

## Article

# Design and Optimization of a Boost Interface for Magnetostrictive Energy Harvesting

Carmine Stefano Clemente \* , Immacolato Iannone , Vincenzo Paolo Loschiavo  and Daniele Davino \* 

Department of Engineering, University of Sannio, 82100 Benevento, Italy

\* Correspondence: carmine.clemente@unisannio.it (C.S.C.); davino@unisannio.it (D.D.)

**Abstract:** Magnetostrictive alloys are very promising for Vibration Energy Harvesting applications to supply power to Wireless Sensor Network (WSN) and Internet of Things (IoT) devices, especially because of their intrinsic robustness. Typically, vibration energy sources are random in nature, usually providing exploitable voltages much lower than the electronic standards 1.6, 3.3 and 5 V. Therefore, a Power Electronic Interface (PEI) is needed to improve the conversion to DC output voltage from AC input over a wide range of frequencies and amplitudes. Very few or no conversion techniques are available for magnetostrictive devices, although several have been presented over the years for other smart materials, such as piezoelectrics. For example, hybrid buck–boost converters for piezoelectrics use one or more external inductors with a high-frequency switching technique. However, because of the intrinsic nature of harvesters based on magnetostrictive materials, such energy conversion techniques are proved to be neither efficient nor applicable. An improved AC–DC boost converter seems very promising for our purpose instead. The key feature is represented by the direct exploitation of the active harvester coil as a storage element of the boost circuit, without using other passive inductors as in other switching methods. Experimental tests of such a converter, driven with a real-time operating Arduino controller to detect the polarity of the input voltage, are presented with the aim to assess the potentiality of the scheme with both sinusoidal and impulse-like inputs. Simulations have been performed with LTspice, and the performance and efficiency have been compared with other energy conversion techniques.

**Keywords:** energy harvesting; AC–DC boost; magnetostrictive materials; Arduino



**Citation:** Clemente, C.S.; Iannone, I.; Loschiavo, V.P.; Davino, D. Design and Optimization of a Boost Interface for Magnetostrictive Energy Harvesting. *Appl. Sci.* **2023**, *13*, 1606. <https://doi.org/10.3390/app13031606>

Academic Editor: Alessandro Lo Schiavo

Received: 8 December 2022

Revised: 23 January 2023

Accepted: 23 January 2023

Published: 27 January 2023



**Copyright:** © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

## 1. Introduction

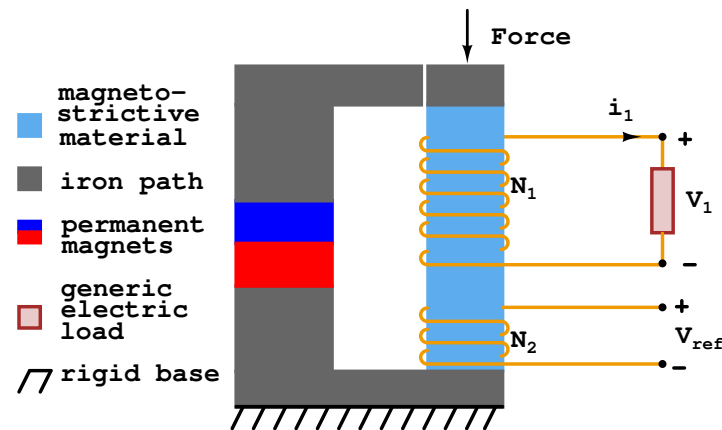
Energy Harvesting (EH) techniques mainly consist of recovering a bit of environmental energy, either due to natural sources or human activities, that would normally be wasted. While renewable energies are being exploited everywhere at large scale, EH is usually performed in remote places where a power grid is unavailable or expensive to connect to but some strategic electronic circuits need to be supplied. In particular, EH could be used to supply relevant low-power consumption electronics, such as Wireless Sensor Networks (WSN), that can be used, for example, in Structural Health Monitoring (SHM) of bridges or viaducts [1,2]. More generally, these techniques are valid candidates to supply power to electronic devices or sensors that strongly interconnected and which constitute the Internet of Things (IoT) [3,4] in such a way that avoids the need for batteries, which require recharging or substitution and are not eco-friendly. Indeed, the main advantages of EH techniques is the capability to harvest and convert ambient energy into electricity in a location that is very close to the end-user [5].

Among all the different EH devices, we will focus on the Vibration Energy Harvesters (VEHs) which convert environmental vibrations into electric energy by using electromagnetic generators [6] or *smart* materials, such as piezoelectrics or magnetostrictives [7,8]. VEHs can be installed as active dampers for internal combustion engines or, more effectively, in common remote places such as roads and bridges. Vibrations and stresses caused

by the ongoing vehicle traffic on such roadways certainly represent one of the less exploited sources of anthropic energy [9].

VEHs based on magnetostrictive materials mainly exploit the so-called “Villari effect” (or inverse magnetostrictive effect) and the Faraday’s law [10]. Magnetostrictive materials, such as *Galfenol*, show good mechanical characteristics, high energy density and low temperature response dependence [11,12], without being affected by cracking and depolarization phenomena as piezoelectrics are [13]. Nevertheless, they have peculiar characteristics such as strong non-linearity and hysteretic behavior, and the harvested energy depends on magnetic bias and mechanical pre-stress, so suitable modeling must be adopted [14–16]. These characteristics lead to the need for a careful modeling in order to exploit them to the fullest, as reported in [17].

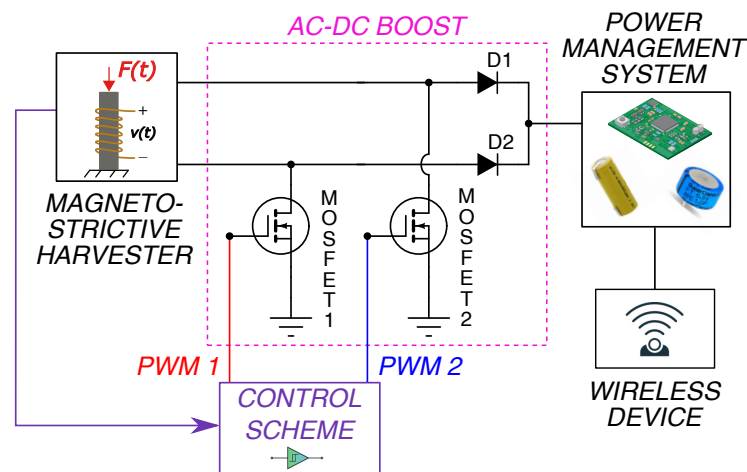
Figure 1 shows a 2D sketch of a force-driven harvester device based on magnetostrictive material. By means of the Villari effect, time-varying mechanical stress applied to the top creates a flux density variation into the material. Then, by exploiting Faraday’s law, the device produces an output voltage ( $V_1$ ) across an electric load through a coil wound around the magnetostrictive material [18]. Permanent magnets and an iron path provide the magnetic bias to increase the converted energy. Moreover, the iron is exploited also as a structural frame.



**Figure 1.** Sketch of the elements composing a VEH with magnetostrictive material. The iron frame and permanent magnets provide a magnetic bias, and one or more coils can be wound around the active material. Further details about a magnetostrictive VEH can be found in [2,10,15].

PEIs play a key role in EH systems, in particular for Vibration Energy Harvesting ones. Indeed, the total power amounts recovered in energy harvesting conversion mechanisms are typically low, even below mW, while output voltages can be far below 1 V [19–21]. Furthermore, the energy source for the EH (vibrations in this case) is typically quite random in nature, and therefore, the need for a custom PEI is often compulsory [22]. The latter aims to increase the harvested energy and the available voltage output [23], with a consequent efficiency improvement. Indeed, depending on the nature of the energy source, the output voltage of the magnetostrictive EH device could be impulsive or, more generally, non-periodic. Consequently, the purpose of any PEI should not only be the rectification and boosting of the voltage, but also self-adaptability with respect to the input voltage, aiming at an optimal conversion efficiency. Then, the system should be able to measure the positive and negative pulses independently and suitably trigger the circuit. This could be easily obtained by winding a secondary coil to the material (as shown in Figure 1), which provides the voltage  $V_{ref}$ . This latter metric can be used to detect the output trend and to trigger a Power Management Electronic circuit, adopted to better couple the VEH with the proper load, similarly to what is carried out in [24]. Scientific literature offers a significant number of papers on power electronic interfaces for piezoelectric EH (e.g., [25–29]), whereas there is still room for magnetostrictive VEHs, also because it is a young technology.

A novel use of the AC–DC boost converter can be beneficial in this case, as schematized in Figure 2. Indeed, as previously described, the inductor is already present in the harvester, and this represents an economical advantage reducing, at the same time, losses. Several hybrid buck–boost converters, typically exploiting one or more external inductors with high frequency switching technique, have been proposed for VEHs based on electromagnetic mechanism or piezoelectric materials [30–34], whereas very few or no conversion techniques are available for magnetostrictive devices. Indeed, because of the intrinsic nature of harvesters based on magnetostrictive materials, such types of energy conversion methods have not been successfully applicable, and a suitable control technique must be applied.



**Figure 2.** Block scheme of a VEH based on a magnetostrictive material with an AC–DC boost converter.

In this paper, we propose a tailored switching technique for an AC–DC boost that is capable to self-adapt to the input voltage frequency in order to optimize the harvested power. As proof of concept, the switching technique is implemented in a digital low-cost controller as an Arduino board. This allows one to easily change the control parameters and find optimum working points. It is worth underlining that, in order to study the AC–DC boost behavior, it is not necessary to use a real magnetostrictive VEH as input to the boost. A particular toroidal transformer has been used in this case, as described in more detail in the next sections. One of the aims of this work is to exploit and investigate the circuit through a programmable board in order to have a versatile tool. Finally, the circuit has been experimentally tested, and results have been compared with simulations of an equivalent circuit in a *LTspice* environment [35].

