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Review

Recent Progress in Piezoelectric Conversion and Energy Harvesting Using Nonlinear Electronic Interfaces and Issues in Small Scale Implementation

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Abstract: This paper aims at providing an up-to-date review of nonlinear electronic interfaces for energy harvesting from mechanical vibrations using piezoelectric coupling. The basic principles and the direct application to energy harvesting of nonlinear treatment of the output voltage of the transducers for conversion enhancement will be recalled, and extensions of this approach presented. Latest advances in this field will be exposed, such as the use of intermediate energy tanks for decoupling or initial energy injection for conversion magnification. A comparative analysis of each of these techniques will be performed, highlighting the advantages and drawbacks of the methods, in terms of efficiency, performance under several excitation conditions, complexity of implementation and so on. Finally, a special focus of their implementation in the case of low voltage output transducers (as in the case of microsystems) will be presented.

Keywords: piezoelectric; energy conversion; energy harvesting; energy scavenging; nonlinear

1. Introduction

The increasing growth in terms of autonomous devices, promoted both by industrial fields (aeronautics and transports, civil engineering, biomedical engineering, *etc.*) and personal applications (home automation, nomad devices, *etc*.) has raised the issue of powering such systems. Primary batteries, that initially have encouraged this development, are nowadays less popular because of their limited lifespan [1], which raise maintenance issues, as well as due to their complex and costly recycling process. Therefore, a recent trend to address this problem has consisted of using ambient energy from the environment to supply autonomous devices, making them self-powered.

Several energy sources can achieve this purpose, for instance solar or thermal [2]. However, much research has focused on using mechanical energy [3], as such a source is commonly available in small-scale systems. In this domain, piezoelectric elements are of particular interest, because of their high energy densities and integration potential, hence making them a premium choice for the design of self-powered small-scale devices [4-12].

Nevertheless, the energy that can be harvested using Piezoelectric Electrical Generators (PEGs) is still limited to the range of a few tens of microwatts to a few milliwatts, as the mechanical source features limited power and because the coupling coefficient of piezoelectric materials is quite low and localized at particular frequencies, especially when using the elements in flexural solicitation (which is the most common approach to match the input vibration spectrum and increase the input mechanical energy). In order to address this issue, several approaches have been proposed, such as the use of intrinsic mechanical nonlinearities [13-16], which aim at increasing the input energy in the host structure to provide more power.

Apart from the mechanical approach, nonlinear electronic interfaces have also been proposed in order to increase the conversion abilities of piezoelements, and therefore to harvest more energy. The purpose of the present study is to provide an up-to-date view of such systems. In this field, Guyomar *et al.* introduced a simple, low-cost process to artificially enhance the coupling coefficient of electromechanical systems using piezomaterials [17-22]. Based on a simple nonlinear process of the output voltage of the active material, this approach, initially developed for vibration damping purposes [23-27], permits a gain of up to 20 in terms of energy conversion, and 10 in terms of harvested energy [28]. Several techniques derived from this original method have been proposed, each of them addressing a particular concern (broadband vibration, impedance matching, energy harvesting ability enhancement, *etc*.).

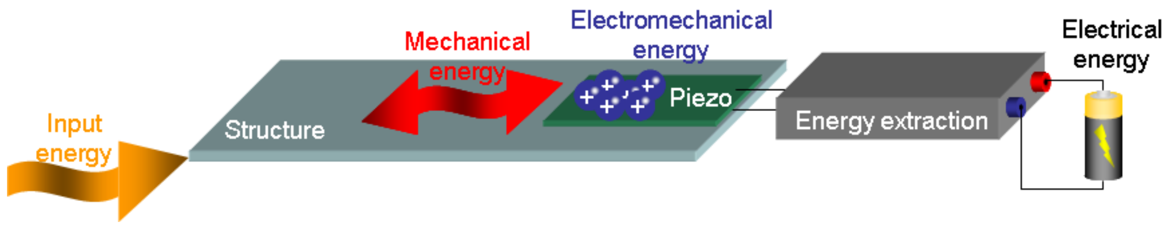
This paper aims at highlighting the specificities, advantages and drawbacks of each of the nonlinear electronic interfaces that have been proposed in the literature (in terms of performance, load independency and so on). A particular focus will be placed on the implementation issues of these techniques for micro-scale devices (for example performance under low voltage output or scalability of the control circuit).

The paper is organized as follows: Section 2 aims at briefly introducing the basics of energy harvesting, exposing the energy conversion chain in microgenerators, as well as the modeling of the structure and the possible options for increasing the conversion abilities. Then the principles of the nonlinear switching approach and its application to energy harvesting is outlined in Section 3. The performance and implementation issues of these techniques derived from the nonlinear approaches will then be discussed in Section 4. Finally, Section 5 briefly concludes the paper, recalling the main observations and tentatively classifying the techniques considering several criteria.

2. Modeling and Conversion Enhancement Principles

Generally speaking, a vibration energy harvester can be represented using the schematic depicted in Figure 1. First the mechanical energy (e.g., applied external force or acceleration) is converted into mechanical energy in the host structure. The latter is then converted into electrical energy by the piezoelectric element, and is finally transferred in electrical form to a storage stage.

Figure 1. General schematic of a vibration energy harvester.



Therefore, there are three steps in the conversion process:

1. Conversion of the input energy into mechanical energy.
2. Electromechanical conversion.
3. Electrical energy transfer.

However, it is important to note that the conversion processes are affected by the next stage, due to backward coupling. Hence, converting mechanical energy leads to a modification of the properties of the global structure, therefore changing the input energy, and extracting electrical energy from the piezoelectric element changes the amount of mechanical energy converted into electricity. Therefore the design of an efficient microgenerator has to consider:

1. The maximization of the input energy.
2. The maximization of the electromechanical energy (coupling coefficient).
3. The optimization of the energy transfer.

Nevertheless, as stated previously, these design considerations cannot be performed independently because of the backward coupling. At this stage it can be noted that the scope of this paper is to review nonlinear electronic interface for the optimization of the conversion. Hence, only the last two items will be considered. Efficient energy harvesters that consist of taking advantage of mechanical nonlinearities (and in particular nonlinear compliance) to ensure a maximization of the input energy [13-16] will therefore not be discussed.

