Wireless Communication System for Wireless Charging of an Arduino-Based Car

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***Abstract*—Smart devices surrounding us in daily life require frequent charging. To deal with the charging issue, wireless power transfer is a good option to provide energy due to its plenty of advantages, such as convenience, user-friendliness, and safety. A thorough wireless charging system consist of not only a transmitter and receiver, but also power generation, a controller, a charging station and a battery.**

Wireless charging enables charging easier for users. The communication between transmitters and receivers should be wireless as well. A communication system with various sensors forms an Internet of things (IoT) structure. It allows everyday objects with network connectivity to send and receive data so that they can talk to each other without human intervention. Moreover, it ensures that power is transferred in a precisely controlled way.

This article uses a quasi-dynamic charging scenario to present the charging system, including an IoT structure and wireless charging, for an Arduino smart car. Our communication system is based on ESP 8266 NodeMCU which is a cost-efficient WiFi Microcontroller. The whole system is verified in experiment. The result shows that the system can provide good performance in a realistic situation, and a good basis for our next step–dynamic wireless charging.

***Index Terms*—wireless charging, communication system, testbed, Internet of Things, Class E inverter.**

I. Introduction

The Internet of Things (IoT) is a paradigm that allows networking of physical devices, which enables daily objects equipped with identifying, sensing, networking and processing capabilities to communicate with each other. The devices can collaborate over the Internet to achieve some purpose [1]. Through the IoT, various devices, such as smart home devices, surveillance system, monitoring sensors, and vehicles, can interact with one another. By 2020, approximately 50 billion devices will be connected to the Internet [2]. In light of this ubiquity, wireless charging can be readily incorporated into daily life. In this paper, we use a wireless communication system with various sensors to develop an IoT structure.

EVs have developed rapidly. In 2018, globally, the number of EVs exceeded 5.1 million. The members of the Electric Vehicles Initiative (EVI) set goals of reaching sales of 23 million EVs and to exceeding an evaluation of $130 million in the stock market by 2030 [3]. However, the limited range, considerably long time for charging, and higher prices than traditional combustion engine cars have proved to be barriers to purchasing EVs. Charging when cars are in motion–dynamic wireless charging–can extend the range and reduce the battery cost and weight of EVs, thereby increasing operational efficiency and range [4].

Wireless charging [5], also called wireless power transfer, is a technology enables a power source to be transformed into electromagnetic energy, which is transmitted through an air gap without requiring connection to an electrical load. Wire-free charging devices improve the wireless charging experience of users. An IHS Inc. study predicted that shipments of wireless charging components, including receivers (RXs) and transmitters (TXs), will be approximately two billion units by 2022 [6]. Wireless charging has the following advantages compared with wired charging [7]:

- User-friendliness: Wires easily become entangled. In wireless charging, wires are removed to improve the charging experience of the user.
- Size reduction: Wireless charging provides easy charging, which allows devices to charged more frequently. Therefore, batteries in devices can be reduced in size, and the size of devices can consequently be reduced.
- Durability: Wires are not required in these types of devices for charging. Therefore, these devices can be better sealed to prevent water or dust intrusion.
- In some devices, such as underwater unmanned vehicles, medical implants, it is expensive or dangerous to replace batteries or to charge with a cord. Wireless charging provides a convenient method to charge such devices.

Wireless charging service requires a precisely controlled power transfer strategy. A remote-controlled car is one of the most popular toy cars [8]. Remote-controlled cars with Arduino microcontroller chips, comprising different sensors, can be used to accomplish various goals. Therefore, we selected an Arduino smart car to decrease expenses and scale down wireless charging for an EV. We developed an IoT structure by using a communication system with various sensor for wireless charging based on an Arduino-based smart car.

Fig. 1 depicts an IoT structure for dynamic wireless charging systems. The objective of the study was to fabricate the system. A wireless power transfer (WPT) management system was constructed using the IoT to ensure a precise charging service and to record the data transmitted from the vehicle.