The paper is organized as described below. In Section 2, the AC–DC boost switching converter is introduced, and its operation is analyzed. Section 3 is devoted to the description of the experimental setup, while in Section 4, the experimental results are compared with the simulations and discussed with some figures of merit. Conclusions end the paper.

## 2. Proposed Boost Architecture for Magnetostrictive Energy Harvesters

Battery-powered mobile electronics, such as IoT devices, smartphones, smartwatches, fitness bracelets, etc., make use of several switching converters stages. For example, alternate to direct current (AC-to-DC) rectification, DC–DC boosting output voltage, filtering, etc. The AC-to-DC stage is typically composed of a passive diode bridge followed by a DC–DC buck or boost converter [36,37]. However, using a passive full bridge rectifier entails energy losses, thus reducing the power efficiency. With the aim to reduce the energy conversion losses, the solution of a direct AC–DC boost converter (active full bridge) can be adopted [38,39].

These converters are based on the “on-off” capability of transistors, exploited as switches. When the switches are closed, the inductor charges and then magnetic energy is

stored in it. Then, if one switch is open, this energy is transferred to the output stage. The timing of switching, with respect to the input voltage changes, is matter of optimization, as is explained in the following.

### 2.1. Circuit Implementation

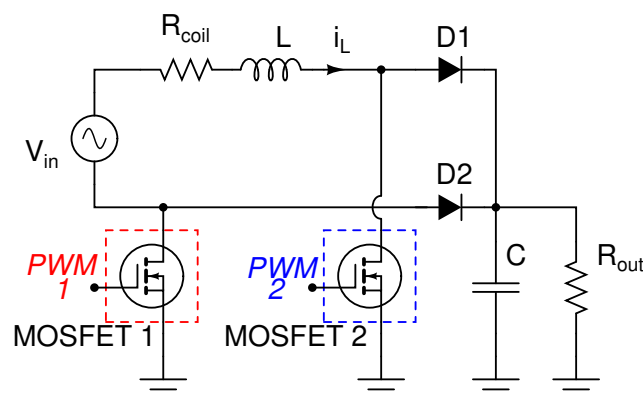
Figure 3 shows the electrical circuit of the full-wave AC–DC boost converter considered in this work, while Figure 4 shows qualitative trends of the most interesting electrical quantities involved.  $V_{in}$  is an AC voltage source ( $T$  is its period), and it represents the generic output voltage of a magnetostrictive EH device, while  $L$  and  $R_{coil}$  represent the inductor and its internal resistance. The two MOSFETs behave as controlled switches where the opening and closing times depend on the voltages applied to the gates. In particular, when the switches are both closed, the AC voltage source is directly connected to the inductor. The latter charges, as represented in magenta color in Figure 4, and their energy  $W_L$  can be expressed as:

$$W_L = \frac{1}{2} L i_L^2 \quad (1)$$

where  $i_L$  is the inductor current. The energy is then released through the diodes D1 and D2, respectively, when each MOSFET alternately opens, as represented in green color in Figure 4. Here, the output load is simplified to a capacitor  $C$  and a load resistor  $R_{out}$ . In more detail, for the circuit of Figure 3, three operating conditions can be identified with respect to the input signal period:

- Both MOSFETs are closed: the inductor  $L$  is positively or negatively charged by the AC source and capacitor  $C$  discharges over the output resistor  $R_{out}$ ;
- MOSFET1 closed and MOSFET2 open: the positively charged inductor  $L$  discharges over the output capacitor–resistor loop through diode D1;
- MOSFET1 open and MOSFET2 closed: the negatively charged inductor  $L$  discharges over the output capacitor–resistor loop through diode D2.

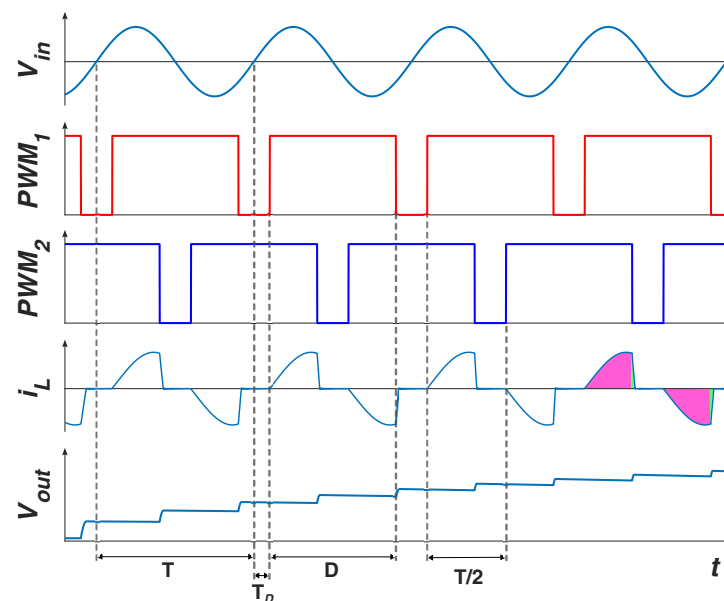
The output voltage ( $V_{out}$ ) then increases at each inductor current commutation until a steady-state condition is reached.



**Figure 3.** Electrical schematic of the proposed AC–DC boost Converter.

With respect to the inductor current trend, three operating modes can be considered: the Discontinuous current Conduction Mode (DCM), the Continuous current Conduction Mode (CCM) and the “Critical” Boundary current Conduction Mode (BCM). The DCM and CCM operating modes refer to whether the inductor fully discharges and the current goes to zero or not during each switching period [40,41]. The BCM mode is the critical condition where the inductor current goes to zero right at the end of each switching period. With the aim to reduce the electromagnetic interference and to increase the efficiency, it is convenient to use the Boost converter in the DCM operating mode. Indeed, in DCM mode, the dissipation switching transition decreases because the switch current always

starts from zero [42,43]. Moreover, at each cycle, the whole energy stored in the inductor is delivered to the output, contrary to what happens in CCM.



**Figure 4.** Qualitative trends of main electrical quantities involved in a AC–DC boost converter in Discontinuous current Conduction Mode (DCM). Magenta color represents the positive or negative inductor charging phase, while the green one is the discharging phase on the output load.

In this paper, the MOSFET's gates are driven by two different Pulse Width Modulation (PWM) signals that are defined by a Time Delay ( $T_D$ ) and a Duty Cycle ( $D$ ) with respect to the sign changes of the input voltage, as sketched in Figure 4. In the following, the Time Delay and the Duty Cycle are defined in percentages with respect to the input voltage period ( $T$ ), and the two PWM signals are simply  $T/2$  out of phase with each other. Nevertheless, the choice of  $T_D$  and  $D$  can be regulated and optimized in order to maximize the output voltage and then the harvested power.

The circuit parameters and the model of the electronic components adopted are reported in Table 1.

**Table 1.** Electrical Parameter Values of the Circuit shown in Figure 3.

| Circuit Element | Value                  | Model                                       |
|-----------------|------------------------|---------------------------------------------|
| $V_{in}$        | 220 mV <sub>peak</sub> | custom secondary winding of the transformer |
| $R_{coil}$      | 700 m $\Omega$         | -                                           |
| $L$             | 1 mH                   | -                                           |
| D1, D2          | -                      | BAT 46 (Vishay Semiconductors)              |
| MOSFET 1, 2     | -                      | IRF 1404 (International Rectifier—Infineon) |
| $C$             | 100 $\mu$ F            | -                                           |
| $R_{out}$       | 2.2 k $\Omega$         | -                                           |
| Arduino         | -                      | Mega 2560 board                             |

The proposed AC–DC boost scheme is shown in Figure 2. Two switching elements as MOSFETs are controlled by a block reading zero crossing of the voltage of the energy harvester. As for the classic AC–DC boost, two diodes are connected to the next energy management stage, which can be as simple as a capacitor. The control block, described in the next subsection, has the task to drive the MOSFETs in order to boost the voltage and maximize the power transfer. The coil of the harvester is exploited as an energy storing element when the two switches are closed. Contrary to a buck–boost converter based on electromagnetic or piezoelectric materials, where double or multi-stages are developed,

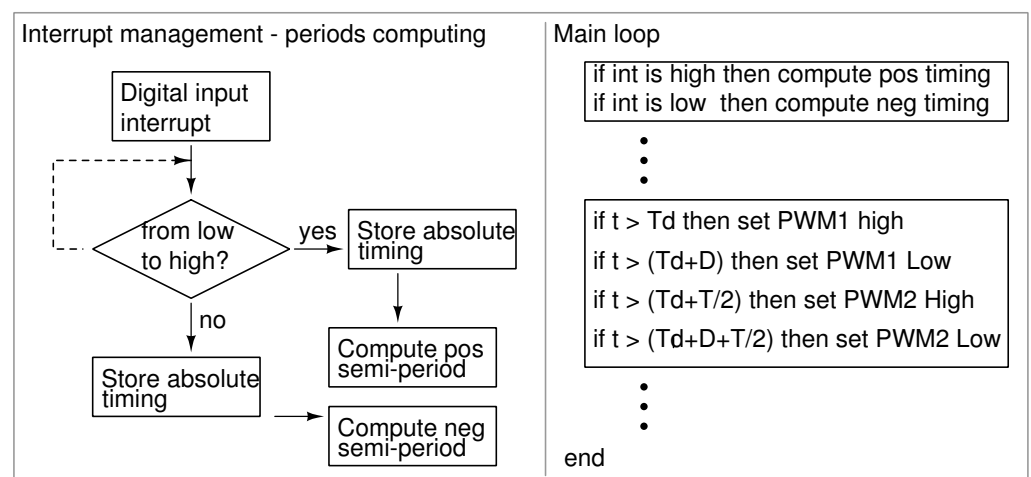
an AC–DC boost coupled with VEH based on magnetostrictive materials has the great potential advantage of using a single-stage with one only switching inductor, namely, the same pickup coil used for energy conversion, as reported in [44]. The possibility to use the output inductor of the VEH as the boost inductor allows for the number of components (switching capacitors, inductors and transistors)—and thus stages—in the circuit to be reduced, as well as the bulkiness of the whole Boost + VEH device.

