学科 代码与名称		
学科评审组 代码与名称		

江苏省高等学校科学技术研究成果奖

（技术发明奖）

推　　荐　　书

项　目 名 称：高效无线电能传输系统关键技术研究及应用

第一完成单位：中国矿业大学

通 信　地 址：江苏省徐州市大学路 1 号中国矿业大学南湖校区

电　　　　话：0516-83599970

邮　政 编 码：221116

推　荐 时 间：2013.11.02

江苏省高等学校科学技术研究成果奖
（技术发明奖）推荐书

（ 2023 年度）

一、项目基本情况

学科评审组：

<table>
<tr><td rowspan="2">项目名称</td><td>中文名</td><td colspan="4">高效无线电能传输系统关键技术研究及应用</td></tr>
<tr><td>英文名</td><td colspan="4">Research on key technology of high-efficiency wireless energy transmission system and its application</td></tr>
<tr><td colspan="2">主要完成人</td><td colspan="4">夏晨阳，廖志娟，刘旭，宋磊，赵书泽</td></tr>
<tr><td colspan="2">主要完成单位</td><td colspan="4">中国矿业大学，安洁无线科技(苏州)有限公司</td></tr>
<tr><td colspan="2">主 题 词</td><td colspan="4">新型无线电能传输系统，智能调控，能量与信号同步传输，辅助功能</td></tr>
<tr><td rowspan="3">学科分类名称</td><td>1</td><td colspan="2">电气工程</td><td>代码</td><td>47040</td></tr>
<tr><td>2</td><td colspan="2"></td><td>代码</td><td></td></tr>
<tr><td>3</td><td colspan="2"></td><td>代码</td><td></td></tr>
<tr><td colspan="2">所属国民经济行业</td><td colspan="4">(D) 电力、燃气及水的生产和供应业</td></tr>
<tr><td colspan="2">所属科学技术领域</td><td colspan="4">先进制造与自动化</td></tr>
<tr><td colspan="2">任务来源</td><td colspan="4">基金资助</td></tr>
<tr><td colspan="6">具体计划、基金的名称和编号：（不超过 5 项）
具体计划、基金的名称和编号，指上述各类研究开发项目列入计划、基金的名称和编号。应已结题，根据与本项目的紧密程度顺序填写，不超过 5 项。要求不超过 300 个汉字
1.国家自然科学基金面上基金，谐波分离与复用磁耦合谐振无线电能传输机理及关键技术研究，项目编号：51777210；
2.国家自然科学基金，三维动态磁耦合无线电能传输系统本征态传能机制及能效提升策略研究，项目编号：52007188；
3.中国博士后科学基金面上项目，水上水下无人探测设备并行无线供电机理及关键技术研究，项目编号：2019M652003；
4.徐州市科技计划项目（重点研发计划），电动汽车动态无线充电系统关键技术及装备研发，项目编号：KC18104；
5.江苏省自然科学基金面上基金，共拓扑多模态磁耦合谐振无线电能传输机理及关键技术研究，项目编号：BK20171190。</td></tr>
<tr><td colspan="2">授权发明专利（项）</td><td>17</td><td colspan="2">授权的其他知识产权（项）</td><td>11</td></tr>
<tr><td colspan="2">项目起止时间</td><td>起始： 2021 年 01 月 01 日</td><td colspan="3">完成： 2022 年 12 月 31 日</td></tr>
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二、项目简介

（限 1 页，限 1200 字）

无线电能传输技术彻底摆脱传统“有线”导线的束缚，显著提升用户体验，具有强灵活性、易操作性以及高安全性等优点。该技术可以实现远距离、高效率、低损耗的电能传输，为移动设备提供可靠的电源供应，拓展了电能应用的场景和范围。无线电能传输技术通过电磁转换实现能量传递，受系统本征传输性能等因素影响，该技术仍面临一系列问题与挑战，阻碍了诸如电动汽车、无人机等产业化进程。例如，如何提高系统的传输效率和稳定性，如何解决系统的偏移和干扰问题，如何实现系统的智能调节和控制，如何保证系统的安全性和兼容性等。本项目通过产学研联合自主创新，开展了新型无线电能传输系统多样化结构、无线电能传输系统智能调控、能量与信号同步传输、无线电能传输系统辅助功能等关键技术研究，突破了一系列技术难题，取得主要技术创新如下：

一、研发了新型无线电能传输系统多样化结构，提出了一种十字型无线电能传输磁路耦合机构，提升了磁路耦合机构的偏移容忍范围；构建了一种高阶 PT 对称 SS 拓扑无线电能传输系统设计方法，提升了磁路耦合机构的传输距离；首创了一种多调制波复合 SPWM 控制技术，增强了系统的灵活性和适应性，实现了多频多负载独立电能传输与控制功能。

二、研发了无线电能传输系统智能调控技术，提出了一种感应电能传输系统稳压综合控制系统，提高了系统的输出质量和输入效率；研发了基于 H∞控制器的 CPT 系统稳压控制，提高了系统的输出稳定性和输入灵敏度；设计了一种无线电能传输系统的改进型自抗扰控制方法及系统，提高了系统的抗干扰能力和鲁棒性。

三、研发了能量与信号同步传输关键技术，提出了单通道能量信号同步传输系统移相控制实现方法，实现了信号高速率传输，且降低了对于能量传输的影响；研发了非接触能量与信号同步传输系统结构，实现了稳定的功率输出和高速的信号传输；首创了多调制波复合 SPWM 控制的电能与信号并行无线传输方法，实现了电能与多路信号无交叉耦合干扰及稳定并行同步传输。

四、研发了无线电能传输系统辅助功能，提出了采用中继线圈切换补偿电容对水下无线电能传输系统进行互感识别的策略，提升了存在动态扰动的传能线圈间互感的实时识别精度；构建了浮频实本征态无线电能传输系统负载及互感双参数辨识方法，保证了高功率、高效率电能传输情况下的快速、准确负载和互感参数计算；设计了电动汽车无线充电对齐技术的自动泊车方法与系统，解决了信息延迟可能带来的泊车误差，提升了泊车的精准度和效率。

该项目研究成果获授权发明专利14项，授权实用新型专利11项，参与标准制定2项。这些专利和标准涵盖了无线电能传输系统的多个方面，其中包括磁路、电路、控制、通信、辨识等，体现了该项目的技术创新和优势。该项目的研究成果突破了国外技术封锁，形成了具备国内自主知识产权的技术路线，极大的促进了国内无线充电产业化进程，对于促进我国“新基建”中新能源汽车充电设施技术体系完善，服务国家“碳达峰、碳中和”绿色低碳能源发展战略具有重要意义。

三、主要技术发明

1. 主要技术发明（限 5 页）

随着双碳战略深入推进与绿色低碳经济快速发展，节能减排力度将不断加大，对绿色能源需求也将不断增加，未来无线电能传输技术的应用将更加广泛，对无线电能传输系统的稳定性、可靠性和智能化水平的要求也越来越高。本项目通过产学研联合自主创新，开展了新型无线电能传输系统多样化结构、系统智能调控技术、能量与信号同步传输、无线电能传输系统辅助功能等各项关键技术的研究，突破了一系列技术难题。主要技术创新如下：

创新点一：研发了新型无线电能传输系统多样化结构。提出了一种十字型无线电能传输磁路耦合机构，构建了一种高阶 PT 对称 SS 拓扑无线电能传输系统设计方法，首创了一种多调制波复合 SPWM 控制技术，提升了磁路耦合机构的偏移容忍范围与传输距离，实现了多频多负载独立电能传输与控制功能。

所属学科分类名称：电气工程。旁证材料：授权中国发明专利5件，授权国际发明专利1件，授权实用新型专利2件。New Wireless Electric Energy Transmission Magnetic Path Coupling Mechanism（一种新型无线电能传输磁路耦合机构），PCT/CN2017/091608（附件**1.1**）；一种PT对称SS拓扑MC-WPT系统及其实现方法，ZL202110251436.8（附件**1.2**）；基于多调制波复合SPWM控制的多频多负载无线电能传输系统，ZL202010342975.8；ZL202011151785.4、ZL202010848401.8、ZL202010677818.2、ZL202022668542.X、ZL202022672797.3。（附件**1.6**）

1. 十字型无线电能传输磁路耦合机构。研究了一种新型无线电能传输磁耦合机构。 十字型电磁耦合机构磁力线分布图如图 1 所示，该机构具有更高的耦合系数，且能够同时在两个相互垂直的水平方向以及绕机构中心轴旋转等三个方向上提供更宽的偏移容忍范围，为无线电能传输系统磁路耦合机构选取提供了更多样化的磁路耦合机构选择。

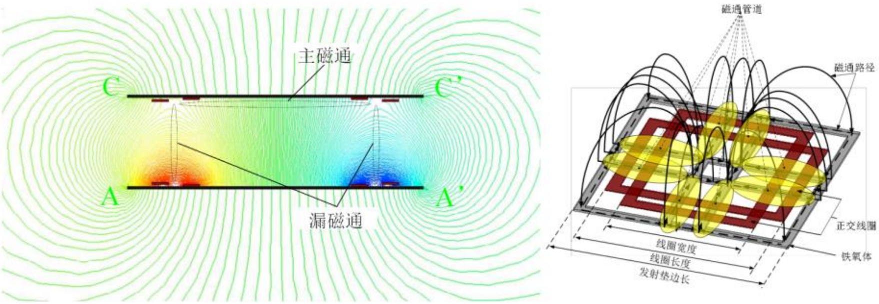


图 1 十字型电磁耦合机构磁力线分布图

2. 高阶 PT 对称 SS 拓扑无线电能传输电路结构。研究了一种高阶 PT 对称 SS 拓扑无线电能传输系统实现方法。三线圈 PT 对称 SS 拓扑 MC-WPT 系统的去耦等效电路如图 2 所示。求解得到了系统 PT 对称态、PT 对称破缺态、奇异点的解析表达式，为 PT 对称 MC-WPT 系统的设计提供了相应的理论准则。将 PT 对称特性应用到了三线圈架构系统中，并建立了相应的参数设计准则，相比传统的两线圈架构 PT 对称系统，传输距离得到了有效的提升。

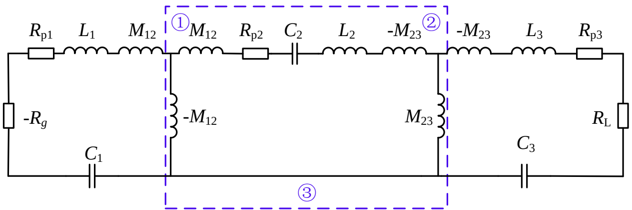


图 2 三线圈 PT 对称 SS 拓扑 MC-WPT 系统去耦等效电路图

3. 多调制波复合 SPWM 控制技术。研究了一种基于多调制波复合 SPWM 控制的多频多负载无线电能传输系统。复合 SPWM 控制的多频多负载无线电能传输系统结构图如图 3 所示，多调制波复合 SPWM 控制电路采用单极性倍频调制方式产生开关驱动信号，副边多频多负载电能接收装置通过各自的谐振网络分离获得对应频率的电能，从而实现多频多负载独立电能传输与控制，可适配不同工作频率负载供电需求，电能传输稳定且传输效率较高。

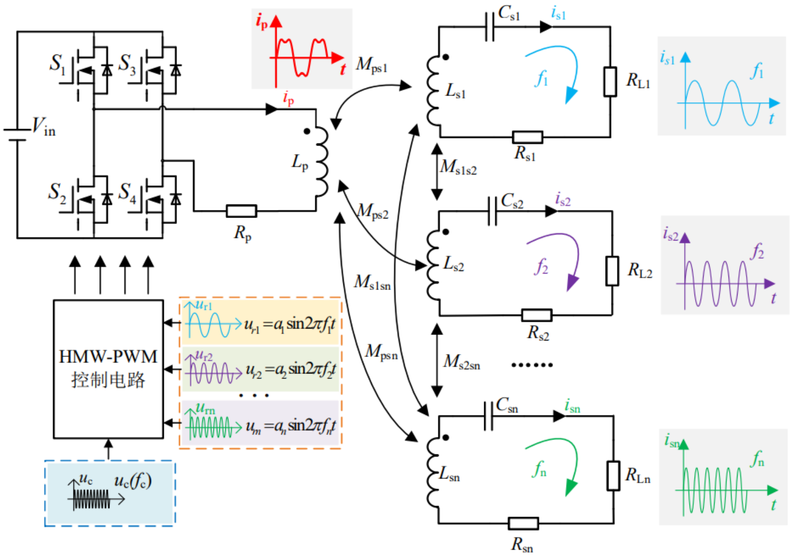


图 3 复合 SPWM 控制的多频多负载无线电能传输系统

创新点二：研发了无线电能传输系统智能调控技术。提出了一种感应电能传输系统稳压综合控制系统，研发了基于 H∞控制器的 CPT 系统稳压控制，设计了一种无线电能传输系统的改进型自抗扰控制方法及系统，保证了系统运行时在多参数摄动下的稳定，鲁棒性更强。

所属学科分类名称：电气工程。旁证材料：授权中国发明专利 3 件，授权实用新型专利 2 件。一种感应电能传输系统稳压综合控制系统及方法，ZL201811350253.6；一种无线电能传输系统的改进型自抗扰控制方法及系统，ZL202011159389.6。一种基于 H∞控制器的 CPT 系统稳压控制方法及系统，ZL202010226545.X；ZL202220702494.8、ZL202221646641.0。（附件 **1.6**）

1. 一种感应电能传输系统稳压综合控制系统及方法。研究了一种感应电能传输系统稳压综合控制系统。系统的电路图如图 4 所示，通过对系统电路建立交流阻抗模型计算出效率表达式，求得最优等效负载，通过建立系统的参数摄动模型，将负载采集电压与输入参考电压的差值送入鲁棒控制器，得到移相角控制原边的高频全桥逆变器实现恒压。有源阻抗匹配网络的最优效率跟踪控制和闭环的鲁棒控制，可以较好地满足系统的最优效率和输出恒定电压的多性能要求。

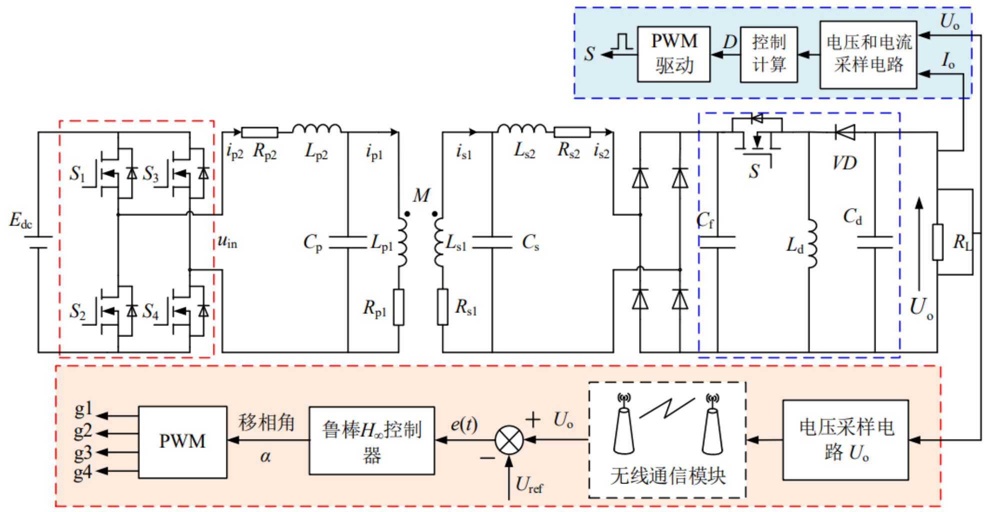


图 4 双 LCL 拓扑 ICPT 控制系统示意图

2. 多基于 H∞控制器的 CPT 系统稳压控制方法。研究了一种基于 H∞控制器的 CPT 系统稳压控制方法及系统。系统的电路图如图 5 所示，根据 CPT 系统电路结构建立系统的数学模型 G，分离系统的摄动部分和标称部分，采用粒子群优化算法选择加权函数，以系统的时域性能指标和鲁棒性能指标作为约束条件，迭代选择合适的加权函数带入 H∞控制器，该优化方法可以根据不同的性能要求协调时域性能和鲁棒性能之间的矛盾，得到的闭环系统可以有效提高多参数摄动下的稳定特性。

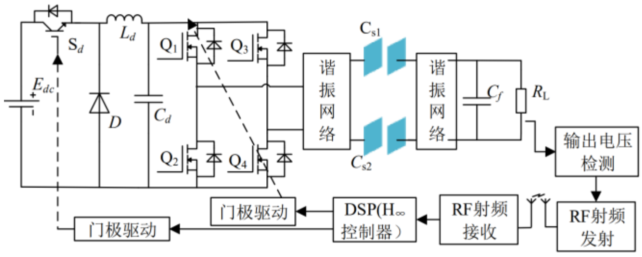


图 5 基于 H∞控制器的 CPT 系统稳压控制电路图

3. 一种无线电能传输系统的改进型自抗扰控制方法及系统。研究了一种无线电能传输系统的改进型自抗扰控制方法及系统。系统的工作原理图如图 6 所示，为了减轻线性扩张状态观测器对复杂扰动的观测压力，基于被控系统已知的部分模型信息 b_1，先采用一个二阶 LESO 对无线电能传输系统的部分扰动量 R_0 进行观测估计，然后线性扩张状态观测器观测估计系统的其他扰动量 $\omega(t)$，并在线性状态误差反馈控制律中对观测的总扰动量 $F(t)$进行补偿。该方法模型依赖度低，在外部干扰和内部参数摄动情况下使得无线电能传输系统能够实现稳压输出、参数易于整定且鲁棒性强。

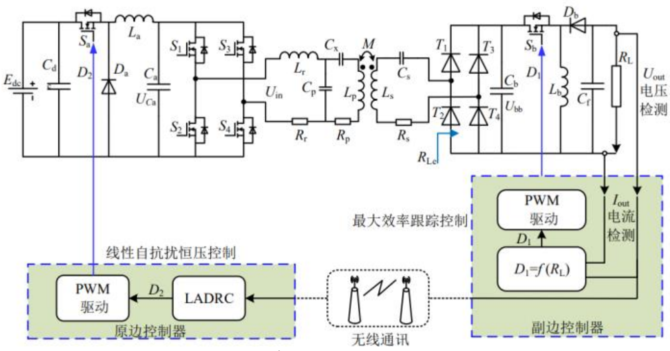


图 6 ICPT 系统复合控制策略原理图

创新点三：研发了能量与信号同步传输关键技术。研发了能量与信号同步传输关键技术，提出了单通道能量信号同步传输系统移相控制实现方法，研发了非接触能量与信号同步传输系统结构，首创了多调制波复合 SPWM 控制的电能与信号并行无线传输方法。在保证电能稳定传输的基础上实现信号高速率传输。

所属学科分类名称：电气工程。旁证材料：授权中国发明专利 3 件，授权实用新型专利 1 件。一种单通道能量信号同步传输系统移相控制实现方法及该系统，ZL201811372757.8（附件 **1.3**）；一种非接触能量与信号同步传输系统及传输方法，ZL201810195763.4；多调制波复合 SPWM 控制的电能与信号并行无线传输系统，ZL202010740959.4；ZL202120608377.0。（附件 **1.6**）

1. 一种单通道能量信号同步传输系统移相控制方法。研究了一种单通道能量信号同步传输系统移相控制实现方法及该系统，单通道能量信号同步传输系统移相控制原理如图 7 所示，该方法通过移相方式控制高频逆变器的移相角，不同移相角所对应的逆变输出阶梯方波中各次谐波含量不同，利用副边选频电路将基波和三次谐波选出分别传输能量和信号。若直接控制高频逆变器的移相角，则可以动态调节三次谐波的含量。该系统能够实现信号高速率传输，且基本不影响能量传输。

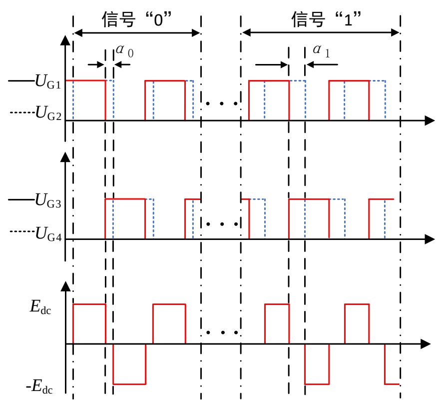


图 7 单通道能量信号同步传输系统移相控制原理图

2. 一种非接触能量与信号同步传输系统及传输方法。研究了一种无线电能传输技术中的能量与信号同步传输系统及传输方法。非接触能量与信号同步传输系统的电路拓扑结构如图 8 所示，高频逆变器后串联接入隔直电容和原边能量发射模块，构成三角波提取通道；信号调制模块通过改变高频逆变器工作频率将基带信号加载到三角波中，经过松耦合变压器将能量与信号同时传输至副边，通过副边能量接收模块和信号解调模块将通道中的能量与信号分离，实现能量与信号同步传输。该系统系统体积小，且能够实现输出稳定功率和高信号传输速率。

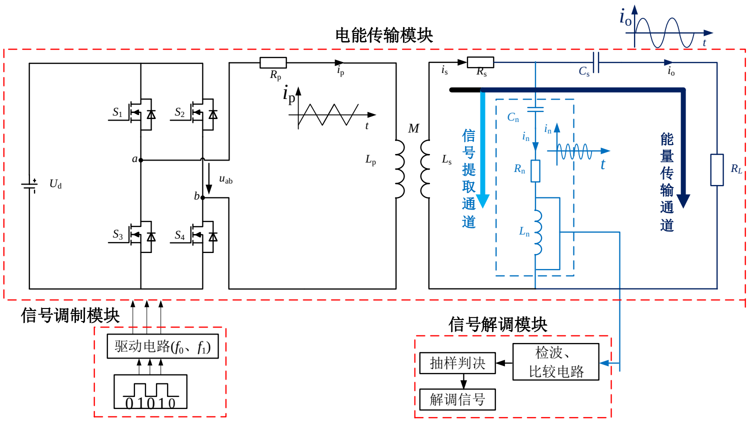


图 8 非接触能量与信号同步传输系统的电路拓扑结构图

3. 多调制波复合 SPWM 控制的电能与信号并行无线传输系统。研究了一种多调制波复合 SPWM 控制的电能与信号并行无线传输系统。复合调制波 PWM 控制 SWPMPST 系统电能与多路信号解调原理示意图如图 9 所示。高速串行比特经编码器形成 n 路并行二进制序列送入多调制波复合 SPWM 控制电路进行调幅调制，然后基于 SPWM 控制输出复合脉冲波，接着通过线圈传输能量，副边侧电能传输通道将复合高频电流中的电能调制波频率分量分离给负载电阻供电，信号分离通道网络分离出 n 路不同频率的信号调制波分量，信号解调电路网络对信号解调后送入译码器恢复高速串行比特。该系统实现了电能与多路信号无交叉耦合干扰及稳定并行同步传输，在保证电能稳定的同时，有效提高了信号传输速率。

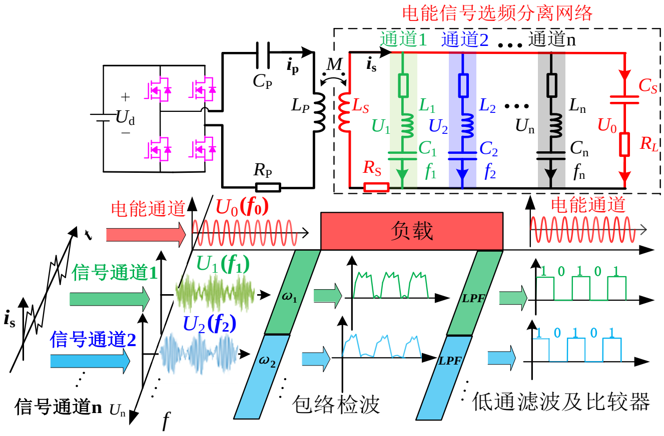
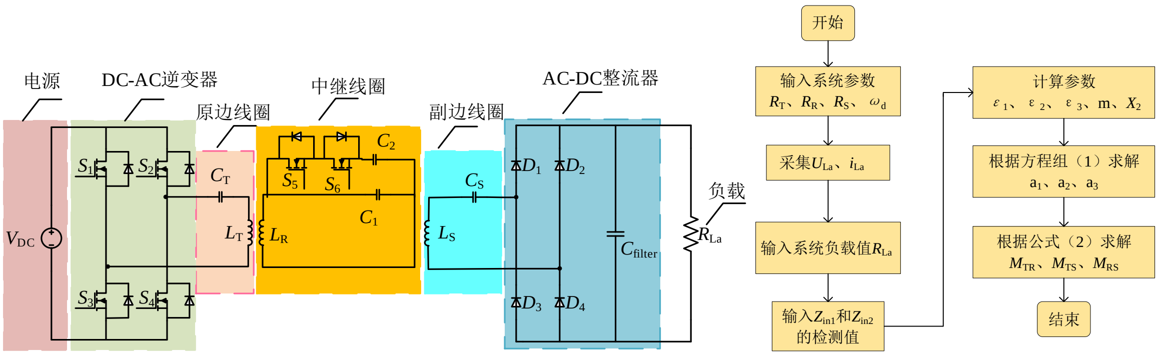


