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Design and Analysis of Wireless Brushless DC Motor System with Primary Control

H. Wang, K. T. Chau, W. Liu, and T. Yang

Department of Electrical and Electronic Engineering, the University of Hong Kong, Hong Kong, China, ktchau@eee.hku.hk

Executive Summary

In this paper, a wireless brushless DC (BLDC) motor system is proposed and analyzed. Prominently, the secondary side is controller-less, as the control process is fully conducted at the primary side. Also, it is not necessary to specially design the motor, as most existing BLDC motors can directly be used. The key is to design a self-driving circuit at the secondary side for the motor, and the control command is retrieved from the wireless power transfer. As a result, the proposed wireless BLDC motor system takes the definite advantages of being electrocution-free and sealable. Computer simulations are conducted to verify that the motor can be flexibly controlled through the primary controller.

Keywords: Wireless charging, synchronous motor, inverter, control system, self-driven.

1 Introduction

As wireless power transfer (WPT) technology can charge the load without physical contact [1], it has been seen as the most preeminent way and promising solution to charge electric vehicles [2]-[4], hand-held [5] and Internet of Things devices [6] nowadays. With successive accomplishments in energy-on-demand wireless power transfer [7] and high efficiency [8] along with electromagnetic energy safety [9] and multi-coil design [10], it is specially fit to charge electric loads in isolated environments [11] or under moving conditions [12]. Therefore, multi kinds of wireless lamps [13], wireless heaters [14], and wireless motors [15] are studied.

For wireless motors, they have more advantages than traditional wired motors [16]. For example, when employing wireless motors in robotic arms, robotic arms can obtain more freedom of movement [17], as there is no need to worry about the power line or signal line limitation. Therefore, robotic arms are free to move irregularly or rotate in one direction continuously with wireless electric motors.

Moreover, it is more reliable to use the wireless motor underwater, such as in piping networks [18] or in submersible pumps. As the wastewater may contain corrosive liquid, the power line protection layer may be corroded, while wireless motors can be totally sealed without leakage problems. Also, unlike traditional wired electric motors, which need to acquire energy from the power grid deployed along with the wired piping network, the power supply system for the piping motor is much easier to be settled with WPT technology. To be more specific, the energy for wireless piping motors can be supplied through an electric energy car [19]. Thus, without complex power grid settlement and expensive maintenance, the system can be safer and more reliable.

For the first wireless motor [20], it is specially designed for the electric vehicle's hub motor. Without power lines abrasion and limitation, the hub motor can be more reliable and flexible. However, the motor control chip is very sensitive to high voltage and current, so it is not reliable to be employed at the remote side. Thus, multi kinds of wireless power and drive transfer (WPDT) technology for electric motors are studied, and all these load motors can be controlled through the single primary controller, such as WPDT for shaded-pole induction motor (SPIM) systems [21], WPDT for switched reluctance (SR) motor system [22], and WPDT for DC motor system [23]. However, from the perspective of power density and energy density, both these motors have obvious shortcomings [24], and the main reason is that there is no permanent magnet (PM) inside [25]. Although wireless DC motors also have been proposed and contain PM, the fragile carbon brushes and commutator need to be cleaned regularly to remove the carbon deposits.

Thus, a wireless single-controller brushless PM motor is more promising to be used in isolated environments. Since brushless DC (BLDC) motors are widely used in household and industry applications [26] because of their high torque density [27] and low costs [28], this paper designs the first wireless BLDC motor. The key is to use two-set three-phase LC branches at the receiver side to provide control signals for self-drive. Hence, the proposed wireless BLDC motor can be sealed to facilitate working in harsh or watery environments.

2 System Configuration and Operating Principle

2.1 System Topology

The proposed system is simplified in Fig. 1, where L_{TU}, L_{TL}, L_{RU}, and L_{RL} are inductances of the upper transmitter, lower transmitters, upper receiver and lower receiver, respectively; C_{TU}, C_{TL}, C_{RU}, and C_{RL} are capacitances of compensations of WPT coils with same subscript; I_{TU}, I_{TL}, I_{RU}, and I_{RL} are currents of WPT coils with same subscript; L_i and C_i (i=1, 2,…, 6) are inductances and capacitance of six-phase of LC tuning circuits; S_i (i=1, 2,…, 6) are switches that constituted the secondary inverter; I_i (i=1, 2,…, 6) are currents of six-phase LC branches, respectively, while I_M is the motor current.

