A Comparison of Different Modulation Techniques for Muli-Coil Inductive Power Transfer

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The Inductive Power Transfer (IPT) is the most popular method of transferring power wirelessly. In order to increase the transferred power, the multi-coil structure can be used. This can also impacts the tolerance to misalignment and rotation between coils. In order to control output voltage, multiple different transmitter modulation techniques can be used. To choose the most suitable modulation method, the most popular modulation methods were implemented on the multi-coil system and experimentally tested under the same working conditions.

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I Introduction

Wireless or more specifically inductive power transfer (IPT) gained more adoption with the development of consumer electronics and electric vehicles, due to its simplicity and robustness [1]. Currently, it is mostly used for providing power to and charging low-power devices such as smartphones, smartwatches, and wireless earphones. The main drawback of transferring power wirelessly is the overall low charging efficiency and low tolerance to misalignment.

By using different single and multi-coil structures, the misalignment tolerance of the system can be significantly improved. On the other hand, the efficiency of the transfer can be increased by transferring power at higher frequencies, using different modulation and control techniques. The modulation technique also depends on the type of high-frequency inverter on the transmitter side of the system.

The IPT system, used in experiments is based on multi-coil double DD coil topology, with better, symmetrical misalignment tolerance and higher power transfer capabilities [2]. The output is connected to a constant resistive load. The experiments with different modulation techniques were performed in order to determine the most suitable modulation technique.

II Modulation methods

The multi-coil system, which is the subject of this research consists of two directional DD coils, perpendicular to one another, forming a double DD coil structure. The double DD coil structure is used as a transmitter and as a receiver. The coil structure is presented in Fig. 1.

The transmitter and the receiver coils are compensated using widely used series-series (SS) compensation topology, which serves a constant current supply at the output of the system. Each of the transmitter coils is driven using a full-bridge inverter, capable of implementing all three most popular modulation techniques.

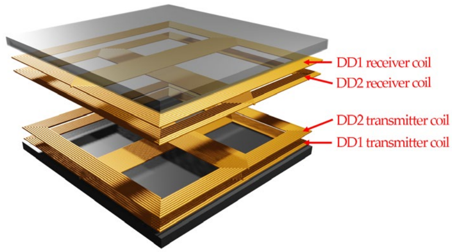

Figure 1: Basic double DD transmitter and receiver coil structure

The output voltage of the IPT system can be controlled using the amplitude of the first harmonic component of the transmitter voltage, using phase-shifted, frequency, or pulse density modulation.

A phase-shifted modulation impacts the amplitude of the first harmonic component by changing the phase angle between the modulation signal for the first and second inverter bridge legs. This can be described using:

$$u_T = \frac{4U_{DC}}{\pi}\sin\left(\frac{\phi}{2}\right)\sin(\omega t) \tag{1}$$

where u_T is the first harmonic component of the transmitter voltage, U_{DC} is the voltage of the transmitter power supply, ϕ is the phase angle of the modulation, and ω inverter frequency.

When using frequency modulation, the phase-shift angle of the inverter is 2π. Therefore, equation (1) can be simplified to:

$$u_T = \frac{4U_{DC}}{\pi}\sin(\omega t) \tag{2}$$

The first harmonic component of generated voltage is constant. SS compensated IPT system acts as a band-pass filter with resonant frequency at:

$$f_i = \frac{1}{2\pi\sqrt{L_{Ti}C_{Ti}}} = \frac{1}{2\pi\sqrt{L_{Ri}C_{Ri}}} \tag{3}$$

where f_i is the resonant frequency of the system, L_{Ti} and L_{Ri} are the inductances of the transmitter and the receiver coils and C_{Ti} and C_{Ri} are the values of compensation capacitors. The parameter i can be either 1 or 2, depending on the selected pair of coils in the double DD structure. By modulating the frequency of the transmitter, the amplitude of the induced voltage on the receiver side can be changed. However, this can impact the efficiency of the IPT system.