## 2.2. The Control Scheme: Arduino Code Design

The *control* unit of the entire setup is the Arduino Mega 2560 board that has been chosen for its versatility. It is powered by an external standard 5 V power supply. Future practical implementations based on the proposed technique should resort to a simpler circuit able to reduce the amount of energy self-consumption.

A schematized algorithm is represented in Figure 5. The reference signal (Figure 2, purple line) drives a digital input that is used as an *interrupt* activated by any input binary change. These interrupts are aimed to set a reference timing and thus allow one to calculate the signal's two positive and negative periods. Then, the two parameters “D” and “ $T_D$ ” are expressed in percentages of the time period T and are *real-time*, translated into effective timing for the PWM signals. This part is the *heart* of the code, since it allows for dealing with non-deterministic, non-periodic input voltage signals, as is expected in any practical application of EH. Furthermore, as shown in Figure 5, in the main Arduino loop block, the two PWM digital outputs are generated as logical combinations of the status of the interrupt change (high or low) and timing parts by means of suitable “if-then” commands. The code requires a low computational burden, allowing it to control and manage accurate PWM signals in the scale of hundreds of Hz of the input voltage frequency, thus covering the majority of VEH applications.

An example of the Arduino code is available in the Supplementary Materials of this paper.

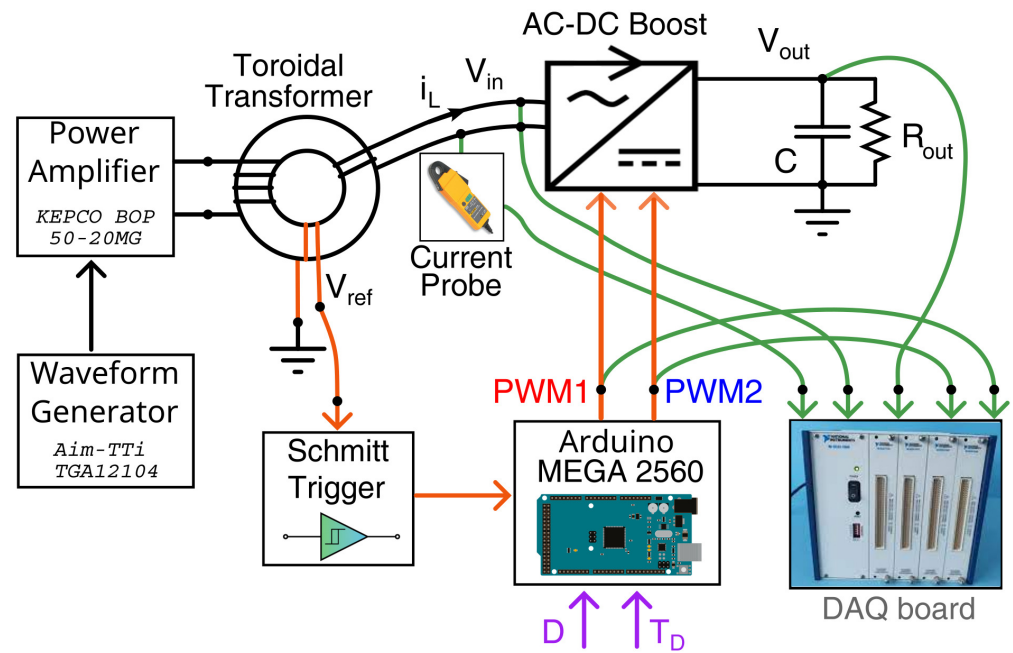


**Figure 5.** Simplified scheme of the real-time code for Arduino. The interrupt is driven by the Schmitt trigger output signal (Figure 6).

## 3. Experimental Setup Description

The exploited experimental setup, shown in Figure 6, has been designed as a proof of concept of the above-described AC–DC boost fed by an almost unknown AC source. It is worth underlining that, since the aim of the paper is to focus on the behavior of the boost converter, in the experimental setup, we considered a transformer in place of the VEH. The iron-core transformer indeed provides a signal compatible with a VEH's output and shows an inductive nature similar to the magnetostrictive devices. This choice allows one to neglect other effects, e.g., non-linearities, typically shown by EH devices based on magnetostrictive materials. The circuit is supplied by a secondary winding of a 150 VA

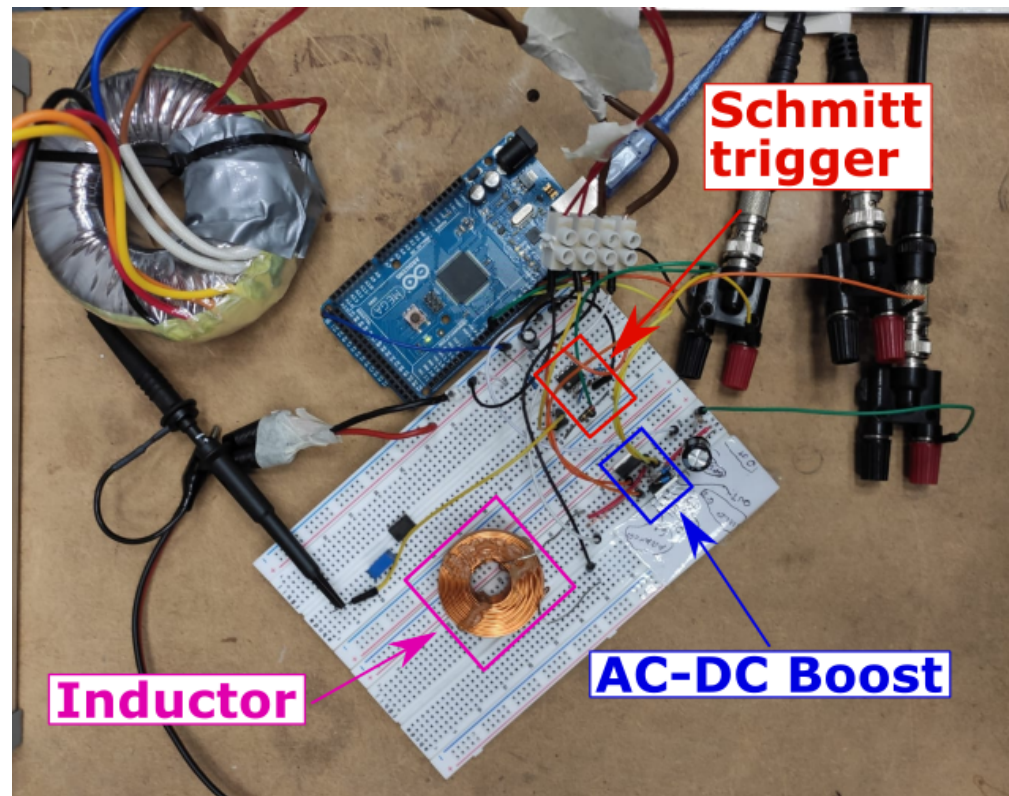
transformer with a peak voltage of 220 mV ( $V_{in}$ ). The transformer output current is then the inductor one ( $i_L$ ) and is measured by a current clamp (model: Fluke i30s). Moreover, the primary winding is fed by a power amplifier (model: KEPCO BOP 50-20MG), driven by an arbitrary waveform voltage generator (model: Aim-TTi TGA12104). The Arduino board needs a reference signal for the timing. This is obtained from a Schmitt trigger that acts as a voltage comparator over another secondary winding referenced to ground. The latter is needed since the AC–DC boost input is floating, see Figure 1.



**Figure 6.** Experimental setup: the two controllable parameters “D” and “ $T_D$ ” are in purple; the orange lines are signals exploited for control purposes; and the green lines are the measured signals.

The boost has a 100  $\mu$ F capacitor in parallel to a 2.2 k $\Omega$  resistor as load. The MOSFETs are driven by the two PWM signals outputs of the Arduino board.

Finally, a DAQ board (model: National Instruments SCXI-1000 + NI 1520 board), at 30 kS/s sampling frequency, measures and acquires the input voltage ( $V_{in}$ ), the inductor current ( $i_L$ ), the two Arduino PWMs (PWM1 and PWM2) and the voltage over the capacitor–resistor parallel ( $V_{out}$ ). The voltage  $V_{in}$  is measured in differential mode, while all the other voltages are single-ended. Figure 7 reports a picture of the experimental setup. It can be noticed that the AC–DC converter circuit is mounted over a breadboard, the Arduino board and the toroidal transformer.

