Energy Harvesting of Synchronized Switch Harvesting On Inductor

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***Abstract*—Energy harvesting is the scavenging of energy from different energy sources. Vibration energy that is not used in our daily life can be utilized by extracting and conditioning it to a usable form by using piezoelectric material (PZT) is discussed in this paper. Piezoelectric Energy Harvester (PEH) will convert the vibration energy in to electrical energy. Different circuits are used as an interface to condition the PZT output. Full bridge energy harvester (FBEH) and Voltage doubler energy Harvester (VDEH) simulations are conducted and results confirms that the VDEH provides double the output voltage compared to FBEH. New energy harvesting scheme is also developed as the energy from PZT is not going completely to the output during each half cycle. At a small interval the output current is zero while the input voltage have to build to a voltage level make to the diodes of rectifier circuit to conduct. Hence a switched inductor is introduced at regular interval at each half cycle of voltage to flip that voltage in short period of time to reduce the power losses occurring in VDEH and FBEH. Synchronized Switched Harvesting on Inductor (SSHI) improve the output of PEH with the LC circuit developed during the circuit operation. MATLAB and MULTISIM simulations are done for all the circuits and the results are analyzed. The power loss is reduced with the SSHI scheme when compared to FBEH and VDEH. SSHI technique can be treated as a technique for extracting maximum power from PEH.**

***Index Terms*— Piezoelectric Energy Harvester (PEH), Full bridge energy harvester (FBEH), Voltage doubler energy harvester (VDEH), Synchronized switch harvesting on inductor (SSHI), Maximum power point tracking (MPPT), Lead zirconate titanate (PZT).**

I. Introduction

Besides the conventional and non-conventional methods of generating power, researchers are finding other ways to utilize the energy available in the environment in the form of vibrations, pressure, heat, sound, etc. Thus energy harvested from these sources comes out as a clean and sustainable energy. The ambient mechanical vibrations can be exploited to generate an appreciable amount of useful power with the help of piezoelectric transducers [1]. Energy Harvesting is the process that captures small amounts of energy that would otherwise lost as heat, light, sound, vibration or movement – accumulating, storing and conditioning it in to a form as per the requirement of the load. Different types of energy harvesting materials are 1) Piezoelectric material – Translates mechanical energy applied to electrical energy. 2) Thermoelectric materials- Temperature difference causes voltage (one side is warmer/cooler than other). 3) Pyro electric materials - Change in temperature generates an electric charge Vibration to Electricity Conversion are mainly: 1) Electromagnetic 2) Electrostatic 3) Piezoelectric. Table I compares the power density achieved by piezoelectric and its other peer technologies and it is clear that among three mechanisms piezoelectric generation has got maximum attention because piezoelectric materials have larger power densities and higher feasibility for practical application than other two mechanisms. [2].

TABLE I
COMPARISON OF POWER DENSITIES OF VARIOUS TECHNOLOGIES

Technology	Power Density ($\mu W/cm^2$)
vibration - electromagnetic	4
vibration - piezoelectric	500
vibration - electrostatic	3.8

Poling treatment is required to activate the piezoelectric properties. In that treatment the piezoelectric material is heated above the Curie point, the crystal structure becomes centro-symmetric, and all electric dipoles vanish and then the material is cooled below the Curie point. In the presence of intense electric field, the dipoles tend to align with the applied field, all together giving rise to a nonzero net polarization forcing the ions to realign along the "poling axis". When the field is removed, the ions remember this poling and the material now has a remnant polarization [2]. Piezoelectricity is the ability of certain materials to convert energy produced from vibrations over the piezoelectric material into electrical energy and also the reverse process can be done. Direct piezoelectric effect is that these materials when subjected to mechanical stress generate an electric charge proportional to the stress applied. Inverse piezoelectric effect is that these materials become strained when an electric field is applied. Piezoelectric materials can be divided as following: Crystal (Quartz, Lithium tantalite ($LiTaO_3$) Tourmaline, Rochelle salt), Ceramics (PZT – Pb $(Ti,Zr)O_3$),Polymers (Poly vinylidenediflouride (PVDF)), Piezo film (ZnO).

