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Optimization of Rotary Transformer for High-Speed Applications

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Abstract—**In grinding applications the processing of hard ceramics can be improved, if an ultrasonic axial vibration is superimposed to the rotation of the grinding tool in the grinding spindle head. The ultrasonic vibration is generated with a piezoelectric transducer which is attached to the rotating part of the spindle. Usually, the electrical energy is transferred with a rotary transformer consisting of a rotating secondary and stationary primary winding. There, the design of the rotary transformer is very crucial, since the available space in the spindle is limited and the cooling of the transformer is difficult. In addition, for high-speed applications the mechanical stresses on the transformer are high. Therefore, in this paper an optimization procedure of the rotary transformer with respect to minimum losses is presented, where magnetic, electrical and mechanical constraints are considered. In general, for a robust operation of the ultrasonic system an LLCC-filter is inserted between the piezoelectric transducer and the power converter, which makes the system insensitive to thermal and mechanical parameter variations. In order to keep the system complexity low, the needed LLCC-filter is magnetically integrated into the rotary transformer. In the literature, typically the components of the LLCC-filter are selected in such a way that the resonances of the LLCC-filter are matched to the mechanical resonant frequency of the piezoelectric transducer. This filter design method, however, doesn't result in minimum transformer losses. Therefore, in this paper also a new design method is proposed, which results in minimum transformer losses while keeping the ultrasonic system behavior stable and the control scheme simple. With a built prototype the proposed optimization procedure is experimentally verified based on a calorimetric measurement setup.**

I. Introduction

Since the discovery of the piezoelectric effect, i.e. the separation of electric charge and/or penetration of an electric voltage resulting from an elastic deformation of materials and vice versa (inverse piezoelectric effect), piezoelectric transducers are used in a wide range of applications and the field of applications is still growing. Beside energy harvesting, especially in applications based on the inverse piezoelectric effect, piezoelectric transducers are used e.g. for exact positioning in the nanometer range where the transducer is operated quasi-statically or for the generation of ultrasonic vibrations in the range of 20 kHz up to several hundred kilohertz where the piezoelectric transducer is operated in resonant mode. Other well-known applications of piezoelectric transducers are found in everyday objects like pocket lighters, ultrasonic toothbrushes, microphones or as guitar pickups, in medical application for medical diagnosis and therapy, in automotive engines for diesel injection, in production and process technology like ultrasonic welding, ultrasonic cleaning, acceleration sensors, cutting of paper stacks, positioning of mirrors and lenses, bonding of integrated circuits or ultrasonic assisted grinding, just to mention a few of a large number of applications [11].

In grinding processes of hard ceramics, for example, where usually spindles with rotational speeds of up to 100'000 rpm are used, an axial ultrasonic vibration is superimposed to the rotation of the grinding tool as shown in **Fig. 1**. As a consequence, the processing time, the cutting force as well as the abrasion of the expensive diamond equipped grinding tools are reduced. Furthermore, the surface quality of the material to be machined is improved [1]–[3], [11]. There, the piezoelectric transducer is attached to the rotating part of the spindle, thus, the electrical energy supplied by the stationary part's power converter has to be transferred with a rotary transformer consisting of a rotating secondary and stationary primary winding (cf. **Fig. 1**). In most rotary transformer concepts, presented in the literature [4]–[8], on both transformer parts a magnetic core material is employed. In high-speed applications, however, due to the high mechanical stresses, the diameter of the rotary transformer has to be minimized. Thus, to down-size the overall dimensions of the transformer a high electrical frequency has to be selected, which demands suited magnetic materials to keep the core losses low. Sintered ferrite-cores, however, are brittle and show only a low mechanical strength and compared to the windings, the core material's mass is high, which leads to a high unbalanced mass in the

