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Vehicle-to-Vehicle charging system fundamental and design comparison

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***Abstract*—The popularisation of the Electric Vehicle (EV) is restrained by the stagnation of energy storage technology and inadequate plug-in charging stations. This paper proposes a new vehicle-to-vehicle (V2V) charging technology platform, that can achieve wireless charging working in harmony with plug-in charging technology, or operate independently. V2V charging technology can effectively solve the problem of the limited number of plug-in stations. Moreover, it can charge the car any-time, anywhere, like a power bank. V2V charging system design requires a number of technical challenges to be overcome including the power balancing between vehicles and charging circuit design to maximizing the power transfer efficiency. In this paper, the schematic of V2V charging system is proposed, and we also propose the fundamentals of calculating the power capacity and the cost of EV energy when an EV is a power source in a V2V charging system. The hardware circuit design is presented and a detailed comparison of different coil shapes/ combinations and compensation circuit topologies is provided using the simulation tool ANSYS.**

***Index Terms*—Vehicle to Vehicle Charging, Wireless Power Transfer, Coil Design, Compensation Circuit Design, ANSYS**

I. Introduction

In order to reduce pressure on fossil fuel and reduce environmental pollution, the use of electric vehicles (EVs) is rapidly increasing replacing that of traditional combustion engine vehicles. Although the government has issued many different incentives to encourage people to buy electric cars, many consumers are still reluctant to purchase a pure battery EV. The main reason is the concern about the battery range, the charging method and availability of charging infrastructure.

The distinction between a pure EV and hybrid EV is clear, however there are a number of classes of pure EVs with varying battery capacity and power capability. The sub-compact EV comes with a battery that has 12-18 kWh, the mid-sized has a 22-23 kWh pack which can provide a driving range of 130-160 km, and the luxury models by Tesla with an oversized battery boasting 60-100 kWh to provide an extended driving range of up to 539 km [1]. Fig.1a shows a comparison of EVs with battery type, range and charging time in wired charging case and wireless charging case, respectively. The Lithium-ion batteries comprise a family that are presently representing the most used technology in EVs [2]. Each combination has distinct advantages and disadvantages in terms of safety, performance, cost, and other parameters, as shown in Fig.1b.

Currently, plug-in charging and wireless charging are the two main charging methods. Wireless charging enables the automated charging of EVs which can be achieved through three different modes: static charging, quasi-dynamic charging and dynamic charging [3]. A very efficient way of wireless charging is the magnetic resonant coupling wireless charging [4]–[6]. Both wireless charging and plug-in charging have advantages and disadvantages. Plug-in charging is a mature, high efficiency technology, but it is inconvenient: EV supply equipment or EV chargers are difficult to access and consume considerable time to charge. In contrast, wireless charging technology is convenient, but it is complicated and still in the early stages of development, which means efficiency is lower than traditional plug-in charging technology and the cost to charge is higher [7].

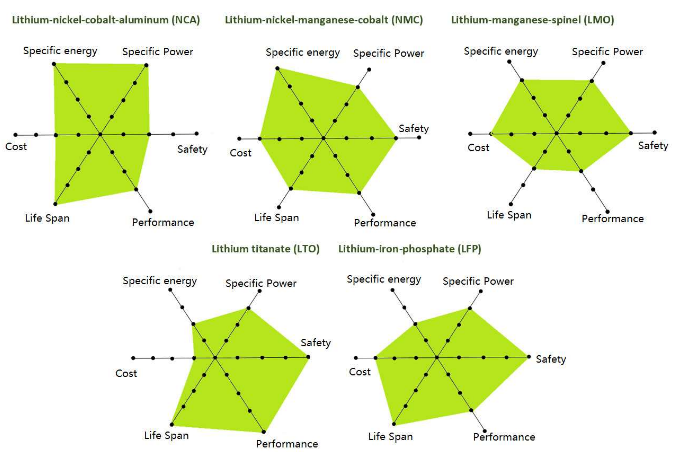
Additionally, another concern of customers is anxiety over the need to recharge the vehicle during a journey. The number of plug-in charging stations is limited and may not be located at a convenient site in relation to their route, as compared to the convenience and ease of locating a petrol station. A further issue may then arise for the user having located a charging station, finding that the designated charging slots are already taken by other vehicles. In order to solve these issues, this paper proposes a new platform of charging technology for EV called vehicle-to-vehicle (V2V) charging that can achieve wireless charging working in harmony with plug-in charging technology, or operate independently. EVs are considered a consumer of energy but they can also be an energy supplier, for example providing energy to the national electricity grid. The power capacity of an EV and the cost of an EV are two main parameters when the EV is an energy provider. This paper proposes the fundamental theory to calculating the power capacity and total cost of an EV when it as an energy provider.

