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Driving Power Supply for an Avionic Piezoelectric Deicing System

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ABSTRACT

The ability of a piezoelectric actuator in energy conversion is rapidly expanding in several applications. Some of these applications for which an ultrasound piezoelectric actuator can be used are surface cleaning, metal cutting and welding, and biomedical applications such as needleless drug delivery. A new application of piezoelectric actuators is the Avionic Deicing System. The working frequency of actuator is between 100 kHz and 150 kHz, depending on temperature and ice thickness, and output power levels at several hundreds of Watts. The power supply of piezoelectric actuators has to provide an output voltage of up to 200 VAC at the resonance frequency with low consumption.

This article discusses and analyzes a low-consumption electromechanical deicing solution based on piezoelectric actuators, its operating principle, and its driving power supply development supported by experimentations on the setup representative of a part of the Nacelle.

Keywords: piezoelectric deicing system, piezoelectric actuator, soft-switching inverter, ARCPI.

1. INTRODUCTION

During the progress towards the "More Electric Aircraft" where the intention is to replace all hydraulic and pneumatic systems by electromechanical ones, the avionic piezoelectric deicing system has proven its efficiency and integrability with low energy consumption.

Compared to other existing deicing and anti-icing systems like pneumatic, thermal, electro-thermal, and chemical ones, the new method of deicing using piezoelectric actuators is more economical regarding energy consumption, congestion, weight and cost. This new method can be applied using piezoelectric patches or Langevin transducers, which are to be bonded on the interior of the Nacelle's or wing's surface via rigid glue (for the patches) or mechanical fixation with a bolt (for the transducers). By controlling the piezoelectric elements with alternating voltages at their resonant frequency, the surface starts to vibrate, creating a stress field at the interface leading edge/ice great enough to delaminate the ice. The vibrations are of very small amplitudes compared to other electro-mechanical technologies, hence inducing less structural fatigue.

However, designing the power supply and its control for driving the piezoelectric actuators would be a challenging task based on the fact that piezoelectric ceramic has a capacitive behavior on nearly all its frequency range, leading to a very low power factor therefore, deteriorating the performance of the converter. In addition to that, the resonant frequency of the actuator will change a lot (a few kHz) according to the temperature and ice thickness, excluding all resonant converter solutions. Furthermore, seen that the operation frequency needed to have an operational deicing is high, the switching frequency for a PWM converter will be much higher (10 times), conducting many challenges (switching losses, EMI problems, ...).

2. SPECIFICATIONS

2.1 Deicing & Anti-icing Systems

In aviation, there are generally two types of design for the ice protection system. The first is the anti-icing system, which has the role of preventing the formation of ice, and the second is the de-icing system, which is to remove the ice after it has formed. Current strategies for deicing and anti-icing can be mechanical, thermal, or chemical [1]. Anti-icing systems

can be either thermal in order to keep the temperature of the surfaces higher than the freezing point (0°C), or chemical to move the melting point to a temperature well below 0°C (-13°C for ethylene glycol, -59°C for propylene glycol). On the other hand, deicing systems use either mechanical technics (pneumatic or electromechanical) to expel the ice or thermal technics (hot air or resistive grid) to melt the ice.

Unfortunately, all actual deicing and anti-icing solutions have many drawbacks. Thermal solutions like the turbine engine bleed air and electrically heated systems require a large amount of energy. Chemical solutions can induce environmental issues and premature wear of the treated parts (like corrosion). Pneumatic solutions have a significant impact on the aerodynamics of the aircraft and are often used in small to medium-sized turboprop aircraft because of the volume constraints imposed by the pneumatic system. Electromechanical systems are considered low-energy solutions, but some of them, like EIDIS (Electro Impulsive DeIcing System), can cause structural fatigue due to repeated deformations.