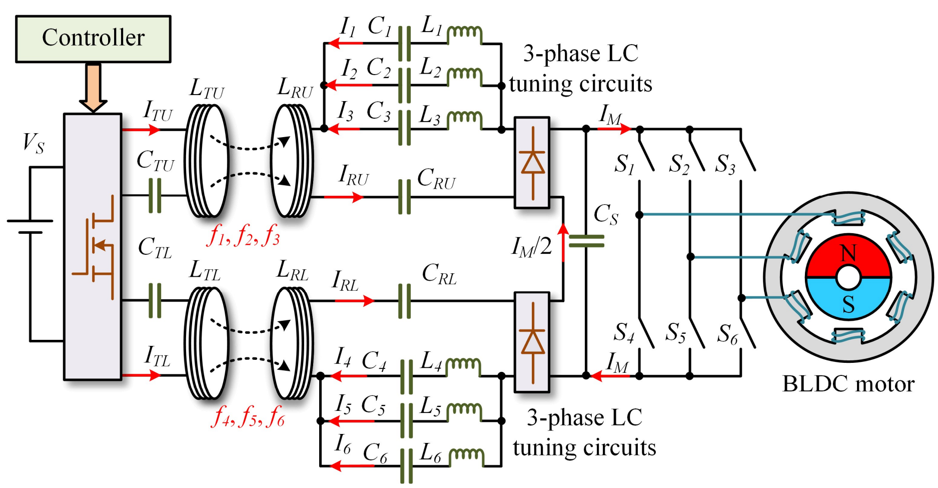


Figure 1: System configuration of the proposed wireless BLDC motor.

It should be mentioned that each pair of WPT coils are designed to transfer power at three different frequencies. To be more specific, the upper transmitting and receiving circuits are designed to transfer power at f_1, f_2 and f_3; while lower transmitting and receiving circuits are designed to transfer power at f_4, f_5 and f_6. Also, six-channel LC tuning circuits are specially designed to resonate at the aforementioned six frequencies with the same subscript, which can be expressed as [29]

$$2\pi f_i L_i = \frac{1}{2\pi f_i C_i} \quad (i = 1, 2, \cdots 6). \tag{1}$$

To control the secondary inverter, the voltages of capacitors C_i (i=1, 2,…, 6) are employed as control signals, and each voltage is used to drive one switch. As shown in Fig. 2, a transformer, a rectifier bridge, a Zener, and a RLC filter are used to isolate, rectify, reduce and stabilize the voltage of C_1, namely, V_{C1}. As a result, the desired control voltage V_{Con1} can be acquired and can be used to control the switch S_1.

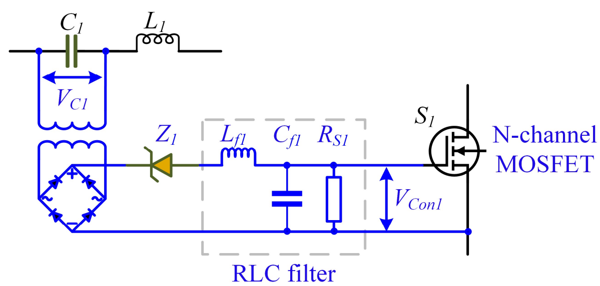


Figure 2: Control module for the first switch.

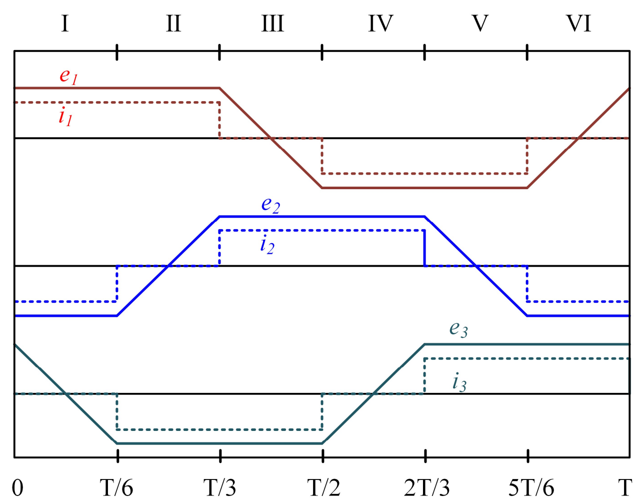


Figure 3: Six steps of BLDC motor in each period.

