

Inductive Wireless Power & Data Transfer for Electric Vehicles (EV)

Bezavada Suresh Babu¹, T. R. Jyothsna²

^{1,2} AU College of Engineering

Abstract—This paper presents the design and implementation of a wireless power transfer (WPT) and data transfer communication schemes for Electric Vehicles (EV) and can operate for harsh environments too. The system employs magnetic resonance for efficient power transfer and free-space optical communication using a 520nm laser for reliable data transmission. The design includes Class-E resonant amplifiers, zero-voltage switching (ZVS) techniques, and planar coil sets optimized for wireless power transfer. Simulations in MATLAB/Simscape, Maxwell3D, and LTSpice validate the system's performance, while conformance with ATEX/IEC 60079 and MIL standards ensures reliability and safety. The proposed solution addresses limitations in traditional wired connectors, offering a robust, flexible, and efficient alternative for wireless power transfer of EVs.

Index Terms—Class E rectifier, Free space optical communication (FSOC), Litz pattern winding, Magnetic Resonant Power Transfer (MRPT), Wireless power transfer (WPT), Zero Voltage switching (ZVS).

I. INTRODUCTION

Wired systems for EVs power transfer face challenges such as limited mobility, high maintenance, and susceptibility to mechanical failure in harsh environments. This paper proposes a wireless system to address these issues, enabling efficient power and data transfer without physical tethers. The system will operate reliably under high pressure, corrosive conditions, and variable distances. Current systems rely on wired connectors for power and communication, using copper cables or fiber optics. These systems, while reliable in controlled settings, suffer from drag, wear, and deployment complexity. Recent advancements include inductive power transfer and acoustic communication, but these are limited by efficiency and bandwidth, respectively. Emerging solutions include magnetic resonance power transfer

and optical communication. Magnetic resonance offers higher efficiency over longer distances compared to inductive methods, while optical systems using lasers provide high-bandwidth, low-latency communication.

II. SOLUTION CONCEPT AND ITS EVOLUTION

a. Wireless Power coil set:

The application considered a power transfer of 300W wirelessly as efficiently as possible. Wireless power transfer can be achieved in two ways (i) Inductively coupled coils (ii) Magnetic resonant coupled coils.

- (i) Inductively coupled coils can be operated at any frequency. However, the effective load impedance presented at amplifier circuit is complex (real + imaginary parts) which makes the circuit highly sensitive to frequency and load variations. A highly dynamic impedance matching network would be required to maintain resonance and ZVS across the switch. This also mandates closed loop control system to ensure stability, maintain ZVS/ZVDS for switch and serve the load simultaneously.
- (ii) Magnetic resonant system on other hand requires careful design of resonant tank, coils and other external components to ensure that natural frequency of the entire circuit is perfectly matched with switching frequency thereby reducing the effective impedance presented to source to purely resistive. Such a circuit can be rapidly synthesized for operating in MHz range, ensuring ZVS across switch at all times and maximizing efficiency of wireless transfer.

To ensure compatibility of the design with MIL810H vibration and shocks, litz wires are not the ideal choice for implementation of wireless coils. The windings maybe loosened and shaken out of alignment/pattern

when subjected to repeated vibrations. Hence planar PCB coils with 70um Copper deposition are ideal as they have good electrical performance while offering robustness in a harsh environment. Design of such coils and patterns of design and evolution of a composite coil are evaluated.

b. Wireless Communication system:

The wireless coils are operating @6.78 Mhz for 300W of power. Conventional wireless systems with -3db frequencies of tuned resonant coils to transfer data is susceptible to high error rates and distortion of data. Further, this method requires complex filters, isolation networks and shielding systems to ensure data accuracy. Implementation of complex protocols such as MIL1553 further complicates the problem as leads within the PCB are also susceptible to powerful 6.78 Mhz ringing from the resonant coils in near vicinity. These teething constraints can be circumvented by using free space optical communication for secure data link using conventional data rates and simple UART protocols with OOK modulation. The link is totally immune to EMI/EMC, consumes little power, is quite compact, secure, can be implemented used simple COTS hardware and is largely error free. Implementation of such an optical data link with 1Mbps speed is evaluated.