There is a necessity to develop efficient energy harvesting methods using power electronics circuits to harvest maximum energy. There are different studies undergoing with various methods – Full bridge rectifier, Voltage doubler, Synchronized Switched harvesting (Parallel SSH & Series SSH), Double Synchronized Switched Harvesting (DSSH) [3] [4]. As the output power from the piezoelectric material is very small, hence need most efficient harvesting technique to extract maximum output. Power electronics circuits have to be implemented to convert the maximum charges developed in the piezoelectric material to the load side. Complete power electronics interface of the piezoelectric energy harvester is shown in figure 1.

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II. POWER ELECTRONICS INTERFACE TO PIEZOELECTRIC ENERGY HARVESTING

Power electronics plays a vital role in the energy harvesting process. Conditioning the power extracted from piezoelectric can be done with different circuits. (a) Full bridge rectifier (b) Voltage doubler (c) Voltage doubler-Synchronized switch harvesting on Inductor (VD-SSHI) and (d) Double Synchronized switch harvesting. A piezoelectric energy harvester can be represented by voltage source with series capacitor and resistor or current source with parallel capacitor and resistor as shown in

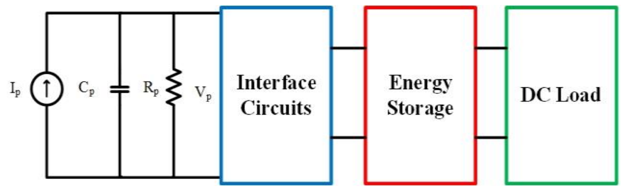


Fig. 1. Piezoelectric Energy Harvester with Power Electronics Interface

figure 2 [5]. The output from harvester cannot be directly used by the loads, hence they should be conditioned by using power electronics circuits. Those circuits should also extract maximum power output from the harvester. Since the piezoelectric harvester outputs a sinusoidal voltage rectifier circuits should be used. Table II shows the values of parameters considered for the simulation.

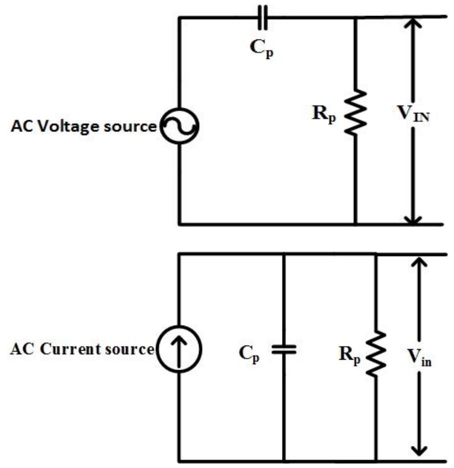


Fig. 2. Equivalent model of piezoelectric material

TABLE II
PARAMETERS CONSIDERED FOR MATLAB SIMULATION OF FBEH AND VDEH

Symbol	Quantity	Values
F	frequency of operation	60 Hz
V_P	piezoelectric voltage	100 V AC
C_P	Internal piezoelectric capacitance	10 nF
R_P	internal piezoelectric resistance	1 MΩ
C_O	output capacitance	10 µF
V_D	diode drop	0.60 V

A. Full Bridge Energy Harvesting Circuit (FBEH)

Full bridge rectifier is used convert an AC voltage from piezoelectric harvester to DC voltage. Circuit diagram of FBEH in figure 3. V_P is the piezoelectric voltage, V_{IN}, is the input voltage to rectifier, V_D is the diode voltage drop and V_O is the output DC voltage across load. The results of FBEH is clearly mentioned in figure 4, input voltage to the rectifier bridge (a) the output current (b). In the first interval in both (a) and (b) current and voltage is developed but after the positive half cycle V_P, which the input piezoelectric voltage is changed to negative half cycle hence the in order to conduct the diode bridge V_{inIN} should reach a voltage equal to $-(V_O + 2V_D)$, for the reversal of voltage from $+(V_O + 2V_D)$ to negative value of the same voltage it takes a time delay. During this interval the output current is zero (b), since piezoelectric energy is not reaching the load. During