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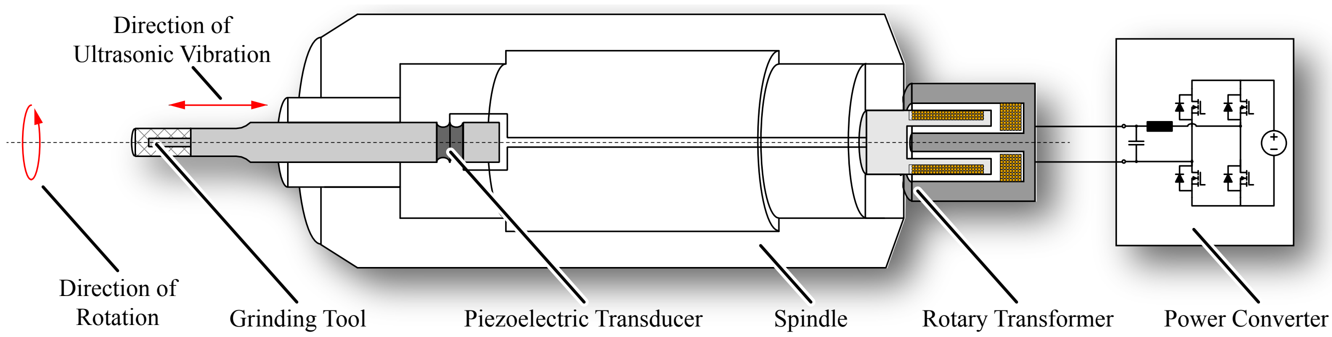

Fig. 1: Schematic view of the inside of the grinding spindle used for ultrasonic assisted grinding.

rotating part.

To overcome these limitations, two rotary transformer concepts for high-speed applications have been presented in [14], where no magnetic material is employed on the rotating part (cf. **Fig. 2**). These concepts feature a simple and mechanically robust design with a lightweight construction resulting in very small unbalanced mass. A detailed analysis concerning magnetic, electrical and mechanical behavior is done in [14]. For the underlying application, the design of the rotary transformer concerning losses is very crucial, since the available space in the spindle is limited - therefore the transformer has to be small - and due to the location of the transformer an efficient cooling is difficult; the ambient temperature in the spindle is already more than 60 °C. Therefore, in this paper an optimization procedure of the rotary transformer concerning minimum losses is presented, where magnetic constraints due to the proper ultrasonic operation, electrical constraints due to the needed efficiency of the transformer and mechanical constraints due to the high centrifugal forces and rotor dynamics resulting in high-speed applications have to be considered. First, in Section II the conditions for proper operation of the ultrasonic system are explained. There, between piezoelectric transducer and the power converter usually an LLCC-filter is inserted, which makes the system robust against thermally or mechanically caused parameter variation.

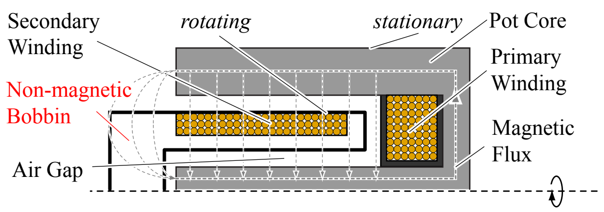

Fig. 2: One of the two proposed rotary transformer concept without any magnetic material employed on the rotating part [14].

Since the rotary transformer already features a magnetizing and leakage inductance, the magnetic part of the LLCC-filter can be integrated into the rotary transformer. Generally, in the literature the components of the LLCC-filter are selected to match the filter resonances to the mechanical resonant frequency of the piezoelectric transducer, which leads to a robust system behavior and allows the implementation of a simple control scheme. However, these design criteria don't result in minimum transformer losses. Therefore, in Section III a new transformer design is proposed, which leads to minimum transformer losses while keeping the system behavior robust and the control scheme simple. With the built prototype for an output power of 200 W, an electrical frequency of 70 kHz, and a rotational speed of 60'000 rpm, the presented optimization procedure is experimentally verified in Section IV. There, the generated losses are calorimetrically measured for different winding configurations, in order to verify the calculations which were done for different designs.