III. DESIGN OF THE POWER CIRCUIT AND RESONANT TANK

The choice of power circuit for this application is guided by operating conditions, desired efficiency, physical dimensions, heat dissipation and mode of power transfer. As indicated previously, there are several ways to achieve power transfer wirelessly. The primary factor for determining the mode of transfer in development of Wireless power is compactness and limitations in dissipating heat from the system affecting other temperature sensitive components. Magnetic Resonant Power Transfer (MRPT) has been chosen for effecting wireless power transfer as it offers significant advantages in terms of higher efficiency, lower number of control variables, stability over wider loads, higher immunity to noise/harmonics, cleaner current and voltage waveforms and lower number of required switching components in comparison to conventional inductive coupling.

a. Design of Power Stage Choices:

The proposed topology used a single switching device operated in ZVS and ZVDS mode for zero switching losses coupled with a high Q filter tuned to operate at switching frequency (fsw). E2 DC-DC convertor with switching filter whose resonant frequency is equal to that of fsw at 6.78MHz followed by a fixed Impedance Matching Network (IMN) and loosely coupled pair of tuned coils followed by a class E rectifier

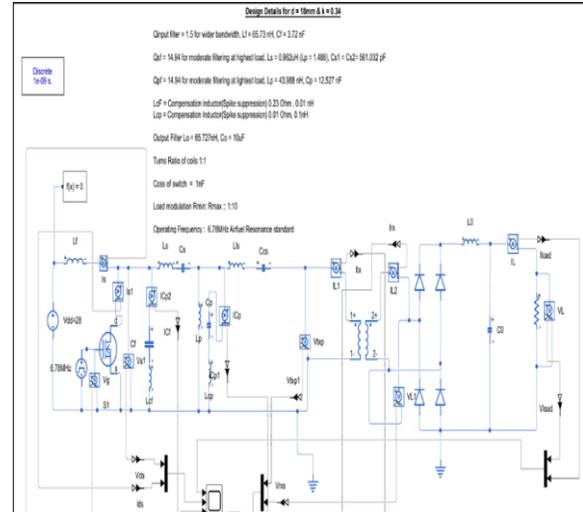


Fig.1 Circuit Diagram for power transfer

b. Modelling of Resonant Coils and tank

The resonant pair of coils designed in this can be effectively modelled as a loosely coupled transformer with 1:1 turns ratio. In this design, Series-Series compensation has been chosen for ease of design and simplicity of the circuit. Equivalent model of the power circuit along with designed coils is as shown below

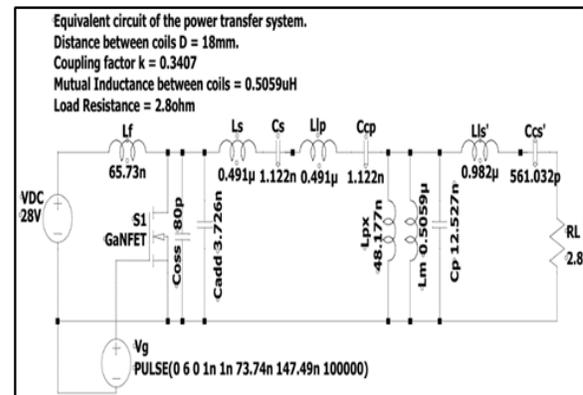


Fig.2 Equivalent power circuit with coils modelled and secondary referred to primary

c. Calculation of Resonant tank values:

Values of self and mutual inductances of coils at

various distances ranging from 14mm to 25mm have been estimated from ANSYS Maxwell 3D simulations. Coefficient of coupling values at various distances have been obtained from these simulations

Sno	Distance (mm)	$L_{coil}(\mu H)$	$L_m(\mu H)$	k(coupling)
1	14	1.5091	0.6147	0.4252
2	16	1.5015	0.5755	0.3833
3	18	1.4940	0.5091	0.3407
4	20	1.4865	0.4930	0.2980
5	22	1.4789	0.3764	0.2484
6	24	1.4763	0.3317	0.2247
7	25	1.4753	0.3116	0.2112

as well. Summary of the values obtained for designed coil sets from ANSYS is tabulated.