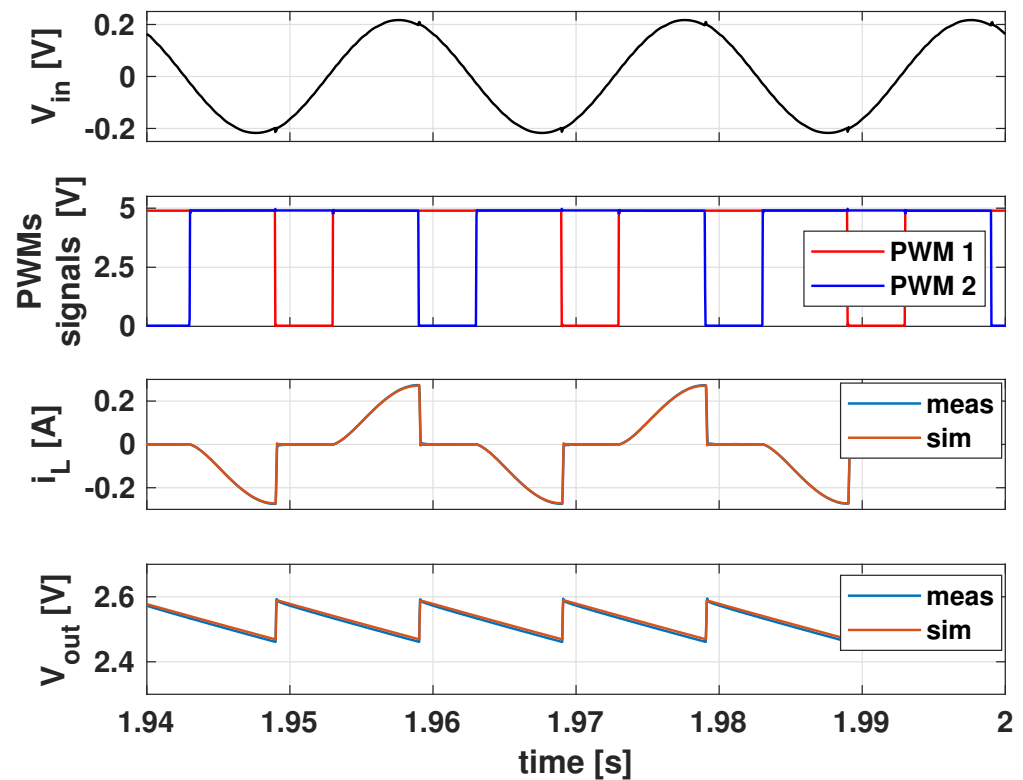


**Figure 7.** Picture of the setup sketched in Figure 6 and used for the experimental measurements.

#### 4. Measurements, Simulations and Discussion

Several measurements have been performed using the experimental setup described in Sections 2 and 3. In particular, different sinusoidal signals have been generated by the power amplifier and applied to the transformer. In more detail, input voltages at constant amplitude and with three different frequencies (i.e., 20, 50 and 80 Hz) have been exploited. Moreover, the controllable parameters  $D$  and  $T_D$  have been varied and the output voltage measured. The experimental signals have been compared with LTspice circuit solver simulations. The circuit of Figure 3 has been implemented, and the experimental  $V_{in}$  and PWMs signals have been used as input voltages of the circuit.

Figure 8 shows an example of a comparison in steady-state between the measured and simulated output voltages at  $T_D = 1\%$  and  $D = 80\%$ , which are the optimal parameters at  $f_{in} = 50$  Hz, as shown in the following. The output voltages and currents are in very good agreement. It is noticeable that the PWM1 (red) signal rises linearly when the input voltage positively crosses zero and falls after about 15 ms, i.e.,  $0.8 T$ , while the PWM2 (blue) signal follows the PWM1's behavior after  $T/2$ , as expected. Finally, the current profiles show that the inductor discharges on the capacitor–resistor parallel after each intersection between the two “ON” states of the PWM signals (i.e., both MOSFETs are closed).



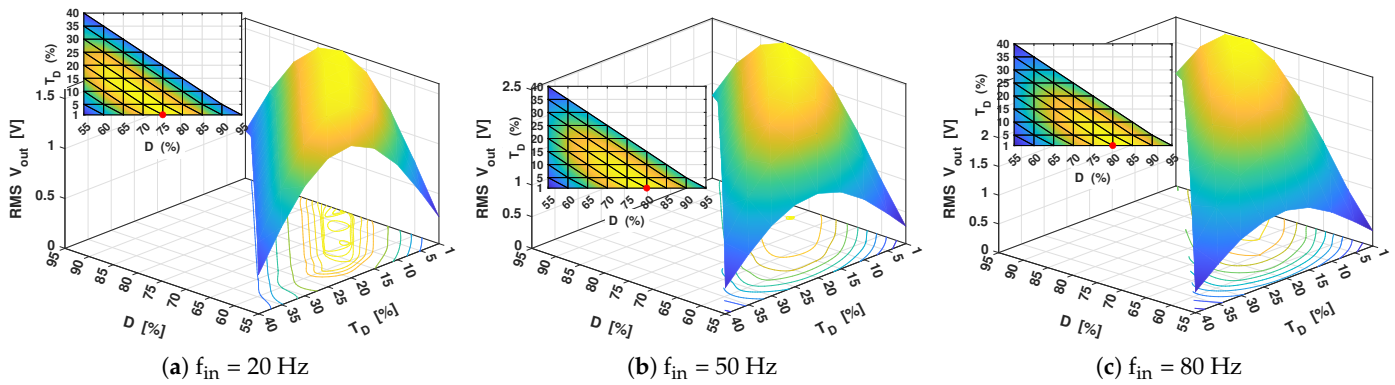
**Figure 8.** Steady-state signals over time at  $T_D = 1\%$  and  $D = 80\%$ . Input voltage frequency  $f_{in} = 50$  Hz. From the top pane to the bottom one: measured input voltage, measured PWMs signals, measured and simulated inductor current, measured and simulated output voltage.

It is worth noting that, in order to exploit the circuit as a boost, the following working conditions should be addressed:

- Duty Cycle  $> 50\%$ , which means that the inductor should be short-circuited on the AC input and then charged in a certain time interval;
- $(T_D + D) < 100\%$ , i.e., Time Delay and “ON” timing of the two PWM signals should belong to a time period  $T$  of the AC input (100% of the time period  $T$ ).

Moreover, because of the intrinsic rising and falling time of the PWM signals and the MOSFET’s switching time,  $T_D$  cannot be null; rather, it needs to start from a minimum value of 1% of the period  $T$ . Then, the RMS output voltages are represented as triangular matrices with respect to  $T_D$  and  $D$ .

Figure 9 shows the RMS voltage surfaces with respect to different values of Time Delay, Duty Cycle and input voltage frequency. The surfaces have similar shapes and show a maximum in the region where the circuit acts as boost, while it decreases near the above-mentioned boundary working condition. The RMS voltage maximums increase with the input frequency because of the related switching frequency that is dependent on  $f_{in}$ . Indeed, the peak RMS voltage increases from 1.6 V at  $f_{in} = 20$  Hz up to 2.94 V at  $f_{in} = 80$  Hz, with a gain of about 10.3 and 19, respectively. Furthermore, the  $T_D - D$  parameters that maximize the voltage are placed on a almost straight line. Finally, maximum RMS voltages are achieved at  $D = 75\%$  and  $T_D = 1\%$  for  $f_{in} = 20$  Hz (see Figure 9a) and at  $D = 80\%$  and  $T_D = 1\%$  for  $f_{in}$  equal to 50 and 80 Hz, respectively (see Figure 9b,c). The corresponding peaks of the RMS powers are about 1.2, 3 and 4 mW, respectively.

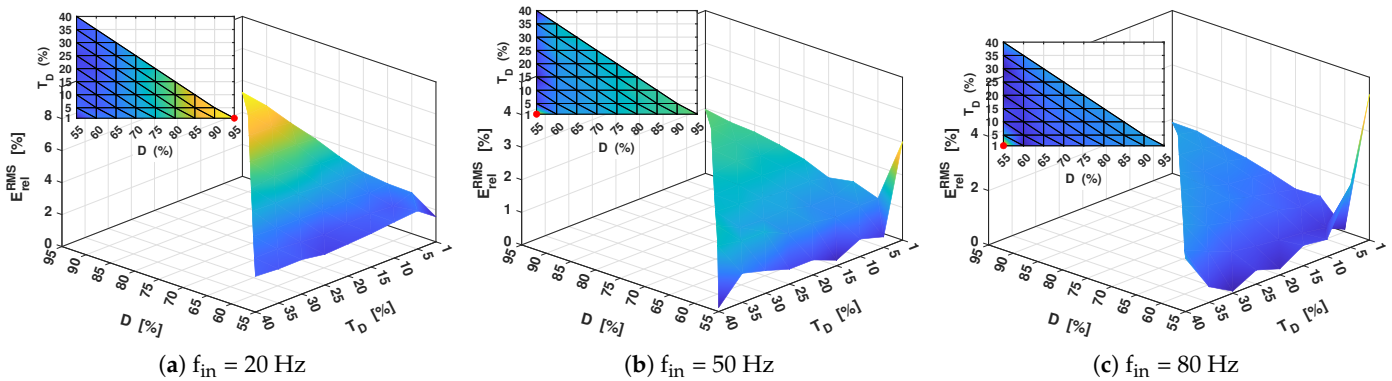


**Figure 9.** Mapping of the RMS output voltages with respect to the Duty Cycle ( $D$ ) and Time Delay ( $T_D$ ), at different frequencies ( $f_{in}$ ) of the input voltage. The insets show the top view of each surface, while the red dots point out the maximums.

