Basic Study on Coil Configurations for Direct Wireless Power Transfer from Road to Wireless In-Wheel Motor

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The Wireless In-Wheel Motor (W-IWM) has been developed to provide high controllability for electric vehicles. While traditional in-wheel motors have had the possibility of their power or signal wires becoming disconnected, the W-IWM solves this problem by receiving both its power and control signals wirelessly. Another benefit of the W-IWM is that it can be powered directly from transmitter coils in the road. This paper discusses the design of the first trial unit, its limitations regarding wireless power transfer from the road, and proposed a novel configuration of coils for the current and future units which improves the transfer efficiency between the road and the wheel, while maintaining a high power transfer efficiency from the vehicle body to the wheel. The effectiveness and efficiency of the novel configuration, compared to that of the traditional configuration, is demonstrated through analyses of the measurements of the mutual inductances.

Keywords: In-Wheel Motor, Wireless Power Transfer, Electric Vehicle, Magnetic Resonance Coupling

1. Introduction

Electric Vehicles (EVs) have recently been gaining attention for being environmentally friendly. Additionally, EVs have a higher degree of controllability than traditional internal-combustion engine vehicles due to their use of motors, which respond quickly to torque commands and allow for accurate knowledge of the output torque simply by monitoring its current [1]. Because compact motors can be manufactured more easily than engines, EVs can have multiple motors distributed throughout its system. Small motors placed within each wheel, known as in-wheel motors, especially provide for a high degree of controllability. However, because their power and signal wires are subjected to constant bending, while being exposed to debris outside of the vehicle-body, the possibility of these wires becoming disconnected has been a problem.

In order to overcome this issue, the authors' research group has developed an in-wheel motor which has its power and signal provided wirelessly. The authors call this system the Wireless In-Wheel Motor (W-IWM). Other than the fact that the W-IWM solves the problem of the signal and power wires becoming disconnected, it also can be powered directly via wireless power transfer (WPT) from power-transmitting coils in the ground, allowing for EVs to extend their driving distance per charge. As their limited driving distance per charge is considered to be a major factor which hinders the widespread adoption of EVs, this is a significant benefit.

In this paper, the road-to-wheel direct WPT for the W-IWM will be discussed. In order to provide a basis for this preliminary discussion, the authors first examine the capabilities of the primary prototype unit regarding road-to-wheel WPT. From this basis, proposals will be made for the modifications necessary to achieve road-to-wheel wireless power transfer. As this is a dynamic WPT system, in which the EV will be in motion as it is powered by the coils in the road, the effects of misalignment will be examined closely in terms of the W-IWM.

This paper is organized in the following manner: In Section 2, the WPT expectations of the W-IWM, as well as its ultimate goals, are outlined. In Section 3, the limitations of achieving direct road-to-wheel power transfer in the first prototype W-IWM, are discussed. In Section 4, a novel coil configuration is proposed for the W-IWM, which makes road-to-wheel power transfer practical. Then, in Section 5, the practicality of the novel configuration is compared to the traditional configuration for the road-to-wheel powering scheme through measurements and analyses. Section 6 gives a summary of the paper with an outline of the topics of future work.

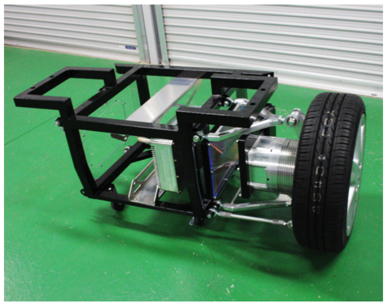

Fig. 1. The Primary W-IWM Unit Prototype

2. WPT for the W-IWM

The prototype unit of the W-IWM is shown in Fig. 1. WPT

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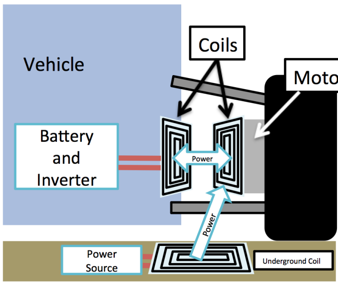

