

耦合共振无线电能传输系统最大效率跟踪控制

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摘 要:耦合共振无线电能传输系统发射端与接收端距离小于某一特定值时,共振频率将发生变化,传输效率将大大降低.为了保持接收端实时以最大效率运行,本文提出一种耦合共振无线电能传输最大效率跟踪控制方法.该方法根据耦合共振无线电能传输效率特点引入粒子群优化策略(PSO),通过迭代求解粒子适应度函数,获得全局最优解,实现系统最大效率跟踪控制.研究表明,所提方法能够找到不同距离下最大传输效率对应的系统谐振频率,使无线电能传输系统电能接收端以最大效率运行.

关键词:谐振频率;粒子群算法;最大效率;跟踪控制

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耦合共振无线电能传输(MCR-WPT)技术目前已在电动汽车、可植入人体医疗设备等领域获得广泛应用^[1-2].为了提高发射端与接收端之间的传输效率,MCR-WPT系统的外接电源激励频率与系统共振频率须保持一致^[3].文献^[4]分析了影响MCR-WPT传输功率的关键因素以及传输效率与传输距离之间的关系,提出了跟踪控制发射端电流频率的方法,消除了MCR-WPT系统失谐造成的不良影响,有效提高了接收端运行效率,但该方法只能跟踪MCR-WPT系统固有谐振频率.文献^[5]通过改变收发线圈结构抑制频率分裂,提高系统传输效率,但线圈结构复杂,增加了理论分析的难度,方程求解过程较繁琐.以上方法均可以达到较好的控制效果,但在发射与接收端距离发生变化时,现有方法不能满足变距离工况下的效率控制要求.文献^[6]对整个系统建模分析,推导出系统传输效率公式,指出效率与频率在不同的传输距离下,为一个单峰值和多峰值的函数,最大效率搜寻可以转化为单/多峰值函数求极值问题.

本文将粒子群优化算法(PSO)引入MCR-WPT系统的频率寻优过程,通过控制驱动源频率使发射端实时以最优效率进行电能传输,并分别在单一峰值和频率分裂条件下,验证了所提方法的正确性和有效性.

1 MCR-WPT 系统效率分析

MCR-WPT系统接收端效率表示为^[7]:

$$\eta = \left| 2 \frac{V_L}{V_S} \left(\frac{R_S}{R_L} \right)^{\frac{1}{2}} \right|^2 \quad (1)$$

当MCR-WPT系统的发射与接收端之间传输距离固定时,接收端传输效率与电源激励频率的函数为单峰值或多峰值曲线.在传输距离较远时,发射与接收端传输距离大于临界距离,MCR-WPT装置传输效率曲线出现单波峰,当发射与接收端距离小于临界距离时,其耦合强度大于临界点值,MCR-WPT装置传输效率会出现频率分裂现象,有2个峰值点.如图1所示.

2 PSO 在多效率峰值点搜寻中的应用

MCR-WPT系统中,效率与频率的关系为一个单峰值或多峰值的函数,用一般算法搜寻效率最优值比

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较困难,PSO 算法在解决多峰值曲线极值点寻找问题时具有较强的优势. 本文将电源激励频率作为粒子的位置,将式(1)所示的传输效率作为适应度函数值,通过迭代计算对最优传输频率进行搜索.

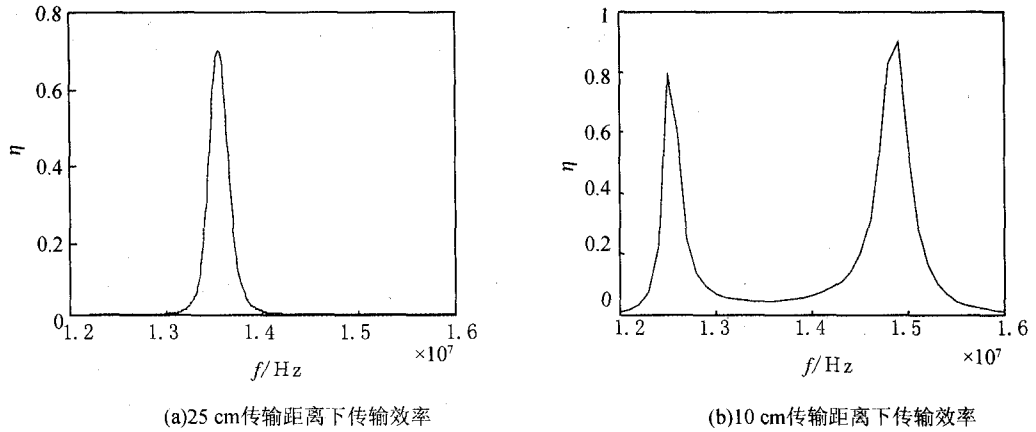


图1 不同传输距离下传输效率

PSO 算法原理简单且应用广泛^[8]. 其原理为:一群规模为 P 的粒子,通过不断更新个体最优值 f_{i-b} 以及全局最优值 f_{i-gb} 来搜寻最优值^[9]. 粒子的速度和位置更新方程为

