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An Architecture of ULP Energy Harvesting Power Conditioning Circuit Using Piezoelectric Transducer for Wireless Sensor Network: A Review

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ABSTRACT

Energy harvesting system converts ambient energy (examples: vibration, light, temperature and wind, etc.) into useable electrical energy. This system can replace the function of battery for small Ultra-Low-Power (ULP) electronic devices. The slag of batteries is harmful to the environment as well as hazardous to human health. Recent research trends in energy harvesting systems are extracting maximum energy from wind energy using piezoelectric cantilever. This study presents the development of a Power Conditioning Circuit (PCC) for maximum harvested energy by using piezoelectric transducers. To achieve this, a self-PCC consisting of voltage doubler, charge pump, DC-DC converter and bypass path was designed. The output from the piezoelectric transducer is an AC voltage. To rectify the piezoelectric output, the voltage doubler was performed. Initially, the capacitor was charged via a bypass path. Once, the storage charge of the capacitor is sufficient to run the Microcontroller unit, this unit will stop the bypass path and on the active path. A low power Microcontroller was used for coding Maximum Power Point Tracking (MPPT) algorithm. The system modeling, design and analysis of the proposed PCC energy harvesting was simulated in active components using PSPICE software and later on the MPPT algorithm was coded in MATLAB. Then the PSPICE simulation and MPPT code was integrated for evaluating the system performance. Finally, a self-powered and fully autonomous energy harvesting power conditioning circuit layout was designed in 0.13 μm CMOS technology under Mentor Graphics. This PCC will ensure sufficient power to drive electronic devices such as Wireless Sensor Network (WSN), hearing aid, electronic watchand calculator, etc. This battery less ULP energy harvester capable to harvest maximum 24 mW power with an expected efficiency of 90% and output voltage of 3 V from low ambient sources of 500 mV at start up. Also, this ULP energy harvesting system reducing power consumption as compared to the conventional approaches.

Key words: Ultra-low-power, power conditioning circuit, energy harvesting, MPPT algorithm, WSN

INTRODUCTION

The energy from ambient sources are known as renewable energy. Collecting small amounts of energy, a long time to power up ubiquitous devices such as sensor measurements or wireless data transmissions etc., is the key of energy harvesting (Spies, 2011). As compared to the other ambient sources example, heat, light, RF, wind and vibration etc., vibration is relatively robust energy source as shown in Table 1. The piezoelectric transducer is used to charge a high efficiency storage device rather than provide power directly to the application circuit (Sarker *et al*., 2011a). Thus, in a general approach, energy harvesting system must have some kind of energy storage devices. This might be a capacitor or battery, depending on application, cost, environment, allowed leakage currents and space (Spies, 2011). Energy transducers do not provide an appropriate voltage level to power-up a ubiquitous device. As their output voltage depends on the design and the amount of available ambient energy such as thermal gradient, vibration amplitude and light intensity, etc. To use the full delivered energy by the transducer, an interface circuit (Tabesh and Frechette, 2010) is needed.

Interface circuits are required for supplying power to the load, because the output voltage and current from the energy harvester are not suitable to be supplied directly to the load. In the power processing stages, the interface circuit to extract as well as transfer maximum power to the load is required. The whole arrangement also provide a regulated output voltage at the load (Rao and Arnold, 2013). Generally, vibrational energy harvesting interface circuit consists of AC-DC converter and DC-DC converter as shown in Fig. 1. The output from the piezoelectric transducer is an AC voltage but ubiquitous loads always require a DC voltage for their operational. Therefore, a rectifier is used to convert AC to DC voltage. When the rectifier output voltage is not sufficient for load operation, a step-up DC-DC converter is inserted to boost-up the voltage. For most cases, the load requires a fixed DC voltage at various input voltage and load current, a control circuit is therefore designed to achieve output voltage regulation through a feedback loop (Rao and Arnold, 2011).

