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Design and Analysis of Piezoelectric Energy Harvesting Circuit for Rechargeable Ultra-Low Weight Lithium-Ion Batteries.

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Abstract

Energy harvesting is expected to be used as a source of energy for tiny low power sensor nodes. Since the amount of harvested energy is unstable, an energy storage device is used with an energy harvesting system. With advancement in rechargeable batteries, ultra-low weight rechargeable lithium-ion batteries are used as energy storage devices with low power wireless sensor nodes at remote places. These ultra-low weight energy storage devices are expected to be charged efficiently with maximum harvested power. The mismatching of the electrical impedance between input (i.e. Piezoelectric Transducer (PZT)) and output (i.e. Load) gives inefficient power transfer. The piezoelectric energy harvesting circuit described in this paper focuses on the design and analysis of op-amp based inductor circuit for matching the impedance by presenting a conjugate impedance match to the Piezoelectric harvester. The values of inductor obtained for optimal power transfer from PZT to storage device tend to be prohibitively large. This becomes an inhibiting factor for Integrated Circuit(IC) realization of the interface circuits. The proposed work implements the required value of inductor using op-amp circuit to match the complex conjugate part of the impedance thereby making it cost effective and suitable for IC realization. Finally, comparison between pure resistive match and complex conjugate match is presented along with results.

Keywords: IOT, PEH, piezoelectric transducer (PZT), Rechargeable Ultra-Low weight lithium-ion batteries

1. Introduction

Application of Low power Sensor Nodes in wireless sensor network (WSNs) and Internet of Things (IoT) is continuously increasing day-by-day. These sensors nodes are useful in many applications to gather various types of real time information like health services, environmental parameter monitoring and surveillance, military application for target tracking etc. Although with the advancement in technology, these low power sensors nodes are very reliable and promising, but still there are some issues to be resolved in order to make these technologies ubiquitous and convenient. One of the major issues in deploying these sensor nodes in remote application is power source [1-4].

Ultra-low weight tiny rechargeable batteries are used as power source, but it requires the periodic charging. Energy source can be obtained from surrounding environment such as solar power, wind, vibration, etc., by using the transducer technology of energy transformation and Energy Harvesting [5-9]. Energy harvesting is expected to be used as a source of energy for these tiny low power sensor nodes. However the harvested power is unstable. Hence in order to ensure that the sensor nodes work efficiently, these sensor nodes in the majority of applications are powered by tiny rechargeable batteries or equipped with an energy storage system. These energy storage systems are powered by an energy harvester of different nature, such as solar, thermal, piezo, RF [10], etc. The energy harvesting interface circuits play a vital role in such scenario. In majority of wireless sensor nodes the piezoelectric transducers are used.

Piezoelectric transducer works on principal of converting the vibrations in to electrical energy. Piezoelectric method of energy harvesting at small scale is of great ease and uses low frequency vibration to generate energy while providing a high power density.

Since rechargeable batteries usually require a DC power supply, a power harvesting and conditioning circuitry is necessary to rectify the AC power to stable DC power. New ultra-low power circuit techniques are constantly being investigated to improve the energy efficiency of electronic circuits in Portable electronics. New power conversion circuits that are interfaced to a piezoelectric micro-power generator which produces electrical energy from ambient vibrations need to be investigated. The circuits which are interfaced to non-conventional energy source generator (Piezoelectric Transducer) and provide conditioned current and voltages to the load are the key elements for study; they should operate with highest possible efficiency, to ensure maximum power transfer to the energy storage devices.

Power conditioning circuit is sensitive to the efficiency of power extraction. Ottman Et al. in [12], propose an adaptive solution using the DC-DC converter to achieve automated power optimization. A step down converter in DCM mode is analyzed along with an optimal duty cycle where the power flow from piezoelectric is maximum. An expression for the optimal duty cycle for a step-down converter in DCM is developed to maximize the power harvested from piezoelectric transducer. Lefeuvre Et al. in [13] proposed a power optimization in piezoelectric energy harvester using

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sensor-less buck-boost converter running in discontinuous conduction mode (DCM).The sensor-less buck-boost converter track the optimal working points of the generator for optimum power.