In the following, particular attention will therefore be placed on the last two points: optimization of the energy conversion and energy transfer. Considering that the electromechanical system can be modeled by a coupled spring-mass-damper system depicted in Figure 2 [25,29]:

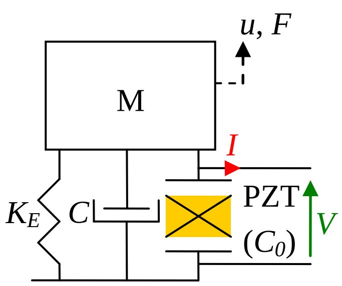
$$\begin{aligned} &M\ddot{u} + C\dot{u} + K_E u = F - \alpha V \\ &I = \alpha \dot{u} - C_0 \dot{V} \end{aligned} \qquad (1)$$

where u, F, V and I respectively represent the displacement, applied force (The force F can be replaced by the product of the mass by the acceleration in the case of seismic harvester (indirect coupling)), piezoelectric output voltage and current flowing out of the piezoelement. M refers to the dynamic mass, C to the structural damping coefficient and K_E to the open-circuit stiffness. Finally, α and C_0 stand for the force factor and clamped capacitance of the piezoelectric insert.

The energy analysis of such a system over a time range $[t_0;t_0+\tau]$ is obtained by integrating in the time domain the product of the motion equation by the velocity and the product of the electrical equation by the voltage:

$$\begin{aligned} &\frac{1}{2}M\left[(\dot{u})^2\right]_{t_0}^{t_0+\tau} + C\int_{t_0}^{t_0+\tau}(\dot{u})^2\,dt + K_E\left[u^2\right]_{t_0}^{t_0+\tau} = \int_{t_0}^{t_0+\tau}F\dot{u}dt - \alpha\int_{t_0}^{t_0+\tau}V\dot{u}dt \\ &\int_{t_0}^{t_0+\tau}VIdt + \frac{1}{2}C_0\left[V^2\right]_{t_0}^{t_0+\tau} = \alpha\int_{t_0}^{t_0+\tau}V\dot{u}dt \end{aligned} \quad (2)$$

Figure 2. Electromechanically coupled spring-mass-damper system.



From Equation (2), it can be shown that the converted energy is represented by the time integral of the product of the voltage by the speed (with a multiplying coefficient α), which can be decomposed into the electrostatic energy on the piezoelectric element and energy transferred to the electrical system. Hence, in order to increase the conversion abilities of the piezoelectric material, three ways can be envisaged:

1. Increase of the voltage.
2. Reduction of the time shift between speed and voltage (approximating the voltage and speed by monochromatic functions ($\dot{u} = u_M\omega\sin(\omega t)$ and $V = V_M\sin(\omega t+\phi)$), the time integral over a time period of their product yields $\int_0^{\frac{2\pi}{\omega}}V\dot{u}dt = \frac{\omega u_M V_M}{2}\cos(\phi)$, which is therefore maximal for $\phi = 0$).
3. Increase the coupling term (α).

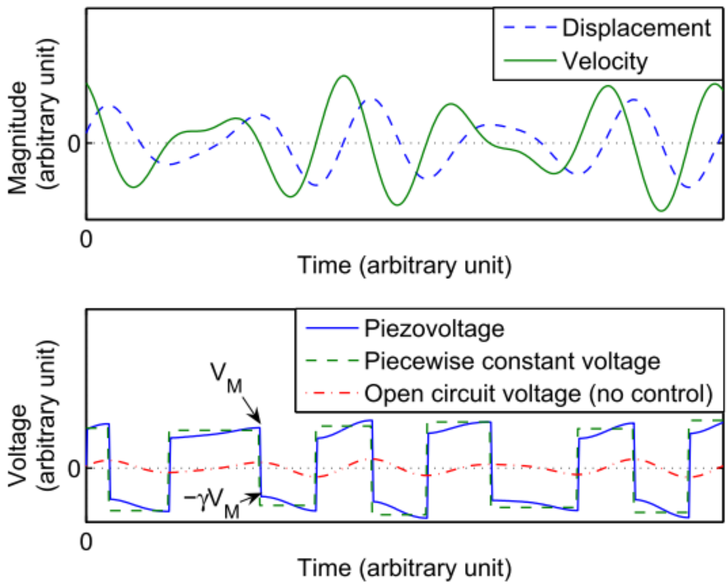
The last option implies the change of the material itself. In this domain, single crystals have recently been investigated [30,31], but their high cost, low conformability and processing complexity make them quite delicate to use in realistic implementations. The discussion about this material aspect is however out of the scope of this paper.

3. Switching Techniques

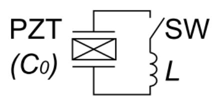
As the principles of energy harvesting enhancement have been described, the aim of this section is to present the various electronic interfaces that have been proposed in the literature, and to discuss the performance of each. Basically, the approaches can be divided into two categories, whether the piezoelectric element is directly connected to the storage stage, or not.

Nevertheless, whatever the considered case, the operation principles are quite similar and consist of using the two possibilities for enhancing the conversion (*i.e.*, voltage increase and reduction of the time shift between voltage and velocity). Actually both of these possibilities may be obtained by taking advantage of the dielectric nature of the piezoelectric element. If the piezoelectric voltage is reversed on zero speed values (extremum displacements) as depicted in Figure 3(a), this shapes an additional piecewise constant voltage proportional to the sign of the speed. The voltage continuity also insures a cumulative process that increases its magnitude, denoting the conversion enhancement as well. Hence, from Figure 3(a) (bottom), it can be seen that the nonlinear approach permits both reducing the time shift between speed and voltage, as well as significantly increasing the voltage level, allowing the conversion magnification.

Figure 3. (**a**) Waveforms of the displacement, speed and piezovoltage induced by the switching process on zero speed values (the bottom figure shows how the voltage in the nonlinear processing may be decomposed into a voltage proportional to the displacement and a piecewise constant voltage that is proportional to the sign of the speed and much larger than the original voltage); (**b**) Implementation of the nonlinear treatment.



(**a**)



(**b**)

Such a processing of the voltage inversion can be implemented in a really simple way, by briefly connecting the piezoelectric element to an inductor (Figure 3(b)), therefore shaping a resonant electrical network. In particular, if the digital switch is closed for half a period of the electrical oscillation (whose period is much smaller than the vibration period), this leads to an almost instantaneous inversion of the voltage. This solution for inverting the voltage across the piezoelectric element requires very low power as it does not need any external energy, except to control the digital switch. This autonomous voltage inverter can therefore be made self-powered [21,26,27,32-38], consuming a very small amount of power (typically 3% of the electrostatic energy available on the active material); as will be discussed in Section 4.2. As the energy conversion gain is typically in the range of a factor of 20, this energy requirement can easily be neglected.

