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ULTRA LOW POWER ENERGY HARVESTER USING HYBRID INPUT FOR WIRELESS COMMUNICATION DEVICES – A REVIEW

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ABSTRACT

Energy limitations are commonly considered as an essential constraint of wireless and mobile devices. Mobile phone needs to be charged frequently which is a time consuming process. Energy harvesting has appeared as a favorable technology to solve the problem of energy constraints in mobile phone. This work proposes a new architecture of Ultra Low Power Hybrid Energy Harvester (ULP HEH) that can be employed in wireless communication devices. The proposed architecture is utilizing three hybrid sources which are: Thermoelectric Generator (TEG), Radio Frequency (RF) and Vibration. TEG is depending on the variance of temperature between the surrounding environment and the heat resulting from the power losses in the device. Vibration is related to the vibrating sources like motor or shaking the device. Radio Frequency signals are on purpose radiated by broadcasting station antennas and cellular phone antennas. Having three hybrid sources will help to overcome the limitations of single source harvester. The ULP HEH will be firstly designed and then modeled to be simulated later by using PSPICE software and finally established in 0.13 µm CMOS technology. Verilog coding under Mentor Graphics will be used for coding the established ULP HEH and then for real time implementation it will be downloaded to Field Programmable Gate Array (FPGA). The expected result from this harvester is to achieve 4.2 V as an output voltage, which all new mobile phones are made to be compatible with, from input range of 20 mV- 500 mV with high efficiency and reliability.

Keywords: *Energy constraints, Energy harvesting, Ultra Low Power (ULP), Hybrid Energy Harvester (HEH), Charging mobile phone*

1. INTRODUCTION

Mobile phone has become an essential part of everyone's life. About 87% of the citizens around the world will be using mobile phone by 2017 [1]. Mobile phones are commonly used and people normally fall into a condition where batteries of their appliances are discharged, and fail to obtain power at a time of necessity [2]. The process of charging this device is considered as a time consuming practice. It needs user's care, suitable electric outlet and specific electrical connections which are some restraints in charging mobile phones [3]. Chargers of these devices are becoming generally standardized because of the power abilities and varied availability of the USB terminals [4]. Mobile phones are becoming similar to portable computers and need to be connected with other devices. The USB connectors have a standard feature and they are enabling a universal charger. USB provides 5 V; so all new mobile phones are manufactured to be compatible with this level of voltage [4]. The voltage that lithium batteries work on is 3.6 V and as a result of that the mobile phones have built in power converters to achieve the desired voltage [4]. Thus, the task of making a universal charger is becoming a lot easier. One of the solutions for generating power for mobile phones is energy harvesting technique [5]. The conversion of ambient energy such as heat, vibration, RF energy, etc. to electrical energy that can be used to recharge the mobile phone batteries or to be used directly to power the devices instead of the batteries is called the energy harvesting.

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There are so many external sources of energy can be scavenged such as thermal, vibration, water, solar and wind [6]. There are some successful attempts for scavenging two kinds of energy sources at hybrid energy [7]. On the other hand, there has not been reported any hybrid energy architecture that can harvest RF, vibration and thermal energies simultaneously.

Energy harvesting that gained from the windmill and water wheel is widely selected as a low maintenance practice for a many various types of applications. It is a process of getting energy from the surrounding environment and transforming it into beneficial electrical energy [8]. Nowadays, we can see an increasing concern in this field. Growing demand on Radio Frequency Identification (RFID) and wireless sensor networks (WSNs) has enlarged the significance of generating power for these kinds of circuits [9]. Batteries of different kinds can easily drain out of energy after certain time of use, thus, these batteries need to be replaced. Replacing batteries, sometimes, is not an easy task. Generally, batteries are expensive and replace the used ones with new ones costs a lot. In spite of the cost, replacing batteries contains technical and physical difficulties due to devices supplied by these batteries are sometimes placed in non-reachable places. As a result, it is highly recommended to use hybrid energy harvesting system as the power supply instead of batteries or to charge them.