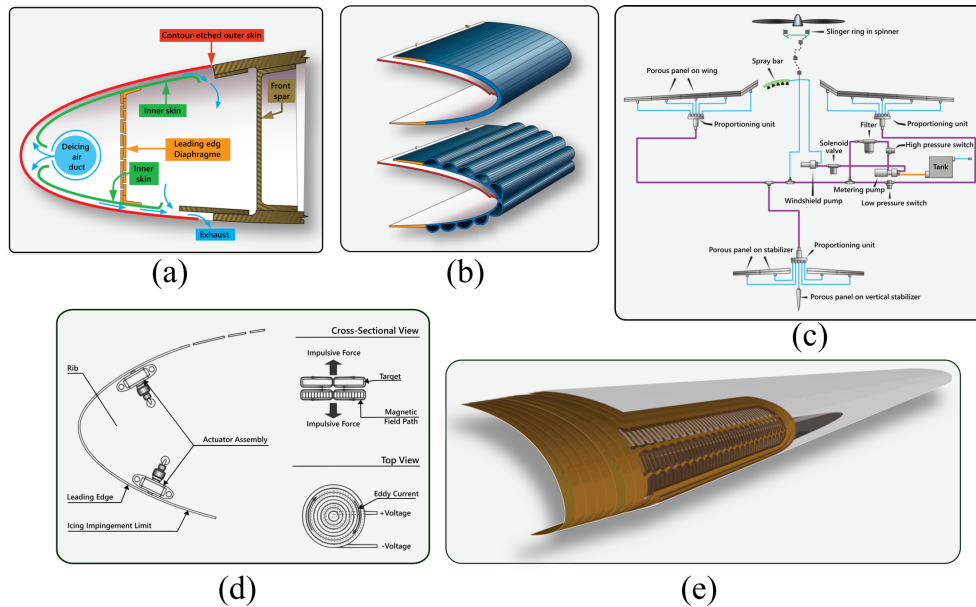


Figure 1: Different deicing and anti-icing systems, (a) turbine engine bleed air [1], (b) pneumatic boot, (c) chemical fluid [1], (d) EIDIS [2], (e) ETIPS [3].

2.2 Piezoelectric Deicing System

The operating principle of deicing systems based on piezoelectric actuators is to apply vibrations at a specific frequency to the structure to delaminate and crack the ice. These piezoelectric actuators are fixed (glue, bolt, or others) on the internal face of the concerned leading edge (nacelle or wing) and generate microscopic mechanical ultrasonic vibration based on the principle of the inverse piezoelectric effect when they are power supplied with an AC voltage. These vibrations have a very low amplitude compared to other electromechanical solutions, eliminating structural fatigue risk.

There are two possible architectures for deicing with piezoelectric actuators. Either the piezoelectric ceramics are bonded to the surface with rigid glue to have good coupling with the leading edge of the part to be de-iced (Figure 2-M1). These ceramics can be shaped and sized as required and are easy to implement, though they are fragile. Or they are stacked in two layers or more and sandwiched between two metallic parts (one from steel and the other from aluminum) in order to transmit the vibrations to the medium through the aluminum part. The whole structure is clamped by a bolt and screwed to the leading edge, thus resistant to stress (Figure 2-M2).

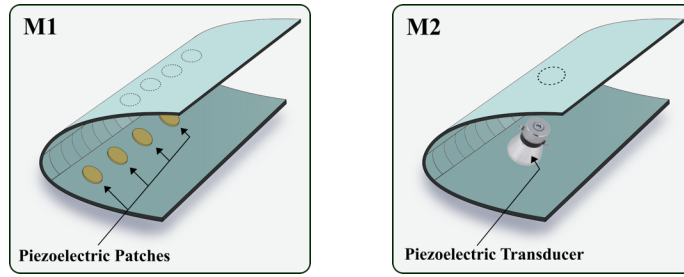


Figure 2: Configuration of a piezoelectric deicing system with piezoelectric patches (M1) and transducers (M2)

Several studies have been conducted on this deicing system, with different types of piezoelectric actuators and on various frequency ranges. A survey of the deicing efficiency of these two architectures concluded that transducers are more advantageous in terms of power consumption, mechanical failure (fracture of the ceramics), and structural fatigue [4].