However, because of the losses in the switching device (especially resistive losses in the inductor), the voltage inversion is not perfect and characterized by the inversion coefficient γ, giving the ratio of the absolute voltage after and before the inversion process ($0 \leq \gamma \leq 1$).

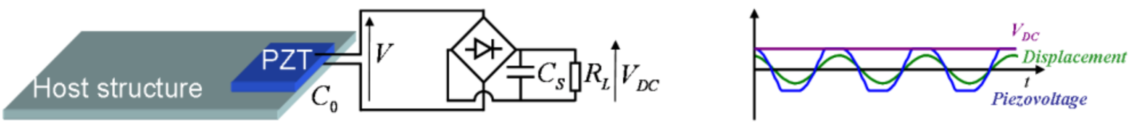
Finally, it can be noted that the concept of the nonlinear operation is independent from the physical phenomenon (as long as one quantity is continuous), allowing its application to other conversion effects [28,39,40].

3.1. Direct Energy Transfer

The first class of nonlinear electronic interfaces for conversion enhancement consists of performing the previously described switching concept with a direct connection of the piezoelectric element to the storage stage.

In this case, starting from the standard implementation of an energy harvester as depicted in Figure 4 which consists of simply connecting the piezoelectric element to a storage capacitor (connected to the load) through a rectifier bridge, several architectures may be considered.

Figure 4. Standard energy harvesting interface.



The first and simplest one consists of connecting the switching element in parallel (Figure 5(a)) or in series (Figure 5(b)) with the piezomaterial, leading to the concept of *Synchronized Switch Harvesting on Inductor* (SSHI).

The principles of operations of the parallel SSHI [14] consist of inverting the voltage after an energy extraction process, while inversion and energy extraction occur at the same time for the series SSHI [18,41]. Hence, the different steps involved in the energy harvesting process are as follows:

Parallel SSHI:

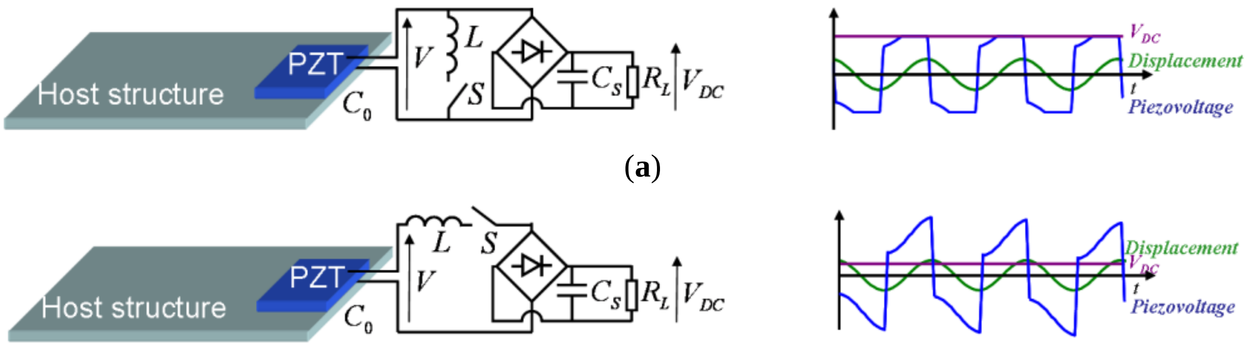
- *(i)* *Open circuit phase*
- *(ii)* *Harvesting phase*
- *(iii)* *Inversion phase*

Series SSHI:

- *(i)* *Open circuit phase*
- *(ii)* *Harvesting and inversion phase*

It can also be noted that the series SSHI harvesting approach may be obtained by replacing the switching inductance by a transformer, which actually allows an artificial change in the load seen by the piezoelectric element (by a factor $1/m^2$, with *m* being the transformer ratio). This approach, called "SSHI-MR" (*Synchronized Switch Harvesting on Inductor using Magnetic Rectifier*), also allows dividing by *m* the voltage gap of discrete components (such as diodes) seen by the piezoelectric element, and is therefore suitable for energy harvesting from low output voltage levels [42].

Figure 5. Synchronized Switch Harvesting on Inductor (SSHI): (**a**) Parallel SSHI; (**b**) Series SSHI.



(**a**)

(**b**)

As the SSHI-MR also permits an electrical decoupling of the storage stage from the extraction stage, it is possible to combine it with the parallel SSHI, leading to the concept of hybrid SSHI (Figure 6—[43]), which allows harvesting four times a period (*vs.* 2 in the previous cases) both during inversion and conduction of the rectifier, when the rectified voltage is less than the maximum piezovoltage (operating parallel SSHI); otherwise only the SSHI-MR is operating. Although the hybrid SSHI does not further improve the conversion enhancement (typical gain of 8 compared to the standard approach), it does permit widening the load bandwidth.

Using typical components, the gain, in terms of harvested energy of the SSHI techniques, can reach up to 10 compared to the classical implementation under constant displacement magnitude. The SSHI also permits increasing the effective bandwidth of the microgenerators [44]. However, extracting energy from a structure also modifies its mechanical behavior. In particular, harvesting energy from vibrations generates a damping effect that limits the power output of the SSHI techniques. This power output is actually the same as in the standard case. However, the nonlinear interface permits harvesting a similar energy to the classical implementation but with a dramatically reduced volume of piezoelectric element, as the power limit is almost reached for a lower global coupling coefficient.

In [45], Wu *et al.* used a similar architecture to the series SSHI, but with a modified switch control. The principles of the method, called SSDCI (Synchronized Switching and Discharging to a storage Capacitor through an Inductor), consists of transferring the electrostatic energy available on the piezoelectric element to a storage capacitor through an inductance (Figure 7). However, the switching process is naturally stopped by a diode bridge rectifier when the piezovoltage equals zero. At this instant there is still energy in the inductance, which is then transferred to the storage capacitor. However, for high load values (high rectified voltage), the piezoelectric voltage does not reach zero, and the circuit performs in a similar fashion than the series SSHI. Such an approach therefore permits harvesting four times more energy than the standard case over a wide load range.

Figure 6. Hybrid SSHI.