图 9 复合调制波 PWM 控制 SWPMPST 系统电能与多路信号解调原理示意图

创新点四：研发了无线电能传输系统辅助功能。提出了采用中继线圈切换补偿电容的方法对水下无线电能传输系统进行互感识别的策略，构建了浮频实本征态无线电能传输系统负载及互感双参数辨识方法，设计了电动汽车无线充电对齐技术的自动泊车方法与系统。确保了高精度互感、负载与位置辨识，解决了信息延迟的误差问题，同时还能保证高功率、高效率电能传输。

所属学科分类名称：电气工程。旁证材料：授权中国发明专利 5 件，授权实用新型专利 6 件。一种基于中继线圈的水下无线供电系统在线互感识别方法，ZL202110179498.2（附件 **1.4**）；一种磁耦合无线电能传输系统负载及互感双参数辨识方法，ZL202110473412.7（附件 **1.6**）；基于无线充电对齐技术的电动汽车自动泊车方法及系统，ZL202110073964.9（附件 **1.5**）；ZL202210053972.1、ZL202022668632.9、ZL202121652638.5、ZL202020095235.4、ZL202010807410.2、ZL202021068953.9、ZL202220700534.5、 ZL202220702455.8。（附件 **1.6**）

1. 水下无线电能传输系统互感识别策略。研究了一种利用中继线圈可切换补偿电容实现波浪扰动工况下，自主水下航行器舰载无线充电系统能量拾取装置与水下无线供电系统能量发射装置之间的实时互感识别方法，无需增加复杂的电路或改变系统驱动频率，对存在动态扰动的系统线圈间互感的实时识别精度高。



(a)系统结构示意图　　(b) 参数辨识流程图

图 10 基于开关电容的无线电能传输系统参数辨识技术

2. 浮频实本征态无线电能传输系统负载及互感双参数辨识方法。研究了应用于磁耦合无线电能传输系统的负载及互感双参数辨识方法，该电路图如图 11 所示。通过调节磁耦合无线电能传输系统至浮频实本征态，然后在浮频实本征态下采集系统原边的输入电压和电流，进而计算出负载的阻抗值和耦合系数，最后计算出互感参数。该方法可快速、准确地计算出负载和互感参数，同时还能保证高功率、高效率电能传输。

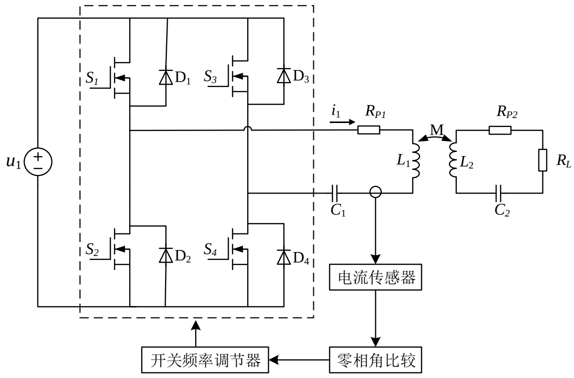


图 11 磁耦合无线电能传输系统电路图

3. 基于无线充电对齐技术的电动汽车自动泊车方法及系统。研究了一种电动汽车无线充电对齐技术的自动泊车方法与系统。基于无线充电对齐技术的自动泊车系统的原理图如图 12 所示。通过实时采集图像和距离数据，系统智能规划泊车路径，并持续监测发射线圈和接收线圈之间的位置偏移矢量，确保泊车位置符合无线充电需求。该方法有效解决了信息延迟可能带来的泊车误差，提升了泊车的精准度和效率。

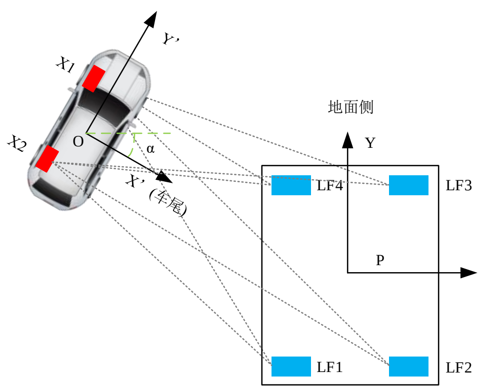


图 12 自动泊车系统原理图

2. 技术局限性（限 1 页）

创新点	现阶段存在的技术局限性	今后的主要研究方向
创新点一	（1）十字型无线电能传输磁路耦合机构提高了工程设计成本； （2）线圈交流电阻理论计算与仿真误差较大； （3）多调制波复合SPWM控制技术对MOSFET的开关速度要求较高。	（1）降低磁路机构的工程设计成本； （2）提出一种精确的磁路机构参数设计方法； （3）设计高开关频率低死区时间的GaN逆变器。
创新点二	（1）鲁棒控制与自抗扰控制方法均需要对无线充电系统进行复杂的电路建模； （2）控制过程中需要使用无线通信模块，这降低了无线充电系统的控制速度。	（1）降低无线充电系统控制器的设计难度； （2）提升无线充电系统控制器的控制速度。
创新点三	（1）基于移相控制的单通道能量信号同步传输方法利用三次谐波传输信号，其信号的传输速率较慢； （2）能量传输之路对于信号通信支路的干扰较强； （3）多调制波复合SPWM控制的电能与信号并行无线传输技术对MOSFET的开关速度要求较高。	（1）提升信号的通信速率； （2）降低能量传输支路对于信号通信支路的干扰程度； （3）设计高开关频率低死区时间的GaN逆变器。
创新点四	（1）互感识别需要依靠额外的一个中继线圈，这增加了系统的体积与成本； （2）建立了电动汽车无线充电互操作性测试系统及方法，但仍需研发一种提升互操作性的方法。	（1）设计一种结构简单且识别精度高的参数辨识方法； （2）研发高互操作性无线电能传输系统。

四、客观评价

（限 2 页。围绕技术发明点的首创性、先进性和技术价值进行客观、真实、准确评价。填写的评价意见要有客观依据，主要包括与国内外相关技术的比较，国家相关部门正式作出的技术检测报告、验收意见、鉴定结论，国内外重要科技奖励，国内外同行在重要学术刊物、学术专著和重要国际学术会议公开发表的学术性评价意见等，可在附件中提供证明材料。非公开资料（如私人信函等）不能作为评价依据。）

（一）第三方检验

1）中国矿业大学研究的一套充电系统功率传能控制与辅助功能开发系统在安洁无线科技(苏州)有限公司进行了成果转化研究试验。2022年5月30日，中国赛宝实验室工业和信息化部第五研究所，对安洁无线科技(苏州)有限公司的无线电能传输控制器进行检验，结论：委托检验项目基本符合要求。（附件**3.1**）

2）2022 年 9 月 19 日，江苏佳世德检测技术有限公司，对中国矿业大学参与研制、安洁无线科技(苏州)有限公司制造的无线电能传输发射器和无线电能转换器等产品进行气体腐蚀和碾压试验等项目的检验，结论：所有委托检验项目符合要求。（附件 **3.2**）

3）2022年9月1日，中汽研汽车检验中心（天津）有限公司，对中国矿业大学参与研制、安洁无线科技(苏州)有限公司制造的WB+GAR+VA的电磁兼容性和各种模式不同频率下天线垂直或水平极化时样品的辐射发射特性进行检验，结论：委托检验项目基本符合要求。（附件**3.3**）

4）2022年9月15日以及9月25日，中国赛宝实验室工业和信息化部电子第五研究所，对中国矿业大学参与研制、安洁无线科技(苏州)有限公司制造的无线电能转换器(11kW)、无线电能传输发射器(11kW)在温度:15C~35C、相对湿度: 25%~75%、气压:86kPa~106kPa的环境下进行检验，结论：委托检验项目基本符合要求。（附件**3.4**）

5）2022年8月8日，中国赛宝实验室工业和信息化部电子第五研究所，对中国矿业大学参与研制、安洁无线科技(苏州)有限公司制造的e线电能传输控制器(11kW)对五点功能测试(试验前)、高低温存储、高温工作、温度梯度、温度循环、交变湿热、结露、防水、振动等各种项目进行检验，结论：委托检验项目基本符合要求。（附件**3.5**）

（二）验收意见

1）2021年4月7日，徐州市科技局组织专家对中国矿业大学承担的市科技计划项目“电动汽车动态无线充电系统关键技术及装备研发”(项目编号:KC18104)进行验收，项目期间提出了一种平行四边形分段导轨式磁路机构实现了分段导轨的智能切换，解决了电动汽车动态无线充电系统电压输出不稳定问题，结论：验收委员会认为中国矿业大学承担的电动汽车动态无线充电系统关键技术及装备研发全面完成了合同规定各项任务和考核指标，对推动电动汽车动态高效自由的无线充电技术发展具有较为现实的意义。（附件**3.6**）

2）2022年01月22日，国家自然科学基金委，对中国矿业大学夏晨阳教授的谐波分离与复用磁耦合谐振无线电能传输机理及关键技术研究（项目编号：51777210）进行验收，结论：完成项目预期目标，一定程度上提高了我国无线电能传输基础理论水平，研究结论丰富了无线电能传输技术基础理论体系，为无线电能传输技术的推广以及产业化发展和应用做出了一定贡献。（附件**3.7**）

3）2020年12月12日，江苏省科技厅，对中国矿业大学夏晨阳教授的省自然科学基金“共拓扑多模态磁耦合谐振无线电能传输机理及关键技术研究 (项目编号：BK20171190) ”项目验收，结论：该项目完成了合同规定的设计并实现该方法，并解决系统关键问题；建立并分析该方法的电路、磁路和动力学模型；构建并优化一个综合考虑系统各项性能和经济性的多目标函数模型，提出一种基于功率分配的控制策略，提高系统稳定性，实现高效可靠的无线电能传输，并且项目经费支出合理规范，同意通过验收。（附件**3.8**）

（三）国内外重要科技奖励

1）2019年7月4日，中国矿业大学夏晨阳教授以双面共芯电动汽车集群无线充电机制及关键技术研究

项目荣获江苏省“六大人才高峰”高层次人才称号（项目编号：XNYQC-012），通过对电动汽车传输系统工作机理、异物检测机理的研究，为未来新能源汽车的应用与产业发展做出了一定的贡献。（附件**3.9**）

2）2021年，夏晨阳，廖志娟，刘冰，刘锋，周娟，李壮，韩潇左，申报的“电动汽车有线/无线一体化充电关键技术及应用”获得2021年度江苏省电力科学技术奖三等奖，证书编号：2021-J-3-07-G1。（附件**3.10**）

（四）参与标准

1）2022年，中国矿业大学夏晨阳教授与廖志娟副教授参与团体标准“多旋翼无人机磁耦合静态无线充电系统通用技术要求”的制定，标准号：T/CPSS 1005—2023，该标准已于2023.8.31发布。（附件**3.11**）

2）2022年，中国矿业大学夏晨阳教授参与团体标准“多旋翼无人机磁耦合静态无线充电系统测试要求”的制定，标准号：T/CPSS 1006—2023，该标准已于2023.8.31发布。（附件**3.12**）

（五）国内外同行在重要学术刊物、学术专著、重要国际学术会议上公开发表的学术性评价意见等

1) Philip T.K等人在其发表论文“Analysis and Design of Multifrequency Compensation Strategy for Wide Misalignment Tolerance in Inductive Power Transfer Systems”中评价，混合调制脉宽调制（PWM）控制方法，能够产生不同的频率来向多个接收器提供能量。（附件**3.13**）

2) Enes A等人在其发表论文“Variable Carrier Phase-Shift Method for Integrated Contactless Field Excitation System of Electrically Excited Synchronous Motors”中指出“通过将叠加的正弦参考信号与高频三角波载波信号进行比较，实现了多频率传输”。（附件**3.14**）

3) Chunhua L等人在其发表论文“Design and Control of a Decoupled Multichannel Wireless Power Transfer System Based on Multilevel Inverters”中评价本项目提出的SPWM控制技术时指出，“仅采用一个全桥逆变器，实现了多频率信号的高度叠加，其调制波包含多个频率成分。”（附件**3.15**）

4)Amir Hakemi等人在其发表论文“Generic Uncertainty Parameter Analysis and Optimization of Series–Series Wireless Power Transfer System for Robust Controller Design”中指出“对于 LCL 补偿网络，采用了同样的控制器设计方法。该控制器能够精确跟踪负载和 K 变化时的参考电压。”（附件**3.16**）

5)张蒙飞等人其发表论文“电场耦合式无线电能传输系统的偏移特性分析”评价，将 LCL系统进行GSSA建模后，为分析ECPT系统的鲁棒性问题将参数不确定性利用线性分式变换进行摄动分离，并利用粒子群算法提高控制器设计效率和改进反馈中时域和鲁棒问题，最终通过仿真和样机实验进行验证控制器的效果和抑制极板偏移和负载变化对系统的影响情况。（附件**3.17**）

6) 殷金安等人其发表论文“动态IPT系统后级稳压器的小信号模型修正和改进控制策略”中评价，通过线性自抗扰恒压输出控制算法，有效的优化了系统启停、跟随参考、变负载的调节时间与超调量。（附件**3.18**）

7) Yunliu W等人在其发表论文“A Capacitive Power and Signal Transfer System Based on Ring-Coupler with Mitigated Inter-Channel Crosstalk”中评价，调整逆时序PWM可以提供更稳定的电流和电压输出，降低系统的波动性，增加系统的稳定性。（附件**3.19**）

8) Przemysław Ptak等人在其发表论文“Model of an Air Transformer for Analyses of Wireless Power Transfer Systems”中指出，该方法适用于低电压高电流和高电压低电流操作，并且可以根据应用调整副绕组电流振幅与主绕组电流振幅之比，因此具有高功率传输效率。（附件**3. 20**）

9) Shimaa Alshhawy等人在其发表论文“Compact and Efficient WPT System to Embedded Receiver in Biological Tissues Using Cooperative DGS Resonators”中指出，谐振移位现象是由于介质依赖性而产生的，与系统进入过耦合状态时发生的频率分裂现象无关。（附件**3. 21**）

五、应用情况和效果

1．应用情况（限 2 页）

无线充电产品的发展在电动汽车领域有着广泛需求，需要满足车企性能要求，尤其是加强要与车辆结合的相关技术的研究，以提供功能强大的产品，不断增加产品吸引力，打造成目标车辆吸引用户的亮点配置，是无线充电可持续发展的基础。

（1）与智能驾驶技术结合

无线充电技术已经与自动泊车、自动驾驶等智能驾驶技术相结合，实现了车辆自动精确定位和自动充电，提高了整车驾驶性能以及无线充电效果，满足了汽车智能化、无人化的发展趋势。中国矿业大学、安洁无线科技(苏州)有限公司与AuTo X公司展开了深入的合作，开发了无线充电搭配自动泊车、自动驾驶的功能，真正的实现了车辆运行的无人化操作。AuTo X公司已采购了100多套安洁无线科技提供的无线充电样机装配在整车上进行测试验证，并取得了良好的效果。这一创新成果不仅为国内外车企提供了最佳的自动充电商业解决方案，还为无线充电技术成为自动驾驶的推动者打下了坚实的基础。

（2）与用户充电行为结合

无线充电技术已经与用户充电行为结合，实现了对动力电池或充电功率的优化配置，从而在整体上降低了包括电动汽车在内的系统成本。中国矿业大学与安洁无线科技(苏州)有限公司根据用户普遍的充电行为习惯，如每日行驶距离、充电频次、充电时间和充电点位置等参数进行配置，优化了动力电池的容量或无线充电传输功率。例如，中国矿业大学与安洁无线科技(苏州)有限公司合作研发的相关技术得到了实际应用。在中国矿业大学技术指导下安洁无线科技(苏州)有限公司就公司内部车位装配无线充电功能，并改装了小鹏、特斯拉、长城、比亚迪等多个车型的无线充电系统，将特斯拉原有的7kW有线充电改为11kW的无线充电，并在27930协议下，做到了一机可无线充电，也可有线充电。这一创新方案获得使用者的一致好评，做到了随停随充，优化了电动汽车充电的体验感，简单、便携、高效。

中国矿业大学与安洁无线科技(苏州)有限公司联合研制的电动汽车无线充电系统性能领先于国内其他同行，安洁无线科技(苏州)有限公司已经成为国内无线充电系列化产品的最大提供商，其无线充电产品已出货给多家车企，如长城（附件**2.1**）、现代（附件**2.2**）、比亚迪、上汽智己、吉利、海尔、北京201所等多个厂家，无论是从产品技术、产品质量、售后服务、技术支持等多方面，都获得了客户的一致好评。随着无线充电技术的进一步成熟，成本的进一步降低，相信在未来的2024、2025年，电动汽车无线充电会进入一个快速发展的时代。

除了与安洁无线科技(苏州)有限公司的合作项目外，中国矿业大学研发的无线充电相关技术还在其他多个领域和行业得到了广泛的应用和推广，为社会创造了更多的价值和效益。以下是中国矿业大学的无线充电技术在其他企业相关的应用情况:

单位名称	应用的技术	应用对象及规模	应用起止时间
中兴新能源科技有限公司	电动汽车磁耦合无线充电关键技术及应用	应用于：无线充电技术研究项目促进相关新增销售额19500万元及新增利润420万元	2021年—2023年
上海汽车集团股份有限公司技术中心	电动汽车磁耦合无线充电关键技术及应用	应用于：无线充电荣威MARVEX车型促进新增销售额141400万元及新增利润3676.4万元	2021年—2022年
中国第一汽车股份有限公司新能源开发院	电动汽车磁耦合无线充电关键技术及应用	应用于：红旗车型无线充电量产产品开发及示范应用节约研发投资成本：500万元	2021年—2023年
重庆长安新能源汽车科技有限公司	电动汽车磁耦合无线充电关键技术及应用	应用于：无线充电技术研究项目节约研发投资成本：400万元	2020年—2022年
上海万暨电子科技有限公司	电动汽车磁耦合无线充电关键技术及应用	应用于：无线充电相关项目节约研发投资成本600万元，促进新增销售额2780万元及新增利润340万元	2021年—2022年
北京有感科技有限责任公司	电动汽车磁耦合无线充电关键技术及应用	应用于：无线充电相关项目节节约研发投资成本600万元，促进新增销售额1410万元及新增利润405万元	2020年—2021年

2．应用效果（限 2 页）

1、经济效益				单位：万元人民币
自然年	安洁无线科技(苏州)有限公司		其他应用单位	
	新增销售额	新增利润	新增销售额	新增利润
2021	1225	62	7650	1952
2022	1760	88	9250	2662
2023	1544	78	2980	884
累计	4529	228	19880	5498

经济效益的有关说明及各栏目的计算依据：

中国矿业大学与安洁无线科技(苏州)有限公司、中兴新能源科技、上汽荣威、上海万暨电子科技、北京有感科技等相关单位合作，开发和推广电动汽车无线充电技术的项目。主要技术贡献是提高电动汽车充电的便利性、安全性和效率，降低充电成本和环境污染，促进电动汽车产业的发展和创新。经济效益主要体现在以下两个方面：

（1）新增销售额：在中国矿业大学技术支持下，安洁无线科技(苏州)有限公司以及其他相关技术转让和合作单位涉及各类电动汽车充电桩、电动汽车无线充电系统等系列产品的生产和销售，这些产品具有先进性、高效性和环保性等优势，受到了市场的欢迎和认可。根据与合作单位之间的协议，中国矿业大学的合作单位安洁无线科技(苏州)有限公司在 2021 年、2022 年和 2023 年共生产销售了这些产品，并获得了相应的新增销售额。

每年新增的销售额计算：根据各类电动汽车相关产品的价格，乘以销售的数量，累计求和得到每年新增的电动汽车相关产品销售额。

（2）新增利润：安洁无线科技(苏州)有限公司以及其他相关技术转让和合作单位在 2021 年、2022 年和 2023 年共生产销售各类电动汽车充电桩、电动汽车无线充电系统等系列产品的新增利润。

每年新增的利润计算：根据年度销售的各类电动汽车相关产品的销售额，减掉生产各类产品的总成本。

从上表可以看出，项目在 2021 年、2022 年和 2023 年分别实现了 2014 万元、2750 万元和 962 万元的新增利润，保持着良好的增长趋势。同时，相关合作项目的利润率也在不断提高，合作项目的盈利能力不断增强。

在成本节约方面，相关项目共节省相关单位研发投资 3900 万元，主要体现在研究投入、人力投入以及材料费用三方面。项目形成了我国行业自主知识产权的无线充电技术路线，相关企业均可采用项目关于无线充电系统的电路、磁路、控制架构，解决了相关的研发投资。

安洁无线科技（苏州）有限公司财务专用章 3205061051023

安洁无线科技（苏州）有限公司 3205061051023

2、社会效益

本项目是关于电动汽车无线充电技术的研究和应用项目，是中国矿业大学与安洁无线科技(苏州)有限公司以及其他相关单位的合作成果。本项目的社会效益主要表现在以下几个方面：

满足社会需求：本项目成果满足了社会对新型、高性能、高可靠性电动汽车的需求，为解决交通拥堵、能源危机和环境污染等问题提供了有效的解决方案。根据统计，我国目前已有超过5000万辆电动汽车，预计到2025年将达到1亿辆，占全球电动汽车市场的一半以上。本项目成果可以为这些电动汽车提供便捷、安全和高效的充电服务，提高用户的出行体验和满意度。

促进技术进步：本项目成果引领了我国电动汽车相关行业和产业的技术进步，为我国在该领域的国际竞争力和影响力提供了强有力的支撑。本项目成果采用了创新的无线充电技术，实现了与有线充电相当甚至超过的充电效率和兼容性，同时降低了充电设备的占地面积和维护成本，提高了充电设备的寿命和安全性。本项目成果在国内外多个重要的展会和论坛上展示和交流，受到了业界和社会的广泛关注和赞誉。

增加经济效益：本项目成果通过安洁无线科技(苏州)有限公司以及其他相关技术转让和合作单位技术转化，产生了显著的经济效益。根据中国矿业大学与合作单位之间的协议，在2021年、2022年和2023年生产销售了各类电动汽车充电桩、电动汽车无线充电系统等系列产品，并获得了相应的新增销售额和利润。

提升研发能力：在项目研发和推广过程中，安洁无线科技(苏州)有限公司获批了江苏省企业研究生工作站等研发平台，获得了高新技术企业称号，培养了60多名工程技术人员和研究生。这些平台和人才为本项目的持续创新和发展提供了坚实的基础和保障。同时，本项目也为中国矿业大学的无线电能传输技术在其他研究领域的应用提供了技术支持和经验借鉴，提高了中国矿业大学在无线电能传输技术方面的整体研发水平和能力。

打造标准体系：本项目提出了我国电动汽车无线充电行业的技术路线，参与发布了我国首批相关标准，打破了国外在本领域的技术壁垒，避免了该领域后期技术“卡脖子”情况，支撑了我国电动汽车无线充电行业的健康可持续发展。同时项目制定的标准解决国内电动汽车无线充电参考设备互操作性标准的溯源问题，统一了系列化电动汽车无线充电系统的车载端和地面端线圈结构、主要参数及通信流程等，为行业上下游相关企业的产品开发提供了技术指导，带动了我国电动汽车无线充电行业的发展。

增强社会责任：本项目成果不仅为社会提供了优质的产品和服务，还为社会承担了责任和义务。本项目成果通过无线充电技术，减少了电动汽车充电过程中的电能损耗和碳排放，为节约能源和保护环境做出了贡献。本项目成果还通过无线充电技术，提高了电动汽车充电的安全性和可靠性，为保障公共安全和社会稳定做出了努力。

促进人才培养：本项目成果不仅为中国矿业大学和合作单位培养了一批优秀的工程技术人员和研究生，还为社会培养了一批具有创新精神和实践能力的人才。本项目成果通过与多所高校和科研机构合作，开展了多项教学和科研活动，为大学生和研究生提供了丰富的学习和实践机会。

六、主要知识产权和标准规范等目录（不超过 10 件）

知识产权（标准）类别	知识产权（标准）具体名称	国家（地区）	授权号（标准编号）	授权（标准发布）日期	证书编号（标准批准发布部门）	权利人（标准起草单位）	发明人（标准起草人）	发明专利（标准）有效状态
发明专利	New Wireless Electric Energy Transmission Magnetic Path Coupling Mechanism	加拿大	PCT/CN2017/091608	2022.5.24	3031438	中国矿业大学	夏晨阳;任思源;郑凯;刘利民;朱从;朱文婷;陈锐;马念	授权
发明专利	一种 PT 对称 SS 拓扑 MC-WPT 系统及其实现方法	中国	ZL202110251436.8	2022.12.27	5665692	中国矿业大学	廖志娟;冯其凯;姜陈慧;吴凡;马帅;夏晨阳	授权
发明专利	一种单通道能量信号同步传输系统移相控制实现方法及该系统	中国	ZL201811372757.8	2021.2.9	4246597	中国矿业大学	夏晨阳；贾仁海；彭昱翔；路强；杨颖；吴镇	授权
发明专利	一种基于中继线圈的水下无线供电系统在线互感识别方法	中国	ZL202110179498.2	2022.12.27	5666451	中国矿业大学	刘旭；宋翔昱；原熙博	授权
发明专利	基于无线充电对齐技术的电动汽车自动泊车方法及系统	中国	ZL202110073964.9	2022.8.19	5391226	安洁无线科技（苏州）有限公司	侯雅静；赵彦斌	授权
发明专利	基于多调制波复合 SPWM 控制的多频多负载无线电能传输系统	中国	ZL202010342975.8	2022.12.9	5639062	中国矿业大学	夏晨阳；魏楠；张宏泰；李晓丽；冯其凯；韩潇左；杨旭浩；李壮；马帅；廖志娟	授权
发明专利	一种基于 H∞ 控制器的 CPT 系统稳压控制方法及系统	中国	ZL202010226545.X	2021.9.28	4709510	中国矿业大学	夏晨阳；魏国玉；李欣宇；周磊；孙琪琪；廖志娟；伍	授权