$$\begin{cases} V_i^{k+1} = \omega V_i^k + c_1 r_1 (p_i - x_i^k) + c_2 r_2 (p_g - x_i^k), \\ x_i^{k+1} = x_i^k + V_i^k, \end{cases} \quad (2)$$

式中, V_i^{k+1} 为 $k+1$ 次迭代时第 i 个粒子速度, V_i^k 代表第 i 个粒子当前速度, c_1, c_2 为学习因子, r_1, r_2 取 $[0, 1]$ 之间随机数, p_i 表示个体极值 f_{i-b} 的粒子位置, p_g 表示最优值为 f_{i-gb} 的粒子位置, x_i^{k+1} 为 $k+1$ 次迭代第 i 个粒子位置, x_i^k 为第 i 个粒子当前位置, ω 代表惯性权重. 算法流程如图 2 所示.

3 寻优过程分析

MCR-WPT 系统结构模型参数在表 1 中给出^[10].

表 1 MCR-WPT 系统参数

电路参数	值	电路参数	值
$R_5=R_L$	50 Ω	$L_2=L_3$	23 μH
$L_1=L_4$	1.05 μH	$C_2=C_3$	6 pF
$C_1=C_4$	130 pF	$R_2=R_3$	1 Ω
$R_1=R_4$	0.25 Ω	k_{23}	0.001~0.200
$k_{12}=k_{34}$	0.10	F	12~16 MHz

根据图 2 设定 PSO 中各个参数,包括粒子群规模 N ,迭代次数 k . 粒子初始位置与初始飞行速度随机分布,令 $k=1$,粒子的位置对应电源驱动频率 f ,通过 $\omega = 2\pi f$ 得到角频率 ω . V_L 与 V_S 的关系为:

$$\begin{cases} \frac{V_L}{V_S} = \frac{i\omega^3 k_{12} k_{23} k_{34} L_2 L_3 R_L \sqrt{L_1 L_4}}{\tau}, \\ \tau = k_{34}^2 L_1 L_2 L_3 L_4 \omega^3 + Z_1 Z_2 Z_3 Z_4 + \omega^2 (k_{12}^2 L_1 L_2 Z_3 Z_4 + k_{23}^2 L_2 L_3 Z_1 Z_4 + k_{34}^2 L_3 L_4 Z_1 Z_2), \\ Z_1 = R_1 + R_5 + j\omega L_1 + \frac{1}{j\omega C_1}, Z_2 = R_2 + j\omega L_2 + \frac{1}{j\omega C_2}, \\ Z_3 = R_3 + j\omega L_3 + \frac{1}{j\omega C_3}, Z_4 = R_4 + R_L + j\omega L_4 + \frac{1}{j\omega C_4}, \end{cases} \quad (3)$$

式中, V_L 为负载电压, V_S 为电源电压. $L_1, L_2, L_3, L_4, C_1, C_2, C_3, C_4, R_1, R_2, R_3, R_4$ 分别为励磁回路,发射回路,接收回路与负载回路各自的电感、电容、电阻. R_5 为电源内阻, R_L 为负载电阻. k_{12} 为励磁线圈与发射线圈之间耦合系数, k_{23} 为发射与接收线圈之间的耦合系数, k_{34} 为接收线圈与负载线圈之间的耦合系数. 根据式

(1) 计算第 i 个粒子的适应度函数值 f_i , 找到粒子的个体最优值与全体最优值. 用公式(2) 更新每个粒子的位置和飞行速度, 令 $k = k + 1$, 判断算法是否达到终止条件. 终止条件: 设粒子群平均适应度值为 f_a . 则粒子群的适应度值方差之和

$$\sigma^2 = \sum_i^N (f_i - f_a/a)^2, \text{其中, } \begin{cases} a = \max(f_i - f_a), & f_i - f_a > 1, \\ a = 1, & f_i - f_a < 1. \end{cases} \quad (4)$$