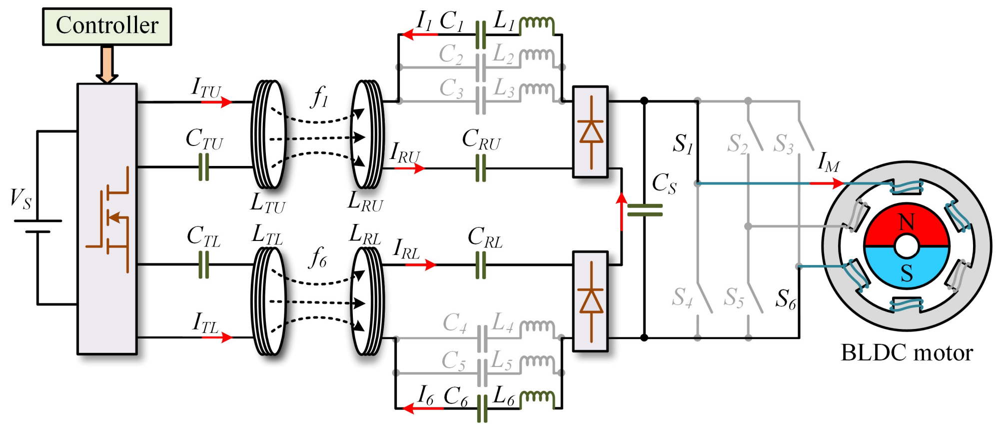
For the closed-loop control, a wireless resolver can be used to transfer the rotor position to the primary side. As it is detailed in [30], this part is omitted in this paper.

2.2 Motor Phase Control

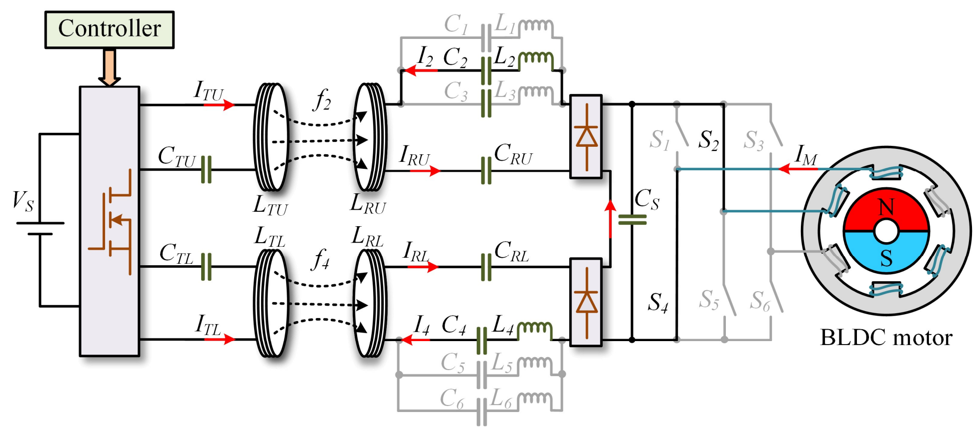
As we all know, for a three-phase BLDC motor, the operation can be divided into six steps [31]. In each step, the primary side will charge the upper and lower receivers at the same time, to activate one higher and one lower inverter arms. Thus, the secondary side can form a loop without the secondary controller.

Taking the second step as an example, as shown in Fig. 4(a). When the primary side charges the upper and lower receivers with frequency f_1 and f_6, respectively and simultaneously, the receiver currents mainly flow through the first and sixth LC tuning circuits because only these two are fully resonant, while others have too high impedances. As a result, the voltage of capacitors C_1 and C_6, namely, V_{C1} and V_{C6} can be very high and can be used to drive S_1 and S_6.

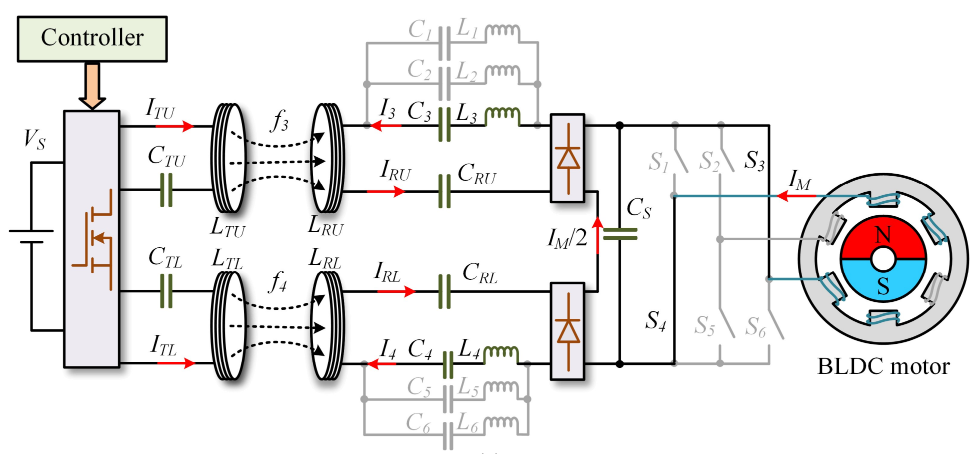
Similarly, when the primary side charges the upper and lower receivers with frequencies f_2 and f_4, respectively, the receiver currents mainly flow through the second and fourth LC tuning circuits. As a result, V_{C2} and V_{C4} can be used to drive S_2 and S_4, as shown in Fig. 4(b).