Huang Et al. in [14] proposed theoretical Analysis on DC-DC Converter for Impedance Matching of Rectifying Circuit for both CCM and DCM mode. The paper concluded that the input resistance of buck-boost converter in DCM is independent of input voltage and load resistance.

The resistive impedance matching circuit for Piezoelectric Energy Harvesting is proposed by Kong Et al. in [15]. The maximum amount of power is extracted from a piezoelectric energy harvester by matching the resistive source impedance of the circuit by adaptively adjusting the duty cycle of DC-DC buck-boost converter. An equivalent electrical circuit representation derived from a distributed-parameter piezoelectric energy harvester model is adapted to enable the impedance matching.

Several other literature [16, 17], suggests the conditioning circuits to harvest and transfer the optimum power from piezoelectric transducer. The circuits incorporated inductors, capacitors, synchronized switch harvesting, and convertors to shape the delivered voltage.

A pulsed-resonant power converter using few micro-Henry inductor at low switching frequency is proposed by Xu Et al. in [18] to reduce the switching losses. The complete design is fabricated in CMOS chip with externally connected inductor.

A PEH circuit using a full-wave Voltage Doubler rectifier and a switched-inductor circuit is proposed by Kushino Et al. in [19]. The proposed circuit includes a switched inductor to improve energy efficiency. They have shown that the voltage doublers rectifier is more suitable for the piezoelectric energy harvesting than the full bridge rectifier when the output voltage is high.The maximum output power of the proposed circuit is larger than that of the energy harvesting circuit using a voltage doubler rectifier.

A bias-flip rectifier circuit is discussed and implemented by Ramadass Et al. in [20], which can improve the power extraction capability from piezoelectric harvesters over conventional full-bridge rectifiers and voltage doublers by greater than 4X.

Kawai Et al. in [21] implemented MPPT control by connecting a step-down chopper circuit in the latter part of VDSSHI (Voltage Doubler Synchronized Switch Harvesting on Inductor) circuit. In this study, low-capacitance filter capacitors are used to reduce the time to reach the open circuit voltage of a SSHI (Synchronized switch harvesting on inductor) circuit. Thereby, the SSHI circuit is operated by the MPPT (Maximum Power Point Tracking) algorithm based on the open circuit voltage method. The circuit operation was confirmed by simulations and circuit experiments.

To the best of our knowledge, technique for presenting complex conjugate match to Piezoelectric Transducer is yet not published for harvesting circuits. This paper presents the design and experimental analysis of Piezo-electric energy harvesting interface circuit. The impedance matching is proposed using resistive and complex conjugate part of the source impedance to transfer the maximum power harvested from piezoelectric transducer to charge ultra-low weight lithium-ion batteries. The paper is organized as follows; section II presents equivalent circuit of piezoelectric transducer and its internal impedance. Section III presents Impedance Matching and Design of Buck-Boost convertor Design in DCM of the proposed circuit and section IV presents the conclusion.

2. Equivalent circuit of Piezoelectric Transducer:

A piezoelectric transducer can be modeled as electrical equivalent circuit having a sinusoidal current source (I) in parallel with a large value of resistance (RP) and internal electrode capacitance (CP) under self-resonant frequency range [18,19], as shown in Figure (1). A vibrating piezoelectric transducer normally generates an AC voltage, which in turn has to be converted into DC for battery charging. Furthermore, the magnitude of the voltage generated across the piezoelectric transducer is relatively high and is in the range of 10V-30V. Hence, a step-down DC-DC converter is needed to reduce the level of piezo voltage [22] as shown in figure (2).

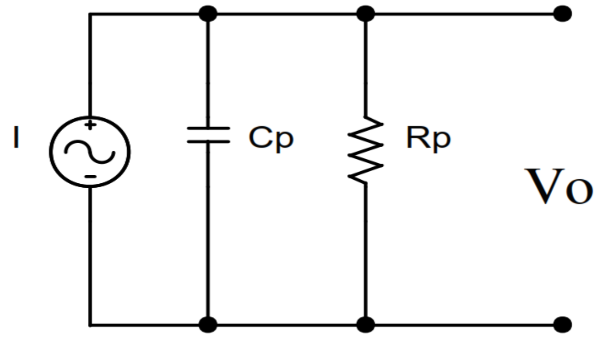

Fig. 1. Equivalent circuit model of piezoelectric transducer.