Table1. Lcoil calculated from ANSYS maxwell at various values of D(mm)

d. Simulation results and graphs

The designed power circuit has been simulated using Simscape toolbox of Simulink in MATLAB. The circuit has been tested with various values of resonant tank to verify the theoretical design values. Additionally, for distance of 18mm the load has been varied from 1A to 20A to see if ZVS/ZVDS across the switch is holding and magnetic resonance is not lost. The circuit successfully was able to transmit demanded power to various loads without losing resonance or ZVS across the switch. However, no significant reduction in input peak current has been seen at light loads thereby contributing to drastic reduction in efficiency at light loads. This is typical of a Class E resonant amplifier. Relevant waveforms and graphs are as presented below

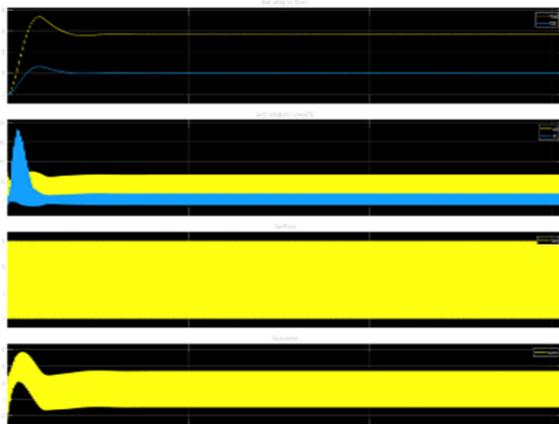


Fig 3. Waveforms of VL = 28Vdc, IL = 10A, Vds, Ids, Vgate, Isource showing initial transient.

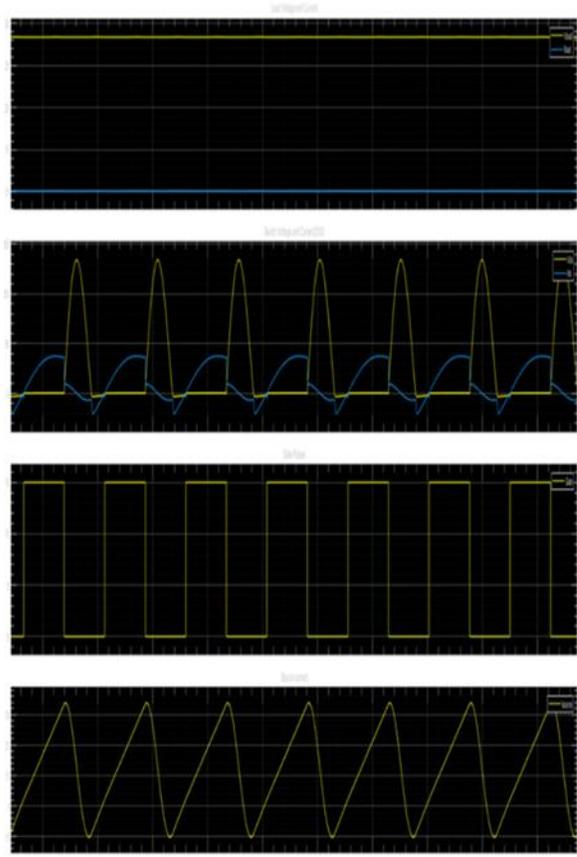


Fig 4. Waveforms of VL = 28Vdc, IL = 10A, Vds= 140V pk Ids = 33A pk, Vgate = 10V, Isource = 34A pk at steady state.