To improve the performance of piezoelectric actuators and generate the desired power supply signal, it is essential to know their electrical characteristics. A good understanding of their characteristics helps a lot in choosing and sizing the associated power supply.

In the literature, several electrical models of a piezoelectric transducer are presented, such as the Van Dyke model, the Sherrit model, and the Guan model [5].

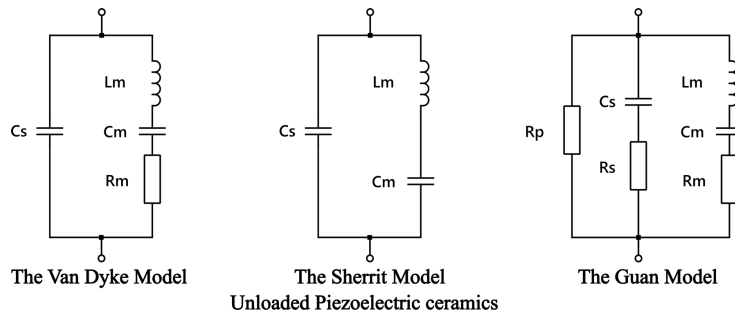


Figure 3: Electrical model of piezoelectric transducer [5].

The most common equivalent circuit that characterizes a piezoelectric transducer around its resonant frequency is the Van Dyke circuit (Figure 3). This model is often used to characterize the electromechanical properties of a piezoelectric material [5]. In this model we identify the static capacitance C_s related to the dielectric behavior of the piezoelectric material with a motional branch (L_m , C_m , R_m) which presents the vibratory behavior of the mechanical part.

Each piezoelectric transducer has several resonance frequencies in which its impedance has a lower magnitude as compared to non-resonance frequencies. To attain higher efficiency and deliver more power to the ultrasound system, the transducer will be excited at its main resonance frequency at 150 kHz for M2 (Figure 4) and at 115 kHz for M1 configuration.

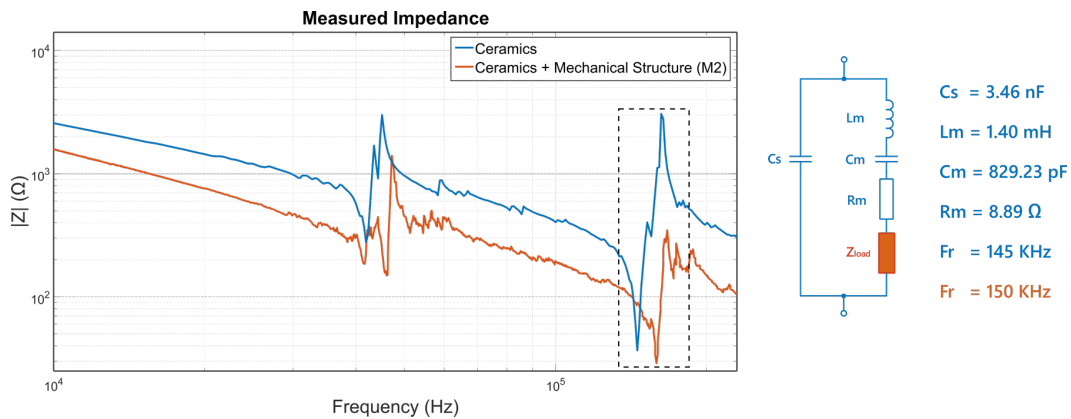


Figure 4: Measured impedance of a loaded and unloaded ceramics + Resonance equivalent circuit.

2.3 Electrical specifications

Designing an appropriate power supply for a piezoelectric actuator is a real challenge in power electronics since its electrical behavior is capacitive in almost all its frequency range and changes depending on temperature and mechanical load. This challenge becomes even more difficult for avionic applications where the deicing system and its power supply must comply with the aviation regulations and standards (DO 160), as well as the installation constraints of the equipment (safety, space requirements), while allowing its proper operation.

