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Wireless Power, Drive and Data Transfer for Ultrasonic Motors

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***Abstract*—Wireless motors offer significant advantages in terms of installation flexibility and cable-free features but inevitably require multiple power semiconductors and electronic components at the receiver side to achieve wireless movement. Moreover, motor speed information is difficult to capture due to technical impediments in realizing wireless speed-sensorless communication. To address these issues, a novel wireless ultrasonic motor (USM) system with highly integrated wireless power, drive and data transfer (WPD^{2}T) is newly proposed in this paper. Innovatively, the proposed WPD^{2}T takes advantage of inherent capacitive characteristics of the USM to simultaneously realize wireless power transfer, wireless drive control, and sensorless speed information communication using a highly integrated magnetic coupler (IMC) with series inductors only, thus greatly simplifying the system structure and improving reliability, flexibility and compactness. Promisingly, the proposed WPD^{2}T system exhibits great potential for miniaturization and biomedical implantable millirobots due to its minimalist structure and flexible controllability. Both theoretical analysis and experimental results are conducted to verify the feasibility of the proposed WPD^{2}T system.**

***Index Terms*—Wireless motor, wireless power, drive and data transfer, speed sensorless.**

I. Introduction

WIRELESS power transfer (WPT) is an emerging charging technology that eliminates the need for cables or wires with convenience and safety [1]-[3], which exhibits immense potential in various applications such as charging portable electronic devices [4], biomedical applications [5], wireless energy routers [6], and electric vehicles [7].

With the development of WPT technology, its seamless integration with motors has become a promising option in the field of motion control [8]-[10]. The application of wireless motors in robotic arms and automotive wheels improves maneuverability by eliminating the tangle of wires. Additionally, in sealed environments such as cleaning underground pipelines [11], wired motors may be susceptible to corrosion of insulating rubber and conductors due to wastewater. In contrast, wireless motors, benefiting from the wireless direct drive through the magnetic field coupling [12], can effectively avoid extreme cases of equipment corrosion.

Recently, various types of wireless motors have been researched with different features [13]-[16]. Wireless DC motors [13] offer the benefits of simple structure and easy control, but multiple sets of WPT coils are necessary to enable bidirectional motion. Wireless switched reluctance motors (SRMs) are highly robust and reliable [14], but their effective operation requires multiple WPT channels or multi-frequency WPT to sequentially excite the stator windings. Wireless shaded pole induction motors (SPIMs) provide full primary-side control capability, but bi-directional motion remains to be developed [15].

All the aforementioned wireless motors require complex compensating components and semiconductor power switches at the motor side to achieve secondary-side self-drive, which inevitably increases the system complexity and costs [16]. Also, bulky configurations hamper system integration and miniaturization, raising concerns for practical applications [17]. Very recently, a magnetic-free wireless ultrasonic motor (USM) [9] was first reported to achieve truly wireless direct drive by WPT, thus improving system robustness and reducing system complexity. Nevertheless, obtaining motor operating status and speed information is still technically challenging. Although the wireless resolver offers a promising solution [18], the complex configuration obstructs its widespread adoption.

To break the dilemma and address these issues, a novel wireless power, drive and data transfer (WPD^{2}T) system is proposed with the following innovations and contributions.

1) The proposed WPD^{2}T system innovatively utilizes the capacitive characteristics of USM to realize an optimal wireless motor system without any capacitors, power semiconductors and electronic components.

2) The proposed WPD^{2}T can simultaneously achieve wireless power-and-drive transfer as well as wireless speed information transfer with only an integrated magnetic coupler (IMC) with series inductors, which greatly reduces component count and simplifies the circuit layout and assembly process.

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3) Efficient and reliable motion can be readily achieved at the primary side, allowing flexible speed regulation and commutation without the need for complex auxiliary circuits.

4) Promising solutions for hermetic applications, especially biomedical implants with the advantages of wireless direct drive, battery-free nature and the simplest receiving end.

II. System Configuration and Analysis

A. Configuration of Proposed WPD^{2}T System

Fig. 1 shows the configuration of the proposed WPD^{2}T system, which mainly comprises five parts: two half-bridge inverters, primary compensating capacitors, an IMC with series inductors, a USM, and a load for wireless data transfer. It can be observed that the receiver side is extremely simplistic with no capacitors, power semiconductors, position sensors, and microcontrollers, which greatly contributes to a high degree of integration and maintenance-free operation. It is worth noting that the receiver inductors serve to compensate for the capacitance of the USM, considering the IMC and the inductors are connected in series, these three inductors can be removed if they are integrated directly into the IMC so that the USM can be directly driven by the IMC. Therefore, in the subsequent analysis, they are considered as a single unit to simplify the analysis. Furthermore, both wireless drive control and wireless data transfer can be entirely performed at the transmitter side without increased control complexity, thus facilitating flexible installation and completing sealing.

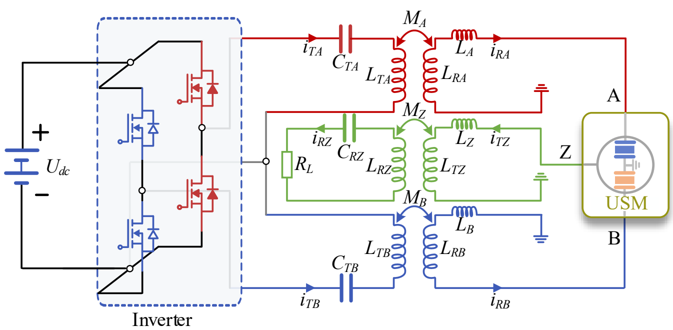


Fig. 1. Configuration of proposed WPD^{2}T system.

B. Comparison with Representative Wireless Motors

With the development of wireless drive technology, wireless motor systems have increasingly been developed. Fig. 2 shows the system configurations of representative wireless motors, which are wireless permanent magnet (PM) DC motor, wireless USM and wireless switched reluctance motor (SRM) with wireless resolver, respectively. The coupling mechanism is highlighted with colored dashed lines, where the red and green dotted lines in Fig. 2(b) indicate two different transmission channels, while in Fig. 2(c), the three channels with green dashed lines are for wireless power transfer and the two channels with red dashed lines are for wireless data transfer.

