ECE 445

Spring 2024

Automatic Drone Wireless Charging Station

Team 29

Samuel Fakunle (sof2)

Pranshu Teckchandani (pat4)

Jason Wuerffel (jasonmw2)

TA: Matthew Qi

Introduction:

Problem:

Drone technology is becoming more vital for our modern society because it improves productivity and precision for several applications. Despite this, the operation time continues to be a key technological challenge because of the drone's battery life limitations. As a result, our project aims to address this issue by implementing an automated drone charging system that extends the drone's flight time without human intervention.

A. Solution:

Our group aims to use resonant inductive coupling to develop a wireless drone charging station that allows the drone to land and charge its battery within an acceptable distance from the transmitter. The combination of the coils on the drone and on the charging pad will essentially act as an air gap transformer. Circuitry leading up to the coil on the charging pad side will consist of a power source, half bridge synchronous rectifier, and resonant tank. Circuitry after the transformer on the drone side will include an AC-DC full bridge converter followed by a synchronous buck converter and ending with a BMS. An MCU will be used to provide PWM to the MOSFETs used throughout the project. In addition, our system should start power transfer only when the drone lands in close proximity to the coil on the pad. We may also add an optional feature where the drone can track back to the pad when low on battery but it is an additional feature we will implement only if time permits.

Visual Aid:

Figure 1: Visual Aid

High Level Requirements:

- The system is able to supply 3.7V± 3% V DC to 1S LiPO battery, when supplied with 24V DC power from the power supply.
- The charging pad is able to charge the drone successfully without human interference with an efficiency of at least 50% only after the coils are within the set proximity of 5 cm.
- The system will operate at the resonant frequency of 120kHz. The system should operate within the 3dB range.

Design:

Block Diagram:

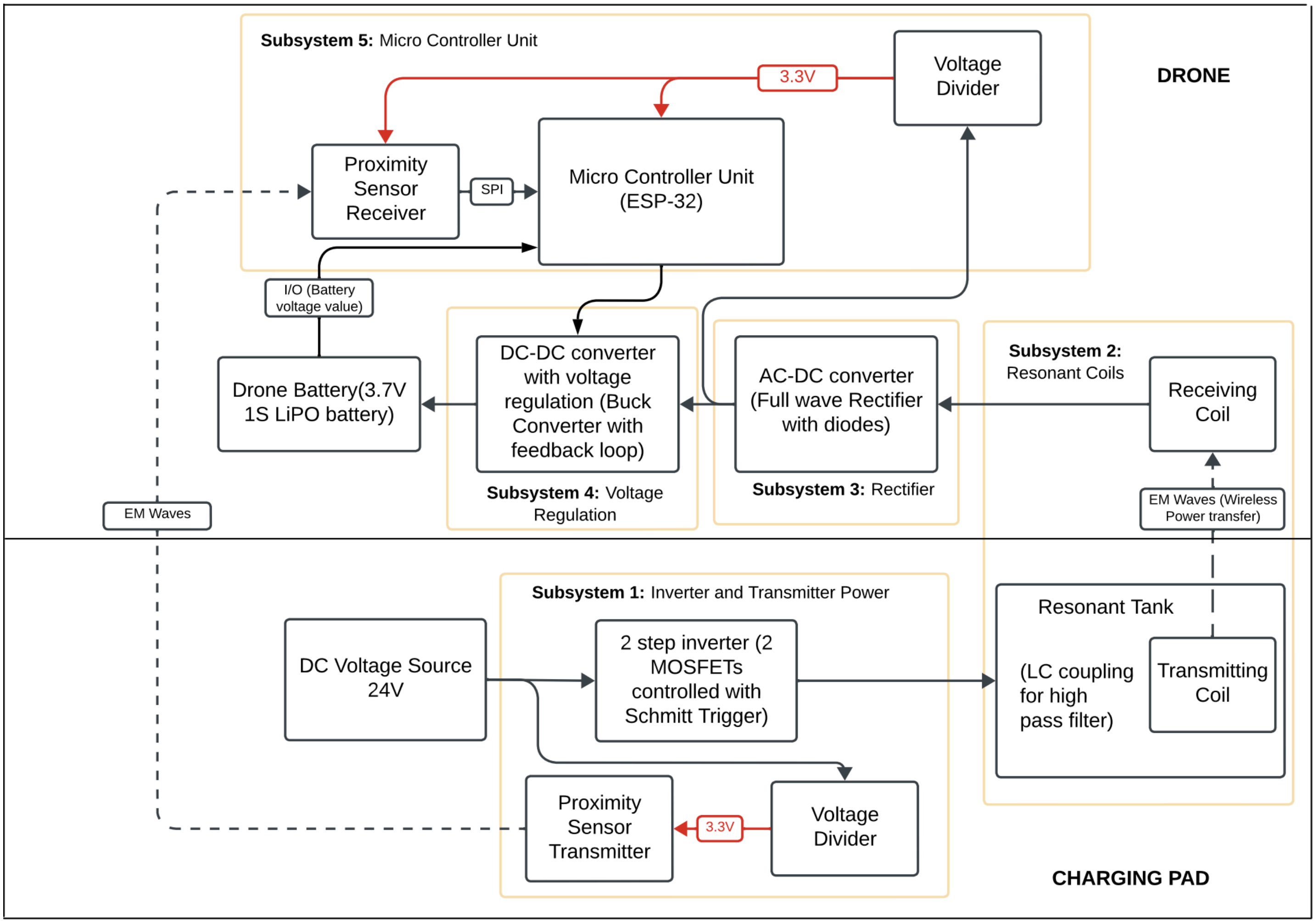

Figure 2: Block Diagram

Subsystem Overview and Requirements:

<u>Subsystem 1: Two Step Inverter and Transmitter power</u>

This subsystem consists of a 24V DC power supply and a half bridge inverter circuit. We also provide power to the transmitter of the proximity sensor as a part of this subsystem.

Inverter Circuit:

Our inverter circuit consists of two MOSFETs as seen in the figure. The circuit takes input from a 24V DC Power Supply and it outputs a square wave. This is a 2 step inverter meaning the output will only have two voltage values 0V and 24V. The inverter circuit will be based on the following topology.

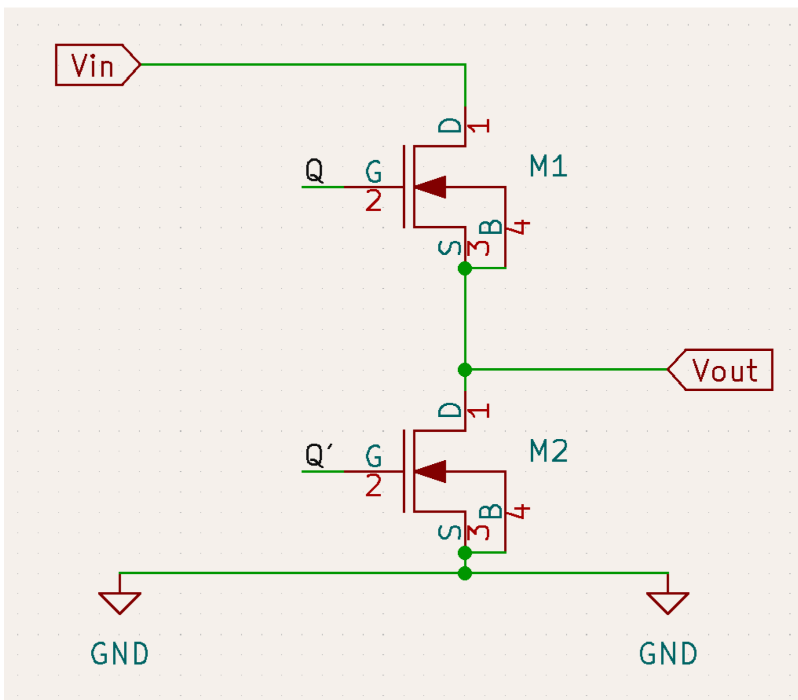

Figure 3: Half bridge inverter

The MOSFETs will be controlled by complementary PWM signals which will be generated by a Schmitt trigger. The figure below shows a schematic based on which we will be generating Q and Q' for the MOSFETs.