Figure (2) shows a block schematic of Piezoelectric Harvester to charge the rechargeable batteries.

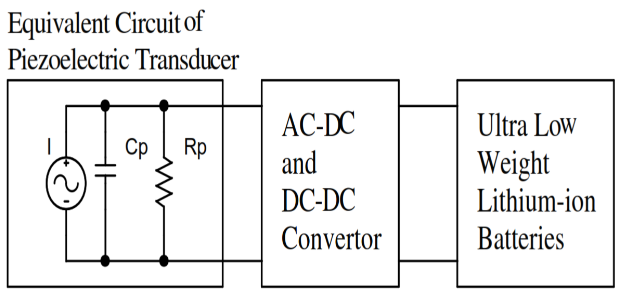

Fig. 2. Block implementation of Piezoelectric Harvester to charge ultra-low power lithium-ion batteries

2.1. Experimental values with commercially available piezoelectric transducer module (Q220-A4-203YB):

The commercially available piezoelectric module (Q220-A4-203YB) is tested for various excitation frequencies as shown in table (1). A Piezo element was mounted on a speaker diaphragm. Speaker was given excitation from PC running single tone frequency generator software (Audacity).

As shown in the figure (3), the maximum output voltage is generated at resonant frequency of 240Hz. For a commercial piezoelectric element, internal impedance of the device can be modeled as Cp=12nF and Rp=600kΩ.

When this device is excited at close to its resonance frequency of 240Hz, the conjugate impedance match to extract maximum power must have a resistance of 600kΩ and an inductance of 36.65H($L=1/(\omega_p^2 C_p)$). This result gives us a fair idea of design constrains as far as design of circuit inductor is concerned.

Table 1. Experiment with Piezoelectric transducer Q220-A4-203YB

Sr. No.	Excitation Frequency (Hz)	Output Voltage Peak to Peak (Volts)
1	30	6.7
2	50	4.8
3	70	6
4	100	12
5	120	10.4
6	150	9.2
7	180	10
8	200	12.2
9	220	18.8
10	240	22.6
11	260	14.6
12	280	9.2
13	300	6.4

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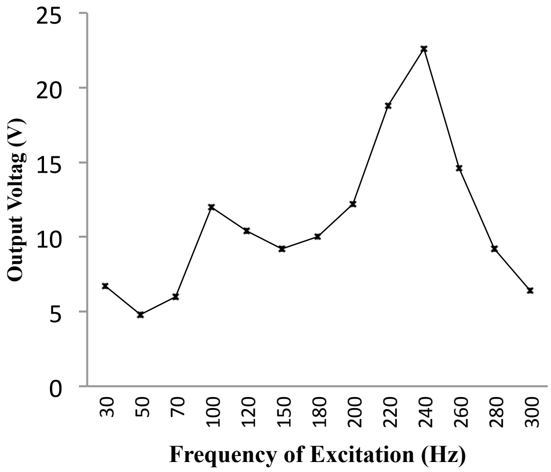

Fig. 3. Measured plot of output voltage at various excitation frequencies (Hz) for Q220-A4-203YB piezoelectric transducer.

3. Impedance Matching and Design of Buck-Boost convertor Design in DCM

Maximum power can be extracted from the piezoelectric harvester if the power conversion and load circuits present an impedance match to the harvester. The 'complete' match is done when the generator output impedance matches with the load impedance. It is well evident from section II, that in order to present a conjugate impedance match to the harvester, the size of inductor becomes prohibitively large, for obtaining maximum power transfer from the Piezoelectric Transducer. This prompts us to investigate innovative way to match the complex conjugate of source impedance with load to extract maximum power from the Piezoelectric Transducer.

