Coreless inductive power supply for ultrasonic transducer on machine tool

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Abstract: An inductive power supply with concentric coreless transformer is proposed for the ultrasonic transducer on machine tools. The concentric coreless transformer is designed not to increase mounting weight onto the spindle and transfer power to the ultrasonic transducer without contact losses. A switching power supply composed of a series-parallel resonant compensation circuit and a full-bridge inverter is also designed to convert the power from stationary side to the rotary ultrasonic transducer (UST) through the coreless concentric transformer. A primary-side controller based on fed back primary-side current is also proposed for output voltage control. Therefore, there are only the secondary winding and the parallel compensation capacitor required to be mounted on to the spindle. From the experimental results, it can be seen that the proposed power supply can provide a stable AC power with 25 kHz/70 V to the ultrasonic transducer. The efficiency of the proposed power supply is up to 90% and the efficiency difference between stationary and rotary operations is only about 2%.

Keywords: inductive power supply, ultrasonic transducer, coreless transformer

Classification: Power devices and circuits

References

1 Introduction

Recently, rotary ultrasonic machining is widely applied to process hard and fragile materials such as glass, Ti-alloys, and so on. Rotary ultrasonic machining has several advantages of better material removal rate, good surface quality and even longer tool life [1, 2]. A UST is integrated into the spindle to provide axial oscillation. The common method to transfer power from the stationary side to the rotary UST is through a slip ring and contact brush [3, 4]. However, this usual way would cause additional contact power losses, sparks, and the maintenance cost of the contact components.
The power transferring through a transformer is a better and more efficient way compared to the common way with contacts [5, 6, 7, 8]. A transformer composed of magnetic cores and windings is the key component in inductive power transferring. However, while the secondary side is mounted onto the spindle, the dynamic response would become slower and required power for acceleration would also increase due to the additional weight of the transformer cores. An inductive power transfer system with a coreless concentric transformer is proposed for the DC power distribution [9]. A full-bridge diode rectifier is integrated into the secondary side for providing DC power output. In [10, 11], the authors proposed an output voltage control strategy with an additional voltage estimation coil. A primary side controller without any output voltage sensing or estimation circuit is proposed in [12]. However, the output voltage is indirectly controlled by adjusting the working frequency. It would be difficult to be implemented in a digital microcontroller chip.

The wide-used series-parallel compensation topology for the inductive power transfer is well-analyzed [13]. Accordingly, the working frequency can be designed for nearly constant voltage gain at different loading conditions. The effect on the voltage gain resulted from the harmonic components of the PWM switching voltage is also considered [14].

In this study, the inductive power supply with a coreless concentric transformer for the UST is proposed. A full-bridge inverter and series-parallel compensation circuit are also integrated into the developed power supply [15, 16]. A primary-side controller without any output voltage feedback circuit would be suitable because of no additional mounting weight to the spindle. The transfer functions of the input voltage to the primary-side current and the primary-side current to the output voltage are analyzed. The working frequency of the proposed power supply is designed to be higher than the resonant frequency of compensation for keeping nearly constant voltage gain. Hence, the output voltage can then be indirectly controlled by primary-side current control. The operation principles and control strategy of the proposed power supply are described as following.

2 Coreless transformer and compensation circuit

Fig. 1 shows the coreless concentric transformer developed in this study. While the inner part is mounted onto the spindle, the flux linkage between the inner and outer parts would be nearly the same under stationary and rotary operations. As a result, the power transferring would be stable enough under different rotation speed. The coreless inner part would not increase the spindle weight and can prevent additional power loss and dangers under high-speed machining conditions. Furthermore, the air gap is designed to be large enough for easy installation and maintenance. However, the coupling coefficient would be much lower than that of the common transformers. The leakage inductance of the transformer should be compensated to transfer power efficiently. The compensation circuit for the coreless concentric transformer shown in Fig. 2 is adopted in this study. At the primary side, a capacitor $C_1$ is connected in series to compensate for the primary leakage inductance. Another compensation capacitor $C_2$ is connected in parallel to provide a more stable output voltage.
Fig. 3(a) shows the general equivalent model of the UST, where resistance $R_s$ is the effective mechanical dissipation, inductance $L_s$ is the oscillatory mass, capacitance $C_s$ is the flexibility and capacitance $C_p$ is the static capacitance of the transducer. While the operating frequency is the resonant frequency $f_S = 1/\sqrt{L_sC_s}$, the equivalent model would be equal to a capacitor connected by a resistor in parallel, as shown in Fig. 3(b). Therefore, the static capacitance $C_p$ should be taken into design consideration of the secondary-side compensation capacitance.