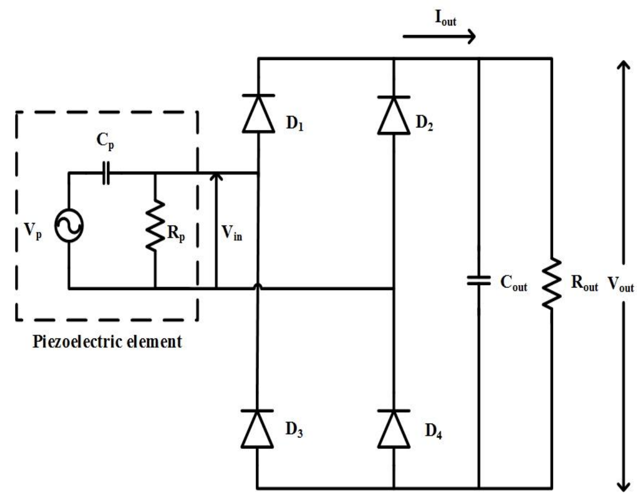


Fig. 3. Circuit diagram of FBEH

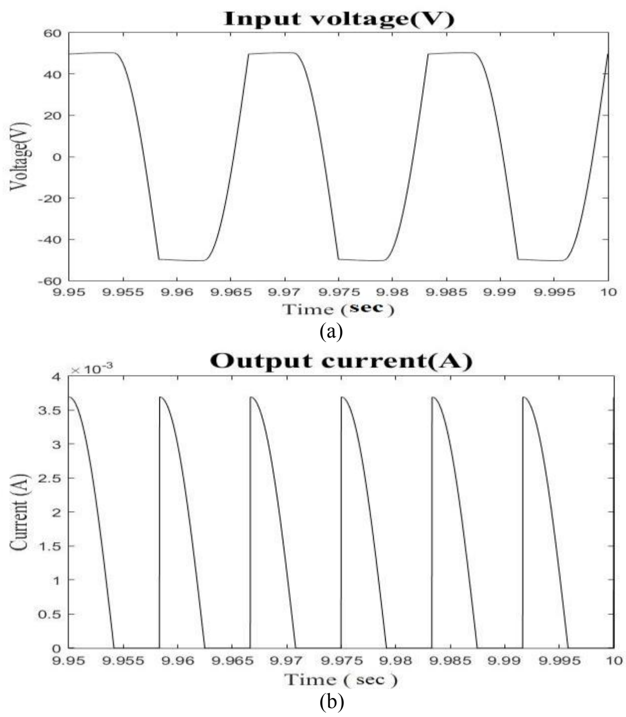


Fig. 4. Input AC voltage to the FBEH (a), Output current (b)

the transition of AC input voltage from positive to negative peak and reverse the output current is zero. This building of voltage is done by the internal piezoelectric capacitor, so it is clear that for a particular time delay piezoelectric energy is lost. As the piezoelectric energy harvesting is considered as micro energy harvesting these losses should be eliminated. For a voltage doubler circuit the operation is same only. Thus the power loss occurring during this period have to be reduced to harvest more power from the harvester. Here comes the major role of power electronics circuits. This interval in have to be reduced by introducing various circuits. Hence the voltage will reach the value to conduct the rectifier instantly so that maximum power flow from harvester to load side will occur. This will improve the energy harvesting. Sudden flipping of voltage can make a major effect in the energy harvesting.

B. Voltage doubler Energy Harvesting Circuit (VDEH)

Voltage doubler circuit is considered as a better option compared to FBEH mainly due to the less number of diode which is shown in figure 5. The main advantage of VDEH compared to FBEH are the power loss from the voltage drop of diode less and the output voltage produced for same condition is double which is shown in figure 6. FBEH is providing 48.8 V as it is the output voltage at maximum power for a full bridge rectifier which is in equation (1) while for VDEH it is 98.9 V as per the output voltage in equation (2) at maximum power for a voltage doubler circuit [6]. This advantage makes VDEH to be used for further works. CMOS diodes can improve the outputs further.