Table 1: Energy harvesting estimates (Sarker *et al*., 2011a)

Ambient energy and its source	Harvested power
Vibration	
Human	4 μW cm^{-2}
Industry	100 μW cm^{-2}
Temperature	
Human	25 μW cm^{-2}
Industry	1-10 mW cm^{-2}
RF	
GSM	0.1 μW cm^{-2}
WiFi	0.001 mW cm^{-2}
Light	
Indoor	10 μW cm^{-2}
Outdoor	10 mW cm^{-2}

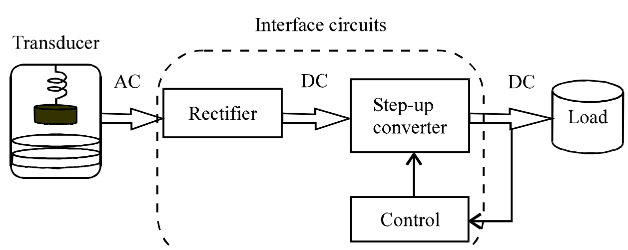

Fig. 1: A typical energy harvesting interface circuit (Rao and Arnold, 2011)

The load will receive maximum power only when it is matched with the source impedance. For that reason, the duty cycle of the DC-DC converter should be precisely matched with the transducer internal resistance. Generally, to achieve maximum power from the piezoelectric transducer the DC-DC converter duty cycle is controlled by using MPPT algorithm. The MPPT is useful especially for large power input source applications. The main challenge of using MPPT algorithm is efficiency degradation of the energy harvesting system due to additional functionality arrangement (Spies, 2011).

This study focus on designing a ULP autonomous power conditioning circuit, instead of using external power supply. To power up, portable and lightweight electronics ubiquitous devices, the battery-less piezoelectric energy harvester will be effective. The proposed energy harvester will capable of handling a wide range of input voltages with high efficiency.

The design of PCC for harvested maximal energy from piezoelectric transducers are two major technical challenges. Firstly, a piezoelectric transducer exhibits a large capacitance therefore, an implicit in approaches requires an impractical size inductor on the load (Kong *et al*., 2010). Secondly, with changing environmental condition the source impedance of the transducer will also change (Kong and Ha, 2012). To solve those problems, researchers are working in conjugate impedance matching techniques with nonlinear theory (Richard *et al*., 1999; Guyomar *et al*., 2005; Badel *et al*., 2006; Xu *et al*., 2007; Lallart and Guyomar, 2008; Liang and Liao, 2009) and resistive matching with controlled circuit (Kong and Ha, 2012; Ottman *et al*., 2007, 2003). Conjugate impedance technique is very effective only when the power is high and vibration frequency is a wider range than the resistive matching. In a resistive matching technique, the power consumption of the control circuit causes low efficiency. Another important requirement of an interfacing circuit for harvesting energy is the ability to self-start. An elementary solution is to include rechargeable battery (Tabesh and Frechette, 2010; Kong *et al*., 2010; Kwon and Rincon-Mora, 2010). Depending on the battery is putting an enormous burden for portable applications due to size, weight or life time constraints (Ramadass and Chandrakasan, 2010; Hehn *et al*., 2008). The output power of such devices is a usable form to operate ubiquitous devices on 10-100 μW (Chandrakasan *et al*., 2008) and output voltage can be high as 2 V (Roundy and Wright, 2004). In this study we have presented an autonomous PCC which is capable of adopting lower voltage and transfer maximum power at the load. To do this, the charge pump was used, DC-DC converter, bypass path and MPPT algorithm for adjusting the input impedance dynamically.

The objectives of the study are:

- To investigate Power Conditioning Circuit (PCC) of micro energy harvester devices, Ultra-Low-Power (ULP) circuit design techniques, piezoelectric based energy harvesterand its chip design and implementation etc., from literature survey
- To model, develop and design of the identified ULP based self-PCC of energy harvester using PSPICE simulator
- To implement, analysis and validate of the designed ULP based self-PCC energy harvester in 0.13 μm CMOS technology under Mentor Graphics

Piezoelectric material such as tourmaline, quartz, Rochelle saltand barium titanate has an ability to convert an ambient energy into electrical energy (Kim *et al*., 2011). Figure 2 shows a typical bimorph cantilever configuration where M is mass, S is strain, V is voltage and z is vertical