II. System Design and Control

For the generation of ultrasonic vibrations, the piezoelectric transducer is operated at its mechanical resonance $\omega_{\mathrm{p,mech}}$ in order to achieve high vibration amplitudes. In **Fig. 3 a)** the equivalent circuit of a piezoelectric transducer is shown. The mechanical behavior of the transducer including the ultrasonic system is represented by a series resonant circuit with the elements $C_{\mathrm{p,mech}}$, $L_{\mathrm{p,mech}}$ and $R_{\mathrm{p,mech}}$, which correspond to the mechanical system's stiffness, mass and damping respectively. The capacitance $C_{\mathrm{p,elec}}$, which is placed in parallel to the mechanical series resonant circuit, is defined by the mechanical dimensions, the piezoelectric material and the arrangement of the piezoelectric transducer's electrodes. Thus, for quasi-stationary applications, the piezoelectric transducer mainly shows a load-independent capacitive behavior. If the piezoelectric transducer is operated in resonant mode, however, it has to be distinguished between a weakly or well damped piezoelectric systems.

For weakly damped piezoelectric systems, at the mechanical resonant frequency, the phase of the input impedance is approximately zero and the impedance magnitude reaches its minimum (cf. **Fig. 3 b)**). Around the mechanical resonant frequency the phase steeply changes from $-90\,°$ to $90\,°$ and the phase shift caused by $C_{\mathrm{p,elec}}$ can be neglected. Consequently, the excitation frequency of the piezoelectric transducer has to be controlled in such a way that the input current and voltage are in phase, if possible component variation due to thermal and mechanical changes are taken into account (cf. **Fig. 3 c)**). Typical values of a weakly damped piezoelectric transducer, which is also employed in the underlying grinding application, are given in **Table I**. With increasing damping, the influence of $C_{\mathrm{p,elec}}$ also increases and leads to a phase shift in the input impedance at the mechanical resonant frequency, which is also the case for the used piezoelectric transducer if it is embedded into the spindle (cf. **Table I**).

Possibilities to overcome this problem for well damped piezoelectric systems are either to adapt the frequency control by calculating the needed phase shift based on measured values of $C_{\mathrm{p,elec}}$ or to insert an additional filter inductor between the power converter and the piezoelectric transducer in such a way that in combination with $C_{\mathrm{p,elec}}$ the resulting LC-filter shows a resonance which coincides with the mechanical

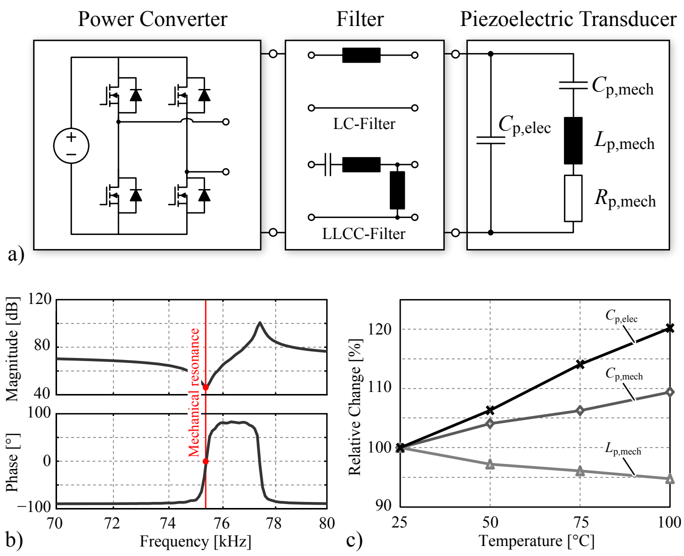

Fig. 3: a) Schematic of the power converter with output filter and piezoelectric transducer, b) input impedance of the employed piezoelectric transducer around the mechanical resonant frequency and c) temperature dependency of the piezoelectric transducer's parameters.

TABLE I: Measured parameters of the piezoelectric system's equivalent circuit of the transducer only and for transducer embedded into the spindle with attached grinding tool.