IV. DESIGN OF COMPOSITE RESONANT COILS FOR WIRELESS POWER TRANSFER

An essential part of a wireless power transfer system is a set of power Transmission and Receiving coils. As discussed previously there are multiple ways in which wireless power transfer can be achieved. The objective of this paper demands a need for transfer of 280-300W watts of power from the source. The spacing between the coils is in order of 12-25mm and since the whole system is required to be quite compact, overall efficiency of the system is required to be very high for a wireless system. Further, EMI/EMC MIL-461F, ATEX/IEC60079 and Environmental MIL-810H compliance of the designed system is mandatory for deployment in the system. These testing and deployment requirements have served as guidelines for system design. Further the system is designed to operate at 6.78MHz which

brings in additional design complications, skin effect and proximity effects being the most prominent.

a. Interleaved windings:

One way in which these effects are minimized in planar transformers is by interleaving the winding foils so that the leakage flux lines cancel out each other and flux lines in same direction are reinforced. This method does counter the proximity effect but skin effect remains largely unchanged. Although interleaving methods are well-known for reducing leakage inductance, however, increasing contact area between the primary and secondary windings has increased parasitic capacitance between windings. To be specific, fully interleaving planar transformer with four primary and four secondary layers has equivalent primary capacitance 8.1 times higher than non-interleaving transformer. Besides, interleaving structures also made transformers more complicated to manufacture and impossible to design when windings have few turns.

b. Using multi-strands and Litz style PCB windings to reduce Skin and Proximity effect:

Further attempts at reducing the skin and proximity effects include splitting a solid track into many parallel strands to reduce the skin effect, thus, reducing the AC to DC ratio of the winding. However, because of the internal proximity effect among strands, the results did not have a significant improvement. A Litz style PCB winding with interleaving strands was proposed. Because all strands were subjected to the same magnetic field strength, they were expected to carry equal currents and help to reduce AC to DC ratio better than parallel strands winding.

However, although these techniques improve AC to DC ratio, both multi-strands and Litz style PCB need to eliminate a significant portion of the copper area that leads to an increase in DC resistance of the winding. Besides, Litz PCB winding needs to use multiple vias to connect strands on top and bottom layer of the winding. Therefore, it is less reliable than other kinds of PCB windings, especially in cases where the winding operates at high temperature, because the expansion of the insulation layer can destroy the vias. Notwithstanding the same, the benefits of interleaved pattern and litz pattern outweigh a solid track coil since at 6.78MHz, Rac dominates and reduces η .

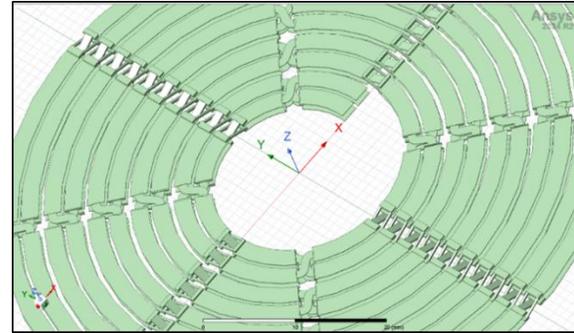
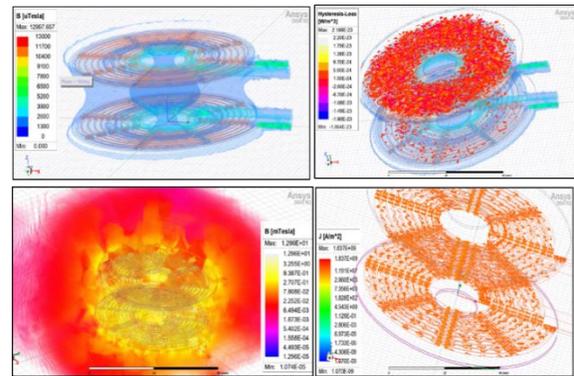


Fig 5.Litz style pattern.



