A Review of Vibrational Micro-Generators and Their Power Processing Circuits

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ABSTRACT: The paper presents a review of the vibrational energy harvesting micro-generators and their respective power processing circuits. The power requirements for the electronic devices has dropped to low values as such it is now possible to power the devices of our day to day use by using energy from the surroundings. The vibrational micro-generators process the energy from ambient background and convert it into electrical form. The paper analyses that the energy given by the micro-generators is very low and there is a need to develop such power processing circuits that utilize this energy and convert it into useable form to be fed to the load.The various power converter topologies for the efficient conversion of micro-generator output voltage into voltage that can be fed to the electronic load is also described.

KEYWORDS:MEMS, micro-generator, low voltage, power processing, boost converter, energy harvesting.

I.INTRODUCTION

With rapid development in power semiconductor devices, the use of power electronic systems has expanded to new and wide application range that includes residential, commercial, aerospace, and industrial and many others. The power requirements for the electronic devices has dropped to low values as such it is now possible to power the devices of our day to day use by using energy from the surrounding. The ambient energy us in the form of light, air, wind, heat, vibration etc. are extracted by devices such as micro-generators that convert the given surrounding energy to electrical form to be fed to the power converter. Hence, there is a need to develop such power processing circuits that utilize the energies from micro generators and convert that energy into useable form.

II. LITERATURE SURVEY

Nowadays all portable electronic devices are powered by batteries [24], [34]. With the decreasing electronic scale the energy consumption decreases and therefore the batteries produced are also of smaller sizes providing enhanced energy storage availability. Energy harvesting from environmental or human sources has proven to be implemented effectively in battery driven devices [7], [24]. Many types of micro-generators are used in the self-powered devices and many of them are reported in various literary works for harvesting energies in different forms [7]-[12], [15], [18], [20]-[22]. Conventional power processing circuits that consist of two stages bridge rectification have been developed earlier for energy harvesting but, these converters proved be inefficient for the micro volts application. To address this problem, direct converters were proposed where bridge rectification is avoided and single stage boost converters were also used for the stepping up of low voltages [13], [16], [18] , [35]-[37]. Reduced power requirements of the analogue and digital circuits have led a way to the development of self-powered devices. The energy for these types of systems is extracted from energy conversion micro-generators whose power is very low. These devices harvest energy from surrounding environment and convert it into usable electric power by using micro-generators [3]. Micro-generators of the size of a dime can produce over one watt of electricity that are used in mobiles, laptops and other electronic equipment. Many types of micro-generators, which are used in the self-powered devices, are reported in the literature for harvesting different forms of energies from the surrounding environment. There are many micro-generators, which harvest mechanical energies from the ambient and they are currently the focus of many research groups [11]-[15]. A general multi domain model is built and analyzed as shown in Fig. 1.

Most of the reported generators are based around resonant mass spring systems, although for some applications (particularly generators designed to power medical devices) non-resonant systems can achieve higher power densities. The majority of reported work to date has concentrated on the design and fabrication of the mass-spring system micro-generator, with many groups using MEMS technology for fabrication. Testing has normally been achieved by measuring dissipated power in a resistor. Little work has been reported on the power processing electronics, one of the functions of which is to form the interface between the micro-generator and the load; load circuitry requires a steady DC voltage rail and the micro-generator of an inertial generator does not produce a stable voltage.

The paper is divided into four sections. The first section gives a brief introduction of the work presented in the paper. The second sections discusses the MEMS technology briefly and a detailed analysis of all the vibrational micro-generators is presented in the third section. The fourth section deals with the description of the power processing circuits for the respective vibrational micro-generators. Eventually the paper is summarized in the conclusion with references to the text given in the end.