V2V charging technology can be used in both wireless charging systems and plug-in charging systems, for this paper we focus on the wireless charging system. The transmitter coil and the receiver coil of wireless V2V charging are embedded in the front and rear of the car, respectively. This allows a vehicle to pass through power to vehicles parked behind and allow multiple cars to charge from a single plug-in station. Additionally, a car with V2V technology can also

Model	Battery	Plug-in Charging Time	Wireless Charging Time (Plugless wireless charger)*
Chevy Volt (PHEV)	16kWh, Li-manganese, liquid cooled, 181kg, all electric range 64km.	10h at 115VAC, 15A; 4h at 230VAC, 15A	30A for charge Chevy Volt: Level2: 3.7-7.7kW power delivery, 240Volt charging, 4-5 hour; Level 3: up to 50kW power delivery, 480Volt, 80% charge at 20-30 min
Nissan Leaf	30kWh, Li-manganese, air cooled; 272kg, driving range up to 250km.	8h at 230VAC,15A; 4h at 230VAC, 30A	30A for charge Nissan Leaf: Level2: 3.7-7.7kW power delivery, 240Volt charging, 4-5 hour; Level 3: up to 50kW power delivery, 480Volt, 80% charge at 20-30 min
BMW i3	22kWh, LMO/NMC, large 60A prismatic cells, battery weights 204kg, driving range of 130-160km.	4h at 230VAC,30A; 50kW supercharger, 80% charge in 30 min	50A for charge BMW i3: Level2: 3.7-7.7kW power delivery, 240Volt charging, 4-5 hour; Level 3: up to 50kW power delivery, 480Volt, 80% charge at 20-30 min
Tesla S	70kWh and 90kWh, 18650 NCA cells of 3.4Ah; liquid cooled; 90kWh pack has 7,616 cells; battery weighs 540kg; S 85 has up to 424km range.	9h with 10kW charger; 120kW supercharger, 80% charge in 30 min	50A for charge Tesla S: 7.2kW power delivery, 208-240 single phase AC charging, get 20-25 mile of range per hour parked.

*Plugless is one electric vehicle supply equipment (EVSE) products manufactured by Evatran that enable inductive charging for electric vehicles. WiTricity is another wireless charging station manufacturer. Their EVSE products use magnetic resonant coupling charging, and the efficiency is 90-93% at charging rates at 3.6-11kW.

(a) The comparison of EVs with battery type, range and charge time



(b) The trade-off among five principal lithium-ion battery technologies

Fig. 1: Overview of EV batteries and charging technology [2]

achieve auxiliary charging between moving vehicles, thus reducing the need to locate a fixed charging station. Wireless V2V charging system design requires a number of technical challenges to be overcome including the coil design and compensation circuit design to maximizing the power transfer efficiency. This paper analyses different design considerations for wireless V2V charging system. Section II introduces the concept of a V2V charging system. Section III proposes the power capacity and net revenue fundamental theory in V2V charging system. Section IV and section V discusses the coil design and the compensation circuit design in a wireless V2V charging system and provides the ANSYS simulation results, respectively.

II. The concept of wireless vehicle to vehicle (V2V) charging system

A V2V charging system is established by transmitting power between EVs (either hybrid vehicle (PHEV) or battery