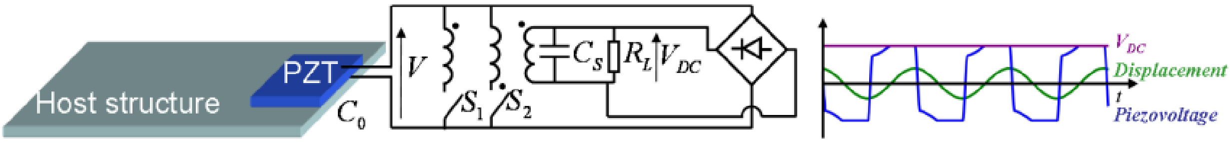
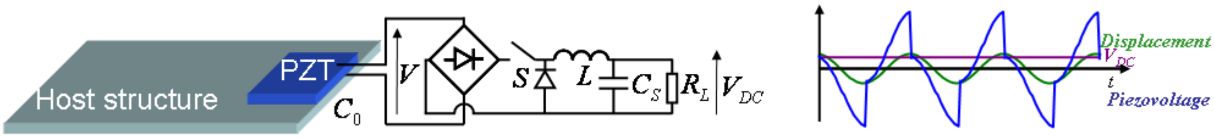
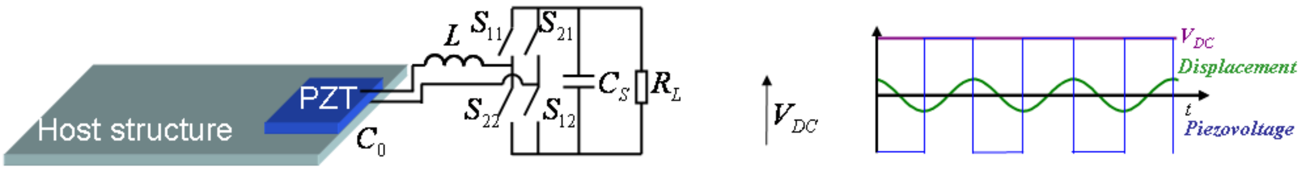


Figure 7. SSDCI.



The last possibility for performing the switching process, consists of assisting the voltage inversion through the use of an inverter, using pulse-width modulation (PWM) approaches (Figure 8), leading to the so-called *active energy harvesting* scheme (that consists of an Ericsson cycle). Such an active technique therefore permits an almost perfect inversion [46,47], yielding an outstanding harvested energy level (proportional to the output voltage, and thus not limited), although requiring significant external energy for driving the PWM command; possibly compromising the operations of the approach as will be discussed later. Another approach for enhancing the inversion (and thus the output power) consists of performing a two-step switching [48], typically increasing the energy output of the SSH techniques by 40%, under constant displacement magnitude.

Figure 8. Active energy harvesting scheme.



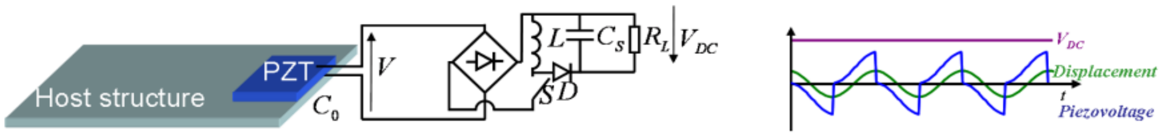
3.2. Load Decoupling Interfaces

The previously exposed approaches consisted of directly connecting the piezoelectric element to the storage stage (possibly through an inductor). However, because of this connection, the extracted energy and, therefore, harvested powers are closely dependent on the connected load. In realistic applications, however, the load may not be fixed in advance, and can even change with time according to the state of the connected system (e.g., sleep mode, RF communication, *etc*.).

Hence, in order to counteract this drawback, using the switching concept in a slightly different way has been proposed. In these techniques, the inductance is used as an energy storage element. The energy harvesting process is therefore performed in two steps. First, the energy available on the piezoelement is transferred to the inductance. Then the piezoelement is disconnected from the circuit, and the energy stored in the inductor is transferred to the storage capacitor. This therefore prevents the direct connection of the piezoelectric element to the load, and thus leads to a harvested energy independent of the connected system.

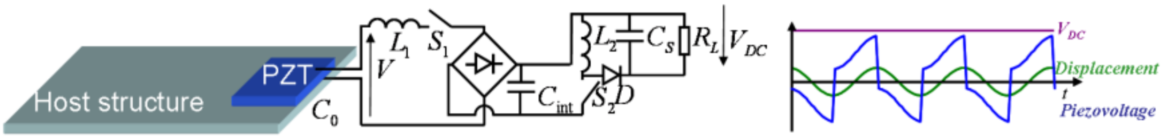
The direct application of this concept leads to the *Synchronous Electric Charge Extraction* (SECE) technique, depicted in Figure 9 [49]. In addition to the independence of the harvested power from the load, such a technique also permits a gain of 4 in terms of scavenged energy compared to the standard approach. However, when considering the damping effect, the SECE features a critical value of the figure of merit given by the product of the squared coupling coefficient k^2 (giving the amount of energy that can be converted into electric energy) by the mechanical quality factor Q_M (reflecting the effective available energy). Above this threshold, the harvested energy decreases as the product k^2Q_M increases. This is explained by the fact that it is not possible to control the trade-off between energy extraction and damping effect. From a mechanical point of view, the SECE technique may be seen to be equivalent to the SSDS (Synchronized Switch Damping on Short-circuit) damping technique ([29]).

Figure 9. Synchronous Electric Charge Extraction (SECE).



In order to be able to control this trade-off, it is possible to combine the series SSHI with the SECE, leading to the Double Synchronized Switch Harvesting (DSSH) technique [50], shown in Figure 10. This approach consists first of transferring a part of the electrostatic energy on the piezoelectric element to an intermediate storage capacitor C_{int}, and using the remaining energy for the inversion process, and then transferring the energy on C_{int} to the inductance and finally to the storage stage. Through the tuning of the capacitance ratio $x = C_{int}/C_0$, such a technique permits controlling the amount of extracted energy, and thus the above-mentioned trade-off, as well as the trade-off between conversion enhancement and harvested energy. By properly tuning the value of the intermediate to piezoelectric capacitance ratio, it can be shown that the harvested power, considering a constant displacement magnitude, can be 6 times higher than when using the classical energy harvesting interface. When considering the damping effect, the DSSH allows harvesting a significant amount of energy even for low coupling coefficient (and typically requires 10 times less piezomaterial than the classical approach for the same power output), although it features the same power limit as the standard technique for highly coupled, weakly damped systems excited at one of their resonance frequencies. The DSSH may be further enhanced by leaving a small amount of energy (*i.e.*, non zero voltage) on the intermediate capacitor, leading to the concept of *Enhanced Synchronized Switch Harvesting* (ESSH—[51], which allows a finer control of the trade-offs between energy extraction and voltage increase, and between extracted energy and damping effect. The ESSH approach also permits a lower sensitivity to a mismatch in the capacitance ratio [51].

Figure 10. Double Synchronized Switch Harvesting (DSSH).