For FBEH topology,

$$V_O = \left(\left(\frac{V_P}{2}\right) - V_D\right) \quad (1)$$

$V_P = 100$ V
$V_D = 0.6$V
Hence Output Voltage, $V_O = 49.4$ V

For VDEH topology,

$$V_O = (V_P - V_D) \quad (2)$$

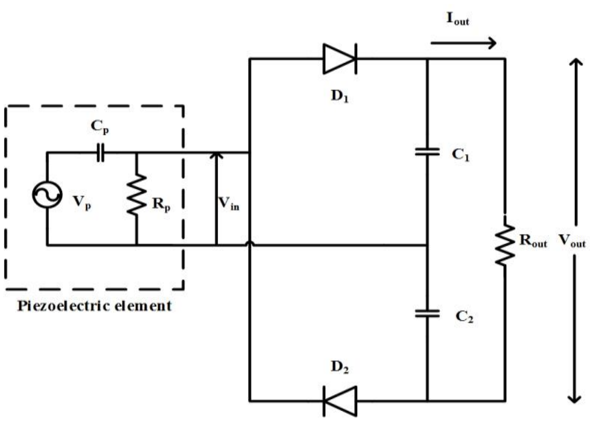
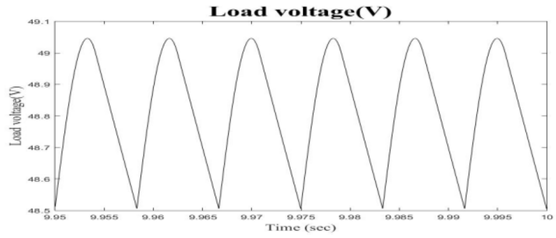
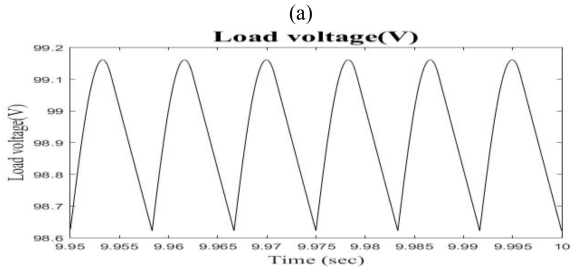


Fig. 5. Circuit diagram of VDEH



(a)



(b)

Fig. 6. Output DC voltage of FBEH (a), Output DC voltage of VDEH (b)

$V_P = 100$ V
$V_D = 0.6$V
Hence Output Voltage, $V_O = 99.4$ V

Here, with the mathematical calculations it is well explained that the output voltage is doubled for the VBEH compared to FBEH. The simulation waveform and equation results are almost matching.

C. Synchronized Switch Harvesting on Inductor (SSHI)

This method have the ability to improve the harvested energy as it reduces the losses developed during the previous circuits. Inductor is introduced in the circuit at regular interval in to the harvesting circuit and it take the circuit at each zero crossing of the piezoelectric current. The input voltage across the rectifier is flipped at short duration of time so that the power is transferred from source to load side for more interval of time. Hence the power loss during the power flow can be reduced by the switching of inductor and there by forming a LC tanked circuit within the harvester and piezoelectric material [7] [8]. In the circuit C_1 and C_2 are negative and positive peak detectors. T_1, T_4 are PNP

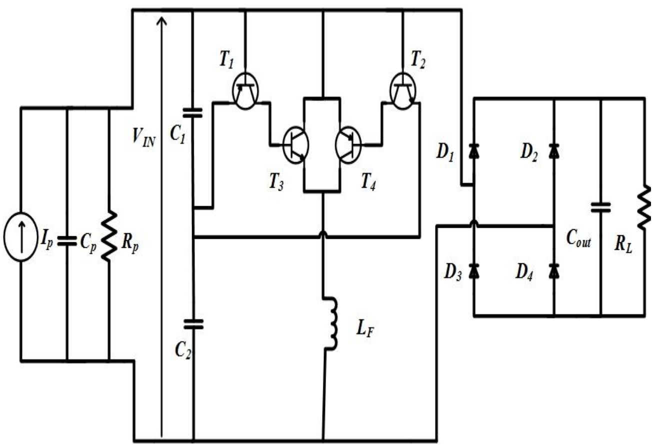


Fig. 7. Circuit diagram of SSHI

transistors and T_2, T_3 are NPN transistors. The SSHI circuit is shown in figure 7. Different modes are introduces to explain the operation of the circuit. In each modes different circuits are operating which is self-controlled with the help of transistors that are working in different patterns. Parameters used for simulations are explained in table III.