III. MICRO ELECTRO MECHANICAL SYSTEMS OR MEMS TECHNOLOGY

Micro-Electro-Mechanical Systems, or MEMS, is a technology that in its most general form can be defined as miniaturized mechanical and electro-mechanical elements (i.e., devices and structures) that are made using the techniques of micro fabrication [2], [4], [89], [107] and [112]. The critical physical dimensions of MEMS devices can vary from well below one micron on the lower end of the dimensional spectrum, all the way to several millimeters. Likewise, the types of MEMS devices can vary from relatively simple structures having no moving elements, to extremely complex electromechanical systems with multiple moving elements under the control of integrated microelectronics. The one main criterion of MEMS is that there are at least some elements having some sort of mechanical functionality whether or not these elements can move. The term used to define MEMS varies in differentparts of the world. In the United States they are predominantly called MEMS, while in some other parts of the world they are called "Microsystems Technology" or "micromachined devices".While the functional elements of MEMS are miniaturized structures, sensors, actuators, and microelectronics, the most notable (and perhaps most interesting) elements are the microsensors and microactuators. Microsensors andmicroactuators are appropriately categorized as "micro-generators",which are defined as devices that convert energy from one form to another. In the case of microsensors, the device typically converts a measured mechanical signal into an electrical signal.A micro-generator is defined as a device that is actuated by power from one systemand supplies power usually in another form to a second
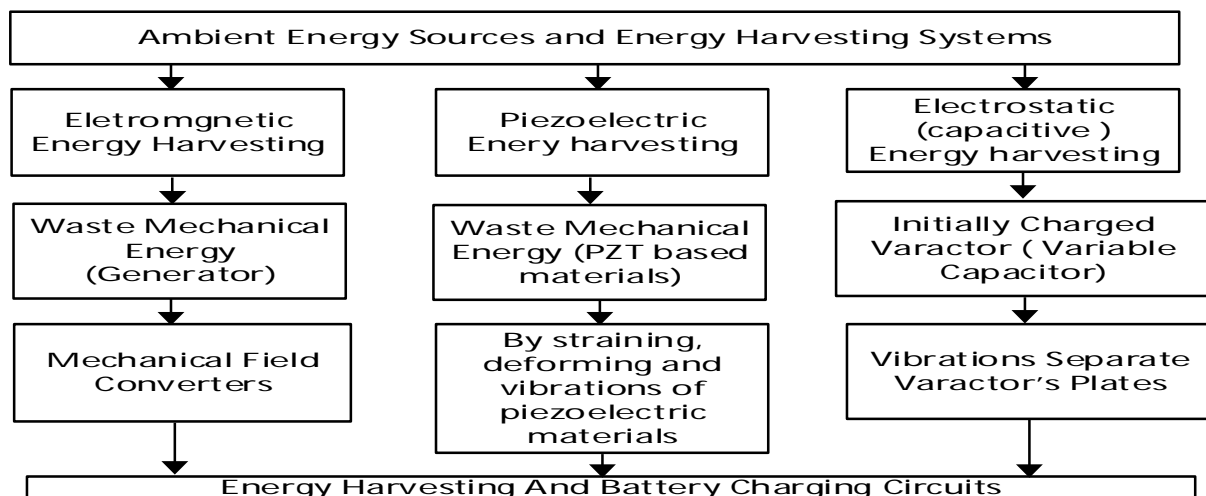

Fig. 1 Multi domain model of energy harvester

system. By acting as a micro-generator, MEMS provide the capability to transfer information between the physical world and the microelectronic world. When a MEMS device is used to transferinformation from the electronic world to the physical, then it is referred to as an actuator. If the MEMS device is used to transfer information from the physical

world tothe electronic, it is referred to as a sensor. The accelerometer that is used in gamingcontrollers is an example of such a MEMS sensor. The physical kinetic energy thatis used to maneuver the controller is transduced to an electrical signal that can bepassed to the gaming console.The system is depicted in Fig. 2 is a mechanical system is modeled as a vibration source which couples into the electrical system through the MEMS micro-generator. A low-power controller directs energy conversion and supplies power to the load. The controller consists of a power electronics subsystem which is responsible for exciting the micro-generator through its energy conversion cycle, and has been optimized to minimize losses, and a digital control core which generates the timing pulses which drive the gates of the power FETS or MOSFETS in the power electronics subsystem.

IV. ENERGY SCAVENGING FROM VIBRATIONAL MICRO-GENERATORS

Inertial micro-generators produce electrical energy when subjected to acceleration. Three architectures of inertial micro-generator were identified as suitable for implementation using MEMS technology. All three of these architectures, two of them which are resonant in nature, have been reported in the existing literature. In a study conducted to test the feasibilityand reliability of the different ambient vibrationenergy sources by Marzencki (2005), three differentvibration energy sources (electrostatic,electromagnetic, and piezoelectric) were investigatedand compared according to their complexity,energy density, size, and encountered problems.The study is summarized in Table 1.