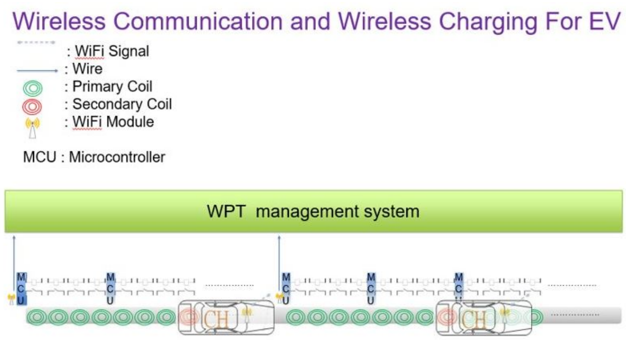

Fig. 1: Wireless charging system for EVs with a communication system

In this paper, we describe how we designed a wireless communication structure for a quasi-dynamic wireless charging system. The rest of the paper is organized in the following sequence. In section II, we describe the design. In section III, we discuss how components were selected for use in our experiment. In section IV, we explain our experiments and results. In section V, we present our conclusion and propose future work.

II. Design

A. Wireless Communication and the Internet of Thing (IoT)

Sensors are used for monitoring in diverse fields such as commodities, agriculture, and biomedicine. As the variety of applications continues to increase, sensors that sense, measure and collect various types of data have become smaller in size and more powerful in performance. Therefore, small platforms such as small robots or Arduino-based cars, can carry such sensors, which perform robustly [9].

In this project, to develop the IoT, we propose a wireless communication architecture for a wireless charging system through the use of different sensors.

Quasi-dynamic charging allows a smart car to be charged while paused at a station. The quasi-dynamic state for charging is a state between static and dynamic. This state validates the static charging and can provide an excellent start for the next state–dynamic charging. Therefore, we used a quasi-dynamic scenario to start our IoT experience in wireless charging system.

The flow chart in Fig. 2 details how the on-board unit (OBU), road-side unit (RSU), and charging station interact with respect to communications and actions; these components comprise our proposed IoT.

Our scenario supposes an Arduino smart car approaches and then stops at a wireless charging station. The procedures from the start of communication to the end of charging are described as follows:

- The OBU/ Secondary side/ Vehicle side starts sending the vehicle and user information over WiFi.

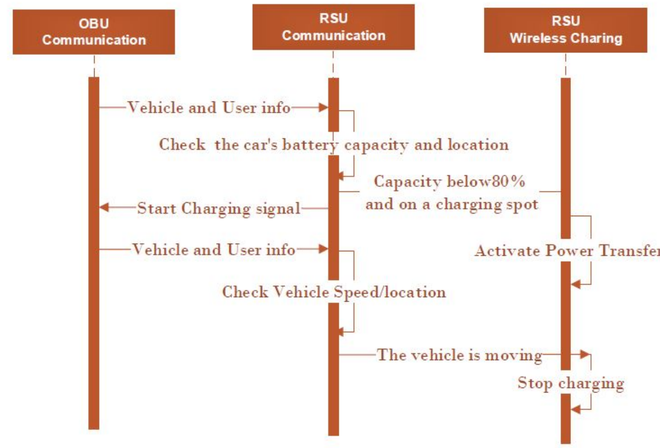

Fig. 2: Quasi-dynamic flow chart

- The RSU/ Primary side keeps checking the battery capacity and the vehicle's speed and location when receiving OBU data.
- The RSU sends a signal to a microcontroller if the cars battery level is less than 80% and it is on the charging spot.
- The RSU wireless charging system is activated when the conditions are satisfied.
- The OBU keeps sending its information, and the RSU keeps receiving and checking data.
- When the OBU moves, the RSU stops charging the battery.

To realize the quasi-dynamic scenario, we used WiFi as the wireless communication medium to access multiple sensors. WiFi uses multiple parts of IEEE802.11 protocol standards. Many devices, such as laptops, computers, smartphones, tablets, drones, and cars, can connect with each other over WiFi through a wireless access point (AP).

Several devices and sensors are required to fulfill the following functions:

- WiFi modules: For communication.
- Speed sensor: For car motion detection.
- Distance sensor: For car location detection.
- Battery management: For charging the battery and fetching the battery information such as voltage, current, power consumption and state of charge. Plus, for protecting the Lithium-Ion battery from over charging or discharging.

Functions of each component/device will be described in details in the following section.

B. Wireless Charging with a Class E Inverter

Fig. 3 details the key parameters and equations [10], [11] used in our system. First, we start from our design choice (input voltage source V_i and output power P_{Ri}) with a Class-E Inverter. Then, we change topology to its equivalent form π2a [10]. This configuration is similar to the equivalent circuit of a loosely coupled transformer (we can determine the leakage inductance on both sides of the circuit and the magnetizing inductance).

