A RESONANT DC/AC INVERTER USING AN ELECTROMECHANICAL DEVICE

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Abstract: This paper presents an electromechanical approach to implement a resonant dc/ac power inverter. The proposed approach uses a two-port electromechanical device called an electrodynamic transformer to provide a solution with lower component count compared to a pure electrical approach. The macroscale (9.6 cm^3) electrodynamic transformer—consisting of a permanent magnet, two coils and a cantilever beam—emulates an electrical transformer, three inductors, and one capacitor at the same time. With the addition of a MOSFET and an output capacitor, the system functions as a resonant dc/ac power inverter. Experimental demonstrations show the power inverter functionality with a tunable output ac voltage amplitude (15 dB dynamic range) when the MOSFET switching frequency is adjusted within 360±3 Hz. The macroscale system exhibits very low power density and efficiency, but improved performance is expected with miniaturization of the electrodynamic transformer.

Keywords: dc/ac inverter, power converter, electrodynamic transformer

INTRODUCTION

Passive energy storage and transfer components such as inductors, capacitors and transformers are often the bulkiest components in a power converter. Much effort has been focused on miniaturizing these components and maximizing the power density of the power converter systems. Optimized structures, materials and fabrication techniques for on-chip integration of these bulky components are being investigated by various studies [1–3]. With the development of the MEMS technology, a clear trend of using mechanical structures to realize electrical functionalities can be observed. Typical examples include switches [4,5], oscillators [6,7], etc.

This paper attempts to investigate the use of mechanical components to perform electrical energy storage and transfer functionalities. A two-port electromechanical device, coined an "electrodynamic transformer (ET)" is used, which emulates several building blocks of a resonant converter. Specifically, the ET mimics a transformer, an LLC resonant tank (two inductors and a capacitor), and an output filtering inductor. To demonstrate the concept of using mechanical motion to convert power, an elementary resonant dc/ac inverter is constructed by adding only two additional components: a switching MOSFET and an output filtering capacitor.

The specific goal of this paper is to demonstrate a functional proof-of-concept electromechanical dc/ac inverter system at the macroscale. Based on reduced-order models, such a system is expected to have relatively low efficiency and energy throughput (because of low mechanical resonant frequencies and low mechanical quality factor). However, microfabrication approaches are being developed to realize a much smaller and higher performance integrated power converter in the future.

THEORY

Electrodynamic Transformer

As demonstrated in [8], an ET is a two-port electrodynamic transducer cascading an electrodynamic actuator and an electrodynamic generator As shown in Fig. 1, electrical input energy is converted to mechanical vibration through the electrodynamic actuator. The mechanical vibration is converted to the electrical output through the electrodynamic generator, in the similar manner as a vibrational energy harvester. Since the electrical power is transferred from the input to the output without direct electrical conduction, this electromechanical device resembles the basic functionality of a transformer.

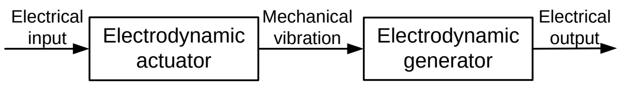

Fig. 1: Block diagram of an electrodynamic transformer.

A structural view and a picture of a proof-of-concept device are shown in Fig. 2. The device consists of an assembly of permanent magnets mounted on the tip of a cantilever beam spring, and two coils (one for input and the other for output) that are fixed to the frame. The permanent magnet assembly consists of four NdFeB (grade 50) ring magnets arranged in such a way that both coils experience a large radial magnetic field. The radial magnetic field creates strongly coupled electrodynamic transduction [9]. The ring magnets are attached to the aluminum cantilever beam by a bolt and nuts (made from stainless steel 18-8 with relative permeability close to 1). The cantilever beam is anchored to the Delrin frame. A primary (AWG 32) and a secondary coil (AWG 36) are attached to the frame as the input and output terminals, respectively.

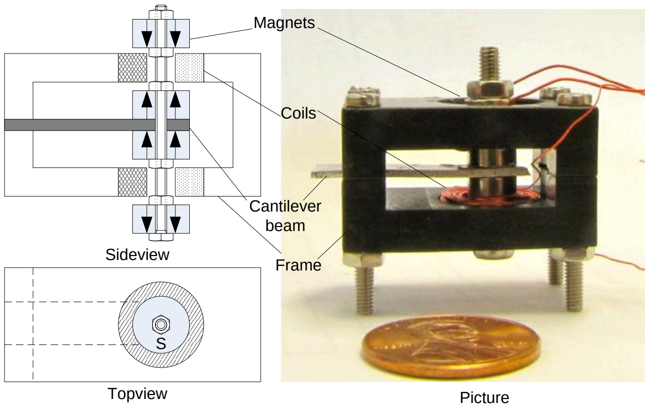

Fig. 2: Schematic and picture of an electrodynamic transformer.