3.1. Proposed Resistive Impedance Matching:

A DC-DC buck-boost converter is used in DCM to match the source resistive impedance, which is connected after the signal conditioning rectifier circuit as shown in figure (4).

A DC-DC converter is able to step-up or step-down the input voltage, so that it can be applied for a wide range of energy harvesters. Some traditional DC-DC converters can provide this, such as buck-boost, fly-back, and single-ended primary-inductor converter (SEPIC). Also importantly, these converters operating in DCM (Discontinuous Conduction Mode) mode behave as resistors (Erickson and Maksimovic, 2001) [22],[23]. A buck-boost converter requires a smaller number of components compared with fly-back and SEPIC converters and hence less complex [13] and hence is selected for the proposed design.

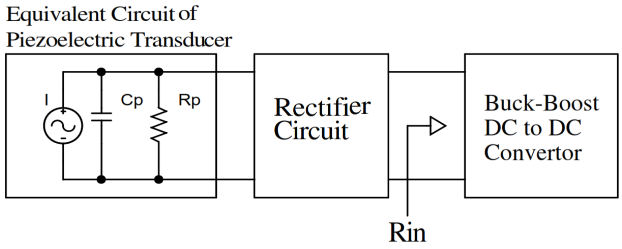

Fig. 4. Block Diagram of Resistive Impedance Matching Circuit for Piezoelectric Energy Harvesting

The R_{in} of the DC-DC buck boost converter in DCM is 2given by [14],[22]

$$R_{in} = \frac{2L\,F_{sw}}{D^2} \qquad (1)$$

The input resistance (R_{in}) of the DC-DC buck-boost convertor in DCM is independent of input voltage (V_{in}) and load resistance (R_L). The input resistance (R_{in}) in this case is only decided by the value of inductance (L), switching frequency (F_{sw}) and duty cycle (D). The duty cycle (D) and the frequency (F_{sw}) of the oscillator can be adjusted in a wide range to match the source impedance.

Figure (5) shows the average power versus load resistance obtained from the simulations of rectifier circuit with piezoelectric transducer. The Load of rectifier is swept and the power delivered to the load is measured. This forms the basis for the input impedance calculation of DC-DC converter. This simulation result gives the value of R_{in} for Buck-Boost converter. The objective here is to match the input impedance of DC-DC buck-boost converter to the impedance of Rectifier circuit as shown Figure (4).

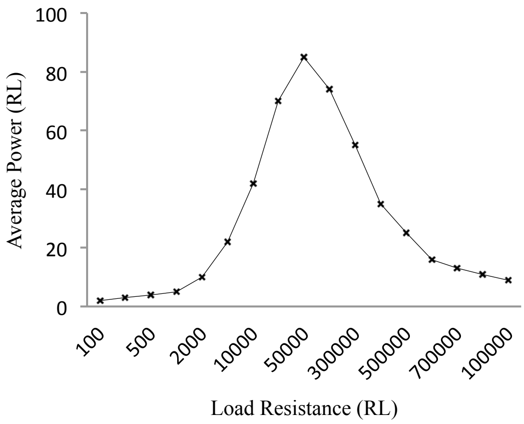

Fig. 5. Avg. Power Vs Load Resistance

3.2. Design and implementation of Buck-Boost convertor Design in DCM:

In the proposed work for resistive impedance matching, the DC-DC converter is designed for the following specification of the Ultra low weight lithium ion battery Model: GEB201212C.

Table 1. Ultra low weight lithium ion battery Model: GEB201212C

Parameter	Specifications	Remark
Nominal Capacity	10 mAh	$0.2C_5A$ discharge
Nominal Voltage	3.7V	Average Voltage at $0.2C_5A$ discharge
Charge Current	Standard : 0.2 C_5A ; Max : $1C_5A$	Working temperature : 0~45°C
Charge cut-off Voltage	4.20±0.05V	
Discharge Current	Continuously: 10 C_5A; Max : $15C_5A$	Working temperature : 0~60°C
Discharge cut-off Voltage	2.75V	
Cell Voltage	3.8~4.0V	When leave factory
Impedance	≤ 650mΩ	AC 1KHz after 50% charge

