gamma\}} \ln f(x;v) \tag{19}$$

$$\hat{v}^* = \arg\max_{v} \frac{1}{N}\sum_{i=1}^{N} I\{S(x) \geq \gamma\} \ln f(x_i; v) \tag{20}$$

The CE method is a multi-level algorithm, and the two of the most critical procedures are as follows:

(1) Adaptive updating of γ_t. For a fixed v_{t-1}, let γ_t be the (1-ρ)-quantile of f(x) under v_{t-1}.

(2) Adaptive updating of v_t. For fixed γ_t and v_{t-1}, v_t can be derived by solving the maximization problem of the Kullback-Leibler distance D(v).

4.2. Brief Introduction to Non-Dominated Sorting

Optimal energy route problem is a multi-objective optimization problem and an NLP problem. Generally, preference parameters are introduced to convert multi-objective optimization problem into a mono-objective optimization problem [13]. However, preference parameters are hard to choose in practice. Meanwhile, the optimized objective functions often unable to achieve at the same time. Improvement of one goal may lead to a deterioration of the others. The optimum solution can be unattainable unless the search space is convex because it is nearly impossible realizing optimum solutions for all the objective functions simultaneously. Whereas, Pareto frontier which is a set of acceptable trade-off optimal solutions is introduced to optimize multi-objective problem [14-18]. Non-dominated sorting sorts one or more solutions into Pareto optimal solutions (non-dominated solutions) therefore reveals Pareto frontier in different ranks.

Mathematically, a minimization problem with m objective functions can be expressed as: minimize $F(x) = \{f_1(x), f_2(x), \ldots\ldots, f_m(x)\}$, where solution $x \in X$, X denotes the feasible search space. To describe the Pareto frontier, we give three definitions.

Definition 1: A solution x_1 dominates x_2 if and only if

$$\forall i \in \{1,2,\cdots,m\},\ f_i(x_1) \leq f_i(x_2)\ \wedge\ \exists j \in \{1,2,\cdots,m\},\ f_j(x_1) < f_j(x_2)$$

Definition 2: For $S = \{x_i,\ i=1, 2,\ldots\ldots, n\}$, solution x denotes a non-dominated solution (Pareto optimal) of set S for every $x \in S$, and there is no solution for any $y \in S$ when y dominates x.

Definition 3: Set S is a Pareto frontier which contains all dominated solutions.

As non-dominated sorting provides an ideal resolution for solving Paetro optimal, a sorting criterion selects the elite examples from the Pareto frontier based on such sorting algorithm is proposed in ICE method.

4.3. The Procedure of ICE method

Energy routes problem of WPTN system is a multi-objective problem that involves objective functions including the output power of a destination node, the power transfer efficiency of an energy route and the network reliability.

CE method is a simple adaptive algorithm of global random search with asymptotic convergence properties. Some improvements have been applied in this paper, to enhance the multi-objective optimization characteristics of the CE method. The general framework and basic concepts of the CE method and non-domination sorting were described in detail above. In this subsection, the algorithm procedures are shown in the following figure.