							小杰	
发明专利	一种非接触能量与信号同步传输系统及传输方法	中国	ZL201810195763.4	2021.7.16	4549480	中国矿业大学	夏晨阳;朱文婷;朱从;刘利民;马念;伍小杰;陈俊	授权
发明专利	一种磁耦合无线电能传输系统负载及互感双参数辨识方法	中国	ZL202110473412.7	2022.8.26	5406483	中国矿业大学	廖志娟;姜陈慧;吴凡;陈张睿威;夏晨阳	授权
发明专利	一种类 EIT 多中继无线电能传输系统及其设计方法	中国	ZL202011151785.4	2022.1.7	4883226	中国矿业大学	廖志娟;冯其凯;马帅;吴镇;夏晨阳;伍小杰	授权

承诺：①项目所列知识产权符合推荐要求且无争议；②所列知识产权、论文（专著）等未获得市厅级及以上科学技术奖励；③所列知识产权用于提名技术发明奖的情况，已征得未列入项目主要完成人的权利人（发明专利指发明人）的书面签字同意，有关知情证明材料均存档备查。④如因上述事项引发争议，将积极配合调查处理并承担相应责任。

第一完成人签名：

七、主要完成人情况表（主要完成人按照排名顺序填写，一人一页）

<table>
<tr><td>姓　　名</td><td>夏晨阳</td><td>性别</td><td>男</td><td>排　　名</td><td>1</td><td>国　　籍</td><td>中国</td></tr>
<tr><td>出生年月</td><td colspan="3">1982.11</td><td>出 生 地</td><td>江苏泰州</td><td>民　　族</td><td>汉族</td></tr>
<tr><td>身份证号</td><td colspan="3">321283198211052817</td><td>归国人员</td><td>是</td><td>归国时间</td><td>2018.8</td></tr>
<tr><td>技术职称</td><td colspan="3">教授</td><td>最高学历</td><td>研究生</td><td>最高学位</td><td>博士</td></tr>
<tr><td>毕业学校</td><td colspan="3">重庆大学</td><td>毕业时间</td><td>2010.12</td><td>所学专业</td><td>控制理论与控制工程</td></tr>
<tr><td>电子邮箱</td><td colspan="3">chyxia@cumt.edu.cn</td><td>办公电话</td><td>0516-83599970</td><td>移动电话</td><td>18260722082</td></tr>
<tr><td>通讯地址</td><td colspan="5">江苏省徐州市大学路 1 号</td><td>邮政编码</td><td>221116</td></tr>
<tr><td>工作单位</td><td colspan="5">中国矿业大学</td><td>行政职务</td><td>副院长</td></tr>
<tr><td>二级单位</td><td colspan="5">电气工程学院</td><td>党　　派</td><td>中共党员</td></tr>
<tr><td rowspan="2">完成单位</td><td colspan="5" rowspan="2">中国矿业大学</td><td>所 在 地</td><td>江苏徐州</td></tr>
<tr><td>单位性质</td><td>高等学校</td></tr>
<tr><td colspan="3">参加本项目起止时间</td><td colspan="5">自 2021.1 至 2022.12</td></tr>
<tr><td colspan="8">对本项目主要技术发明的贡献：（限 300 字）
对创新点一、创新点二和创新点三做出贡献：提出了新型磁路机构与多调制波复合 SPWM 控制技术，提升了磁路耦合机构的偏移容忍范围，实现了多频多负载独立电能传输与控制功能。研发了无线电能传输系统智能调控技术，保证了系统运行时在多参数摄动下的稳定性，提出的多调制波复合 SPWM 控制的电能与信号并行无线传输技术，在保证电能稳定传输的基础上实现信号高速率传输。
旁证材料：授权中国发明专利 11 件。PCT/CN2017/091608（附件 1.1），ZL201811372757.8（附件 1.3），ZL201811350253.6，ZL202010848401.8，ZL202010677818.2，ZL202010342975.8，ZL202011159389.6，ZL202010226545.X，ZL201810195763.4，ZL202010740959.4，ZL202210053972.1（附件 1.6）。</td></tr>
<tr><td colspan="8">曾获省部级以上科技奖励情况：
无</td></tr>
<tr><td colspan="5">**声明：**本人同意完成人排名，自觉遵守《江苏省高等学校科学技术研究成果奖实施细则》及有关规定，遵守评审工作纪律，保证所提供的有关材料真实有效，且不存在违反相关法律法规、违背科学伦理道德及侵犯他人知识产权的情形。本人工作单位已知悉本人申报情况且无异议。如产生争议，将积极配合调查处理工作。如有材料虚假或违纪行为，愿意承担相应责任并按规定接受处理。

本人签名：

年　　月　　日</td><td colspan="3">**完成单位声明：**本单位确认该完成人情况表内容真实有效，且不存在违反相关法律法规、违背科学伦理道德及侵犯他人知识产权的情形。如产生争议，将积极配合调查处理。
工作单位声明：该完成人热爱祖国、遵纪守法、诚实守信、学风严谨，本单位对该完成人申报无异议。

单位（盖章）

年　　月　　日</td></tr>
</table>

姓　　名	廖志娟	性别	女	排　　名	2	国　　籍	中国
出生年月	1992.9			出 生 地	湖南邵阳	民　　族	汉族
身份证号	430522199109261444			归国人员	否	归国时间	无
技术职称	副教授			最高学历	研究生	最高学位	博士
毕业学校	重庆大学			毕业时间	2019.09	所学专业	控制理论与控制工程
电子邮箱	zjliao@cumt.edu.cn			办公电话	0516-83599970	移动电话	13648325294
通讯地址	江苏省徐州市大学路 1 号					邮政编码	221116
工作单位	中国矿业大学					行政职务	无
二级单位	电气工程学院					党　　派	中共党员
完成单位	中国矿业大学					所 在 地	江苏徐州
						单位性质	高等学校
参加本项目起止时间	自 2021.1 至 2022.12						

对本项目主要技术发明的贡献：（限 300 字）

对创新点一、四做出贡献：构建了一种高阶 PT 对称 SS 拓扑无线电能传输系统设计方法，提升了磁路耦合机构的传输距离，构建了浮频实本征态无线电能传输系统负载及互感双参数辨识方法，保证了高功率、高效率电能传输情况下的快速、准确负载和互感参数计算。

旁证材料：授权中国发明专利 3 件。ZL202110251436.8（附件 1.2），ZL202011151785.4，ZL202110473412.7（附件 1.6）。

曾获省部级以上科技奖励情况：

无

声明：本人同意完成人排名，自觉遵守《江苏省高等学校科学技术研究成果奖实施细则》及有关规定，遵守评审工作纪律，保证所提供的有关材料真实有效，且不存在违反相关法律法规、违背科学伦理道德及侵犯他人知识产权的情形。本人工作单位已知悉本人申报情况且无异议。如产生争议，将积极配合调查处理工作。如有材料虚假或违纪行为，愿意承担相应责任并按规定接受处理。

本人签名：

年　　月　　日

完成单位声明：本单位确认该完成人情况表内容真实有效，且不存在违反相关法律法规、违背科学伦理道德及侵犯他人知识产权的情形。如产生争议，将积极配合调查处理。

工作单位声明：该完成人热爱祖国、遵纪守法、诚实守信、学风严谨，本单位对该完成人申报无异议。

单位（盖章）

年　　月　　日

<table>
<tr><td>姓 名</td><td>刘旭</td><td>性别</td><td>男</td><td>排 名</td><td>3</td><td>国 籍</td><td>中国</td></tr>
<tr><td>出生年月</td><td colspan="3">1990.1</td><td>出 生 地</td><td>江苏徐州</td><td>民 族</td><td>汉</td></tr>
<tr><td>身份证号</td><td colspan="3">320323199001152214</td><td>归国人员</td><td>是</td><td>归国时间</td><td>2017.9</td></tr>
<tr><td>技术职称</td><td colspan="3">副教授</td><td>最高学历</td><td>研究生</td><td>最高学位</td><td>博士</td></tr>
<tr><td>毕业学校</td><td colspan="3">中国矿业大学</td><td>毕业时间</td><td>2018.6</td><td>所学专业</td><td>电气工程</td></tr>
<tr><td>电子邮箱</td><td colspan="3">xu.liu@cumt.edu.cn</td><td>办公电话</td><td>0516-83599970</td><td>移动电话</td><td>15162229971</td></tr>
<tr><td>通讯地址</td><td colspan="5">江苏省徐州市大学路 1 号</td><td>邮政编码</td><td>221116</td></tr>
<tr><td>工作单位</td><td colspan="5">中国矿业大学</td><td>行政职务</td><td>系副主任</td></tr>
<tr><td>二级单位</td><td colspan="5">电气工程学院</td><td>党 派</td><td>民盟</td></tr>
<tr><td rowspan="2">完成单位</td><td colspan="5" rowspan="2">中国矿业大学</td><td>所 在 地</td><td>江苏徐州</td></tr>
<tr><td>单位性质</td><td>高等学校</td></tr>
<tr><td colspan="3">参加本项目起止时间</td><td colspan="5">自 2021.1 至 2022.12</td></tr>
</table>

对本项目主要技术发明的贡献：（限 300 字）

对创新点三、四做出贡献：提出并发明了一种基于中继线圈的水下无线供电系统在线互感识别方法，解决了无线电能传输系统外部持续扰动下，线圈间耦合互感的高精度识别。

旁证材料：授权中国发明专利 1 件。ZL202110179498.2（附件 1.4）。

曾获省部级以上科技奖励情况：

无

声明：本人同意完成人排名，自觉遵守《江苏省高等学校科学技术研究成果奖实施细则》及有关规定，遵守评审工作纪律，保证所提供的有关材料真实有效，且不存在违反相关法律法规、违背科学伦理道德及侵犯他人知识产权的情形。本人工作单位已知悉本人申报情况且无异议。如产生争议，将积极配合调查处理工作。如有材料虚假或违纪行为，愿意承担相应责任并按规定接受处理。

本人签名：

年 月 日

完成单位声明：本单位确认该完成人情况表内容真实有效，且不存在违反相关法律法规、违背科学伦理道德及侵犯他人知识产权的情形。如产生争议，将积极配合调查处理。

工作单位声明：该完成人热爱祖国、遵纪守法、诚实守信、学风严谨，本单位对该完成人申报无异议。

单位（盖章）

年 月 日

<table>
<tr><td>姓　　名</td><td>宋磊</td><td>性别</td><td>男</td><td>排　　名</td><td>4</td><td>国　　籍</td><td>中国</td></tr>
<tr><td>出生年月</td><td colspan="3">1976-04-07</td><td>出 生 地</td><td>上海</td><td>民　　族</td><td>汉族</td></tr>
<tr><td>身份证号</td><td colspan="3">321102197604070495</td><td>归国人员</td><td>否</td><td>归国时间</td><td>无</td></tr>
<tr><td>技术职称</td><td colspan="3">高级工程师</td><td>最高学历</td><td>研究生</td><td>最高学位</td><td>博士</td></tr>
<tr><td>毕业学校</td><td colspan="3">上海大学</td><td>毕业时间</td><td>2007.7</td><td>所学专业</td><td>电子、通信与自动控制技术其他学科</td></tr>
<tr><td>电子邮箱</td><td colspan="3">huestone.song@anjiewl.com</td><td>办公电话</td><td>0512-69556915</td><td>移动电话</td><td>13918562904</td></tr>
<tr><td>通讯地址</td><td colspan="5">江苏省苏州市吴中区光福镇福聚路 66</td><td>邮政编码</td><td>215159</td></tr>
<tr><td>工作单位</td><td colspan="5">安洁无线科技（苏州）有限公司</td><td>行政职务</td><td>总经理</td></tr>
<tr><td>二级单位</td><td colspan="5"></td><td>党　　派</td><td>中共党员</td></tr>
<tr><td rowspan="2">完成单位</td><td colspan="5" rowspan="2">安洁无线科技（苏州）有限公司</td><td>所 在 地</td><td>江苏苏州</td></tr>
<tr><td>单位性质</td><td>民营企业</td></tr>
<tr><td colspan="3">参加本项目起止时间</td><td colspan="5">自 2021.1 至 2022.12</td></tr>
<tr><td colspan="8">对本项目主要技术发明的贡献：（限 300 字）
对创新点二、四做出贡献：设计了电动汽车无线充电对齐技术的自动泊车方法与系统，确保了电动汽车的高精度位置辨识。
旁证材料：授权中国发明专利 1 件。ZL202110073964.9（附件 1.5）。</td></tr>
<tr><td colspan="8">曾获省部级以上科技奖励情况：
无</td></tr>
<tr><td colspan="5">声明：本人同意完成人排名，自觉遵守《江苏省高等学校科学技术研究成果奖实施细则》及有关规定，遵守评审工作纪律，保证所提供的有关材料真实有效，且不存在违反相关法律法规、违背科学伦理道德及侵犯他人知识产权的情形。本人工作单位已知悉本人申报情况且无异议。如产生争议，将积极配合调查处理工作。如有材料虚假或违纪行为，愿意承担相应责任并按规定接受处理。

本人签名：

年　　月　　日</td><td colspan="3">完成单位声明：本单位确认该完成人情况表内容真实有效，且不存在违反相关法律法规、违背科学伦理道德及侵犯他人知识产权的情形。如产生争议，将积极配合调查处理。
工作单位声明：该完成人热爱祖国、遵纪守法、诚实守信、学风严谨，本单位对该完成人申报无异议。

单位（盖章）

年　　月　　日</td></tr>
</table>

<table>
<tr><td>姓　名</td><td>赵书泽</td><td>性别</td><td>男</td><td>排　名</td><td>5</td><td>国　籍</td><td>中国</td></tr>
<tr><td>出生年月</td><td colspan="3">1994.1</td><td>出 生 地</td><td>河北衡水</td><td>民　族</td><td>汉</td></tr>
<tr><td>身份证号</td><td colspan="3">131126199401065412</td><td>归国人员</td><td>否</td><td>归国时间</td><td>无</td></tr>
<tr><td>技术职称</td><td colspan="3">无</td><td>最高学历</td><td>本科</td><td>最高学位</td><td>学士</td></tr>
<tr><td>毕业学校</td><td colspan="3">中国矿业大学</td><td>毕业时间</td><td>2018.6</td><td>所学专业</td><td>电气工程及其自动化</td></tr>
<tr><td>电子邮箱</td><td colspan="3">TB20130011B3LD@cumt.edu.cn</td><td>办公电话</td><td>0516-83599970</td><td>移动电话</td><td>18361267189</td></tr>
<tr><td>通讯地址</td><td colspan="5">江苏省徐州市大学路 1 号</td><td>邮政编码</td><td>221116</td></tr>
<tr><td>工作单位</td><td colspan="5">中国矿业大学</td><td>行政职务</td><td>无</td></tr>
<tr><td>二级单位</td><td colspan="5">电气工程学院</td><td>党　派</td><td>无</td></tr>
<tr><td rowspan="2">完成单位</td><td colspan="5" rowspan="2">中国矿业大学</td><td>所 在 地</td><td>江苏徐州</td></tr>
<tr><td>单位性质</td><td>高校</td></tr>
<tr><td colspan="3">参加本项目起止时间</td><td colspan="5">自 2021.1 至 2022.12</td></tr>
</table>

对本项目主要技术发明的贡献：（限 300 字）

对创新点四做出贡献：目前正在对无线电能传输系统中的金属异物检测辅助功能开展相关研究。

旁证材料：发表学术期刊论文 1 篇。“Bipolar Checkerboard Metal Object Detection Without Blind Zone Caused by Excitation Magnetic Field for Stationary EV Wireless Charging System”（附件 4.4）。

曾获省部级以上科技奖励情况：

无

声明：本人同意完成人排名，自觉遵守《江苏省高等学校科学技术研究成果奖实施细则》及有关规定，遵守评审工作纪律，保证所提供的有关材料真实有效，且不存在违反相关法律法规、违背科学伦理道德及侵犯他人知识产权的情形。本人工作单位已知悉本人申报情况且无异议。如产生争议，将积极配合调查处理工作。如有材料虚假或违纪行为，愿意承担相应责任并按规定接受处理。

本人签名：

年　　月　　日

完成单位声明：本单位确认该完成人情况表内容真实有效，且不存在违反相关法律法规、违背科学伦理道德及侵犯他人知识产权的情形。如产生争议，将积极配合调查处理。

工作单位声明：该完成人热爱祖国、遵纪守法、诚实守信、学风严谨，本单位对该完成人申报无异议。

单位（盖章）

年　　月　　日

八、主要完成单位情况表（主要完成单位按照排名顺序填写，每单位一页）

<table>
<tr><td>单位名称</td><td colspan="3">中国矿业大学</td><td>所 在 地</td><td>江苏徐州</td></tr>
<tr><td>排　　名</td><td>1</td><td>单位性质</td><td>高等学校</td><td>传　　真</td><td>0516-83590172</td></tr>
<tr><td>联 系 人</td><td>江卫东</td><td>联系电话</td><td>0516-83590172</td><td>移动电话</td><td>18652270132</td></tr>
<tr><td>通讯地址</td><td colspan="3">江苏省徐州市大学路 1 号中国矿业大学</td><td>邮政编码</td><td>221116</td></tr>
<tr><td>电子信箱</td><td colspan="5">4649@cumt.edu.cn</td></tr>
<tr><td colspan="6">对本项目的贡献：
中国矿业大学是本项目的独立设计研发单位，在本项目的开发实施中：
1、根据项目提出进行总体设计方案；
2、对项目创新点进行了理论、仿真和实验验证；
3、对系统工程应用推广进行了相关工作，以提高系统的稳定性及安全可靠性。
4、参与制定了无线充电器和系统的技术标准与要求；
5、参与设计了整车级的无线充电系统，完成国内首次无线充电量产产品设计开发、整车系统匹配及验证。
6、知识产权：授权发明专利 12 项。</td></tr>
<tr><td colspan="6">声明：本单位同意完成单位排名，保证所提供的有关材料真实有效，且不存在任何违反《中华人民共和国保守国家秘密法》和《科学技术保密规定》等相关法律法规及侵犯他人知识产权的情形。如产生争议，将保证积极配合调查处理。如有材料虚假或违纪行为，愿意承担相应责任并按规定接受处理。

法定代表人（签章）　　　　　　　　　　单位（公章）

年　月　日　　　　　　　　　　　　　　年　月　日</td></tr>
</table>

单位名称	安洁无线科技(苏州)有限公司			所 在 地	江苏苏州
排　　名	2	单位性质	民营企业	传　　真	0512-69556915
联 系 人	宋磊	联系电话	0512-69556915	移动电话	13918562904
通讯地址	江苏省苏州市吴中区光福镇福聚 66 号			邮政编码	215159
电子信箱	Test@anjiewl.com				

对本项目的贡献：

安洁无线科技(苏州)有限公司对电动汽车无线充电产品进行量产，对无线充电在整车上的应用和推广起到了积极的作用：

1、基于整车需求与技术现状，提出了无线充电的产品和系统级的需求，制定了无线充电器和系统的技术要求，完成软硬件接口定义；

2、设计了整车级的无线充电系统，搭建了无线充电的整车高压电气架构和网络架构；

3、细分无线充电功能并制定无线充电系统方案，对无线充电器以外的整车系统提出了支持无线充电的需求和方案，并推进落实。配合智驾系统定义系统及部件的交互策略，实现自动充电功能；

4、根据内部系统设计、产品定义负责人提供的输入，跟踪无线充电零件研发，落实推进系统及整车开发；

5、完成无线充电整车布置、结构匹配，设计支架，并根据仿真结果，设计整车屏蔽措施；

6、跟踪带无线充电功能的整车试制，完成产品整车匹配、调试、测试，配合智驾系统完成用户无感充电体验；

7、解决产品应用问题，优化产品及系统设计；

8、完成产品及整车功能及可靠性验证，保证产品及系统的稳定运行；

9、完成国内首次无线充电量产产品设计开发、整车系统匹配及验证。

声明：本单位同意完成单位排名，保证所提供的有关材料真实有效，且不存在任何违反《中华人民共和国保守国家秘密法》和《科学技术保密规定》等相关法律法规及侵犯他人知识产权的情形。如产生争议，将保证积极配合调查处理。如有材料虚假或违纪行为，愿意承担相应责任并按规定接受处理。

法定代表人（签章）　　　　　　　　　　单位（公章）

年　月　日　　　　　　　　　　　　　　年　月　日

九、推荐单位意见

推荐意见：（限 600 字）
声明： 本单位严格按照有关规定和要求，对推荐书内容及全部附件材料进行了严格审查，确认该项目符合《江苏省高等学校科学技术研究成果奖奖励实施细则》规定的推荐资格条件，推荐材料全部内容属实，且不存在任何违反《中华人民共和国保守国家秘密法》和《科学技术保密规定》等有关法律法规及侵犯他人知识产权的情形。如产生争议，将积极调查处理。如有材料虚假或违纪行为，愿意承担相应责任并按规定接受处理。 法定代表人（签章） 推荐单位（公章） 年 月 日 年 月 日

十、主要附件

1. 必备附件

（1）“主要知识产权和标准规范等目录”证明前 5 项

附件 **1.1**

Innovation, Sciences et Développement économique Canada
Office de la propriété intellectuelle du Canada

Innovation, Science and Economic Development Canada
Canadian Intellectual Property Office

Brevet canadien / Canadian Patent

3,031,438
Numéro de brevet
Patent number

Le commissaire aux brevets a accordé un brevet pour l'invention décrite dans le mémoire descriptif portant le numéro de brevet susmentionné. Le mémoire descriptif est accessible dans la Base de données sur les brevets canadiens sur le site Web de l'Office de la propriété intellectuelle du Canada.

The Commissioner of Patents has granted a patent for the invention described in the specification under the above-noted patent number. The specification is accessible in the Canadian Patents Database on the website of the Canadian Intellectual Property Office.

Commissaire aux brevets
Commissioner of Patents

PATENT OFFICE · BUREAU DES BREVETS · CANADA

Titre de l'invention / Title of invention
NOUVEAU MECANISME DE COUPLAGE DE TRAJET MAGNETIQUE DE TRANSMISSION SANS FIL D'ENERGIE ELECTRIQUE

NEW WIRELESS ELECTRIC ENERGY TRANSMISSION MAGNETIC PATH COUPLING MECHANISM

Breveté(s) / Patentee(s)
CHINA UNIVERSITY OF MINING AND TECHNOLOGY

Inventeur(s) / Inventor(s)
XIA, CHENYANG; REN, SIYUAN; ZHENG, KAI; LIU, LIMIN; ZHU, CONG; ZHU, WENTING; CHEN, RUI; MA, NIAN

Date de l'octroi et de la délivrance du brevet / Patent grant and issue date
2022-05-24

Date de dépôt de la demande / Filing date of the application
2017-07-04

Date d'accessibilité au public / Date application open to public inspection
2018-10-18

(CIPO - 91) 2020-08-15

Canada

Claims

1. A magnetic path coupling mechanism for wireless electric energy transmission, characterized in that, it comprises: a primary side energy emission cushion and a secondary side energy collection cushion, which are arranged opposite to each other and in parallel with each other; both the primary side energy emission cushion and the secondary side energy collection cushion are of a two-layer structure, wherein, one layer is a coil layer formed by winding Litz wires, and the other layer is a magnetic core layer; both the coil layer and the magnetic core layer are of a centrosymmetric structure; wherein, the coil layer consists of two identical rectangular coils laminated orthogonally, and the magnetic core layer is a Sudoku-shaped grid layer consisting of 8 ferrite strips with the same length; the coil layer of the primary side energy emission cushion and the coil layer of the secondary side energy collection cushion are opposite to each other, and the opposite surfaces of the primary side energy emission cushion and the secondary side energy collection cushion are in mirror symmetry.
2. The magnetic path coupling mechanism for wireless electric energy transmission according to claim 1, characterized in that, the length of the ferrite strips is equal to the length of the rectangular coils.
3. The magnetic path coupling mechanism for wireless electric energy transmission according to claim 2, characterized in that, among the 4 ferrite strips in the middle of the magnetic core layer, the positions of any two ferrite strips parallel to each other meet the following condition:

$$w=0.2a$$

wherein, w is the outer margin between two ferrite strips parallel to each other; a is the length of the rectangular coil.

4. The magnetic path coupling mechanism for wireless electric energy transmission according to claim 3, characterized in that, the ratio of the width to the length of the rectangular coil is 0.7.