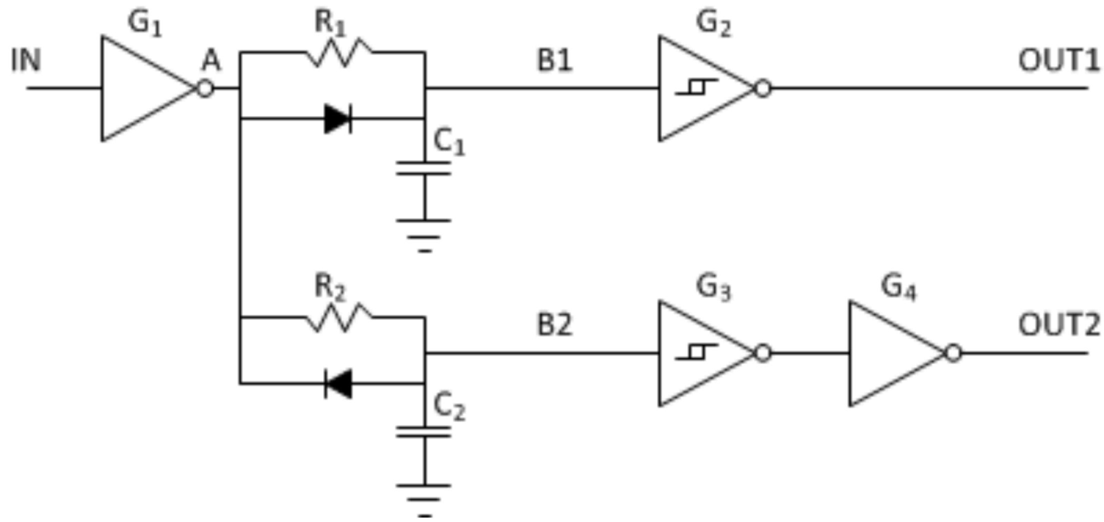

Figure 4: Schmitt Trigger Schematic

The output of this subsystem is going to be a square wave with voltages 24V and 0V.

Power for the transmitter Circuit:
This will be a basic circuit which will involve a Voltage divider topology to provide the Transmitter with 3.3V power. We will be using resistances of different values to get the desired output.

Requirements	**Verification**
The output of the circuit is a square wave with voltages 0V and 24V	Input 24V DC and use an oscilloscope to check the waveform of the output
The power supplied to the proximity sensor transmitter should be 3.3V	Input 24V Dc and check the output of the voltage divider with the help of an oscilloscope

Subsystem 2: Resonant Coils

This system consists of the LC Resonant tank and the transmitting and the receiving coils. The LC coupling will be used as a high pass filter for the incoming square wave. The Inductance over here will be the inductance of the transmitting coil. We will be designing the circuit to output only AC with 120kHz. The schematic for this subsystem will be similar to the following figure:

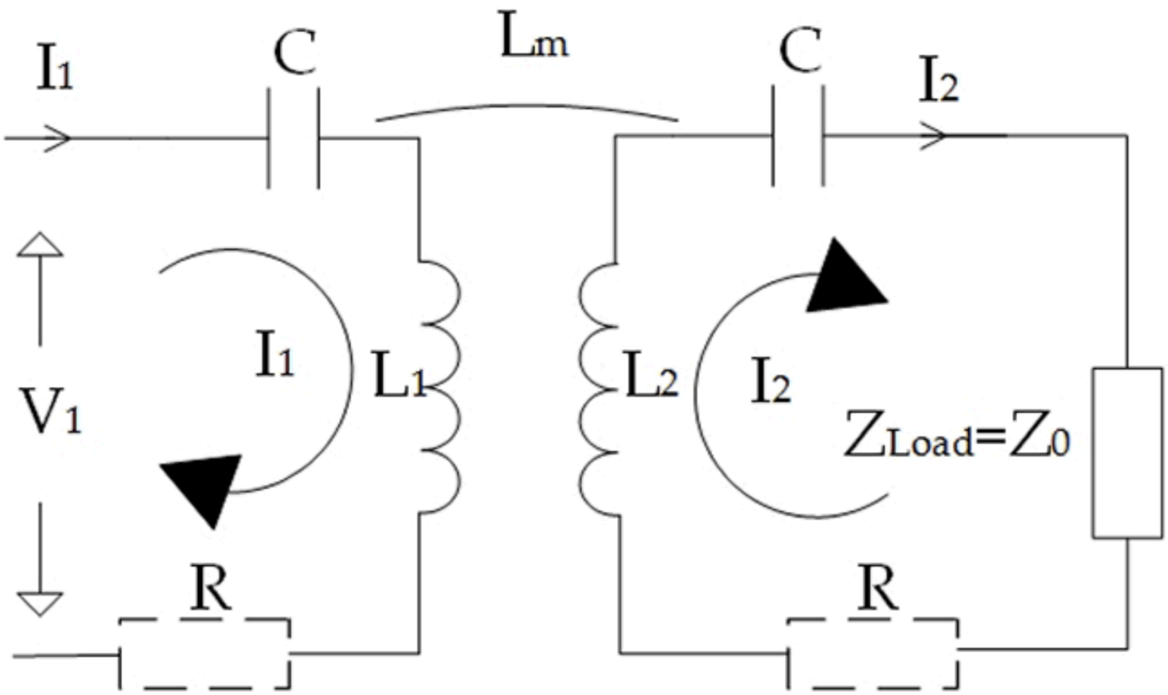

Figure 5: Coil Network with LC Resonant Tank

The left side will be the transmitting side. The input to the transmitting side will be the square wave. L1 represents the inductance of the transmitting coil. The capacitor will be chosen in such a way that the resonant frequency of the circuit is equal to 120kHz. For our design, we won't be including the capacitor on the receiving side(right side). The resistances indicate the resistances of the wires and L2 indicates the inductance of the receiving coil. Lm is the mutual inductance.

The main thing in this subsystem is to keep the quality factor of the LC circuit high to ensure that the waveform for wireless power transmission is of high frequency.

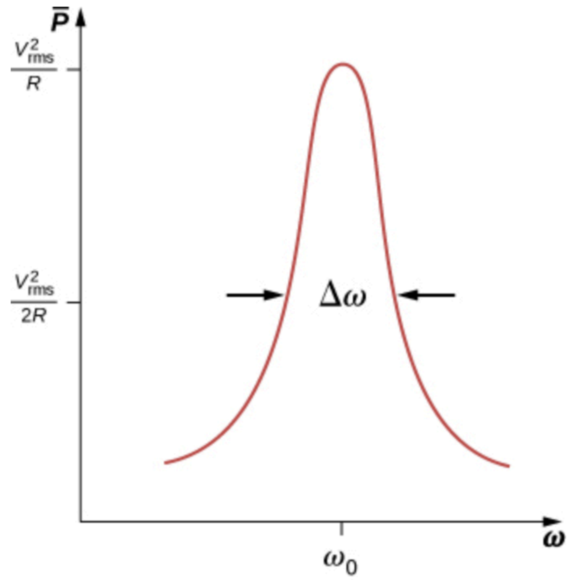

Figure 6: Bode Plot

To ensure high efficiency the peak of this plot should be as narrow as possible. The quality factor is a function of L,C, and R and all of them will have to be tuned appropriately to get a high quality factor.

Another factor to consider here is the coupling coefficient of the coils. The coupling coefficient depends on the individual inductances of the coils and the mutual inductance.

Requirements	**Verification**
The efficiency of the wireless power transmission should be more than 50%	Given an input AC, the input power on the transmission side and output power on the receiving side will be measured with the help of watt meters. The output power should be greater than 50% of the input power.
The LC circuit on the transmission side should be operating within the 3dB of the resonance frequency i.e. 120kHz.	We will check this by testing the transmission side circuit separately. We will input an AC voltage and check the current. Under resonant conditions, the circuit should be purely resistive.
The distance between the coils should be less than 5cm	Checked physically with the help of a tape measure/ruler.

Subsystem 3: Full Bridge Rectifier

This subsystem includes a full bridge rectifier with a filter, which is responsible for converting 12V AC to 10V DC. The filter would include a capacitor tank to allow for more flexibility. The rectifier would utilize four 1N4007-T diodes, hence communication with ESP32 microcontroller is not required.