	Transducer only	*Transducer embedded*
$R_{\mathrm{p,mech}}$	$190-2500\,\Omega$	$1900-3000\,\Omega$
$L_{\mathrm{p,mech}}$	147 mH	1300 mH
$C_{\mathrm{p,mech}}$	30 pF	4 pF
$C_{\mathrm{p,elec}}$	540 pF	580 pF
$f_{\mathrm{p,mech}}$	73...75 kHz	69...71 kHz

resonant frequency (cf. **Fig. 3 a)**). However, both solutions are sensitive to component variations (cf. **Fig. 3 c)**) whereat especially $C_{\mathrm{p,elec}}$ shows a strong temperature dependency [9]–[13] and thus would result in a more complex control scheme. In order to reduce the sensitivity on component variations and to achieve a robust piezoelectric system with a simple control scheme, in the literature [9]–[13] the insertion of a LLCC- instead of a LC-filter is proposed (cf. **Fig. 3 a)**). With a proper filter design, at the mechanical resonant frequency a transfer function with unity gain without any phase shift is achieved. In addition to the system's robustness, higher order filters have the advantage that in combination with switch mode power supply the generated harmonics of the power converter are more attenuated, which is necessary, since higher order harmonics are shorted out by $C_{\mathrm{p,elec}}$ and thus result in additional losses in the piezoelectric transducer [13]. The major drawback of the LLCC-filter is the higher number of components, especially if large inductance values have to be realized [13]. Compared to the LC-filter, however, the LLCC-filter results in a smaller and lighter design and also shows a better dynamic response [12]. In addition, for the underlying grinding application a rotary transformer is needed, which already features a certain magnetizing and leakage inductance, as shown in **Fig. 4**. These values are deduced from the general transformer model by proper selection of the transformation ratio n as will be shown in the final paper. Consequently, the LLCC-filter can be magnetically integrated into the rotary transformer. Accordingly, in combination with the capacitance $C_{\mathrm{p,elec}}$ for the realization of the LLCC-filter only an additional series capacitance C_{s} as well as a proper design of the rotary transformer are needed.

III. Magnetic Integration and Transformer Optimization

As proposed in the literature [9]–[13], for a robust system behavior concerning parameter variation, the LLCC-filter's transfer function $G(\mathrm{j}\omega)_{LLCC} = V_{\mathrm{g}}/V_{\mathrm{p}}$ is designed to achieve at the mechanical resonant frequency $\omega_{\mathrm{p,mech}}$ unity gain without any phase shift. This can be realized if the resonant frequencies of the two LC-filters - magnetizing inductance $L_{\rm mag}$ with piezoelectric transducer's capacitance $C_{\rm p,elec}$ and leakage inductance L_σ with series inductance $C_{\rm s}$ - are matched to the mechanical resonant frequency

$$\omega_{\rm p,mech} = \frac{1}{\sqrt{C_{\rm p,elec} L_{\rm mag}}} = \frac{1}{\sqrt{C_{\rm s} L_\sigma}}. \quad (1)$$

Then, $L_{\rm mag}$ compensates the reactive power drawn by $C_{\rm p,elec}$ and $C_{\rm s}$ compensates the series impedance of the transformer $L_{\rm sigma}$ [13]. Consequently, at the input of the LLCC-Filter a purely resistive behavior can be measured if the excitation frequency equals the mechanical resonant frequency.

Thus, the excitation frequency can be easily controlled by keeping the input current and voltage in phase, which means that only active power is drawn from the power converter. Consequently, the rated power of the inverter stage can be minimized which results in a downsized power converter with higher efficiency. As one could think, also the current ratings in the rotary transformer are reduced, however, doesn't result in an optimized transformer design concerning minimum losses. Since the reactive power drawn by $C_{\rm p,elec}$ is fully compensated with $L_{\rm mag}$ ($Z_{\rm t} = R_{\rm L}/n^2$, cf. **Fig. 5 a)**), the current in the secondary winding is much larger than the primary current transformed to the secondary, which results in disproportional higher losses in the secondary winding. In addition, the stronger H-field generated by the secondary ampere-turns $N_2 I_2$ leads to higher proximity losses in both windings and therefore in higher transformer losses as will be further explained in the final paper. The corresponding magnetic field distribution across the primary and secondary winding for full compensation (f.c.) of the reactive power is shown in **Fig. 5 b)**, where $N_2 I_2 \gg N_1 I_1$.