Fig. 2. The Concept of the W-IWM

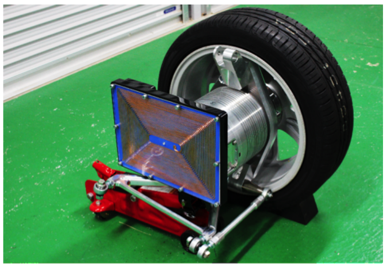

Fig. 3. The Wheel Side of the W-IWM

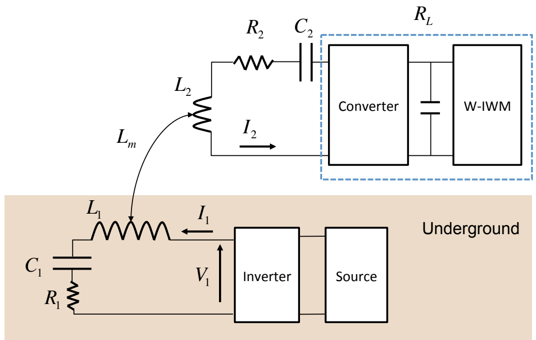

Fig. 4. Road-to-Wheel Power Transfer Circuit

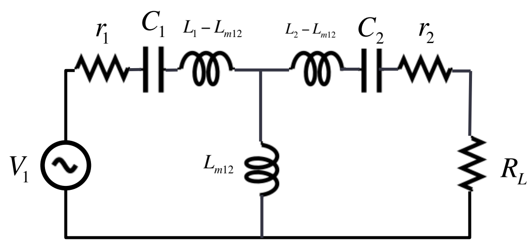

Fig. 5. Equivalent Circuit for WPT

in the W-IWM occurs in three ways, as shown in Fig. 2: between the vehicle and the wheel, between the road and the wheel, and between the road and the vehicle. In this paper, only the vehicle-to-wheel and road-to-wheel cases are considered, as this is a preliminary study and the road-to-vehicle case is not crucial in the operation of the W-IWM.

Since the transmitting and receiving coils of the W-IWM may become misaligned due to motion of the suspension system, we have opted to use the magnetic resonance coupling method for power transfer, as it is robust to misalignment [10]. This is also ideal for road-to-wheel power transfer, as the transmitting and receiving coils are not always aligned.

2.1 Vehicle-to-Wheel WPT Although road-to-wheel WPT is desirable, it is unrealistic and very limiting for a personal vehicle to only be able to drive on roads that are equipped with power-transmitting coils. Therefore, it is important that the vehicle can be powered from the battery loaded on the vehicle-body. However, in such a case, the battery has a limited charge and its efficient use becomes important. The primary prototype unit of the W-IWM is designed to operate at 3.3kW, and it has been demonstrated that the current configuration achieves high efficiency in vehicle-to-wheel WPT, with initial experiments recording 88.8% efficiency from the battery to the motor [4]. This is considered to be efficient enough to justify implementing the W-IWM.

The W-IWM side of the unit is equipped with a flat, rectangular receiver coil, visible in Fig. 3. The transmitting and receiving coils of the prototype were designed to achieve a mutual inductance around 50 μH, as this allows the transmitting side and receiving side voltages to be about the same at 350 V [2]. The coils include a ferrite backplate to allow for a higher mutual inductance.

2.2 Road-to-Wheel WPT Although powering the W-IWM via WPT from the vehicle has been demonstrated to be efficient and practical [2] [3] [4], direct road-to-wheel power transfer has yet to be achieved.

In designing this initial prototype unit, direct road-to-wheel powering was not considered. The WPT circuit of a ground-side transmitter coil to the wheel-side receiver coil is shown in Fig. 4. The mutual inductance, L_m, is small in this case due to the perpendicularity and distance of the coils. The receiver coil of the current W-IWM prototype is 20 cm from the ground. Furthermore, depending on the position of the road-side coil, cross coupling between the road-side coil and the vehicle-side coil would be approximately equal to the mutual inductance between the road-side and wheel-side coils.

In order to allow for widespread implementation of road-to-wheel WPT coils in our infrastructure, several things must be considered.