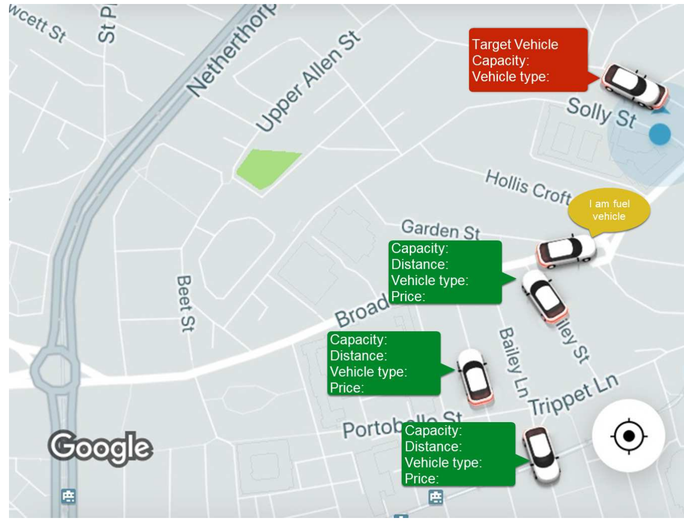


Fig. 2: Schematic of V2V charging system

EV (BEV)). In order to meet this objective, the vehicle is required to integrate three modules: 1: V2V charging device, for transmitting electrical energy flow between vehicles, can be either wired or wireless; 2: V2V communication module, for establishing control or logical connection between vehicles; 3: Vehicle-mounted supervisory module, for control and metering.

Fig.2 schematically illustrates the operation of V2V charging system. When the target vehicle (Red) sends a charging request, the on-board system of the vehicles in close proximity to the target vehicle automatically calculate their available supply power, distance, vehicle type, and price, *etc.* This information is received by the target vehicle where it can select the appropriate vehicle and choose the charging location to complete the charging task. Either plug-in charging or wireless charging can be used in V2V charging. Consideration for the environment (traffic/headway/parking), the type of on-board charging device, *etc.* V2V charging technology can provide the charging of an EV in emergency situations where there are no available charging stations within range.

III. Vehicle-to-vehicle power fundamentals theory: calculating capacity and net revenue

In V2V charging the power capacity of an EV and net revenue are the two main parameters for consideration for a viable system.

A. The power capacity of an EV as a power source

Firstly we need to define the parameters of the EV as an energy provider based on the costs and potential revenue through energy trading.

$P_{vehicle}$ is the maximum power from the EV supply in kW, as below:

$$P_{vehicle} = \frac{(E_s - \frac{d_{rb}}{\eta_{veh}}) \cdot \eta_{inv}}{t_{disp}} \tag{1}$$

where E_s is the stored energy available as DC (kWh) to the inverter, d_{rb} is the distance in miles of the range buffer required by the driver, *e.g.* the return commute or distance reserved for an unanticipated trip to a convenience store or hospital. η_{veh} is the vehicle driving efficiency in miles/kWh, η_{inv} is the electrical conversion efficiency of DC to AC inverter, t_{disp} is the time that the vehicle's stored energy is dispatched in hour. Equation also can be rewritten as [8]:

$$P_{vehicle} = \frac{(E_s - \frac{d_{rb}}{\eta_{veh}})}{t_{disp} \cdot \eta_{charger}} \tag{2}$$

where $\eta_{charger}$ is the efficiency of the charger.

B. The cost of an EV as power source

The cost of the EV as power source includes three parts, the cost of the requested energy $C_{request}$, the cost of the energy transfer $C_{transfer}$ and the cost of power delivery $C_{delivery}$. The equation can be written as below:

$$C_{total} = C_{requst} + C_{transfer} + C_{delivery} \tag{3}$$

1) The cost of request energy $C_{request}$:

$$C_{request} = P_t \cdot E_{request} \tag{4}$$

where P_t is the current price per unit of power (£/kWh), $E_{request}$ is the requested energy to consumer EV.

2) The cost of energy transfer $C_{transfer}$:

$$C_{transfer} = \frac{C_{pe}}{\eta_{conv}} + C_d \tag{5}$$

where $C_{transfer}$ is the per kWh cost to produce electricity through storage back to electricity, C_{pe} is purchased energy cost (cost of electricity) in £/kWh, η_{conv} is the efficiency of vehicle's conversion of electricity through storage back to electricity. C_d is the cost of equipment degradation (wear) due to the extra use for V2V (in £/kWh) of delivered electricity.

Degradation cost C_d is calculated as wear for V2V due to extra running time on hybrid engine/ extra cycling of a battery [8]. For hybrid running in motor-generator mode, degradation cost is:

$$C_d = \frac{C_{engine}}{L_h} \tag{6}$$

where C_{engine} is the capital cost per kWh of engine, including replacement labor in £/kWh, L_h is the engine lifetime in hour.

For a battery vehicle, degradation cost is:

$$C_d = \frac{C_{battery}}{L_{ET}} \tag{7}$$

where $C_{battery}$ is battery capital cost in £(including replacement labor), and L_{ET} is battery lifetime throughput energy in kWh for a particular cycling regime.