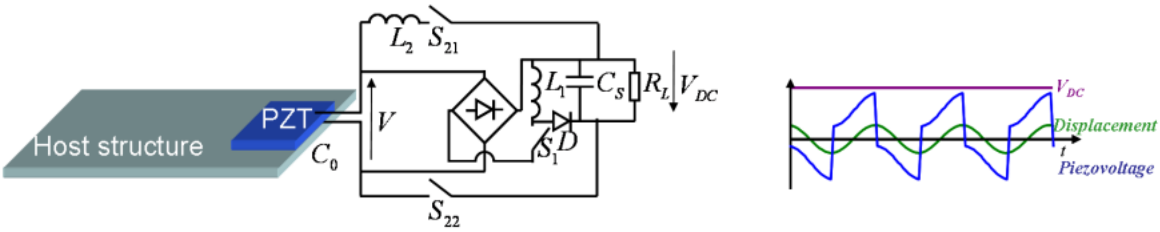
Another approach consists of using the SECE technique but adding an energy feedback loop from the energy storage stage to the piezoelectric element itself that permits applying an initial voltage to the active material [52]. The principles of such an approach, depicted in Figure 11, consist of:

i. *Extracting the energy from the piezoelectric element (using the SECE interface - S1 and L1).*

ii. *Providing energy to the piezoelectric insert, from the storage stage (S21, S22 and L2).*

iii. *Let the voltage increase by leaving the active material in open-circuit condition.*

Figure 11. Energy harvesting, featuring energy injection.



Such an energy injection technique therefore permits bypassing the limits of the unidirectional stand-alone techniques presented so far (this excludes the case of the active energy harvesting scheme), and features a harvested energy gain of up to 40 (typically 20 using off-the-shelf components) compared to the classical system when considering constant displacement magnitude. When the damping effect cannot be neglected, the energy feedback loop, by a particular "energy resonance" effect, allows bypassing the power limit of the previously exposed techniques.

4. Discussion

This section outlines the performances of the considered energy harvesting schemes as well as their implementation issues.

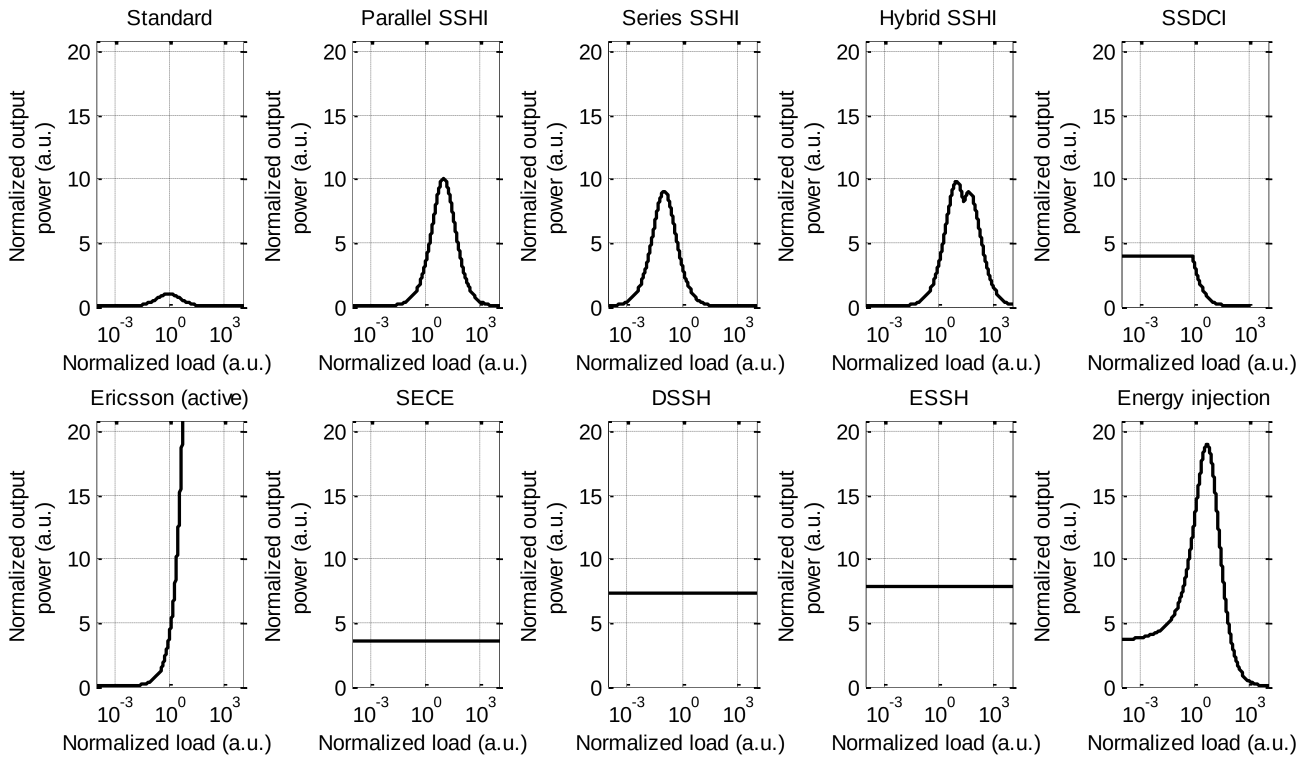
4.1. Performance Comparison

Here the performance of the energy harvesting systems will be compared. For the sake of simplicity, it is assumed that the input force is monochromatic (broadband excitation will be discussed in Section 4.2). When considering that the system features a constant displacement magnitude u_M (This assumption relates to the case where the structure is excited out of resonance or when the global electromechanical coupling is weak and/or the mechanical quality factor low so that the backward coupling of the piezoelectric element can be neglected), the power that can be harvested as a function of the connected load for each of the discussed technique is depicted in Figure 12. In order to make these charts as independent as possible from the system parameters, the loads and powers have been normalized with respect to the optimal load and maximum power in the standard case:

$$\left.(R_L)_{opt}\right|_{stand} = \frac{1}{4C_0 f_0}$$
$$\left.P_{max}\right|_{stand} = f_0 \frac{\alpha^2}{C_0} {u_M}^2 \tag{3}$$

and the figures only depend on the inversion factor γ and extraction efficiency γ_C, which are respectively fixed at 0.8 and 90%, and transformer ratio m for the hybrid SSHI (set to 20). In the case of the ESSH, the remaining voltage on the intermediate capacitor has been set close to its optimal value [51].

Figure 12. Normalized harvested powers under constant vibration magnitude.