The figure below shows a typical full bridge rectifier circuit [9]:

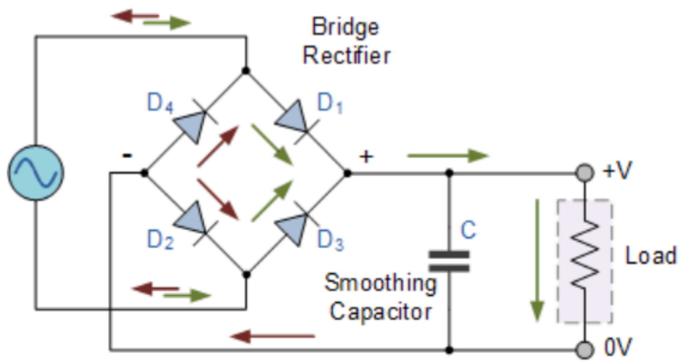

Figure 7: Full Bridge Rectifier

Requirements	**Verification**
The full bridge rectifier must be able to convert 12V± 5% AC voltage from the WPF system to 10 ± 3% V DC.	We will use the variac, wattmeter, and oscilloscope in the lab to confirm this AC-DC conversion.

Subsystem 4: Synchronous Buck Converter with Voltage Regulation

This subsystem includes a synchronous buck converter responsible for converting 10 ± 3% V DC to 5 ± 3% V DC for the drone's battery. The buck converter would use two MOSFET switches, which require complementary PWM signals; hence, communication between converter and ESP32 microcontroller is required. This unit would also include a TPS54561 (TI) buck converter chip responsible for converting 5 ± 3% V DC to regulated 3.7 ± 3% V DC. We will rely on the feedback control loop capabilities of the chip to perform output voltage dynamic regulation. It is vital to ensure effective and safe charging of the drone's battery in all scenarios, thus ensuring system stability. This would be achieved by controlling the duty ratio of the converter chip.

The figure below shows a typical schematic for a synchronous buck converter [11]:

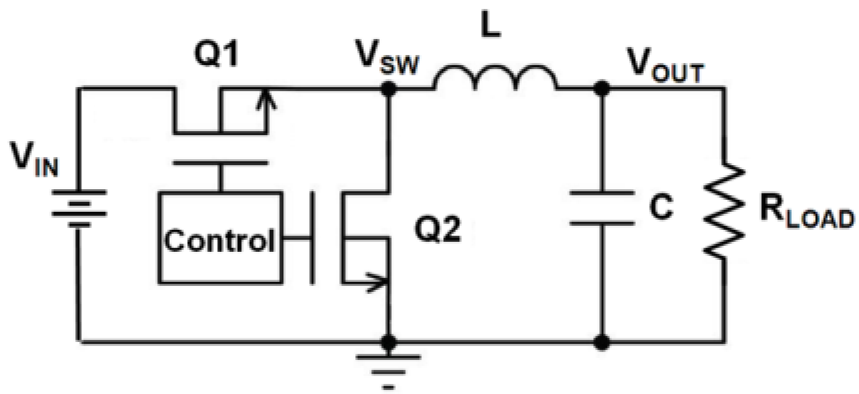

Figure 8: Synchronous Buck Converter

Requirement	Verification
The synchronous buck converter should be able to convert 10 ± 3% V DC to regulated 5 ± 3% V DC.	This DC-DC conversion would be confirmed using a testbench DC power supply and oscilloscope.
ESP32 microcontroller successfully sends complementary PWM signals. to the MOSFET switches	This would be verified by observing the MOSFET switch voltages on the oscilloscope.
The synchronous buck converter operates at 100kHz switching frequency.	This would be confirmed using an oscilloscope.
Output power must be between 15-25 W.	This would be confirmed using the wattmeter.
Successful dynamic regulation of output voltage.	We will use the testbench DC power supply to send low input voltages into the

	converter to verify that the chip is able to control the duty ratio in order to maintain output voltage. Additionally, we will also test to see if the chip changes the duty ratio to prevent overcharging of the drone's battery.

Subsystem 5: Micro Controller Unit

This subsystem would include the ESP32 microcontroller responsible for sending PWM signals to all MOSFET switches, successful communication with the proximity sensor, and communication with the TI buck converter chip and battery sensor for voltage regulation. If time permits, this unit would also be responsible for communicating with LED displays to visually convey the charging status of the drone’s battery.