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Date Reçue/Date Received 2021-03-08

附件 **1.2**

证书号第 5665692 号

发明专利证书

发 明 名 称：一种 PT 对称 SS 拓扑 MC-WPT 系统及其实现方法

发　　明　人：廖志娟；冯其凯；姜陈慧；吴凡；马帅；夏晨阳

专　　利　号：ZL 2021 1 0251436.8

专利申请日：2021 年 03 月 08 日

专 利 权 人：中国矿业大学

地　　　　址：221116 江苏省徐州市铜山区大学路 1 号

授权公告日：2022 年 12 月 27 日　　授权公告号：CN 113013994 B

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局长
申长雨

2022 年 12 月 27 日

第 1 页 (共 2 页)

其他事项参见续页

1.一种PT对称SS拓扑MC-WPT系统实现方法，将PT对称特性应用至目前常用的两线圈SS拓扑磁耦合无线电能传输系统中，并进一步推广到任意n线圈架构的高阶SS拓扑磁耦合无线电能传输系统中，其中，n＝2时为两线圈PT对称MC-WPT系统，当n>2时为带有中继线圈的高阶PT对称MC-WPT系统，其特征在于，包括，通过以下步骤1至步骤4构建传输参数模型，通过以下步骤A至步骤C，应用传输参数模型，确定任意n线圈架构PT对称SS拓扑MC-WPT系统：

步骤1、获得磁耦合无线电能传输系统中各个回路分别对应电路的电路参数，所述电路参数包括线圈自感L、线圈等效串联内阻R_p、谐振补偿电容C、负载电阻R_L，随后进入步骤2；

步骤2、结合获得的磁耦合无线电能传输系统的电路参数，分别确定磁耦合无线电能传输系统电能发射端、中继端以及电能接收端的电阻参数，其中，所述电阻参数包括电能发射端的总增益、中继端的总电阻以及电能接收端的总损耗，随后进入步骤3；

步骤3、分别针对各个线圈，根据步骤1中获得的电路参数、以及步骤2中获得的电能发射端的总增益、电能接收端的总损耗，得到各个线圈分别对应的固有频率、特征阻抗、衰减参数，并结合宇称时间对称系统的结构对称条件，使各个线圈分别对应的固有频率、特征阻抗、衰减参数满足约束条件，随后进入步骤4；

步骤4、结合步骤1中得到的电路参数、步骤3中得到的各个线圈的固有频率、特征阻抗、衰减参数、并结合磁耦合无线电能传输系统的特征方程表达式和相应的特征值条件，求解得出磁耦合无线电能传输系统的PT对称参数的解析表达式，所述PT对称参数包括奇异点参数、PT对称态参数、以及PT对称破缺态参数，从而获得任意n线圈架构PT对称SS拓扑MC-WPT系统的传输参数模型；

步骤A、按照步骤1至步骤4中的方法，应用传输参数模型，通过磁耦合无线电能传输系统中各个回路的电路参数、以及电路的特征方程和特征值条件，获得磁耦合无线电能传输系统的PT对称参数的解析表达式，随后进入步骤B；

步骤B、针对磁耦合无线电能系统中的各个线圈，结合PT对称参数中的奇异点参数，确定磁耦合无线电能传输系统的相邻线圈间的临界耦合系数k_0，根据临界耦合系数k_0确定系统相邻线圈间的最大临界传输距离D_{max}，随后进入步骤C；

步骤C、结合磁耦合无线电能传输系统相邻线圈间的最大临界传输距离D_{max}，根据磁耦合无线电能传输系统内各个线圈对应的电路参数，并结合磁耦合无线电能传输系统中的负电阻电路，得到任意n线圈架构的高阶PT对称SS拓扑MC-WPT系统。

2.根据权利要求1所述的一种PT对称SS拓扑MC-WPT系统实现方法，其特征在于，所述步骤2中，根据以下公式，获得任意n线圈系统的电能发射端的总增益、中继端的总电阻、以及接收端的总损耗：

$$g=R_g-R_{p1}$$

$$R_i=R_{pi}\ (i=2,\cdots,n-1)$$

$$R_n=R_L+R_{pn}$$

其中，g为电能发射端的总增益，R_g为负电阻的阻值，R_{p1}为发射线圈的内阻，R_i为第i个中继端的总电阻，R_{pi}为第i个中继线圈的内阻，R_n为接收端的总电阻，R_L为负载电阻，R_{pn}为接收线圈的内阻。

3.根据权利要求1或2所述的一种PT对称SS拓扑MC-WPT系统实现方法，其特征在于，所述步骤3中，获得系统电能发射端、电能中继端、电能接收端分别对应的固有频率、特征阻

附件 1.3

证书号第4246597号

发明专利证书

发明名称：一种单通道能量信号同步传输系统移相控制实现方法及该系统

发明人：夏晨阳；贾仁海；彭昱翔；路强；杨颖；吴镇

专利号：ZL 2018 1 1372757.8

专利申请日：2018年11月19日

专利权人：中国矿业大学

地址：221116 江苏省徐州市大学路1号中国矿业大学科研院

授权公告日：2021年02月09日　　授权公告号：CN 109462466 B

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局长
申长雨

2021年02月09日

第1页（共2页）

其他事项参见续页

1.一种单通道能量信号同步传输系统的移相控制实现方法，其特征在于：所述单通道能量信号同步传输系统包括：信号调制模块、高频逆变器、原边能量发射电路及副边能量和信号接收电路；其中，

所述的信号调制模块将数字信号转换成高频逆变器的移相角；

所述高频逆变器根据不同的移相角输出不同的阶梯方波，该阶梯方波由基波和一系列奇次谐波组成，不同移相角的阶梯方波中各次谐波含量不同；

所述原边能量发射电路在阶梯方波的作用下产生包含有调制信号的近似梯形波的非正弦周期电流，该电流展开为傅里叶级数后仍由基波和奇次谐波组成，其中的基波分量传输能量，其中的三次谐波分量传输信号；

所述副边能量和信号接收电路包含基波、三次谐波选频电路和信号解调电路，其中的副边能量接收电路的固有谐振频率与基波频率一致，其中的信号接收电路的固有谐振频率与三次谐波频率一致，通过检测三次谐波选频电路中的电感电压实现信号解调；

通过移相方式控制高频逆变器移相角，不同移相角时逆变输出阶梯方波中各次谐波含量不同；控制高频逆变器移相角，动态调节三次谐波的含量；利用副边能量和信号接收电路将基波和三次谐波选出分别传输能量和信号；

具体包括以下步骤：

(1)信号调制：在信号调制模块中利用DSP把数字基带信号调制成高频逆变器的移相角，再通过不同的移相角改变逆变器输出电压中的三次谐波含量；首先定义两个移相角度来分别表示数字信号“0”和“1”，然后设置一个数组来表示待传的数字信号，数组中的数据由两个移相角组成，再根据信号传输速率要求设置定时器定时时间，每次定时时间到达时将数组的一个数据作为PWM信号发生模块中的延迟时间，不同的延迟时间即代表不同的移相角，最后把此PWM信号发生模块产生的四路PWM信号作为逆变器开关管的驱动信号；如此循环往复，根据待发送的数据来控制高频逆变器的移相角产生变化；不同移相角时逆变输出电压中三次谐波含量会产生变化，因此数字信号以三次谐波电压含量的形式被调制到系统中；

(2)信号解调：高频逆变器输出不同移相角的阶梯方波加载到原边能量发射电路中后会在原边产生谐波含量丰富的近似梯形波的电流，该梯形波的电流中的三次谐波含量也会随着逆变输出电压中的三次谐波含量发生变化，副边能量和信号接收电路设置有基波和三次谐波选频电路，在三次谐波选频电路中的电感上能够检测到电压幅值的变化，再利用解调电路提取电感电压包络，最后通过比较电路就能够实现信号解调，还原基带信号；

数字信号经过DSP控制后，一个移相角视作信号“1”，另一个移相角视作信号“0”。

2.根据权利要求1所述的一种单通道能量信号同步传输系统的移相控制实现方法，其特征在于：所述的信号调制模块由C2000系列DSP构成，在DSP中将数字信号转换成高频逆变器的移相角。

3.根据权利要求1所述的一种单通道能量信号同步传输系统的移相控制实现方法，其特征在于：所述副边能量和信号接收电路分为能量接收电路、信号接收电路及信号解调电路，其中，能量接收电路由拾取线圈L_s、内阻R_s、谐振电容C_s和负载R_L组成，其固有谐振频率和基波频率一致；信号接收电路由信号检测线圈L_n、内阻R_n和谐振电容C_n组成，其固有谐振频率和三次谐波一致；能量接收电路和信号接收电路分别从拾取电压中选取出基波来传输

附件 **1.4**

证书号第5666451号

发明专利证书

发 明 名 称：一种基于中继线圈的水下无线供电系统在线互感识别方法

发 明 人：刘旭;宋翔昱;原熙博

专 利 号：ZL 2021 1 0179498.2

专利申请日：2021年02月07日

专 利 权 人：中国矿业大学

地 址：221116 江苏省徐州市铜山区大学路1号

授权公告日：2022年12月27日　　授权公告号：CN 112994267 B

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局长
申长雨

2022年12月27日

第 1 页 (共 2 页)

其他事项参见续页

1.一种基于中继线圈的水下无线供电系统在线互感识别方法，其特征在于，所述方法具体包括如下步骤：

步骤1，构建三线圈无线电能传输系统的电路拓扑结构图，所述电路拓扑结构具体包括：直流电源(1)、高频逆变器(2)、发射线圈模块(3)、中继线圈模块(4)、接收线圈模块(5)、整流滤波模块(6)和系统负载(7)；

其中，直流电源(1)与高频逆变器(2)的输入端相连接，高频逆变器(2)的输出端与发射线圈模块(3)的输入端相连，发射线圈模块(3)的输出端与中继线圈模块(4)的输入端相对设置，中继线圈模块(4)的输出端与接收线圈模块(5)的输入端相对设置，接收线圈模块(5)的输出端与整流滤波模块(6)的输入端相连，整流滤波模块(6)的输出端与系统负载(7)相连；

所述中继线圈模块(4)包括中继线圈L_R、第一补偿电容C_1、第二补偿电容C_2、第一开关管S_5和第二开关管S_6；其中所述第一开关管S_5的D极分别与中继线圈L_R的第一端、第一补偿电容C_1的第一端电性连接；所述第一开关管S_5的S极与第二开关管S_6的D极电性连接；所述第二开关管S_6的S极与第二补偿电容C_2的一端电性连接；所述第二补偿电容C_2的第二端分别与所述中继线圈L_R的第二端、第一补偿电容C_1的第二端电性连接；

步骤2，控制中继线圈模块(4)中的第一开关管S_5和第二开关管S_6保持开通状态，加压并判断系统正常工作时，获取发射线圈模块(3)和系统负载(7)的瞬时电压和瞬时电流，并计算系统的输入阻抗以及负载阻值；

步骤3，控制中继线圈模块(4)中的第一开关管S_5和第二开关管S_6保持关断状态，判断系统正常工作时，获取发射线圈模块(3)的瞬时电压和电流，并计算系统的输入阻抗；

步骤4，确定三线圈无线电能传输系统的等效电路，根据基尔霍夫电压电流定律，得到关于输入阻抗、系统负载以及中继线圈补偿电容关系的方程组；

步骤5，根据步骤2和步骤3得到的系统的输入阻抗和负载阻值，代入步骤4的方程组中，得到系统线圈之间的互感M_{TR}、M_{TS}、M_{RS}，实现互感识别。

2.根据权利要求1所述的一种基于中继线圈的水下无线供电系统在线互感识别方法，其特征在于，步骤2所述方法具体包括：

步骤2.1：控制中继线圈模块(4)中的第一开关管S_5和第二开关管S_6保持开通状态，加压并判断系统正常工作；

步骤2.2：获取系统负载(7)的瞬时电压U_{La}和瞬时电流i_{La}，计算系统负载的阻值与等效阻值；其中，系统负载阻值的计算公式为：$R_{La}=U_{La}/I_{La}$；系统等效负载阻值的计算公式为$R_{Le}=\frac{8}{\pi^2}R_{La}$；

式中，R_{Le}表示系统等效负载的阻值；R_{La}表示系统负载的阻值；U_{La}表示系统负载的瞬时电压；i_{La}表示系统负载的瞬时电流；

步骤2.3：获取发射线圈模块(3)的瞬时电压U_T和瞬时电流i_T，计算得到系统的输入阻抗$Z_{in1}=U_T/i_T$；

式中，Z_{in1}表示第一开关管S_5和第二开关管S_6保持开通状态时系统的输入阻抗；U_T表示第一开关管S_5和第二开关管S_6保持开通状态时发射线圈模块的瞬时电压向量；i_T表示第一开关管S_5和第二开关管S_6保持开通状态时发射线圈模块的瞬时电流向量。

附件 **1.5**

证书号第5391226号

发明专利证书

发 明 名 称：基于无线充电对齐技术的电动汽车自动泊车方法及系统

发　明　人：候雅静;赵彦斌

专　利　号：ZL 2021 1 0073964.9

专利申请日：2021年01月20日

专 利 权 人：安洁无线科技（苏州）有限公司

地　　址：215159 江苏省苏州市吴中区光福镇福聚路66号

授权公告日：2022年08月19日　　　授权公告号：CN 112721704 B

国家知识产权局依照中华人民共和国专利法进行审查，决定授予专利权，颁发发明专利证书并在专利登记簿上予以登记。专利权自授权公告之日起生效。专利权期限为二十年，自申请日起算。

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局长
申长雨

2022年08月19日

第1页（共2页）

其他事项参见续页

CN 112721704 A　　　**权 利 要 求 书**　　　1/2页

1.一种基于无线充电对齐技术的电动汽车自动泊车方法，其特征在于，所述电动汽车自动泊车方法包括如下步骤：

S1、采集无线充电系统发射线圈的图像数据及周围物体距电动汽车的距离数据；

S2、基于采集的图像数据和距离数据，实时规划泊车路径并开始泊车；

S3、实时计算发射线圈和接收线圈之间位置偏移矢量并发送该位置偏移矢量；

S4、电动汽车接收到位置偏移矢量后暂停泊车；

S5、当接收到的位置偏移矢量在预设的时间内不发生变化后，重新规划泊车线路；

S6、当到达目标位置后，再次暂停泊车；

S7、判断泊车位置是否满足无线充电需求，如满足则完成泊车。

2.根据权利要求1所述的基于无线充电对齐技术的电动汽车自动泊车方法，其特征在于，所述步骤S2还包括：在实时规划泊车路径的同时，同步调整电动汽车的转向和车速，并发送开始计算发射线圈和接收线圈之间位置偏移矢量的启动信号。

3.根据权利要求1所述的基于无线充电对齐技术的电动汽车自动泊车方法，其特征在于，所述步骤S3还包括：通过车辆CAN总线发送该位置偏移矢量至电动汽车。

4.根据权利要求1所述的基于无线充电对齐技术的电动汽车自动泊车方法，其特征在于，所述预设的时间为至少三个发送该位置偏移矢量的通信周期。

5.根据权利要求1所述的基于无线充电对齐技术的电动汽车自动泊车方法，其特征在于，所述重新规划泊车线路包括：以接收到的位置偏移矢量指示的发射线圈的位置作为目标位置进行泊车线路的重新规划。

6.根据权利要求5所述的基于无线充电对齐技术的电动汽车自动泊车方法，其特征在于，所述步骤S7具体包括：

检测发射线圈和接收线圈之间的对齐状态，若返回线圈对齐状态在允许充电的误差范围内，则停止泊车；否则，重复执行步骤S5和S6。

7.根据权利要求1所述的基于无线充电对齐技术的电动汽车自动泊车方法，其特征在于，所述重新规划泊车线路包括：根据接收到的位置偏移矢量进行泊车线路的重新规划。

8.根据权利要求7所述的基于无线充电对齐技术的电动汽车自动泊车方法，其特征在于，所述步骤S6具体包括：

当到达目标位置后，检测发射线圈和接收线圈之间重复发生交叠，如发生交叠则再次暂停泊车。

9.根据权利要求8所述的基于无线充电对齐技术的电动汽车自动泊车方法，其特征在于，所述步骤S7具体包括：

在电动汽车收到该位置偏移矢量在预设时间内不发生变化后，判断电动汽车当前位置是否满足无线充电系统位置偏移要求，若满足则停止泊车；否则，以电动汽车最小泊车距离为单元控制自动泊车的启停，直至电动汽车位置满足无线充电系统位置偏移要求后，则停止泊车。

10.一种基于无线充电系统对齐技术的电动汽车自动泊车系统，其特征在于，所述电动汽车自动泊车系统包括：无线充电单元和自动泊车单元；

所述无线充电单元包括：第一通信子单元、发射线圈、接收线圈以及位置检测子单元；

所述发射线圈设置于地端，所述接收线圈设置于车端，所述位置检测子单元计算发射

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附件 **1.6**

知识产权（标准）类别	知识产权（标准）具体名称	国家（地区）	授权号（标准编号）	授权（标准发布）日期	权利人(标准起草单位)	发明人（标准起草人）
发明专利	基于多调制波复合 SPWM 控制的多频多负载无线电能传输系统	中国	ZL202010342975.8	2022.12.9	中国矿业大学	夏晨阳;魏楠;张宏泰;李晓丽;冯其凯;韩潇左;杨旭浩;李壮;马帅;廖志娟
发明专利	一种类 EIT 多中继无线电能传输系统及其设计方法	中国	ZL202011151785.4	2022.1.7	中国矿业大学	廖志娟;冯其凯;马帅;吴镇;夏晨阳;伍小杰
发明专利	一种 IPT 系统圆角方形耦合器的参数设计方法	中国	ZL202010848401.8	2022.4.8	中国矿业大学	夏晨阳;李欣宇;殷嘉诚;杨旭浩;孙琪琪;廖志娟;伍小杰
发明专利	一种磁耦合结构及无线电能传输系统	中国	ZL202010677818.2	2022.2.22	中国矿业大学	夏晨阳;杨旭浩;李晓丽;李壮;冯其凯;魏楠;韩潇左;马帅
实用新型专利	磁场均匀分布的发射端及无线充电系统	中国	ZL202022668542.X	2021.7.6	安洁无线科技(苏州)有限公司	高摇光
实用新型专利	无线充电结构及系统	中国	ZL202022672797.3	2021.9.17	安洁无线科技(苏州)有限公司	高摇光
发明专利	一种感应电能传输系统稳压综合控制系统及方法	中国	ZL201811350253.6	2021.6.1	中国矿业大学	夏晨阳;孙琪琪;李欣宇;吴镇;贾仁海;吴远航;路强
发明专利	一种无线电能传输系统的改进型自抗扰控制方法及系统	中国	ZL202011159389.6	2022.4.8	中国矿业大学	夏晨阳;李晓丽;李壮;杨旭浩;魏楠;韩潇左;冯其凯;马帅;廖志娟;伍小杰
发明专利	一种基于 H∞控制器的 CPT 系统稳压控制方法及系统	中国	ZL202010226545.X	2021.9.28	中国矿业大学	夏晨阳;魏国玉;李欣宇;周磊;孙琪琪;廖志娟;伍小杰
实用新型专利	一体式有线无线充电控制系统	中国	ZL202220702494.8	2022.9.16	安洁无线科技(苏州)有限公司	梁永峰;任如昱;吴天龙;徐喜红;宋磊
实用新型专利	一种用于汽车无线充电系统静态参数测试装置	中国	ZL202221646641.0	2022.11.4	安洁无线科技(苏州)有限公司	魏善峰;杨洋;汤明明

发明专利	一种非接触能量与信号同步传输系统及传输方法	中国	ZL201810195763.4	2021.7.16	中国矿业大学	夏晨阳;朱文婷;朱从;刘利民;马念;伍小杰;陈俊
发明专利	多调制波复合 SPWM 控制的电能与信号并行无线传输系统	中国	ZL202010740959.4	2021.11.19	中国矿业大学	夏晨阳;张宏泰;魏楠;吴镇;贾仁海;廖志娟;刘旭;伍小杰
实用新型专利	线盘装置	中国	ZL202120608377.0	2021.12.14	安洁无线科技(苏州)有限公司	任如昱;李国政;徐喜红
发明专利	一种磁耦合无线电能传输系统负载及互感双参数辨识方法	中国	ZL202110473412.7	2022.8.26	中国矿业大学	廖志娟;姜陈慧;吴凡;陈张睿威;夏晨阳
发明专利	一种电动汽车无线充电互操作性测试系统及方法	中国	ZL202210053972.1	2022.11.8	中国矿业大学	夏晨阳;陈张睿葳;李云俊;杨子跃;孙安冉;廖志娟;荣灿灿
实用新型专利	车载接收端及无线充电系统	中国	ZL202022668632.9	2021.7.6	安洁无线科技(苏州)有限公司	高摇光
实用新型专利	电动汽车无线充电系统	中国	ZL202121652638.5	2021.12.31	安洁无线科技(苏州)有限公司	孟浩
实用新型专利	车载活体检测的大功率无线充电系统	中国	ZL202020095235.4	2021.1.5	安洁无线科技(苏州)有限公司	柳元富;宋磊
发明专利	无线充电保护系统及方法	中国	ZL202010807410.2	2022.3.22	安洁无线科技(苏州)有限公司	黄永华;于刚
实用新型专利	电源盒散热系统	中国	ZL202021068953.9	2021.4.9	安洁无线科技(苏州)有限公司	梁永峰;李国政;任如昱;宋磊
实用新型专利	有线无线充电控制装置的散热系统	中国	ZL202220700534.5	2022.7.1	安洁无线科技(苏州)有限公司	梁永峰;任如昱;吴天龙;徐喜红;宋磊
实用新型专利	一体式有线无线充电控制盒	中国	ZL202220702455.8	2022.7.15	安洁无线科技(苏州)有限公司	梁永峰;任如昱;吴天龙;徐喜红;宋磊

（2）应用证明（主要提供重要的、有代表性应用单位的证明）

附件 **2.1**

合同编码：GF2210245

配套产品采购合同

甲方： 长城汽车股份有限公司

乙方： 安洁无线科技（苏州）有限公司

2022年 1月签订于 河北保定

1

甲方（需方）：长城汽车股份有限公司	乙方（供方）：安洁无线科技（苏州）有限公司
地址：河北省保定市朝阳南大街2266号	地址：江苏省苏州市吴中区光福镇福聚路66号
法定代表人：魏建军	法定代表人： 王春生
授权代表：牛军辉	授权代表 陈卫东
开户银行：中行保定裕华支行	开户银行：中国农业银行苏州太湖度假区支行
帐号：100148043458	帐号：10541301040010611
税号：91130000105941835E	税号：91320506MA1W957053
邮编：071000	邮编： 215159
日期： 2022年 1 月 1 日	日期： 2022 年 1 月 1 日

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附件 **2.2**

合同编号：HMTC-7-20220520-28

项目委托开发合同书

프로젝트 위탁 개발 계약서

项目名称：[安洁11kw无线充电系统开发]

프로젝트 : [______________]

1. 合同各方都清楚并愿意严格遵守中华人民共和国关于反商业贿赂的有关法律法规的规定，双方都清楚任何形式的贿赂行为都可能触犯法律，并受到法律的严惩。

2. 合同各方均不得向对方或对方人员或其他相关人员索要、收受、提供、给予合同约定外的任何利益，包括但不限于明扣、暗扣、现金、购物卡、实物、有价证券、旅游或其他非物质性利益等，但如该等利益属于行业惯例或通常做法，则须在合同中明示。

3. 甲方严格禁止其人员的任何商业贿赂（包括行贿及受贿）行为。甲方人员在签订、履行本合同过程中及其后发生本条款第2条所列示的任何一种行为，都是违反甲方公司制度的，其他合同当事人及其工作人员均有义务向甲方公司举报有关人员及行为。

4. 其他合同当事方违反本合同约定，为谋取直接或间接的商业利益（包括但不限于合作机会和合同利益）而向甲方公司人员行贿的，视为该合同当事方违约，甲方有权解除本合同。有关人员的商业贿赂行为构成犯罪的，移交司法机关处理，合同各方应积极配合司法机关处理。

5. 甲方亦反对其他合同当事人及其人员为了本合同之目的，与本合同以外的任何第三方发生本条所列示的任何一种行为。

第十九条 其他事项 기타 사항

1. 本合同自双方签字盖章之日起生效。

   본 계약은 쌍방이 서명,날인한 날짜부터 발효한다.

2. **本合同附件作为本合同的有效组成部分，与本合同具有同等法律效力；但附件与主合同约定不一致的，以主合同为准。**

   본 계약의 별첨은 본 계약의 구성부분으로서 본 계약과 동등한 법적 효력을 가진다. 다만 본 계약의 별첨과 본 계약의 구성부분 내용이 일치되지 않을 경우, 본 계약 내용을 준한다.

3. 本合同一式二份，双方签订后各执一份，每份合同具有同等法律效力。

   본 계약서는 1식 2부로 작성되며, 쌍방이 각각 1부씩 보관한다. 2부 계약서는 동등한 법률효력을 가지고 있다.