First, the road-side coils should be kept as simple as possible, meaning the large-scale use of expensive materials such as ferrite or powerful inverters and high-caliber electrical components to meet current and voltage requirements should be avoided.

Second, in a dynamic system such as the W-IWM, some misalignment between the receiver coil and transmitting ground coil must be allowed.

Third, both road-to-wheel and vehicle-to-wheel WPT should have high efficiencies, but the efficiency in road-to-wheel WPT is not as crucial as it is for the vehicle-to-wheel case, since the road presumably has no limit for how much charge it can provide. However, from an environmental and economical standpoint, it is still important to keep losses to a minimum.

2.3 Efficiency and Power Transferred The wireless circuits shown in Fig. 4 can be expressed as the equivalent circuit shown in Fig. 5. For simplicity, the transmitting-side (primary-side) source and inverter are replaced with an ideal AC voltage source with the effective value of V_1. In the same fashion, the receiving-side (secondary-side) converter, inverter for the W-IWM, and the motor itself are assumed to be a resistor with the value $R_L = 30\Omega$, which is calculated to be the approximate impedance of the system for optimal WPT. The input impedance as seen from the transmitter coil is then expressed as

$$Z_{in} = r_1 + \frac{(\omega_0 L_m)^2}{r_2 + R_L}, \qquad (1)$$

where r_1 and r_2 are the AC resistances of the primary and secondary coils, respectively, R_L is the equivalent resistance of the load, ω_0 is the angular resonance frequency, and L_m is the mutual inductance between the two coils. Since the total input power P_{in} is defined as

$$P_{in} = V_1 I_1 = \frac{V_1^2}{Z_{in}}, \qquad (2)$$

where V_1 is the effective values of the primary-side voltage, power transferred to the secondary side, P_2, is therefore defined as

$$P_2 = \left[\frac{(\omega_0 L_m)^2}{r_2 + R_L}\right]\left(\frac{V_1}{Z_{in}}\right)^2. \qquad (3)$$

The power lost in the transmitter-side AC resistance, P_1, is defined as

$$P_1 = r_1 \left(\frac{V_1}{Z_{in}}\right)^2. \qquad (4)$$

Furthermore, the efficiency of WPT can be calculated as [6]

$$\eta = \frac{(\omega_0 L_m)^2 R_L}{(R_L + r_2)(r_1 R_L + r_1 r_2 + (\omega_0 L_m)^2)}. \qquad (5)$$

Since the wheel-side coil will not be modified in this study, and the operating frequency will be maintained, an increase in efficiency is only possible with an increase in L_m.

2.4 Cross Coupling It is also important to note that this system has three coils, each of which can, depending on the operation and control mode, become a transmitter, receiver, or a shorted coil. The wheel-side control regularly shorts the coil to maintain the desired voltage [4]. The vehicle-side coil will mainly transmit to power the W-IWM. However, if the W-IWM is regenerating, or if the power provided by the road is more than sufficient to drive the W-IWM, the vehicle-side coil will act as a receiver. The wheel-side coil in the prototype uses a hysteresis comparator to regulate its voltage, and alternates between receiving power and short-circuiting its coil. This makes it effectively behave as both a receiver coil and a repeater coil. The road-side coil acts simply as a transmitter.

Depending on the mode, there exists multiple receivers and multiple transmitters within the system. Cross-coupling between unwanted coils, such as the vehicle-side and road-side coils when they are both transmitting, should be avoided, as it can degrade transmission efficiency and limit the amount of power that can be transmitted [8] [9].

3. Road-to-Wheel WPT Capabilities of the Prototype Unit

The goal of the W-IWM is to achieve road-to-wheel dynamic WPT. That is, the system is envisioned to be able to operate solely, if not largely, with power from the ground, and limiting the use of battery power. Furthermore, the onboard battery should be chargeable from the coils in the ground.