Requirement	**Verification**
Successful communication between proximity sensor, battery sensor, and ESP32 microcontroller over bluetooth or Wifi.	Confirmation that other subsystems work. Also, serial printing onto the monitor would also be used to validate this subsystem.
Successful communication with TI buck converter chip	Validated via serial printing onto the monitor.

Tolerance Analysis:

The frequency of the LC circuit should be within 3db of the resonant frequency i.e. 120kHz.
The capacitors we are using have a tolerance of ±20% and the inductance of the transmitting coil will also have a general tolerance of ±20%.
Thus the frequency of the LC circuit would be between 100kHz and 150kHz.
This can be explained as follows :

$$\omega_0 = \frac{1}{\sqrt{LC}}$$

The formula for the resonant frequency is:
If we take the worst case values of L and C, i.e. 1.2*L and 1.2*C, we will get a new frequency of 100kHz. If we take the values of L and C on the other spectrum, we get a frequency of 150kHz.

Now, let's calculate our 3dB frequency range. It is the frequency when the power output of the system is half of the maximum power output of the system.
The lower cutoff frequency is given by the formula -

$$\omega_L = -\frac{R}{2L} + \sqrt{\left(\frac{R}{2L}\right)^2 + \frac{1}{LC}}$$

Whereas the upper cutoff frequency is given by the formula-

$$\omega_H = +\frac{R}{2L} + \sqrt{\left(\frac{R}{2L}\right)^2 + \frac{1}{LC}}$$

The wire we are using for the circuits has a resistance value of 1.029 ohms per foot. We will be using at maximum 5 feet of wire and the recommended tolerance for this thickness of wire is ±5%. The 3dB bandwidth of the circuit is given by

$$BW = \frac{f_r}{Q}, \quad f_H - f_L, \quad \frac{R}{L}\ \text{(rads)} \quad \text{or} \quad \frac{R}{2\pi L}\ \text{(Hz)}$$

For our case, the worst case bandwidth is 50kHz.

For our circuit, with a resonant frequency of 120kHz, the value of L*C will be $6.944*10^{-11}$. With a capacitor value of 470μF, the value of the inductor is going to be around 150nH.

For R=5 ohms ±5% and L = 150nH ±20%, we see that our worst case bandwidth will be well within the 3dB limit and so our system will work as expected.

Ethics and Safety

Ethics:

Most ethical concerns to do with this project are more so about the drones and their enhanced capabilities when used with our wireless charger than the actual wireless charger itself. The biggest ethical concern to do with drones is privacy because they have the capability to record people without their knowledge or permission. Another ethical concern is the potential weaponization of drones. Drones are already used in combat, and cutting out the need for them to get plugged in in order to charge could make them more useful in this area. Our project is not intended to be used in either of these ways. It is, however, intended to be used for research purposes. This would create environmental ethical concerns such as noise and congestion issues. We would hope that the drones would be used in moderation to limit these concerns. The last potential ethical issue would be the loss of jobs as this technology would take over the need for people to charge the drone. We do not really foresee this becoming an issue.

Safety:

There are a few safety issues to consider with both the drone and charger components of the project. The biggest potential issue would be the drone colliding with people or objects. This could be caused by control malfunction or, more related to our project, the battery runs out. There are also risks related to cybersecurity and drones getting hacked. The drone we will use will follow IEEE 1936.1-2021 for drone applications[1].

The charger safety issues include shock risks along with overheating leading to fire. The shock risk is our main concern in this project since we anticipate having exposed coils with live voltage running through them. We will make sure to follow appropriate standards to mitigate all risks involved with our project. This includes, but is not limited to, the “Interface definitions” (IEC PAS 63095-1: 2017) standard and the SAE J2954: 2020 which regulates wireless power charging[2].

The charger will be charging a 3.7 V lithium ion battery which also comes with some safety concerns. These include battery failure due to aging, thermal abuse, and electrical abuse[6]. Our group is aware of the possible risks and will abide by ISO 26262[7] as well as take the battery safety training.