In order to improve the current and magnetic field distribution, which would result in lower total transformer losses, the reactive power drawn by $C_{\rm p,elec}$ can also be compensated from both windings as described in [14]. Therefore, the value of $L_{\rm mag}$ which was found according to (1), is continuously reduced - less reactive power is compensated by $L_{\rm mag}$, thus, only partial compensation is given ($Z_{\rm t} \neq R_{\rm L}/n^2$, cf. **Fig. 5 a)**) - and $C_{\rm s}$ is adjusted in such a way that the input impedance of the LLCC-filter is still purely resistive in order to keep the control scheme simple. For each combination of $L_{\rm mag}$ and $C_{\rm s}$, with the given load specification and the magnetic behavior of the rotary transformer, the primary and secondary currents and the magnetic field distribution can be calculated. With this iteration the best combination of $L_{\rm mag}$ and $C_{\rm s}$ resulting in the lowest total losses can be found. The corresponding shape of the magnetic field with optimal partial compensation (p.c.) is shown in **Fig. 5 b)**.

For the transformer optimization it also has to be considered that due to the low coupling and low magnetizing inductance the primary and secondary current - consequently also the magnetic fields - are not in phase with each other. As will be shown in the final paper, for large phase differences this can result in significant calculation errors if for the magnetic

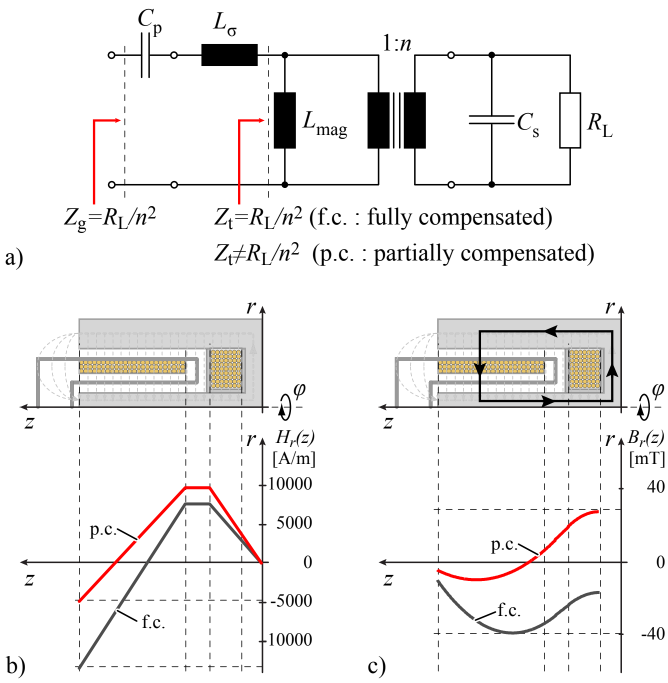

Fig. 5: a) Schematic circuit of the LLCC-Filter with resistive load and impedances $Z_{\rm g}$ and $Z_{\rm t}$, b) magnetic field distribution and c) flux density for full compensation (f.c.) and partial compensation (p.c.) of the reactive power drawn by $C_{\rm p,elec}$ with $L_{\rm mag}$.

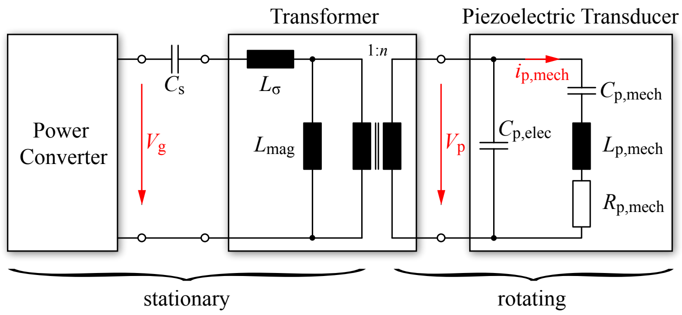

Fig. 4: Electrical circuit diagram of the piezoelectric system with LLCC-filter magnetically integrated into the rotary transformer.