Table 1. Parameters of the Coils

Parameter	Road	Wheel
AC Resistance	2.06 Ω	0.382 Ω
Inductance	1355 μH	223 μH
Size	730 x 610 mm	300 x 218 mm
Mutual Inductance	11.55 μH	
Resonance Frequency	85 kHz	

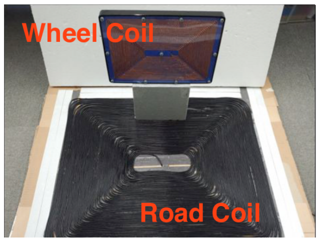

Fig. 6. Prototype Road-Side Coil and Wheel-Side Coil

In order to increase the mutual inductance L_m between the road-side and wheel-side coils with the current configuration, their individual inductances must be increased. However, due to space constraints on the W-IWM unit, increasing the size of the wheel-side coil is impossible. Therefore, a large road-side coil, shown in Fig 6, was constructed to measure the direct road-to-wheel WPT capabilities of the prototype unit, which was designed to operate with 3.3 kW of transferred power. The design of this coil will be discussed further in Section 4.

3.1 The Road-to-Wheel Mutual Inductance Table 1 shows the parameters of the road-side coil in comparison with that of the wheel-side coil. Here, two things must be noted. First, increasing the size of the coil not only increases its inductance, but also increases its internal resistance. Second, with this configuration, despite the relatively large size of the road-side coil, the road-to-wheel mutual inductance is still only 11.6 μH, while the vehicle-to-wheel mutual inductance is 48.6 μH.

With such a low L_m, from Eq. (1), the impedance Z_{in} decreases. In order to send 3.3 kW, from Eqs. (2)-(4), the voltage across the ground coil is found to be $V_1 = 171.1$ V. Therefore, the current through the ground coil I_1, calculated to be

$$I_1 = \frac{V_1}{Z_{in}}, \qquad (6)$$

which yields a value of 51.7 A. This puts a tremendous burden on the primary side power source, which must produce more than 50 A of alternating current at a frequency of 85 kHz.

Furthermore, from Eq. (5), the theoretical efficiency of road-to-wheel WPT is calculated to be 37.3%. This leads to 5.6 kW in copper losses when transferring 3.3 kW to the load. These low efficiency and high primary-side current values are unacceptable for WPT.

4. Novel Coil Configuration Designed for Road-to-Wheel WPT

The coil configuration of the current prototype is deemed undesirable for road-to-wheel WPT. Therefore, a novel coil configuration is proposed, where the W-IWM is mounted

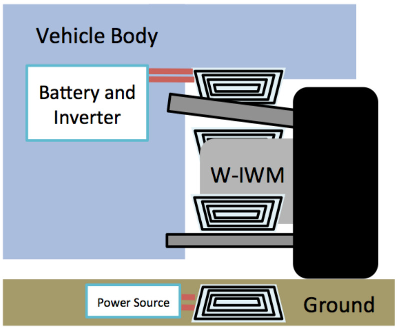

Fig. 7. Proposed Coil Configuration

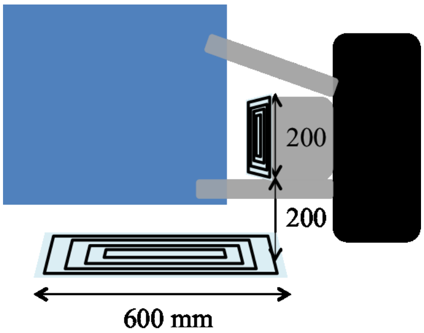

Fig. 8. Conventional Orientation

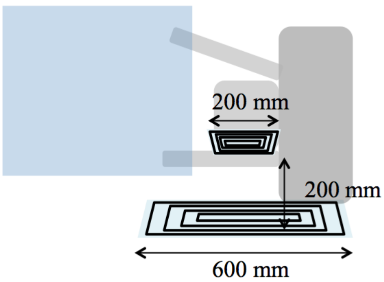

Fig. 9. Proposed Orientation

with a coil positioned parallel to the ground. The coil configuration for future prototype units are envisioned to be like the configuration seen in Fig. 7. In the pictured configuration, the W-IWM is mounted with two coils, each serving for road-to-wheel and vehicle-to-wheel WPT separately.