The inertial micro-generators have different energy conversion principles and hence they can be classified into three major types that are [3], [25]:

- Electromagnetic
- Electrostatic
- Piezoelectric

3.1 Electromagnetic Micro-Generator

In the electromagnetic micro-generator, mechanical energy is converted into electrical energy by electromagnetic coupling [30]. The conversion technique by which an electromagnetic generator produces electricity is called as the process of electromagnetic induction. A magnet induces current in a coil when it is in motion and the filed lines of the magnet cross the coil. These electromagnetic generators are resonating spring mass damper based systems where the small amplitude surrounding mechanical vibrations are amplified into translational movements larger in amplitude. The mechanical energy of the motion is converted to electrical energy by the process of electromagnetic coupling.
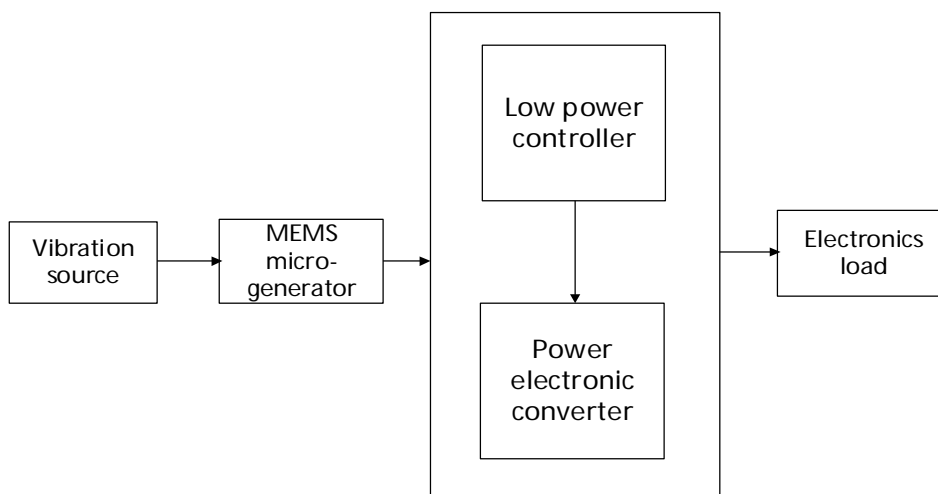
Fig. 2 MEMS block diagram

Table 1: Comparison of Vibrational Energy Sources

Micro-generator type	Electro- magnetic	Electro-static	Piezoelectric
Complexity of process flow	Very high	Low	High
Energy density	24.8 mJ cm^3	4 mJ cm^3	35.4 mJ cm^3
Current size	Macro	Integrated	Macro
Problems	Very low output voltages	Very high voltage and need of adding charge source	Low output voltages

Electromagnetic generator uses the permanent magnet and coil arrangement for damping purpose. It can also be called as the VDRG or the velocity damping resonant generator since, the damping force is opposing the proof mass integral velocity and it is best suited for sources that have high frequency and low amplitude [3], [15], [18], [29].
The optimal damping factor ζ is given by

$$\zeta = \frac{Y_o}{2Z_l}$$

Where, Y_o = source vibration amplitude
$= 25\boldsymbol{\mu}$m
And $Z_l = 1$mm
In this case, $\zeta = 0.0125$
The power extracted is hence given by:

$$P_D^{opt} = \frac{v^2}{2D} = \frac{(\omega Z_l)^2 \, (2m\omega_n\zeta)}{2}$$

Where   v = proof mass velocity
D = damping coefficient
ω_n = resonating frequency, where frequency f in Hz is 322Hz
m = proof mass = 0.5 g
The power obtained from the above damper based system is 52mW.
The Fig. 3 depicts the circuitry of a typical inertial electromagnetic micro-generator. A key design choice to process this power circuit is the current and the corresponding voltage at which the power has to be extracted for rectification.To minimize the conduction power loss occurring in the diode in the conventionalswitch diode circuits to the smallest value they must work at voltage above 1V.Even if the synchronous rectification is carried outwith a MOSFET switch, then tooit must bekept in mind that the current value should be minimum and the voltage should have a sufficiently
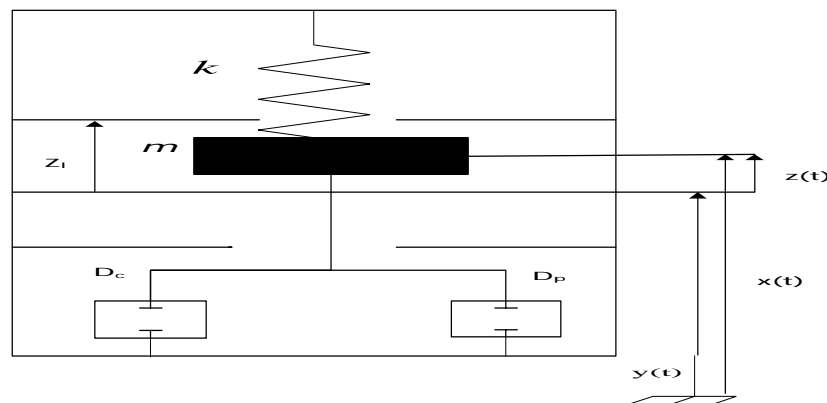

Fig. 3 Typical inertia micro-generator

high voltage. To meet this requirement the size of the coil may exceed the available space or it may be difficult to fabricate. Also, if a large size of the coil is utilized then it may increase the number of turns which increases the self-inductance of the coil close to the square of the total   number of turns and   the induced voltage may increase proportionately. To counteract this, if more conductor material is added to the coil or more turns with the same area of cross section or same turns at greater area of cross section will increase the area over which the flux will be supported in the air gap between the two magnetic materials resulting in greater volume of permanent magnet.
 The voltage induced in the generator is

$$V_g = NBI_a \omega Z_l$$

Where I_a= active length of coil (length cutting the magnetic field during vibration)
         N = number of turns
         B = maximum flux density (approx. 1.2 tesla)
For a VDRG micro engineered generator the active length can be taken as 20mm. This will give an induced voltage per turn to be 48mV. Hence, if a single turn is used then the power that may be extracted will be sound 48mV and the impedance of the turn will be very low. Now, if six turns are used instead then too the voltage will be about 300mV, which is very low for the conventional diode rectifiers. The voltage will have to be stepped up by 10 times for use in standard electronics.The literature indicates that often such high voltages are quite difficult to achieve even if the flux gradient, active length and operating frequency are lower.Hence, low voltage rectification and stepping up of the voltage are the basic requirements of inertial micro-generator systems.

3.2 Electrostatic Micro-Generators

The basic principle outlining the operation of these generators is that a varactor or a variable capacitor can be charged to a low value of voltage at a relatively high capacitance [3], [10], and [25]. But the major disadvantage of working with the electrostatic micro-generators is that at very high voltages they carry very small amount of charge. When the plates of the capacitor are accelerated the capacitance falls down to a low value and this increases the order of voltage to a few hundred volts. The charge must be converter to low voltages for powering the loads. The energy generated is given by:

$$E = \frac{Q^2}{2} \left(\frac{1}{C_{open}} - \frac{1}{C_{closed}} \right)$$

By the above equation it is clear that to achieve maximum energy the ratio between maximum and minimum values of the capacitor should be kept high. The main challenge to design such a generator and power converter is the development of parasitic capacitance connected to the generator. There are two types of electrostatic generators:
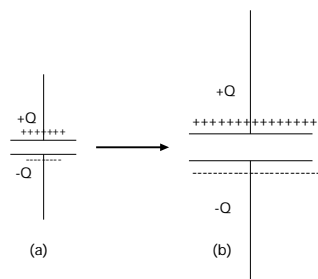

Fig. 4 Operation of an electrostatic generator in constant charge, (a) and (b) depict the two conditions of the capacitor.