Wireless PM DC motors require rectifiers at the motor side for high-frequency AC power to DC power conversion as shown in Fig. 2(a). However, bi-directional motion cannot be realized unless active power switches and additional compensation circuitry are added. The wireless USM in Fig. 2(b) is more simplified compared to the wireless PM DC motor, as there is no power switch at the receiver side. Meanwhile, motor commutation control can be performed at the transmitter side, but the receiving end must be equipped with inductor and capacitor compensations. Moreover, the motor speed information cannot be observed wirelessly for either of the above wireless motors. Therefore, a wireless resolver for the SRM is developed in response to this issue, as shown in Fig. 2(c). Motor speed and rotor position can be transmitted wirelessly to the control end. However, the whole system is highly complex and cumbersome, which not only requires two independent sets of magnetic couplers but also extensive compensation components, which are not conducted for system integration and practical applications.

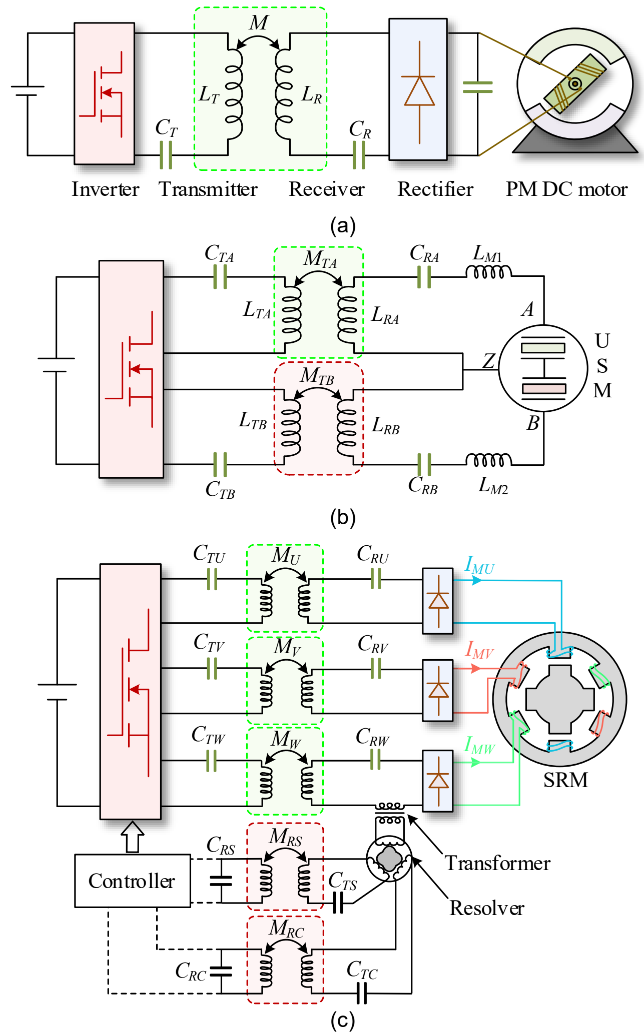


Fig. 2. Representative wireless motors. (a) Wireless PM DC motor [13]. (b) Wireless USM [17]. (c) Wireless SRM with wireless resolver [18].

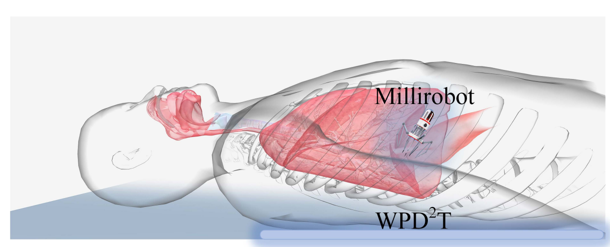


Fig. 3. Schematic of biomedical implantable millirobots.

Although these representative wireless motors can achieve effective wireless mobility, their system configurations are highly complex and the functionalities are not fully developed. To address these issues, a novel WPD^{2}T system with distinguished advantages is proposed, the contributions and novelties can be summarized as follows.

1) Multifunctional wireless motor system: Full primary control with flexible speed and commutation control can be easily performed at the transmitter side to greatly simplify the control complexity. Meanwhile, wireless speed-sensorless communication can be innovatively implemented without increasing any compensation and complexity, artfully enabling simultaneous WPD^{2}T.

2) Optimal wireless motor system: The USM is innovatively performed both as the driven mechanism as well as the compensating capacitors that resonate with the receiving coils (including the series inductors), enabling no compensating components, power devices, or auxiliary drive circuitry at the receiver side, making the proposed WPD^{2}T more compact and lightweight with high economy and flexibility.

3) Promising biomedical applications: Fig. 3 shows the potential application scenario of the proposed WPD^{2}T system in biomedical implantable millirobots. The elimination of power semiconductors and electronic components at the receiver side offers the WPD^{2}T system infinite possibilities for further miniaturization. Compared to its conventional counterparts, the wireless motor-embedded biomedical millirobots can be driven wirelessly and directly without battery charging. The convenience and sustainability of wireless direct drive allow biomedical millirobots to operate without interruption, which is important for tasks such as drug delivery and minimally invasive therapy that require continuous execution. Moreover, the wireless speed information transmission allows real-time observation of the operational status of millirobots, thus eliminating the need for speed sensors and facilitating further miniaturization.

III. System Design and Operating Principles

A. Design of Integrated Magnetic Coupler

The proper magnetic coupler design is essential for the feasible operation of WPT systems, especially for multi-channel transfer WPT, since different coupler topologies induce flux with different directions. The design of the bipolar coils is highly beneficial in enhancing the power transfer capability as well as increasing the tolerance of coil misalignment. In addition, the integration of unipolar and bipolar coils facilitates the realization of multi-load wireless power transfer. In this study, the designed magnetic coupler utilizes one unipolar coil and two orthogonal bipolar coils for simultaneous WPD^{2}T as shown in Fig. 4.

The two orthogonal bipolar coils, i.e., the vertical bipolar coil (coil A) and the horizontal bipolar coil (coil B), are designed for wireless power and drive transfer. The orthogonal overlap construction allows the magnetic flux generated by coil A to be orthogonal to that of coil B, which means the mutual inductance between the two coils is theoretically zero, thus realizing the magnetic decoupling. On the other hand, the unipolar coil Z is employed for wireless data transfer. The magnetic flux flowing into the Z-coil from the A and B coils is equal to the magnetic