4.1 The Proposed Orientation In this configuration, the coil which was previously perpendicular to the road is now parallel to the road. This allows for a more ideal configuration for road-to-wheel WPT, while the vehicle-side and wheel-side coils maintain their parallel orientation with respect to one another, which is ideal of WPT. Furthermore, this configuration not only provides a higher mutual inductance between the road-side and wheel-sue coils, but also keeps the vehicle-side and road-side coils further apart, minimizing potential effects of unwanted coupling.

4.2 Design and Construction of the Road-Side Coil While the road-side has no spatial limitations when it comes to installing a large coil, there are two things that limit the construction of a needlessly large coil. One thing is that, while having a mutual inductance that is too high will im-

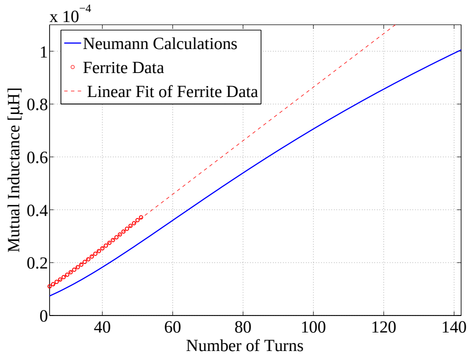

Fig. 10. Neumann Calculations and Data with Ferrite

prove efficiency, the impedance, from Eq. 1, will increase on the transmitting side. This will require the road-side inverter to operate at a higher voltage. In order to avoid this, the authors aimed at a mutual inductance of about 50 μH, which is what the vehicle-to-wheel mutual inductance is [2]. This allows for the transmitting and receiving sides to operate at the same voltage of 350V. Furthermore, increasing the size of the transmitting coil increases its internal resistance, which hurts the efficiency of WPT. Therefore, it is desirable to construct the coil to be as small as possible while still being large enough to guarantee a mutual inductance of 50 μH around the center.

To accomplish this, the Neumann formula was used to design the road-side coil. The Neumann formula is described as

$$L_m = \frac{\mu_0}{4\pi} \oint_{C_1} \oint_{C_2} \frac{dl_1 \cdot dl_2}{D}, \tag{7}$$

where μ_0 is the magnetic permeability, dl_1, dl_2 are the line elements for the line integers C_1 and C_2, and D is the distance between the elements. This can be used to calculate the mutual inductance of coils [10]. From this, a range of road-side coils starting at the same size as the transmitter coil, with an increasing number of turns and size, were calculated. However, because the receiving wheel-side coil has a ferrite backplate, simply using the Neumann formula would not be accurate. As the ferrite is used to increase the mutual inductance [4], the necessary coil size should be smaller than the value projected by the Neumann formula.

In order to account for the effect of the ferrite, a road-side coil was constructed, and measurements of its mutual inductance with the receiving coil of the W-IWM were taken as its size was varied from twice the size of the receiver to approximately the same size.

Fig. 10 shows the Neumann calculations, the data taken of the mutual inductance between the road-side coil varying in size and the wheel-side coil, as well as a linear fit to approximate the size necessary. The fit of the data suggests that the wheel-side coil and the road-side coil will have a mutual inductance of over 50 μH when the road-side coil is around 70 turns. This would be a coil of approximately 720mm x 600mm in size.

The road-side coil, shown in Fig. 6, was made slightly larger to be a size of 730 mm x 610 mm, but with only 58 loops, as small loops in the center of the coil are found to have a negligible effect on the mutual inductance, while causing

Table 2. Mutual Inductances and Efficiency

Parameter	Conventional	Proposed
Road-to-Wheel L_m	11.55 μH	50.38 μH
Road-to-Wheel Efficiency	37.3%	90.9%
Resonance Frequency	85 kHz	

significant losses. This led to a mutual inductance of 50.38 μH.