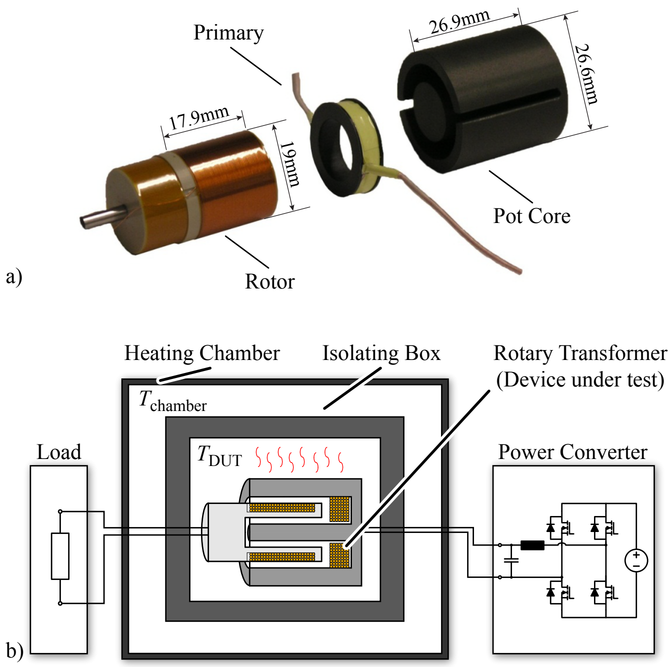

Fig. 6: Photo of the rotary transformer prototype, b) principle of the calorimetric measurement setup in order to verify the optimization procedure of the rotary transformer.

field distribution only the magnitudes of the magnetic fields but not also the phases are considered. In addition, for the optimal compensation also the resulting core losses have to be considered, which is done in detail for the optimization procedure in the final paper. However, it is obvious that with lower magnetic fields also the flux density in the core material and therefore the core losses are reduced (cf. **Fig. 5 c)**). As can be noticed, with the optimum transformer design and the resulting LLCC-filter (1) is no more valid. However, in the final paper it will be shown that with the adapted filter design the robustness of the LLCC-filter is not decreased.

Under the above-mentioned side conditions, in the final paper the optimization procedure of the rotary transformer for ultrasonic assisted grinding is presented in detail, where also the mechanical constraints concerning rotor dynamics and the centrifugal forces resulting in high-speed applications are considered.

IV. Experimental Results

In the final paper the proposed transformer design and optimization procedure will be verified with a built rotary transformer prototype designed for the optimum and other winding arrangements (cf. **Fig. 6 a)**).

For the experimental measurements instead of a piezoelectric transducer an equivalent resistive load is used. In order to be able to accurately measure the losses of the rotary transformer a calorimetric measurement setup is used. There, the rotary transformer is placed into an isolating box, which in turn is placed into a heating chamber with constant chamber temperature T_{chamber} (cf. **Fig. 6 b)**). During operation, the temperature difference between the T_{chamber} and the temperature inside the isolating box T_{DUT} is measured until a thermal equilibrium is reached. With the known R_{th} of the isolation box, which is first deduced with a resistor powered from a dc-supply, the losses of the rotary transformer can be calculated. In addition, thermocouples are attached to the windings and the core, in order to get a qualitative statement of the loss distribution in the rotary transformer.

V. Conclusion

In ultrasonic assisted grinding applications the design of the rotary transformer concerning losses is very crucial, since the available space in the spindle is limited and an efficient cooling of the transformer is difficult. Therefore, in this paper an optimization procedure of the rotary transformer concerning minimum losses is presented, where magnetic, electrical and mechanical constraints are considered. In order to keep the system complexity low, the needed LLCC-filter, which enables the proper and robust operation of the ultrasonic system, is magnetically integrated into the rotary transformer. In addition, a new design method resulting in minimum transformer losses while keeping the system behavior robust and the control scheme simple is proposed. With a built prototype the presented optimization procedure is experimentally verified for different designs with a calorimetric measurement setup.

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