甲方（盖章）：	乙方（盖章）：
现代汽车研发中心（中国）有限公司	安洁无线科技（苏州）有限公司
法定代表人或	法定代表人或
授权委托人（签字）： 金龙灿	授权委托人（签字）：
签约日期： 2022年 5月30日	签约日期： 年 月 日

（3）评价证明及国家法律法规要求行业审批文件

附件 **3.1**

报告编号	B2208CR8888-00775-2
总页数	共 27 页

检 测 报 告

产品名称： 无线电能传输控制器（11kW）

型号规格： C03-VA

检测类别： 委 托 检 测

生产企业： 安洁无线科技(苏州)有限公司

委 托 人： 安洁无线科技(苏州)有限公司

CEPREI 中 国 赛 宝 实 验 室

工业和信息化部电子第五研究所

中 国 赛 宝 实 验 室

工业和信息化部电子第五研究所

检 测 报 告

报告编号：B2208CR8888-00775-2　　　　第 3 页共 27 页

产品名称	无线电能传输控制器（11kW）	样品型号	C03-VA
		商　标	/
生产企业	安洁无线科技(苏州)有限公司	检测类别	委托检测
生产企业地址	苏州市吴中区光福镇福聚路 66 号		
委 托 人	安洁无线科技(苏州)有限公司		
委托人地址	苏州市吴中区光福镇福聚路 66 号		
样品数量	12+6 件	样品接收日　期	2022 年 9 月 20 日、2022 年 9 月 25 日
送 样 者	同委托人	检测日期	2022 年 9 月 20 日至 2023 年 2 月 14 日
检测环境	温度：15℃～35℃　相对湿度：25%～75%　气压：86kPa～106kPa		
检测项目	见第 8-13 页。		
检测依据	测试计划（编号：TPCDQD-2206-025-C03-V6）		
检测结论	温度交变项目检测结果不符合要求，其余项目检测结果符合要求，本次检测结论不合格。 （检验检测专用章） 报告发布日期：2023 年 3 月 20 日		
说　明	检测项目按委托人要求。		

编制：卜宏泽　日期：2023.03.20　　审核：雷强　日期：2023.03.20　　批准：刘明　日期：2023.03.20

CEPREI-ZB-BG01-202102

附件 **3.2**

LABone®

报告编号： CJ2208058R01C

检 测 报 告

样品名称	：	无线电能传输发射器+无线电能转换器、无线电能传输发射器
样品型号	：	C30-WB，C30-GA、C30-GA
委托单位	：	安洁无线科技(苏州)有限公司
检验类别	：	委托检验

江苏佳世德检测技术有限公司

LABone®

检 测 报 告

报告编号: CJ2208058R01C 报告日期: 2022/11/11 页码: 1 of 9

委托单位名称	：	安洁无线科技(苏州)有限公司
委托单位地址	：	上海嘉定百安公路538号4栋2楼

以下检测的样品由委托人提供及确认：

样品描述

样品名称	：	无线电能传输发射器+无线电能转换器、无线电能传输发射器
样品型号	：	C30-WB，C30-GA、C30-GA
样品数量	：	5 pcs
样品编号	：	A-1~A-、B-1~B-3
委托方编号	：	/
生产厂家	：	/
接收日期	：	2022/08/20
检测周期	：	2022/09/19~2022/10/11

检测要求

以下检测依照委托人的要求进行，具体内容参见附页。

批 准 审 核 主 检

声明：本报告无佳世德"检测专用章"无效；本报告仅对本次受测样品的测试数据、结果负责（不包括由客户提供的数据、结果）；任何变更、修改或部分复制本报告均属无效；本报告中所出具的检测数据及结果仅供委托方使用。

江苏佳世德检测技术有限公司

地址：☐ 江苏省常熟市高新技术产业开发区东南路8号
☒ 江苏省常熟市高新技术产业开发区新安江东路8号

www.labone.com.cn

附件 **3.3**

报告编号：QA22XX2DR5151

检　验　报　告

WB+GAR+VA 的电磁兼容性

产品名称	WB+GAR+VA
产品型号	C03
测试计划编号	TPXNY_2206_005_C03_V7
委托单位	安洁无线科技（苏州）有限公司
检验类别	委托检验

中汽研汽车检验中心（天津）有限公司

注　意　事　项

1. 报告无“检验检测专用章”或“试验专用章”无效。
2. 未经本检验中心批准，不得部分复制本检验报告。复制报告未重新加盖“检验检测专用章”或“试验专用章”无效。
3. 报告无主检、审核、批准人签字无效。
4. 报告涂改无效。
5. 对检验报告若有异议，请以书面形式通知本检验中心总师室受理。
6. 送样检验仅对样品负责。
7. 委托方（客户）对样品及提供的数据和信息的真实性承担责任。
8. 报告中未注资质认定标志时，仅供委托方（客户）内部使用，不具有对社会的证明作用。

检验单位地址电话:
地　　址: 天津市东丽区先锋东路 68 号主楼 526 室
电　　话: 022-84379607
邮政编码: 300300

委托单位地址电话:
地　　址: 苏州光福镇福聚路 66 号
电　　话: 15050387720
邮政编码: ----

附件 3.4

报告编号	B2208CR8888-00775-4
总页数	共 27 页

检 测 报 告

产品名称：无线电能转换器（11kW）、无线电能传输发射器（11kW）

型号规格：C03-WB、C03-GA

检测类别：委 托 检 测

生产企业：安洁无线科技(苏州)有限公司

委 托 人：安洁无线科技(苏州)有限公司

中 国 赛 宝 实 验 室
工业和信息化部电子第五研究所

CEPREI

中 国 赛 宝 实 验 室
工业和信息化部电子第五研究所

检 测 报 告

报告编号：B2208CR8888-00775-4　　第 3 页共 27 页

产品名称	无线电能转换器（11kW）、无线电能传输发射器（11kW）	样品型号	C03-WB、C03-GA
		商　标	/
生产企业	安洁无线科技(苏州)有限公司	检测类别	委托检测
生产企业地址	苏州市吴中区光福镇福聚路 66 号		
委 托 人	安洁无线科技(苏州)有限公司		
委托人地址	苏州市吴中区光福镇福聚路 66 号		
样品数量	24+12 件	样品接收日　期	2022 年 9 月 15 日、2022 年 9 月 25 日
送 样 者	同委托人	检测日期	2022 年 9 月 15 日至 2023 年 2 月 14 日
检测环境	温度：15℃～35℃　相对湿度：25%～75%　气压：86kPa～106kPa		
检测项目	见第 8-11 页。		
检测依据	测试计划（编号：TPCDQD-2206-026-C03-V5）		
检测结论	高温耐久、温度交变项目检测结果不符合要求，其余项目检测结果符合要求，本次检测结论不合格。 （检验检测专用章） 报告发布日期：2023 年 3 月 20 日		
说　明	检测项目按委托人要求。		

编制：卜宗洋　　审核：雷强　　批准：
日期：2023.03.20　　日期：2023.03.20　　日期：2023.03.20

CEPREI-ZB-BG01-202102

附件 3.5

报告编号	B2208CR8888-00775-1
总页数	共 55 页

检 测 报 告

产品名称：无线电能传输控制器(11kW)

型号规格：C03-VA

检测类别：委 托 检 测

生产企业：安洁无线科技(苏州)有限公司

委 托 人：安洁无线科技(苏州)有限公司

中 国 赛 宝 实 验 室
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工业和信息化部电子第五研究所
检 测 报 告

报告编号：B2208CR8888-00775-1　　第 3 页共 55 页

产品名称	无线电能传输控制器(11kW)	样品型号	C03-VA
		商　标	/
生产企业	安洁无线科技(苏州)有限公司	检测类别	委托检测
生产企业地址	苏州市吴中区光福镇福聚路 66 号		
委 托 人	安洁无线科技(苏州)有限公司		
委托人地址	苏州市吴中区光福镇福聚路 66 号		
样品数量	7 件	样品接收日　期	2022 年 8 月 8 日
送 样 者	同委托人	检测日期	2022 年 8 月 23 日 至 2022 年 11 月 14 日
检测环境	温度：15℃～35℃　相对湿度：25%～75%　气压：86kPa～106kPa		
检测项目	见第 10-28 页。		
检测依据	测试计划（编号：TPCDQD-2206-025-C03-V6）		
检测结论	交变湿热项目检测结果不符合要求，其余项目检测结果符合要求，本次检测结论不合格。 （检验检测专用章） 报告发布日期：2023 年 3 月 20 日		
说　明	检测项目按委托人要求。		

编制：卜宋泽　日期：2023.03.20　　审核：雷强　日期：2023.03.20　　批准：刘根[illegible]　日期：2023.03.20

CEPREI-ZB-BG01-202102

附件 3.6

验收意见

2021 年 4 月 7 日，徐州市科技局组织专家对中国矿业大学承担的市科技计划项目“电动汽车动态无线充电系统关键技术及装备研发”（项目编号：KC18104）进行验收。验收专家听取了项目承担单位所作的工作总结报告，审查了相关资料。经质询与讨论，形成以下验收意见：

1、提供的资料齐全、完整，符合验收要求。

2、项目实施期间，提出了一种平行四边形分段导轨式磁路机构，实现了分段导轨的智能切换，解决了电动汽车动态无线充电系统电压输出不稳定问题，对推动电动汽车动态高效自由的无线充电技术发展具有较为现实的意义。

3、项目实施期间，申请专利 10 件，其中发明专利 10 件；授权专利 5 件，其中发明专利 5 件；发表论文 8 篇。

4、项目计划投入 100 万，实际投入 98.828 万元，其中市拨款 20 万元，自筹 78.828 万元。

5、项目经费落实到位，使用合理，符合科技计划项目经费管理规定。

验收委员会认为中国矿业大学承担的电动汽车动态无线充电系统关键技术及装备研发全面完成了合同规定各项任务和考核指标，一致同意通过验收。

验收委员会主任：萧付泽

2021 年 4 月 7 日

附件 **3.7**

22100801-2463

国家自然科学基金

资助项目准予结题通知

夏晨阳　同志：

您承担的国家自然科学基金项目：(谐波分离与复用磁耦合谐振无线电能传输机理及关键技术研究)，批准号：(51777210)按有关规定已审核完毕，准予结题。

与本项目资助有关的后续成果，请您继续及时报送。

祝您在研究工作中取得更好的成绩！

国家自然科学基金委员会

工程与材料科学部

2022年03月29日

附件 **3.8**

验收意见

2020 年 12 月 12 日，江苏省科技厅委托中国矿业大学组织召开了“共拓扑多模态磁耦合谐振无线电能传输机理及关键技术研究（BK20171190）”项目验收会，验收专家组（名单附后）听取了课题组所做的研究工作汇报，审查了相关验收资料，经质询与讨论，形成如下验收意见：

1. 提供相关验收资料齐全、完整，符合江苏省自然科学基金项目验收要求。

2. 项目主要研究内容和创新点如下：

（1）提出一种共拓扑多模态磁耦合谐振无线电能传输方法，研究了基、谐波双通路电能传输、信号传递和负载在线识别机理，并提出关键问题创新解决方案。

（2）提出了基谐波两线圈同轴共面磁路机构空间物理模型，基于磁场干涉原理，结合系统电路模型与磁路有限元分析模型，全面分析系统电路及磁路特性，揭示了电路系统及电磁机构特性共同作用下系统的复杂动力学行为演变规律。

（3）综合考虑系统功率传输能力、逆变器损耗、谐振网络效率、稳定性，兼顾系统建设经济性指标，构建并优化了系统多目标函数模型，提出了基及双通路功率分配控制策略，提高了系统的鲁棒稳定特性。

3. 依托项目总结、发表论文 15 篇，其中 SCI 论文 12 篇，EI 论文 3 篇；已申请发明专利 29 项，授权发明专利 12 项；获得厅局级奖励 3 项；近三年毕业硕士研究生 22 人；在培养博士研究生 2 人，在培养硕士研究生 18 人。

综上所述，验收专家组认为：该项目完成了合同规定的目标任务，项目经费支出合理规范，同意通过验收。

验收专家组组长：徐子

2020 年 12 月 12 日

附件 **3.9**

中共江苏省委组织部
江苏省人力资源和社会保障厅文件
江苏省财政厅

苏人社发〔2019〕147 号

省委组织部 省人力资源和社会保障厅 省财政厅 关于实施第十六批“六大人才高峰”高层次人才选拔培养资助计划的通知

各设区市市委组织部、市人力资源和社会保障局、市财政局，省各有关部门：

按照省“十三五”人才发展规划关于实施“产业人才高峰行动计划”的部署要求，省人力资源和社会保障厅会同省委组织部、省财政厅组织实施了第十六批“六大人才高峰”高层次人才选拔培养评审工作。经单位推荐、各设区市人力资源和社会保障局和省有关行业（产业）主管部门审核、专家评审委员会评审，确定了第十六批“六大人才高峰”高层次人才选拔培养资助方案（附后），现予公布，并就有关事项通知如下：

第十六批“六大人才高峰”高层次人才选拔培养资助方案

（高层次人才项目：新能源汽车产业）

序号	项目编号	项目名称	项目承担单位	项目承担人	资助类型	资助金额（万元）
546	XNYQC-002	新型高比能电池技术	南京大学	何平	B	10
547	XNYQC-001	电动新能源汽车多种类型公用充电设施多期动态优化部署系统	南京大学	吴婷	C	4
548	XNYQC-003	新能源公交系统可靠性分析与风险评估方法研究	东南大学	李大韦	C	4
549	XNYQC-005	锂离子电池热失控诱发的高压气固混合物泄放与喷射火燃烧特性	南京工业大学	周魁斌	C	4
550	XNYQC-006	基于动态感知与强鲁棒性的多端无线充电关键技术开发	南京航空航天大学	刘福鑫	C	4
551	XNYQC-007	新能源汽车用光电催化H202液流电池	南京理工大学	张侃	C	4
552	XNYQC-012	双面共芯电动汽车集群无线充电机制及关键技术研究	中国矿业大学	夏晨阳	C	4
553	XNYQC-027	面向电动汽车电池热管理的柔性热管关键技术研究	江苏大学	屈健	C	4
554	XNYQC-030	客车轻量化技术	南京金龙客车制造有限公司	张勇	C	4
555	XNYQC-036	高温PEM燃料电池低Pt载量膜电极的开发	常州博能新能源有限公司	唐琪雯	C	4
556	XNYQC-052	汽车电子水泵研发与产业化	江苏同征新能源汽车零部件有限公司	沈伟	C	4
资金合计						50

附件 3.10

江苏省电力科学技术进步奖

获奖证书

为表彰在促进江苏电力科学技术进步工作中做出重大贡献者，特颁发此证，以资鼓励。

奖项名称： 江苏省电力科学技术进步奖

获奖项目： 电动汽车有线/无线一体化充电关键技术及应用

获奖等级： 三等

获 奖 者 ： 夏晨阳

奖励年度： 2021年

发证机构： 江苏省电机工程学会

江苏省电机工程学会

江苏省电力科学技术奖 专用章

证书号：2020-J-3-07-G1

附件 **3.11**

ICS 49.060
CCS V 86

团 体 标 准

T/CPSS 1005—2023

多旋翼无人机磁耦合静态无线充电系统通用技术要求

Magnetic coupling static wireless charging system for multi-rotor UAV general technical requirements

2023-08-31 发布　　2023-09-01 实施

中国电源学会 发布

前 言

本文件按照GB/T 1.1—2020《标准化工作导则　第1部分：标准化文件的结构和起草规则》的规定起草。

本文件由中国电源学会提出并归口。

请注意本文件的某些内容可能涉及专利。本文件的发布机构不承担识别专利的责任。

本文件起草单位：广西电网有限责任公司电力科学研究院，重庆大学，重庆华创智能科技研究院有限公司，国网电力科学研究院有限公司，千寻位置网络有限公司，江苏方天电力技术有限公司，重庆前卫科技集团有限公司，浙江华飞智能科技有限公司，深圳瓦特源检测研究有限公司，清华四川能源互联网研究院，南方电网科学研究院有限责任公司，云南电网有限责任公司电力科学研究院，广西电网有限责任公司，台达电子企业管理（上海）有限公司，中国矿业大学。

本文件主要起草人：陈绍南，肖静，周柯，吴晓锐，王智慧，卓浩泽，唐春森，左志平，李小飞，蒋成，白浩，桑林，王可，叶辉，王成亮，赵鱼名，范正伟，罗勇进，彭庆军，王山，奉斌，廖永恺，夏晨阳，廖志娟。

本文件首次发布。

附件 3.12

ICS 49.060
CCS V 86

团 体 标 准

T/CPSS 1006—2023

多旋翼无人机磁耦合静态无线充电系统测试要求

Magnetic coupling static wireless charging system for multi-rotor UAV testing requirements

2023-08-31 发布　　　　2023-09-01 实施

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前　言

本文件按照GB/T 1.1—2020《标准化工作导则　第1部分：标准化文件的结构和起草规则》的规定起草。

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本文件主要起草人：吴晓锐，陈绍南，周柯，龚文兰，王智慧，韩帅，唐春森，左志平，李小飞，蒋成，白浩，桑林，王可，叶辉，王成亮，赵鱼名，范正伟，罗勇进，彭庆军，王山，奉斌，廖永恺，夏晨阳，荣灿灿。

本文件首次发布。

附件 3.13

Analysis and Design of Multifrequency Compensation Strategy for Wide Misalignment Tolerance in Inductive Power Transfer Systems

Zirui Yao, *Student Member, IEEE*, Shiying Luo, Zhuhaobo Zhang, *Student Member, IEEE*, Guanxi Li, Xuan Wei, *Student Member, IEEE*, Xiangwei Shen, Ni Zhang, Philip T. Krein, *Fellow, IEEE*, and Hao Ma, *Senior Member, IEEE*

***Abstract*—In inductive power transfer systems, misalignment can lead to inconsistent output power. In this article, a topology based on a primary-side detuned multifrequency compensation circuit is proposed to provide consistent output over a wide misalignment range. This topology exhibits multiple intersecting power versus coupling coefficient curves given multiple switching frequencies. The coupling range, and associated misalignment range, can be extended without increasing power and current variability by changing the switching frequency strategically at curve intersections. Parameter design and selection of the number of switching frequencies are presented. Fundamental relationships between power variation and coupling range are established. With this approach, a choice of two suitable switching frequencies changes output power by only 10% over a coupling coefficient range from 0.14 to 0.35. Three frequencies can support lower power variation or a wider coupling range. Primary current at low coupling is lower with the strategy than for conventional alternatives because reactive power can be limited. A 1.5 kW prototype has been prepared to verify the topology. The prototype confirms a power variation of 10% over a coupling coefficient range from 0.14 to 0.35 with two frequencies. With three frequencies, power variation drops to 6.7% over the same coupling range.**

***Index Terms*—Detuned primary, inductive power transfer (IPT), misalignment tolerance, multifrequency compensation, resonant conversion.**

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Zirui Yao, Zhuhaobo Zhang, and Hao Ma are with the College of Electrical Engineering, Zhejiang University, Hangzhou 310027, China, and also with the Zhejiang University/University of Illinois at Urbana-Champaign Institute, Haining 314400, China (e-mail: 11810009@zju.edu.cn; zzhbpain@163.com; mahao@zju.edu.cn).

Shiying Luo, Guanxi Li, Xuan Wei, and Xiangwei Shen are with the College of Electrical Engineering, Zhejiang University, Hangzhou 310027, China (e-mail: luoshiying0318@qq.com; 270342773@qq.com; 1029244098@qq.com; 12010014@zju.edu.cn).

Ni Zhang is with the College of Information Engineering, Zhejiang University of Technology, Hangzhou 310027, China (e-mail: zn@zjut.edu.cn).

Philip T. Krein is with the College of Electrical Engineering, Zhejiang University, Hangzhou 310027, China, also with the Zhejiang University/University of Illinois at Urbana-Champaign Institute, Haining 314400, China, and also with the University of Illinois at Urbana-Champaign, Urbana, IL 61820 USA (e-mail: krein@illinois.edu).

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I. Introduction

INDUCTIVE power transfer (IPT) systems can transfer energy to loads through magnetic coupling [1], [2], [3], [4], [5]. Compared to conventional wire-connected electrical transfer systems, IPT systems are appealing for electric ferries and other large systems because of contactless performance metrics [6]. In IPT-charged electric ferries, for instance, relative positions of primary and secondary coils change in real time owing to water motion. The coupling coefficient and transmission power will be affected continuously by misalignment [6]. Other large systems such as IPT for long-haul trucks or construction loaders are less dynamic but still subject to uncertain misalignment [3], [4], [5]. In any such system, improved performance is needed across high coupling and low coupling. Although internal charge regulation can maintain the charging voltage or current, the power limit is affected by misalignment. Wide power variation with misalignment will increase charging time, impose higher component ratings, and decrease system efficiency [7]. A practical IPT system will benefit if it can maintain consistent output power over a useful misalignment range.

In this article, a primary-side detuned multifrequency compensation structure is proposed to enhance output characteristics and keep them consistent over a wide misalignment range. Multiple separate switching frequencies are employed, and the proper frequency is selected to enforce a limited input impedance range to maintain consistent output power. The multifrequency approach here leads to multiple intersecting power versus coupling coefficient curves. Based on these curves, the control strategy changes the switching frequency to extend the misalignment range given constrained power variation. The input impedance angle range follows a similar level of variation. This is used to advantage to keep reactive input low and reduce the primary current at low coupling. The topology can ensure zero voltage switching (ZVS) over the allowed range of coupling conditions.

Multifrequency methods are known in IPT systems and have been used in multiport applications. Multi-inverter parallel operation was presented in [8], [9], and [10] to transfer power

from multiple primary coils to independent loads. In [11], [12], and [13], a hybrid modulation pulsewidth modulation (PWM) control method was proposed to generate different frequencies to supply energy to multiple receivers. Hard switching and a relatively high switching frequency affected system efficiency. A selective power transfer method with multiple receivers [14] has been proposed to achieve controllable power division by changing the switching frequency to match different secondary resonant frequencies. A two-phase orthogonal coil structure with a two-frequency phase-shifted control method was presented in [15] to realize targeted power distribution between loads with misalignment, but the operation improved only for rotational misalignment. In [16], a two-frequency hybrid compensation topology integrates series–series (S-S) compensation and *LCC*-S compensation for the fundamental and third-order harmonic voltages of a full-bridge inverter to compensate misalignment. The coupling coefficient needed to be high to achieve target output power at the two frequencies because the third harmonic voltage is one-third of the fundamental voltage.

The system described in this article is different. It uses a single IPT stage without extra inverters or coils and employs multiple switching frequencies to manage output power and input current variation over a substantial misalignment range. Although it requires multiple resonant tuning tanks, it achieves consistent performance for a single power transfer port.

IPT systems are characterized by loosely coupled transformers. Many prior methods sought to enhance coupling rather than adapting to it. Flux pipe magnetic couplers [17], double-D polarized couplers [18], double-D quadrature configurations [18], quadrature coils [19], and bipolar pads [20] have been proposed to extend the misalignment range. In [21], parameters of the transformer that include coil shapes, coil diameters, and ferrite arrangements have been used to optimize the coupling coefficient. A cubic-magnetic coupler was presented in [22] based on concentrated magnetic flux. These methods can alleviate the impact of decreased coupling, but output power is still affected. In some methods, extra coils were added to improve misalignment performance [23], [24], [25]. Although the output power can be relatively constant, added coils introduce extra loss, volume, and cost.

Topologies such as T-type [26] and X-type circuits [27] based on detuned compensation structures have been proposed to reduce output power variation with misalignment. The transferred power changed by as little as 20% with misalignment in these cases. In [28], a reconfigurable topology used ac switches to apply two power-transfer coupling-coefficient curves. The output power changed by only 10% over a coupling coefficient range from 0.10 to 0.25, but the added ac switches and controllers limit the ability to scale the approach to higher power. Hybrid structures constructed with conventional series compensation circuits and *LCC* compensation circuits were proposed in [29] and [30]. In those methods, the structure of the magnetic coupler and performance in certain directions are limited because of decoupling requirements among compensation circuits.

Converter control that includes pulse frequency modulation (PFM) [31], [32] and PWM [33], [34] has been proposed to improve misalignment performance. For PFM, primary current increases as coupling coefficient decreases [31], [32]. PWM and active rectification are used to maintain consistent power, but hard switching is employed for the inverter and rectifier [33]. In [34], a control method that integrates PWM with frequency control is proposed to achieve soft switching over the allowed range of operating conditions. This method will increase input impedance angle and reactive power even with soft-switching operation.

The proposed system seeks to address disadvantages of ac switch approaches and control limits. By making use of switching frequency selection, it adapts to misalignment. Compared to conventional single-frequency compensation topologies, the proposed topology extends the useful misalignment range while enforcing a power variation limit. The use of discrete switching frequencies helps to avoid frequency bifurcation [35] compared to continuous frequency control, and the system can avoid chattering near the coupling intersection point by encompassing a hysteresis control in its frequency selection strategy.

The rest of this article is organized as follows. The proposed primary detuned multifrequency compensation topology is analyzed in Section II. Output characteristics of the proposed topology for different numbers of switching frequencies and misalignment performance comparisons are described in Section III. Parameter design and selection of the number of switching frequencies are provided in Section IV. Experimental results from a 1.5 kW prototype IPT system and comparisons to other methods are presented in Section V. Finally, Section VI concludes the article.

II. Analysis of the Proposed Primary Detuned Multifrequency Compensation Topology

The proposed multifrequency IPT system is shown in Fig. 1, with an equivalent circuit. L_p and L_s are self-inductances of the primary and secondary coils. The primary and secondary resonant circuits consist of one series *LC* resonant tank and n–1 parallel *LCC* resonant tanks, and have n resonant frequencies. There is one resonant tank for each potential choice of switching frequency. When $n = 1$, the circuit is a conventional S-S compensation topology. The ideal input-to-output voltage gain versus frequency for the resonant set is shown in Fig. 2. The network acts as a multiple bandpass filter, and when the switching frequency matches any of the multifrequency network resonances, the ideal voltage gain is 1. An important consideration is that component quality factor Q will enter into practical performance. Each additional tank introduces its own series resistance, reducing the overall voltage gain. The dc source V_{in} supplies a MOSFET bridge (S_1, S_2, S_3, S_4). The secondary resonant circuit drives load R_o through rectifier bridge D_1, D_2, D_3, D_4.