The power supply should be capable of converting 270 VDC input voltage to an AC output voltage with minimum THD (Total Harmonic Distortion) in order to excite only the desired mode. Otherwise, many modes could excite simultaneously, increasing power consumption and decreasing the piezoelectric actuator's lifetime.

Also, the power supply should be isolated from the load by an isolation transformer in order to prevent any problem that could occur to the load from returning to the equipment. In addition to that, the load will be fed through 2 meters length cables because of the space constraints that do not allow to place the converter to be as close as possible to the load.

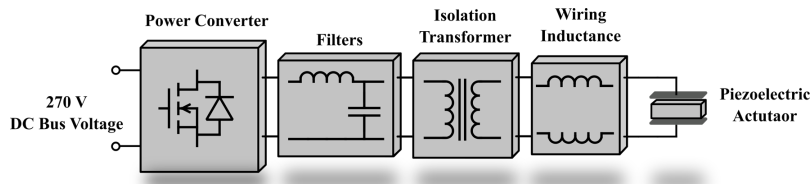


Figure 5: Synoptic board of the complete system.

3. SYSTEM CHARACTERIZATION

The structure of the leading edge and the deicing system has to be designed. The type and shape of piezoelectric ceramics and their position on the inner side of the leading edge should be properly chosen. For our two samples, a rectangular aluminum plate of dimension $50 \times 30 \times 2 \text{ mm}^3$ was curved to have the shape of a wing's or nacelle's leading edge. In the M1 configuration, PZT-4 piezoelectric patches of a round shape of 1.5 mm thickness and 20 mm diameter were chosen. PZT-4 considered as a hard ceramic and has much less mechanical and dielectric losses than PZT-5. The round shape suffers less stress on the edges than rectangular shape. 16 patches were placed on the inner side of the curved aluminum plate using rigid glue and connected in parallel.

As for the M1 configuration, we used similar aluminum plate for the M2 configuration. Two piezoelectric transducers were fixed with a bolt to the leading edge.

The ice formation tests were performed in a regular freezer at a temperature of -15°C . By spraying droplets of water to the aluminum plates several time at this temperature we could form layers of glaze ice. Several thicknesses of ice were performed and tested.

In order to determine values of the equivalent electrical models of actuators attached to the leading edge with ice layers, the impedance should be measured. To investigate the impedance, an impedance analyzer is used. In this case, piezoelectric actuators are connected to an impedance analyzer and excited by an electrical signal (Voltage signal most of the time) of 500 mV. Then the feedback current is measured to determine the impedance of actuators connected to the structure. Piezoelectric actuators have special impedance curves where the impedance amplitude of each transducer is decreased at several frequencies. These frequencies are known as resonance frequencies of the whole structure and its main resonance is where the magnitude is the lowest. Compared to non-resonance frequencies, the piezoelectric actuator's vibrations are greater at the main frequency.

Measured impedance of the two configurations M1 (Figure 7) and M2 (Figure 8), shows clearly the effect of ice thickness on their electrical behavior where the main resonance frequency shift of 2 kHz to the left by each 0.5 mm of ice thickness and also get damped of round 10Ω . This change caused by ice thickness can be modeled by adding more serial inductance and resistance to the Van Dyke model, as in the circuit in Figure 4.



Figure 6: Set up measurement protocol with an impedance analyzer.