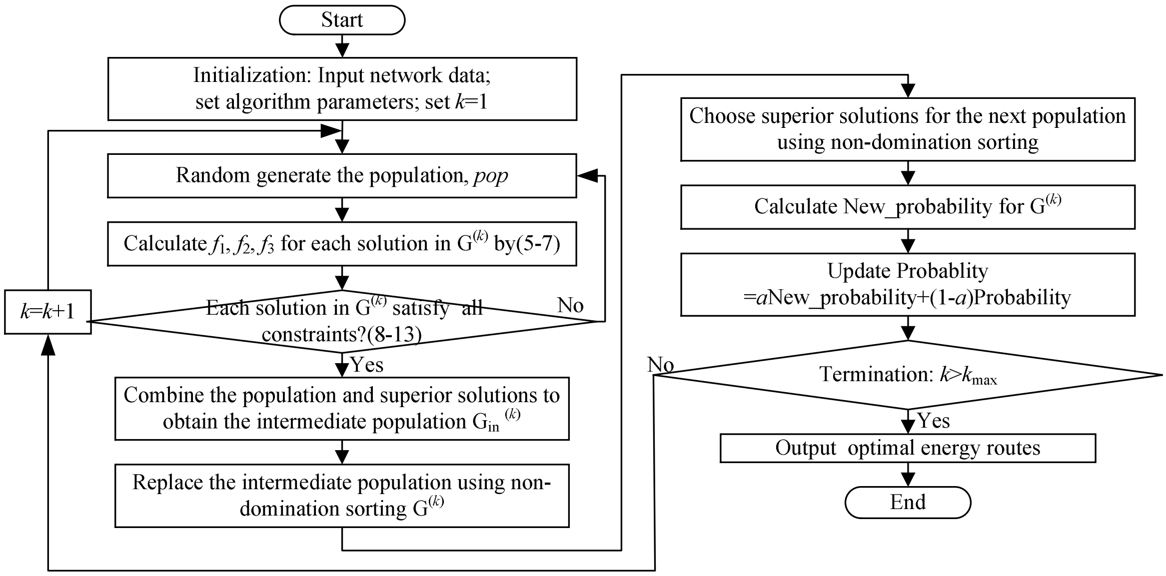


Fig. 4 Flow chart of ICE method for multi-objective energy route problem

Fig. 4 shows the flow chart of the ICE algorithm. First, an initial population is randomly formed. Then Pareto frontier is obtained by the non-dominated sorting strategy based on the objective function values. Superior solutions are selected from the Pareto frontier, which is used for the next generation. Update the next generation population by combining the current population and the superior solutions. Meanwhile, the probability of each solution is updated. Along with the iteration, superior solutions update as the population updates. It is important to note that non-nominated sorting is used to improve the multi-objective optimization ability. Elites examples will be kept during the process of the iteration. Non-dominated sorting also contributed the construction of a healthy route with diversity. The main procedures of the proposed method are given in the following:

(1) Initialize all the ICE and WPTN parameters input.

(2) Generate reasonable population and evaluate against all the objective functions f_1, f_2 and f_3 respectively, using the NLP model.

(3) Combine the contemporary population and superior solutions to the new population using non-domination sorting strategy.

(4) Update the population generation probability, in case of getting the local optimal solutions.

(5) Get the final solution set.

5. Simulation and Results

To illustrate the applicability and effectiveness of the proposed method, a program was coded in MATLAB software to optimize a 30-node WPTN system in 1m*1m area is taken, as shown in Fig. 5 with each node labeled. Let the node 1 be the source node, and node 30 be the destination node. Simulations were conducted.

The parameters of ICE method and their break flag are as following: Population size *pop* = 200, Maximum of generations k_{max} = 1000, Smooth parameter a = 0.7. Parameters of WPTN are as listed in Table 1. Totally three cases are studied.

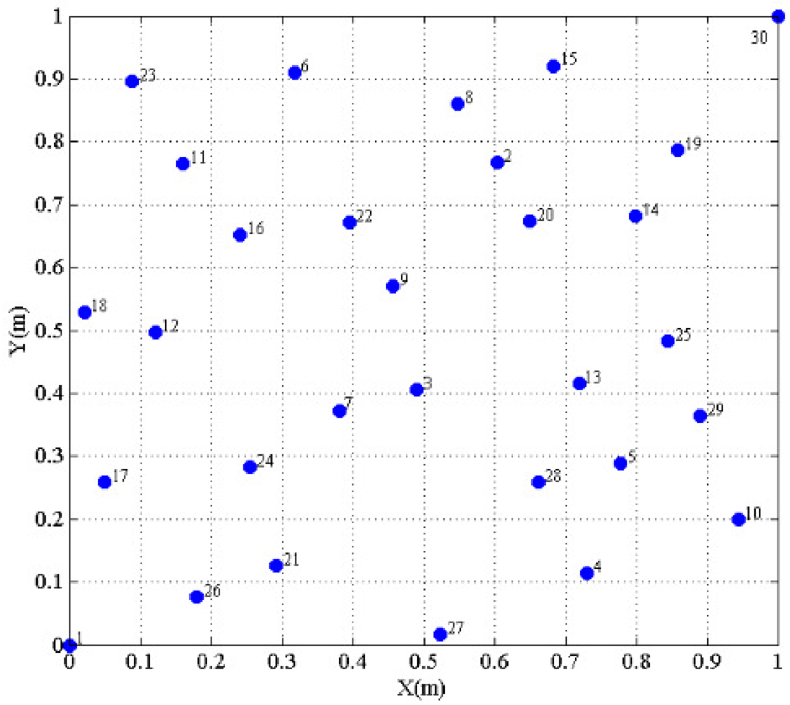


Fig. 5 30-node WPTN

Case 1: When obtaining a maximum power transfer efficiency, objective function f_1 is considered. When achieving the highest power capacity, the output power of the destination node (objective function f_2) is considered.