### 3 Operation principles of proposed inductive power supply

Fig. 4 shows the circuit topology of the proposed coreless inductive power supply for UST. The full-bridge inverter composed of four switches, $Q_1$-$Q_4$, is used to provide a high-frequency AC voltage to the coreless transformer. The relative waveforms of the power supply are shown in Fig. 5. The switching frequency is designed to be the resonant frequency of the UST. $T_s$ is the switching period and $D_{on}$ is the duty ratio of the turned-on time. $D_b$ is the duty ratio of the deadtime for preventing short-circuit. $D_a$ is the duty ratio of the recovery time of resonant power. In this study, duty ratio $D_{on}$ is taken as the control variable to control the effective current of the transformer primary side. As shown in Fig. 5, the effective AC voltage provided by the full-bridge inverter $V_p$ and primary side current $I_p$ are adjusted by the duty ratio $D_{on}$. Through the compensation capacitors and coreless
transformer, the output voltage to UST will be stable and nearly sinusoidal. Fig. 6 shows the operation modes in one switching cycle. The corresponding operation principles are described as following.

**Mode 1** \((t_0\sim t_1)\): switches \(Q_1\) and \(Q_4\) are turned on and switches \(Q_2\) and \(Q_3\) are turned off as shown in Fig. 6(a). The input voltage is applied to the compensation capacitor and the coreless transformer. The primary-side current is positive and the input source is delivering power to the transformer. The voltage stress on switches \(Q_2\) and \(Q_3\) is equal to the input voltage in this mode.

**Mode 2** \((t_1\sim t_2)\): In this mode, all switches are turned off to reduce the effective applied voltage to the transformer primary winding, i.e. the fundamental component of the transformer primary voltage \(V_p\) is reduced. Part of the energy is transferred to the secondary and part of that is released back to the input source through the body diodes of switches \(Q_2\) and \(Q_3\) as shown in Fig. 6(b).

**Mode 3** \((t_2\sim t_3\ and\ t_5\sim t_6)\): While the energy stored in leakage and magnetizing inductances is total released, all switches and body diodes are turned off as shown in Fig. 6(c). The primary-side current becomes negative because of the resonance in primary-side inductance, series compensation capacitor and the parasitic capacitances of active switches.
**Mode 4 (t$_3$~t$_4$):** In this mode, switches Q$_2$ and Q$_3$ are turned on to apply a negative voltage to the transformer primary winding as shown in Fig. 6(d). Part of the input power is transferred to the secondary side and part of that is stored into the leakage and magnetizing inductances. The voltage stress of switches Q$_2$ and Q$_3$ is equal to the input voltage.

**Mode 5 (t$_4$~t$_5$):** Switches Q$_2$ and Q$_3$ are turned off in this mode and the stored energy of the transformer is going to release. Part of this energy is transferred to the secondary side and the rest part is released back to the input source through the body diodes of switches Q$_1$ and Q$_4$.

![Diagram showing operation modes](image)

**Fig. 6.** Operation modes in one switching cycle.

From the above illustration of the operation principles, it can be seen that the primary-side current can be controlled by changing the duty ratio, $D_{on}$. To further realize the relationship between the primary-side current and the output voltage, the fundamental component response of the inductive power supply is analyzed.

The voltage gain between the input and output voltages can be illustrated by the fundamental equivalent model shown in Fig. 7 [11]. The input voltage source $V_{in}$ represents the fundamental component of the output switching voltage of the full-bridge inverter, namely $V_p$. The inductors $L_p$ and $L_s$ are the primary-side and secondary-side inductances and the mutual inductance is noted by $M$. The equivalent resistances of the windings are $R_p$ and $R_s$. The secondary-side capacitor $C_s$ is composed of the compensation capacitance $C_2$ and the equivalent capacitance $C_p$ of the UST. The voltage gain of the equivalent model can be expressed as follows.

$$\frac{V_o(s)}{V_{in}(s)} = \frac{i_p(s)}{V_{in}(s)} \times \frac{V_o(s)}{i_p(s)}$$

(1)
\[ G_{ipV\text{in}}(s) = \frac{i_p(s)}{V_{in}(s)} = \frac{Z_s}{Z_sZ_p + \frac{1}{\omega C_1}} \]  
\[ G_{Voip}(s) = \frac{V_o(s)}{i_p(s)} = \frac{sM}{Z_s + \frac{1}{\omega C_s} \parallel R_o} \]

where,

\[ Z_p = R_p + sL_p + \frac{1}{sC_1} \quad \text{and} \quad Z_s = R_s + sL_s + \frac{1}{sC_s} \parallel R_o. \]

Fig. 7. Fundamental equivalent model of the series-parallel compensated inductive power supply

Fig. 8. Responses of (a) the voltage gain and (b) the transfer function \( G_{ipV\text{in}} \)

The frequency responses of the voltage gain and the transfer functions \( G_{ipV\text{in}} \) are shown in Fig. 8. It can be seen that the voltage gain will remain nearly constant at different loading conditions if the working frequency is designed to be the frequency \( \omega_R \). However, the practical parasitic components and the voltage harmonic components would cause non-ideal effect on the voltage gain [12]. Therefore, an extra output voltage controller is still necessary for providing a stable output power.