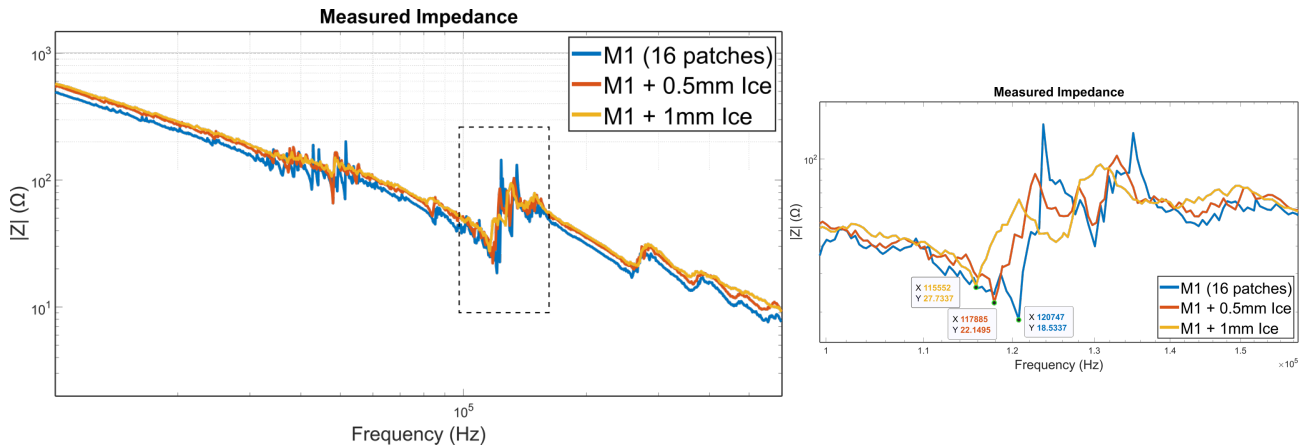


Figure 7: Measured impedance of the M1 architecture depending on ice thickness.

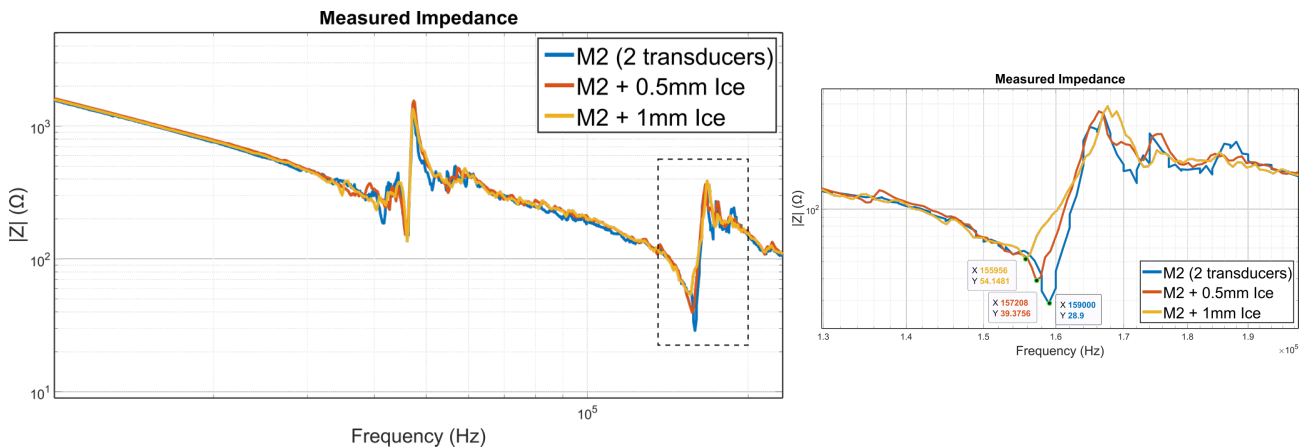


Figure 8: Measured impedance of the M2 architecture depending on ice thickness.

4. DRIVING POWER SUPPLY

Since piezoelectric actuators have a particular impedance that changes a lot with frequency and depends on the mechanical load and the temperature, it's essential to consider some aspects when designing the power supply. Among these aspects is the driving frequency, which must correspond to the mechanical resonance frequency of the actuator attached to the leading edge. In fact, at this resonance, the power transfer is better, and the reactive energy consumption is reduced (less loss). Another important aspect is the quality of the excitation signal, which has an important role in the performance of the piezoelectric transducer and its lifetime [6].