This figure clearly demonstrates the ability of the nonlinear processing to significantly enhance the conversion enhancement (and thus the power generation ability) of microgenerators when the backward coupling can be neglected (high mechanical damping coefficient and/or low coupling). When using the SSH approach, the harvested power gain is typically 10 compared to the classical technique. However, it will be further shown that the two schemes feature the same power limit for highly coupled, weakly damped systems. The particular principles of the active energy harvesting scheme also permit an outstanding power output (theoretically infinite), but it has to be noted that the switching and driving losses have not been taken into account in the figure. A full analysis of the energy transfer and energy balance would show the limits of this technique. The damping effect (in the constant displacement magnitude case, the input energy is neither fixed nor bounded) not taken into account here, would also decrease the power harvested by the active scheme.

Although the series SSHI features a power slightly less than the parallel SSHI, it permits a decrease of the optimal load, which may be beneficial for realistic systems, as the dielectric behavior of piezodevices associated with the low frequencies of vibration leads to relatively high optimal resistance (usually several hundreds of kiloohms in standard case). Hence the series SSHI may be more adapted to electronic devices whose input impedance is less than this value, which is generally the case. However, although they permit a high power gain, the SSHI approaches are strongly dependent on the connected load, which would be problematic if the connected system would have an input impedance varying with time (corresponding, for example, to a change in state, e.g., from active transmission to sleep mode). An additional stage aimed at providing a constant load seen by the piezoelectric element would therefore be required [53-58], but would also introduce some losses (the efficiency of self-powered load adaptation stage is typically around 75–80% [54,55]).

Such an case does not occur when using the SECE, DSSH or ESSH approaches, as these techniques provide a natural load adaptation, although providing lower power output (it can however be noted that the global output of SSHI generator with load adaptation stage is similar to the harvested power of the DSSH and ESSH; the latter requiring less components as well). To a lesser extent, the SSDCI also permits an independent harvested power from the load as long as the rectified voltage (or equivalently the load) is less than a critical value.

Finally, using a part of the harvested energy to allow a bidirectional energy transfer (energy injection technique) allows outperforming all the previously exposed techniques, with a typical energy gain of 20 using typical off-the-shelf components. Such an energy harvesting magnification may be explained by a particular "energy resonance" effect that occurs at the optimal load. As the power output increases, the injected energy increases as well; this leads to an increase of the harvested energy and so on. It can be seen on Figure 12 that for low load value (and thus low voltage output), the energy injection technique performs in a similar way to the SECE.

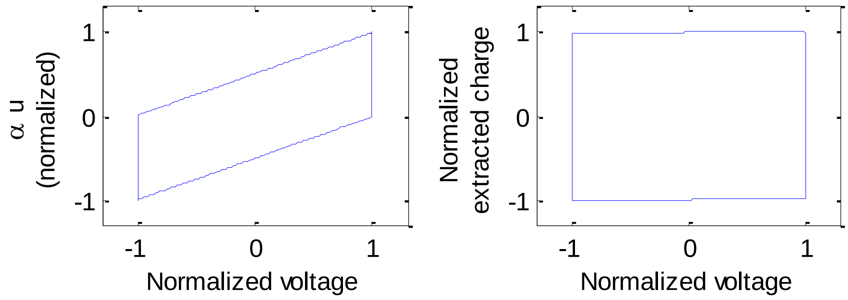
The associated energy cycles for each technique are depicted in Figure 13, showing that the nonlinear techniques describe either a Stirling cycle (series SSHI, SSHI-MR, SSDCI, SECE, DSSH, ESSH and energy injection), an Ericsson cycle (active scheme), or a combination of the two (parallel SSHI, hybrid SSHI).

When considering that the converse piezoelectric effect may not be neglected (low damping and high electromechanical coupling), harvesting electrical energy decreases the amount of mechanical energy in the structure, leading to a damping effect that limits the conversion. In this case, when considering that the system is driven by a constant force magnitude, the harvested powers as a function of normalized loads and powers, as well as of the figure of merit k^2Q_M, given by the product of the squared coupling coefficient by the mechanical quality factor, are depicted in Figure 14. The load axis has been normalized in the same way as previously stated and the parameters γ, γ_C and m are the same, but the power is in this case normalized with respect to the maximal output power of the unidirectional techniques:

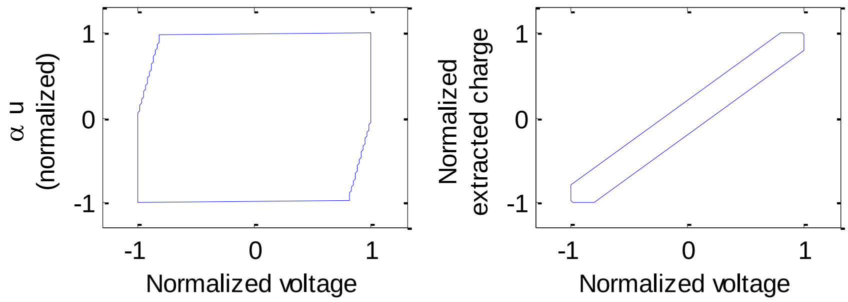
$$P_{lim} = \frac{{F_M}^2}{8C} \quad (4)$$

which occurs because of the damping effect.

Figure 13. Normalized energy cycles (converted and transferred) for different energy harvesting interfaces: (**a**) Standard; (**b**) Parallel SSHI, hybrid SSHI; (**c**) Series SSHI, SSHI-MR, SSDCI, SECE, DSSH, ESSH, Energy injection; (**d**) Ericsson (active harvesting).



(**a**)