(a)



(b)



(c)

Figure 4: Simplified circuit of wireless BLDC motor. (a) In the second step. (b) In the fourth step. (c) In the fifth step.

Moreover, when the primary side charges the upper and lower receivers with frequencies f_3 and f_4, respectively, the receiver currents mainly flow through the third and fourth LC tuning circuits. Thus, V_{C3} and V_{C4} can be used to drive S_3 and S_4, as shown in Fig. 4(c).

For the whole cycle, the required control voltage can be extracted, as shown in Fig. 5. In other words, the load machine can rotate without involving the motor controller at the secondary side. Also, bi-directional rotation can easily be achieved by regulating the frequency sequence during the power transfer process.

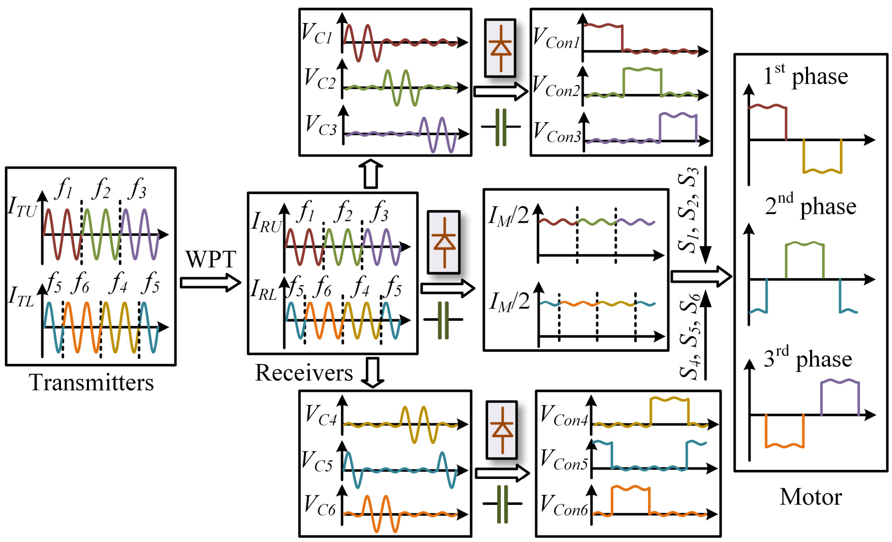


Figure 5: Current and voltage transfer diagram.

3 Transmitting and Receiving Circuits Design

As aforementioned, each pair of WPT coils should transfer power at three different frequencies. To simplify the system, a series capacitor is used for compensation, and the resonant frequencies of upper and lower circuits, namely, f_U and f_L, are expressed as

$$\begin{cases} f_U = \dfrac{f_1 + f_2 + f_3}{3} \\ f_L = \dfrac{f_4 + f_5 + f_6}{3} \end{cases}. \tag{2}$$

To improve the power factor, f_1, f_2 and f_3 are near to f_U, while f_4, f_5 and f_6 are near to f_L. To be more specific, the frequency difference should be limited to 5 kHz. However, the system selectability may be impaired with such a small frequency difference. Taking the upper receiver as an example, the current of each circuit can be expressed as [32]

$$\begin{cases} I_1 = I_{RU} \dfrac{Z_{LC1} \,||\, Z_{LC2} \,||\, Z_{LC3}}{Z_{LC1}} \\ I_2 = I_{RU} \dfrac{Z_{LC1} \,||\, Z_{LC2} \,||\, Z_{LC3}}{Z_{LC2}} \\ I_3 = I_{RU} \dfrac{Z_{LC1} \,||\, Z_{LC2} \,||\, Z_{LC3}}{Z_{LC3}} \end{cases} \tag{3}$$

where Z_{LC1}, Z_{LC2} and Z_{LC3} are impedances of the first, second and third LC tuning circuits, respectively.