Figure 10 reports the RMS output voltage relative errors between measured and simulated data, with respect to Time Delay and Duty Cycle, at three different input voltage frequencies. The relative error  $E_{rel}^{RMS}$  has been computed as follows:

$$E_{rel}^{RMS} = \frac{|V_{out, meas}^{RMS} - V_{out, sim}^{RMS}|}{V_{out, meas}^{RMS}} \times 100 \quad (2)$$

where  $V_{out, meas}^{RMS}$  and  $V_{out, sim}^{RMS}$  are the measured and simulated RMS output voltage, respectively. The relative error peaks are limited to 5.25% at  $f_{in} = 20$  Hz, 3% at  $f_{in} = 50$  Hz and 5.35% at  $f_{in} = 80$  Hz. Moreover, the total average relative errors are 2.98%, 1.26% and 1.36% at 20, 50 and 80 Hz, respectively. Furthermore, the relative error peaks are located in working regions where the AC–DC converter should not work as a voltage booster. Then, the goodness of simulations results compared with experimental data show the possibility to use LTspice circuitual model for further comparing simulations of this technique with respect to a standard switching technique, reported in the Appendix A.



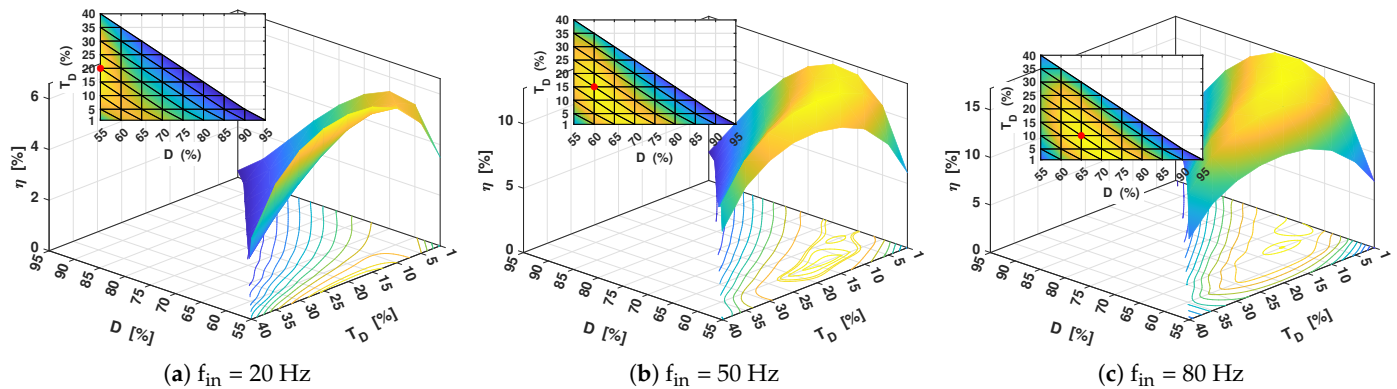
**Figure 10.** Mapping of the relative errors between measured RMS output voltages and simulated data with respect to Duty Cycle ( $D$ ) and Time Delay ( $T_D$ ) at different frequencies ( $f_{in}$ ) of the input voltage. The insets show the top view of each surface, while the red dots point out the maximums.

One of the main figures of merit in the design of an electronic interface is the conversion efficiency. The efficiency ( $\eta$ ) has been computed as:

$$\eta = \frac{P_{out}}{P_{in}} \times 100 \quad (3)$$

where  $P_{in}$  and  $P_{out}$  are the measured RMS input and output power of the boost converter. The discrepancy between  $P_{in}$  and  $P_{out}$  is represented by the Power losses ( $P_{loss}$ ), which is

manly due to the switching, conduction and passive devices losses [40]. Figure 11 shows the efficiencies of the considered AC–DC boost, with respect to Time Delay and Duty Cycle, at three different input voltage frequencies. As expected, it is observable that the efficiency increases within the  $f_{in}$  because of the related increase in switching frequency. Furthermore, it seems that the efficiency peak is located in low  $D$  and medium  $T_D$  value regions at 20 Hz, while it moves towards higher  $D$  and lower  $T_D$  by increasing the input frequency.



**Figure 11.** Mapping of the RMS power efficiencies with respect to Duty Cycle ( $D$ ) and Time Delay ( $T_D$ ) at different input voltage frequencies ( $f_{in}$ ). The insets show the top view of each surface, while the red dots point out the maximums.

Another important figure of merit to take into account in the design of an AC–DC converter is the Ripple Factor (RF). Indeed, in order to reduce the size of converters, it is necessary to use small inductors and capacitors, with a corresponding increase in ripple value. An estimation of the signal shape is the Form Factor (FF), which is defined as [45]:

$$FF = \frac{V_{out}^{RMS}}{V_{out}^{AVG}} \quad (4)$$

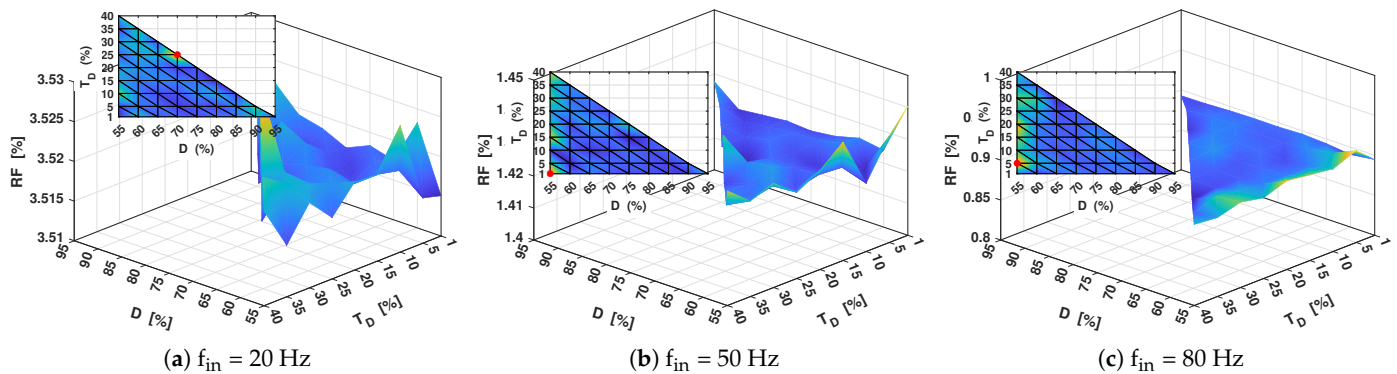
where  $V_{out}^{RMS}$  and  $V_{out}^{AVG}$  are the RMS and average output voltage computed in a certain time interval, respectively. A measure of the ripple content of the output is then the Ripple Factor, defined as [45]:

$$RF = \sqrt{(FF)^2 - 1} \quad (5)$$

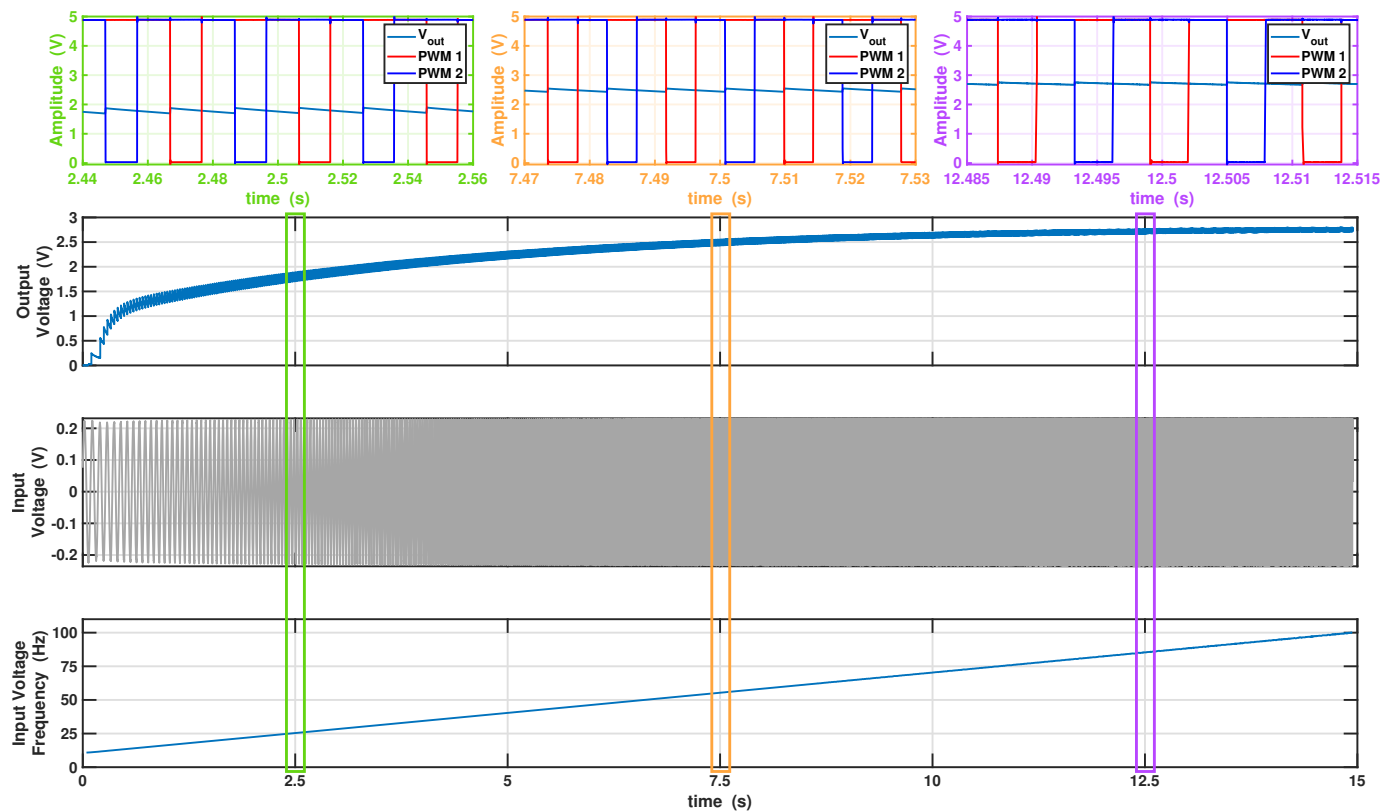
Figure 12 shows the Ripple Factor of the considered AC–DC boost, with respect to Time Delay and Duty Cycle, at three different input voltage frequencies. It can be seen that the RF is very low (about 3% at 20 Hz), and it decreases around zero by increasing the input frequency, without a clear dependency with respect to  $D$  and  $T_D$ . The lower the RF is, the lower the discrepancy between RMS and average output voltages. Consequently, the designed boost converter seems to have a low harmonic content in the output voltage, which is a desirable property.