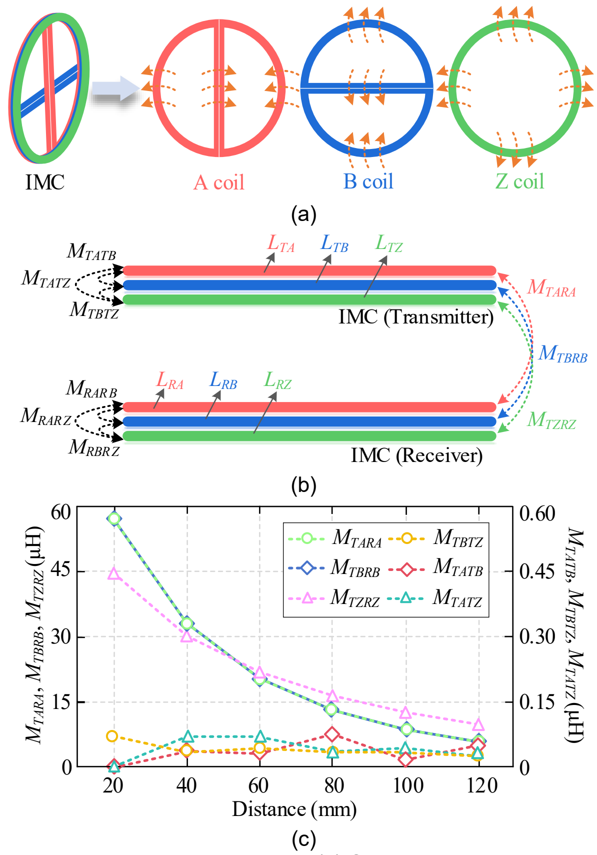


Fig. 4. Integrated magnetic coupler. (a) Structure and composition. (b) Direct and cross mutual inductances. (c) Mutual inductances with respect to transmission distance.

flux flowing out of the Z-coil, which results in zero net magnetic flux among the bipolar and unipolar coils.

In order to quantitatively analyze the characteristics of IMC, the mutual inductance against the transfer distance is investigated as shown in Fig. 4(c), where the left and right vertical axes are the scales of direct mutual inductance and cross mutual inductance, respectively, where the subscripts "T" and "R" denote the transmitter and receiver coils, respectively. It can be seen that the direct mutual inductance is more than 600 times larger than the cross-mutual inductance in close transmission, and even if the transmission distance is increased to 120 mm, there is still a difference of 100 times, so the cross-mutual inductance can be reasonably ignored. Therefore, each coil in the IMC can be well decoupled so that WPD^{2}T can be conducted simultaneously.

B. Wireless Power and Drive Transfer

The configuration of the proposed WPD^{2}T is shown in Fig. 5(a). Since the series inductors and IMC can be integrated, they are considered as a single unit for analysis. According to the physical structure of the USM, the stator mechanical quantities can be equated to suitable electrical quantities by the equivalent circuit model [19]. Therefore, the single-phase equivalent circuit of the proposed system is shown in Fig. 5(b), where the USM is directly driven by the orthogonal bipolar coils, and the simplified stator model of USM is composed of series-parallel connections of L_m, C_d, C_m, and R_m. It should be noted that for simplicity of analysis, the load torque and other characteristics due to pressure, temperature and friction are not considered in

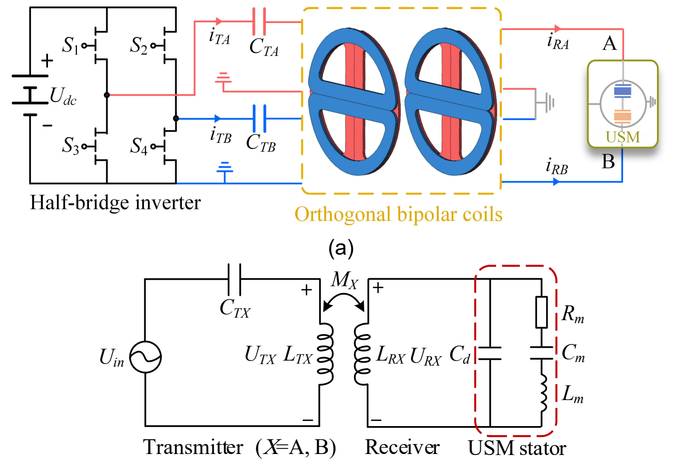


Fig. 5. Proposed wireless power and drive transfer. (a) Structure configuration. (b) Equivalent single-phase stator drive circuit.

the UMS model. The complete dynamic model of the USM can be found in [20], [21].

Under specific driving frequencies, the stator of USMs is externally capacitive. For further simplification, the equivalent stator model can be simplified to a series connection of the capacitor C' and resistor R', as shown in Fig. 6, where their values can be deduced as

$$\begin{cases} C' = \dfrac{1+\omega^2 C_p{}^2 R^2}{\omega^2 C_p R^2} \\ R' = \dfrac{R}{1+\omega^2 C_p{}^2 R^2} \end{cases} \tag{1}$$

where the intermediate variables C_p and R can be expressed as

$$\begin{cases} C_p = C_d - \dfrac{L'}{R_m^2 + (\omega L)^2} \\ R = R_m + \dfrac{(\omega L')^2}{R_m} \end{cases} \tag{2}$$

where $L'=L_m-1/(\omega^2 C_m)$,

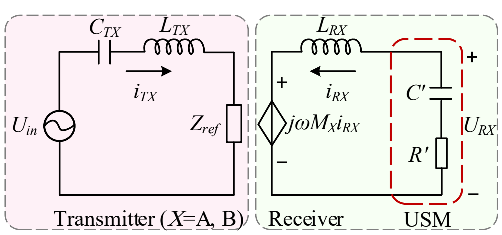


Fig. 6. Simplified equivalent model of single-phase drive circuit.

The operating performance of USMs is highly dependent on the quality of the driving voltage, and the high-order harmonics of the input voltage may be detrimental to their stable operation. Therefore, an impedance-matching circuit is generally added before the stator to improve the operating characteristics of USMs [22], [23]. In this study, the bipolar magnetic coupler is not only employed for wireless power and drive transfer but also as the inductive matching element for impedance matching of USMs to filter the input voltage so as to improve the load characteristics and drive capability.

According to Fig. 6, the impedance of the receiver side can be expressed as

$$Z_{RX} = j\omega L_{RX} + \frac{1}{j\omega C'} + R' \tag{3}$$

where ω is the operating angular frequency.