(Source: http://www.powerstream.com/ultra-light.htm)

As per table 1 and [23]**:**

I_{omax}= $1C_5A$ = 10mA (take 7 mA)
I_{omin}= $0.2C_5A$= 200uA
Vo= 3.7V
Vi= 2V to 20 V

The minimum, nominal, and maximum values of the dc voltage transfer function are calculated as follows:

$$M_{VDCmin} = \frac{V_0}{V_{Imax}} = \frac{3.7}{22} = 0.1682 \quad (2)$$

$$M_{VDCnom} = \frac{V_0}{V_{Inom}} = \frac{3.7}{20} = 0.185 \quad (3)$$

$$M_{VDCmax} = \frac{V_0}{V_{Imin}} = \frac{3.7}{6.4} = 0.5781 \quad (4)$$

Assuming the converter efficiency η = 85%. The minimum, nominal, and maximum values of the duty cycle are calculated as follows:

$$D_{min} = \frac{M_{VDCmin}}{(M_{VDCmin} + \eta)} = 0.1652 \quad (5)$$

$$D_{nom} = \frac{M_{VDCnom}}{(M_{VDCnom} + \eta)} = 0.1787 \quad (6)$$

$$D_{max} = \frac{M_{VDCmax}}{(M_{VDCmax} + \eta)} = 0.4048 \quad (7)$$

Taking the switching frequency fs = 10 kHz, the maximum inductance required for DCM operation is

$$L_{max} = \frac{R_{Lmin}(1 - D_{max})^2}{2f_s} \quad (8)$$

$$L_{max} = \frac{50K \times 0.3543}{20K} = 0.8857\ \mu H$$

Select L_{max} = 1μH, and C_{min} can be calculated as,

$$C_{min} = \frac{D_{max}}{f_s R_{Lmin}} \frac{V_0}{V_{Cpp}} = 149\text{ nf } (V_{cpp} = 20mV) \quad (9)$$

We have following design and output waveforms as shown in Figure (7) and Figure (8) respectively.

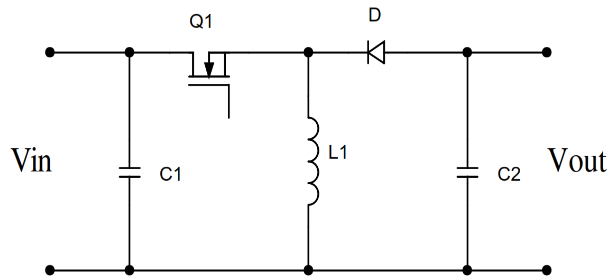

Fig. 7. Proposed Buck Boost Topology

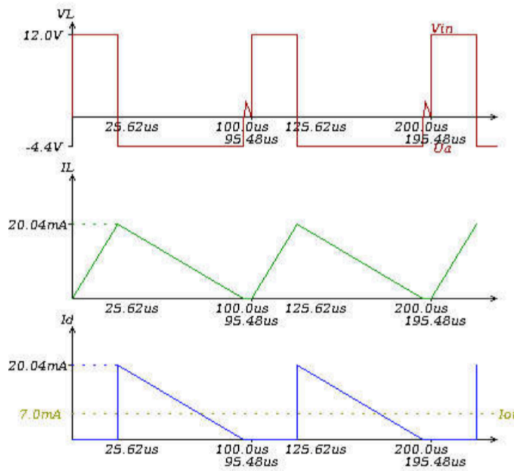

Fig. 8. Obtained Waveforms for Buck- Boost Converter.

3.3. Proposed design for Complex Conjugate Impedance Matching

In this proposed research work conjugate impedance matching is realized by op-amp based inductor design. As discussed in the section-II, the value of the inductor calculated as 39.60H which is very large and impractical to design. To overcome the problem of large value of inductor for conjugate impedance matching, an op-amp based GIC (Generalized Impedance Converter) circuit is used. The GIC invented by Antoniou. The work proposed here makes the use of inductor simulation using GIC as shown in figure (10).