TABLE III
PARAMETERS CONSIDERED FOR SIMULATION OF SSHI AND FBEH IN MATLAB AND MULTISIM

Symbol	Quantity	Values
F	frequency of operation	60 Hz
I_P	piezoelectric current	0.2 mA AC
C_P	Internal piezoelectric capacitance	10 nF
R_P	internal piezoelectric resistance	1 MΩ
C_O	output capacitance	10 µF
C_1	input capacitance	10 pF
C_2	input capacitance	1 nF
V_D	diode drop	0.60 V
L_F	inductor value	50 mH

Mode I

When $V_{IN} = V_O + 2V_D$

V_{C1} is +ve then T1 (PNP) and T3 (NPN) are off as T1 requires $-V_{BE}$ to make it on as it is PNP. T3 also will be off since T1 is off. T2 (NPN) is forward biased but not able to on

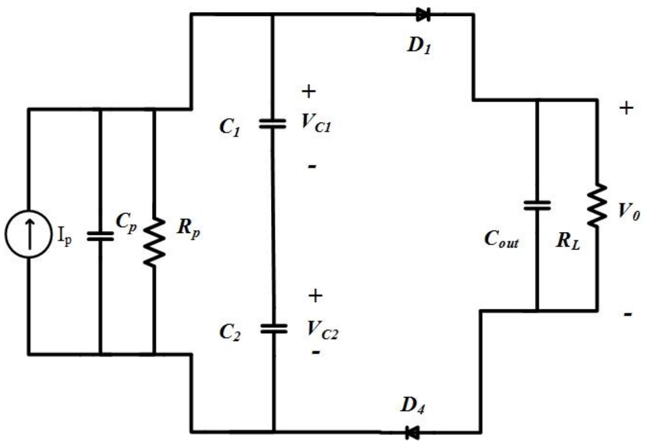


Fig. 8. Circuit diagram of SSHI when $V_{IN} = V_O + 2V_D$ (Energy Harvesting period)

T4 (PNP) as V_{CE} of T4 is positive. Thus all the 4 transistors are off and Diode Bridge is conducting, hence the circuit will act as in figure 8, output current is delivered to load from PEH.

Mode II

When $V_{IN} < V_O + 2V_D$

Diode Bridge will not conduct during this period as the voltage is less, slowly V_{C1} will change from +ve to –ve during this interval (all transistors are off), energy is wasted as no current is reaching the output during these period. I_P is feeding to C_p, C_1 and C_2. The circuit operation during this

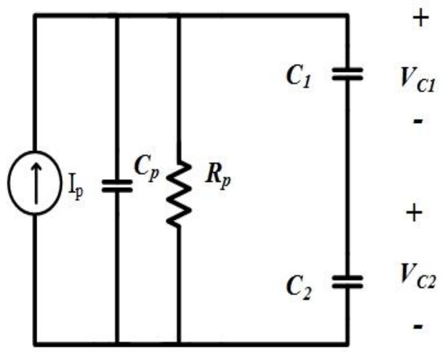


Fig. 9. Circuit diagram of SSHI when $V_{IN} < V_O + 2V_D$ (All transistors and switches are not conducting)

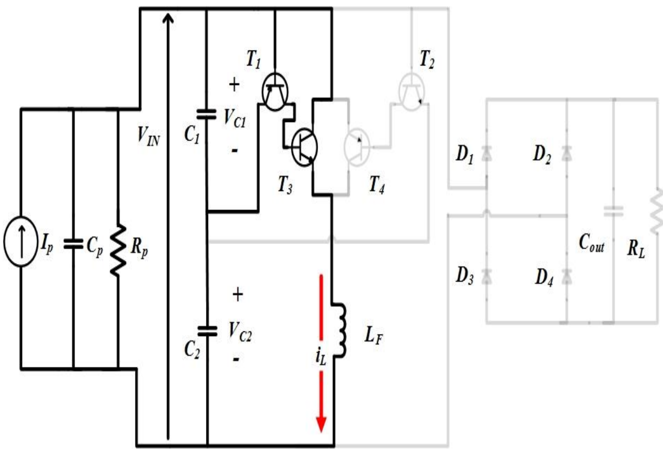


Fig. 10. Circuit of SSHI when $V_{IN} < V_O + 2V_D$ (Flipping of voltage from +ve to -ve)