The reflected impedance from the receiver to the transmitter can be deduced as

$$Z_{ref} = \frac{(\omega M_X)^2}{Z_{RX}} = \frac{(\omega M_X)^2}{j\omega L_{RX} + \dfrac{1}{j\omega C'} + R'} \tag{4}$$

Based on Kirchhoff's voltage law, the following equation can be obtained as

$$\begin{cases} (j\omega L_{TX} + \dfrac{1}{j\omega C_{TX}} + Z_{ref}) i_{TX} = U_{in} \\ Z_{RX} i_{RX} = j\omega M_X i_{TX} \end{cases} \tag{5}$$

To maximize transmission efficiency, both the transmitter and receiver operate at the resonant frequency. Therefore, the receiver inductance can be deduced as

$$L_{RX} = \frac{\omega^2}{C'} \tag{6}$$

Accordingly, the output voltage U_{RX} can be calculated as follows

$$U_{RX} = \frac{U_{in}}{\omega^2 M_X C'} (1 + j\omega C' R') \tag{7}$$

The proposed driving topology can boost the voltage output to facilitate the wireless driving of USMs. By fully utilizing the capacitive characteristics of the USMs, the motor can be driven wirelessly with only a bipolar magnetic coupler. The receiver magnetic coupler is not only used for wireless power transfer but also forms resonance with the USM at a specific frequency to increase the drive voltage and compensate for the reactive power generated due to the capacitance nature of the USM. Therefore, the receiver side can be completely sealed for better integration, high robustness and maintenance-free operation.

C. Wireless Data Transfer

Currently, the speed information of wireless motors is difficult to capture due to the technical bottlenecks that still exist in the implementation of wireless speed sensors. To address this issue, a novel wireless sensorless speed data transfer using the arc-pole feedback of USM is proposed, which can seamlessly implement wireless speed information communication with the transmitter side.

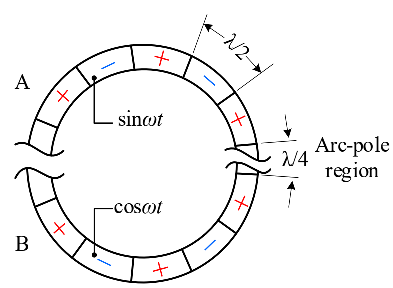


Fig. 7. Electrode structure of the piezoelectric ceramic of the USM.

Fig. 7 shows the electrode structure of the piezoelectric ceramic of USMs, where the arc-pole region and the two-phase polarization regions adhere to the same rigid body. When two-phase excitation voltages are applied to the two polarization regions, vibrations are generated due to the inverse piezoelectric effect, which will enable the piezoelectric ceramics in the arc-pole region to generate a voltage signal with the same frequency as the excitation voltage. The amplitude of the arc-pole feedback voltage is proportional to the stator vibration amplitude, which is the same as the characteristic between motor speed and stator vibration amplitude. Therefore, the arc-pole feedback voltage can be utilized for wireless data transfer to reflect the motor speed information under constant load conditions. The configuration of the proposed wireless data transfer is shown in Fig. 8, which skillfully utilizes the capacitive property of the arc-pole region to achieve wireless speed-sensorless communication without any additional compensation at the motor side.

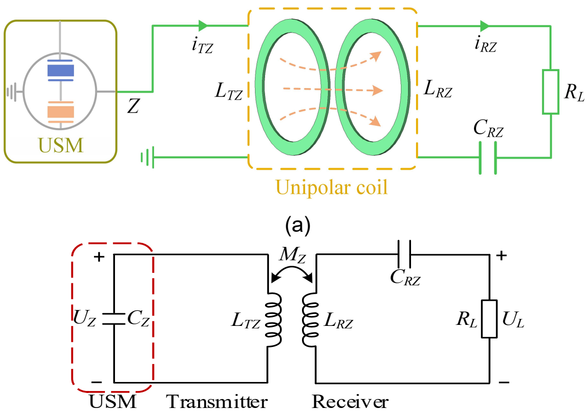


Fig. 8. Proposed wireless data transfer. (a) Structure configuration. (b) Equivalent circuit.

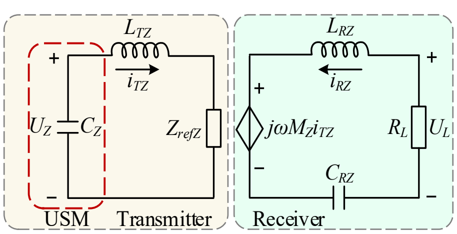


Fig. 9. Simplified equivalent circuit.

Fig. 9 shows the simplified equivalent circuit of the proposed system, where L_{TZ} and L_{RZ} are the inductances of the transmitter and receiver coils, respectively; C_Z is the inherent capacitance of the arc-pole of USM; C_{RZ} is the compensation capacitor; R_L is load and M_Z is the mutual inductance of the magnetic coupler; and Z_{refZ} is the reflected impedance, which can be derived as

$$Z_{refZ} = \frac{(\omega M_Z)^2}{j\omega L_{RZ} + \frac{1}{j\omega C_{RZ}} + R_L} \quad (8)$$

Accordingly, based on Kirchhoff's voltage law, the circuit model of the proposed system can be given as

$$\begin{cases} (j\omega L_{TZ} + Z_{refZ}) i_{TZ} = U_Z \\ (j\omega L_{RZ} + \frac{1}{j\omega C_{RZ}} + R_L) i_{RZ} = j\omega M_Z i_{TZ} \end{cases} \quad (9)$$

Then the gain of the output voltage over the arc-pole voltage can be deduced as

$$G_{LZ} = \frac{U_L}{U_Z} = \frac{j\omega M_Z}{j\omega L_{TZ} + Z_{refZ}} \quad (10)$$

To achieve high transmission efficiency, the capacitance of the arc-pole and the induction of the receiver coil should be fully compensated. Therefore, the following relations need to be satisfied at the resonance frequency

$$\omega = 2\pi f = \frac{1}{\sqrt{L_{TZ} C_Z}} = \frac{1}{\sqrt{L_{RZ} C_{RZ}}} \quad (11)$$

The proposed wireless data transfer enables the motor speed information to be wirelessly transferred to the primary side, enabling wireless speed communication without speed sensors. Moreover, it can be seamlessly integrated with the proposed wireless power and drive transfer using an IMC without any compensation at the motor side, achieving the WPD^{2}T simultaneously.

D. Full Primary Control for Speed and Commutation

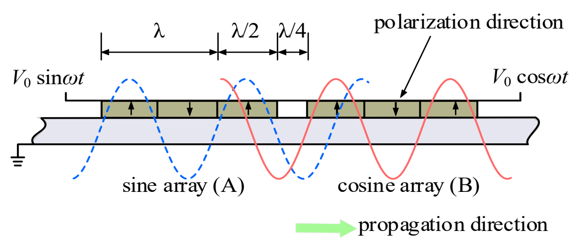


Fig. 10. Driving principle of USMs.