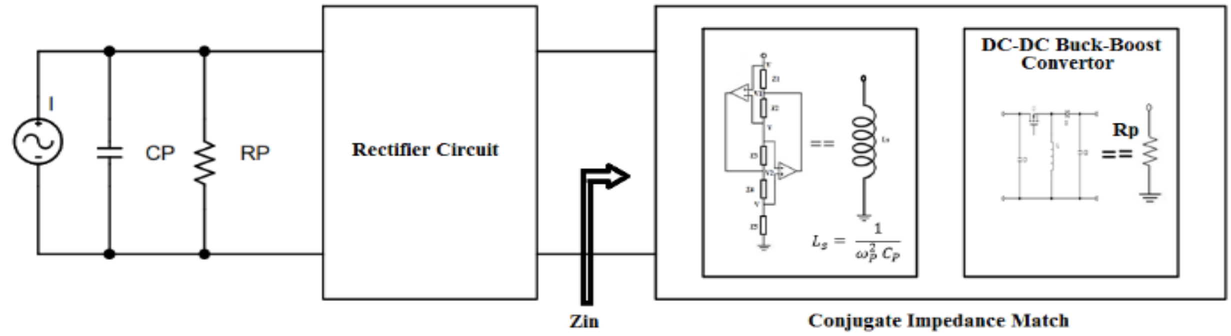

Fig. 9. Proposed Complex conjugate impedance matching.

The simulated inductor (LS) consists of the active component namely the operational amplifier and passive component like resistors and capacitors. The source conjugate impedance match is obtained by analyzing the circuit using the basic assumption of op-amp. The various assumptions made are:

- The op-amps are ideal.
- Virtual short circuit appears between the two terminals of op-amp so that the potential drop across terminals is zero.
- The current drawn by the two terminals of the op-amp is zero.

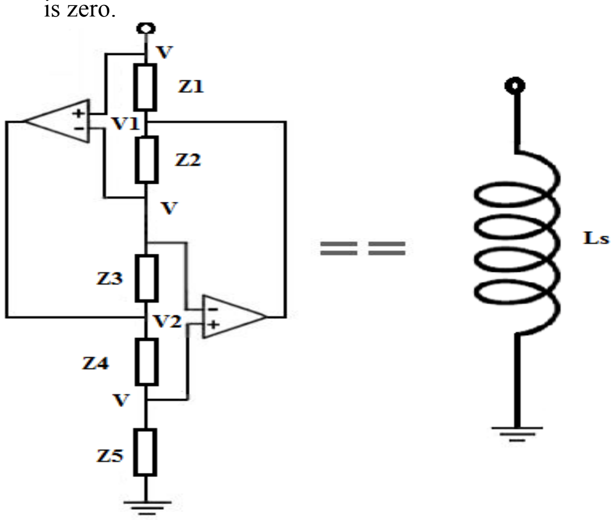

Fig. 10. Proposed op-amp based GIC (Generalized Impedance Converter).

The input impedance of the op-amp based inductor circuit shown in figure (10) is obtained by writing the nodal equations at the nodes V_1 and V_2 and current I is given by

$$I = \frac{V-V_1}{Z_1} \tag{10}$$

$$\frac{V_1-V}{Z_2} + \frac{V_2-V}{Z_3} = 0 \tag{11}$$

$$\frac{V_2-V}{Z_4} - \frac{0-V}{Z_5} = 0 \tag{12}$$

On solving these equation for input impedance with respect to ground gives

$$Z_{in} = \frac{Z_1Z_3Z_5}{Z_2Z_4} \tag{13}$$

and if $Z_1 = R_1$, $Z_2 = R_2$, $Z_3 = R_3$, $Z_4 = Xc_4$ and $Z_5 = R_5$ then the value of simulated inductor (Ls)

$$L_S = \frac{R_1R_3R_5C_4}{R_2} \tag{14}$$

and

$$Z_{in} = \frac{s\,R_1R_3R_5C_4}{R_2} \tag{15}$$

3.4. Design and implementation of op-amp based inductor for complex conjugate impedance matching:
Here in the proposed research work we need the inductor of value 39.60H, which can be selected by choosing the appropriate value of $R_1= R_2 = R_3 = 4.7K$ and $R_5 = 7.79K$ (Use 10K POT) and C= 1μF as shown in figure (11). The value of inductor can be calculated by using equation (14).