2. LITRATURE REVIEW

The concept of energy harvested from nearby light and thermal to overcome the drawbacks of using a single source by using only one circuit for power management unit has been introduced by [10]. Using the same power management unit with less number of components reduced the power losses and cost. A new architecture called a dual path architecture that contains a rebuild multi-input and multi-output with an enhancement in efficiency which is 11% to 13% has been demonstrated by [11] . By using single inductor, the system could deal with input voltages ranges from 20 mV to 5 V and derive maximum power from single harvester. [12] reconstructed Hybrid Energy Harvester combined in parallel using a DC-DC boost converter from as low input voltage as 18mV to 907mV into a 310mV to 27.9V when appropriate parametric values are well selected for the harvester. Matching the harvester impedance to the load is very important in order to obtain maximum power transfer.

Basically, vibration and RF energy circuits require a converter step which is a rectifier circuit to convert output voltage from AC to DC [13]. The proposed ULP HEH architecture will have three input sources from TEG, vibration and RF to give appropriate threshold input voltage that can be implemented in wireless communication applications. Losses of conduction and switching occurred by the parasitic resistance and capacitance respectively, leakage current and power used of the control circuit contributes in decreasing the capability of the ULP HEH source.

Practically, energy harvesters can supply 10μW to 100μW output power, by doing a restricted regulation on the power that can be used by the load circuitry for self-powered operation [14]. In general, the voltage produced by vibrational and RF energy harvesting is AC, while loads always need DC voltage for their processes. Thus, a rectification circuitry is needed to convert AC voltage to DC voltage [15]. There must be a specific control circuit to regulate the output voltage.

2.1 Vibration

In general, the voltage produced by vibrational is AC, while loads always deal with DC voltage for their processes. Consequently, a rectification circuitry is required to convert AC voltage to DC voltage [15]. The output voltage coming out from rectifier must be regulated.

There are three main types of vibration-based generators which are: electromagnetic, piezoelectric and electrostatic [16]. Since 2010 these harvesters have faced many developments due to development of piezoelectric resources like Polyvinylidene Fluoride (PVDF) and Lead Zirconate Titanate (PZT) [17], encapsulated PZT nanofiber structure with output power around 0.03 µW and output voltage about 1.63 V [18], multiple PZT structures [19]. Generally, PZT supplies range of power from 10 µW up to 100 µW [20]. [15] solved the problem of the nonzero power consumption that occurred when no energy is being harvested, by using an input interface. [21] used a modified converter that excerpts power at efficiency of 60%. [20] improved the extraction of power by using bias-flip rectification with power consumption of less than 2 µW.

[22] recommended not overlooking the operating point of the converter by achieving an efficiency of 64 % for the overall system. [23] introduced rectifiers using active diodes, trickle charger and shunt pass in order to reduce power consumption less 1 µW with an efficiency of 50-60%. However,

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the architecture of [20] needs charged batteries at 1.8 V to begin with.

2.2 TEG

TEG has a desirable energy harvester environment that attracts significant interest due to its nil emission, compactness, few moving parts, high reliability, low noise, cleanness of produced energy and no fuel consumption [24]. According to Seebeck effect, it is possible to harvest energy from heat by using TEG which converts thermal energy into electrical power. In recent times, researchers begin to concentrate on a method of CMOS technology enabled devices, circuits, processors and even System-on-Chips (SoCs) with ultra-low power consumption. When two junctions are being at hot and cold temperatures respectively (TH and TC), and TH > TC, an open circuit of electromotive force will be established between the two junctions [25].