Coupling Coeff Table 1 Maxwell3DDesign1 Ansys 2024 R2	
Freq [MHz]	6.780000
Matrix1_CplCof(RX-IN1, TX-IN)	0.269569
Setup1 : LastAdaptive	
Matrix1_CplCof(TX-IN, RX-IN1)	0.269569
Setup1 : LastAdaptive	
Matrix1_L(TX-IN, TX-IN) [uH]	1.470723
Setup1 : LastAdaptive	
Matrix1_L(RX-IN1, TX-IN) [nH]	396.439680
Setup1 : LastAdaptive	
Matrix1_L(TX-IN, RX-IN1) [nH]	396.439680
Setup1 : LastAdaptive	
Matrix1_L(RX-IN1, RX-IN1) [uH]	1.470558
Setup1 : LastAdaptive	
Matrix1_R(TX-IN, TX-IN) [mOhm]	237.549116
Setup1 : LastAdaptive	
Matrix1_R(RX-IN1, TX-IN) [mOhm]	91.471877
Setup1 : LastAdaptive	
Matrix1_R(TX-IN, RX-IN1) [mOhm]	91.471877
Setup1 : LastAdaptive	
Matrix1_R(RX-IN1, RX-IN1) [mOhm]	236.844588
Setup1 : LastAdaptive	

Fig 6. Results for Litz pattern d = 20mm between Tx-Rx coils

V. DESIGN OF COMMUNICATION SCHEME

Conventional methods include using Bluetooth, wifi or injecting the signal into the wireless coils itself at half power frequencies for transmission and extracting information at the other end. However, several issues present themselves with these methods. The power frequency of the coils is 6.78MHz which is quite high. Wifi/Bluetooth signals, if used, are subjected to high power RF frequency of 6.78MHz which might result in data corruption and unreliable data link. Further, the equipment if used in high EMI environment again affects the quality of data and if used unshielded, these

signals can be received by any external wifi/Bluetooth device creating a security gap. Therefore, a scheme of communication which is fast, secure, reliable and has total immunity to EMI environment is required. Free space optical communication link (FSOC) is one such communication mode.

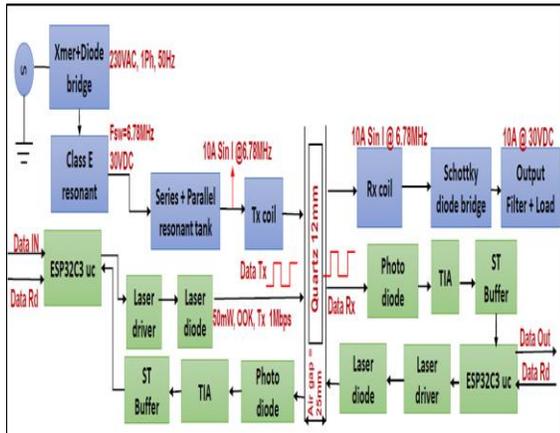


Fig 7. Block diagram for Hardware scheme of FSO

The primary components of the FSO communication scheme are ESP32C3 microcontroller used as a UART controller and data packet generator, High speed laser driver, Laser diode, photo diode, high speed Trans-impedance amplifier, Schmitt trigger buffer.

Data link layer and UART communication of customized protocol:

A customized communication protocol FSO-UART-SFP v1.0 (Free Space Optical-UART- Secure Framing Protocol) has been evolved to deal with data transfer received from optical layers, processing it accurately using SEEED XIAO ESP32C3 microcontroller. It is a lightweight, framed communication protocol for Free-Space Optical (FSO) links using UART over OOK modulation, with integrated error detection, link quality tracking, and message authentication.

VI. CONCLUSION

This paper presents the design and implementation of a wireless Power transfer and data transfer for Electric vehicles. The proposed wireless power transfer is very efficient and safe method compared to the existing wired power transfer which suffers from drag, wear and tear. Due to space constraint, this design used very limited no. of power switches using high switching frequency to minimize component size, using space

grade Aluminum heat sinks and flux shaping using advanced ferrite sheets. Hence, a class-E configuration amplifier with ZVS turn on is chosen to achieve the objectives. The proposed design uses Magnetic Resonant Power Transfer (MRPT) for wireless power transfer as it offers significant advantages in terms of higher efficiency, lower number of control variables, stability over wider loads, higher immunity to noise/harmonics, cleaner current and voltage waveforms and lower number of required switching components in comparison to conventional inductive coupling.