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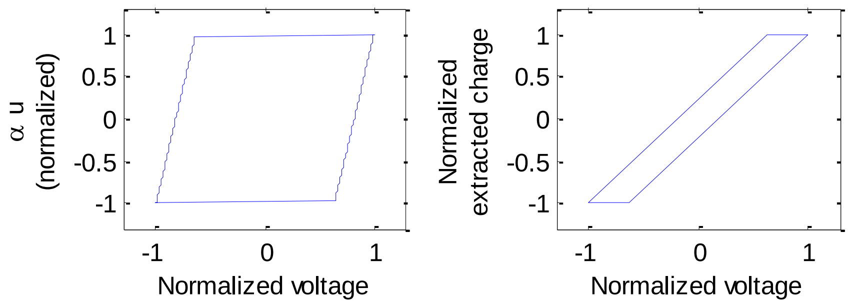
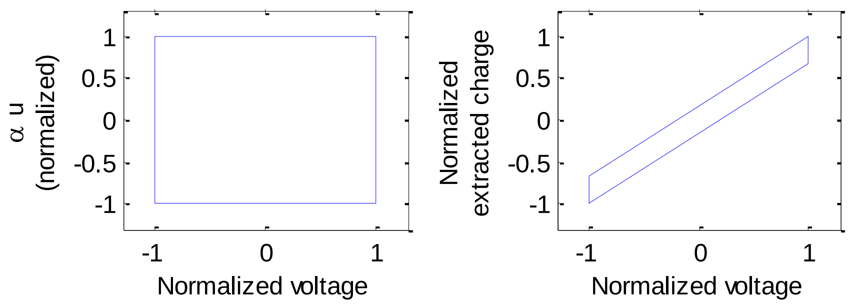
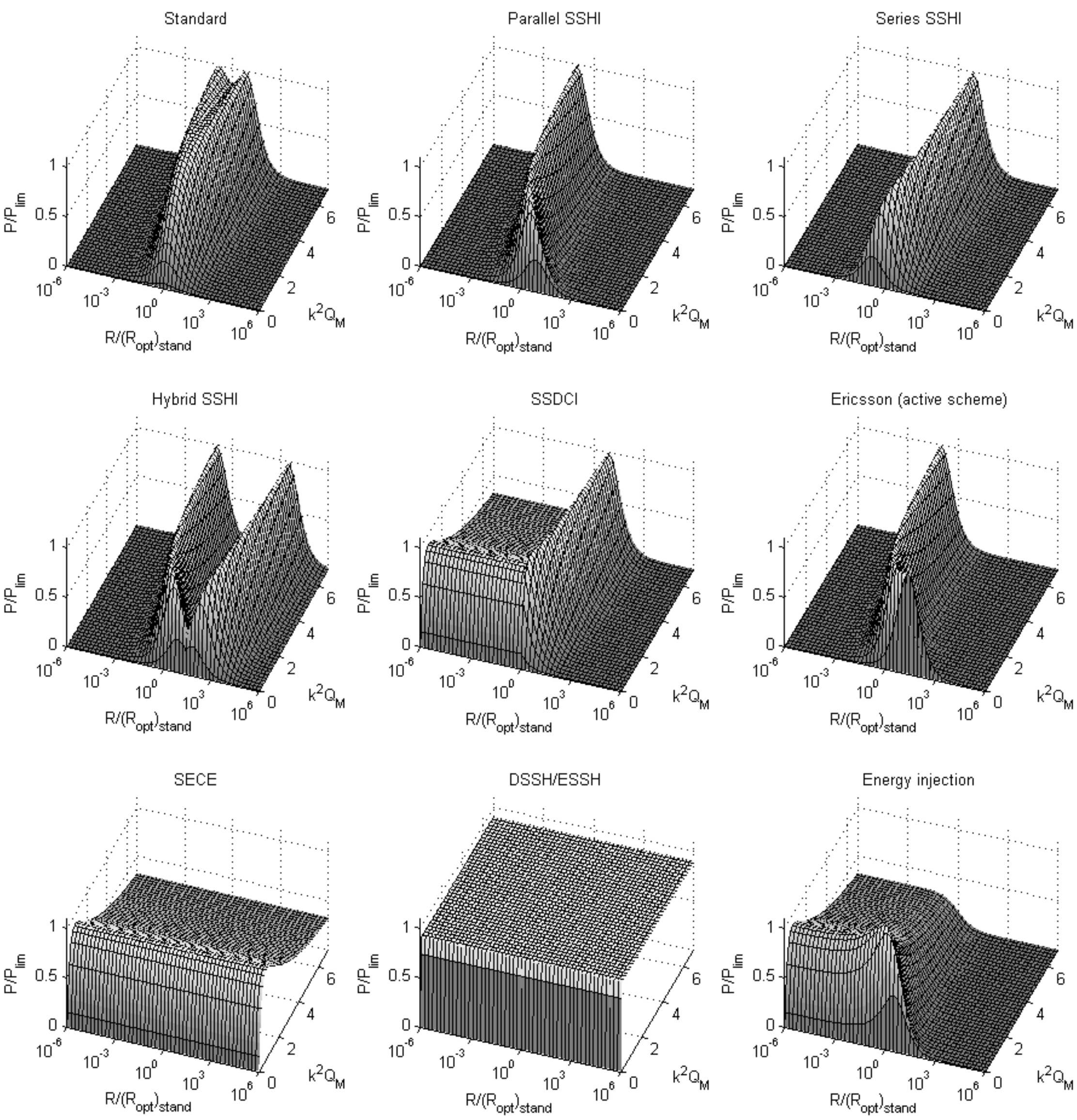


(**c**)

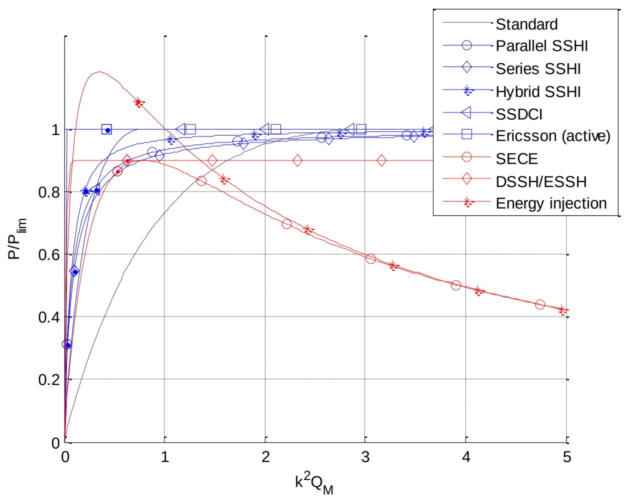


(**d**)

Figure 14. (**a**) Normalized harvested powers and (**b**) maximal harvested powers under constant force magnitude.



(**a**)



(**b**)

In this case, it can be shown that the use of nonlinear approaches permits harvesting the same amount of energy than the standard approach but using much less volume of active materials (*i.e.*, for much lower values of k^2Q_M), although the unidirectional techniques no longer improve the harvesting abilities for high values of k^2Q_M compared to the standard case. In particular, the DSSH and ESSH (which have been depicted in a single plot because of their similarity) and energy injection techniques show high slopes for low values of the figure of merit, having the same power generation abilities as the standard approach, but with 10 times less active materials. These approaches, through the tuning of the capacitance ratio x, also feature a constant power output after a critical value of k^2Q_M, contrary to the SECE which is a decreasing function of k^2Q_M after a critical value of the figure of merit ($(k^2Q_M)_{critical} = \pi/4$).