period is clearly explained in figure 9. When V_{C1} reaches a negative value which is equal to $-V_{BE}$, T2 will get turned on and thus makes T3 on and I_P will freewheel through L-C circuit formed and flipping of voltage takes place suddenly to make the voltage to build to a value near to $-(V_O + 2V_D)$ from $(V_O + 2V_D)$ since the current is now in negative half cycle. The circuit operation is as shown in figure 10. This period continues till I_L reaches zero or V_{IN} reaches to $-V_F$ (V_F is the flipped voltage) then T3 gets turned off as current through collector is turned to zero. After this since all switches and transistors are off thus inductor is not in the circuit and I_P alone charges the C_P, C_1 and C_2 until V_{IN} builds from $-V_F$ to $-(V_O + 2V_D)$. During this period output power is not extracted from PEH and the circuit is as shown figure 9. Mode III and Mode IV is similar to previous modes of operation, the direction of inductor current will change from positive to negative as the input voltage to rectifier is to be flipped from $-(V_O + 2V_D)$ to $(V_O + 2V_D)$ to make the complete cycle.

III. MATLAB SIMULINK SIMULATION OF SSHI

In MATLAB the piezoelectric energy harvester is simulated with synchronized switch harvesting on inductor and is shown in figure 11. The inductor circuit operates at small intervals in each half cycle. During this time interval where inductor current is flowing in the circuit, the input voltage to the rectifier is flipped suddenly in opposite direction till the inductor current reach zero, change in the slope of flipping is clearly identified in the result as shown in figure 12. The inductor is making the power loss reduced by reducing the time period in which the output current is