As an ac voltage is applied to the primary coil, the electrical current results in an oscillatory force on the magnet assembly, causing it to vibrate. The vibrational mechanical energy is transferred to the secondary coil through magnetic induction.

Our previous study has demonstrated that the ET can more effectively transfer energy at relatively low frequencies, as compared to conventional core-based electromagnetic transformers [8]. In addition, the theoretical power density in electromechanical energy transfer can be orders of magnitude higher than that of the electromagnetic energy transfer.

Equivalent Circuit Model of an Electrodynamic Transformer

The equivalent circuit model of an ET is shown in Fig. 3. The combined primary and secondary side electrodynamic transductions are represented by a transformer, where the turns-ratio is the ratio of the electrodynamic transduction coefficients (commonly known as *Bl*). The cantilever beam and the magnets assembly form a mechanical resonator. The self-inductance and resistance of the coils are also included in the model.

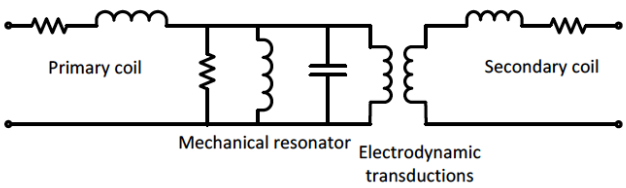

Fig. 3: The equivalent circuit model of an electrodynamic transformer.

LLC-PRC Power Converters Using Electrodynamic Transformer

It is not difficult to relate the equivalent circuit model in Fig. 3 with a resonant power converter. In a typical resonant power converter, the input signal is converted into a square wave through a switching network. A resonant tank (common tanks include LC, LLC, or LCC) filters the high frequency harmonic components of the square wave. The near-sinusoidal output of the resonant tank is connected to a transformer for galvanic isolation and voltage boost or buck. Depending on the type of the converter, the last stage can be a rectifier (for dc/dc converters) or an LC filter (for dc/ac inverters).

A careful inspection of the equivalent circuit representation shown in Fig. 3 reveals that the mechanical resonator and the self-inductance of the primary coil form an LLC resonant tank, the electrodynamic transductions form a transformer, and the self-inductance of the secondary coil forms the filtering inductor of a resonant inverter. As shown in Fig. 4, all the components in Fig. 3 can be integrated to a circuit called LLC-PRC (inductor-inductor-capacitor parallel resonant converter) power inverter [10]. In other words, an ET can replace the three inductors, one capacitor and one transformer in a conventional LLC-PRC power inverter. This could dramatically reduce the physical size and increase the power density of the circuit.

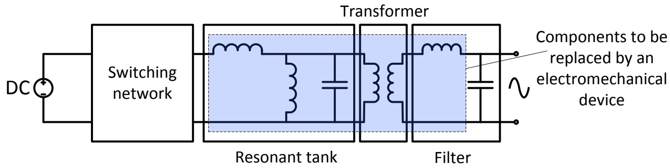

Fig. 4: The circuit diagram of an LLC-PRC power inverter.

In an ET-based resonant inverter, the switching network chops the input dc voltage into a square wave. The square wave electrical signal is then converted to a nearly sinusoidal motion of the vibrating structure in the ET. This is attributed to the filtering and resonant amplification afforded by the mechanical resonator. As the frequency of the clock signal varies, the magnitude of the mechanical vibration can be tuned which is evidenced by a varying output voltage at the secondary coil. AC voltage amplification or attenuation can be achieved by using more or fewer secondary coil turns, respectively. The output waveform is further filter with the help of the self-inductance of the secondary coil and the external output capacitor.

EXPERIMENTAL

The ET is first tested alone to characterize its frequency response and efficiency. Then, an LLC-PRC power inverter is constructed and tested by adding one MOSFET and one output capacitor.

Standalone Testing of the Electrodynamic Transformer

The open-circuit voltage gain frequency response is captured with a network signal analyzer (Stanford Research Systems, SR785). With the ET clamped on a steady bench, an input swept sine signal (100-500 Hz) of 0.1 V_{pk} from the signal analyzer is connected to the primary coil. The amplitude ratio and phase difference of the open-circuit sinusoidal output voltage and the actual input voltage is measured versus the frequency.

As shown in Fig. 5, a maximum voltage gain of 0.95 is obtained at 360.5 Hz, which is close to the mechanical natural frequency of the resonator. The anti-resonant point at ~275 Hz is attributed to compliance of the supporting frame.