Constant charge generators: If a varactor is charged to a certain value previously at maximum capacitance level and then disconnected from external circuitry before the geometry of the capacitor is altered by the motion, additional energy will be stored in the electric field between the two electrodes of the capacitor as work has been performed against the electrostatic force. This additional energy generated will be utilized to give power to a circuit. The most common implementation of this approach is explained briefly in Fig. 4. The Fig. 5 shows QV diagram for the operation of the generation. The devices is charged previously to a low value of voltage in the first phase hence making a connection to the voltage source (1-2). The source is then disconnected from the source and separated under constant

charge during the generating phase of the cycle (2-3). The capacitor is finally discharged in the third phase (3-1) and the capacitance is again increased to restart the operation. They are traced out by the QV diagram is the electrical energy generated.
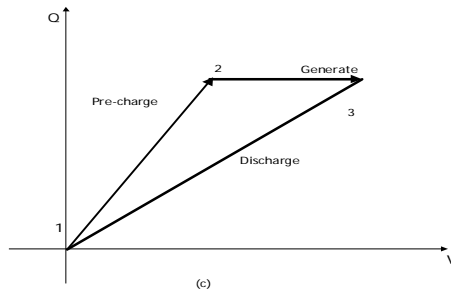

Fig. 5 QV diagram of the constant charge cycle

Constant voltage generators: If the capacitor is pre charged, while the capacitor is connected to constant source of voltage, which is usually provided by a battery, motion between the two plates or electrodes would result in charge being transferred to the voltage source and being removed from the capacitor electrodes.The plates are transitioned by a sliding movement.This sliding movement of the capacitor platesmakes the force between the plates in the direction of relative motion almost constant (as shown in Fig. 6).
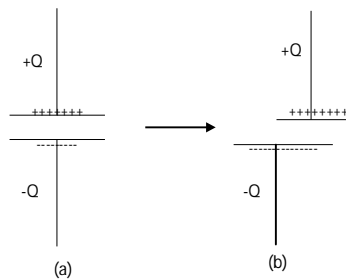

Fig. 6 Operation of an electrostatic micro-generator in constant voltage, (a) and (b) depict the two conditions of capacitor

The Fig. 7 shows QV diagram demonstrating this approach. The previously charged capacitor is set to a voltage when the capacitance is high (1-2). Being connected to the voltage source, which is a battery, the capacitance is decreased forcing the charge back to the source (2-3). This constitutes the generation phase of the cycle. Capacitor is then disconnected from the voltage source by switches before the capacitance value is increased again and (3-1) ready to restart. Area enclosed by the diagram is the energy generated.
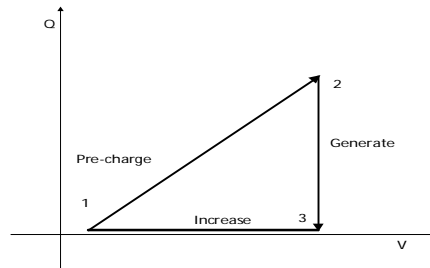

Fig. 7 QV diagram of the constant voltage cycle

3.3 Piezoelectric Micro generator

A piezoelectric material has the ability to convert electrical energy into mechanical energy of deformation (inverse piezoelectric effect-actuator), and also to transform mechanical strain energy into electrical charge (direct piezoelectric effect [1, 2, 3].
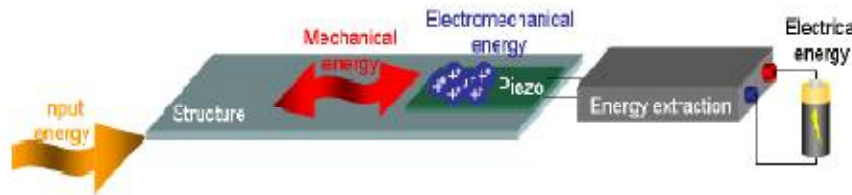