In this context, several techniques are proposed in the literature [7],[8],[9]. Linear power amplifiers (A, B, AB, ...) are used to drive piezoelectric loads since they provide signals with low harmonic distortion. However, they have low efficiency and are often bulky and heavy. As a result, switching-mode converters are increasingly used and dominate the market due

to their good efficiency and high-power density. These converters are a promising alternative solution for driving piezoelectric actuators.

In this regard, a variety of studies has focused on using voltage source inverters to drive piezoelectric actuators. Resonant inverters (LC or LLC) and PWM inverters (LC or LLC) are the most commonly used. Alternative topologies, such the three-level NPC inverter and the current inverter, have also been employed [10]. The size and weight of the magnetic elements of the resonant filter as well as the relatively small range of the working frequency are the main drawbacks of resonant inverters.

To overcome these drawbacks, PWM-controlled inverters (LC or LLC) have been proposed [11]. The disadvantages of PWM control are always related to the switching frequency, which generates high switching losses and EMC constraints.

In the literature, a number of topologies of soft-switching inverters have been proposed [12],[13],[14]. The goal of this kind of inverter is to operate at high frequencies with minimum switching losses and electromagnetic interference (EMI). An interesting example of soft-switching inverters of the "Resonant Pole Inverter (RPI)" family is the Auxiliary Resonant Commutated Pole Inverter (ARCP) [15],[16]. The circuit topology, and its theoretical waveforms, are illustrated in Figure 9.

The inverter consists of two main arms and an auxiliary circuit linked to a capacitive divider bridge. In order to limit as much as possible the losses, EMI problems as well as the number of components, one arm will be switched to Low Frequency (LF) synchronized to the frequency of the output voltage and the other arm will be switched at High Frequency (HF) to which the auxiliary circuit is connected. This circuit's function is to charge and discharge the C_{oss} parasitic capacitances in order to ensure ZVS on the HF arm. On the other hand, the control law of the auxiliary circuit implies zero current switching (ZCS) of its transistors. Moreover, since the auxiliary circuit is not in the main power path, the power rating of its switches will be reduced compared to that of the main switches. The control applied is a unipolar PWM which reduces the output voltage harmonics.