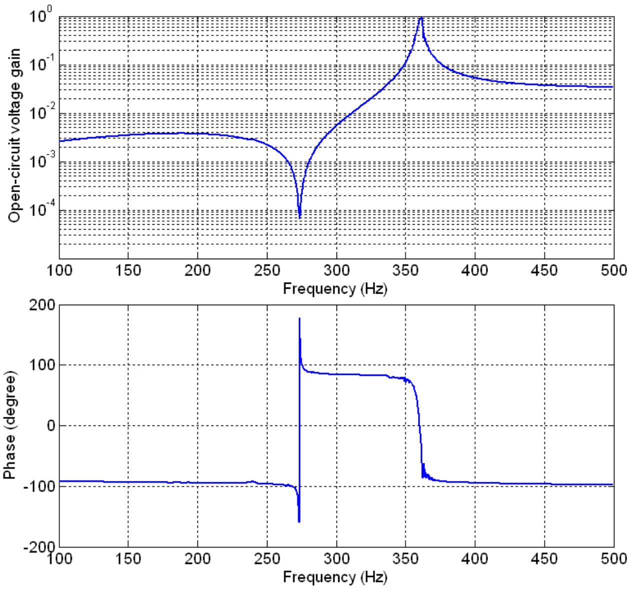

Fig. 5: Open-circuit voltage gain and phase frequency response.

In order to measure the efficiency of the device, a sinusoidal voltage at 360.5 Hz and 0.1 V_{pk} is connected to the primary coil, and a variable resistor is connected to the secondary coil. An oscilloscope (Tektronix TDS5104B) and a current probe (Tektronix TCP312 with TCPA300 amplifier) are used to capture the input and output voltages and the input current waveforms. With varying load resistance, the average input and output power and the efficiency are calculated. As shown in Fig. 6, a maximum load power of 63 μW is obtained when the load resistance is 10 Ω. This resistance is believed to the equivalent output impedance of the device at 360.5 Hz. Also at 10 Ω, the efficiency goes to a maximum of 6.5%.

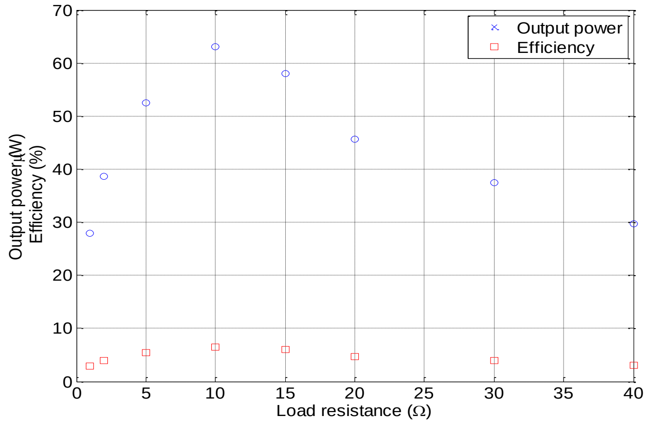

Fig. 6: Output power and efficiency at different load conditions.

Due to the weak electrodynamic coupling of the device [9], the change in input power at different load resistances is negligible compared to the change in output power. This explains why one load resistance yields both maximum output power and maximum efficiency. The low overall efficiency is attributed to design factors such as low radial flux density at the coils, low coil packing density, high mechanical damping, etc. All of these factors result in low coupling strength [9] of the device, which is believed to play a significant role in the power efficiency of the ET. In addition, a higher resonant frequency could potentially increase the efficiency by reducing the mechanical loss (increasing the mechanical quality factor). High operating frequency also helps improve the power handling capability of the mechanical structure, since energy can be transferred at a faster rate.

Measurement of the ET-based LLC-PRC Power Inverter

From Fig. 4, an LLC-PRC power inverter is simply the combination of a switching network, an ET, and an output capacitor. For concept demonstration purposes, the switching network in this work is implemented by a single MOSFET. This is not the best topology for inverter performance, but plenty of high-performance switching networks are available in power electronics literatures that are compatible with ET-based circuits. The final system is shown in Fig. 7.

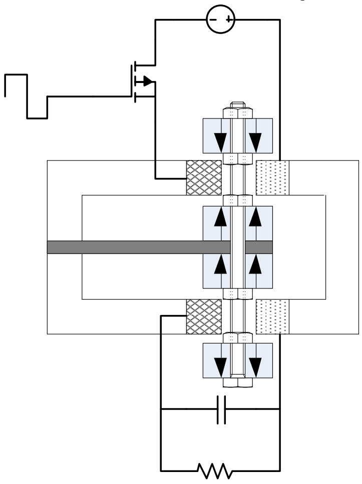

Fig. 7: Schematic of the ET-based power inverter.

The measurement of the inverter is performed by using a 0.1 V_{dc} isolated voltage source (Stanford Research Systems, SIM928) as the input, and a function generator (Agilent, 33120A) as the clock signal to drive the MOSFET. With the circuit operating at 360.5 Hz at open load condition, the measured input and output voltage, the input current waveforms, and the clock signal are shown in Fig. 8. The clean sinusoidal output indicates that the system functions as a power inverter.