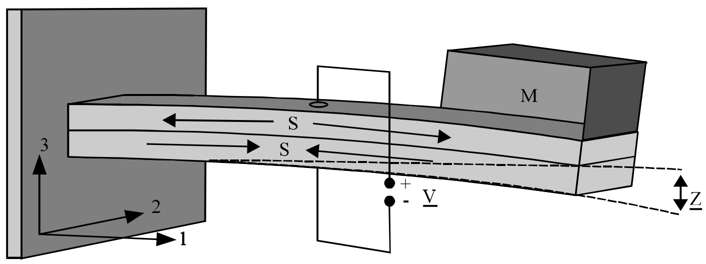

Fig. 2: A bimorph cantilever configuration

displacement. When the beam is bending due to the motion of the base, the piezoelectric layers will generate an AC output voltage under the assumption of the piezoelectric material were experiencing one dimensional stress (Kong *et al*., 2010).

Many years ago, the research on energy harvesting system is related to the development of an energy conversion transducer structure itself only for improving output power but generally the harvested output power cannot be directly powered to any applications (Hehn *et al*., 2012). Recently, vast amount of publications has regressed on the design of efficient interface circuit. Thus, the proposed work highlights on the design of an interface circuit for collecting power from piezoelectric cantilever for powering ubiquitous devices. In the last 10 years, researchers are grouped into two categories: First group of researchers designed an efficient AC-DC conversion technique, by reducing losses in the rectifiers and its control circuitry. To do this, many of researcher is working based on integrated Complementary Metal-Oxide Semiconductor (CMOS) design (Hehn *et al*., 2009). The important issue of the first group of researchers is impedance matching for any vibration based harvester, such as resistive, inductive, or capacitive. The second group of researchers focuses on extracting maximum power from piezoelectric cantilever. To do this, a few of researchers are working on MPPT algorithm and nonlinear power processing techniques. Due to the higher complexity as compared to the first group, some early publication introducing the basic principle implemented discretely and hence required an external power supply. But integration of the CMOS designs will allow self-powered, stand-alone operation (Marinkovic *et al*., 2009).

To transfer power as much as possible to the load, the main challenge is to design a ULP interface circuit. Based on the output voltage of the piezoelectric material the first challenge is making low forward voltage drop rectifier. The simplest way to realize full-wave bridge rectification is to use four silicon diodes in a bridge configuration (Kwon and Rincon-Mora, 2010). The voltage drops of each silicon diode generally 0.7 V. So, in a full wave rectifier it becomes 1.4 V. This is too high as compared to the piezoelectric transducer output. Therefore, at the first stage researchers are used Shocktty diode instead of conventional diode. This reduced the forward voltage drop from 1.4-0.6 V. Although, Schottky diodes actually have a lower forward voltage drop, they have higher reverse leakage current when they are reversing biased. In addition to having high reverse leakage current, their fabrication costs are also high, as they are not compatible with CMOS technology (Hashemi *et al*., 2009; Herbawi *et al*., 2013; Raisigel *et al*., 2007). Later, researchers are used four passive discrete MOSFETs, instead of four passive diodes to reduce forward voltage by using CMOS technology. The main sources of power loss, such kind of rectifier occurs during switching transition (Peters *et al*., 2007; Ahmed and Mukhopadhyay, 2013). Then researchers are found active or synchronous rectifier which increases rectification efficiency by decreasing the power loss in switches (Hashemi *et al*., 2009). Finally, passive diodes are replaced by actively driven MOSFETs. In terms of output power and efficiency, several passive and active rectifiers are compared (Le *et al*., 2006). Another active rectifier power conditioning circuit presented in (Colomer-Farrarons *et al*., 2009), within a fixed voltage window 1.2-1.4 V for powering WSN. Peters *et al*. (2011) designed another active rectifier for low input voltage 0.38 V and verified by inductive micro generator. To achieve a wide range of tolerated input voltage 0.48-3.3 V, a few researchers uses a common gate stage. The output voltage of piezoelectric transducer is possible to boost up above actual voltage level by using MPPT system. The efficiency of the rectifier by using MPPT system is below 0.48, due to the high losses in the integrated capacitance (Maurath *et al*., 2012). The active rectification can also be applied to voltage doubler. Dallago *et al*. (2008), presented active voltage doubler with a peak efficiency of 92% by keeping the current consumption of the involved active elements until 500 nA. Cheng *et al*. (2011), proposed another voltage doubler topology has been tested by using discrete components and it shows relatively high efficiency of 85% and tolerates very low input voltage amplitudes down to 5 mV. Furthermore, the operating principle has been tested with irregular input voltages. However, an external voltage supply is needed to power the involved comparators, limiting the practicability in stand-alone energy harvesting applications.