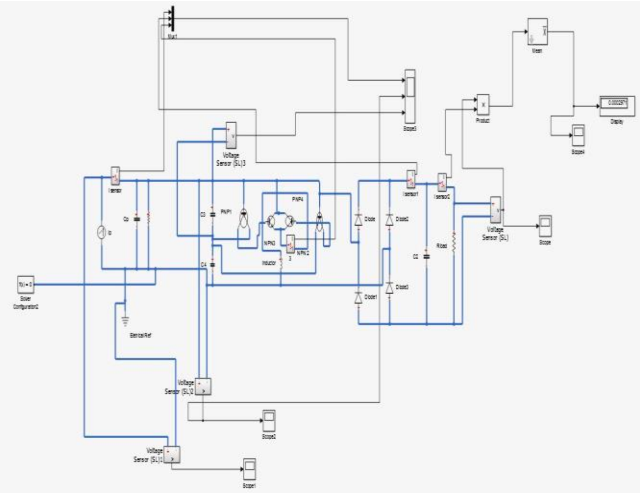


Fig. 11. MATLAB diagram of SSHI

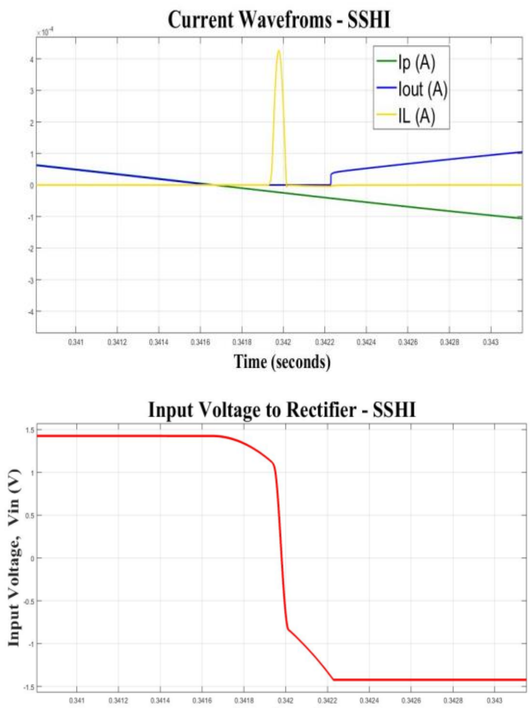


Fig. 12. MATLAB results of SSHI

not developed and is compared with FBEH, comparison of results in MATLAB for FBEH and SSHI is mentioned in Table IV. In figure 12 blue colour waveform represents the output current (I_o) and yellow colour waveform is the inductor current (I_L) and green colour waveform is the input current (I_P). The variation of each waveforms are according to modes of operation which is described in previous section. It is clear that at the moment when the inductor current waveform starts building, the voltage V_{IN} (red colour) is flipping with a sudden slope and it reaches a value till the inductor current is flowing in the circuit. Then the shape of the slope is varied and it is taking more time to build the voltage needed to conduct the rectifier circuit. Hence the power losses can be reduced in this interval in an efficient manner. In table IV comparison of FBEH and SSHI is explained clearly. Output power has a variation while considering both the circuits. The time delay at which power loss is occurring is having a considerable reduction which reduces the power loss. The L-C circuit is helping the whole system to improve the efficiency. The results are compared with the FBEH results and analysis is done with the power, time delay taken for similar conditions. It is clearly seen that SSHI is improving the outputs. Table IV gives the analysis of results in both the cases.

TABLE IV
COMPARISON OF RESULTS FROM MATLAB SIMULATION

Parameters	FBEH	SSHI
Output Power	2.6 µW	3.2 µW
Time delay	1 msec	0.6 msec

IV. MULTISIM SIMULATION OF SSHI AND COMPARISON WITH FBEH

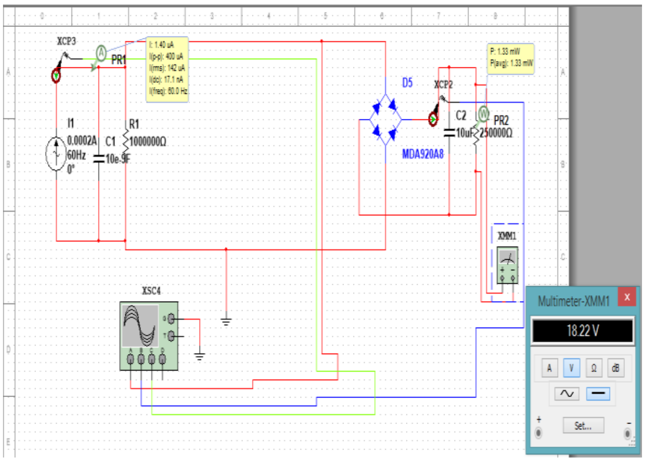


Fig. 13. Circuit diagram of FBEH in MULTISIM

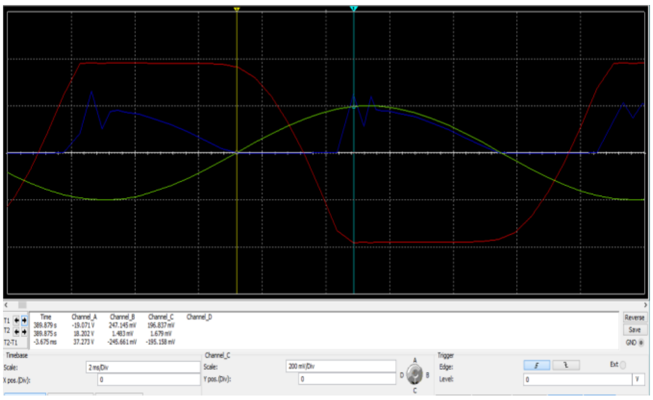


Fig. 14. Results of FBEH in MULTISIM

Further efficient analysis same circuits are simulated in MULTISIM software and the comparison study is done. Output power, voltage are improved and the time delay taken for the input voltage (V_{IN}) to the rectifier to build from (V_O +