Citations

[1] “IEEE SA - IEEE standard for drone applications framework,” IEEE Standards Association, https://standards.ieee.org/ieee/1936.1/7455/ (accessed Feb. 7, 2024).

[2] A. Marinescu, "Current Standards and Regulations for Wireless Battery Charging Systems," 2021 7th International Symposium on Electrical and Electronics Engineering (ISEEE), Galati, Romania, 2021, pp. 1-6, doi: 10.1109/ISEEE53383.2021.9628689. keywords: {Wireless communication;Roads;Inductive charging;Sociology;Regulation;Production facilities;Batteries;Wireless Power Charging;Standards and Regulation for Consumer Devices;EVs and PHEVs},

[3] Resonant converter with coupling independent resonance for Wireless Power Transfer Application, https://cpes.vt.edu/library/viewnugget/622#:~:text=Another%20challenge%20of%20the%20resonant,transfer%20standard%2C%20is%206.78MHz. (accessed Feb. 8, 2024).

[4] “Understanding LLC operation (part I): Power switches and resonant tank: Article: Mps,” Article | MPS, https://www.monolithicpower.com/understanding-llc-operation-part-i-power-switches-and-resonant-tank (accessed Feb. 8, 2024).

[5] A. Raciti, S. A. Rizzo, and G. Susinni, “Drone charging stations over the buildings

based on a Wireless Power Transfer System," 2018 IEEE/IAS 54th Industrial and Commercial Power Systems Technical Conference (I&CPS), May 2018. doi:10.1109/icps.2018.8369967

[6] X. Zhou, L. Cheng, Y. Wan, N. Qi, L. Tian and F. You, "Research on Lithium-ion Battery Safety Risk Assessment Based on Measured Information," 2020 IEEE Sustainable Power and Energy Conference (iSPEC), Chengdu, China, 2020, pp. 2047-2052, doi: 10.1109/iSPEC50848.2020.9351160. keywords: {Lithium-ion batteries;Temperature measurement;Voltage measurement;Thermal management;Battery charge measurement;Safety;Risk management;lithium-ion battery;thermal runaway;risk assessment;active safety}

[7] S. S. Tikar, "Compliance of ISO 26262 safety standard for lithium ion battery and its battery management system in hybrid electric vehicle," 2017 IEEE Transportation Electrification Conference (ITEC-India), Pune, India, 2017, pp. 1-5, doi: 10.1109/ITEC-India.2017.8333870. keywords: {Batteries;ISO Standards;Hardware;Hazards;Software;Lithium;ISO 26262;Lithium ion battery;Battery management system;HARA;ASIL},

[8] A. Agcal, S. Ozcira, and N. Bekiroglu, "Wireless Power Transfer by Using Magnetically Coupled Resonators," *www.intechopen.com*, Jun. 29, 2016. https://www.intechopen.com/chapters/51254 (accessed Feb. 23, 2024).

[9] W. Storr, "Full wave rectifier and bridge rectifier theory," Basic Electronics Tutorials, https://www.electronics-tutorials.ws/diode/diode_6.html (accessed Feb. 22, 2024).

[10]"15.6: Resonance in an AC Circuit," *Physics LibreTexts*, Nov. 01, 2016.

https://phys.libretexts.org/Bookshelves/University_Physics/University_Physics_(OpenStax)/Book%3A_University_Physics_II_-_Thermodynamics_Electricity_and_Magnetism_(OpenStax)/15%3A_Alternating-Current_Circuits/15.06%3A_Resonance_in_an_AC_Circuit

[11] On semiconductor is now - onsemi, https://www.onsemi.com/pub/Collateral/AND9135-D.PDF (accessed Feb. 23, 2024).

[12]“H-bridge Control | Modular Circuits,” Mar. 09, 2012. https://www.modularcircuits.com/blog/articles/h-bridge-secrets/h-bridge-control/

[13]“Frequency Data as per AWG size in Litz Wire,” *YDK Litz Wire & Cable*. https://www.hflitzwire.com/frequency-as-per-awg-size/

[14]Electronics tutorials, “Series Resonance in a Series RLC Resonant Circuit,” *Basic Electronics Tutorials*, Jun. 04, 2018. https://www.electronics-tutorials.ws/accircuits/series-resonance.html