Previous measurements have pointed out that, given controllable parameters  $T_D$  and  $D$ , the programmed Arduino board is capable of self-adapting in order to generate the suitable PWM signals with respect to the AC input voltage frequency. Figure 13 shows the AC–DC converter's output voltage with a linear sweeping of the input voltage frequency from 10 up to 100 Hz, in a time-window of 15 s. The input voltage amplitude remains constant at  $220 \text{ mV}_{peak}$ . The controllable parameters have been fixed at  $D = 75\%$  and  $T_D = 1\%$ . The colored rectangular boxes represent three different time spans that have been analyzed in the corresponding top panes (same axes colors), where the output voltage and PWM signals are shown. It is noticeable that the output voltage (second pane from the top) is continuously increasing over time, up to about 3 V when the input frequency approaches 100 Hz. Furthermore, the Arduino board correctly measures the input frequency and properly drives the switching signals to the MOSFET's gates in a self-adapting fashion.

This measurement is representative of a generic AC source behavior, which is typical of an EH device that exploits an engine vibration during its transient phases.



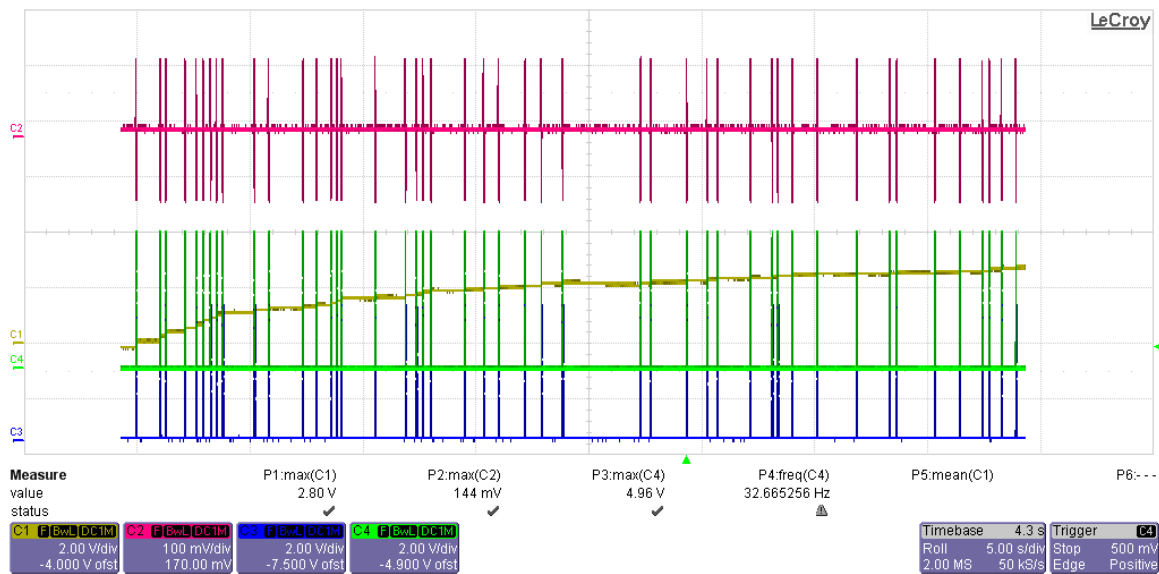
**Figure 12.** Ripple Factor (RF) values with respect to Duty Cycle (D) and Time Delay ( $T_D$ ) at different input voltage frequencies ( $f_{in}$ ). The insets show the top view of each surfaces, while red dots identify the maximum values.



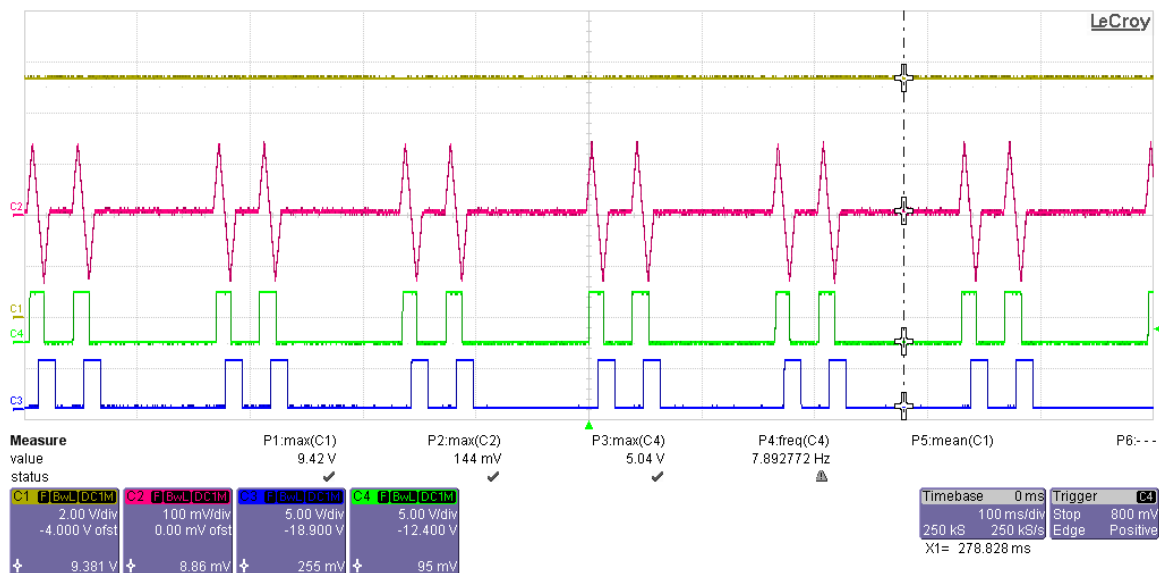
**Figure 13.** Measured signals of a linear swept–frequency input voltage over 15 s time interval, at  $D = 75\%$  and  $T_D = 1\%$ . Colored boxes represent three different time spans, where the input frequency is varying around about 25 Hz (green), 55 (orange) and 85 Hz (purple), respectively. Top panes show the output voltage and PWM signals for each analyzed time span.

With the aim to explore the operating conditions and behaviors, a randomic impulse-like voltage has been given as input to the AC–DC boost converter, thanks to the arbitrary waveform generator. The signal is designed as shown in Figure 14b, where two heartbeat-like pulses, with peaks equal to about 200 mV and 20 ms time period, are shifted by 20 ms. This signal is representative of a typical output voltage coming from an EH device based on magnetostrictive materials, installed under the asphalt on a viaduct or bridge, that recovers energy from the passing vehicles [46].

In Figure 14a, a screenshot of the oscilloscope (model: LeCroy WaveRunner 6030A) showing the measurements of output and PWM voltages together with the randomic impulse-like input voltages, at  $D = 75\%$  and  $T_D = 1\%$ , over a  $1\text{ M}\Omega$  resistor is shown. The yellow line is the output voltage, the magenta line is the input voltage while the green and blue lines are PWM1 and PWM2 signals, respectively. The output voltage increases at each impulse because of the energy stored by the inductor and transferred to the capacitor. The considered load is representative of a possible configuration where a super-capacitor with very low equivalent series resistance (low ESR) is adopted to store electric energy. Figure 14b shows the output voltage when steady-state condition is reached (after about 90 s), with a periodic impulse-like input voltage. It is noticeable that in such working conditions, the output voltage reaches a maximum value of about 9.4 V.



(a) Randomic impulse-like train over 40 s time window



(b) Steady-state conditions

**Figure 14.** Oscilloscope screenshots of the measurements with impulse-like input voltage. Yellow line is the output ( $V_{out}$ ), magenta line is the input voltage ( $V_{in}$ ) while green and blue lines are PWM1 and PWM2 signals, respectively. Controllable parameters are  $D = 75\%$  and  $T_D = 1\%$ , while  $R_{out} = 1\text{ M}\Omega$ .

## 5. Conclusions

Magnetostrictive Energy Harvesting devices can be connected to a properly controlled AC–DC boost stage in order to increase their output voltage and manage the harvested power. This technique has the advantage to exploit these devices' internal inductors as a storage element.

This paper discussed the experimental characterization of an AC–DC boost interface driven with a novel strategy able to self-adapt with respect to the input voltages. Indeed, because of typical applications of Vibration Energy Harvesters, the input source vibration may have fundamental frequencies changing over time without a deterministic behavior. By exploiting the Arduino code, an optimum set of control parameters has been found. A peak output voltage of about 3 V has been obtained with a peak input voltage of 220 mV at an input frequency of 80 Hz. The maximum achieved RMS output power is about 4 mW, with a voltage gain factor of about 19.