When the primary side provides the power at f_1, the branch currents in (3) becomes

$$\begin{cases} I_1 = I_{RU} \dfrac{R_{LC1} \| Z_{LC2} \| Z_{LC3}}{R_{LC1}} \\ I_2 = I_{RU} \dfrac{R_{LC1} \| Z_{LC2} \| Z_{LC3}}{Z_{LC2}} \\ I_3 = I_{RU} \dfrac{R_{LC1} \| Z_{LC2} \| Z_{LC3}}{Z_{LC3}} \end{cases} . \tag{4}$$

where R_{LC1} is the inner resistance of the first LC tuning circuit.

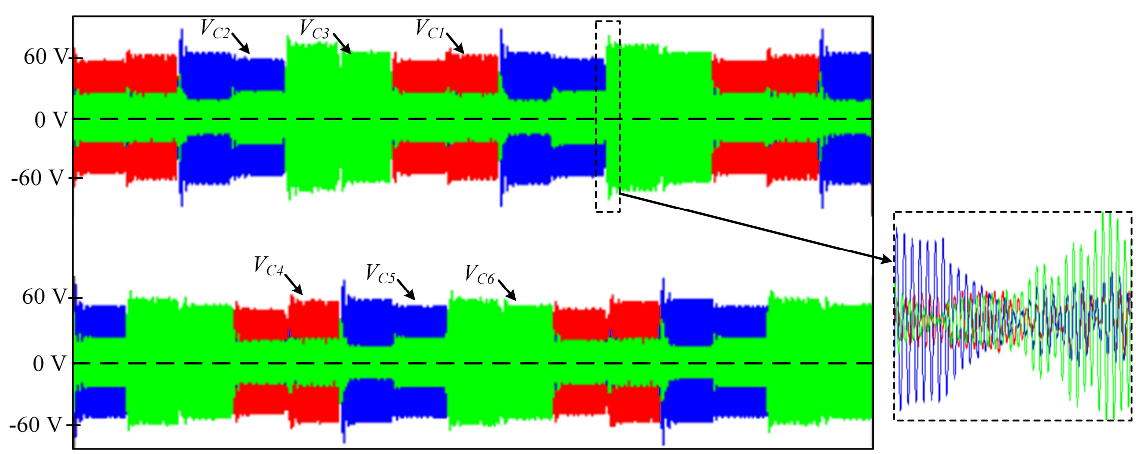
Since the second and third LC tuning circuits also operate at near-resonant condition, Z_{LC2} and Z_{LC3} should not be very high under this condition. Thus, the voltages V_{C2} and V_{C3} may be a little higher than zero, which may switch on S_2 and S_3 accidentally.

To completely turn off the MOSFET when the corresponding LC tuning circuit is not selected, a Zener is highly required to reduce the capacitor voltage in the control module, and that's the reason why Z_1 is depicted in Fig. 2. The voltage regulation value can be set to 3V or 5V, depending on the inner resistance of LC branches in real applications.

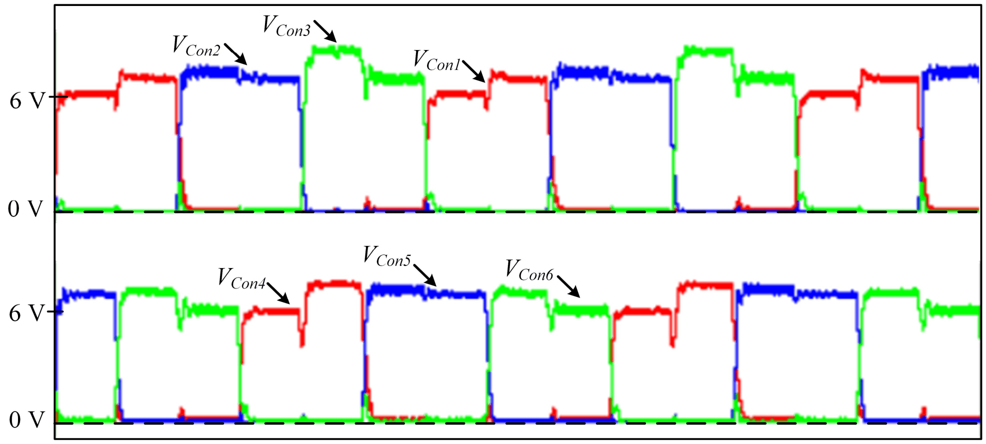
Therefore, three close frequencies can be selected to transfer three-phase power, and a simple series-series compensation structure can be employed. Meanwhile, the unwanted switch will not be switched on accidentally.

