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Power enhancement of piezoelectric transformers for power supplies

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Abstract

This paper studies power enhancement of piezoelectric transformers to be used in inductorless, half-bridge, piezoelecteric-based switch mode power supplies for driving a piezo actuator motor system in a high strength magnetic environment for magnetic resonance imaging and computed tomography applications. A new multi element-piezo transformer solution is proposed along with a dual mode piezo transformer, providing power scaling and potentially improving the internal heat-up of a high power piezo transformer system.

1 Introduction

The Piezo actuator drive (PAD) is a drive technology transforming the linear motion of high performance piezoelectric multilayer actuators into a powerful and precisely controllable rotation. PAD aims to enable reliable motor performance in strong magnetic fields for magnetic resonance imaging (MRI) and computed tomography (CT scan) treatment tables. There are some limitations in the current treatment tables, e.g. motors cannot operate in the presence of strong magnetic field inside the MRI room. Furthermore, imaging and motor operation cannot take place simultaneously. PAD characteristics, i.e. nonmagnetic high speed independent torque, integrated force and position feedback allow for better performance and higher flexibility in the construction of treatment tables. However, there are technological limitations in operation of this motors and drive systems related to magnetic interference. The creation of a motor based on the PAD principle, exhibiting nonmagnetic behaviour which requires the development of innovative driver solutions for the piezoelectric actuators. Moreover, designing a nonmagnetic driver for providing power to the PAD motor is quite challenging since the driver also should be nonmagnetic. Piezoelectric transformers (PTs) are suitable candidates for addressing this challenge to provide solutions, which are far beyond any existing technology.

Employment of PT has become popular since it can replace magnetic and reactive components in both resonant and traditional magnetic transformer-based converters due to smaller size, lighter weight, lower cost, lower electromagnetic interference (EMI), higher power density, and higher efficiency [1]. The operating principle of the PT is based on electromechanical energy conversion. PTs use electromechanical coupling between the primary and secondary sides compared to conventional transformers which use electromagnetic coupling. This introduces PTs as applicable candidates for applications that have a high sensitivity to electromagnetic interference [2]. Therefore, PTs with nonmagnetic drivers may be able to work in high electromagnetic fields, e.g. 7 Tesla. Transmitted energy ratio in PTs cannot exceed 95% due to piezoelectric material losses [3], but a proper design is needed to benefit from maximal obtainable power density.

This paper is organized as follows. Section 2 presents challenges and short comings in power capability of PTs for driving a piezo actuator. The solutions for enhancing PT's power throughput are introduced, designed and investigated. Furthermore, explanation about construction method and mounting is provided. Results of different designs are compared and explained in the Section 3. Finally, the conclusion is provided in section 4.

2 Challenges

This Section deals with detailed explanation of requirements for PTs and design methodology used for increasing the power throughput of transformers.

2.1 PAD

The PAD shown in Fig.1 consists of four single piezo actuators (PAs) with capacitive behavior. Structure of one PA is shown in Fig. 2. Theoretically, power level of up to 100 W is needed to drive a PA placed inside the PAD motor. The maximum output power density of piezo transformers are limited to around 52 W/cm3 [4] which depends on the type of the piezo ceramic. The most two important keys in design of transformers have been thermal management and power scalability. Providing the required power through a PT for one single element is quite challenging due to limited technology of PTs. The PT generates heat during operation and this causes considerable changes in its operating point and consequently voltage gain. The main target for reduction of self-heating has been to reduce the interlayer thickness and keep the power density to a certain level. However, the PT should be capable of transferring large power to the PA to drive the PAD motor. Furthermore, having nonmagnetic driver implies that the PT should be capable of handling massive power peaks and do this without the help of coils to support soft switching for the converter methodology. This arises need for new solutions, which is of the interest of this research.

Figure 1: PAD motor.

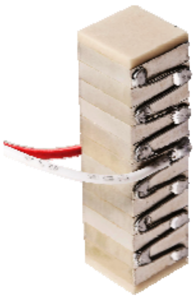


Figure 2: Piezo actuator as a load of the driver.

