

Study of Contactless Power Supply for Spindle Ultrasonic Vibrator

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Abstract. In this study, a contactless power supply for the ultrasonic motor on the spindle is proposed. The proposed power supply is composed of a series-parallel resonant circuit and a cylindrical contactless transformer. Based on the study and rotation experiments, it can be seen that the proposed power supply can both provide a stable ac power with 25 kHz / 70 V to the ultrasonic motor. When the output power is 250 W, the efficiency of the proposed supply is 89.8 % in respectively rotation tests. When the output power is more than 150 W, the efficiency of the proposed supply is higher than 80 % within the rated output power range.

1. Introduction

Due to the material brittleness of workpieces processed and the industry's demand for process precision, workpieces have become increasingly complex in terms of shape, while precise workpiece specifications and surface roughness requirements have substantially increased, resulting in greater difficulty in brittle material processing. Therefore, targeting brittle material processing, the front-end and back-end high-speed vibration of ultrasonic cutting processing have become mainstream in time.

Figure 1 shows the schematic diagram of the traditional ultrasonic motor[1-2] structure. The rotation force is driven by the spindle motor. In the coupler, a set of slip ring mechanism is used to convert electric energy and send it to the ultrasonic transducer[3]. In addition, it after prolonged work, is likely to overheat. Hence, when applied in the semiconductor industry requiring long hours of production, the slip ring wear and tear causes doubts about the service life of this structure.

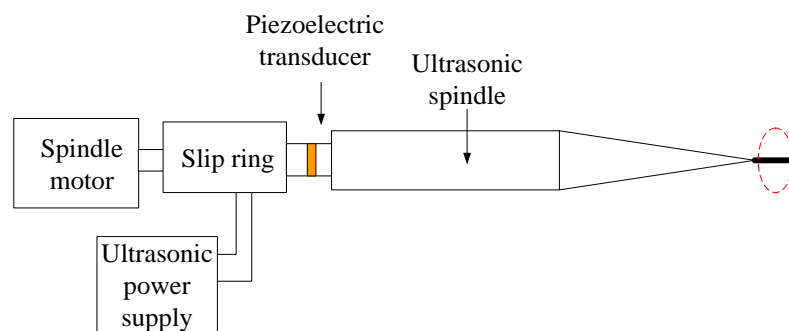


Figure 1. Traditional ultrasonic motor

2. Topology and System Design

This paragraph follows a section title so it should not be indented. Figure 2 shows the ultrasonic motor's improved system frame, which consists of two parts: the spindle and the ultrasonic power supply. For the spindle part, the slip ring mechanism was improved into a contactless transformer. Figure 3 shows the cylindrical transformer proposed in this study. The primary transformer is the hollow cylinder with a larger radius; the secondary transformer is a hollow cylinder with a smaller radius, presenting a concentric circular frame. According to the magnetic field distribution, it shows that the air gap area has the largest magnetic field. In this paper, the co-axial coupling principle was adopted to implement electric energy conversion in the ultrasonic motor at a high speed and improve the low speed limitation of traditional slip rings. Additionally, series-parallel resonance circuits are combined to compensate the energy loss of the contactless transformer. The system specifications are: input voltage of 110 Vac, output power of 400 W, and rated output voltage of 70 Vac/ 25 kHz.

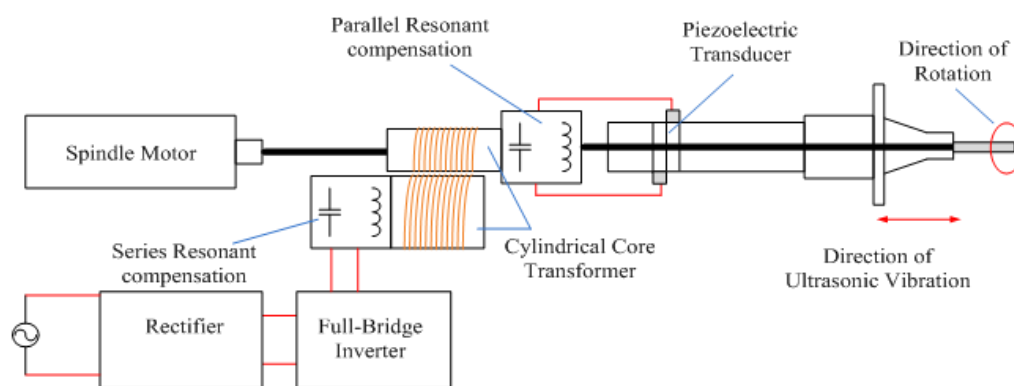


Figure 2. Improved system framework

The full-bridge resonant converter[4] in this paper has primary compensation capacitor and primary winding inductor, forming a series resonant compensation[5] slot in order to prevent the instant generation of switching loss caused by switch component in on and off states. In terms of control, the signal inputs of the upper arm switches and the lower arm switches are complementary operations. When the system's operating frequency is higher than the resonant frequency of the series resonance slot, the voltage phase on the switch is higher than the circulating current in the switch, enabling the voltage toll return to zero within the switch cut-off period and achieving zero-voltage switching. The secondary resonance capacitor and the secondary winding inductor form a parallel resonance compensation slot. Since the circuit in actual applications have no fixed load, in general, the full-bridge converter generates an unstable voltage gain. Therefore, the fixed voltage feature of parallel resonance was applied in this study to stabilize the voltage during replacement.