Table 1: System parameters

Item	Value	Unit
L_{TU}, L_{TL}, L_{RU}, L_{RL}	300, 300, 300, 300	μH
C_{TU}, C_{TL}, C_{RU}, C_{RL}	8.44, 8.44, 8.44, 8.44	nF
L_1, L_2, L_3, L_4, L_5, L_6	53.36, 50.66, 51.06, 53.36, 50.66, 48.27	μH
C_1, C_2, C_3, C_4, C_5, C_6	52.6, 50, 45, 52.6, 50, 47.6	nF
f_1, f_2, f_3, f_4, f_5, f_6	95, 100, 105, 95, 100, 105	kHz
f_U, f_L	100, 100	kHz
Transformer ratio	3:1	
Zener breakdown voltage	4	V



(a)



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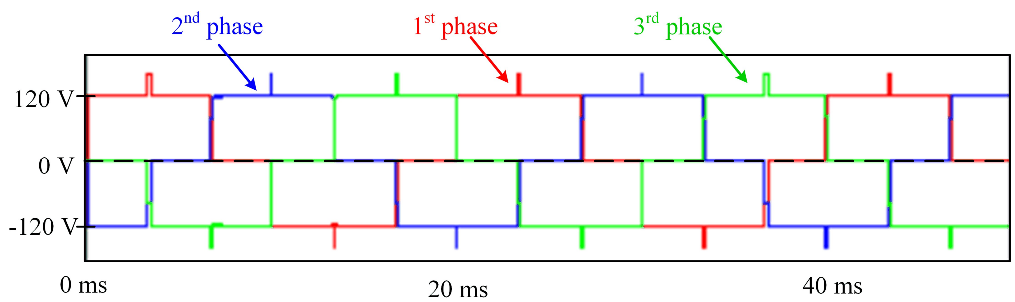

(c)

Figure 6: Simulation results. (a) Capacitor voltages. (b) Control signals. (c) 3-phase load voltages.

4 System Analysis

For verification, a circuit simulation is conducted, and key parameters are given in Table. 1. It should be mentioned that three 100 Ω resistors are used to replace the load motor to avoid the effect of back-emf. The results are shown in Fig 6, which are consistent with the theoretical analysis.

When the primary side provides the power with the designed frequency sequence in Fig. 5, upper and lower three-phase LC tuning circuits are activated in turns. As shown in Fig. 6(a), the receiver currents mainly flow through the resonant LC tuning circuit, thus the voltage of the corresponding capacitor is high. Therefore, the signal for MOSFETs can be extracted, as depicted in Fig. 6(b). As a result, 50 Hz three-phase AC power can be acquired at the secondary side, thus the BLDC motor can be driven wirelessly, as depicted in Fig. 6(c). Besides, it is worth to be mentioned that the load motor can be driven from 10 Hz to 500 Hz, and the waveforms are basically the same.

5 Conclusion

In this paper, a secondary controller-less wireless BLDC motor is designed, which uses six-LC tuning circuits to replace the motor controller at the secondary side. Therefore, the secondary side is very robust and can be employed in isolated environments, such as submerged pumps or pipeline cleaning pigs. Meanwhile, there is no need to specially design the BLDC motor, as most BLDC motors can be directly used. A circuit simulation is used to verify this system, which proves this system works well without a secondary controller.

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Presenter Biography

Wei Liu received the B.Eng. and M.Eng. degrees in electrical engineering from China University of Petroleum, Qingdao, China, and the Ph.D. degree in electrical and electronic engineering from The University of Hong Kong (HKU), Hong Kong, China, in 2014, 2017, and 2021, respectively. He is currently a Research Assistant Professor with the Department of Electrical and Electronic Engineering, HKU. He also worked as a Visiting Researcher with Nanyang Technological University, Singapore (NTU), since 2019. His research interests include wireless power transfer, power electronics, artificial intelligence, and electric vehicle technologies. Dr. Liu was the recipient of Power Engineering Prize from HKU, Excellent Paper Awards and Best Presentation Award from international conferences in the area of Electric Vehicles and Transportation Electrification. He is also a Guest Editor of international journals and a Session Chair of international conferences.