Fundamental harmonic analysis is used here. The simplified ideal circuit in Fig. 1(b) defines

$$\begin{cases} U_{AB} = \frac{2\sqrt{2}}{\pi} V_{\text{in}},\ U_{CD} = \frac{2\sqrt{2}}{\pi} V_{\text{out}} \\ M = k\sqrt{L_p L_s},\ R_{\text{eq}} = \frac{8}{\pi^2} R_o \end{cases} \quad (1)$$

where U_{AB} and U_{CD} are the rms values of first-harmonic input and output voltages, respectively; R_{eq} is the ac equivalent load; k

附件 **3.14**

Variable Carrier Phase-Shift Method for Integrated Contactless Field Excitation System of Electrically Excited Synchronous Motors

Enes Ayaz, Ogün Altun, and Ozan Keysan

***Abstract*—This article presents a novel contactless field excitation (CFE) system based on wireless power transfer (WPT), which utilizes the existing voltage source inverter (VSI) of the motor drive for electrically excited synchronous motors (EESMs). In conventional CFE systems, an extra high-frequency converter is required to excite the field winding. In this article, it is proposed to utilize existing voltage switching harmonics of the VSI for exciting the field winding while the low-frequency modulated component is used to drive the motor. In the proposed system, a novel variable carrier phase-shift method is developed to achieve constant input excitation voltage for the WPT part independently from the motor operation. In addition, a hybrid frequency detuning control method is introduced to adjust the field current. For experimental validation, a small-scale prototype with a 100-V dc-link and a 60-kHz switching frequency is established. It is observed that the field current could be kept almost constant at 5 A under different motor driving conditions operations regarding modulation index and fundamental frequency. Also, it is shown that the field current could be reduced by detuning the switching frequency. In brief, without an additional active converter and only with a software update, a cost-effective CFE system for EESMs can be easily implemented.**

***Index Terms*—Carrier phase shift (CPS), contactless field excitation (CFE), motor drive, sinusoidal pulsewidth modulation (SPWM), wireless power transfer (WPT).**

I. Introduction

THE interest of the automotive industry is continuously increasing in electric vehicles (EVs) or hybrid EVs (HEVs) rather than internal combustion engine vehicles [1]. One of the critical parts of EVs and HEVs is the traction system, where permanent magnet synchronous motors are commonly preferred due to their high torque density [2]. However, high cost and limited supply of rare-Earth magnets such as Neodymium (Nd) and Samarium (Sm) encourage less-PM or no-PM motors such as electrically excited synchronous motors (EESMs) [3], [4], [5], [6]. EESMs can decrease the total cost and have flexible control thanks to their externally excited field windings [7], [8].

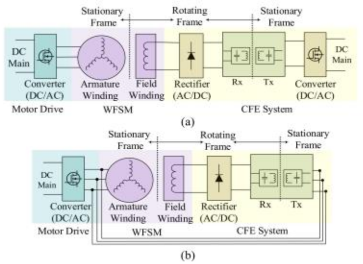

Fig. 1. Circuit diagram of a conventional and the proposed CFE based on a WPT system for EESMs. (a) Conventional system. (b) Proposed system.

Moreover, they are more reliable as the demagnetization of PMs due to high temperature is not an issue in EESMs. However, power transfer to their rotating field windings is challenging.

The most common method to excite field windings is to use slip rings with conductor rings and carbon brushes. Although slip rings are a mature and cost-effective technology, they require periodic maintenance due to the wear of the brushes [9]. Another method is to use brushless exciters that are, in fact, synchronous generators (SGs) with rotating rectifiers. However, this method is not applicable for variable speed drives such as in EVs [10]. Alternative to these methods, contactless field excitation (CFE) systems based on wireless power transfer (WPT) are proposed, as shown in Fig. 1(a) [11], [12], [13], [14], [15]. They have no physical contact between the rotating and stationary frames, eliminating the maintenance issue. However, extra high-frequency converter increases the cost and complexity.

The VSI of the motor drive generates a low-frequency modulated voltage with high-frequency switching harmonics. This low-frequency modulated voltage controls the speed and torque of the motor, whereas the motor windings filter out the high-frequency voltage harmonics thanks to high phase inductances. In this article, it is proposed that these high-frequency voltage harmonics of the existing motor drive can be utilized to energize the field winding while the low-frequency modulated voltage can

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The authors are with the Department of Electrical and Electronics Engineering, Middle East Technical University, 06800 Ankara, Turkey (e-mail: enes.ayaz.1996@gmail.com; ogun.altun@metu.edu.tr; keysan@metu.edu.tr).

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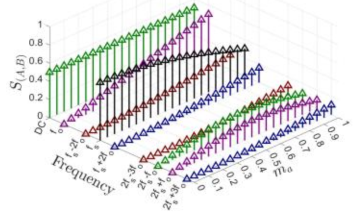

Fig. 3. Harmonic distribution of SPWM for varying modulation index.

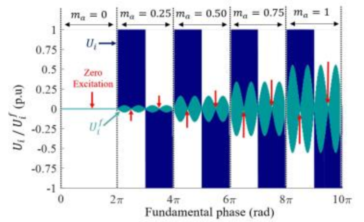

Fig. 4. Normalized input excitation voltage waveforms of the WPT system. Zero-voltage points at input excitation voltage are indicated by red arrows.

The first switching harmonic and its sideband components $[S_{(A,B)}^{f_s}(t)$, $S_{(A,B)}^{f_s-2f_o}(t)$, and $S_{(A,B)}^{f_s+2f_o}(t)]$ of the switching function can be calculated as in (3), (4), and (5) by taking $(i = 1)$, $(i = 1, k = -2)$, and $(i = 1, k = 2)$ in (2), respectively

$$S_{(A,B)}^{f_s}(t) = \frac{2}{\pi} J_0\left(m_a \frac{\pi}{2}\right) \cos\left(2\pi(f_s)t + \phi_{c_{(A,B)}}\right) \quad (3)$$

$$S_{(A,B)}^{f_s-2f_o}(t) = \frac{2}{\pi} J_2\left(m_a \frac{\pi}{2}\right) \cos\begin{pmatrix} 2\pi(f_s - 2f_o)t \\ +\phi_{c_{(A,B)}} - 2\theta_{o_{(A,B)}} \end{pmatrix} \quad (4)$$

$$S_{(A,B)}^{f_s+2f_o}(t) = \frac{2}{\pi} J_2(m_a \frac{\pi}{2}) \cos\begin{pmatrix} 2\pi(f_s + 2f_o)t \\ +\phi_{c_{(A,B)}} + 2\theta_{o_{(A,B)}} \end{pmatrix} \quad (5)$$

where f_o is the fundamental frequency, f_s is the switching frequency, $f_s - 2f_o$ is the lower sideband harmonic, and $f_s + 2f_o$ is the higher sideband harmonic. After that, U_i^f can be calculated as in (6) shown at the bottom of this page, by subtracting the switching and its sideband harmonics of leg B from those of leg A In conventional SPWM, each phase uses the same carrier signals, which means that the carrier phase of leg A (ϕ_{c_A}) and leg B (ϕ_{c_B}) are equal. Hence, according to (6), the switching frequency disappears in $U_i^f(t)$, and just only its sidebands exist. $U_i(t)$ and $U_i^f(t)$ are plotted in Fig. 4 for different modulation indices. It is observed that $U_i^f(t)$ increases with the modulation index, and zero voltage (zero excitation) occurs at some moments. These zero excitation instants create low-frequency power fluctuations that disrupt constant power transfer. Therefore, a control method is required to achieve a continuous/constant power transfer at the switching harmonic for the WPT system without disturbing the fundamental component. However, conventional control methods of the WPT system are not suitable for this.

A conventional method is to control the duty cycle but this also affects the fundamental component. Another method is frequency detuning control, but it cannot guarantee continuous power transfer since zero-voltage moments exist, indicated via red arrows in Fig. 4. The last method is to add a postregulation converter or use an active rectifier at the output of the WPT system. However, this increases the system's cost and complexity, and the problem of zero voltage moments still exists. In this article, a new control method, introducing variable carrier phase shift (CPS), is proposed to avoid zero-voltage moments and achieve continuous power transfer for changing modulation indices. The proposed method is similar to a dual-frequency power transfer system with a single converter [32], [33], [34], [35], [36]. In [33], a single-inverter-based dual-frequency WPT system is proposed using the programmed PWM method.

However, the programmed PWM method is computationally complex and requires switching angle calculations using offline algorithms, which is not feasible in dynamic systems such as our cases. In [34] and [35], multifrequencies are achieved by comparing superimposed sinusoidal reference signals with a high-frequency triangular carrier signal. However, in these methods, the switching frequency is higher than the operating frequencies of the WPT system, which increases the switching losses. In [36], multifrequency components are achieved by a

$$\begin{aligned} \frac{U_i^f(t)}{V_{\mathrm{DC}}} = {} & \frac{2}{\pi} J_2\left(m_a \frac{\pi}{2}\right) \cos\left(2\pi(f_s - 2f_o)t + \phi_{c_A} - 2\theta_{o_A}\right) - \frac{2}{\pi} J_2\left(m_a \frac{\pi}{2}\right) \cos\left(2\pi(f_s - 2f_o)t + \phi_{c_B} - 2\theta_{o_B}\right) \\ & + \frac{2}{\pi} J_0\left(m_a \frac{\pi}{2}\right) \cos\left(2\pi(f_s)t + \phi_{c_A}\right) \\ & - \frac{2}{\pi} J_0\left(m_a \frac{\pi}{2}\right) \cos\left(2\pi(f_s)t + \phi_{c_B}\right) + \frac{2}{\pi} J_2\left(m_a \frac{\pi}{2}\right) \cos\left(2\pi(f_s + 2f_o)t + \phi_{c_A} + 2\theta_{c_A}\right) \\ & - \frac{2}{\pi} J_2\left(m_a \frac{\pi}{2}\right) \cos\left(2\pi(f_s + 2f_o)t + \phi_{c_B} + 2\theta_{o_B}\right). \end{aligned} \quad (6)$$

附件 **3.15**

Design and Control of a Decoupled Multichannel Wireless Power Transfer System Based on Multilevel Inverters

Yuxin Liu, *Student Member, IEEE*, Chunhua Liu, *Senior Member, IEEE*, Xingran Gao, and Senyi Liu, *Member, IEEE*

***Abstract*—Traditional multichannel wireless power transfer (WPT) systems suffer from the complex system structure and cross-interference among receivers. To solve such problems, this article presents the design and control methods of a decoupled multichannel WPT system based on multilevel inverters. A single-phase multilevel inverter is utilized to drive the transmitter circuit with a voltage waveform consisting of multiple components. Particularly, these components are independent in the frequency spectrum, and their amplitudes can be controlled independently. Moreover, primary compensation is used to offer multiple frequencies for the primary circuit. Additional damping filters are used in the secondary circuits to reduce the cross-interference between the receivers. In addition, the features of the system topology are analyzed, and an exact parameter design method is presented. Furthermore, combined with the neutral point voltage balance strategy, a simple vector-based control method is proposed to regulate the transmitted power in each power channel. As a result, the power can be transferred to loads through the designed power channels simultaneously without mutual interference. Finally, both simulation and experiment of a 1-kW experimental prototype with SIC-MOSFET are given to verify the feasibility of the proposed multichannel WPT system and the control strategy.**

***Index Terms*—Compensation network, multilevel inverter (MLI), multiple power channel, wireless power transfer (WPT).**

I. Introduction

Wireless power transfer (WPT) has been widely used in various applications, such as electric vehicles (EVs), unmanned aerial vehicles, and portable electronics, due to its convenience, safety, and better user experience [1]–[3]. Recently, the multichannel WPT has attracted more and more attention for its advantage over single-channel WPT in delivering power to multiple loads simultaneously. Multichannel WPT can be realized using multiple transmitters [4], [5] or only one transmitter. Particularly, the way of using one transmitter and many receivers is also known as one-to-multiple WPT (O2M-WPT) [12].

O2M-WPT has been applied in applications of EV charging systems [7], wireless motors [8], [9], and inductive heating [10]. In an O2M-WPT system, the power allocation of multiple loads is usually achieved by multifrequency channels [6]. To enhance the efficiency of O2M-WPT, compensated capacitor switchers [9] or multiple-frequency resonating compensation (MFRC) [12], [17] can be used to offer multiple resonant frequencies for the transmitter circuit. Different resonant frequencies are set for loads, and when a specific frequency is selected, the corresponding load is activated [6]–[8]. Commonly, the output power can be regulated by adjusting the amplitude of the corresponding frequency components [10]–[12].

Although O2M-WPT has broad application prospects, there are still some issues that need to be handled. One issue is about the cross-interference, which affects the independence of each channel and reduces the efficiency [15], [16]. In [7], dc–dc circuits are placed for the receivers of a dual-pickup wireless EV charging system to allocate power to each load accurately. However, the system structure is complex due to the additional dc–dc circuits. In [13], auxiliary circuits are added to receiver circuits and relay circuits to reduce the cross-interference. However, the use of relay circuits complicates the system. Fu *et al.* [14] proposed a compensation method to lessen the influence of cross-interference by calculating the derived optimal load reactances. However, this method is challenging to apply when the loads change frequently. Narayanamoorthi *et al.* [15] used a frequency bifurcation approach to realize O2M-WPT with reduced cross-interference. However, the system parameters are difficult to design, especially when the number of receivers increases. In [16], three types of compensation networks with damping filters are introduced into receivers, and the cross-interference among multiple receivers can be reduced flexibly. However, the cross-interference can be further reduced by enhanced control.

The multifrequency superposition is another issue of OWPT, which superimposes multiple power components to drive the transmitter [12]. Many attempts have been made to realize

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The authors are with the School of Energy and Environment, City University of Hong Kong, Hong Kong, China, and also with the Shenzhen Research Institute, City University of Hong Kong, Shenzhen 518057, China (e-mail: yuxin.liu@my.cityu.edu.hk; chunliu@cityu.edu.hk; xingran.gao@cityu.edu.hk; senyiliu2-c@my.cityu.edu.hk).

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multifrequency superposition for O2M-WPT. Liu *et al.* [11] used a transformer to combine all the power components from multiple inverters. However, the primary part still has only one resonant frequency, which prevents the system from operating in high efficiency. To solve this problem, Huang *et al.* [12] introduced resonant tanks to the topology presented in [11] and, therefore, employed different resonant frequencies to the transmitter. However, multiple inverters and additional transformers are still required. In [10], a family of power converters is proposed to provide two simultaneous frequencies for dual-frequency inductive heating. However, many passive components are required in the proposed topologies, which makes the system structure complex. In [30], a hybrid sinusoidal pulse width modulation (SPWM) method is proposed to realize multifrequency superposition with only one full-bridge inverter, where the modulation wave contains components with multiple frequencies. However, the power switches are required to operate at a frequency much larger than the transmission frequency, which increases switching losses and adds cost to power switches and digital controllers. Therefore, the hybrid SPWM method is more suitable for applications with low transmission frequencies. Multilevel inverters (MLIs) can generate more voltage levels than two-level inverters, which makes MLIs have the potential to realize multifrequency superposition with a simple system structure and a relatively low switching frequency.

In addition, MLIs surpass traditional two-level inverters in various applications because of the advantages such as lower voltage stress on power switches, better power quality, and smaller EMI [18]–[20]. Several topologies of MLIs have been proposed, such as neutral point clamped (NPC), flying capacitor, and cascaded H-bridge. As the number of voltage levels increases, MLIs can offer O2M-WPT with more possible solutions to superimpose multiple power components and regulate power allocation in each power channel. However, as more power switches are utilized in MLIs, the control of MLIs is more challenging [18], [19]. Moreover, the problem of neutral point (NP) voltage imbalance reduces the reliability of MLIs, which may lead to increased voltage stress of power switches, distorted output voltage, and additional losses [20]–[22].

Driven by combining the advantages of MLIs with O2M-WPT, this article proposes a decoupled multichannel WPT system based on MLIs. The main contributions of this article are listed as follows.

1) The multiple voltage levels of the MLIs can generate voltage waveforms with multiple frequency components, which naturally realize multifrequency superposition without additional transformers. The power components have no overlap in the frequency spectrum and can therefore be regulated independently.
2) MFRC with multiple resonant frequencies is applied in the transmitter circuit, which enhances the efficiency. Damping filters are used in the receiver circuits to reduce the cross-interference between two power channels.
3) Detailed parameter design methods for both transmitter circuit and receiver circuit are proposed as the flowcharts.
4) A simple vector-based control method with NP voltage balancing and third harmonic reduction is proposed to regulate the transmitted power in each power channel.

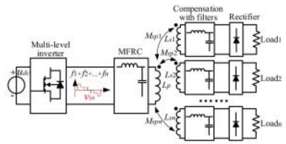

Fig. 1. Proposed multichannel WPT system based on an MLI.

TABLE I
Switching States of the Single-Phase TNPC Inverter

V_j	S_1	S_2	S_3	S_4	u_{in}	i_o	Category
V_1	1	0	0	1	u_{dc}	0	Large
V_2	1	0	0	0	$0.5u_{dc}$	$-i_{in}$	Medium
V_3	0	0	0	1	$0.5u_{dc}$	i_{in}	Medium
V_4	1	0	1	0	0	0	Zero
V_5	0	0	0	0	0	0	Zero
V_6	0	1	0	1	0	0	Zero
V_7	0	1	0	0	$-0.5u_{dc}$	$-i_{in}$	Medium
V_8	0	0	1	0	$-0.5u_{dc}$	i_{in}	Medium
V_9	0	1	1	0	$-u_{dc}$	0	Large

II. System Configuration and Model

The proposed multichannel WPT system is shown in Fig. 1, which composes one transmitter part and n receiver parts. The primary part contains a dc voltage source (u_{dc}), a single-phase MLI, an MFRC network, and a transmitter coil (L_P). Each secondary part has a receiver coil (L_{si}, $i = 1,\ldots,n$), a compensation network with damping filters, rectifier, and load. The voltage levels of the MLI can work at different frequencies. Therefore, a voltage waveform containing components with frequencies of f_i ($i = 1,\ldots,n$) can be generated, corresponding to the resonant frequencies of n receiver circuits. The MFRC network provides the primary circuit with multiple resonant frequencies [12], [17]. The damping filters used in the receiver circuits can produce a high impedance at nontargeted frequencies, which helps in reducing the cross-interference [16].

Generally, more power channels can be built by increasing the number of the voltage level of the MLI and the number of resonant frequencies of the MFRC network. Therefore, no additional transformer is needed to realize multifrequency superposition, and no additional inverter and dc voltage source are needed to regulate the power allocation among each load. In this article, a typical dual-channel WPT system based on a T-type NPC (TNPC) inverter is used as a representative example to illustrate the design and control method, and the circuit configuration is shown in Fig. 2.

In the case of neutral voltage balance, the two dc-link capacitors (C_1 and C_2) share the dc-link voltage equally as $u_{c1} = u_{c2} = 0.5u_{\mathrm{dc}}$, where u_{dc} is the voltage of the dc link. As shown in Table I, nine switching states (V_j, $j = 1,\ldots,9$) of the eight SIC-MOSFETs (S_n and $\overline{S_n}$, $n\in\{1, 2, 3, 4\}$) are available to generate five levels of inverter output voltage. Based on the

附件 **3.16**

Generic Uncertainty Parameter Analysis and Optimization of Series–Series Wireless Power Transfer System for Robust Controller Design

Amir Hakemi, *Student Member, IEEE*, Dejan P. Jovanovic, *Member, IEEE*, Don Mahinda Vilathgamuwa, *Fellow, IEEE*, Geoffrey R. Walker, *Senior Member, IEEE*, and Jo P. Pauls

***Abstract*—In a typical wireless power transfer (WPT) system, the load, the mutual inductance, and the required tuning frequency can vary in a particular range. Variation of each parameter can substantially impact the dynamic characteristics of the system. Thus, they can be considered as sources of uncertainty in the system. To address this, robust control methods such as μ-synthesis are developed to deal with possible system uncertainties. This article first undertakes the generic dynamic analysis of the series–series WPT compensation network for two modes of operation, i.e., constant output voltage (COV) mode and constant output current (COC) mode, in the presence of three aforementioned uncertainty sources. Subsequently, the frequency detuning as a function of the compensation capacitor variation is explored and broadened as a technique to obtain the optimized compensation capacitor value that can lead to a plant with minimized dynamic deviations from its nominal system in the operating range between COC and COV modes. As such, this approach offers a design procedure for a least conservative robust controller, which can significantly improve the system performance. The optimized structure and the corresponding designed μ-synthesis controller are comprehensively elaborated. The theoretical achievements and experimental results show superior dynamic performance of the optimized structure and the corresponding designed controller in the presence of three uncertainty sources compared to the COC and COV modes of operation.**

***Index Terms*—μ-synthesis robust controller, medical implants, series–series compensation, wireless power transfer (WPT).**

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(Corresponding author: Amir Hakemi.)

Amir Hakemi, Dejan P. Jovanovic, Don Mahinda Vilathgamuwa, and Geoffrey R. Walker are with the School of Electrical Engineering & Robotics, Queensland University of Technology, Brisbane, QLD 4000, Australia (e-mail: amir.hakemi@ieee.org; dejan.jovanovic@qut.edu.au; mahinda.vilathgamuwa@qut.edu.au; geoffrey.walker@qut.edu.au).

Jo P. Pauls is with the School of Engineering and Built Environment, Griffith University, Southport, QLD 4222, Australia, and also with the Innovative Cardiovascular Engineering and Technology Laboratory, Critical Care Research Group, The Prince Charles Hospital, Brisbane, QLD 4032, Australia (e-mail: j.pauls@griffith.edu.au).

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NOMENCLATURE

ω_o	Operating frequency.
C_1, C_2	Compensation capacitor of the primary side and the secondary side, respectively.
$C_{\min}, C_{\max}$	Required compensation capacitor for COC and COV modes, respectively.
$C_{\mu,C1}$	Controller for C''_1 compensating capacitor.
$C_{\mu,C9}$	Controller for C''_9 compensating capacitor.
$C_{\mu,C21}$	Controller for C''_{21} compensating capacitor.
$C_{\mu,C1,C2,C3}$	Controller for the set of compensating capacitors (C''_1, C''_2, C''_3).
$C_{\mu,C7,C8,C9}$	Controller for the set of compensating capacitors (C''_7, C''_8, C''_9).
$G_{\text{nom}}(s)$	Transfer function of the nominal system.
$G(s)$	Transfer function of the system with uncertainty.
K	Coupling coefficient of the two WPT coils.
L_{11}, L_{22}	Primary and secondary self-inductances, respectively.
M	Mutual inductance of two WPT coils.
R_L	Load across the dc link.
$R_{L,\text{ac}}$	Equivalent ac load of R_L.
v_{AB}, v_{CD}	Input voltage and the output voltage of the resonant circuit, respectively.
v'_{AB}, v'_{CD}	Fundamental component of the input voltage and output voltage of the resonant circuit, respectively.
V_o, V_{in}	Output (dc link) voltage and input voltage of the WPT system, respectively.

I. INTRODUCTION

A. Background and Motivation

WIRELESS power transfer (WPT) technology has been widely used for different applications from high-power applications such as electrical vehicles [1], [2] to low-power applications such as medical implants [3]–[5]. For medical devices, the supply requirements vary significantly. For example, mechanical circulatory support system (MCSS) is a common therapy for patients with heart failure where a WPT system has been proposed as the system supply due to the natural isolation feature WPT provided [6]–[9]. The motivation of this work is to first identify the potential difficulties a WPT system parameter

variation imposes on the realization of a closed-loop system. Then, based on the general requirements of commercialized MCSS (in particular, ventricular assist devices [10], [11]) with rated power (2–5 W), rated output voltage, and a range of possible system parameter variations, a reliable closed-loop system based on robust controller methodology is implemented.

The WPT coils can be modeled as a transformer with a high leakage inductance and low magnetizing inductance. To cancel out the leakage inductance effect, compensation networks need to be introduced in the system [12]. Various studies have been carried out for the development of compensation networks, such as series–series (SS) and series–parallel (SP) [13], [14]. Mostly, WPT systems are studied under constants K and R_L and a known resonant frequency. However, in most WPT applications, system parameters vary in a particular range leading to drift in system dynamics to a new set of operating setpoints generating an infinite number of plants. Such demanding conditions require a sophisticated controller.

The proportional and integral (PI) controls are mainly chosen for WPT systems due to their simplicity and convenient implementation [15]–[17]. Since WPT plants are generally associated with several sources of parameter uncertainties and due to the limited capability of PI controllers to handle such system parameter variations, these control methods cannot guarantee robust stability (RS) and robust performance (RP) for all possible parameter variations. In [18]–[20], the performance of conventional linear controllers, such as PI controllers, is investigated under parameter variations, which shows its vulnerability against the drift of system parameters from nominal values. Moreover, the effect of load variation and communications delays on PI controllers is investigated [21]. As it is pointed out in [22], PI controllers have a good robustness where they are used for first- and second-order systems. However, when it comes to a WPT system, which is typically a nonlinear higher order system, the robustness of PI controllers becomes questionable. Since PI controller design is based on the nominal plant, their performance for the nominal plant leads to satisfactory results. However, when system parameters deviate from their nominal values, the performance of PI controllers significantly deteriorates, and they are not able to maintain RS and RP anymore, which makes them undesirable for systems with parameter uncertainty. Therefore, robust controllers are developed for systems with parameter variations or uncertainties, such as load perturbation [18]–[20], [22], [23].