The first harmonic component of the transmitter voltage is also constant during the pulse density modulation (PDM) [3]. By reducing the density with the introduction of the pulse skipping, the average value of the first harmonic component can be reduced. The relationship between the transmitter voltage and PDM can be described using [4]:

$$u_T = \frac{4U_{DC}}{\pi} d \sin\left(\omega t\right) \tag{4}$$

where d is the pulse density of modulation, which can be between 0 and 1.

Phase-shifted modulation can only be implemented on the system using the full-bridge inverter. Other two techniques can also be implemented on the half-bridge inverter.

III Experimental Results

A. Experimental platform

The three most popular modulation methods were tested on the small-scale multi-coil experimental platform. The output voltage was controlled using a tuned PI output voltage controller. The main parts of the IPT system are highlighted in Fig. 2. The IPT coils are mounted on the 3D positioning mechanism, which enables the positioning of the double DD coils in the 3D space. The transmitter coil, placed on the bottom platform can be moved in the *x-y* plane and the receiver coil, placed on the top platform can be moved along the *z* axis.

The transmitter part of the system consists of a dual high-frequency inverter and two transmitter DD coils with their respective series compensation circuits. The receiver side consists of two series compensated DD coils, connected to the diode rectifiers. The communication between the transmitter and the receiver side is implemented using Bluetooth communication protocol.

The system was connected to a 25 V power supply, supplying up to 3 A of DC. The power of the system is limited by the voltage ratings of compensating capacitors and the DC voltage of the inverter. The distance between coils was between 0 and 25 mm, with angle varying between 0 and 90°. The rectifiers were connected to the constant 21.4 Ω load.

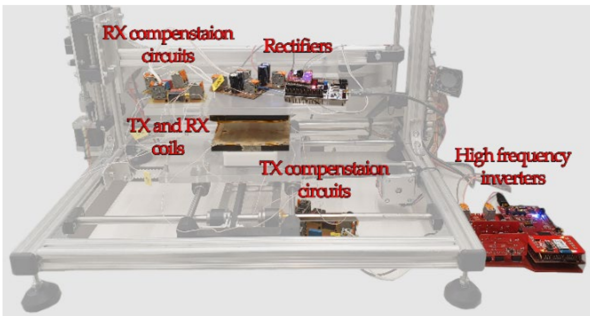

Figure 2: Multi-coil experimental platform.

B. Experimental results

The 3D positioning platform enabled the evaluation of modulation techniques under the same conditions. First, the system was tested under different output voltages, which affected the efficiency of the system. The output voltage reference was changed from 5 V to 30 V in 5 V steps. The results are presented in Table I. Among the three modulation techniques, the most efficient was phase-shifted modulation and frequency modulation was least efficient. The PDM was more efficient than frequency modulation and less efficient than phase-shifted modulation.

In all three cases, the PI controller eliminated the error due to the change of coupling coefficients between the transmitter and the receiver DD coil structures. The rotation of the coils around the *z*-axis had a greater effect on the output voltage than misalignment in the horizontal *x-y* plane. The maximum overshoot was under 10% of output voltage during the rotation and under 3% during the horizontal movement.

Table 1: Efficiency of the inductive power transfer system

Reference voltage $U_{o,ref}$	Frequency modulation	Phase-shifted modulation	Pulse density modulation (PDM)
5 V	32.92%	42.82%	35.94%
10 V	52.37%	55.03%	59.47%
15 V	56.88%	63.39%	58.12%
20 V	63.17%	68.11%	63.28%
25 V	66.22%	72.27%	69.35%
30 V	69.54%	72.36%	70.4%

IV Conclusion

The results clearly present that the phase-shifted modulation is the most efficient modulation technique, due to the use of constant frequency and ideal transistor soft-switching. Frequency and pulse density modulation should only be used in systems using half-bridge high-frequency inverters that reduce system complexity, where phase-shifted modulation is impossible to implement.

Acknowledgement

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