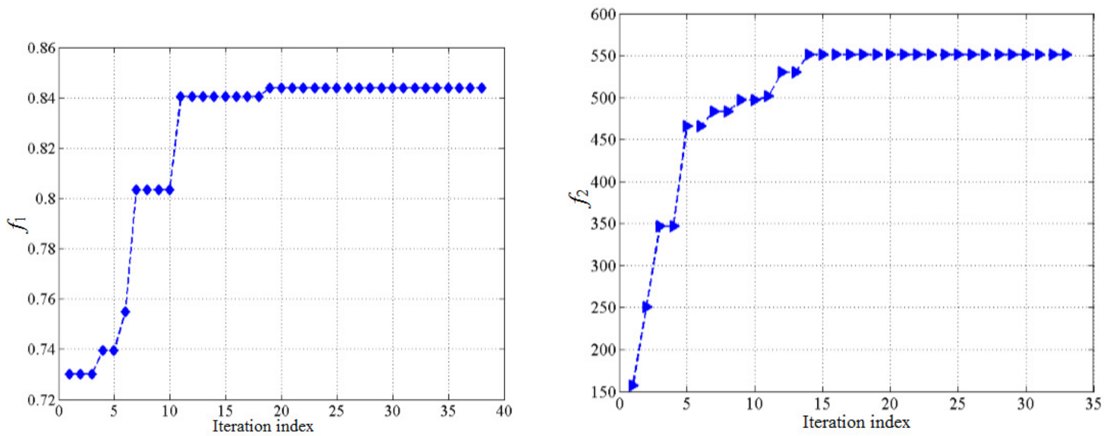
Case 2: Combining f_1 and f_2, then we have a bi-objective optimization problem, where both power transfer efficiency and output power are considered.

Case 3: All the objective functions f_1, f_2, f_3 are chosen to obtain the maximum network reliability and power transfer ability.

To verify that the crude CE method holds the characteristics of fast convergence and global search ability, mono-objective optimization is considered, optimize f_1 and f_2 respectively. And the dynamic convergences are shown in Fig.6. For mono-objective optimization problem, the crude CE method converges within 10-20 iterations and enlarges the local optimum to global maximum, regardless of the limitation of the partial optimum. The greatest value of power transfer efficiency f_1, is 89.43%, when the optimum solution is (1, 26, 17, 7, 22, 15, 30), shown in Fig.6(a). Equation (6) gives the output power, f_2 = 37.94W. The greatest f_2 of the node 30 is 551.18 W, when the optimum solution is (1, 26, 22, 15, 30) and f_1=47.37%, shown in Fig.6(b). Fig.7 shows the profiles of current magnitudes in case 1. The currents are higher with a maximized f_2 compared to those with a maximized f_1.

Table 1: 30-node WPTN Parameters

Parameters	Values	Parameters	Values	Parameters	Values
Number of nodes(N)	30	Resistance of load	10 Ω	P_0	30 W
Current of source node(I_S)	1 A	Frequency(f)	100 kHz	U_0	95 V
Equivalent resistance of coil(R_i)	0.05 Ω	M_{max}	6.8 uH	I_{max}	150 A
Inductance of coil (L_i)	147.9 uH	M_{min}	0.05 uH	L_{max}	0.3 m



(a)maximize f_1 (b)maximize f_2

Fig.6 Convergence plot for the crude CE method for maximized f_1 and f_2

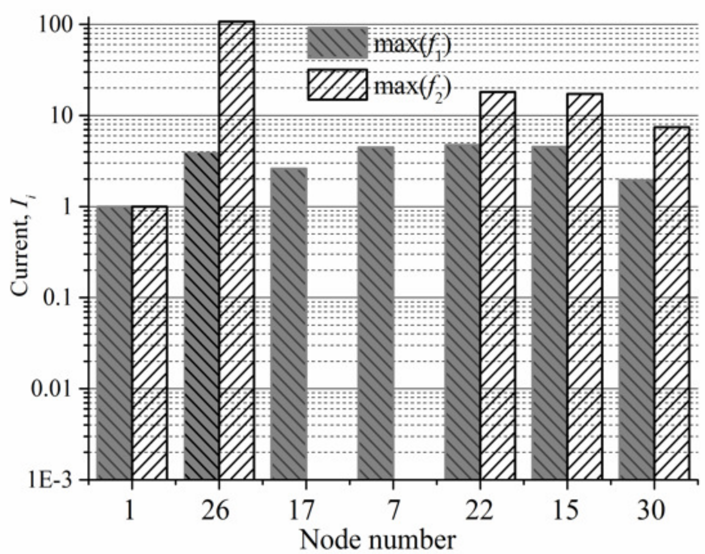


Fig.7 Node current profiles of max (f_1) and max (f_2)