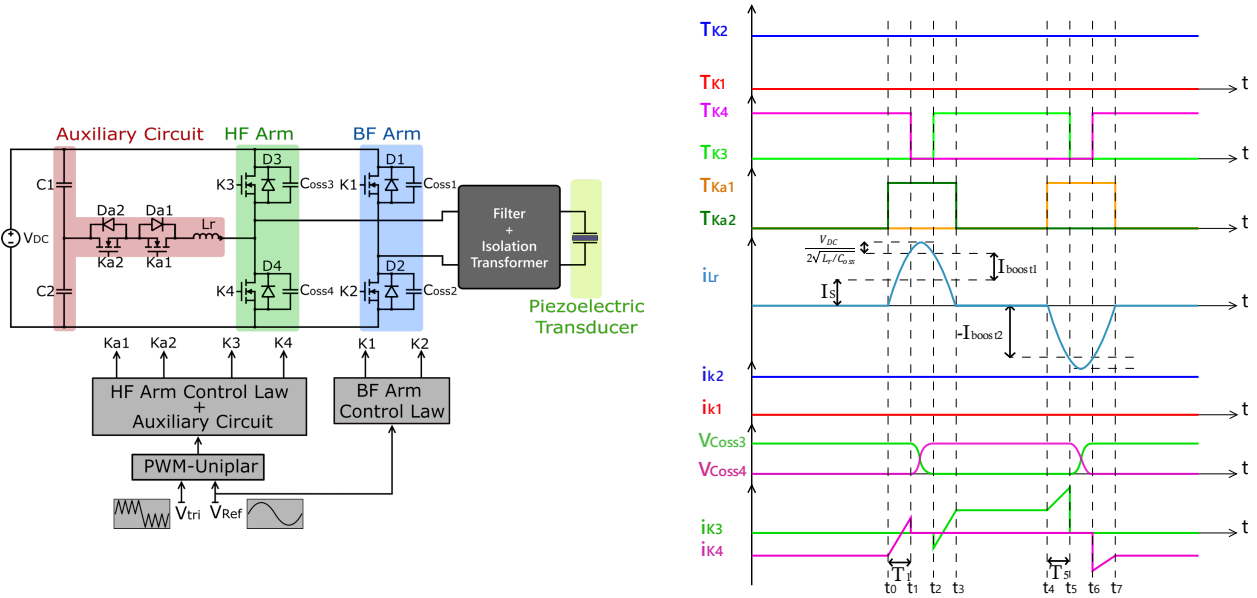


Figure 9: Circuit topology of the ARCP Inverter + its output theoretical waveforms.

Simulation:

The resonant inductor L_r should be properly sized in order to achieve ZVS on all main switches of the HF arm. To do so, the energy stored in this inductance must be sufficient to charge and discharge the parasitic capacitances of the concerned transistors. Therefore, the following conditions must be respected:

$$\frac{V_{DC}}{2L_r} T_1 \geq I_{s_{max}} \quad et \quad \frac{V_{DC}}{2L_r} T_5 \geq I_{s_{max}} \quad (1)$$

With $T_1 = t_1 - t_0$ et $T_5 = t_5 - t_4$.
From (1):

$$L_r \leq \frac{V_{DC} \cdot T_1 \cdot V_{s_{\max}}}{4P_{s_{\max}}} \quad (2)$$

With: $P_{s_{\max}} = \frac{1}{2} V_{s_{\max}} I_{s_{\max}}$

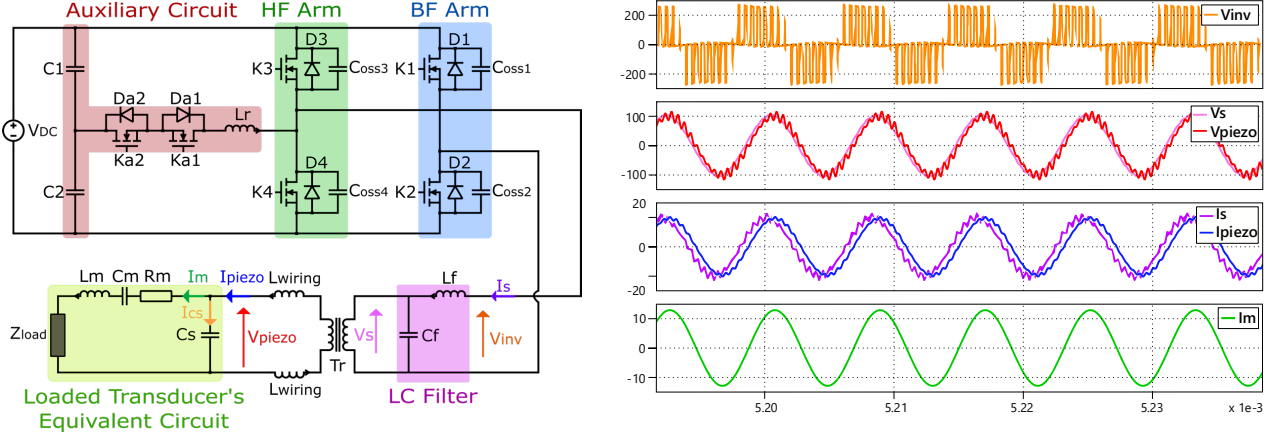


Figure 10: Circuit topology of the complete system (ARCPI + LC filter + isolation transformer + wiring inductance + loaded transducer) + its simulated output waveforms.

The inverter output filter was sized to have a current ripple of less than 20% I_s and a cutoff frequency $f_{LC} = f_{sw}/10$, knowing that $f_{sw} = 2 \text{ MHz}$. This implies $L_f = 8.5 \mu\text{H}$ and $C_f = 76 \text{ nF}$.