3) The cost of energy delivery:

$$C_{delivery} = D_{distance} \cdot B_{distance} \cdot P_t \tag{8}$$

where $D_{distance}$ is the distance between supply EV to customer EV in km, $B_{distance}$ is the energy cost per kW (kWh/km), P_t is the current price per unit power (£/kWh).

Substituting equations (4) (5) (8) into (3) can get the total cost of EV as power supply C_{total} as following:

$$C_{total} = P_t \cdot E_{request} + \frac{C_{pe}}{\eta_{conv}} + C_d + D_{distance} \cdot B_{distance} \cdot P_t \tag{9}$$

IV. COMPARISON OF COIL DESIGN FOR WIRELESS V2V CHARGING SYSTEM

Implementation of a V2V charging system can be achieved using either plug-in charging or wireless charging. For plug-in charging, one cable between two vehicles can complete V2V charging. However, plug-in charging has a number of disadvantages compared to wireless charging mainly related to the physical process of connecting the cable which means that the EVs have to be stationary and in adverse weather is unpleasant for the user. In this paper we focus on the wireless V2V charging system. Literature provides many coils design for wireless EV [9]–[11], *e.g.* square shape, circle shape, D shape, and double D shape, *etc.* In this paper, we use ANSYS Maxwell to simulate several coils design and give a detailed comparison for each combination.

Fig.3 shows the chosen cases of coil design for the comparison. The yellow part is the winding, and the green part is the ferrite plate which can improve the magnetic flux. The length (square coil)/diameter(circle coil) of transmitter coils ($T_1 - T_5$) are 50 cm, the length of receiver coils ($R_1 - R_5$) are 40 cm, respectively. The gap between transmitter coil and receiver coil are 200 mm, with no lateral misalignment. All the transmitter coils have the same number of turns (18 turns), and in the middle have a ferrite core. All the receiver coils have the same number of turns (15 turns), and in the middle do not have a ferrite core. The different design between T_3 and others is that T_3 has a ferrite edge, and the other transmitter coils are flat (no edge). T_5 also has the same turns as the others, however, the winding in the middle and edge are tight. The right column shows the simulation results of B value from ANSYS Maxwell: The T_3R_3 combination is calculated to achieve the highest B value, and the B value of T_4R_4 combination is the lowest.

Moreover, the misalignment problem is a common problem in wireless an EV charging system, and it can influence the power transfer efficiency of the charging system. One important parameter of power transfer efficiency in magnetic resonant wireless EV charging system is mutual inductance (M), which can be expressed by the coupling coefficient (K) $M = K \cdot \sqrt{L_T L_R}$.

Fig.4 shows the coupling coefficient value in different coil designs. The X-axis is the lateral misalignment distance, and the Y-axis is the coupling coefficient value (K). In this simulation, the gaps between transmitter coil and receiver coil