4.3 Comparisons with the Conventional Orientation The mutual inductances between the wheel-side and ground-side coils were measured. For the conventional orientation, shown in Fig. 8, the off-center positioning of the wheel-side coil was chosen to yield the highest mutual inductance. Similarly, in the proposed orientation shown in Fig. 9, the wheel-side coil was positioned in the center to yield the highest mutual inductance. The measured mutual inductances, as well as the calculated efficiencies for the conventional configuration and the proposed configuration are shown in Table 2. When compared to the conventional configuration, the newly proposed configuration provides a higher mutual inductance between the road-side and wheel-side coils. In thee proposed orientation, when compared to the conventional orientation, the mutual inductance increases nearly fivefold, and the efficiency increases from a calculated efficiency of 37.3% to a calculated efficiency of 90.9%. The road-side coil, shown in Fig. 6, was constructed with nylon insulated wire, but could yield a lower internal resistance, and therefore a higher transfer efficiency, if constructed with more efficient wires such as Litz wires.

This also reduces the necessary primary-side current, making the design of the ground-side coil much less expensive and more realistic for widespread implementation in our infrastructure.

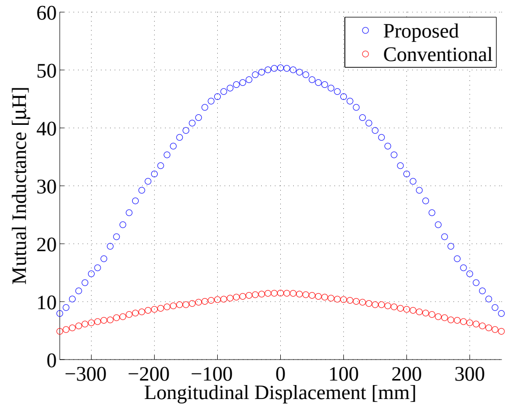

Fig. 11. Mutual Inductances with Displacement

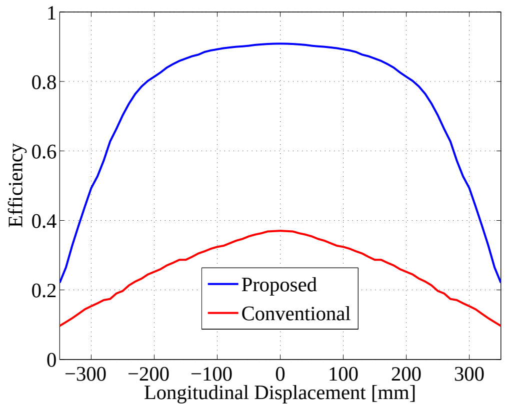

Fig. 12. Calculated Efficiency with Displacement

5. Measurements and Analysis

In order to demonstrate the effectiveness of the proposed orientation, measurements of the actual mutual inductance and analyses based on those measurements were made.

5.1 Misalignment and the Mutual Inductance The mutual inductances as the receiver coil is misaligned in the longitudinal direction was measured for both orientations, as shown in Fig. 11. Here, longitudinal signifies the direction along the longer length of the coils, or the direction of the vehicle's motion. The mutual inductances were assumed to be symmetrical along the center of the coil.

The efficiency at each point was calculated, as shown in Fig. 12. This was calculated by assuming the W-IWM to be a pure resistance, with its value set to 30 Ω. This value is determined to maximize efficiency while keeping the motor within the operable range. It can be clearly seen that the proposed orientation is more efficient than the conventional orientation. The conventional orientation has its maximum mutual inductance near the lateral edge of the road-side coil. As it approaches the center, it becomes lower and lower until the efficiency is nearly zero. Therefore, in the conventional case, the lateral displacement of the conventional orientation was set to 250 mm, as it was near-zero efficiency across the board when lateral displacement was zero. Even at 250 mm lateral displacement, the conventional orientation showed to only reach 37%, and declines more rapidly as it becomes misaligned.

The proposed orientation on the other hand, proved to be much more robust to misalignment. The calculated efficiencies remain above 80% for most of the length of the coil, with its peak efficiency being above 90%.

However, due to the fall in mutual inductances, even though the efficiency may be high enough, actually transferring 3.3 kW becomes a problem due to the high current that becomes required. Fig. 13 demonstrates this problem, as it shows the transmitting-side current requirements to transfer the rated power of 3.3 kW with respect to the misalignment of the coils. The current limit of 15 A is the maximum allowable current of the capacitors used on the transmitting side. The conventional orientation is shown to require huge amounts of current.