The next step is to calculate resonant inductance L (L=L_a+L_b) and leakage inductance from the value of load resistance (R_i) of the class-E inverter and the real load resistance (R_L).

The final step is to add the mutual inductors, that compensate for the secondary inductance with a capacitor in series. Then, leakage inductance (L_a) in the primary side is checked to determine the difference from the resonant inductor (L=L_a+L_b, calculated at the first step) and an additional inductor is added to compensate for the value.

- Input/Supply voltage V_I: Our design choice.
- Output power P_{Ri}: Our design choice.
- Switching frequency f_s and angular frequency w: Our design choice.

$$w = 2\pi f_s \tag{1}$$

- Phase angle of resonant circuit that satisfies ZVS and zero derivative switching (ZDS) ϕ_{opt}
  According to the design procedure of a class-E amplifier [12], ZVS and ZDS can be achieved when the phase angle is equal to 32.48° or 0.567 rad.

$$\phi = tan^{-1}\left[\frac{wL_{at}(1 - w^2L_{at}C_1 - C_1R_i^2)/L_{at}}{R_i}\right] \tag{2}$$

- Coupling coefficient k We can get k when

$$\phi = \phi_{opt} \tag{3}$$

This experiment is for charging an Arduino-based smart car whose coil in not necessarily right on the top of the primary coil. Therefore, some air gap should be acceptable for high efficiency (above 85%). From [13], primary inductance can be measured through short-and open-circuited of the secondary for different air gaps, coupling coefficients can be obtained. (4) shows the equation in which $L_{p'}$ represents primary inductance when the secondary winding is short-circuited and L_p represents the inductance when the secondary winding is open-circuited.

$$k = \sqrt{1 - \frac{L_{p'}}{L_p}} \tag{4}$$

In [11] a proper air-gap distance ($k = 0.77$) can maintain high efficiency.

After k is obtained [13], the distance between two coils is calculated by measuring primary inductance when the secondary is short- and open-circuited.

III. COMPONENTS IN OUR DESIGN

A. Wireless Communication and the IoT

Developed on approachable hardware and software, Arduino is a freely available platform. The hardware boards of Arduino are capable of turning a read input, a command from different types of sensors or Internet connections, into an output–an interaction that responds accordingly. Arduino programing language and its software are established on Processing [14]. A series of instructions based on the requirements can be sent to the microcontroller on a hardware board. Its openness and ease of use of Arduino has led to its wide adoption, especially in the IoT. By 2021, Arduino is predicted to be valued $6 trillion dollar [15].

ESP8266, also known as system on a chip, is a microchip that has an integrated chip with TCP/IP protocol stack and can easily access any WiFi network by using its transceiver. It is capable of switching among various stations, Access Point (AP) and Station+AP. The AT mode enables the chip to conveniently establish its own WiFi network without needing to connect to any other network. ESP8266 has 17 general-purpose input/outputs (GPIOs). The GPIOs allow the chip to be connected to various sensors and application devices at the same time. ESP8266 functions like any other Arduino device and is its most popular IOT device [16]. Consequently, we selected the ESP8266 NodeMCU to be our WiFi module.

A lithium-ion battery (LIB), also known as an Li-ion battery, is a type of rechargeable battery that has a high energy density energy, negligible memory effect, and low discharge rate compared with other batteries. Therefore, LIBs are extensively used in electric mobility applications [17]. The goal of our study was to apply our method for wireless charging to EVs. Therefore, we selected an Li-ion battery to power our Arduino smart car, reflecting a realistic situation.

However, an LIB requires battery protections to prevent over charging and over discharging [17]. Consequently, an LIB management was applied in our system. To simply our experiment and ensure replication of the function, the SparkFun Battery Babysitter management system was used. It is a half battery charger and monitor [18]. Thus, the battery data could be fetched, and the battery could be protected during charging and discharging using this all-in-one management board.

In our next step, a wireless charging scheme was installed for the rechargeable battery. To validate the communication and decision-making flow quickly, we turned to a commercial cell phone wireless charging pair to transmit the power. An iTechShop Wireless Charging Pad and a Nillkin Magic Tags Wireless Charger RX were used to form our wireless charging system.

Our control system activates the charging system if a car is paused (sensed on the car) at the correct location (sensed on the station). Therefore, we used an IR optocoupler speed sensor to detect the rotation per minute (rpm) and an HC-SR04 ultrasonic sensor to detect the distance between the charging pad and the RX. According to these two signals (speed and distance), the rely switch turned the power supply to the charging pad ON and OFF.