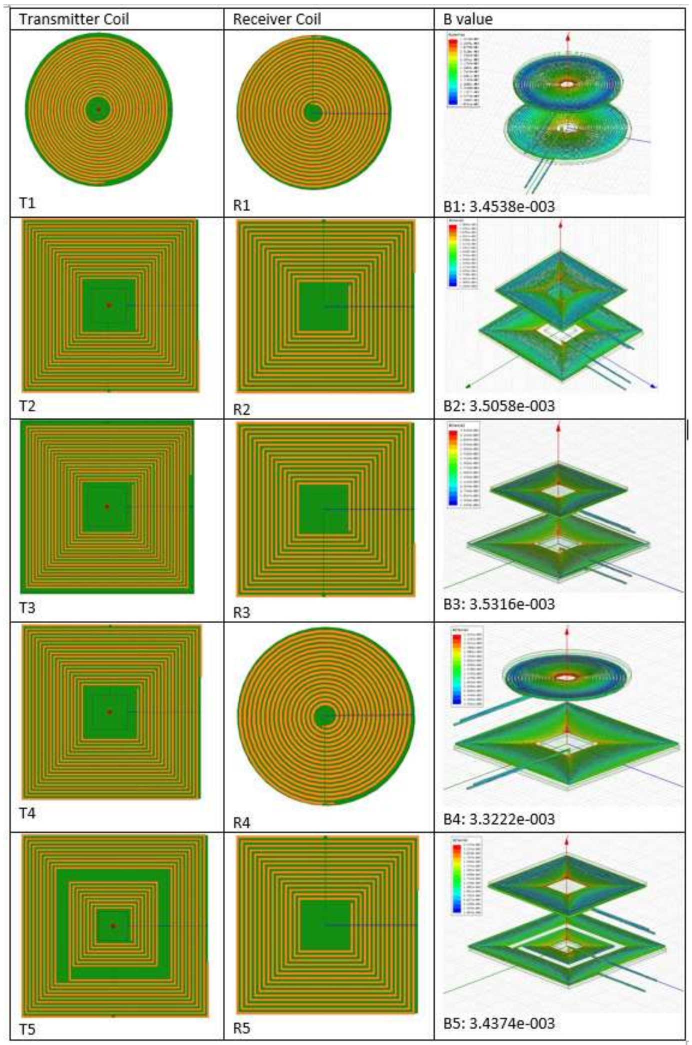
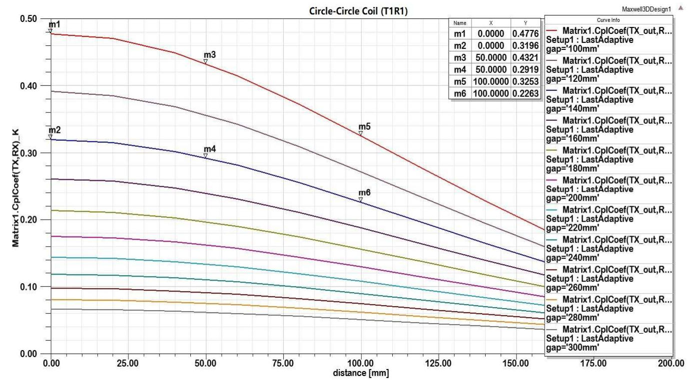


Fig. 3: Comparison of coil design for wireless V2V charging system

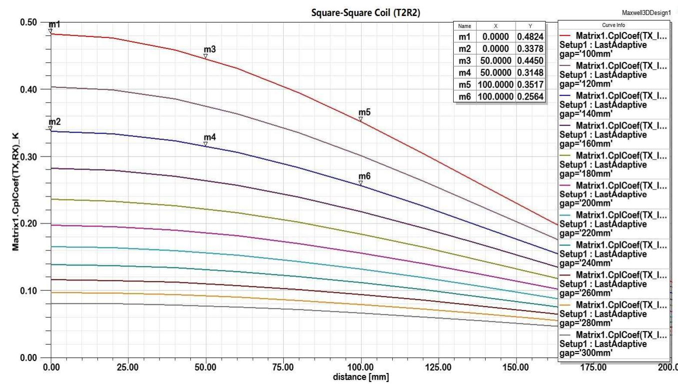
are from 100 mm to 300 mm, and the step is 20 mm. The lateral misalignment is set from 0 mm to 200 mm, with a step of 20 mm. Overall, the coupling coefficient (K) decreases which means the efficiency of system decreases when the gap and lateral misalignment increase. Compared with a circle coil (T1R1), the coupling coefficient of a square coil (T2R2) has greater stability and changes more slowly when a horizontal offset occurs. The square-circle combination (T4R4) looks like the worst case in the result. However, the current at the right angle of a square coil is uneven due to skin effect and proximity effect; a fillet design can be adopted to avoid the effect at the corner of a square coil to reduce resistance losses.

V. Comparison of the compensation circuits design for wireless V2V charging system

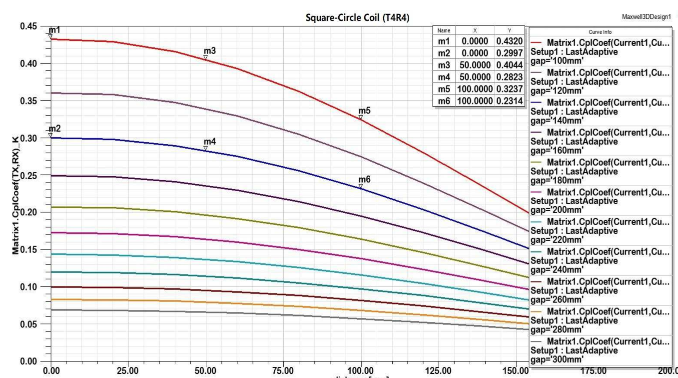
In a wireless power transfer technology system, the series-series compensation and the parallel-parallel compensation are common and widely used [12]. However, the series-series compensation is unsuitable for primary side of a movable wireless EV charging system due to its difficulty in generating a large primary current. Meanwhile, the parallel-parallel compensation can not meet the requirement of secondary sides in a variable load system. The LCL compensation has distinct advantages such as a large resonant capability, low voltage and current stresses of the power device, constant voltage or current output characteristics, and fault-tolerance capability. This paper focuses on discussing the series-parallel compensation and LCL compensation circuit design for V2V wireless charging system. The role of battery in V2V wireless