Fig. 8 General schematic diagram of a piezoelectric energy harvester

Piezoelectric transducers are a promising choice for microfabricated electric microgenerators, scavenging ambient mechanical energy, are potential power sources for autonomous systems [6, 7]. These devices use bimorph cantilevers because obtaining a damping force is difficult in these devices and they have a low frequency. There are a number of power processingcircuits that convert the piezoelectric energy into usable form [26], [40].Also the piezoelectric devices can produce voltages that can be processed with semiconductor devices directly as shown in Fig. 8. The electrical circuit block diagram of the piezoelectric material is shown in Fig. 9.
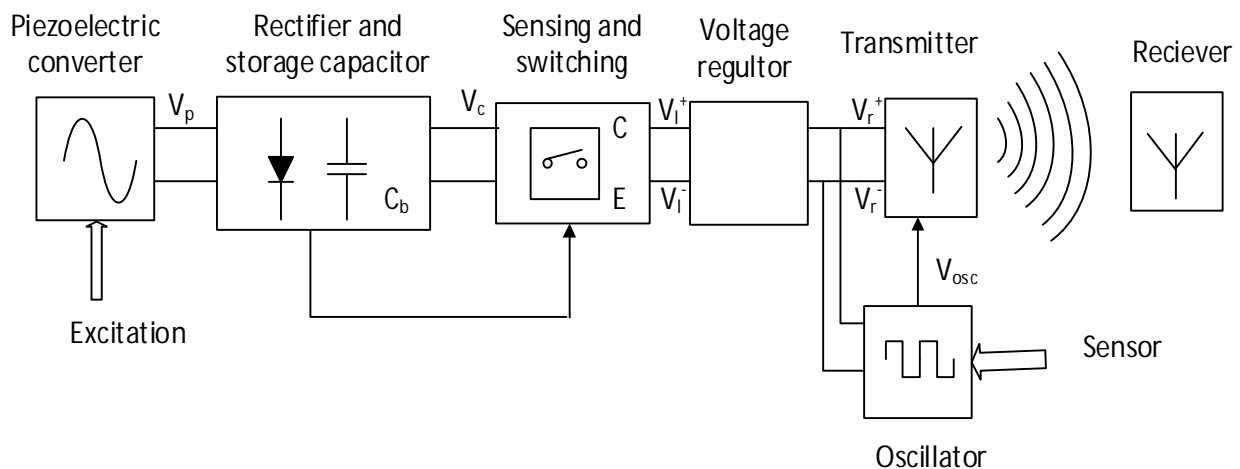

Fig. 9 Block diagram of the developed autonomous piezoelectric system

V. CONVERTER TOPOLOGIES FOR MICRO-GENERATORS

For the micro-generator systems of all the three kinds, electrostatic, electromagnetic or piezo electric, there are certain topologies for the power processing circuits that have been presented previously. Some of those topologies have been briefed here for every micro-generator [3], [10], [12].

Dual polarity boost converter for the electromagnetic systems: The task for the scavenging of energy from themicro-generators can be carried out by processing the positive and the negative half cycles of the voltagegenerated. The proposed converter (Fig. 10) operates the boost converters in discontinuous conduction mode and hence it is able to avoid the turn ON power loss in MOSFET and the reverse recovery effects in diode. The converter used is shown depicts a dual polarity boost converter for electromagnetic energy scavenging micro-generators. The target output is 3.3 V and this will provide us a result of +1.65 V to -1.65 V [35]-[37].
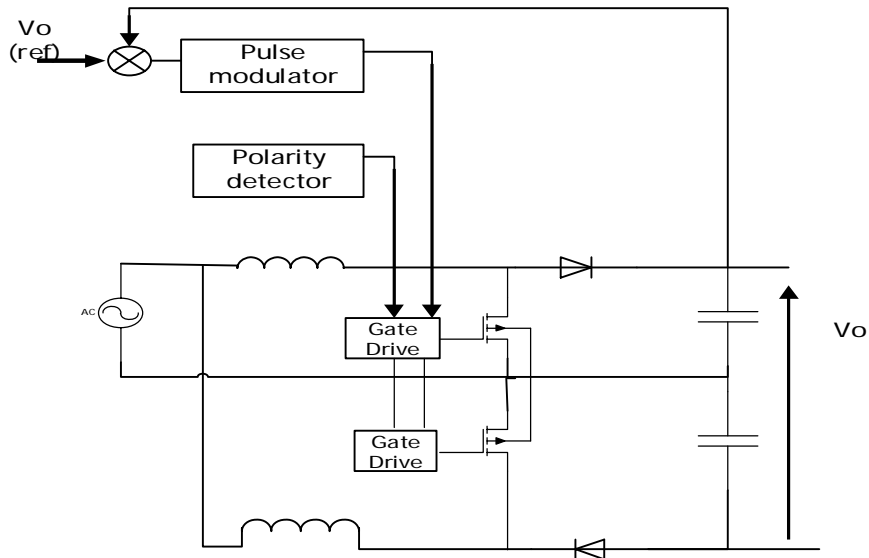
Fig. 10 Dual polarity boost converter for electromagnetic energy scavenging micro-generators