B. Related Works and Contributions

Among different approaches to design a robust controller, $H\infty$ optimization controller design and μ-synthesis controller design based on structured singular values have gained popularity in recent years. Controller design based on solving $H\infty$ optimization problem is investigated for various WPT networks with respect to single- or multiple-parameter variations, i.e., load and/or K [18]. However, the main problem with this approach is that it cannot guarantee RP of the system due to the simplification in the process of solving $H\infty$ optimization problem [24].

As an alternative, the μ-synthesis controller design has gained popularity since it guarantees both RS and RP. A controller based on the μ-synthesis is designed for an SP compensation network to deal with K variations in [25] for accurate reference tracking. The same controller design approach is adopted in [26] for an *LCL* compensation network. This controller can accurately track the reference voltage under load and K variations. However, previous papers fail to consider the effect of frequency detuning on the dynamic characteristic of the system. Such detunings make the system prone to instability, violating RP and RS operating criteria and consequently affecting their reliability for delicate applications.

For medical implants, SS is the most common compensation structure. In spite of variations in R_L and K, such an SS compensated system is required to keep the system stable and to obtain satisfactory performance [27]. Two main operating modes of SS compensation networks, i.e., 1) constant output current (COC) mode and 2) constant output voltage (COV) mode, can be achieved by tuning to the exact required operating frequency with respect to the WPT network parameters [27], [28]. However, in practice, the operating frequency can get detuned from its designed value. Deliberate shifting of the switching frequency above resonance frequency (2%–10%) to achieve zero-voltage switching (ZVS) [28], deterioration of capacitance due to high voltage stress across capacitors, inaccurate capacitor selection, stray capacitance at high frequencies, and aging are possible causes of detuning [29], [30]. It is shown in this article that even a slight deviation from the nominal capacitor value gives rise to a significant variation in the dynamics of the system in COC and COV modes.

In view of such crucial operational situations, the major contributions of this work can be summarized as follows.

1) The importance of frequency detuning as a source of uncertainty for dynamic analysis of COC and COV modes under K and R_L variations is disclosed in this article.
2) The frequency detuning as a function of compensation capacitor variations is explored and expanded to find the system with the least dynamic deviation from the nominal plant in the presence of uncertainties.
3) For the new structure, a μ-synthesis controller is designed to explore the dynamic performance of the new capacitor selection criterion and to show how the new approach helps to design the least conservative controller.
4) A novel approach for the microcontroller implementation of high-order μ-synthesis controller that can substantially reduce the computational time without resorting to order reduction methods is proposed.

The rest of this article is organized as follows. First, the required condition for the SS network to operate in COC mode or COV mode as a function of the compensation capacitor is reviewed. Then, the effect of frequency detuning in the presence of K and R_L uncertainties is investigated. Thereafter, the concept of frequency detuning is explored as a degree of freedom to find the optimum structure, which offers the best plant uncertainty profile in the sense of the robust controller design. After a brief review of μ-synthesis controller design requirements, five controllers with the help of the DK-iteration algorithm are

附件 **3.17**

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Research on Constant Current/Constant Voltage Output of LCC-S IPT System Based on Frequency Switching*

XIONG Mingxing[1,2], ZHANG Haojun[2], ZOU Yunru[2], YANG Zewei[2], DING Ning[3], LI Weihua[1,2*]

(1.Institute of Rail Transit, Jinan University, Zhuhai Guangdong 519000, China;
2.School of International Energy, Jinan University, Zhuhai Guangdong 519000, China;
3.School of Intelligent Systems Science and Engineering, Jinan University, Zhuhai Guangdong 519000, China)

Abstract: To achieve constant current/constant voltage high-efficiency output of inductive power transmission (IPT) system under variable load conditions, a parameter configuration and optimization method of LCC-S IPT system based on frequency switching is proposed. Starting with LCC-S compensation topology, the conditional equations of zero phase angle output at the constant current or constant voltage are obtained respectively, and the quantitative relationship between current gain, voltage gain, and system parameters is derived. Furthermore, by defining the output gain ratio of the system, the relationship between the output gain, load resistance and the overall efficiency in the constant current/constant voltage mode is analyzed. On this basis, the overall efficiency of the system is maximized by selecting the optimal output gain value. The simulation results show that the load resistance can maintain a stable output in the range of 3~300 Ω, including the instant of constant current/constant voltage mode switching, and ZPA operation can be achieved under constant current/constant voltage mode, while the overall efficiency of the system is maintained above 90%.

Key words: inductive power transfer; LCC-S; constant current/constant voltage; output gain ratio; parameter optimization
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基于频率切换的 LCC-S 型 IPT 系统恒流/恒压输出研究*

熊明星[1,2],张皓钧[2],周芸如[2],杨泽伟[2],丁　宁[3],李伟华[1,2*]

(1.暨南大学轨道交通研究院,广东 珠海 519000;2.暨南大学国际能源学院,广东 珠海 519000;
3.暨南大学智能科学与工程学院,广东 珠海 519000)

摘　要:为实现感应电能传输(Inductive Power Transfer,IPT)系统在变负载条件下的恒流/恒压高效输出,提出一种基于频率切换的 LCC-S 型 IPT 系统参数配置及优化方法。从 LCC-S 补偿拓扑入手,分别得到系统恒流或恒压零相位角(Zero Phase Angle,ZPA)输出的条件方程,并推导了电流增益、电压增益与系统参数之间的定量关系;进一步通过定义系统的输出增益比,分析了恒流/恒压模式下输出增益、负载电阻与整体效率的关系;在此基础上,通过选取最佳的输出增益值,使得系统整体效率达到了全局最大化。仿真结果表明,负载电阻在 3~300 Ω 的变化范围内包括恒流/恒压模式切换瞬间都能保持稳定的输出,并且恒流/恒压模式下均能实现 ZPA 运行,同时系统整体效率都维持在 90%以上。

关键词:感应电能传输;LCC-S;恒流/恒压;输出增益比;参数优化
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感应电能传输(Inductive Power Transfer,IPT)技术以电磁场为媒介,可安全灵活地实现能量从电源到负载的无接触传输[1-2],被广泛应用于电动汽车、消费电子和医疗设备等领域[3-5]。在 IPT 系统实际应用中,为提高电池的充电效率和循环寿命,通常采用先恒流后恒压的充电模式[6],然而,在整个充电过程负载的变化会对系统的输出特性和效率特性产生很大影响[7]。因此,如何在变负载条件下实现恒流/恒压高效输出是 IPT 技术研究的关键问题之一。为此国内外做了大量的研究,现有方法主要集中于控制策略[8-9]、拓扑切换[10-11]和频率切换[12-15]三个方面。其中,引入控制单元或交流开关不仅增加了系统电路的复杂度,还带来了多余的功率损耗,相比之下频率切换是目前实现恒流/恒压输出的较好方式。文献[12]采用 SS 补偿拓扑,通过推导传输特性与参数配置,实现了恒流/恒压输出,但该结构无法满足恒压模式下的 ZPA 输出,导致系统效率偏低。文献[13-14]提出双 LCC 补偿拓扑的 IPT 系

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动态IPT系统后级稳压器的小信号模型修正和改进控制策略

殷全安[1]，陈乾宏[1]，尹艳浩[1]，何明亮[1]，刘立东[2]
（1. 南京航空航天大学 自动化学院，江苏 南京 211116；2. 横店集团东磁股份有限公司，浙江 东阳 322118）

摘要：针对单轨动态无线供电系统，在考虑整流桥前的电流断续及副边谐振电路寄生参数的影响下，分析了整流电压与负载的关系，指出因负载变化导致的整流电压大范围波动给后级稳压器的建模和闭环参数设计带来了挑战。为使后级稳压器小信号模型描述得更为准确，考虑了副边谐振电路的影响，引入幅值／频率修正系数，对后级稳压器小信号模型的低频段增益和中频段谐振峰频率进行了修正。在此基础上，为进一步提高系统的变负载动态响应能力，提出加入整流电压前馈环节。仿真与实验结果验证了理论分析的正确性和所提方案的有效性。

关键词：动态无线电能传输；寄生参数；整流电压；小信号模型；控制策略
中图分类号：TM46　　**文献标志码**：A　　DOI：10.16081/j.epae.202301012

0 引言

相比接触式供电，感应电能传输（inductive power transfer，IPT）具有无磨损、维护成本低、可靠性高等优点[1]，受到了广泛关注，其中动态IPT技术能为运动的负载实时供电，在电动汽车[2-3]、单轨物流分拣[4]、自动导引小车[5]等领域具有良好的应用价值。

在单轨物流分拣系统中，由于分拣小车电机的负载变化范围大，存在动态响应性能差的问题。为改善系统的输出动态性能，需要选取合适的控制策略对输出进行控制。常见的控制策略有原边控制[6-8]、原副边控制[9-11]以及副边控制[12-16]。原边控制通过在原边设置检测电路，检测电压、电流信息，计算得到副边侧的输出电压、电流，从而实现对输出的调控，其副边轻便，但原边需要额外的检测电路，控制器实时计算量大。原副边控制通过原副边的实时通信反馈，调整原边输入电压、频率、相角等参数，实现对输出的调控，其延时大，不能实时响应输出的变化。副边控制响应速度快，动态IPT系统中常在副边侧加入DC-DC变换器直接针对输出进行调控。

现有的副边控制，多只针对后级稳压器进行设计，通过优化算法或使用非线性控制方法来提高特定工况下的系统输出特性。如：文献[14]通过多目标优化算法，改善了系统在耦合条件、负载和补偿网络参数变化时的恒压性能。文献[15]通过线性自抗扰恒压输出控制算法，优化了系统启停、跟随参考、变负载的调节时间与超调量。文献[16]通过设计后级Buck变换器的滑模控制器，解决了各负载之间互相扰动的问题。这些控制策略虽然提高了系统的动态性能，但在设计时仅考虑了后级DC-DC变换器，存在负载调节范围小、变负载工况输出扰动大的问题。而在实际中，整流桥电流会发生断续情况，谐振电路的寄生参数不可被忽略。在负载大范围变化时，DC-DC变换器输入电压会产生较大的波动，这使得系统输出动态性能进一步恶化。因此在设计控制策略时，需要考虑DC-DC变换器前级电路的影响。

为此，本文在考虑副边整流桥与谐振电路的影响的前提下，提出后级稳压器的小信号模型修正方法，分别对后级稳压小信号模型的低频段增益和中频段谐振峰频率进行修正，使其表达得更为准确。在此基础上，本文针对因负载变化导致的整流电压波动，提出加入整流电压前馈环节的改进控制策略。最后搭建了1 000 W单轨动态IPT系统实验平台，验证了理论分析的正确性和控制策略的有效性。

1 单轨动态IPT系统拓扑

单轨动态IPT系统的设计规格要求：输入电压为AC 380 V，输出电压恒定为48 V，单模块额定功率为500 W，最大功率为1 000 W，且稳压精度为±1%，负载调整率为±0.5%，要求较高。因此，本文采用了一种原边恒流、副边恒压的无线电能传输拓扑，并在后级增设一级DC-DC变换器进行稳压。图1为单轨动态IPT系统拓扑架构。图中：V_{in}、V_{rec}、V_O分别为输入电压、整流电压、输出电压；C_{in}、C_{rec}、C_O、L_1、L_2分别为输入电容、整流电容、输出滤波电容、输出滤波电感；L_{f1}、C_{f1}、C_P、C_S分别为谐振电感、谐振电容、轨道补偿电容、副边串联补偿电容；L_P、L_S、M分别为轨道自感、拾取器自感、轨道与拾取器互感；R_L为分拣小车的等效负载电阻；S_1—S_4为逆变金属-氧化物-半导体（metal-oxid-semiconductor，MOS）管；D_1—D_4为整流二极管；Q_1—Q_4为同步整流MOS管。

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ORIGINAL PAPER

A capacitive power and signal transfer system based on ring-coupler with mitigated inter-channel crosstalk

Yunliu Wang[1] · Shiyun Xie[2] · Long Chen[2]

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Abstract

Wireless power and signal transfer systems are becoming increasingly important in rotary applications due to their ability to charge and communicate rotating devices without physical contact. Capacitive coupler is one of the preferred solutions to achieve the above functions because of its advantages of size and weight. However, there are currently no suitable decoupled capacitive coupler design for CPT systems to mitigate the crosstalk between the power and signal transfer channels. This paper proposes a capacitive power and signal transfer (CPST) system based on ring-coupler with extremely weak cross-coupling. A comprehensive model for the dual-input and dual-output capacitive coupler is established, and the decoupling characteristics of the two channels of the proposed coupler are demonstrated based on this model. Then, analysis of both the power and signal channels was conducted, and design methodologies for both two channels were presented. Finally, the proposed decoupled coupler is experimentally verified and applied in the proposed CPST system. The results demonstrate that the proposed system can efficiently transmit 100W of power with an efficiency of 84.5%. Additionally, it is capable of transmitting signals using Amplitude Shift Keying (ASK) modulation at a rate of 4800 bit/s, with an error rate lower than 0.1%.

Keywords Capacitive power and signal transfer (CPST) · Ring coupler · Inter-channel crosstalk · Multiple channels

1 Introduction

Wireless power transfer (WPT) is a technology that enables the transmission of power from a power source to devices without the use of physical electrical conductors [1]. This technology offers several significant advantages over traditional wired power transmission methods, including greater flexibility in power delivery and strong environmental compatibility [2]. In particular, WPT technology is highly suitable for powering devices installed on rotating mechanisms, where laying power cables and ensuring continuous power supply can be challenging [3]. Examples of such scenarios include torque sensors, brushless motors, robotic arms, wind power generator, and other similar applications.

Capacitive power transfer (CPT) is a wireless power transfer technology that employs high-frequency electric fields for transmitting power between pairs of electrodes [4, 5]. Typically, the coupling electrodes of a CPT system are fabricated from metallic plates or foils, which endow the CPT coupler with several advantages such as light weight, small size, low cost, and reduced eddy-current effects in its surroundings [6]. Currently, researchers are actively investigating the potential applications of CPT technology in diverse fields, including biological implantation [7], unmanned aerial vehicles [8], electric vehicles [9], and rail transit [10].

However, in the case of current CPT systems, wireless signal transmission is also a crucial component. This is because wireless signal transfer serves two important purposes: (1) It enables the creation of control loops that span both primary and secondary sides of the system, leading to improved smoothness and efficiency of power transmission [11]. (2) Wireless signal transfer also facilitates the exchange of information between electrical devices and power sources. For instance, in the wireless charging of electric vehicle batteries, it is essential for the vehicle-side to provide feedback to the power transmitter regarding the charging status of the battery and the position of the electric vehicle [12]. In existing research, wireless signal transfer can be divided into three categories based on different signal loading methods and channel designs: power-modulated, shared channel, and separated channel-based wireless power and signal transfer (WPST) methods.

✉ Long Chen
chenlong118@cqut.edu.cn

Yunliu Wang
yunliu1206@163.com

Shiyun Xie
xieshiyun1987@cqut.edu.cn

1 Substation Electrical Group, Powerchina Sichuan Electric Power Engineering Co. Ltd., No. 299 Shuxiu West Road, High Tech Zone, Chengdu 610041, Sichuan, China

2 School of Electrical and Electronics Engineering, Chongqing University of Technology, 69 Hongguang Avenue, Banan District, Chongqing 400054, Chongqing, China

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Currently, most power-modulated methods change the main circuit structure or parameters to achieve signal modulation. In this case, the main circuit voltage and current of the system produce responsive changes, which are detected through voltage and current measurements to finish the demodulation. Existing modulation methods for signals include adjusting the operating frequency [13], input DC resistance [14], switching compensation capacitors [15], changing current phase [16], and adjusting the inverse PWM timing [17], with corresponding demodulation methods including voltage, current detection, and harmonic detection. However, because of the low carrier frequency of power transmission, the baud rate of signal transmission based on power modulation is also low.

The shared channel-based WPST technology refers to the use of the existing power channel to transmit signals by designing proper circuits to suppress the inter-channel crosstalk. Reference [18] uses a double-side LCCL and dual-notch filter to isolate the interference of the power transmission on the signal channel and achieve a full-duplex communication. Similar functions have also been studied in the CPT system [19–22]. Time-division multiplexing is also applied in the shared channel-based WPST system. Reference [23] utilizes the first half-cycle to transfer power and the remaining half-cycle for signal transmission. In addition, a signal channel with wide bandwidth is researched to improve the baud rate [24]. Nevertheless, due to the sharing of the same channel for power and signal transmission, the isolation and suppression of crosstalk is more difficult, and higher requirements are placed on the design of filtering circuits.

The separated channel-based WPST technology refers to the implementation of signal transmission by adding an independent signal channel while retaining the original power channel. To reduce the inter-channel crosstalk caused by power transmission, the current main methods include: (1) increasing the distance between the power and signal couplers; (2) using decoupled coupler. Larger distance between two couplers helps reduce the coupling strength between channels and mitigate the crosstalk, but this method increases the coupling area. In addition, decoupled design of the coupler can achieve the same goal with less impact on the coupling area. However, current research on decoupled couplers mainly focuses on the Inductive Power Transfer (IPT) system, including DDQ [25], bipolar [26], orthogonal [27] and tetra-polar coils [28]. However, there is currently no suitable decoupled capacitive coupler design for CPT systems.

To address the research gap, this paper proposes a capacitive power and signal transfer (CPST) system based on ring-coupler with mitigated inter-channel crosstalk. The focus of this system lies in the design of the coupler, which aims to mitigate the impact of cross-coupling between two channels on the crosstalk of the signal transmission. Section 2 establishes a comprehensive circuit model and mathematical model for the dual-input and dual-output capacitive coupler. The coupling strength between the power and signal channels in the model can be represented by mutual impedances, based on which a capacitive coupler with weak cross-coupling has been proposed to suppress crosstalk between the two channels. In Sect. 3, analysis of both the power and signal channels is conducted, and design methodologies for both two channels are presented. Finally, in Sect. 4, the proposed decoupled coupler is experimentally verified and applied in the proposed CPST system, and the paper concludes with a summary in the last section.

2 Analysis of circular DIDO coupler

2.1 Circular coupler structure and modelling

In Fig. 1, circuit of the proposed CPST system with a dual-input and dual-output (DIDO) coupler is illustrated. The DIDO coupler composed of eight metal plates $P_{a1} \sim P_{a4}$ and $P_{b1} \sim P_{b4}$ forms two channels. The plates $P_{a1} \sim P_{a4}$ form the power transfer channel, and the plates $P_{b1} \sim P_{b4}$ form the signal transfer channel. The power transfer circuit consists of an H-bridge inverter, a double-sided LC compensation network, and an H-bridge rectifier. The signal transfer circuit consists of a carrier generation circuit, a modulator, a band-pass filter, and a demodulation circuit. Power is trans-

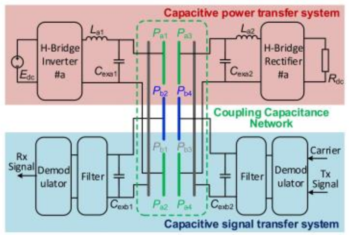

Fig. 1 Capacitive power and signal transfer system

附件 **3.20**

energies

Article

Model of an Air Transformer for Analyses of Wireless Power Transfer Systems

Kalina Detka, Krzysztof Górecki * and Przemysław Ptak

Department of Marine Electronics, Gdynia Maritime University, 81-225 Gdynia, Poland
* Correspondence: k.gorecki@we.umg.edu.pl

Abstract: This article presents a new model of a dedicated air transformer for computer analyses of wireless power transfer systems. This model includes a form of subcircuit for SPICE. It takes into account the electric, magnetic and thermal properties of the modeled device. The form of the elaborated model is presented and the results of its experimental verification are shown. Some results from measurements and computations of an air transformer and a wireless power transfer system containing this transformer are shown and discussed. The structure of the tested system and the measuring setup used are also described. The results of measurements and computations illustrating the influence of the distance between the windings of the air transformer and the displacement between its windings on the output voltage of the power transfer system are presented and discussed. The influence of load resistance on the properties of the considered system is analyzed.

Keywords: air transformer; inductive wireless power transfer; IPT; modeling; SPICE; wireless power transfer; WPT

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1. Introduction

Wireless power transfer (WPT) technology has been known for years; the pioneer in this field was Nicola Tesla, who in 1891 designed a coil that could transmit power wirelessly over a distance of 3 km [1,2]. However, wider interest in the transmission of power over a distance without the use of traditional cables appeared only in 2007, when a group of scientists from the Massachusetts Institute of Technology (MIT) designed a WPT system that allowed the power transfer to light a 60 W bulb at a 2 m distance [1,3].

Recently, there has been an increase in interest in new technologies, i.e., various types of portable devices used in various industries. There can be devices of general use (tablets, laptops, mobile phones) or devices used in medicine (implantology), mining (sensors, headlamps) or the automotive industry [4–8]. However, the problem of these devices is their power supply [8,9]. For example, mobile phones, tablets or laptops can typically operate for several dozen hours without recharging [4,8,10]. This usage time is a function of many factors, such as the capacity of the battery, how the device is equipped, the operating time of the device, etc. It is therefore important to ensure that devices can be charged without the need for a classic corded power supply, especially in mining or medical applications [5,8,11].

Wireless power transfer systems occupy more and more space in the literature [5,8,11–13]. These systems differ in terms of their manufacturing technology depending on the application and the distance over which the power is to be transferred [4,6,14,15]. However, from the point of view of consumer devices or devices used in medicine, mining or the automotive industry, IPT (induction power transfer) technology is typically used for wireless power transfer. The concept of this technology is based on the principle of an air transformer and is described in more detail in [8,16].

As shown in [8,17], IPT technology is characterized by the highest efficiency of power transfer compared with other technologies, reaching up to 90% [8,17]. Additionally, papers [18–20] demonstrate that the properties of an IPT system, including its efficiency of

are no transformer windings in the same axis and there is an evident current associated with the leakage flux.

On the other hand, in [23] a basic model of a system for wireless power transfer is presented. The simplified network representation of the model presented in this paper includes an inverter and a rectifier represented by voltage sources. Instead of an air transformer, a T-type transformer model known from the literature is used. In this model, its leakage inductance and magnetizing inductance are introduced. Resistors representing power losses in both the windings related to the resistance of the winding wire, increased due to skin and proximity effects, are also used. The authors performed calculations using the proposed model and compared them with the results of their measurements. From the presented results it can be seen that the use of the simplified model, which also assumes sinusoidal coil currents, enables the optimal selection of PTO system parameters in terms of energy efficiency. However, the distortion of the currents becomes more pronounced as the magnetic coupling coefficient increases.

The authors of [24] presented analytical considerations regarding the use of an air transformer with low power consumption used in high-voltage power transfer systems (HVDC). Relationships for calculating self-inductance and mutual inductance of an air transformer operating in the mentioned systems are proposed. In order to verify the proposed dependences, a prototype of such a transformer was built. Calculations made using this model proved that very good results are obtained as far as determining the air transformer parameters are concerned, including its self- and mutual inductances.

In [25], a system for wireless power transfer based on a model of an ideal transformer with magnetic coupling (IT MC-WPT) was considered. In the proposed system, simplifications were assumed consisting in the assumption that the amplitudes of the primary and secondary winding currents are constant and do not depend on mutual inductance. Thanks to this, the proposed system is suitable for both low voltage–high current and high voltage–low current operation, and the ratio of the amplitude of the secondary winding current to the primary winding current can be adjusted depending on the application. The proposed solution is characterized by high power transfer efficiency. This paper presents theoretical considerations, analytical dependences and principles of designing systems for wireless power transfer with air transformers. It demonstrates theoretically and experimentally that an IT MC-WPT system can achieve a high and constant value of transmitted energy and efficiency with changes in the coupling coefficient between the transformer coils.

In [26], an air transformer design procedure is discussed. This procedure boils down to a combination of analytical methods and finite element analysis to calculate the parameters of the transformer. It is pointed out that analytical methods are used to calculate parameters and to design the appropriate windings of various dimensions and number of turns. How to determine the coupling coefficient for each transformer using these methods is also demonstrated. In turn, after determining the abovementioned parameters using the appropriate programs for finite element analysis, the characteristics corresponding to the magnetic properties of the transformer are obtained, which can then be used in a commercial program for the analysis of electric circuits. Calculations were carried out in accordance with the procedure presented in the paper. Tests were carried out for air transformers containing oval coils with a different number of turns and different external and internal diameters. From the results presented, it can be observed that up to a frequency of 1 MHz the resistance of the coil windings and their inductance do not depend on frequency but only on the number of turns. Above this frequency, resistance significantly increases and inductance decreases.