The components of the overall test system for IoT are listed in Table I.

Fig. 4 represents the wireless communication structure for wireless charging of an Arduino-Based car. The smartphone is not listed in the component table because any smart devices

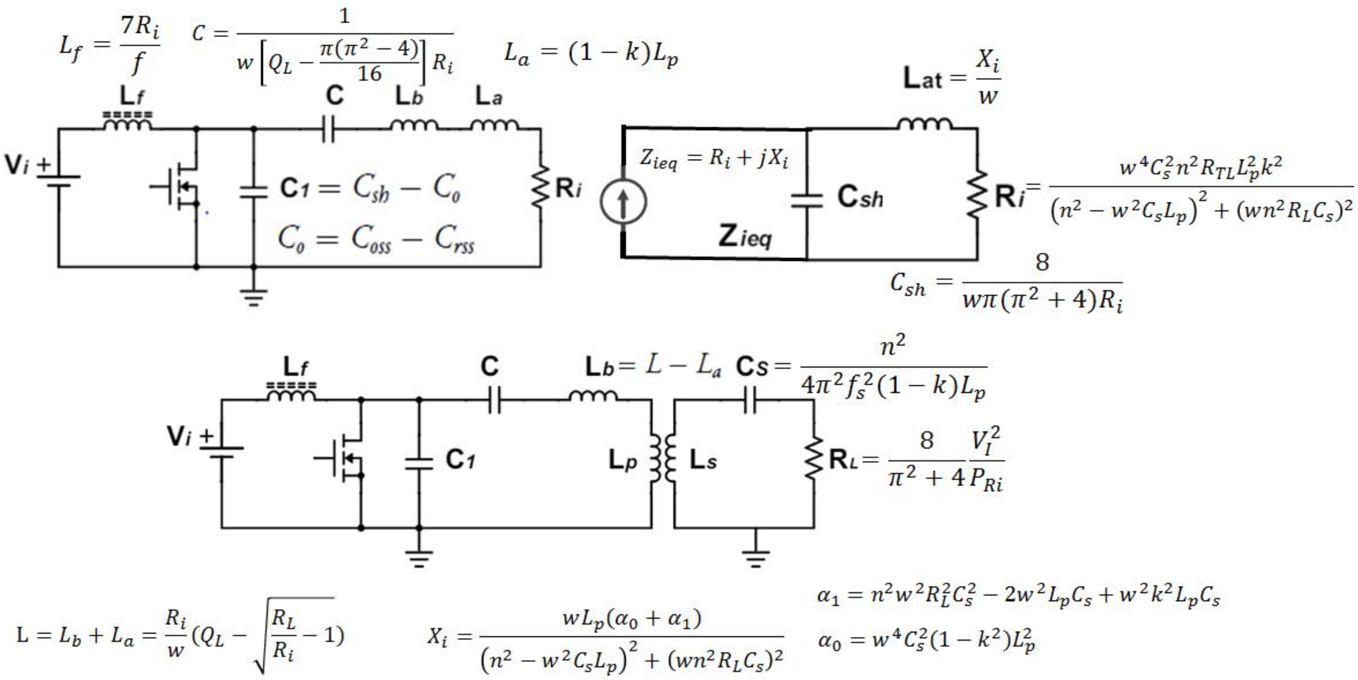

Fig. 3: Equations used in wireless charging

TABLE I: The components used in IoT

Unit func	detail		
	device	*Spec*	*QTY*
OBU	car	Arduino Smart Car Kit 4WD	1
OBU	WiFi Module	ESP8266 NodeMCU	2[a]
OBU	motor controller	L293D Motor Drive Shield[b]	1
OBU	battery	Lithium-ion 2AH	2
OBU	battery management	SparkFun Battery Babysitter	1
OBU	charging pad	output 5V1A	1
OBU	speed sensor	IR Optocoupler Speed Sensor[c]	1
RSU	WiFi Module	ESP8266 NodeMCU	1
RSU	charging RX	5W Receiver	1
RSU	distance sensor	HC-SR04 Ultrasonic Sensor	1
RSU	relay	3V Relay Power Switch	1
RSU	power supply	AC110V to DC5V	1

[a] One for car control; the other for communication.
[b] L293D WiFi Motor Drive Expansion Board Shield Module for ESP8266
[c] IR Optocoupler Speed Sensor Module LM393 for Arduino

can be used as long as it connects to the same communication system (WiFi connection).