Furthermore, the setup has been excited with an impulse-like random input voltage, representing a general VEH output voltage when the device undergoes random force profiles, and a 10 V open circuit output voltage has been achieved in steady-state conditions. Experimental tests have been compared with simulations of an LTspice model, showing a good agreement. Finally, the proposed technique has been compared in simulations with standard switching frequency techniques, which are often adopted for other types of VEHs. The comparison highlighted the drawbacks of such techniques when VEH based on magnetostrictive materials are adopted.

In conclusion, this work can be considered as the proof of principle of a boost circuit for magnetostrictive VEH. Future works will include the verification of the performances with a real magnetostrictive VEH, which will have a dual function of input source voltage and storage inductor. Moreover, further investigation with other output electric loads will be addressed in future works.

**Supplementary Materials:** The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/app13031606/s1>.

**Author Contributions:** Conceptualization, C.S.C., I.I., V.P.L. and D.D.; methodology, C.S.C. and D.D.; algorithm, D.D.; investigation, C.S.C., I.I., V.P.L. and D.D.; data curation, C.S.C.; simulation curation, C.S.C.; writing—original draft preparation, C.S.C. and D.D.; writing—review and editing, C.S.C., I.I., V.P.L. and D.D.; supervision, D.D. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** The Arduino code is available in the attached Supplementary Materials.

**Conflicts of Interest:** The authors declare no conflict of interest.

## Abbreviations

The following abbreviations are used in this manuscript:

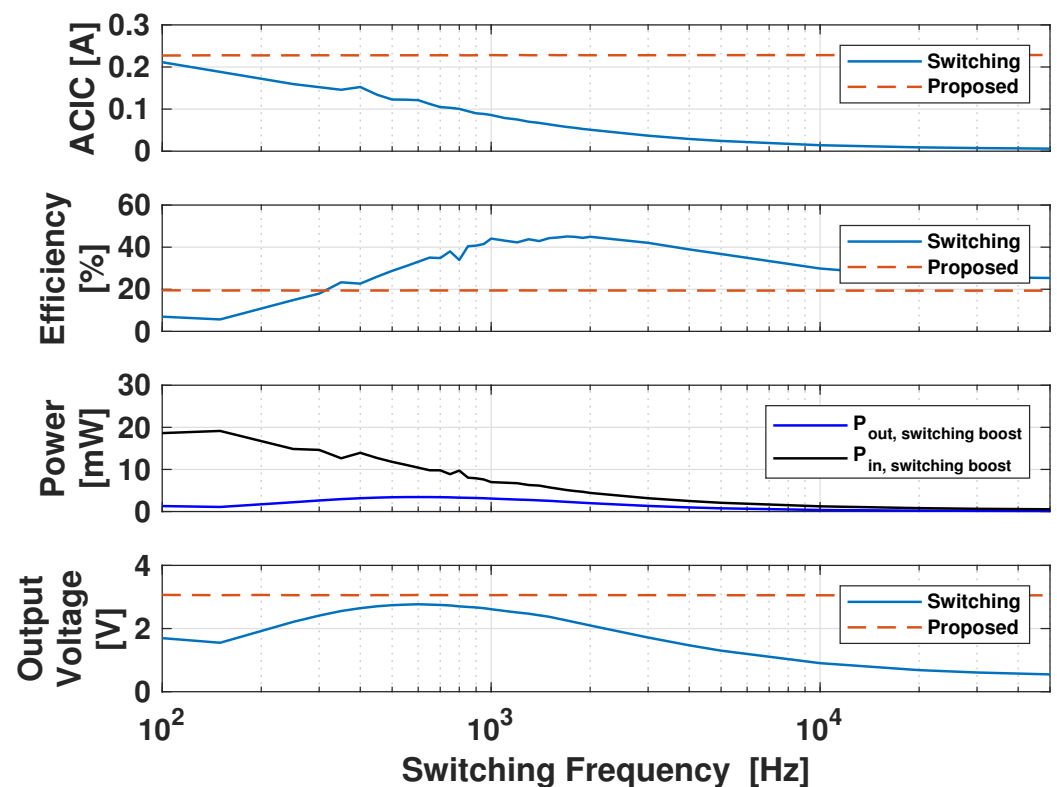
|     |                                             |
|-----|---------------------------------------------|
| WSN | Wireless Sensor Network                     |
| IoT | Internet of Things                          |
| PEI | Power Electronic Interface                  |
| EH  | Energy Harvesting                           |
| SHM | Structural Health Monitoring                |
| VEH | Vibration Energy Harvester                  |
| DCM | Discontinuous current Conduction Mode       |
| CCM | Continuous current Conduction Mode          |
| BCM | “Critical” Boundary current Conduction Mode |
| PWM | Pulse Width Modulation                      |
| DAQ | Data Acquisition                            |

|      |                                      |
|------|--------------------------------------|
| RF   | Ripple Factor                        |
| FF   | Form Factor                          |
| ESR  | Equivalent Series Resistance         |
| HFS  | High-Frequency Switching             |
| ACIC | Average Commutation Inductor Current |

## Appendix A

With the aim to compare the proposed boosting approach with other methodologies, commonly used in boost converter coupled with other types of VEHs, some simulations have been carried out. In particular, in different buck–boost converters [30,31,33,34], the PWM regulation block shows a continuous high-frequency switching (HFS) of the external inductors. This methodology has been added within the studied boost instead of the proposed PWM control scheme, and simulations have been compared.

In Figure A1, the average commutation inductor current (ACIC), efficiency, power and output voltages are reported (from the top to bottom pane) between the proposed PWMs control algorithm and the synchronous high-frequency switching one, respectively. Despite the efficiency of the HFS method increasing with the switching frequency (up to a certain value), it is possible to note that output voltage is always lower than the value (about 3 V) achieved with the proposed boost. Furthermore, the larger efficiency of HFS technique is due, for switching frequencies higher than 800 Hz, to a constantly decreasing input power, and this represents a contradiction in the Energy Harvesting paradigm. The increasing switching frequency would help the efficiency conversion bringing the boost circuit in a highly DCM condition. However, when the pickup coil constitutes the switching inductor itself, as in our case, this could lead to global performances worse than the ones achieved with the proposed algorithm. This is mainly due to the fact that  $i_L$ , representing the stored energy determined by Equation (1), is lower than the one considered in the proposed PWM control scheme and constantly reducing with the switching frequency.



**Figure A1.** Performance comparison between the proposed switching method based on the Arduino board and the HFS method. From top to bottom pane: average commutation inductor current (ACIC), efficiency, input and output power of the HFS boosting technique, output voltage.