The proposed WPD^{2}T system allows full primary control, including speed regulation and commutation control, without any peripheral circuits and secondary side controllers. According to the driving principle of USMs shown in Fig. 10, when the two-phase driving voltage with a certain phase difference is applied to the A and B polarization regions, two-phase standing waves can be generated on the stator and superimposed to induce a traveling wave to drive the rotor [24]. The motor speed is related to the amplitude of the traveling wave [25], so flexible speed regulation can be achieved by adjusting the input voltage at the primary side. In addition, motor commutation control can be easily realized by reversing the traveling wave propagation direction by changing the phase difference between the two-phase driving voltage [26].

Therefore, the proposed WPD^{2}T system can be completely controlled at the primary side to achieve wireless direct drive. In addition, the phase delay between the transmitter and receiver voltages does not affect the control performance because the driving of USMs is only related to the phase difference of the two-phase driving voltage, but not the phase delay between the transmitter and receiver voltages, thus ensuring the effective wireless control of the motor.

IV. Finite Element Method Analysis

To visualize the magnetic field characteristics of the IMC, Fig. 11 shows the current flow direction of the IMC and the simulation results using the finite element method (FEM). First, the three-dimensional (3-D) magnetic flux density of the

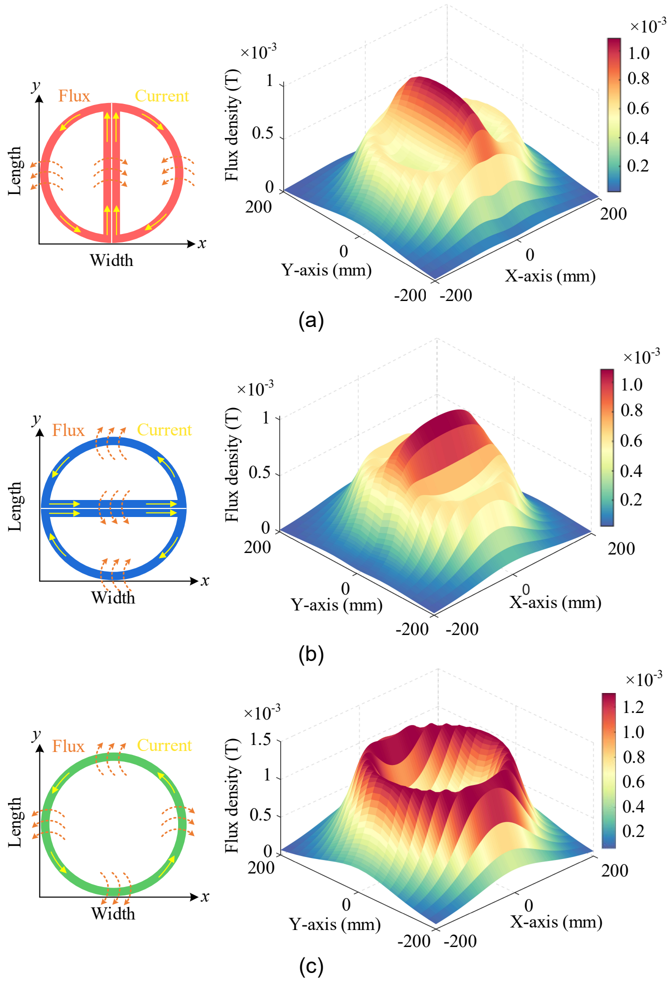


Fig. 11. FEM analysis of IMC. (a) A-coil magnetic flux density. (b) B-coil magnetic flux density. (c) Z-coil magnetic flux density.

A-phase coil is shown in Fig. 11(a). The current flows clockwise on the right side of the coil and counterclockwise on the left side, and thus the excited magnetic field is unidirectional and the magnetic flux density is strongest along the center of the coil. Similarly, the 3-D flux density of the B-phase coil is shown in Fig. 11(b), where the current flows from the center of the coil, into one unipolar coil and then to another unipolar coil so that the magnetic field is superimposed along the x-axis direction and the density is maximum. The 3-D flux density of the Z coil is shown in Fig. 11(c), the flux is circularly distributed in space and well decoupled from the other two-phase coils.

Therefore, by configuring both the transmitter and receiver coils as the IMC structure with decoupling properties, the magnetic fields of the three coils can be transmitted independently with good magnetic decoupling characteristics. It should be noted that coil misalignment may occur between two IMCs in a dynamic wireless motor drive system. In biomedical applications, the position and status of microrobots are required to be monitored in real-time in order to perform operational procedures. Therefore, the allowable misalignment capability of a movable receiver can be ensured by monitoring the position of the receiver IMC in real-time and actively de-positioning the transmitter IMC to ensure that the receiver can adapt to different positions and attitudes.

V. Experimental Implementation and Verification

A. Experimental Platform and Implementation

In order to experimentally implement and validate the proposed WPD^{2}T system, the experimental platform is built as shown in Fig. 12, which is aligned with the system configuration block diagram shown in Fig. 1. Specifically, the experimental waveforms are recorded by the oscilloscope LeCroy 6100A, while the voltage and current are measured by using the high-precision probes LeCroy ADP300 and LeCroy CP030, respectively. The fully-primary control is programmed and implemented by using a digital signal processor (DSP) TMS320F28335. The power module is powered by a DC power source KIKUSUI PWR1600M, while two half-bridge gallium nitride inverters are employed for two-phase high-frequency power conversion. The transmitter and receiver IMCs are wound with litz wire to minimize the skin effect, while the compensation capacitors are matched by using polypropylene film capacitors. It should be noted that since the IMC and three inductors at the receive side are connected in series, further integration can be realized if inductors are integrated directly into the IMC. Design specifications and parameters are listed in Table I in detail.

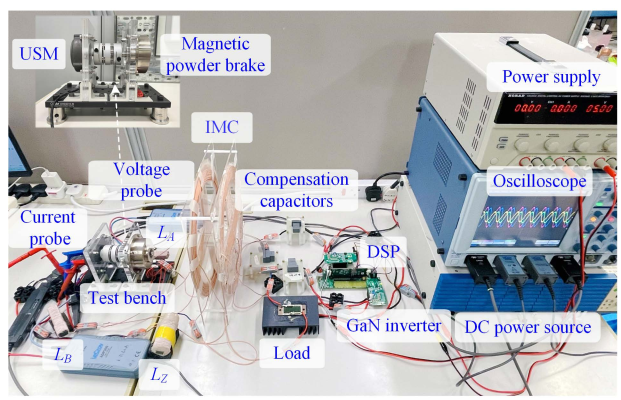


Fig. 12. Experimental setup of proposed WPD^{2}T system.