Researchers are working on MPPT algorithm and in most cases, the duty cycle of DC-DC step down converter is adjusted such a way can harvest the maximum power. They investigated nonlinear extraction techniques by using one or more switches and with or without additional inductor acting as temporary energy storage. The techniques of using inductor are called Synchronized Switch Harvesting on Inductors (SSHI) and Synchronous Electric Charge Extraction (SECE), as theoretically discussed by Lefeuvre *et al*. (2005) and Kwon and Rincon-Mora (2009). A Bias-flip rectifier is established by placing a simple switch parallel with piezoelectric cantilever (Ramadass and Chandrakasan, 2010).

At first, MPPT algorithm was applied to piezoelectric harvesters using a DC-DC step down converter (Ottman *et al*., 2003, 2007). Although (Ottman *et al*., 2003), a discrete implementation is presented consuming much power of 30 mW which was extracted from the harvester, a stand-alone operation had been claimed. This circuit is harvesting power only for open circuit voltage higher than 20 V. When open circuit voltage is 50 V, the system efficiency became 70%. Lu *et al*. (2011), presented a CMOS technology to achieve peak efficiency of 95.6% by using vibration tracker. Due to the self-starting capability, they claimed that the system allows stand-alone operation. In the past, the implementation of the nonlinear processing techniques SSHI and SECE have been challenged for several times. The challenge main goal was to derive the MOSFETs switches for both the rectifier and DC-DC converter. The shape changes of piezoelectric voltage signal and the self-powered stand-alone implementation of SSHI is more complex as compared to SECE. Due to the control circuitry power consumption, the discrete-type self-powered SSHI implementation presented (Liang and Liao, 2009) has a performance below the theoretical values. Ramadass and Chandrakasan (2010), has been implemented a self-powered CMOS SSHI which achieves peak efficiency of 87% for a harvested power level of 60 μW. Xu *et al*. (2007), implemented a CMOS integrated SECE system but the buffer capacitor must be pre-charged to a certain voltage level. This chip ensures 70% efficiency. In order to achieve acceptable efficiency from SSHI (Liang and Liao, 2009) and SECE (Tan *et al*., 2008) techniques, high output power (mW ranges) were required. Sun *et al*. (2012) replaced passive rectifier by an active counterpart achieves a significantly higher efficiency (Ramadass and Chandrakasan, 2010). Different (Kwon and Rincon-Mora, 2009, 2010) researchers used a step-up DC-DC converter topology directly connected to the piezoelectric cantilever and controls the involved switches such that the energy is directed into the buffer capacitor, similar to the SECE technique. The absence of a rectifier permits the minimum tolerated low input voltage and power levels. But on the other hand, in order to process negative piezoelectric voltages, an external -2 V voltage signal has to be applied separately, representing a significant limitation in practical use.

The CMOS technology is used where energy efficiency was vital and offers to enhance the power management circuit of the chip. The piezoelectric energy harvester was fabricated in a 0.50, 0.35, 0.18 and 0.13 μm process as shown in Fig. 3 (Ramadass and Chandrakasan, 2010; Hehn *et al*., 2008). Though, recent 0.13 μm technologies are expensive but the present energy harvesting system was designed using 0.13 μm CMOS chip fabrication technology. Because, this technology requires lower threshold voltage and the number of stages will be less than other process. Table 2 summaries a few researchers work have been done on energy harvesters.