## References

1. Park, G.; Farinholt, K.; Farrar, C.; Rosing, T.; Todd, M. Powering wireless SHM sensor nodes through energy harvesting. In *Energy Harvesting Technologies*; Springer: Boston, MA, USA, 2009; pp. 493–506. [\[CrossRef\]](#)
2. Clemente, C.S.; Davino, D.; Loschiavo, V.P. Magnetostrictive Materials and Energy Harvesting for Structural Health Monitoring Applications. *IOP Conf. Ser. Mater. Sci. Eng.* **2020**, *949*, 012012. [\[CrossRef\]](#)
3. Atzori, L.; Iera, A.; Morabito, G. The Internet of Things: A survey. *Comput. Netw.* **2010**, *54*, 2787–2805. [\[CrossRef\]](#)
4. Ning, H. *Unit and Ubiquitous Internet of Things*; CRC Press: Boca Raton, FL, USA, 2016; pp. 1–219.
5. Stephen, N. On energy harvesting from ambient vibration. *J. Sound Vib.* **2006**, *293*, 409–425. [\[CrossRef\]](#)
6. Beeby, S.; Torah, R.; Tudor, M.; Glynne-Jones, P.; O'Donnell, T.; Saha, C.; Roy, S. A micro electromagnetic generator for vibration energy harvesting. *J. Micromech. Microeng.* **2007**, *17*, 1257–1265. [\[CrossRef\]](#)
7. Beeby, S.; Tudor, M.; White, N. Energy harvesting vibration sources for microsystems applications. *Meas. Sci. Technol.* **2006**, *17*, R175–R195. [\[CrossRef\]](#)
8. Anton, S.R.; Sodano, H.A. A review of power harvesting using piezoelectric materials (2003–2006). *Smart Mater. Struct.* **2007**, *16*, R1–R21. [\[CrossRef\]](#)
9. Roshani, H.; Dessouky, S.; Montoya, A.; Papagiannakis, A. Energy harvesting from asphalt pavement roadways vehicle-induced stresses: A feasibility study. *Appl. Energy* **2016**, *182*, 210–218. [\[CrossRef\]](#)
10. Deng, Z.; Dapino, M.J. Review of magnetostrictive vibration energy harvesters. *Smart Mater. Struct.* **2017**, *26*, 103001. [\[CrossRef\]](#)
11. Engdahl, G. (Ed.) *Handbook of Giant Magnetostrictive Materials*; Academic Press: San Diego, CA, USA, 2000; pp. 1–386. [\[CrossRef\]](#)
12. Clemente, C.S.; Davino, D. Overview on Energy Harvesting Materials. In *Encyclopedia of Smart Materials*; Elsevier: Oxford, UK, 2022; pp. 483–502. [\[CrossRef\]](#)
13. Pillatsch, P.; Xiao, B.L.; Shashoua, N.; Gramling, H.M.; Yeatman, E.M.; Wright, P.K.. Degradation of bimorph piezoelectric bending beams in energy harvesting applications. *Smart Mater. Struct.* **2017**, *26*, 035046. [\[CrossRef\]](#)
14. Clark, A.; Restorff, J.; Wun-Fogle, M.; Lograsso, T.; Schlagel, D.L. Magnetostrictive properties of body-centered cubic Fe-Ga and Fe-Ga-Al alloys. *IEEE Trans. Magn.* **2000**, *36*, 3238–3240. [\[CrossRef\]](#)
15. Davino, D.; Giustiniani, A.; Visone, C.; Adly, A.A. Energy harvesting tests with Galfenol at variable magneto-mechanical conditions. *IEEE Trans. Magn.* **2012**, *48*, 3096–3099. [\[CrossRef\]](#)
16. Palumbo, S.; Rasilo, P.; Zucca, M. Experimental investigation on a Fe-Ga close yoke vibrational harvester by matching magnetic and mechanical biases. *J. Magn. Magn. Mater.* **2019**, *469*, 354–363. [\[CrossRef\]](#)
17. Clemente, C.S.; Davino, D.; Loschiavo, V.P. Analysis of a Magnetostrictive Harvester with a Fully Coupled Nonlinear FEM modelling. *IEEE Trans. Magn.* **2021**, *57*, 4001204. [\[CrossRef\]](#)
18. Zhao, X.; Lord, D.G. Application of the Villari effect to electric power harvesting. *J. Appl. Phys.* **2006**, *99*, 08M703. [\[CrossRef\]](#)
19. Szarka, G.; Burrow, S.; Stark, B. Ultralow power, fully autonomous boost rectifier for electromagnetic energy harvesters. *IEEE Trans. Power Electron.* **2013**, *28*, 3353–3362. [\[CrossRef\]](#)
20. Wang, H.; Tang, Y.; Khaligh, A. A bridgeless boost rectifier for low-voltage energy harvesting applications. *IEEE Trans. Power Electron.* **2013**, *28*, 5206–5214. [\[CrossRef\]](#)
21. Choetchai, P.; Thanachayanont, A. A Self-starting AC-to-DC Step-up Converter for Energy Harvesting Applications. *Procedia Comput. Sci.* **2016**, *86*, 144–147. [\[CrossRef\]](#)
22. Burrow, S.G.; Mitcheson, P.D. Power Conditioning for Energy Harvesting Theory and Architecture. In *Micro Energy Harvesting*; John Wiley & Sons: Weinheim, Germany, 2015; pp. 85–101.
23. Szarka, G.D.; Stark, B.H.; Burrow, S.G. Review of power conditioning for kinetic energy harvesting systems. *IEEE Trans. Power Electron.* **2012**, *27*, 803–815. [\[CrossRef\]](#)
24. Xiao, H.; Peng, H.; Liu, X.; Sun, H. Fully Self-Powered Inductor-Less Electromagnetic Vibration Energy Harvesting System Using Auxiliary Coils for Hysteresis Current MPPT Control. *IEEE Trans. Power Electron.* **2022**, *37*, 13192–13204. [\[CrossRef\]](#)
25. Han, J.; von Jouanne, A.; Le, T.; Mayaram, K.; Fiez, T. Novel power conditioning circuits for piezoelectric micropower generators. In Proceedings of the Nineteenth Annual IEEE Applied Power Electronics Conference and Exposition (APEC '04), Anaheim, CA, USA, 22–26 February 2004; Volume 3, pp. 1541–1546. [\[CrossRef\]](#)
26. Lefeuvre, E.; Audigier, D.; Richard, C.; Guyomar, D. Buck-Boost Converter for Sensorless Power Optimization of Piezoelectric Energy Harvester. *IEEE Trans. Power Electron.* **2007**, *22*, 2018–2025. [\[CrossRef\]](#)
27. Yu, H.; Zhou, J.; Deng, L.; Wen, Z. A vibration-based MEMS piezoelectric energy harvester and power conditioning circuit. *Sensors* **2014**, *14*, 3323–3341. [\[CrossRef\]](#) [\[PubMed\]](#)
28. Costanzo, L.; Lo Schiavo, A.; Vitelli, M. Power Extracted from Piezoelectric Harvesters with Passive and Active AC/DC Stages. In Proceedings of the 2020 15th International Conference on Ecological Vehicles and Renewable Energies (EVER 2020), Monte-Carlo, Monaco, 10–12 September 2020. [\[CrossRef\]](#)
29. Edla, M.; Lim, Y.; Mikio, D.; Padilla, R. A Single-Stage Rectifier-Less Boost Converter Circuit for Piezoelectric Energy Harvesting Systems. *IEEE Trans. Energy Convers.* **2022**, *37*, 505–514. [\[CrossRef\]](#)
30. Dayal, R.; Dwari, S.; Parsa, L. Design and implementation of a direct ACDC boost converter for low-voltage energy harvesting. *IEEE Trans. Ind. Electron.* **2011**, *58*, 2387–2396. [\[CrossRef\]](#)
31. Dwari, S.; Parsa, L. An efficient AC-DC step-up converter for low-voltage energy harvesting. *IEEE Trans. Power Electron.* **2010**, *25*, 2188–2199. [\[CrossRef\]](#)

32. Shi, G.; Xia, Y.; Xia, H.; Wang, X.; Qian, L.; Chen, Z.; Ye, Y.; Li, Q. An Efficient Power Management Circuit Based on Quasi Maximum Power Point Tracking with Bidirectional Intermittent Adjustment for Vibration Energy Harvesting. *IEEE Trans. Power Electron.* **2019**, *34*, 9671–9685. [\[CrossRef\]](#)
33. Lallart, M.; Lombardi, G. Synchronized Switch Harvesting on ElectroMagnetic System: A nonlinear technique for hybrid energy harvesting based on active inductance. *Energy Convers. Manag.* **2020**, *203*, 112135. [\[CrossRef\]](#)
34. Yuan, J.; Peng, H.; Sun, H.; Xiao, H. A Single-Stage Dual-Mode AC-DC Converter for Vibration Energy Harvesting with Uninterrupted Output. In Proceedings of the 2021 IEEE Energy Conversion Congress and Exposition (ECCE 2021), Vancouver, BC, Canada, 10–14 October 2021; pp. 5862–5866. [\[CrossRef\]](#)
35. Linear Technology. LTspice Circuit Simulator. Available online: <https://www.analog.com/en/design-center/design-tools-and-calculators/ltspice-simulator.html> (accessed on 25 December 2022).
36. Horowitz, P.; Hill, W.; Robinson, I. *The Art of Electronics*; Cambridge University Press: Cambridge, UK, 1989.
37. Arrillaga, J.; Smith, B. *AC-DC Power System Analysis*; Institution of Engineering and Technology: London, UK, 1998.
38. Liu, K.; Chen, M.; Gong, Y.; Fan, S.; Wang, G. A 100  $\mu$ W AC-DC Boost Converter for Electromagnetic Energy Harvesting with 0.2  $V_{Peak}$  Self-starting Voltage and 85% Efficiency. In Proceedings of the 2018 IEEE Asia Pacific Conference on Circuits and Systems (APCCAS), Chengdu, China, 26–30 October 2018; pp. 493–496. [\[CrossRef\]](#)
39. Iannone, I.; Clemente, C.; Davino, D.; Loschiavo, V. AC-DC Boost Modelling for Magnetostrictive Energy Harvesting. In Proceedings of the 2021 IEEE International Conference on Environment and Electrical Engineering and 2021 IEEE Industrial and Commercial Power Systems Europe (IEEEIC / I&CPS Europe), Bari, Italy, 7–10 September 2021. [\[CrossRef\]](#)
40. Cervellini, P.; Antoszczuk, P.; Garcia Retegui, R.; Funes, M. Efficiency analysis on DCM interleaved boost power converters. In Proceedings of the 2017 17th Workshop on Information Processing and Control (RPIC 2017), Mar del Plata, Argentina, 20–22 September 2017. [\[CrossRef\]](#)
41. Rastmanesh, M.; El-Masry, E.; El-Sankary, K. Trade-Offs Between Efficiency and Output Voltage of a Single Boost DC-DC Converter for Photo-Voltaic Low Power Harvesting Applications. In Proceedings of the 2019 IEEE 10th Annual Information Technology, Electronics and Mobile Communication Conference (IEMCON 2019), Vancouver, BC, Canada, 17–19 October 2019; pp. 839–842. [\[CrossRef\]](#)
42. Maksimovic, D.; Cuk, S. A unified analysis of PWM converters in discontinuous modes. *IEEE Trans. Power Electron.* **1991**, *6*, 476–490. [\[CrossRef\]](#)
43. Cao, S.; Wang, X.; Zheng, J.; Cao, S.; Sun, J.; Wang, Z.; Zhang, C. Modeling and Design of an Efficient Magnetostrictive Energy Harvesting System with Low Voltage and Low Power. *IEEE Trans. Magn.* **2018**, *54*, 8207005. [\[CrossRef\]](#)
44. Chen, J.; Peng, H.; Feng, Z.; Chen, Y.; Zeng, C.; Kang, Y. A Fully PCB Integrated Self-Powered Micro Generator for Vibration Electromagnetic Harvesting. In Proceedings of the 2020 Thirty-fifth Annual IEEE Applied Power Electronics Conference and Exposition (APEC), New Orleans, LA, USA, 15–19 March 2020; pp. 3594–3599. [\[CrossRef\]](#)
45. Fuchs, E.; Masoum, M. *Power Quality in Power Systems and Electrical Machines*; Elsevier Academic Press: Burlington, MA, USA, 2008.
46. Viola, A.; Franzitta, V.; Cipriani, G.; Di Dio, V.; Raimondi, F.; Trapanese, M. A Magnetostrictive Electric Power Generator for Energy Harvesting From Traffic: Design and Experimental Verification. *IEEE Trans. Magn.* **2015**, *51*, 8208404. [\[CrossRef\]](#)

**Disclaimer/Publisher’s Note:** The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.