2.2 PT's power enhancement

This paper studies power enhancement of PTs to be used in inductorless, half-bridge, PT-based SMPS [2]. The transformer type is selected to be interleaved interdigitated electrode (IDE) multilayer PT, regarding easy manufacturing as well as high efficiency advantages by utilizing longitudinal mode vibration [5]. In this work two solutions are suggested and designed to raise the power capability of the PT. New ideas are designed, fabricated and tested for the purpose of this work. The first solution is multi-piezo element and the second one is scaled-size PT. Both solutions are for obtaining higher power transformation by keeping the same power density to avoid thermal increase. Fig. 3 shows design simulation of a PT element which is used as a root element of further designs. The root element is constructed as a true piezo transformer in regards to temperature, zero voltage switching and voltage gain.

The first design uses a configuration with extended width to excite the first thickness mode operation as well as a standing wave across the width of the PT structure. Although this may prove difficulty to tune, it has a wide potential for a powerful transformer configuration with low internal heat generation due to the large power generating zone. Fig. 4 shows simulation results of scaled-size PT at the resonance frequency. The second design is a combination of multi root elements in one block. Every two adjacent elements are polarized in the opposite directions; hence three individual PTs are presented in the structure. In this design there are nineteen electrodes accessible for polarization. Therefore, polarization is a difficult task from the research point of view, but in mass production this will not be an issue. The major benefit is that this design potentially solves the power scaling issue of PTs, since a whole PT block can resonate at the resonance of a root PT design. In other hand, its entirety contributes linearly to the output power. This property becomes important in this application since the power levels are needed to be extended beyond the capabilities of the theoretical limit of a single PT element in terms of stress and material properties. Fig. 5 shows the fabricated transformers.

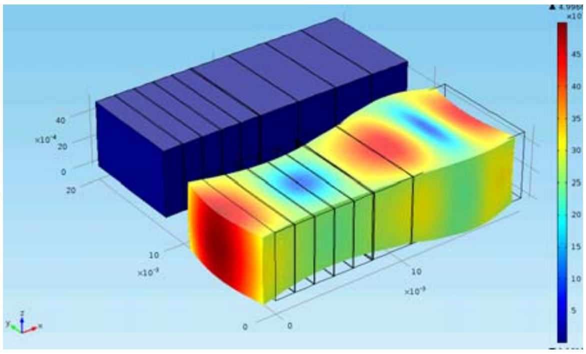


Figure 3: The root element of piezoelectric transformer. Simulation is done in COMSOL Multiphysics and shows operation of the root element in its first resonance mode. The colour blue illustrates the point of maximum stress but minimum deformation.

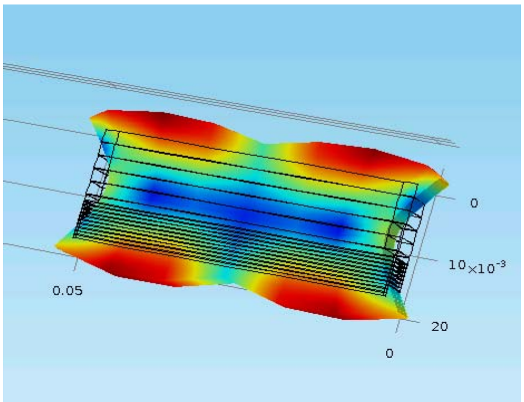


Figure 4: The scaled-size PT is a large transformer that utilizes a multimode approach for obtaining the required stresses for energy transfer. Please note the extended blue area where the PT can be mounted.