B. Wireless Charging

The wireless charging pair in the previous section was used for testing the communication structure and scenario verification. However, the pair was designed for static charging of smart phones. Although the scenario test was successful in our experiment (described in next section), the air gap between RX and TX was approximately 2 mm and the allowed misalignment was almost zero. The air gap and the misalignment did not satisfy the wireless charging conditions of a regular Arduino car.

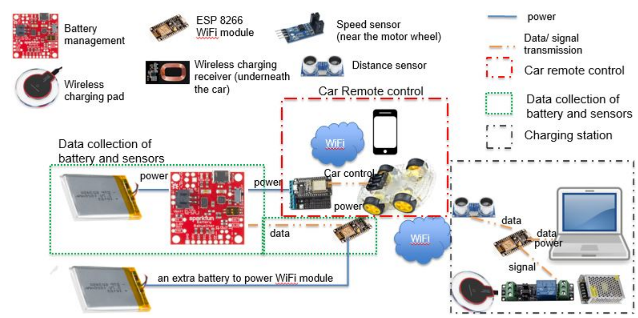

Fig. 4: Wireless communication structure for wireless charging

For the development of our wireless charging system, we calculated the required parameters from the last section/ design. The goal was to calculate all parameters in Fig. 3.

- Input/Supply voltage V_I: Our design choice is 10 V.
- Output power P_{Ri}: Our design choice is 10 W.
- Loaded quality factor Q_L: We assume it is equal to 10.
- Turn ratio n: Our design choice is 1.
- Primary and secondary coils: Our design choice is 24 μH for each coil.
- Coupling coefficient k from (2) and (3)
  We used MATLAB to draw these two functions (and get Fig. 5). Therefore, we set our coupling coefficient k as 0.77. With this value, we calculated the following parameters.

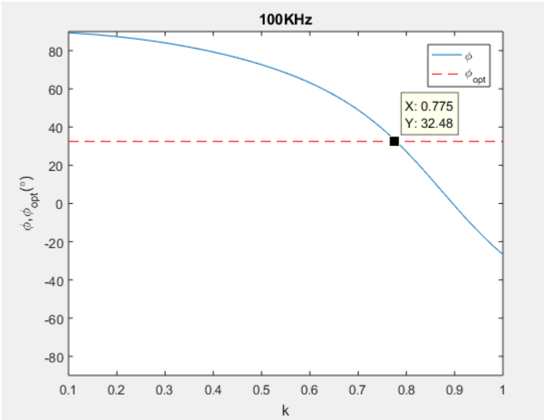

Fig. 5: Phase angle as a function of k and optimum phase angle

We calculated every parameter in Fig. 3. Fig. 6 presents the all values we require.

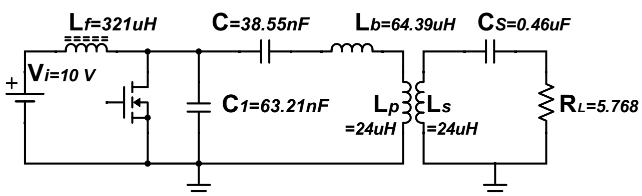

Fig. 6: Wireless charging circuit with values

IV. Simulation, Experiments and Results

A. Wireless Communication system and the IoT

We assembled all the sensors and components on our Arduino smart car and developed a charging station to form an OBU and an RSU. We designed a wireless quasi-dynamic charging system (Fig. 2) and we used the Processing software on which Arduino code is based to display and record data from the OBU and RSU. Fig. 7 illustrates the data displayed on the Processing window. These data were uploaded to ThingSpeak. ThingSpeak is a platform service for analyzing IoT data. In our design, we used a WPT management system to collect, visualize, and analyze data in real time in the cloud. The trial version of commerical ThingSpeak can provide all the required functions [19]. Therefore, we used ThingSpeak as our temporary WPT management system to test our scenario.

Fig. 8 demonstrates the wireless communication in a wireless quasi-dynamic system. We used a laptop within the same WiFi connection to control the Arduino car. When the car approached the charging pad along the track, its data were successfully collected, recorded and uploaded. When the car was paused on the pad, the red led light-emitting diode (LED) on the battery management turned OFF and the blue LED

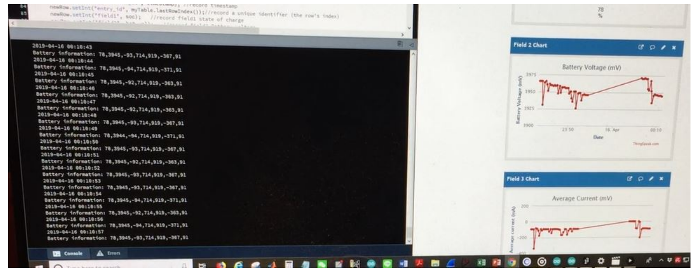

Fig. 7: Data displayed by Process and uploaded to ThinkSpeak

turned ON. Thus, the battery got charged and all processes in the flow chart were fulfilled.