Table 2: Comparison between the past researcher works on energy harvesting

		Voltage (V)						
Circuit type	External supply	Input	Output	Output power (μW)	CMOS Technology (μm)	Efficiency (%)	Application	References
Active full-wave rectifier	Yes	2.5	2.45	22	0.25	8600	Resistor	Le *et al*. (2006)
Full- wave rectifier	No	1-3.3	<3	No	0.35	9000	Resistor	Raisigel *et al*. (2007)
Active voltage doubler	Yes	3.0		No	0.35	9000	No	Dallago *et al*. (2008)
Active full-wave rectifier and power conditioning circuit	Yes	2.5	No	No	0.13	75-85	No	Colomer *et al*. (2009)
Active voltage doubler	Yes	>0.25	0.5	100-1000	Discrete	8000	Resistor	Cheng *et al*. (2011)
Active full-wave rectifier	Yes	>0.35	0.38	26	0.35	90	No	Peters *et al*. (2011)
Power conditioning circuit with MPPT	No	2-6.5	No	21	0.35	90	No	Lu *et al*. (2011)
(a) Full wave rectifier and (b) MPPT	Yes	0.5-3.3	No	(a) ≤350 (b) ≤150	0.35	(a) 90 (b) 48	 Resistor	Maurath *et al*. (2012)
Active full-wave rectifier	Yes	0.5-1.2	<1	10	0.35	94	Resistor	Herbawi *et al*. (2013)
Boost regulator	Yes	>0.012	0.66-1.33	6	0.13	82	No	Ahmed and Mukhopadhyay (2013)
Power conditioning circuit with MPPT	No	0.5	3	>24	0.13	90	WSN	Fei *et al*. (2014)

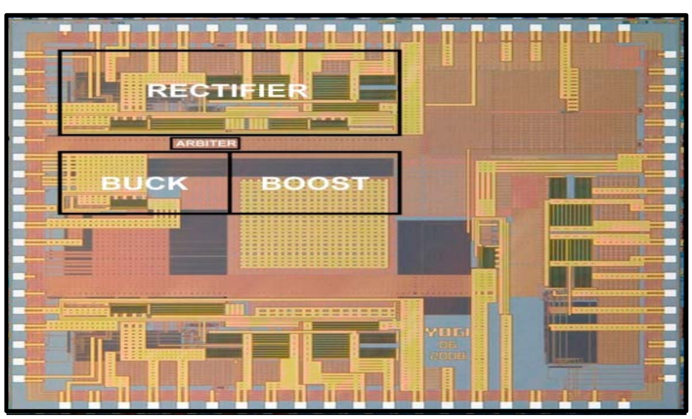

Fig. 3: Piezoelectric energy harvesting chip (Badel *et al*., 2006)

Except Lu *et al.* (2011), a startup capability is missing in all of the impedance matching described above. This means, the buffer capacitor has to be recharged initially in order to start and not suitable for practical applications. In addition, the output of the piezoelectric material is very low. So, an interface circuit to reduce the overall power loss of the proposed system was designed. The main objective of propose energy harvesting system is to enhance the practicability of a CMOS integrated interface circuit for piezoelectric harvesters applying ubiquitous device. Furthermore, maximum power will be transmitted to the load from the ambient input.

DESCRIPTION

Power Conditioning Circuit (PCC) is a vital issue associated with most ambient energy harvesting technologies. Most ambient sources (vibration, radiation, light and heat, etc.) of the current research on energy harvesting technology are unable to generate enough voltage or current (Lien *et al.*, 2010). Therefore, the strategy is accumulating energy in an energy buffer for a long time and utilize this energy to power up ubiquitous devices in a short period. A conventional block diagram of the energy harvesting system is shown in Fig. 4. Generally, vibration energy harvester circuit consists of a rectifier and a step-up converter (Sarker *et al.*, 2011b). The output from the transducer is typically an AC voltage but electronic loads almost require a DC voltage for their operation. Therefore, the AC-DC converter is used to convert the AC to DC voltages (Sarker *et al.*, 2013). When the DC voltage is not high enough for load operation, an additional step-up DC-DC converter (boost converter) is added to boost it to a higher level (Rao and Arnold, 2013). In most cases, the load requires a fixed DC voltage at various input voltage and load current, a control circuit is therefore designed to achieve output voltage regulation through a feedback loop (Rao and Arnold, 2011).