In Case 2 which verifies the effectiveness of the proposed method (shown in Fig.4), focuses on both power transfer efficiency and output power level. Since applications are different, the objective functions and results are different. In this case, Fig. 8 shows the Pareto frontier (rank = 1) after 30 iterations. It also shows that the ICE method has better performance with various diversity, continuous and uniformity. Besides, the ratio getting the solution within 30 iterations is 96.7%, which proves the ICE method a practical tool for solving bi-objective problems. Fig. 9 shows the solution sets of different ranks within 15 iterations, and the blue line represents the Pareto frontier in this iteration and finally converges to a similar pattern shown the Fig. 8.

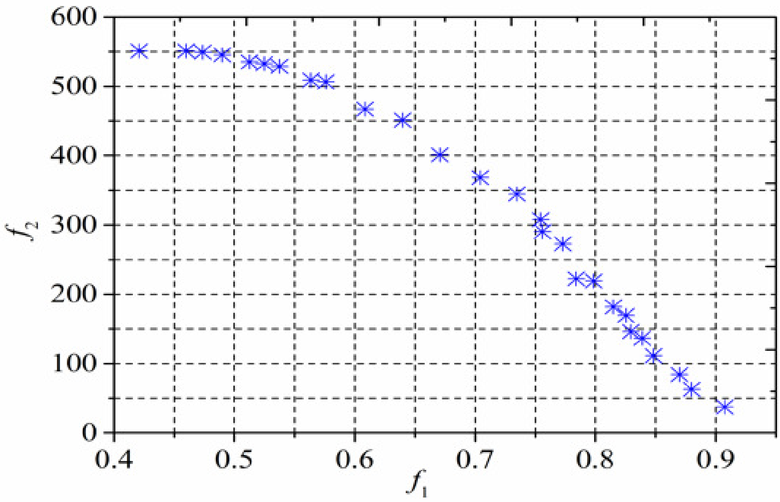


Fig.8 Pareto frontier obtained by the proposed ICE method after 30 iterations

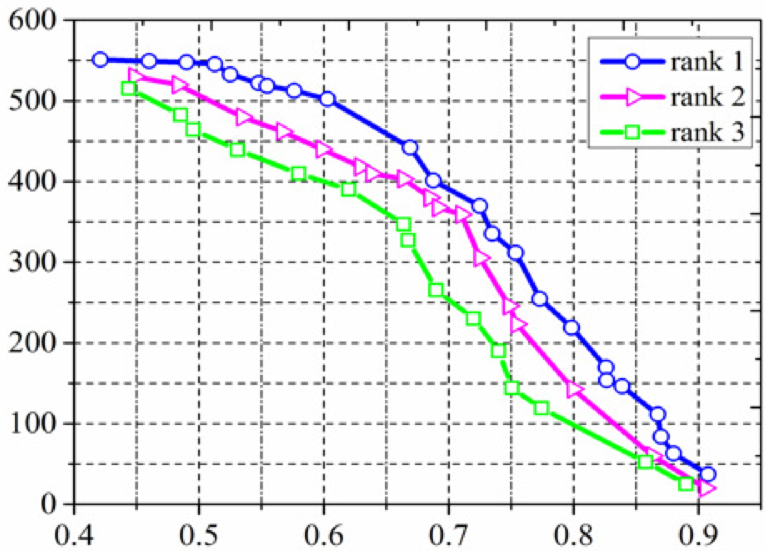


Fig.9 Different ranks (rank=1, 2, 3) in 15 iteration

Fig. 10 demonstrates the Pareto frontier at various I_1 values when the current of the source node increases from 1 A to 2 A. As current I_1 changes, all the power transfer efficiency increases from 40% to 90%. Thus, we can conclude that the power transfer efficiency is immune to the increase in current I_1. Meanwhile, the output power level changes rapidly. The maximum f_2 can reach up to 500 W, 1.25 kW and 2.25 kW approximately when $I_1 = 1$ A, $I_1 = 1.5$ A and $I_1 = 2$ A respectively. (Shown in Fig.10)