(a) Circle-Circle (T1R1) Coil



(b) Square-Square (T2R2) Coil



(c) Square-Circle (T4R4) Coil

Fig. 4: The Coupling Coefficient (K) of different coils combination

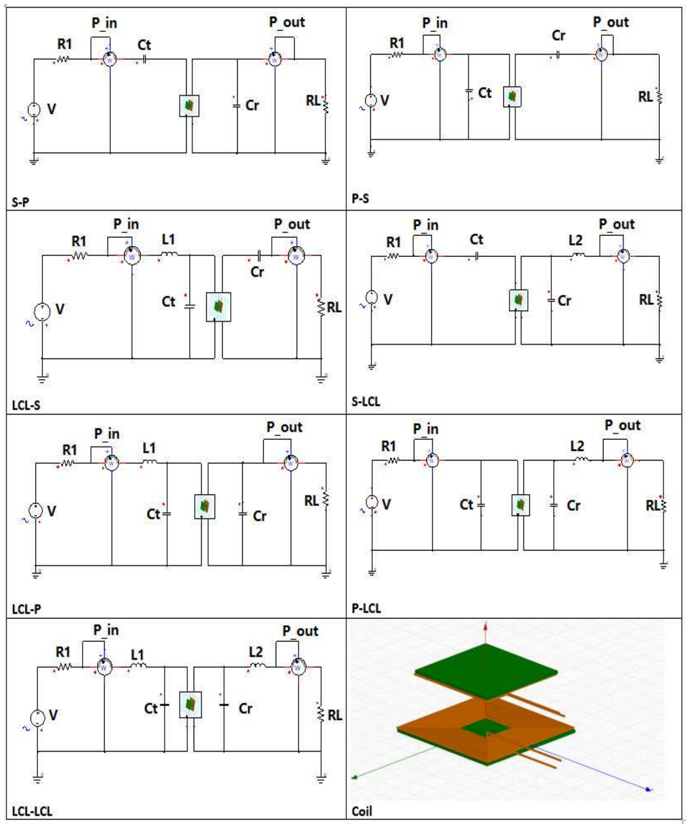


Fig. 5: The compensation of circuit topologies

charging system is not only a power supplier, but also a load. The resonant compensation circuit design should there be considered for its compensation performance in both directions. Fig.5 shows the simulation circuit used by ANSYS Simplorer and ANSYS Maxwell.

Because the EV's battery parameters are variable during charging, we simulate the efficiency of different kinds of S-P/(P-S) compensation circuit and the LCL compensation circuit at different load values. Fig.6 shows the efficiency of S-P/(P-S), LCL-S/(S-LCL), LCL-P/(P-LCL), and LCL-LCL compensation resonant circuit simulated in different load values at the resonant frequency (50 KHz), respectively. The efficiencies of the LCL-LCL compensation circuit, the S-LCL compensation circuit, and S-P compensation circuit are similar and maintain the highest efficiency with increasing loads. The efficiency of the P-S compensation circuit and the LCL-S compensation circuit drops sharply when the load values increase. Compared with LCL-S compensation circuit, the LCL-P/P-LCL compensation circuits all have higher efficiency values, however, these two compensation circuit are not steady when the load values are changed. Due to considering the double-direction compensation performance required of V2V wireless charging system, the LCL-LCL compensation circuit and the LCL-P/ (P-LCL) compensation circuit would be the best choice.