Furthermore, by varying the frequency ±3 Hz, the output voltage amplitude can be tuned from 3.1 mV to 17.1 mV, a dynamic range of ~15 dB. The open-circuit output voltage amplitude vs. switching frequency is shown in Fig. 9.

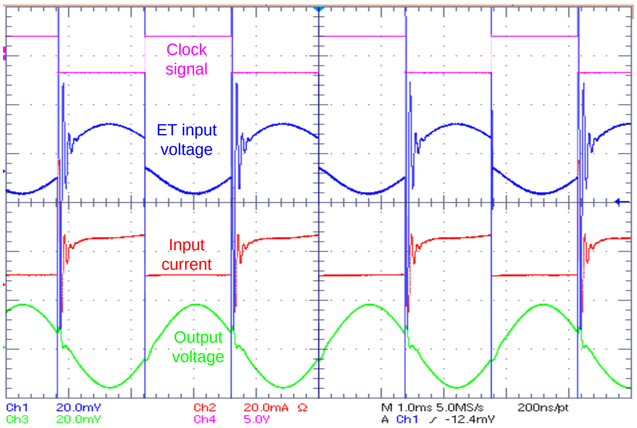

Fig. 8: Captured waveforms of the power inverter.

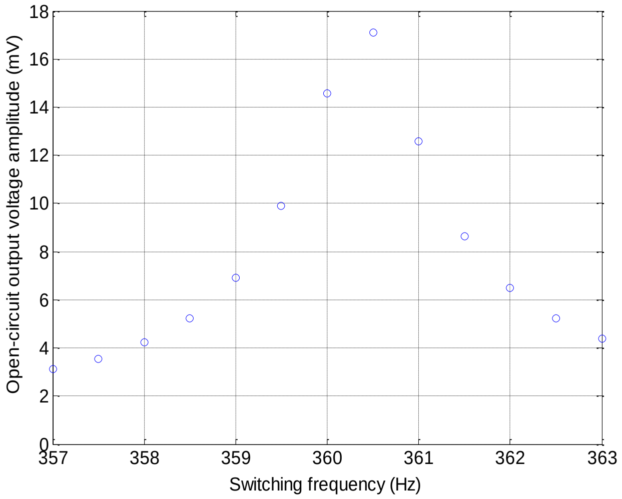

Fig. 9: Open-circuit output voltage amplitude vs. switching frequency.

Lastly, by connecting a variable load resistance to the output, the output power and power efficiency are measured, and shown in Fig. 10. Due to the inefficiency of the ET prototype, as well as the simple switching network, the maximum efficiency is only 5.5% when the load resistance is 5 Ω.

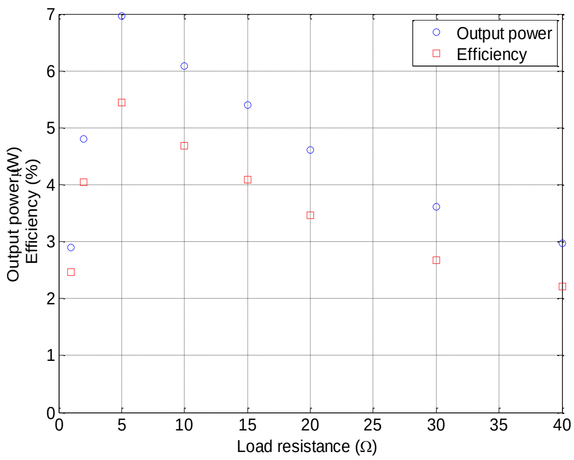

Fig. 10: Output power and efficiency of the power inverter at different load conditions.

CONCLUSION

The ET provides an alternative implementation to a resonant power inverter. For the demonstration system shown here, a maximum output power of 7 μW is delivered to a resistive load at an efficiency of 5.5% with a 0.1 V dc input voltage. The efficiency and power density of the specific demonstrated system is much too low to be practically useful. However, multiple design optimization approaches can be used to significantly improve the performance. These include constructing a better magnetic assembly, improving the packing density of the coils, using vacuum packaging, increasing the natural frequency to increase the mechanical quality factor, etc.

In ongoing/future work, a more compact or even monolithic power converter is envisioned via microfabrication of the ET. Such a device could potentially enable a smaller component count and potentially smaller mass/volume for implementing the LLC-PRC converter. The power inverter circuit can also be modified to other useful circuit topologies such as dc/dc converter. More importantly, by scaling down the device, the system would benefit from the increased natural frequency. As a result, the power efficiency and power density are expected to scale favorably as the physical dimension decreases.

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