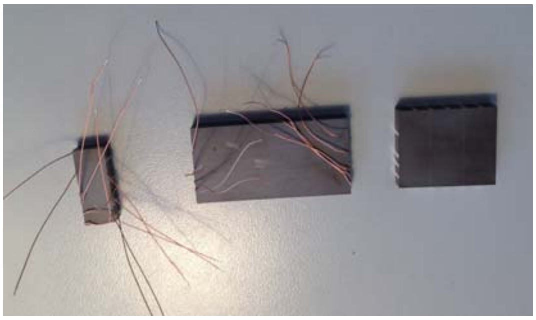


Figure 5: All of key transformers side by side; from left to right – The root element; the scaled-size PT; the multi element PT with three active root elements mechanically coupled together.

2.3 PT construction method

During the construction of the PT elements either hard or soft-doped piezo ceramic materials could be used. For a resonating transformer usually a hard-doped ceramic is used, due to the stiffness and very high Q factor, which is often associated with these types of ceramics. The material selected was NCE46 provided by Noliac A/S. The material is well understood and provides the necessary flexibility in prototype production. However the material demands that all of the internal electrodes to be comprised of Platinum/Palladium, instead of Silver/Palladium as seen in other builds due to the high sintering temperatures needed for this material.

To construct the piezo structures proposed in this paper, the selected build-up method is the newly developed IDE stacking process, which allows the producer of piezo components to make virtually any thickness mode design since each PT is constructed from a series of piezo layers that is stacked with very accurate positioning. With this new technology, a PT operating in thickness modes becomes possible which leads to multiple geometrical shapes that can be realized in the prototype development stage. For our selection, we have chosen to build an IDE transformer that is square allowing for maximal usage of the whole piezo wafer, therefore increasing our yield per production.

Furthermore, this technology allows for many different designs in one singular build-up to easier spread the risk, and since an isolation layer is needed, analogies to that of a regular magnetic transformer, an IDE based transformer only needs one section instead of the radial mode solution that had to have two sections of isolation – due to the symmetrical build-up principles in place for a stable radial mode transformer.

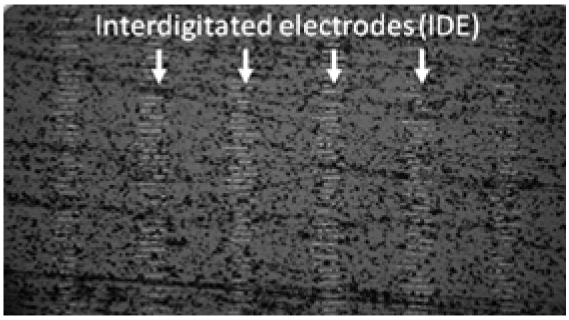


Figure 6: Illustration of IDE electrodes inside the actual piezo transformer

One downside to this build process is that the minimum production qualified electrode thickness is a 70 [μm]. This means that we are going to have some inactive material that does not generate electrical energy but reduces the energy transferring mechanisms, which cannot be avoided at this point.

2.4 Mounting the transformers

Since the two mentioned transformers will operate at two different modes (the first and the second mode, respectively) this also leads to two different mounting strategies as seen in Figure 7. The main aim for the authors mounting strategy is to minimize the damping from fixing the transformer in place. However, from heat-buildup analysis, it has been found that mounting the transformer at the nodal point(s) will not only provide an undamped fixing of the PT, but also provide a method of shunting most of the heat away from the PT. This is derived from the analytical work on zero voltage switching (ZVS), that discovered the area of maximum internal stresses inside the piezo structure is also responsible for the majority of the heat generated by the PT, hence it could be recommend that the mounting bracket of a PT should also be capable of heat transference in high stress high frequency operation.