3. Design of resonant circuit parameters

Through impedance analysis[6] and with the cylindrical transformer design in this study as parameter references. Since the weak coupling feature of the transformer[7] falls short compared an ideal transformer, in design, it is important to measure the leakage inductance and precisely measure the mutual inductor M and magnetized inductor L_m based on the equivalent circuit.

In this study, series-parallel resonance is used as compensation in the circuit design. Series-parallel resonance is characterized by a fixed voltage, while the voltage gain at the resonance frequency is considerably stable. In the non-ideal state, the power output is 50 W~400 W, and its gain can be maintained at 0.5~1.5. As shown in Figure 3, the full-bridge converter power switch has a wider range of tuning. Conversely, the series-series resonance curve at the resonance frequency point shows that the voltage gain reaches the highest point, while the respective load voltage gains vary greatly, which are unfavorable for loads that need a stable voltage, as shown in Figure 4.

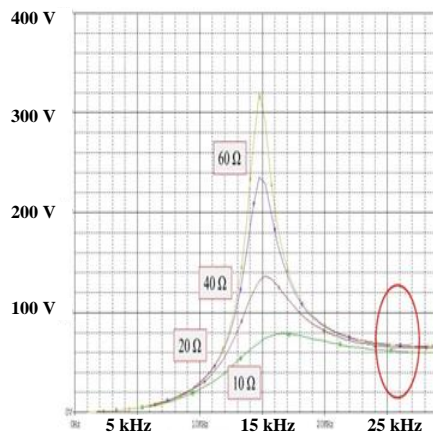


Figure 3. Series-parallel resonance frequency responses

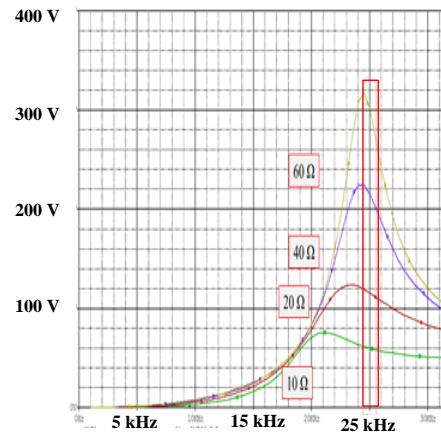


Figure 4. Series-series resonance frequency responses

4. Experimental results

The input voltage is the supply mains, and the full load power is 400 W. Through equivalent impedance analysis, the switching frequency and resonance frequency design were set as 25 kHz. In terms of the cylindrical transformer design, the turn ratio design in this study is 2. After analysis and calculation using the transformer equivalent model, the mutual inductance value is approximately 22.4 μ H, the air gap is about 8 mm, the coupling coefficient is 0.16.

During a rotary test, the actual processing state was considered. At a low speed, the ultrasonic motor power supply drew a low power output; at a high speed, the ultrasonic motor power supply drew a high power output. Figure 5 shows the switch voltage and current state of the full-bridge converter. The switch is turned on and when the switch voltage V_{ds} is 0, the switch current I_{ds} elevates to a positive value, reaching zero voltage switching. Figure 6 shows the output voltage and current waveform at 1600 rpm/300 W; the switch signal waveform at 1600 rpm was observed. In terms of switch voltage, no noise interference was produced at 1600 rpm; in terms of output current, the maximum output power at 1600 rpm remains unaffected. However, for the output voltage part, slight resonance distortion was seen, possibly because the rotary connector already reached the maximum speed.

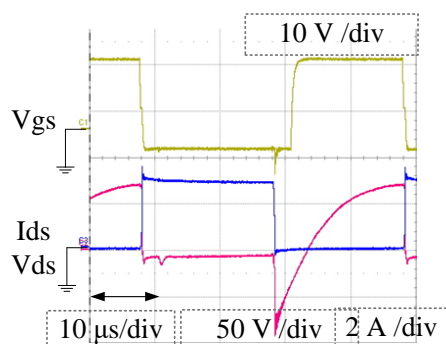


Figure 5. Low power switch waveform

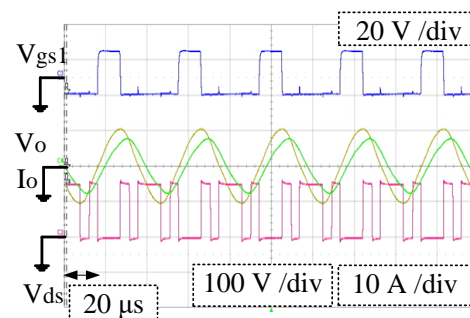


Figure 6. High power output waveform

Figure 7 shows the measurement of the system efficiency at 200 rpm~1600 rpm, with the output power fixed at 350 W. Figure 8 shows the system efficiency curve. According to the efficiency curves above and the system's gradual speed increase, which validates "the stability of the cylindrical transformer's co-axial coupling applied in the ultrasonic spindle" proposed in this study.