TABLE I
DESIGN SPECIFICATIONS AND PARAMETERS

Items	Value/type
Operation frequency (f)	40 kHz
Inductance of A coils (L_{TA}, L_{RA})	139.9, 142.1 μH
Resistance of A coils (R_{TA}, R_{RA})	0.2, 0.2 Ω
Compensated capacitance of A coil (C_{TA})	113.8 nF
Inductance of B coils (L_{TB}, L_{RB})	138.5, 137.2 μH
Resistance of B coils (R_{TB}, R_{RB})	0.21, 0.2 Ω
Compensated capacitance of B coil (C_{TB})	114.1 nF
Inductance of Z coils (L_{TZ}, L_{RZ})	103.8, 104.2 μH
Resistance of Z coils (R_{TZ}, R_{RZ})	0.15, 0.15 Ω
Compensated capacitance of Z coil (C_{RZ})	154.1 nF
Transfer distance (d)	50 mm
Load resistor for wireless data transfer (R_L)	10 Ω
Series inductors (L_A, L_B, L_Z)	1.37, 1.36, 16.48 mH
GaN inverter	GS66508T
Number of turns of IMC	14
Inner diameter of IMC	250 mm
Outer diameter of IMC	300 mm

B. Verification of Control Motility

The control motility of the proposed WPD^{2}T system is evaluated as shown in Fig. 13, where the waveforms show the two-phase motor terminal voltages u_{RA} and u_{RB} as well as the stator currents i_{RA} and i_{RB} without load. It can be seen that the sinusoidal degree of the voltage and current is excellent, which can meet the driving requirements of the USM, thus ensuring the smooth operation of the motor. In addition, the current leads the voltage by a certain phase angle because USMs are capacitively characterized, which is consistent with the theoretical analysis. By taking full advantage of the capacitive characteristics of the USM, wireless direct drive of the motor can be achieved by using a magnetic coupler only.

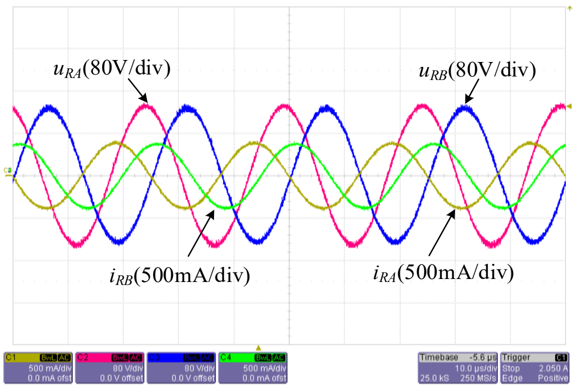


Fig. 13. Measured motor terminal waveforms of proposed WPD^{2}T system without load.

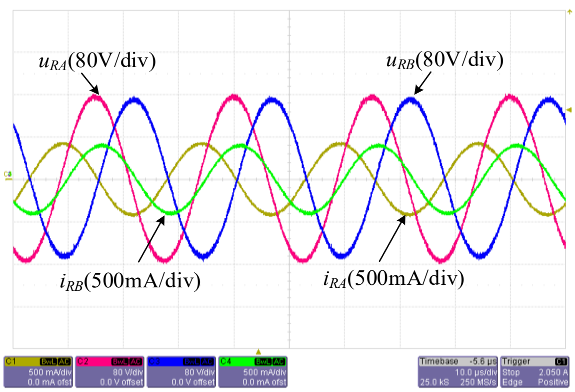


Fig. 14. Measured motor terminal waveforms of proposed WPD^{2}T system with load operation.

To further assess the controllability of the proposed WPD^{2}T system under various operational scenarios, Fig. 14 shows the motor terminal voltage and current waveforms at a load torque of 20 Ncm. The voltages and currents are slightly higher than the no-load operation shown in Fig. 13, which improves the ability to operate with load. The higher voltage can enhance the amplitude of ultrasonic vibration, producing a stronger driving force, while the increase in current provides more power to the USM to overcome the increase in load torque. In addition, the measured waveforms are relatively sinusoidal, ensuring stable and reliable operation of the USM while minimizing unnecessary vibrations caused by harmonics. These experiments well validate the feasibility of the proposed WPD^{2}T system for controlling USMs in different working conditions.

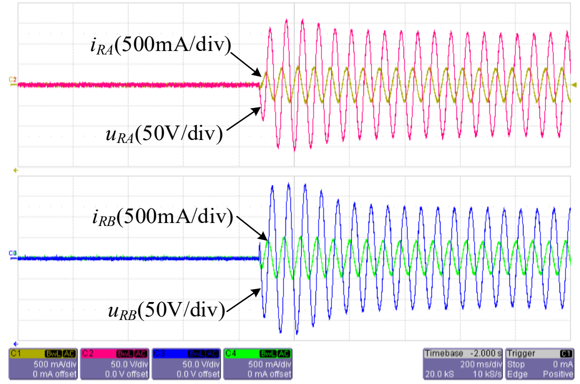
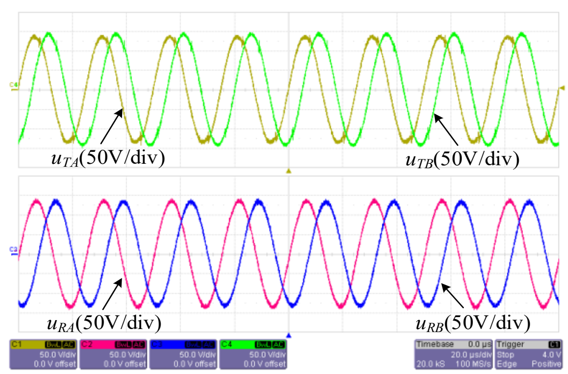


Fig. 15. Measured motor terminal waveforms of startup transient response of the proposed WPD^{2}T system.

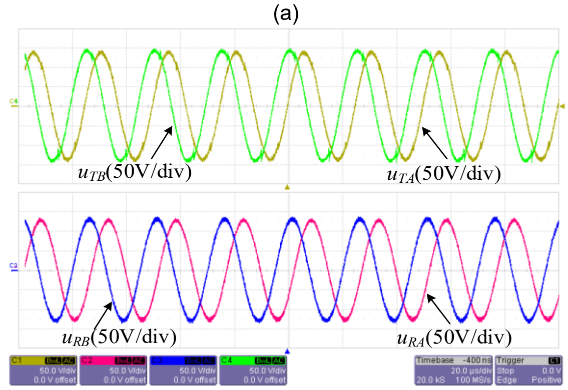
Fig. 15 shows the transient characteristic response of the proposed WPD^{2}T system during startup. The motor terminal voltage increases slightly at the instant of motor startup but quickly returns to stability. Additionally, there is no overshooting in voltage and current, ensuring a smooth startup of the motor.