The proposed design uses a unique method of data transfer technique using a 520 nm Laser and photo diode scheme as it is superior to the available conventional methods of data transfer using Bluetooth, wifi or injecting the signal into the wireless coils itself at half power frequencies for transmission and extracting information at the other end. However, several issues present themselves with these methods. The power frequency of the coils is 6.78MHz which is quite high. Wifi/Bluetooth signals, if used, are subjected to high power RF frequency of 6.78MHz which might result in data corruption and unreliable data link. Further, the equipment is intended to be used in high EMI environment which again affects the quality of data. Therefore, a scheme of communication which is fast, secure, reliable and has total immunity to EMI environment is required which is Free space optical communication link (FSOC).

Simulations in MATLAB/Simscape, Maxwell3D, and LTSpice validate the system’s performance, while conformance with ATEX/IEC 60079 and MIL standards ensures reliability and safety.

REFERENCES

- [1] N O Sokal & A D Sokal, “Class E- A new class of high efficiency tuned single ended switching power amplifiers,” IEEE J. Solid state circuits, volume 10 no.3 PP.168-176, June 1975.
- [2] Patrawut Srimuang, Nutdechattron Puangngermak –“13.56 Mhz Class E power amplifier with 94.6% efficiency and 31 watts output power for RF heating applications” May 2014 DOI. 101109/ECTICon.2014.6839809