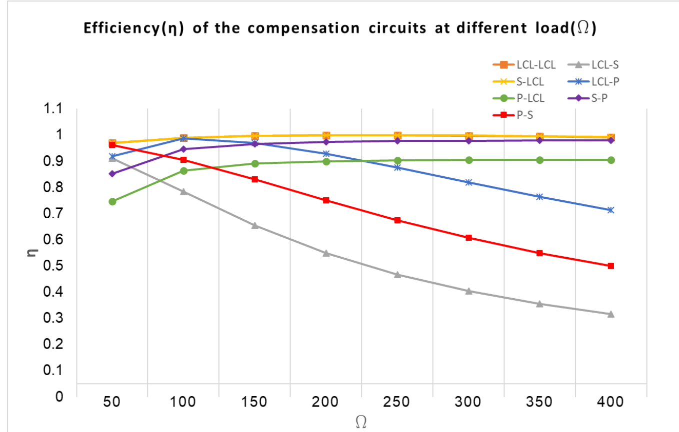


Fig. 6: Efficiency η of the compensation circuits at different Load values Ω

VI. Conclusion

This paper proposed a V2V charging platform exploiting the advances of plug-in charging and wireless charging technologies. The main reasons inhibiting the sales of EVs are the limited number of plug-in stations and the power capacity of batteries. While an ideal battery that is compact, high capacity and low-cost remains elusive, by promoting each EV from simply a power consumer to an energy provider, this platform is able to build a grid for transmitting power between EVs, significantly improving the efficiency and convenience of travelling using an EV.

This paper presents the fundamentals of calculating power capacity and cost of EV when EV as an power supplier. In addition, a detail comparison of different coil shapes/ combinations and the compensation circuit topologies for wireless V2V charging system are proposed. The ANSYS simulation results show that the square-square coil combinations have a good performance for wireless charging. Considering the key difference between wireless V2V charging and common wireless EV charging is that V2V charging needs double-direction compensation, LCL-P/(P-LCL) and LCL-LCL compensation circuit are shown to provide the best performance. In future work, the authors will focus their attention on the hardware implementation of this proposed wireless V2V charging system.

References

[1] C. Iclodean, B. Varga, N. Burnete, D. Cimerdean, and B. JurchiÅ§, "Comparison of different battery types for electric vehicles," *IOP Conference Series: Materials Science and Engineering*, vol. 252, no. 1, p. 012058, 2017.

[2] T. B. consulting group, "Batteries for electric cars: Challenges, opportunities, and the outlook to 2020." [Online]. Available: https://www.bcg.com/documents/file36615.pdf

[3] A. Ahmad, M. S. Alam, and R. Chabaan, "A comprehensive review of wireless charging technologies for electric vehicles," *IEEE Transactions on Transportation Electrification*, vol. 4, no. 1, pp. 38–63, March 2018.

[4] X. Mou, O. Groling, and H. Sun, "Energy-efficient and adaptive design for wireless power transfer in electric vehicles," *IEEE Transactions on Industrial Electronics*, vol. 64, no. 9, pp. 7250–7260, Sept 2017.

[5] C. Cai, J. Wang, Z. Fang, P. Zhang, M. Hu, J. Zhang, L. Li, and Z. Lin, "Design and optimization of load-independent magnetic resonant wireless charging system for electric vehicles," *IEEE Access*, vol. 6, pp. 17 264–17 274, 2018.

[6] S. Li and C. C. Mi, "Wireless power transfer for electric vehicle applications," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 3, no. 1, pp. 4–17, March 2015.

[7] C. Li, T. Ding, X. Liu, and C. Huang, "An electric vehicle routing optimization model with hybrid plug-in and wireless charging systems," *IEEE Access*, vol. 6, pp. 27 569–27 578, 2018.

[8] W. Kempton and J. Tomic, "Vehicle-to-grid power fundamentals: Calculating capacity and net revenue," *Journal of Power Sources*, vol. 144, no. 1, pp. 268 – 279, 2005.

[9] Y. Liu, R. Mai, D. Liu, Y. Li, and Z. He, "Efficiency optimization for wireless dynamic charging system with overlapped dd coil arrays," *IEEE Transactions on Power Electronics*, vol. 33, no. 4, pp. 2832–2846, April 2018.

[10] Y. Cheng and Y. Shu, "A new analytical calculation of the mutual inductance of the coaxial spiral rectangular coils," *IEEE Transactions on Magnetics*, vol. 50, no. 4, pp. 1–6, April 2014.

[11] H. Zeng, Z. Liu, Y. Hou, T. Hei, and B. Zhou, "Optimization of magnetic core structure for wireless charging coupler," *IEEE Transactions on Magnetics*, vol. 53, no. 6, pp. 1–4, June 2017.

[12] S. Baroi, M. S. Islam, and S. Baroi, "Design and simulation of a wireless charging system for electric vehicles," in *2017 2nd International Conference on Electrical Electronic Engineering (ICEEE)*, Dec 2017, pp. 1–4.