C. Verification of Full Primary Control

Control flexibility is critical for the performance evaluation of wireless motors. The proposed WPD^{2}T system allows full primary control without the need for any power switches, auxiliary drive circuits and sensors at the receiver side. Fig. 16 shows the flexible commutation control of the proposed WPD^{2}T system, where u_{TA} and u_{TB} are the voltages of the transmitting coils, and u_{RA} and u_{RB} are the motor terminal voltages, respectively.



(a)



(b)

Fig. 16. Flexible commutation control of the proposed WPD^{2}T system. (a) Forward operation. (b) Backward operation.

The flexible bi-directional operation can be easily realized by simply changing the phase difference of the two-phase voltages at the transmitter side. As shown in Fig. 16(a), when the phase angle of u_{TA} is ahead of that of u_{TB}, which results in the motor terminal voltage u_{RA} leading u_{RB}, the forward operation control can be achieved. However, when the phase difference between u_{TA} and u_{TB} is reversed, that is the B-phase voltage is leading over the A-phase voltage as shown in Fig. 16(b), in such a way the direction of the traveling wave on the stator is reversed, thus driving the rotor to rotate in the opposite direction. Therefore, the proposed WPD^{2}T system exhibits distinct advantages in terms of high control flexibility and simplification of the secondary side circuits with non-utilization of semiconductors and passive components.

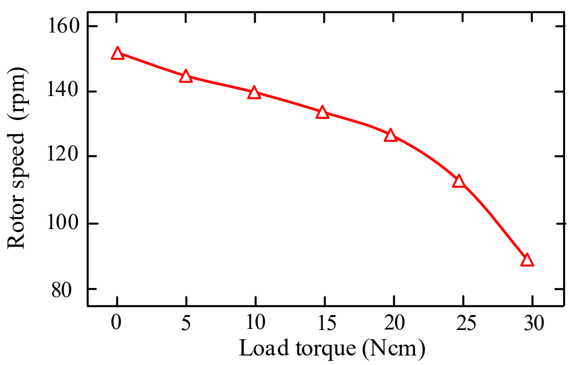


Fig. 17. Measured speed characteristics of proposed WPD^{2}T system under different loads.

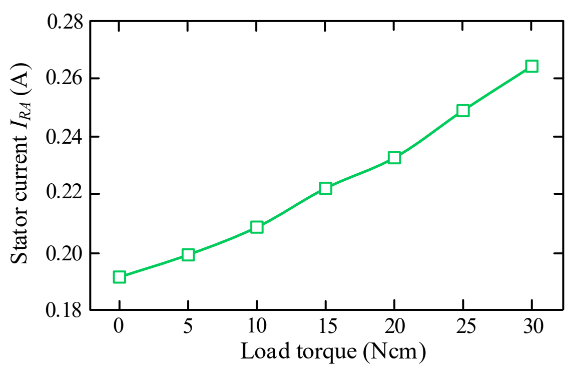


Fig. 18. Measured stator current characteristics of proposed WPD^{2}T system under different loads.

In addition, the speed and stator current characteristics of the USM under different loads are experimentally evaluated, as shown in Fig. 17 and Fig. 18, respectively. It can be observed that as the load increases, the motor speed gradually decreases from 152 rpm at no-load to 89 rpm at 30 Ncm. Furthermore, the stator current increases proportionally with the increasing load, ranging from 190 mA at 0 Ncm to 266 mA at 30 Ncm, demonstrating excellent linearity. These experimental results indicate that the proposed WPD^{2}T system has stable operating characteristics under different load conditions.

D. Verification of Wireless Data Transfer

Wireless data transfer for speed-sensorless communication under no-load conditions is shown in Fig. 19, where u_Z is the arc-pole voltage related to motor speed, and u_L is the receiver side voltage. Fig. 19(a) shows the measured waveforms when

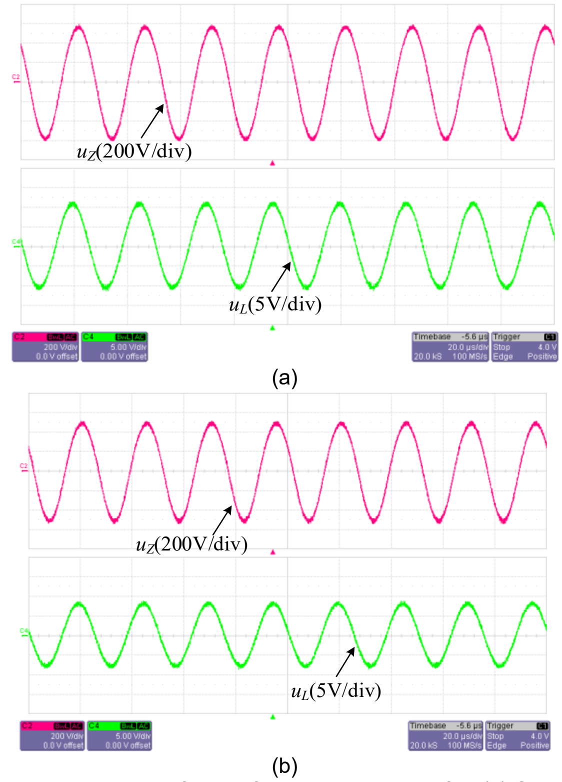


Fig. 19. Measured waveforms of wireless data transfer. (a) Speed with 144 rpm. (b) Speed with 100 rpm.

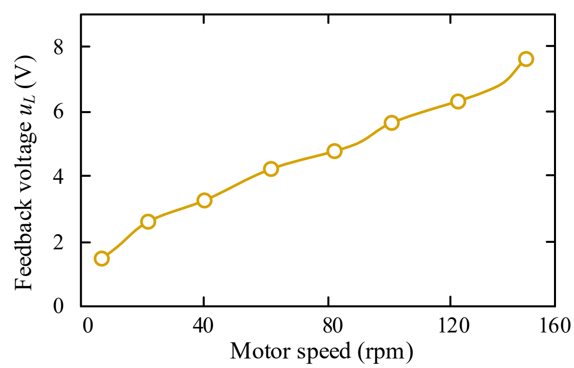


Fig. 20. Measured characteristics of wireless data transfer over a wide speed range.

USM operates at the speed of 144 rpm, the root-mean-square (RMS) value of u_L is 7.57 V. As the motor speed decreases, the arc-pole voltage u_Z decreases and the RMS value of u_L decreases accordingly, as shown in Fig. 19(b), where the motor speed is 100 rpm and the RMS value of u_L is 5.64 V. Therefore, the motor speed can be obtained from the RMS value of u_L.