The circuit is tested for different value of inductor and RL =50K. Figure (12) shows the graph plotted between the various value of inductors and average power(of the load). The maximum power is extracted for the calculated value of inductor (36H) for complex conjugate impedance match.

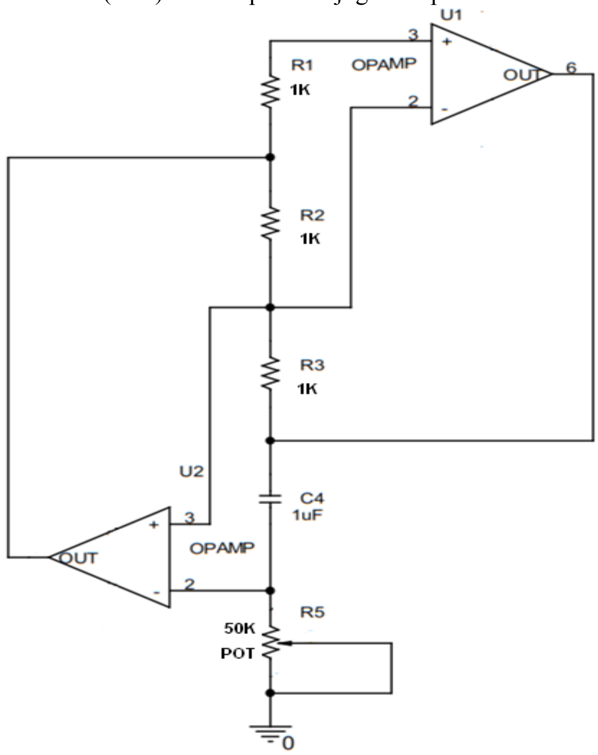

Fig. 11. Proposed Antoniou inductor simulation circuit for complex conjugate impedance matching.

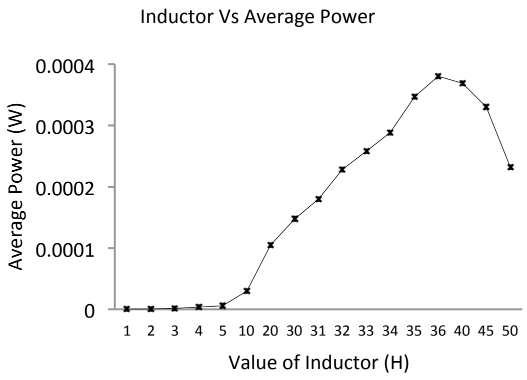

Fig.12. Graph plotted between Proposed Antoniou inductor simulation circuit for complex conjugate impedance matching and Average power.

4. Conclusions

This paper proposed an approach for impedance matching to maximize the power extraction to charge the ultra-low power lithium-ion battery. The equivalent discrete component piezoelectric transducer model is used to study the source impedance characteristics. We have taken up a circuit approach to arrive at the topology for power extraction improvements. For extracting maximum power through the piezoelectric transducer, a resistive impedance matching with R_{in} of DC-DC converter is proposed. The Simulation results show that the maximum energy could be extracted, when the mechanical vibration is around the resonance frequency of the piezoelectric transducer. We have also presented the design and simulation of Buck-Boost Converter in DCM mode to achieve the impedance matching.

Energy harvesting is a wide spectrum of enabling technologies. In order to miniature the circuits and for Integrated circuit (IC) realization, we still find that inductors pose a serious bottleneck. Inductor-less design hence need to be carefully investigated so as to bring the complete circuits under minimum silicon area in IC form. We have proposed design and implementation of op-amp based inductor for complex conjugate impedance matching. Figure (5) and Figure (12) show that the average power delivered to the load is substantially enhanced for complex conjugate matching (Approx. 4.4X increase). Simulations show promising results. Also different circuit topologies need to be investigated to claim maximum power (Charge) transfer from piezoelectric element to the battery.

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