The simulation is performed taking into account the wiring inductance ($2 \cdot L_{wiring} = 2 \mu\text{H}$). Figure 10 shows sinusoidal waveforms with a total harmonic distortion (THD) of 13% for the voltage V_{piezo} across the transducer, and 5% for the output current I_s . The relatively high THD on V_{piezo} is due to the resonance between the wiring inductance and the transducer's static capacitance C_s . This resonance deteriorates the operation of the filter leading to low attenuation and even amplification of some harmonics around this resonance. The choice of the output filter is not definitive. The use of an LLC filter might be considered later.

5. EXPERIMENTAL RESULTS

The test procedure was established in order to, in one hand, validate the ARCPI converter topology and its agility to adapt to the load variation while ensuring zero voltage switching. In another hand to validate the piezoelectric deicing concept and compare the efficiency of the two architectures M1 and M2.

The experimental set-up is shown in Figure 11. The power supply (ARCPI converter topology) is connected to the piezoelectric actuator. The FPGA controller is driving the converter at the resonance frequency of the piezoelectric actuators.

The tests were performed in a regular freezer at a temperature of -15°C . Several layers of glaze ice were formed on the leading edge M1. Different tests at different frequencies were performed, especially at the two resonance frequencies and the range as in Figure 7.

Partial deicing was achieved only for a 2 mm thickness of ice at the main resonance frequency at 115 kHz with 150 VAC and 1.5 A (Figure 12). At this frequency we could initiate cohesive fractures in the ice and adhesive fractures at the ice/support interface. An interesting side effect can be observed during the experiments is that after certain time, the accreted ice close to the attached actuators starts to melt due to its heat dissipation.

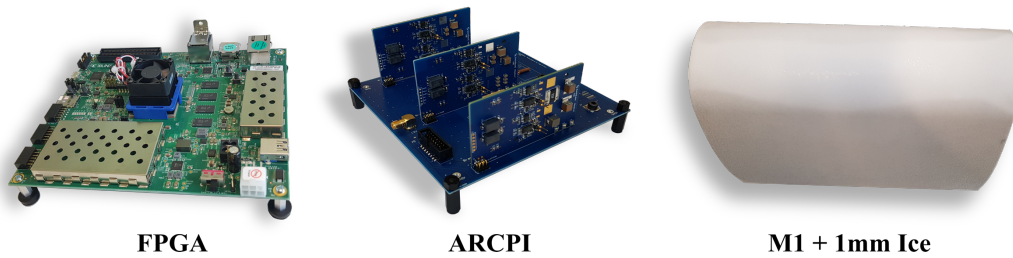


Figure 11: Experimental setup of the ARCP Inverter.

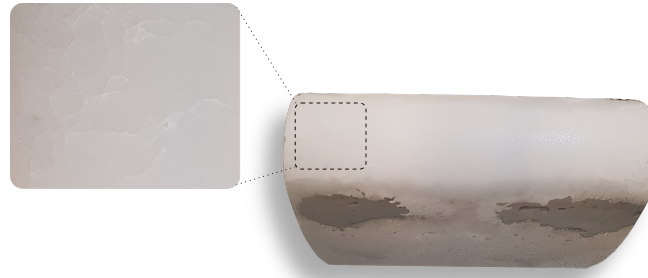


Figure 12: Partial deicing of the M1 configuration with piezoelectric patches (delamination and cracks).

6. CONCLUSION

This article has discussed and analyzed a new electromechanical deicing method based on piezoelectric actuators. The electrical behavior sensitivity to the ice thickness has been demonstrated on two different architectures with piezoelectric patches and Langevin transducers. The driving power supply was properly developed and designed in laboratory in order to ensure the specifications. Deicing tests were performed with different ice thicknesses, and partial deicing was ensured for 2 mm ice thickness at the resonance frequency of the structure. Tests are still in progress to identify the appropriate mode of these piezoelectric patches for complete deicing. Ongoing tests on the M2 configuration with piezoelectric transducers will help to conclude in terms of efficiency between these two configurations. Further tests in an icing wind tunnel are planned in order to investigate the influence of ice nature (glaze ice, rime ice or mixed ice) on the deicing process.

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