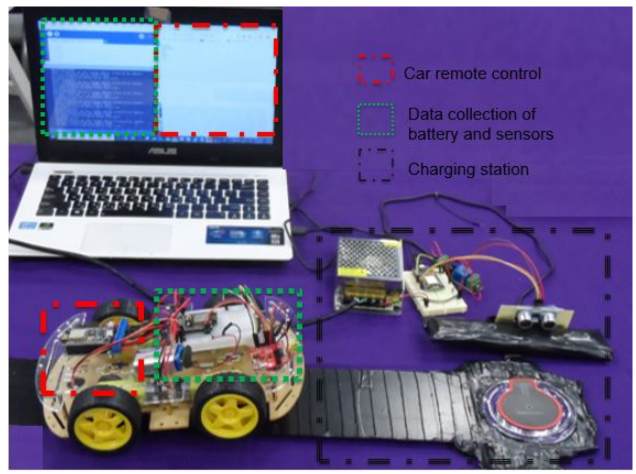

Fig. 8: The experimental setup for wireless communication

B. Wireless Charging System

We used the ideal component parameters listed in previous section and run our simulation. The result is depicted in Fig. 9. Fig. 10 depicts that ZVS (zero voltage switching) was achieved and the average efficiency was 95.1% from 0.5 ms to 5 ms (input 13.2 W output 12.55 W).

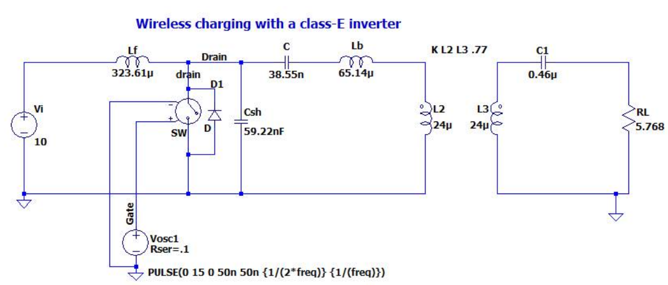

Fig. 9: Simulation of a wireless charging system using a Class-E inverter

Such high efficiencies can be achieved by loosely coupled circuit with coupling coefficient of k = 0.77. The distance

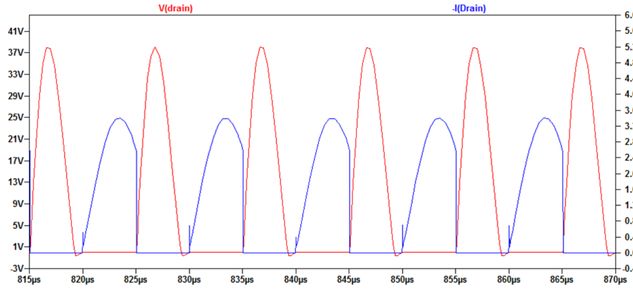

Fig. 10: Simulation result illustrating ZVS

between the primary and secondary is 25 mm [11]. This will improve our wireless charging system because of the lager air gap and higher misalignment durability, which can be beneficial for our future wireless dynamic charging systems.

V. CONCLUSIONS AND FUTURE WORK

This paper presented a novel quasi-dynamic wireless charging system that comprises a wireless charging system and a wireless communication system. The wireless communication system enables the system to function as the IoT and provide energy without human intervention.

The inverter, using a loosely coupled transformer, satisfies the ZVS condition, which provides the charging system with high efficiency at an optimum coupling coefficient through the design method. Therefore, we can utilize this method to calculate the maximum distance between two devices. This method ensures the feasibility of static charging and is an excellent start to the next step – dynamic charging.

In the future, we plan to use the quasi-dynamic charging system and put the class-E inverter into practice. Then, we will use the inverter in our dynamic charging system, which will be used more widely in daily life. For the communication systems, we should consider the communication range and the continuity between two WiFi ranges and the connection speed because of car motion.

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