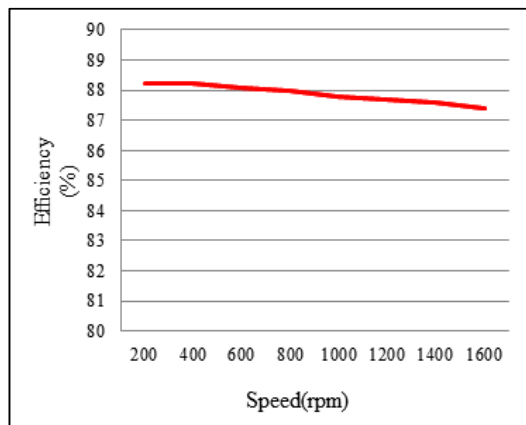


Figure 7. The system efficiency at 200 rpm ~ 1600 rpm

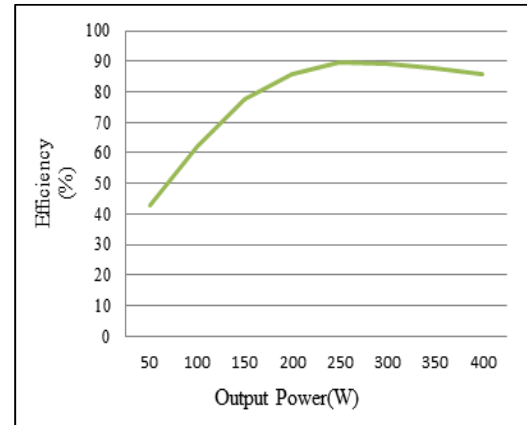


Figure 8. Overall system efficiency

5. Conclusion

Through the impedance analysis and weak coupling transformer equivalent circuit analysis, this study explored the frequency responses of series-series resonance compensation and parallel-parallel resonance compensation, confirming that the series-parallel resonance compensation voltage feature is more suitable for use in the piezoelectric vibrator that demands voltage stability. Compared to traditional ultrasonic spindles, this system has a cylindrical contactless transformer in place of the traditional slip ring design. On the application side, it ensures ultrasonic processing not limited by the speed, while substantially enhancing the cutting efficiency. The experimental results validate this system's dynamic and static efficiency reaching above 80 % at 150 W, with the dynamic and static error of about 2 %.

Acknowledgments

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References

- [1] Y. Liu, et. al., 2013 High-Power Linear Ultrasonic Motor Using Bending Vibration Transducer *IEEE Transactions on Industrial Electronics* vol 60 chapter 11 pp 5160 – 5166.
- [2] P. Smithmaitrie 2014 Design and performance testing of an ultrasonic linear motor with dual piezoelectric actuators *IEEE Trans. Ultrasonics, Ferroelectrics, and Frequency Control* vol 61 chapter 3 pp.535 – 546.
- [3] Y. Liu, et. al., 2011 A cylindrical traveling wave ultrasonic motor using a circumferential composite transducer *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control* vol 58 chapter 11 pp 2397 – 2404.
- [4] A. Mallik and A. Khaligh 2017 Variable-Switching-Frequency StateFeed- back Control of a Phase-Shifted FullBridge DC/DC Converter *IEEE Trans. Power Electro* vol 32 chapter 8 pp 6523 – 6531.
- [5] J. Hou, et. al., 2014 Analysis and Control of Series/Series-Parallel Compensated Resonant Converter for Contactless Power Transfer *IEEE Journal of Emerging and Selected Topics in Power Electronics* vol 3 chapter 1, pp 124 – 136.
- [6] Z. Cong, et. al., 2015 High-Efficiency Contactless Power Transfer System for Electric Vehicle Battery Charging Application *IEEE Journal of Emerging and Selected Topics in Power Electronics* vol 3 chapter 1 pp 65 – 74.
- [7] A. Abdolkhani, H.P. Aiguo, and, and C.K. Nirmal 2014 A Double Stator Through-hole Type Contactless Slipping for Rotary Wireless Power Transfer Applications *IEEE Transactions on*

Energy Conversion vol 29 chapter 2 pp 426 – 434.