- [3] Shuangke Li, Ming Liu, Songnan Yang, “A Novel Design Methodology for High-Efficiency current mode and voltage mode class E Power Amplifiers in wireless power transfer systems” *IEEE transactions on Power Electronics*32(6):1-1, DOI. 10.1109/TPEL.2016.2600268
- [4] You Fu, Yu Zhu, Dequan Jiang, Bing Ji “Improved Design of PCB coil for Magnetically Coupled wireless power transfer”.
- [5] Fu, Y.; Zhu, Y.; Jiang, D.; Ji, B.; Peng, Z. “Improved Design of PCB Coil for Magnetically Coupled Wireless Power Transfer”. *Electronics* 2024, 13, 426. 10.3390/electronics13020426.
- [6] Safae, A.; Woronowicz, K. “Time-domain Analysis of Voltage-Driven Series-Series Compensated Inductive Power Transfer Topology.” *IEEE Trans. Power Electron.* 2017, 32, 4981–5003.
- [7] Minh Huy Nguyen and Handy Fortin Blanchette, “A Review and Comparison of Solid, Multi-Strands and Litz Style PCB Winding”, Received: 30 June 2020; Accepted: 7 August 2020; Published: 16 August 2020.
- [8] Thummala, P.; Schneider, H.; Zhang, Z.; Andersen, M.A.E. “Investigation of Transformer Winding Architectures for High-Voltage (2.5 kV) Capacitor Charging and Discharging Applications”. *IEEE Trans. Ind. Electron.* 2016, 31, 5786–5796.
- [9] Lee, C.K.; Su, Y.P.; Hui, S.Y.R. “Printed Spiral Winding Inductor with Wide Frequency Bandwidth”. *IEEE Trans.Ind. Electron.* 2011, 26, 2936–2945.
- [10] Saket, M.A.; Shafiei, N.; Ordonez, M. “Planar transformer winding technique for reduced capacitance in LLC power converters. In Proceedings of the 2016 IEEE Energy Conversion Congress and Exposition (ECCE)”, Milwaukee, WI, USA, 18–22 September 2016; pp 1-6.
- [11] Stadler, A.; Albach, M.; Macary, F. “The minimization of copper losses in core-less inductors: Application to foil- and PCB-based planar windings”. In Proceedings of the 2005 European Conference on Power Electronics and Applications, Dresden, Germany, 11–14 September 2005.
- [12] Marian, K. Kazimierzczuk, “Winding resistance at high frequencies. In High Frequency Magnetic Components”, 2nd ed.; Wiley: Coshocton, OH, USA, 2014; p. 303.
- [13] Su, Y.; Liu, X.; Lee, C.K.; Hui, S.Y. “On the relationship of quality factor and hollow winding structure of coreless printed spiral winding (CPSW) inductor”. *IEEE Trans. Ind. Electron.* 2012, 27, 3050–3056
- [14] Kim, D.-H.; Park, Y.-J. “Calculation of the inductance and AC resistance of planar rectangular coils. *Electron. Lett.*”2016, 52, 1321–1323
- [15] Nguyen, M.H.; Fortin Blanchette, H. Optimizing AC Resistance of Solid PCB Winding. *Electronics* 2020, 9, 875.
- [16] Varghese, B.J.; Smith, T.; Azad, A.; Pantic, Z. “Design and optimization of decoupled concentric and coplanar coils for WPT systems. In Proceedings of the 2017 IEEE Wireless Power Transfer Conference (WPTC)”, Taipei, Taiwan, 10–12 May 2017; pp. 1–4.
- [17] Lope, I.; Carretero, C.; Acero, J.; Burdío, J.M.; Alonso, R. “PCB multi-track coils for domestic induction heating applications”. In Proceedings of the IECON 2012-38th Annual Conference on IEEE Industrial Electronics Society, Montreal, QC, Canada, 25–28 October 2012; pp. 3287–3292.
- [18] Serrano, J.; Lope, I.; Acero, J.; Carretero, C.; Burdío, J.M. Mathematical description of PCB-adapted litz wire geometry for automated layout generation of WPT coils. In Proceedings of the IECON 2017-43rd Annual Conference of the IEEE Industrial Electronics Society, Beijing, China, 29 October–1 November 2017; pp. 6955–6960
- [19] Lope, I.; Carretero, C.; Acero, J.; Alonso, R.; Burdío, J.M. “AC Power Losses Model for Planar Windings with Rectangular Cross-Sectional Conductors”. *IEEE Trans. Ind. Electron.* 2014, 29, 23–28.
- [20] Wang, S.; de Rooij, M.A.; Odendaal, W.G.; van Wyk, J.D.; Boroyevich, D. “Reduction of high-frequency conduction losses using a planar litz structure”. *IEEE Trans. Ind. Electron.* 2005, 20, 261–267
- [21] Lope, I.; Acero, J.; Serrano, J.; Carretero, C.; Alonso, R.; Burdío, J.M. “Minimization of vias in PCB implementations of planar coils with litz-wire structure”. In Proceedings of the 2015 IEEE

Applied Power Electronics Conference and Exposition (APEC), Charlotte, NC, USA, 15–19 March 2015; pp. 2512–2517.

- [22] Rehlaender, P.; Grote, T.; Tikhonov, S.; Niejende, H.; Schafmeister, F.; Bocker, J.; Thiemann, P. A PCB Integrated Winding Using a Litz Structure for a Wireless Charging Coil. In Proceedings of the 2019 21st European Conference on Power Electronics and Applications (EPE'19 ECCE Europe), Genova, Italy, 2–5 September 2019; pp. P.1–P.9
- [23] Mil-Std-810h- “Environmental Engineering Considerations and Laboratory Tests”
- [24] Mil-Std-202g- “Test Method Standard Electronic and Electrical Component Parts”
- [25] Mil-Std-461f- “Requirements for The Control of Electro Magnetic Interference Characteristics of Subsystems and Equipment”
- [26] Ipc-2221a- “Requirements for The Control of Electromagnetic Interference Characteristics of Subsystems and Equipment”
- [27] IEC 60079-14 “Explosive atmospheres - Part 14: Electrical installation design, selection and installation of equipment, including initial inspection” & Part 15- “Equipment protection by type of protection "n”.