Fig. 14 represents how much power can be transmitted while limiting the current through the primary side circuitry to a value of 15 A. This further demonstrates that the original coil configuration cannot send anywhere near the maximum power of 3.3kW for our prototype W-IWM, while the proposed coil configuration can achieve rated power for about half of the length of the coil. Near the edges, although it cannot achieve rated power under these limitations, it can still provide sufficient power to operate the W-IWM. Further improvements to the maximum transferrable power is thought to be made possible with longer coils on the road-side.

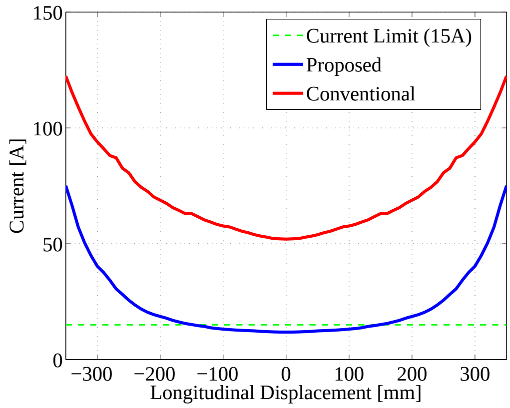

Fig. 13. Calculated Road-Side Current

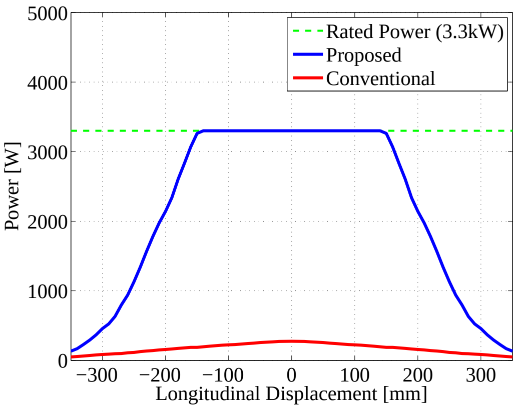

Fig. 14. Calculated Transferrable Power

6. Conclusion and Future Work

In this paper, the overall concept of the Wireless In-Wheel Motor, as well as the ultimate goal to power it directly from coils in the road, was discussed. As a preliminary study, the road-to-wheel WPT capabilities of the current W-IWM were examined, and the authors concluded that in order to achieve WPT from the road without any modifications, the requirements of the primary side circuitry would be too impractical, as there would need to be over 50 A of current with an efficiency of 37.3%.

Therefore, the proposal for a new system which faces the receiver coil to the road was proposed, which envisions the configuration shown in Fig. 7. The advantages of this system compared to the conventional system, shown in Fig. 2, are that the road-to-wheel mutual inductance is increased, the vehicle-to-wheel mutual inductance is unchanged, and the vehicle-side transmitter and road-side transmitter coils are far apart, which could mitigate any negative effects of cross-coupling. The maximum calculated efficiency for this configuration, based on measurements of the mutual inductance, was found to be 90.9%.

The details of this configuration are the subject of future work. While the additional coil slightly increases the cost and weight of the system, these increases are thought to be negligible. In order to properly handle power from both the road and the vehicle, the circuitry of the W-IWM must be modified, and new control schemes are necessary to guarantee stable operation.

Measurements of the mutual inductances showed that the proposed configuration can achieve efficient road-to-wheel WPT. The road-side coil, shown in Fig. 6, was designed to provide a mutual inductance of about 50 μH with the receiver coil near the center. Longer coils could extend the efficient, high power regions shown in Fig. 11 and Fig. 14. Although in this paper, the coil was assumed to be similar in shape to the receiver, future designs will focus on optimizing and extending the range in which maximum power can be supplied.

While the conventional configuration was shown to be impractical for road-to-wheel powering, the proposed configuration is shown to be efficient. Furthermore, as this paper focused on keeping the transmitting side as simple as possible, direct road-to-wheel powering of the W-IWM is shown to be practical. Future work will focus on the wheel-side circuitry, the control methods to handle the power flow of multiple sources, and optimal coil design for a W-IWM capable of road-to-wheel dynamic WPT.

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