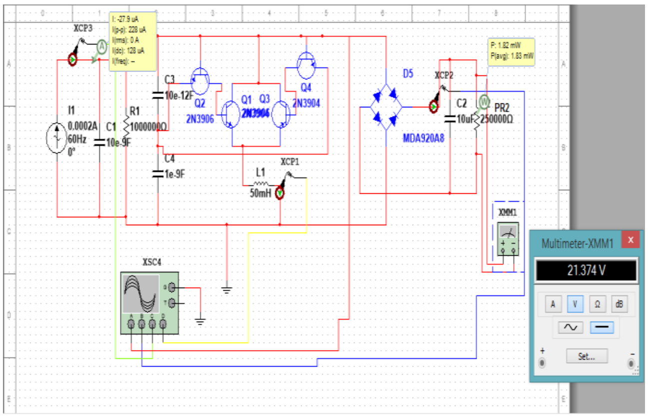


Fig. 15. Circuit diagram of SSHI in MULTISIM

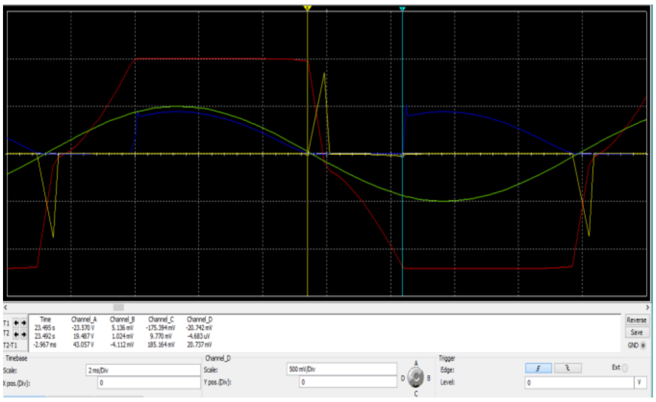


Fig. 16. Results of SSHI in MULTISIM

$2V_D$) to - ($V_O + 2V_D$) is reduced when both FBEH and SSHI circuits are compared. Thus proposed circuit gives efficient piezoelectric energy harvesting. The simulation circuit in MULTISIM for FBEH and SSHI are shown in figure 13 and figure 15 respectively. In figure 14 and figure 16 results obtained in the simulations are shown for both FBEH and SSHI respectively. The improvement in reducing the power loss is clearly explained with SSHI results. The V_{IN} (red waveform) is dropping as the (I_P, green waveform) input current waveform and is shifted to negative half cycle. I_O (blue waveform) is the output current and is not developed from PEH during the time interval where building of V_{IN} takes place. At that moment as per the modes described in previous sections the inductor current (I_L-yellow waveform) is developed in the circuit and the V_{IN} is varied with a sudden flip during this period till the I_L reached to zero. After this point V_{IN} reaches to a value which is equal to – ($V_O + 2V_D$) with the charging of capacitors C_P, C_1, C_2 by the PEH. During this interval the more power loss is occurred. But SSHI reduces the loss occurred to a great extent. The comparison study of the outputs are done and is shown in table V.

TABLE V
COMPARISON OF RESULTS FROM MULTISIM SIMULATION

Parameters	FBEH	SSHI
Output Power	1.33 mW	1.83 mW
Time delay	3.67 msec	2.96 msec

V. Conclusion

In this paper different energy harvesting topologies of piezoelectric energy harvesting are discussed. The energy harvesting techniques with full bridge, voltage doubler is proposed by simulation and the output results are analyzed. The maximum power with double voltage is obtained with VDEH compared to FBEH. Also the necessity of reducing the power loss during the interval while the input voltage is flipped is explained clearly with the simulations. The circuits are implemented in MATLAB and MULTISIM simulations, the results are verified and the power losses are reduced by using SSHI when compared to FBEH. Flipper circuit or SSHI with MPPT techniques can improve the efficiency as operating points will be always maximum. Stacking of piezoelectric elements in series and parallel arrangement can extract more amount of power. As a future work implementation of the overall scheme can improve the power in the efficient way and piezoelectric energy harvester can lead major role in the future energy resources.

Acknowledgment

This work is sponsored and supported by Research Centre Imarat (RCI), DRDO, Hyderabad sanctioned under project bearing reference no: RCI/DCMM/LPD/CARS-389 dated 17.01.2017.

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