The block diagram of the propose PCC energy harvesting system is shown in Fig. 5. This model consists of 9 sub-blocks which are ambient energy, piezoelectric cantilever, voltage doubler, bypass

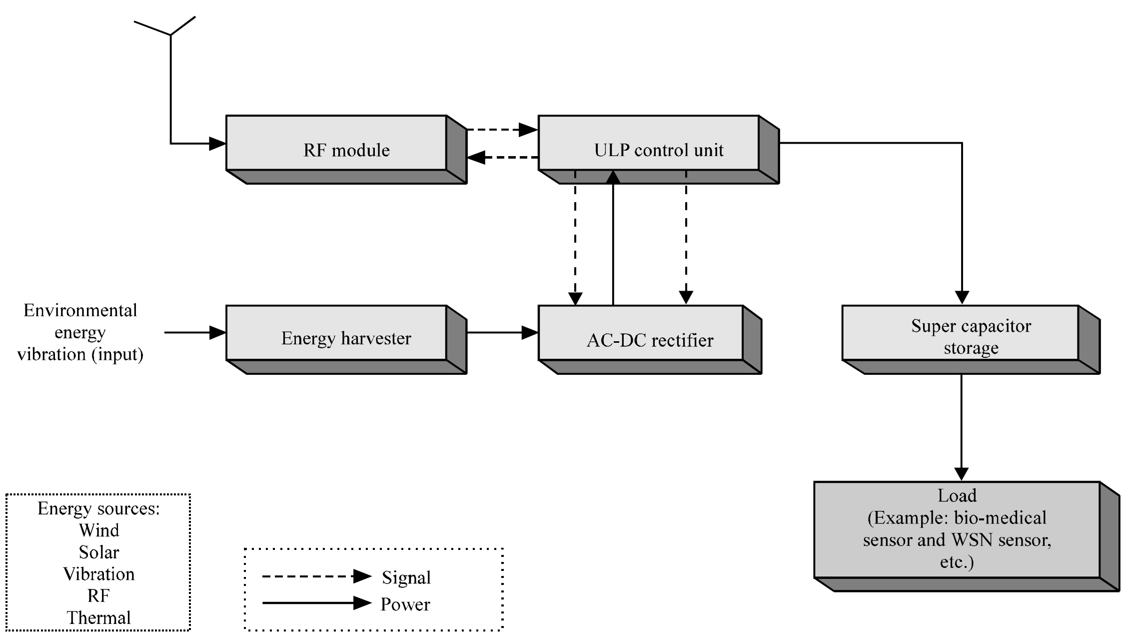

Fig. 4: Conventional energy harvesting system (Sarker *et al.*, 2011b)