Paper [27] presents a heuristic approach to the design of WPT systems. Tests were carried out for rectangular transmitting and receiving coils. The focus was on an analysis of the efficiency of power transfer as a function of the coupling coefficient between the coils. Analysis was carried out using Maxwell software, which allows the simulation to be performed using the finite element method (FEM). Using this method, the influence of the thickness and size of the air transformer coils and the displacement between the coils on

附件 3.21

Compact and Efficient WPT System to Embedded Receiver in Biological Tissues Using Cooperative DGS Resonators

Shimaa Alshhawy, *Student Member, IEEE*, Adel Barakat, *Member, IEEE*, Kuniaki Yoshitomi, *Member, IEEE*, and Ramesh K. Pokharel, *Member, IEEE*

***Abstract*—This brief presents a compact and efficient resonance-shift insensitive wireless power transfer (WPT) system. This is possible by using a small electrical length defected ground structure (DGS) resonator, which is found effective against the resonance-shift phenomenon resulted from the higher permittivity of the tissue. Tissue has two undesired effects on a WPT system: (i) reduced coupled quality factor, and (ii) self-resonance shifting that leads to mismatch loss. So, the efficiency of a WPT system degrades in a tissue environment. Then, using the small electrical length DGS, we build a WPT transmitter (TX) using three cooperative DGS resonators to mitigate both issues. The fabricated prototype operates at 49 MHz in the air and tissue. This shows no change in operating frequency when the same receiver (Rx) is kept in the air or embedded inside tissues, which proves the effectiveness of the proposed cooperative DGS-WPT system against the resonance shift. The measured efficiency is 62% when the RX is embedded inside the tissue and is 68% in the air.**

***Index Terms*—Medical implant, resonance-shift, small electrical length DGS, wireless power transfer.**

I. Introduction

WIRELESS power transfer (WPT) technology [1] is an emerging candidate for charging embedded sensors and implantable medical devices (IMDs) [2]–[7]. A WPT system which is more effective against misalignment effects is necessary to guarantee stable efficiency. Misalignment is a major challenge in an inductively coupled WPT system as it causes mismatch loss due to coupling and coupled quality factor (kQ-product) [8] changes leading to low efficiency.

Recently, circuit-based [9] and structure-based solutions [10] have been presented to improve efficiency during lateral misalignment using coupled defected ground structure (DGS) resonators [9] and separation misalignment

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The authors are with the Graduate School of Information Science and Electrical Engineering, Kyushu University, Fukuoka 819-0385, Japan (e-mail: shimaa8512@gmail.com; barakat@ed.kyushu-u.ac.jp; yoshitomi@ed.kyushu-u.ac.jp; pokharel@ed.kyushu-u.ac.jp).

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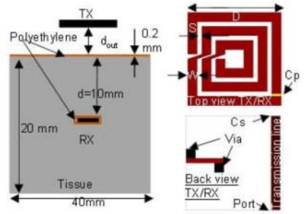

Fig. 1. Conventional DGS-WPT System with embedded RX in tissue.

using a two-plane printed inductor transmitter (TX) [10]. However, the receiver (RX) size is quite large for an IMD and no in-tissue experimental verification was provided. Wang *et al.* [3] realized a hybrid array resonator structure to reduce lateral misalignment effect in tissue measurement and a peak efficiency of only 53%.

When an RX of a WPT system is embedded in tissue, two undesired effects will occur. The first is the reduction of the kQ-product because of the dielectric and conduction losses of tissue. The second one is the shift in self-resonance frequency of TX that leads to mismatch loss. Consequently, efficiency is degraded and becomes position-dependent [4]. To address the former one, many approaches were proposed to improve the coupled quality factor when RX is embedded in tissue [2], [3], [5], [11]. We are the first ones who investigated the problem addressed the second issue. In [4], our team has overcome the resonance-shift problem by realizing a metamaterial-inspired geometry in a stacked configuration that has a self-shielded configuration from the tissue. In this brief, we provide detailed explanations about the resonance-shift phenomenon when an RX is embedded in tissue and solutions employing a small electrical-length DGS resonator to overcome this phenomenon. Then, we propose cooperative DGS resonators based on the small electrical length DGS to achieve a high efficiency. Electromagnetic (EM) simulations were performed using ANSYS High-Frequency Structure Simulator (HFSS).

II. Medium Independent SISO WPT System

A. Resonance Shift Phenomenon

A typical single-input-single-output (SISO) DGS-WPT system is shown in Fig. 1 [9]. A very thin polyethylene layer

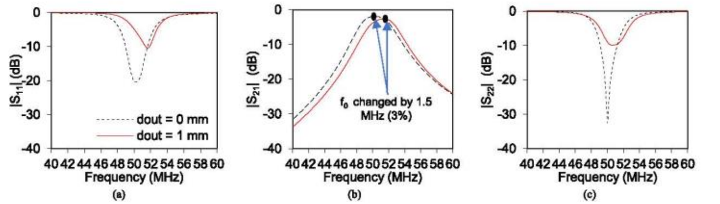

Fig. 2. Simulated S-parameters of the WPT system designed with maximum efficiency method when d_{out} changes from 0 to 1 mm. (a) TX reflection coefficient ($|S_{11}|$) (b) Transmission coefficient ($|S_{21}|$) (c) RX reflection coefficient ($|S_{22}|$).

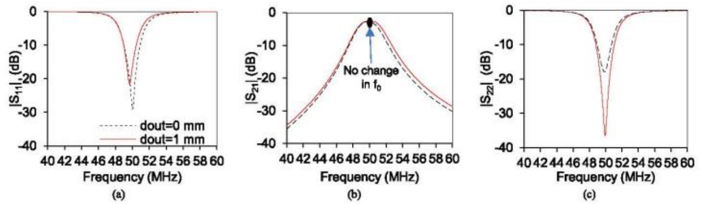

Fig. 3. Simulated S-parameters of the WPT system designed with medium independent method when d_{out} changes from 0 to 1 mm. (a) TX reflection coefficient ($|S_{11}|$) (b) Transmission coefficient ($|S_{21}|$) (c) RX reflection coefficient ($|S_{22}|$).

around the RX and between tissue and TX was placed for isolation [3], [11]. The separation, d_{out}, represents an undesired spacing between the TX and the surface of tissue that may occur during system operation. We considered human muscle (relative permittivity = 77, Loss tangent = 3.16, and conductivity = 0.68 S/m) [12] during the simulations.

We have designed two SISO DGS-WPT systems having the same RX and different TXs to illustrate the resonance shift phenomenon. This phenomenon results from medium dependence and has no relation to the frequency splitting phenomenon [13] that occurs when the system enters the over-coupling regime. Both TXs have an area of 20 mm × 20 mm. The first WPT system's TX has been designed to maximize the obtainable efficiency at 50 MHz, which is obtained with three turns. Instead, the second WPT system's TX has been designed to achieve independence from the medium that is explained in detail in the following section. The dimensions of both WPT systems are summarized in Table I. Values of the capacitors are calculated following the method in [14]. The TX and RX are printed on RO3003 Substrate (dielectric constant = 3, height = 0.762 mm, and copper thickness = 17 μm).

In Fig. 2, the simulated Scattering (S) parameters of the first WPT system when d_{out} is changed from 0 to 1 mm. The TX suffers from a change in its resonance frequency as shown in Fig. 2 (a). Fig. 2(b) shows the effect on the corresponding transmission coefficient as it decreases from −1.9 dB to −3.3 dB at 50 MHz when d_{out} changes. The corresponding efficiency is listed in table I, which shows more than 17% degradation. Finally, the resonance frequency of the RX is not affected when this change occurs as shown in Fig. 2(c). Alternatively, Fig. 3 shows the simulated S-parameters of the second WPT system when d_{out} is changed from 0 to

TABLE I
Dimensions and Capacitors of SISO DGS-WPT Systems in Fig. 1 and Corresponding Efficiency

Method	Maximize efficiency		Medium independent	
Parameter	TX	RX	TX	RX
D (mm)	20	10	20	10
N "turns"	3	3	1	3
w (mm)	0.75	1	0.75	1
s (mm)	0.5	0.5	-	0.5
Cp, Cs (pF)	23, 10	175, 35	158, 23	180, 30
Efficiency @ 50 MHz	64.5% (dout = 0 mm) 47% (dout = 1 mm)		56% (dout = 0 mm) 52.5% (dout = 1 mm)	

1 mm. Neither TX reflection coefficient nor the transmission coefficient has any resonance shift when d_{out} changes as shown in Fig. 3(a) and Fig. 3(b), respectively. A reduction from −2.5 dB to −2.8 dB in the transmission coefficient is attained at 50 MHz when d_{out} changes, which is mainly due to the reduction of the coupling coefficient between the TX and the RX. The corresponding efficiency is listed in table I, which shows only about a 3% drop. Also, as shown in Fig. 3(c), the RX reflection coefficient has a similar performance to the RX of the first WPT system. In summary, the second WPT system does not suffer from the resonance shift because it utilizes a small electrical length DGS as described in the following section.

B. Electrical-Length of a DGS Resonator

In tissue, resonance-shift of the TX results in severe degradation in the WPT system's performance as detailed in the previous section. The reason is that a realized DGS, using the maximum efficiency method, becomes dependent on the medium's dielectric properties because the electrical length

（4）完成人合作关系说明及情况汇总表

完成人合作关系说明

一、项目第一完成人夏晨阳教授与第二完成人廖志娟副教授属同课题组教师关系，共同发表"一种 PT 对称 SS 拓扑 MC-WPT 系统及其实现方法（ZL202110251436.8）"发明专利（附件 **1.2**）、撰写"多旋翼无人机磁耦合静态无线充电系统通用技术要求（T/CPSS 1005—2023）"团体标准（附件 **3.11**）、于"IEEE TRANSACTIONS ON POWER ELECTRONICS"期刊共同发表"Analysis and Design of Ideal Transformer-Like Magnetic Coupling Wireless Power Transfer Systems"论文（附件 **4.1**）、其他共同发表的发明专利：ZL202010342975.8、ZL202011151785.4、ZL202010848401.8 、 ZL202011159389.6 、 ZL202010226545.X 、 ZL202010740959.4 、ZL202110473412.7、ZL202210053972.1（附件 **1.6**）。

二、项目第一完成人夏晨阳教授与第三完成人刘旭副教授属同课题组教师关系，共同发表"多调制波复合 SPWM 控制的电能与信号并行无线传输系统（ZL202010740959.4）"发明专利（附件 **1.6**）、于"IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS"期刊发表"Simultaneous Wireless Power and Information Transmission Based on Harmonic Characteristic of Soft-Switching Inverter"论文（附件 **4.2**）。

四、项目第一完成人夏晨阳教授与第四完成人宋磊总经理属校企合作关系，共同签署"无线充电系统功率传能控制与辅助功能开发"合同（附件 **4.3**）。

三、项目第一完成人夏晨阳教授与第五完成人赵书泽博士属导师与博士生关系，于"IEEE TRANSACTIONS ON POWER ELECTRONICS"期刊共同发表"Bipolar Checkerboard Metal Object Detection Without Blind Zone Caused by Excitation Magnetic Field for Stationary EV Wireless Charging System"论文（附件 **4.4**）。

承诺：本人作为项目第一完成人，对本项目完成人合作关系及上述内容的真实性负责，特此声明。

第一完成人签名：

完成人合作关系情况汇总表

序号	合作方式	合作者（本项目排名）	合作时间	合作成果	证明材料	备注
1	专利	夏晨阳 1，廖志娟 2	2021.3.8-2022.12.27	一种 PT 对称 SS 拓扑 MC-WPT 系统及其实现方法	附件 1.2	属同课题组教师关系
2	团体标准	夏晨阳 1，廖志娟 2	2022.8.1-2023.8.31	多旋翼无人机磁耦合静态无线充电系统通用技术要求	附件 3.11	属同课题组教师关系
3	论文合著	夏晨阳 1，廖志娟 2	2022.4.19-2022.7.18	Analysis and Design of Ideal Transformer-Like Magnetic Coupling Wireless Power Transfer Systems	附件 4.1	属同课题组教师关系
4	专利	夏晨阳 1，刘旭 3	2020.7.28-2021.11.19	多调制波复合 SPWM 控制的电能与信号并行无线传输系统	附件 1.6	属同课题组教师关系
5	论文合著	夏晨阳 1，刘旭 3	2021.1.7-2021.6.10	Simultaneous Wireless Power and Information Transmission Based on Harmonic Characteristic of Soft-Switching Inverter	附件 4.2	属同课题组教师关系
6	技术服务合同	夏晨阳 1，宋磊 4	2022.7.1-2023.6.30	无线充电系统功率传能控制与辅助功能开发	附件 4.3	属校企合作关系
7	论文合著	夏晨阳 1，赵书泽 5	2022.9.19-2023.1.23	Bipolar Checkerboard Metal Object Detection Without Blind Zone Caused by Excitation Magnetic Field for Stationary EV Wireless Charging System	附件 4.4	属导师与博士生关系

附件 4.1

Analysis and Design of Ideal Transformer-Like Magnetic Coupling Wireless Power Transfer Systems

Zhi-Juan Liao, Fan Wu, Chen-Hui Jiang, Zhang-Ruiwei Chen, and Chen-Yang Xia

***Abstract*—An ideal transformer-like (IT-like) magnetic coupling wireless power transfer system is proposed in this article, which can achieve a large constant power and efficiency output over a wide transfer range. First, the general circuit model is presented along with the analysis of fundamental and harmonic current characteristics. Then, the IT-like operation mechanism with a fixed desired secondary-primary current amplitude ratio independent of mutual inductance is proposed, based on which the transfer range capable of both power and efficiency is greatly improved. The corresponding parameter criteria and implementation methods, including the zero-phase-angle mode and the zero-voltage-switching mode are derived and verified in a practical prototype. The experimental results show that the proposed system can take the output power, transfer efficiency, transfer range, and current characteristic into account at the same time, with strong position robustness and high tolerance to variable couplings.**

***Index Terms*—Ideal transformer, magnetic coupling, position robustness, tolerance to variable couplings, wireless power transfer.**

I. Introduction

Intelligent unmanned equipment such as the unmanned aerial vehicle (UAV) has broad application prospects in the military and civilian fields. Wireless power transfer (WPT) is an indispensable supporting technology to realize unmanned operation and improve the endurance of the equipment [1]–[7]. Magnetic coupling WPT (MC-WPT), as the most mature and the most widely used wireless charging technology, has been widely researched in recent years [8]–[10].

The transfer efficiency, transfer power, transfer range, and the tolerance to variable couplings are key metrics for such dynamic wireless charging systems. Due to the volume and weight requirements of UAVs, the wireless charging system structure is usually asymmetric in practice [1]–[4], [7], [11]–[13]. Meanwhile, using asymmetric coils is also an effective way to improve the tolerance to variable couplings [14]–[16]. A large primary coil can effectively increase the coupling area and then improve the misalignment tolerance. The secondary coil with small size and/or few turns can not only meet the volume and weight requirement of the equipment, but also reduce the losses of the secondary side.

However, the application of asymmetric MC-WPT systems brings some challenges as follows.

1) High coupling strength in the central area causes frequency splitting and then reduced power [17]–[20].
2) High harmonic influence in the strong coupling region leads to current waveform distortion that increases switching loss and reduces transfer efficiency [21], [22].
3) The misalignment results in small reflection impedance that may cause overcurrent in the primary side.

The asymmetric MC-WPT system has received great attention in recent years. At present, most researches on asymmetric systems focus on the design of magnetic coupling structure [1]–[5], [7], [11]–[13], which is an important aspect to improve the misalignment tolerance. However, the system performance depends jointly upon the coupling structure and circuit characteristics that such researches merely on magnetic aspects are not sufficient. To be specific, even if the magnetic coupling structure is well designed, it is difficult to ensure the energy efficiency if the operation mechanism is not suitable. Meanwhile, magnetic coupling structure design cannot improve the current characteristics. Therefore, it is very necessary to optimize the operation mechanism and improve the overall performance of the system, including the power, efficiency, transfer range, current characteristics, and tolerance variable couplings.

In terms of frequency splitting reduction in asymmetric systems, the commonly used methods include adding impedance matching networks, adjusting coupling strength, and frequency tracking control [17]–[20], [23]. Impedance matching and adjusting coupling strength is to keep the system out of the splitting region, which easily reduces the maximum power and efficiency. Traditional frequency tracking is to track the maximum power or the maximum efficiency, hence, it is difficult to take into account both the power and efficiency. Moreover, taking efficiency or power as the tracking goal usually requires secondary side information, making the control very complex.

In terms of overcurrent and current distortion suppression, few progresses were reported. It is revealed in [21] and [22] that the strong coupled MC-WPT system with the traditional operation mechanism has high harmonic currents, and that the transfer efficiency is reduced by harmonic current. Accordingly, a

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The authors are with the Jiangsu Province Laboratory of Ming Electric and Automation, China University of Ming and Technology, Xuzhou 221116, China (e-mail: zjliao@cumt.edu.cn; wufan200204@163.com; 1439642552@qq.com; 1596549485@qq.com; bluesky198210@163.com).

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附件 **4.2**

Simultaneous Wireless Power and Information Transmission Based on Harmonic Characteristic of Soft-Switching Inverter

Xu Liu, Chenyang Xia, Xiaozuo Han, Zhen Wu, and Zhijuan Liao

***Abstract*—The existing simultaneous wireless power and information transmission (SWPIT) technology used for wireless power transfer (WPT) systems is seriously plagued by the interference between the power and information transmission and the complex design of the information transmission and receiving circuits. To combat these problems, this article proposes a novel SWPIT method, which does not need additional information transmitting or receiving coils. The stroboscopic mapping model of the WPT system is established first, and the soft-switching points of the dc–ac inverter are derived and compared for better utilizing deviation frequency enlargement effect (DFEE) to transfer power and information simultaneously. Subsequently, the information detection circuit is designed based on DFEE. The impacts caused by the detection circuit on the power and information transmission are analyzed in detail. Then, the parameters of the detection circuit are optimized for minimizing the mutual interference between the power and information transmission. Finally, a 50 W experimental platform is established to verify the correctness and effectiveness of the proposed SWPIT strategy. The experimental results show that the information transmission rate can reach up to 16 kbps, the load voltage fluctuation can be controlled below 3%, and the efficiency of the whole system can be maintained at 90%.**

***Index Terms*—Constant output voltage, information transfer, power transfer, soft-switching, wireless power transfer (WPT).**

I. Introduction

WITH the rapid development and wide applications of the wireless power transfer (WPT) technology, higher speed, and more stable wireless communication in the WPT system has become an urgent requirement for achieving output voltage feedback, load identification, foreign object detection, etc., as the transmitting and receiving sides of the WPT system are totally separated [1]–[4]. Recently, a new wireless communication method named simultaneous wireless power and information transmission (SWPIT) technology is proposed and has attracted a lot of attention. SWPIT can achieve the information transmission from the transmitting side to the receiving side [5], from the receiving side to the transmitting side [6], or bidirectional transmission between the transmitting side and the receiving side [7] for various equipment. Compared with the traditional means of communication, such as Bluetooth, Zigbee, and radio frequency (RF) [8]–[11], the SWPIT technology does not need to additionally equip communications devices in the WPT systems, therefore, the volume and cost of the whole system can be greatly reduced.

The SWPIT technology can be generally divided into two modes: dual-channel mode and single-channel mode [12]–[14]. The dual-channel mode utilizes two sets of coils to transfer the power and the information, respectively. However, the electromagnetic interference between the power transmission channel and the information channel seriously affects the quality of the power and information transmission [14]. Compared with dual-channel mode, the single-channel mode can utilize the original power transfer coils to transfer the information with the power simultaneously. Therefore, the mutual interference between the power and information transmission coils in the dual-channel mode does not exist in the single-channel mode. Meanwhile, the cost and volume of the system can thereby be reduced. Besides, for a single-channel SWPIT system, frequency-shift keying (FSK) modulation is widely adopted in it benefiting by lower errors and simpler detection/recovery process compared with amplitude-shift keying modulation or phase-shift keying (PSK) modulation [15]–[17]. Therefore, single-channel SWPIT mode and FSK modulation are adopted in this study, and the information transmitting direction is set to be from the transmitting side to the receiving side. However, the SWPIT technology proposed and studied in this article can also be used for transmitting the information from the transmitting side to the receiving side when the positions of the modulation and demodulation circuits are exchanged, or bidirectional transmitting when the WPT system is symmetrically designed.

For the WPT system with the SWPIT module, information transmission rate and power transfer quality are the critical

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The authors are with the Jiangsu Province Laboratory of Mining Electric and Automation, China University of Mining and Technology, Xuzhou 221116, China (e-mail: xu.liu@cumt.edu.cn; 5115@cumt.edu.cn; h_xzuo@cumt.edu.cn; wuzhen@cumt.edu.cn; zjliao@cumt.edu.cn).

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附件 **4.3**

合同登记编号：

技术服务合同

项目名称： 无线充电系统功率传能控制与辅助功能开发

委托方（甲方）： 安洁无线科技(苏州)有限公司

受托方（乙方）： 中国矿业大学

签订时间： 2022.6.22

签订地点： 江苏苏州

有效期限： 2022 年 7 月 1 日至 2023 年 6 月 30 日

中华人民共和国科学技术部印制

4．技术标准和规范：无；

5．原始设计和工艺文件：无；

6．其他：无。

第十五条 双方约定本合同其他相关事项为：无。

第十六条 本合同一式 肆 份，具有同等法律效力。

第十七条 本合同经双方签字盖章后生效。

甲方：安洁无线科技（苏州）有限公司 合同专用章（盖章）

法定代表人／委托代理人：（签名）

2022 年 7 月 4 日

乙方：中国矿业大学 技术合同专用章（盖章）

法定代表人／委托代理人：（签名）

2022 年 7 月 4 日

6

附件 **4.4**

Bipolar Checkerboard Metal Object Detection Without Blind Zone Caused by Excitation Magnetic Field for Stationary EV Wireless Charging System

Shuze Zhao, Chenyang Xia, *Member, IEEE*, Ziyue Yang, Hao Lu, Hongtai Zhang, and Chenhao Lu

***Abstract*—Metal object detection (MOD) technology provides a guarantee for the safe operation of electric vehicle (EV) wireless charging system. To solve the problem of detection blind zone caused by excitation magnetic field in the existing MOD technology, a bipolar checkerboard MOD technology is proposed. By adding an excitation source, not only the blind zone is eliminated but also it makes the EV wireless charging system and the MOD system work independently. First, the positions and causes of the blind spot caused by the excitation magnetic field of the Tx coil in the EV wireless charging system are analyzed. Second, the structure and principle of the bipolar checkerboard MOD system are analyzed. Third, a definition of the detection sensitivity of MOD is given, and the relationship between sensitivity and the size parameters of bipolar checkerboard sensing coil sets is analyzed. Moreover, the parameter optimization method of the sensing coil sets and detection circuit is analyzed. Finally, a MOD system experimental setup is built to verify its feasibility. The results show that the highest sensitivity can reach 20% for a square aluminum plate of 80 × 80 × 1 mm^3 without a blind zone and the two systems can work independently with each other.**

***Index Terms*—Bipolar checkerboard, blind zone, electric vehicle (EV) wireless charging, independent work, metal object detection (MOD).**

I. Introduction

DUE to the advantages of zero emission and zero pollution, electric vehicle (EV) is gaining widespread attention and its global market share is increasing rapidly. The magnetic field coupled wireless charging technology provides a more safe and convenient way to replenish energy for EVs [1], [2], [3], [4], [5]. To promote the industrialization of EVs wireless charging technology, four wireless charging standards for EVs: IEC 61980, SAE J2954, ISO 19363, and GB/T 38775 have been developed in many countries around the world [6], [7], [8], [9]. Furthermore, they have been continuously updated and improved.

With the continuous development and progress of EVs wireless charging technology, the requirements for safety performance during its charging process are becoming higher and higher. Therefore, foreign object detection technology is specified in detail in the EV wireless charging standard, which includes metal object detection (MOD) and living object detection [10], [11]. Since there is a high-frequency electromagnetic field between the transmitting (Tx) coil and receiver (Rx) coil of the EV wireless charging system, eddy currents will be generated inside the metal objects (MOs) that appear in the high-frequency electromagnetic field. Thus, it can affect the transmission power and efficiency, whereas there is also a fire risk due to the heat generation problem caused by MOs' eddy currents [12], [13], [14], [15], [16]. Therefore, MOD technology has received extensive research and attention.

Existing MOD methods include detection techniques based on magnetoresistive sensors [17], ultrasonic radar [11], wireless charging system parameters [18], [19], sensing coils [20], [21], [22], [23], [24], [25], [26], [27], etc. Among them, the MOD method based on wireless charging system parameters and sensing coils has the advantages of simple principle, low cost, and high reliability.

For the MOD method based on the parameters of the wireless charging system, the literature [18] proposes a method for MOD by detecting the fifth harmonic current amplitude of the Tx coil. A method for MOD by detecting the deviation of the Tx coil current amplitude and the resonant frequency is proposed in the literature [19]. Compare with the MOD method based on sensing coils, the method based on wireless charging system parameters does not require additional coil sets structure. However, due to the advantages of high detection sensitivity and scalability of auxiliary functions, the detection method based on sensing coils has become the mainstream technology of current research.

For the MOD method based on sensing coils, a dual-purpose nonoverlapping coil sets structure is proposed in the literature [20], which enables MOD and detection of position (DoP) by detecting the amplitude of the induced voltage in the coil sets. In the literature [21], a double-layer symmetrical coil sets structure is proposed that can realize the MOD position determination function. This type of MOD method is based on passive sensing coils, using Tx coil to generate MOD excitation magnetic field,

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The authors are with the School of Electrical Engineering, China University of Mining and Technology, Xuzhou 221116, China (e-mail: timelyrainy@163.com; 18260722082@163.com; cumt_yzy1997@163.com; ts21130168p31@cumt.edu.cn; 3465281940@qq.com; 1036759138@qq.com).

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（5）学校内网公示证明

2. 其他附件

（1）应用情况和效果佐证材料

（2）其他