Further, the characteristics of wireless data transfer over a wide speed range are measured as shown in Fig. 20. As the motor speed increases, the feedback voltage u_L gradually increases. This is because the increase in motor speed indicates the enhancement of the vibration of the stator. Therefore, u_Z gradually increases due to the piezoelectric effect, and u_L increases accordingly with the motor speed. Wireless speed information communication can be readily performed without the need for speed sensors and complex circuity at the motor side, which enables seamless integration with the proposed wireless power and drive transfer. It should be noted that the accuracy of the feedback of the speed information is guaranteed under constant load conditions [27]. To observe the speed information under different loads, one potential approach is to pre-measure the arc-pole voltage of the USM at different speeds under various loads and then use a lookup table to determine the corresponding speed information, but this requires prior knowledge of the load torque information. Additionally, for applications that require high-precision speed information, installing a speed sensor at the motor side and transmitting the data back to the primary side wirelessly is also a feasible method. However, this inevitably increases the cost and complexity of the system.

It should be noted that the proposed wireless data transfer may experience voltage offset due to potential misalignment of the coupling coils, which will affect the accuracy of speed observation. However, the observed speed information is only used for monitoring the motor status and does not affect wireless power drive transfer. Additionally, transmitting arc-pole feedback voltage via Bluetooth is a feasible solution for applications requiring high-precision speed information. The tiny delay of Bluetooth does not impact the control and monitoring of USMs. Furthermore, the capacitive power transfer (CPT) technology provides a notable advantage in maintaining constant voltage output regardless of coupler misalignment [28]. Therefore, actively developing and applying CPT in wireless data transfer holds the potential for accurate speed observation.

TABLE II
Comprehensive Comparison with Reported Wireless Motors and Proposed WPD²T

Ref.	Motor types	Resonant frequencies	Secondary switches	Secondary components	Wireless speed sensorless	Simplicity/ Economics
[13]	DC	130, 160 kHz	12	8	×	☆
[14]	SRM	100 kHz	12	3	×	☆
[15]	SPIM	109, 116 kHz	33	25	×	☆
[16]	SM	85 kHz	16	4	×	☆
[17]	USM	40 kHz	0	4	×	☆☆
[18]	SRM	50 kHz	12	6	√	☆
Proposed	USM	40 kHz	0	3	√	☆☆☆

E. Discussion and Comparison

To illustrate the uniqueness of the proposed WPD²T system, a comprehensive comparison with reported wireless motors is conducted as shown in Table II. The comparison reveals that the receiver side of DC motors, SPIMs, SRMs and stepping motors (SMs) are rather cumbersome and not favorable for integration. These motors require numerous passive compensations and multiple power semiconductor switches to achieve wireless drive. Although the wireless USM is innovatively proposed to eliminate the power switches at the receiver side, additional compensations, such as capacitors, are still required for wireless control [17]. Additionally, capturing motor speed information without using electronic devices like Bluetooth is a challenge for existing wireless motors. Wireless resolvers realize the rotor information transfer from the motor side to the primary side, but auxiliary circuitry is necessary to adapt the resolver, making it a complex solution [18]. Therefore, the above solutions need to be further improved in terms of techno-economics.

In contrast, the proposed WPD²T system effectively addresses some drawbacks associated with existing wireless motors, such as the need for complex compensation and multiple power switches at the receiver end, the difficulty in obtaining motor speed information, and the inability to achieve miniaturization and integration of the overall system. Firstly, the receiver side of the proposed WPD²T system does not require any compensation capacitors as it innovatively utilizes the capacitive properties of USMs to achieve an optimal wireless motor system, which greatly simplifies the structure and leads to cost savings and techno-economic improvement. Additionally, considering the series connection of inductors L_A, L_B, and L_Z with the IMC, it is theoretically feasible to integrate the three inductors directly into the IMC, allowing the USM to be directly driven by the IMC without any compensation at the receiver side, which will significantly contribute to high integration and miniaturization. Furthermore, the proposed WPD²T system can wirelessly transmit motor speed information within a specific applicable range without the need for any active or passive components and electronic devices, which provides great potential and competitive advantages for further promotion from both technical and economic points.

For practical applications, achieving motor miniaturization and increasing the equivalent capacitance can be accomplished by specifically designing the ultrasonic motor, which will help to reduce the amount of matching inductance, allowing the entire matching inductance to be provided by the IMC without any compensation at the receiver side. Furthermore, due to the diverse designs and mechanisms of USMs, their driving frequency can generally reach hundreds of kilohertz, so the volume of the matching inductance will be further reduced as the resonant frequency of the USM increases, which can contribute to the integration of the IMC and the overall miniaturization of the system.

It should be pointed out that due to the time-varying and nonlinear nature of USMs, the equivalent capacitance of the motor drifts with temperature, friction, and other conditions [27]. Consequently, the resonance frequency of motors will drift by around 1-2 kHz under different operating conditions, leading to degradation of performance and efficiency. To ensure that USMs consistently operate at their optimal state, a feasible solution is to employ real-time feedback control to adjust their driving frequency. One promising approach for achieving this is through phase locking of the transmitter voltage and current. The phase difference between the voltage and current of a single-phase can accurately reflect the impedance and resonant characteristics. By continuously adjusting the driving frequency to track and maintain the phase difference between the transmitter voltage and current at zero, it becomes possible to achieve zero-phase-angle operation of the system under varying loads. Additionally, this approach eliminates the installation of voltage and current sensors or detection circuits at the receiving side, but only at the transmitter side, simplifying the integration and miniaturization of the receiving components. Moreover, in the case of USMs equipped with arc-poles, frequency tracking can also be accomplished by utilizing the phase difference between the driving voltage and arc-pole voltage to achieve frequency-adaptive control of wireless USMs with enhancing performance and versatility.

VI. Conclusion

In this paper, a novel WPD^{2}T system has been proposed and implemented to innovatively transfer power, drive and data simultaneously for ultrasonic motors. Notably, the configuration of the receiver side is extremely simplified, requiring a magnetic coupler with three series inductors only without any electronic and passive components, enabling the proposed WPD^{2}T with distinct advantages in terms of integration, simplification and economics. In addition, wireless direct drive and complete primary control can be easily achieved, allowing the proposed system much more flexibility in controllability. Also, speed information can be readily obtained through wireless data transfer, enabling real-time monitoring of motor operating status. This extreme simplicity of the proposed WPD^{2}T offers excellent potential for further miniaturization, which is promising for addressing the charging hassles in biomedical applications.

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