Converters for electrostatic micro-generator energy scavenging: Modified buck circuit was simulated for electrostatic scavenging of micro-generators. They have high voltage blocking capability, around 250V, low junction temperature and low off-state leakage. This was believed to be the simplest method to convert the high voltage on the generator to low voltages [3], [17] and [42].
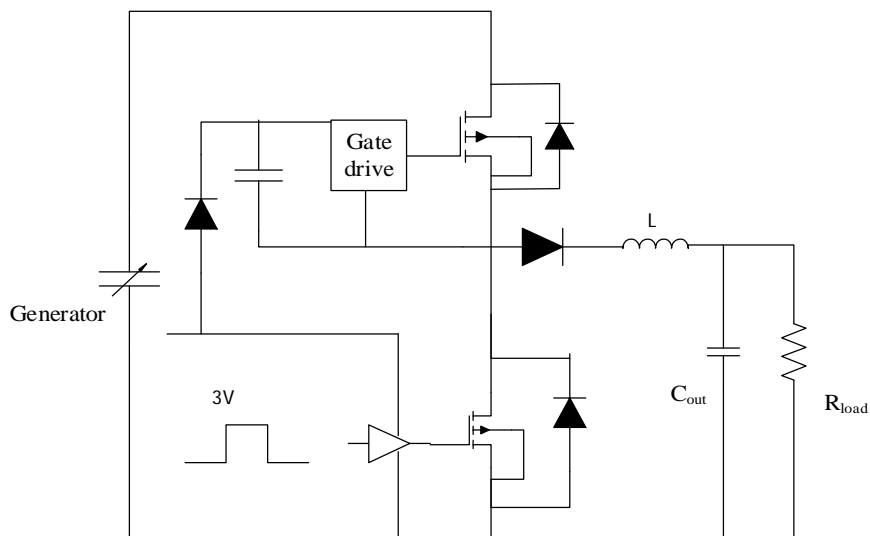

Fig. 11 A modified buck converter for electrostatic energy scavenging.

The efficiency of the generator can be expressed as a product of two main efficiencies, they are generation efficiency and the conversion efficiencies. For the constant charge mode in electrostatic case it can be expressed as:

$$\eta_{gen} = \frac{E_{open}}{W_{field} + E_{closed}}$$

$$\eta_{conv} = \frac{E_{out}}{E_{open}}$$

where

E_{open} =   energy stored in the moving plate capacitor at minimum capacitance

E_{closed} =   energy of capacitor at maximum capacitance

W_{field} =   amount of work done against the electric field as the plates separate

E_{out} = energy available after processing by the converter

The parasitic capacitance that develops in parallel reduces efficiency of the generation and the conversion efficiency is reduced by switching and conduction losses. Hence, the overall generation efficiency is affected. A buck converter was proposed for the electrostatic energy harvesting to eliminate the short comings of the conventional methods ofbridgeless rectification as shown in Fig. 11.A modified fly back converter was also proposed to scavenge energy from electrostatic micro-generator [39]. The overall effectiveness of a micro-generator is more complex than the efficiency of these power processing circuit. Fig. 12 depicts the modified fly back converter.
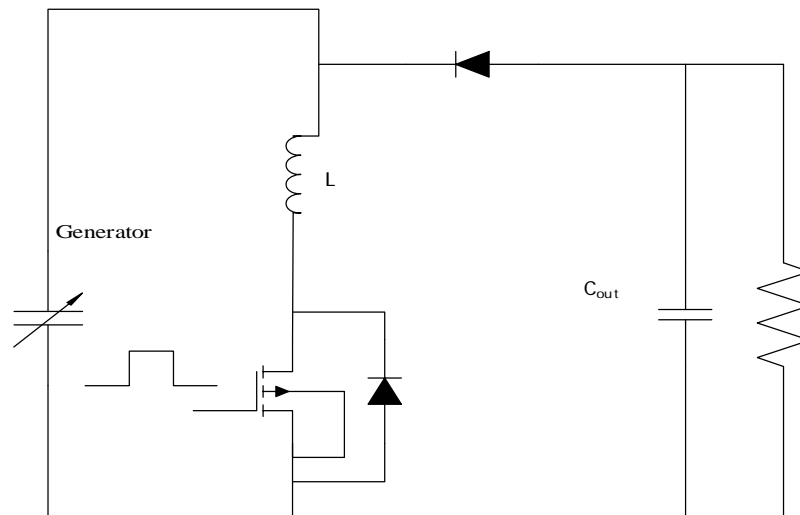