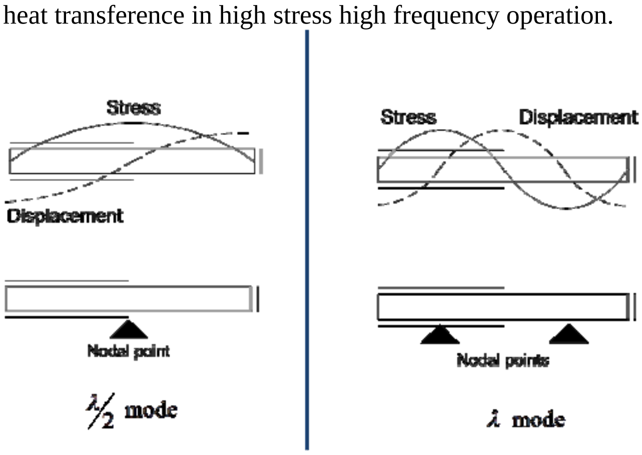


Figure 7: Mounting piezo transformers is preferably done at the point of maximum stress, which is the point of minimum displacement.

3 Results

From simulation results it became obvious, that matching the desired operational frequency and geometry lead to the process of adding or subtracting material of the PT in order to tune to the correct frequency of the transformer. Furthermore, it was experienced that the polarization of the PT become more and more difficult along with the length increase of the PT, since the polarization happens roughly around 10 times the normal operation voltage and the polarization happens more or less rapid at a certain voltage level allowing for a shock to travel through the entirety of the structure creating chipping or breakage. In many cases the achieved power levels were somewhat comparable to the simulated results, but in high strain PT structures it is was clear that temperature increase hindered further power throughput. It was found that this might be linked to the ZVS capabilities inherent to this design and some investigation on ZVS leading to increase in thermal losses concluded that this presumable is the case. The ZVS result was interesting since is also partly states that stresses beyond certain levels inside the PT forces the PT to become much more thermally active. As seen in the Figure 8.

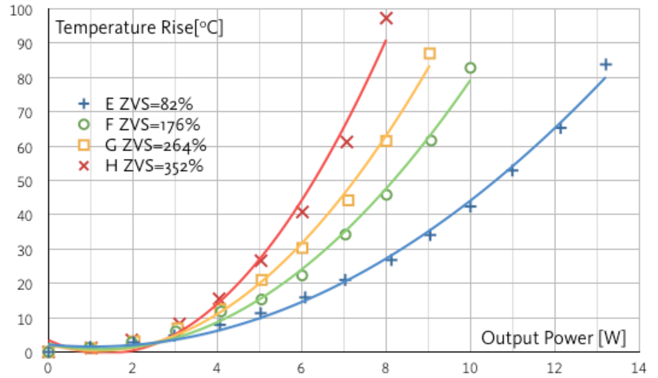
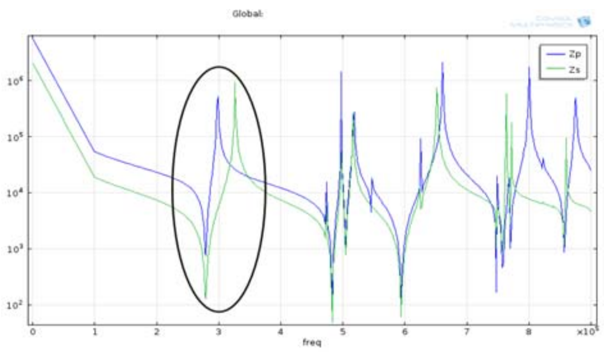


Figure 8: Heat generation at different ZVS levels and throughput.

Concerning the resonance of the system it was found that a piezo design with a low ZVS also provided another interesting feature since a ZVS close to 100% would in some sense be better for a bi-directional transformers since a ZVS of 150% forward conduction mode would be a unmatched system at bi-directional operations see Figure 9.



Figurer 9: Impedance plot of the given test system

4 Conclusion

In this research two possible PT solutions are proposed and tested. Furthermore, this paper dealt with power enhancement of PT in order to be able to transfer enough energy for driving a piezo actuators placed inside the PAD motor. Increasing power transmission capability of PT has led to an array of interesting observation that launched analysis on ZVS capability and stress buildup inside the PT unit, as a result from the excess heat generated by the prototype samples. Furthermore, a novel suggestion of using a multiple of PT operating in thickness mode coupled together in one single unity was proposed to tackle the power scaling issue that operating the PAD motor poses.

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