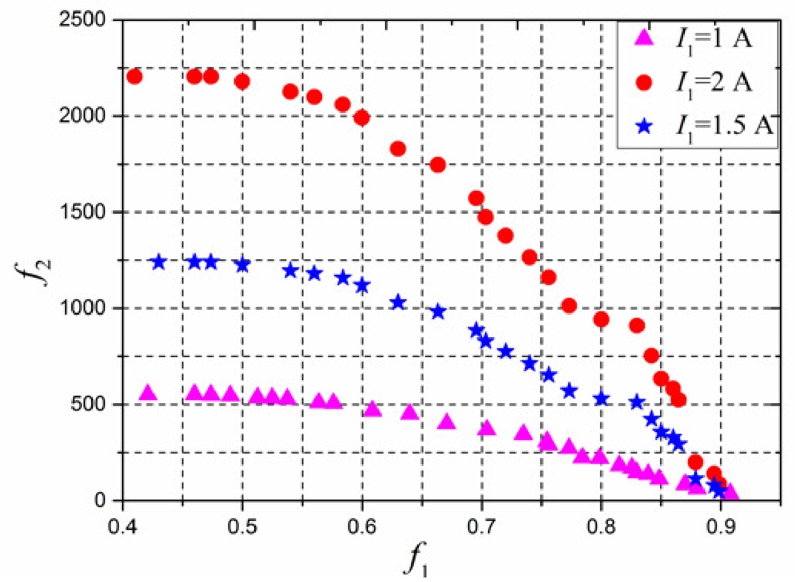


Fig.10 Pareto frontiers for bi-objective optimization at different I_1

Case 3 takes both the network reliability and power transfer ability into consideration. That is when all the three objective functions are considered. The final global Pareto frontier for multi-objective (f_1, f_2, f_3) after 40 iterations is shown in Fig.11. The Pareto frontier comprises a curved surface because of the mutual inductance discontinuously among those nodes in WPTN. The Pareto solution is scattered among the feasible solutions; specifically, the difference of the energy routes design brings unpredictable changes to the three objective functions.

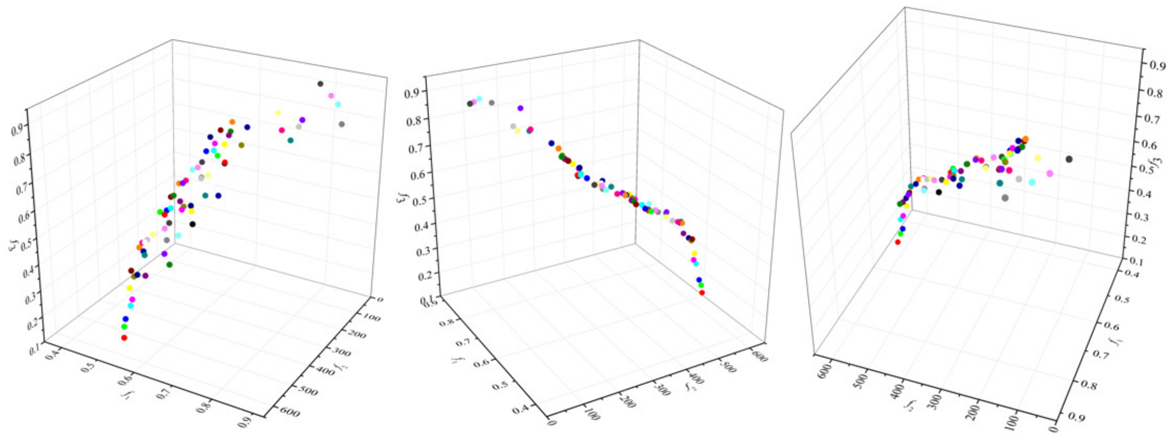

(a) Angle 1 (b) Angle 2 (c) Angle 3

Fig.11 Pareto frontier for multi-objective optimization (Angle 1-3)

6. Conclusions

With the rapid development and a more extensive application scope of WPT technology, the WPTN can become a new framework in wireless power transfers. In such a network, optimal energy routes designing should also provide a high network reliability while maximizing the power transfer efficiency as well as output power for WPT systems. The new multi-objective energy routes designing model developed in this paper addresses various concerns from the power transfer ability and network reliability. The ICE method applied to solve the multi-objective problem shows its simplicity, efficiency and fast asymptotic convergence properties. Based on the proposed method, the optimal solution for f_1, f_2, the Pareto frontier for (f_1, f_2) and (f_1, f_2, f_3) can be achieved. Results amply demonstrate the merit of our proposed WPTN and optimization approach, encourage WPT's future application, and motivate similar studies for the development of optimization algorithms.

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