Fig. 12 Modified fly back converter

Converter for piezoelectric micro-generator: The first electronic nonlinear interface for conversion enhancement consists of switching concept with a straight connection of the piezoelectric element to the storage stage [26].Standard energy harvesting interface is depicted in the Fig. 13 that consists of simply connecting the piezoelectric element to a storage capacitor which is in turn connected to the load, by a rectifier bridge. The first and simplest implementation consists of connecting the switching element in parallel, or in series with the piezoelectric material that eventually leads to the concept of SSHI orsynchronized switch harvesting on inductor. Given below is the diagram of standard piezoelectric interface and blockdiagram of the piezoelectric mechanical electrical converter at the input side of the designed system.A buck-boost converter is observed to be most suitable for low excitation levels, and high efficiency requirements [1]. The buck-boost converter circuit is shown. Buck converters are not very efficient at low excitation levels. It has been shown that these converters require at least 35 V DC open circuit rectifier voltage to obtain 60 - 70% efficiency [7]. Moreover, buck-boost
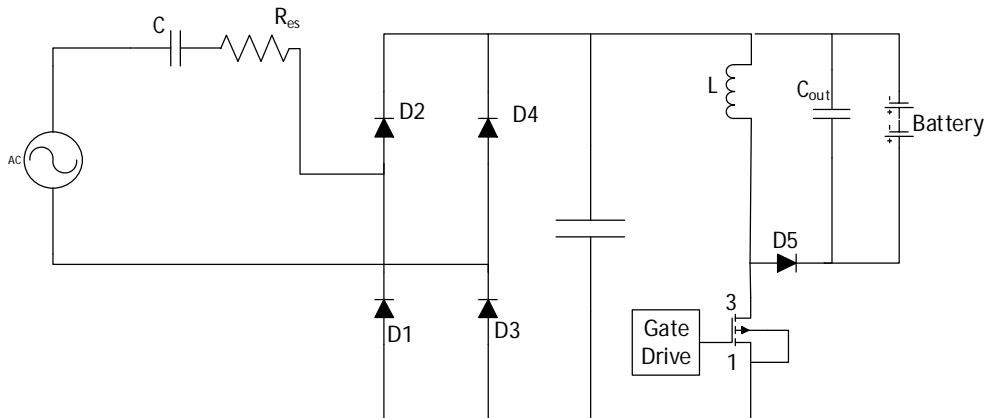
Fig. 13 Buck Boost Converter for Piezoelectric Micro-Generator

converters effectively work at input voltages above or below its output voltage (V_{bat}). Both these converters must operate in discontinuous conduction mode (DCM) for higher efficiency [7,8].

$$Rin = \frac{2Lf_{SW}}{D^2}$$

where:

L= inductance, f_{SW} = switching frequency, and D = duty cycle. Therefore, for a given f_{SW} and D, R_{in} scales linearly with L. For large values of R_{in}, a larger L is necessary. However, this is not desirable since the losses due to the inductor ESR increase significantly as its value increases. Condition for DCM operation is given by

$$V_{rect} < \frac{1-D}{D} V_{bat}$$

Note that if this condition is not adhered to, the converterenters continuous conduction mode (CCM) with

$$R_{in} = \left(\frac{1-D}{D}\right)^2 \frac{V_{bat}}{I_{bat}}$$

Here, Rin is no longer constant, and the converter will require feedback for adjusting D to obtain constant Rin. This is a serious overhead resulting in lower efficiency, and therefore, must be avoided.

VI. CONCLUSIONS

The paper presented a review of the three basic types of vibrational micro-generators and their respective power processing circuits. The micro-generators that form the basis of the low voltage energy harvesting technique are explained, the broad classification of the microgeneration has been considered with citations from the literary papers. The power converter topologies for the three basic kinds of micro-generators and the previous work done on their respective converter circuits has been discussed. The MEMS technology has been described briefly and the vibrational energy harvesting micro-generators have been discussed and analyzed in detail. Thereafter the power processing circuits for the electromagnetic, electrostatic and piezoelectric micro-generator have been studied.

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