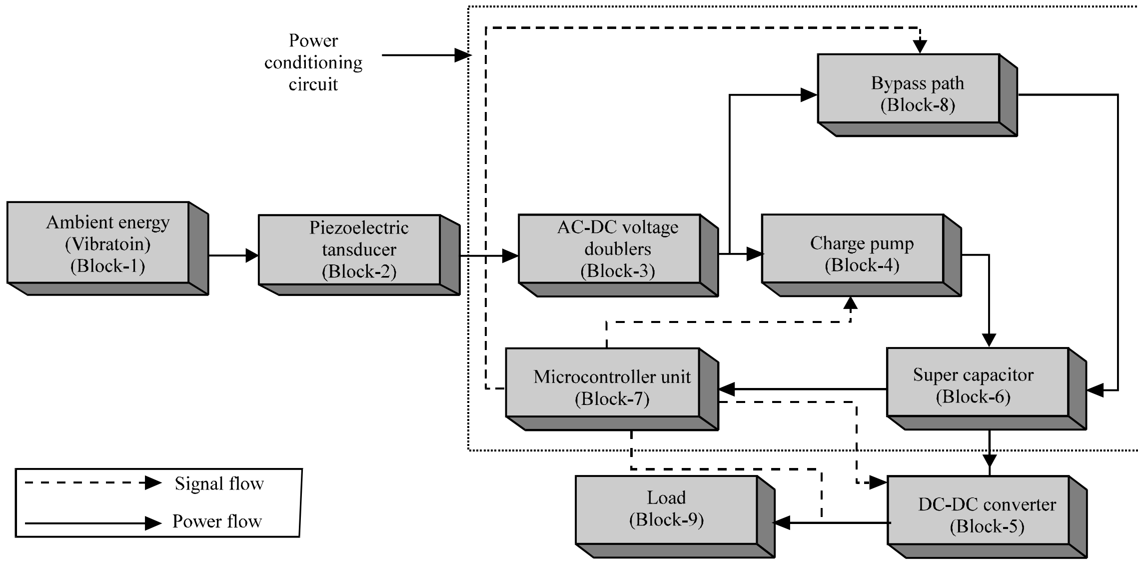

Fig. 5: Proposed block diagram of the ULP based PCC for ubiquitous devices

path, charge pump, DC-DC converter, microcontroller unit, super capacitor and load. Here all sub-blocks are explained briefly.

Energy harvesting system is a promising technique that harvest ambient energy (Block-1) in electrical form from sources such as vibration, radiation, light and heat, etc. A piezoelectric energy harvester (Block-2) attract an enormous interests because of its relatively high energy density and wide availability of energy sources in the environment (Darmayuda *et al*., 2012). The piezoelectric material produces low AC voltage (500 mV) using ambient energy (e.g., Vibration) and are not suitable to be supplied directly to the load. Therefore, in this study, a voltage doubler (Block-3) and a charge pump (Block-4) was used to boost up the voltage (Fei *et al*., 2014). Another purpose of using voltage doubler is voltage rectification without a significant forward voltage drop. This is possible by employing a normal diode/ Schottky diode/MOSFET switch structure. Then the output of the charge pump is fed to the DC-DC converter (Block-5). But at the initial state the active path that means charge pump and DC-DC converter will be switched off. Because, at this time the voltage across the super capacitor (Block-6) is not sufficient to drive microcontroller unit (Block-7). At this moment, the capacitor is charging via a bypass path (Block-8). Once the storage capacitor attains sufficient voltage to power up the microcontroller unit and this unit output voltage is higher than zero, then the circuit enters active charging modes (directly) where impedance matching is achieved to maximize power extraction. The DC-DC converter will be used for impedance matching between piezoelectric cantilever and the load (Block-9) by changing, switching frequency, duty cycleand inductor value (Darmayuda *et al*., 2012). To achieve maximum power extraction from piezoelectric cantilever, Maximum Power Point Tracking (MPPT) algorithm (Kong *et al*., 2010) was used. A low power microcontroller unit was used for extracting maximum power and controlling the charge pump. When all blocks are functioning together and the storage charge of the super-capacitor is sufficient to deliver power, then it start deliver power of 24 mW at output voltage 3 V from the low ambient sources.

METHODOLOGY

The design flow chart for the proposed energy harvesting Power Conditioning Circuit (PCC) is shown in Fig. 6. Where it was started with comprehensive literature reviews and ended with the