However, the most efficient technique among the unidirectional energy transfer approaches remains the active scheme, which permits reaching the power limit for very low value of k^2Q_M (theoretically, P_{lim} is reached as soon as $k^2Q_M \neq 0$). Hence, it can be concluded that unidirectional nonlinear approaches are particularly interesting for low coupled systems, but do not induce any improvement for highly coupled, weakly damped systems (which is however an unusual case—the value of k^2Q_M is generally less than 0.2 in realistic applications). As can be seen in Figure 14, only the energy injection scheme (that features bidirectional energy transfer) permits bypassing this limit, thanks to the energy resonance effect. The technique also shows a decrease in the harvested power for high values of k^2Q_M, as the trade-off between energy extraction and damping effect cannot be controlled. However, it is possible that the implementation of a DSSH-like energy extraction interface would permit a non-decreasing harvested power.

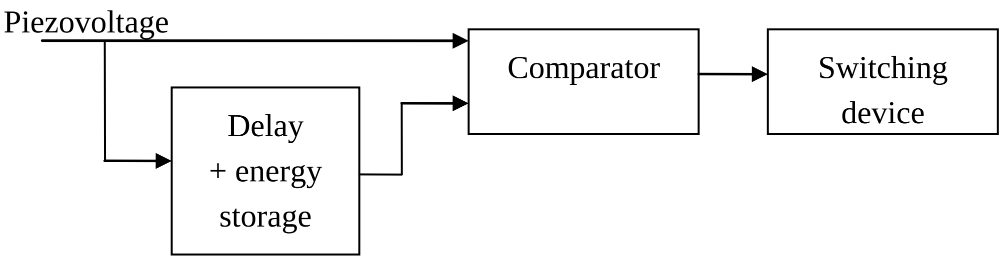
From Figure 14 it can be seen that the optimal load also varies with k^2Q_M (denoting the trade-off between energy harvesting and vibration damping), which shows the advantage of using load decoupling techniques (SECE, DSSH and ESSH), and, although the latter features a lower harvested power because of the extraction efficiency γ_C, one has to keep in mind that the realistic implementation of SSH techniques requires the use of an additional load adaptation stage whose losses make their global maximum power output similar to that obtained with the SECE or DSSH

4.2. Implementation Issues

When designing systems that aim at scavenging energy from environmental sources, particular attention has to be placed on the design in terms of realistic implementation (e.g., the energy balance between harvested energy and required energy should be positive).

In terms of implementation issues, several architectures have been proposed to make the switch control autonomous [21,26,27,32-35]. In these works, the extremum detection is usually designed by computing the derivative of the piezovoltage (which gives the extremum position when it cancels), but the derivative operator is not really stable and is sensitive to noise. Another commonly used approach for the design of the self-powered switch lies in the use of a differentiation of the piezovoltage. This is obtained by comparing the voltage itself with its delayed version (Figure 15). The *Synchronized Switch* systems can therefore be made truly self-powered using a few typical off-the-shelf components [32-34]. In addition, thanks to the principles of the maximum detection, the device can operate in a wide frequency range. However, for the other techniques (SECE, DSSH, ESSH and energy injection), the self-powered design may be a bit more complex because of the command of the digital switch, although some implementations have been proposed [58].

Figure 15. Principles of the self-powered switching device.

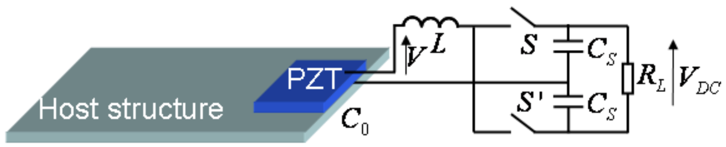


Although the previous analysis has been done considering sine excitation, realistic solicitation would more likely be random. Although few analyses have been conducted in this domain for nonlinear systems [60], it can be stated that load-independent techniques would perform better than the other approaches, as the optimal loads are frequency-dependent.

In the particular case of small-scale systems and microsystems (e.g., MEMS devices), some considerations occur with respect to the implementation of the control systems [61]. In particular, the magnetic components (inductor and transformers) may be seen as a limitation in terms of the miniaturization of the device. However, Liu *et al.* proposed a process for realizing on-chip inductors and transformers which typically require a surface of a few square millimeters [62,63]. In [39], changing the inductor with a capacitor for a better integration has been proposed. However, the dielectric nature of piezoelectric elements makes such an approach quite unsuitable for these systems.

However, the main limitations of piezoelectric generators at microscale are due to the electronic command, and particularly discrete components (such as diodes and transistors) that feature voltage gap whose values which are typically a few hundreds of millivolts [35]. As the voltage output of microscale generator is often below this threshold, no power can be harvested. In this case, the cumulative voltage increase allowed by the nonlinear process is helpful to bypass this minimum voltage requirement, and the use of a transformer in the SSHI-MR and hybrid SSHI techniques permits a great reduction of the impacts of discrete electronic components (the voltage gap seen by the piezoelectric element is divided by the transformer ratio *m*). It is also possible to slightly modify the series SSHI technique to remove the diodes without changing the circuit operations as shown in Figure 16.

Figure 16. Diodeless Series SSHI.



5. Conclusion

This paper proposed a comprehensive review of nonlinear energy harvesting interfaces for performance enhancement of vibration energy harvesters featuring the piezoelectric element. The principles of each scheme have been presented and main results summarized, and the specificities of each of them emphasized, in terms of output power, load dependency and performance under low piezoelectric output voltage. From the analyses done though the paper, it is possible to classify the techniques according to several criteria. As a conclusion, Table 1 proposes a tentative visual description of the performance of the exposed techniques considering several factors.

Table 1. Classification of the harvesting techniques.

Technique	**Harvested energy**			**Low voltage harvesting**	**Load independency**	**Implementation easiness**
	Constant displacement magnitude	**Constant force magnitude-Low coupling**	**Constant force magnitude-High coupling**			
Standard	☹	☹	😐	☹	☹	☺
Parallel SSHI	☺	😐	😐	☹	☹	😐
Series SSHI (diodeless)	☺	😐	😐	😐	☹	😐
SSHI-MR	☺	😐	😐	☺	☹	😐
Hybrid SSHI	☺	😐	😐	☺	😐	😐
SSDCI	😐	😐	😐	😐	😐	☹
Active Scheme (Ericsson)	☺☺	☺☺	😐	☹	☹	☹
SECE	😐	😐	☹	😐	☺	☹
DSSH/ESSH	☺	☺	😐	😐	☺	☹
Energy injection	☺☺	☺	☺/☹[64]	😐	😐	☹

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