In this study, the working frequency, i.e. frequency \( \omega_H \), is designed to be higher than the frequency \( \omega_R \). It is seen that if the working frequency is designed to be frequency \( \omega_H \), the gain of \( G_{ipV\text{in}} \) and the voltage gain are both decreased when the loading is increased. The primary-side current can, therefore, be used to estimate the output voltage while the loading is changed. A primary-side controlled based on the analyzed result is developed in this study as shown in Fig. 9. The primary-side current is sensed, rectified and filtered for feedback controlling. Accordingly, the output voltage would be stable if the primary-side current is under well-controlled to corresponding reference value.
4 Experimental results

Table I shows the parameters of the constructed inductive power supply prototype. The equivalent static capacitance $C_p$ of UST is also considered in the design of secondary compensation capacitance. Fig. 10 shows the measured waveforms of gate-driving voltage and drain to source voltage of active switch $Q_1$, i.e. $V_{gs1}$ and $V_{ds1}$, and the primary-side current $I_p$ and inverter output voltage $V_p$. The waveforms are good agreement with the analysis in previous section. Load changing dynamic experiments are also carried out to verify that the output voltage dynamic performance. The measured waveforms under load changing from 120 W to 300 W are shown in Fig. 11. It can be seen that the output voltage dips while the load is increased and it can be well regulated back to the reference level, i.e. $70 \text{V}_{\text{rms}}$, with the proposed primary-side controller. The output voltage and current waveforms under 120 W output power are shown in Fig. 12. The output AC voltage $V_o$ for UST is nearly sinusoidal. The efficiency of the proposed power supply under different rotation speed and constant output power 300 W is measured and shown in Fig. 13(a). Fig. 13(b) shows the efficiency under stationary and rotary operations with different loading. The efficiency difference between stationary rotary operations is only about 2%.

![Control block diagram of the primary-side current control](image)

**Table I. Parameters of the prototype circuit**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input Voltage $V_i$</td>
<td>$155 \text{V}$</td>
</tr>
<tr>
<td>Output Voltage $V_o$ (rms)</td>
<td>$70 \text{V}$</td>
</tr>
<tr>
<td>Switching frequency $\omega_H$</td>
<td>$25 \text{kHz}$</td>
</tr>
<tr>
<td>Resonant frequency $\omega_R$</td>
<td>$18 \text{kHz}$</td>
</tr>
<tr>
<td>Primary side inductance $L_p$</td>
<td>$261.88 \mu\text{H}$</td>
</tr>
<tr>
<td>Secondary side inductance $L_s$</td>
<td>$77.25 \mu\text{H}$</td>
</tr>
<tr>
<td>Mutual inductance $M$</td>
<td>$80.91 \mu\text{H}$</td>
</tr>
<tr>
<td>Air gap</td>
<td>$8.0 \text{mm}$</td>
</tr>
<tr>
<td>Series-connected compensation capacitor $C_1$</td>
<td>$0.33 \mu\text{F}$</td>
</tr>
<tr>
<td>Parallel-connected compensation capacitor $C_s = C_2 + C_p$</td>
<td>$1 \mu\text{F}$</td>
</tr>
</tbody>
</table>
Fig. 10. Measured waveforms of $V_{gs1}$, $V_{ds1}$, $I_p$, and $V_p$ under 300 W loading power

Fig. 11. Measured waveforms of $V_{gs1}$, $V_{ds1}$, $V_o$, and $I_o$ under 120 W loading power

Fig. 12. Output voltage and output current waveforms under load changing from 120 W to 300 W.
5 Conclusion

An inductive power supply with a coreless concentric transformer for UST was proposed in this study. The equivalent models of the coreless transformer and UST were both analyzed and taken into design consideration. Based on the analysis of transfer functions, a primary-side current controller is also developed to control the output voltage. There are only the secondary winding of the coreless transformer and a parallel compensation capacitor mounted on to the spindle. By adjusting the duty ratio of the inverter gating signals, the power supply can provide a stable and nearly sinusoidal AC voltage to the UST. Finally, experimental results of stationary and rotary tests were given to verify the validity and performance of the proposed power supply. The inductive power transferring between the stationary side and the rotating side of the coreless concentric transformer was then verified in this study. The efficiency difference between stationary and rotary operations was only about 2%.

Acknowledgments

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