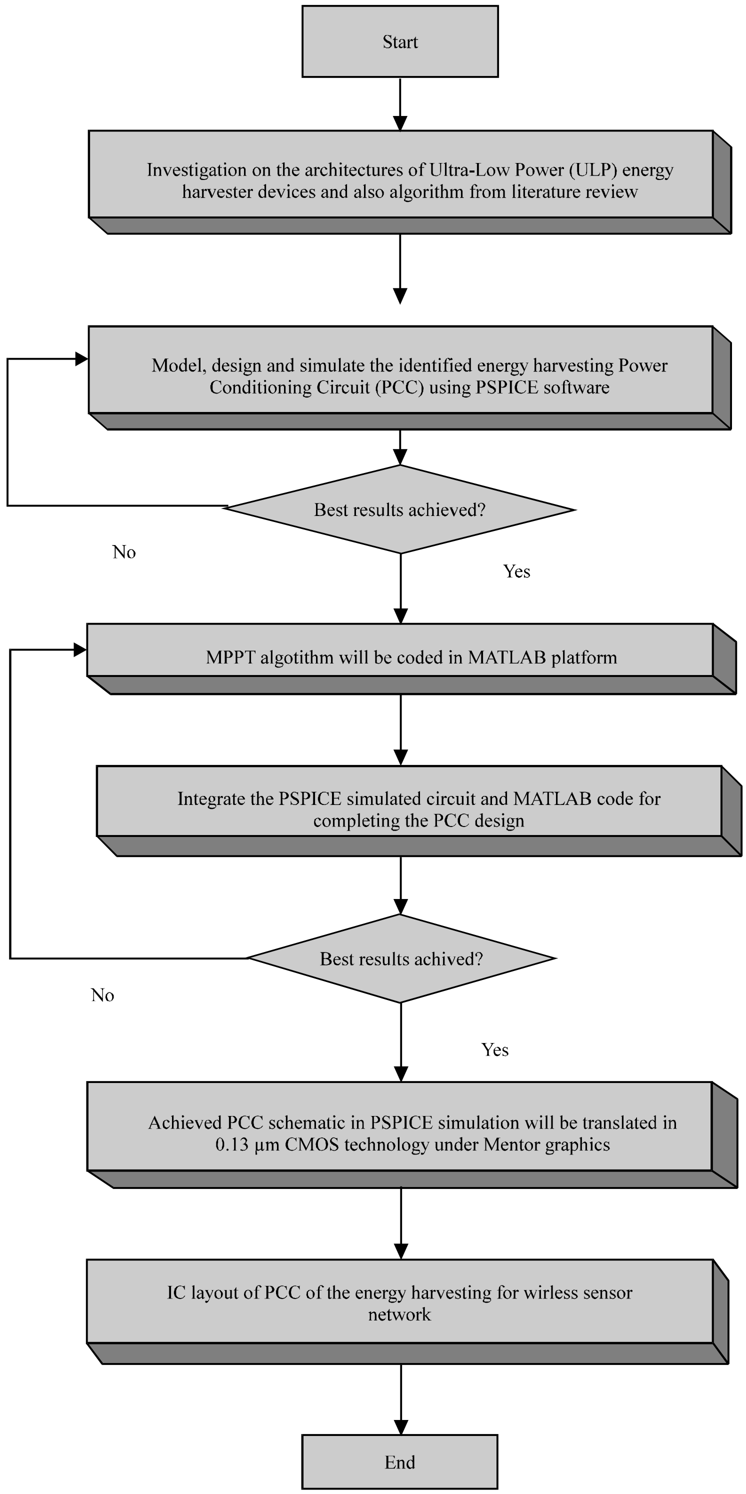

Fig. 6: Design flow chart of energy harvesting PCC

generation of complete IC layout. This implementation process will be sequentially discussed in brief. To design and implement this research work, we will investigate the literature review on the architectures of ULP energy harvester devices and also the behavior of the MPPT algorithm. Next, each sub-block of the energy harvester device will be modeled, designed and simulated in PSPICE software (Mi *et al.*, 2013). Here, if any undesirables or erroneous simulation results occur on the efficiency, power consumption, input and output voltages; back to the design or literature level. After completing simulation of the identified PCC in PSPICE successful, we will write a MATLAB code for MPPT algorithm. Once we get the best result in both PSPICE and MATLAB platforms, then we will convert our design in 0.13 μm CMOS technology under mentor graphics. Finally, IC layout of energy harvesting PCC will be achieved.

CONCLUSION

The main challenge in this study is to maximize the extracted power from the piezoelectric transducer and too minimize the power losses of the whole circuits. To achieve maximum power from piezoelectric transducer, an impedance matching technique was performed using MPPT algorithm. The proposed ULP PCC will be modeled, designed and simulated in PSPICE software and the MPPT algorithm will be coded in MATLAB. Then the designed power conditioning circuit will be simulated using Mentor Graphics in a 0.13 μm technology. Finally, a battery less ULP energy harvester will harvest up to 24 mW power with an output voltage of 3 V and efficiency of 90% for powering WSN. Furthermore, this ULP energy harvester will reduce power consumption comparing to the conventional approaches.

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