算法迭代运行过程中, 若 $\sigma^2 \neq 0$, 算法继续搜索最优值, 算法 $\sigma^2 = 0$, 输出最优解, 系统以最大效率运行. 若系统频率发生偏移, 需重新搜索最优值, 特设定算法重启条件: 令最大电流峰值波动范围 $\Delta i_m(k)$ 为负载的第 k 个电流周期电流峰值, $i_m(k+1)$ 为负载的第 $k+1$ 个电流周期的电流峰值, 在系统运行过程中, 判断公式 $|i_m(k+1)| - |i_m(k)| > \Delta$ 是否成立. 如果判断结果为是, 算法重启, 如果判断结果为否, 表明系统仍在稳定运行, 算法结束.

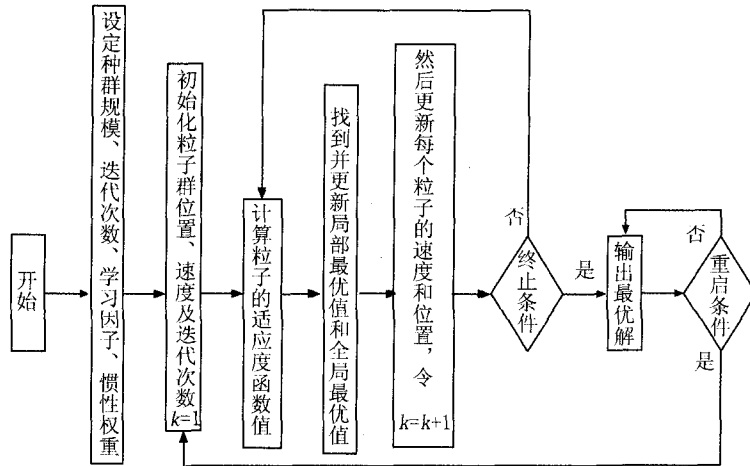


图2 PSO算法流程图

3.1 单一峰值下最大效率搜寻

不同传输距离下, 系统传输效率特性曲线有单峰值和多峰值之分, 首先对单一峰值情况进行寻优分析. 当发射与接收线圈之间耦合强度小于临界值时, MCR-WPT 系统的效率曲线只有一个峰值点. 在传输距离为 25 cm 时, 将 PSO 算法对发射端传输效率进行寻优计算, 得到图 3.

图 3(a) 为 PSO 算法寻优计算过程, 曲线代表粒子群每一次迭代所找到的全局最优值, 算法到迭代到 156 次找到最优频率, 图 3(a) 中曲线停止代表算法结束, 用时 3.352 s; 由图 3(b) 可以看出, 传输距离为 25 cm 时, MCR-WPT 系统的效率曲线为单峰值函数, PSO 算法能够快速找到系统谐振频率, 使接收端以最大效率运行. 此时算法搜索得到的最优频率 $f = 13\,544\,961.681\,6$ Hz, 此时传输效率 $\eta = 70.01\%$.

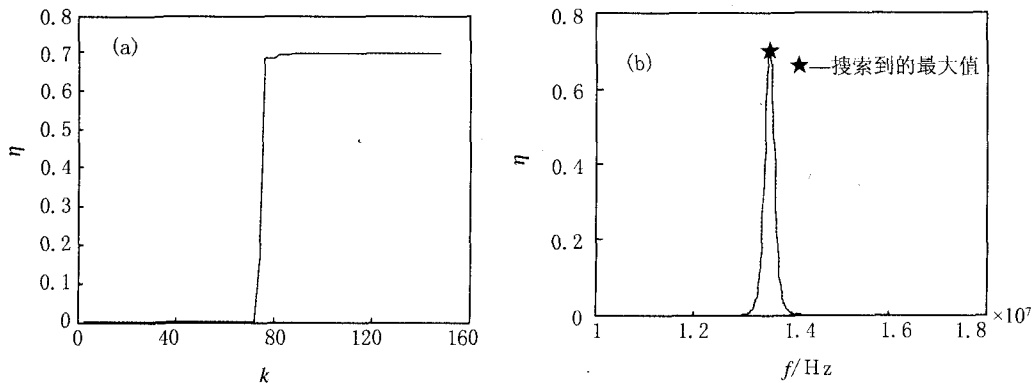


图3 25 cm处单峰值时PSO算法寻优

3.2 频率分裂下最大效率搜寻

当发射端与接收端小于临界距离时, MCR-WPT 装置的传输效率与频率的曲线出现频率分裂现象, 此时寻优对象为双峰函数. 在传输距离为 10 cm 处, 将 PSO 算法对发射端传输效率进行寻优计算, 得到图 4.

图 4(a) 为 PSO 算法寻优计算过程, 频率分裂情况下, 算法通过迭代搜寻全局最优值, 粒子群算法迭代到 180 次搜索到最优频率值, 算法结束, 用时 3.643 s; 由图 4(b) 可以看出, 算法搜索到的最优频率 $f = 13\,872\,890.786\,6\text{ Hz}$, 此时传输效率 $\eta = 93.78\%$. 当传输距离为 10 cm 时, 系统传输效率会出现频率分裂现象, 此时函数有两个极值点, 搜寻过程比单峰值时复杂. PSO 算法能够快速搜索到系统共振频率 f , 调节驱动源输出频率, 使 MCR-WPT 系统以最大效率传输电能.

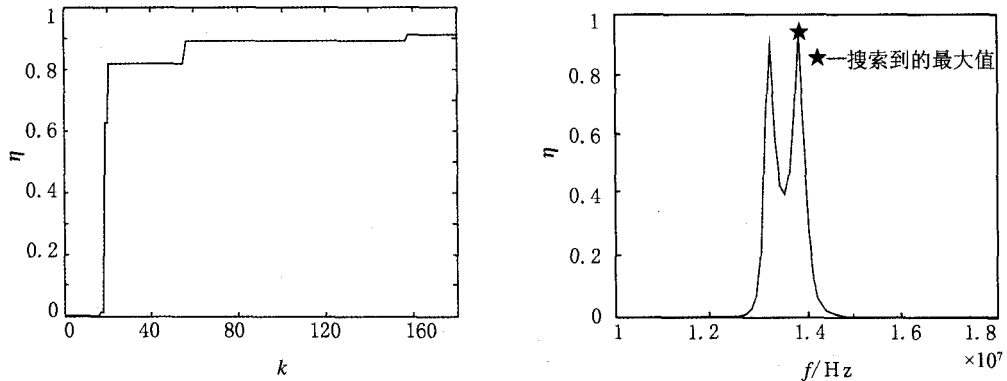


图4 10 cm处频率分裂下PSO算法寻优

4 总 结

针对收发线圈距离改变造成 MCR-WPT 系统电能接收端效率剧烈下降的问题, 本文提出了一种基于 PSO 寻优算法最大效率跟踪控制方法, 并分别在单一峰值和频率分裂条件下分析了算法寻优过程. 研究表明, 所提方法可以有效消除收发线圈距离改变对 MCR-WPT 系统传输效率的影响, 通过对共振频率的搜索, 使 MCR-WPT 系统高效率传输能量.

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Preparation of ZnTe/ZnO Globular-like Composites and Its Photocatalytic Performance

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Abstract: Using with Sodium tellurite and zinc oxide as precursor ZnTe/ZnO globular-like composites were synthesized by the solvothermal method. The photocatalytic activity of ZnTe/ZnO globular-like composites were studied by adjusting the ratio of the amount of synthetic ZnTe particles. The XRD results showed the samples ascribed to ZnTe/ZnO composite. The SEM results showed that the morphologies of the composite were globular-like. UV-Vis used to test optical properties. PL and EIS explained the reason why photocatalytic activity of composites developed. The experimental results showed that photocatalytic activity of ZnTe/ZnO compositions were better than pure phase. In addition, when the molar ratio of Na₂TeO₃ and ZnO was 1 : 0.4, the obtained composite showed the best photocatalytic performance because of degradation efficiency of methylene blue reached to 91% after 40 min UV irradiation.

Keywords: ZnTe/ZnO composites; solvothermal; photocatalytic

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Maximum Efficiency Tracking Control for Magnetic Resonant Coupling Based Wireless Power Transfer System

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Abstract: For magnetically-coupled resonant wireless power transfer (MCR-WPT) system, the resonance frequency changes and the transfer efficiency reduces when the distance between the transmitter and the receiver is smaller than a certain distance. To keep the receiver operates at a maximum efficiency, this work proposes a control method which is able to track the maximum efficiency. According to the characteristics of the MCR-WPT system, particle swarm optimization (PSO) strategy is introduced. Maximum efficiency tracking control is realized by solving particle fitness function iteratively to obtain the global optimal solution. The results indicate that the resonance frequency at the maximum transfer efficiency can be found with the proposed method for different distance to make the MCR-WPT system operate at the maximum efficiency.

Keywords: resonance frequency; PSO; maximum efficiency; tracking control