[26] stated that the circuits of TEG have reached the efficiency up to 73% and [27] have achieved 75% of the efficiency. Another technique for applying maximum power scheme is used by controlling the converter duty cycle in order to boost the output of the power system [28]. During installation TEG power converter needs one time impedance tuning with inductor sharing that has 58% peak efficiency of power converter [11]. To reduce the consumption of power and increase the efficiency, the boost converter functions in intermittent conduction mode because the inductor current is not allowed to flow from negative side [29].

[27] has applied the discontinuous conduction mode with a synchronous rectification and producing a converted method DC/DC boost converter that is effective to produce an output voltage of 1V from a low input voltage which is as low as 20 mV. The converter that operates in discontinuous conduction mode is more capable to decrease the switching losses for low power loads [30]. [31] introduced a parametric analysis with passive components for boost converter. To start the system a start-up circuit with an array of discrete MOSFETs working with a suitable gate threshold is used. [32] have suggested storage or high voltage to make the system ready and kick start operation from low voltage together with power management circuit and they proposed a charge pump with flexible number of stages for that. Essentially, a start-up circuit is depending on energy storage, inductive boost converter and a regulated DC/DC buck converter. [33] have introduced a start-up voltage step up DC-DC converter to be used in energy harvesting implementations. Two systems from [32] have been introduced that are using battery or primary high voltage input to start up process of the system from low voltage.

It is significant to have the sensor initialize from no stored energy which is called ‘cold start’ as reported in literature of [34] but using the term of ‘kick start’. [35] demonstrated a start-up failure technique due to the power up flow current drawn by control circuitry that does not allow the storage capacitor to be charged.

The maximum power point tracking (MPPT) system working in an intermittent conduction mode using Pulse Frequency Modulation (PFM) is suggested and applied to a boost converter and also a pseudo zero current switching (P-ZCS) scheme is applied to achieve high efficiency as presented in [29]. Pulse Counting Control (PCC) is an adaptive method offered in [36], thus the imitative resistance of the converter causes maximum power gained from each source.

2.3 RF

RF energy harvesting depends on picking up propagated RF energy that transfers power with radio waves [4] in the surroundings and converting it into a valuable power. RF is considered as a unique source because it is not affected by changes of time or weather [37]. [38] used an operating frequency of 900 MHz with a converter module built on the Villard voltage doubler circuit that produces 2.12V as an output voltage through simulation and 5V through measurement at 0dBm as an input power level. [39] used 915 MHz band for biomedical purposes. [40] concluded that an input power of -24dBm (4μW) could produce output voltage of 1V from an RF input signal at 915MHz using a combination of interfacing circuits for matching and a 17 stage self-compensated rectifier fabricated in 90nm CMOS technology. [41] used 5 stage 915 MHz orthogonally switching CPR (OS-CPR) with MOS transistor as voltage-controlled switches produced 1.35V into 1MΩ load for an input -18.2dBm through simulation. [42] employed a seven-stage Cockroft-Walton voltage multiplier and got output voltage of 2V with -9dBm (0.13mW) sensitivity at an operating frequency of 2.48GHz.

[43] worked on a differential microstrip antenna, on chip novel CMOS rectifier, off chip matching circuit and control circuitry in 180nm CMOS technology that achieved an efficiency of 40% for -11dBm of the power received by the antenna. [44] introduced a 900 MHz system which implemented an efficient power path structure with a suitable

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control and start-up circuit which offered an output voltage of 2V at Pin of -15dBm. [45] employed a five- stages cross connected differential rectifier and a 7 bit binary weighted capacitor bank made-up in 90nm CMOS technology at 868 MHz validate a -27dBm sensitivity for 1V output across a capacitive load and 27m range for a 1.78W RF source. In the same time, [46] offered a dual-band CMOS harvester which obtained more than 9% of efficiency for dual bands (around 900Mhz and around 1900Mhz) at an input power as low as -19.3dBm and DC output over 1V.

Sensitivity of multi-stages rectifier in the RF energy harvesting is highly contributed by the rectifier threshold voltage [40]. Generally, the voltage of the input signal is very small comparing to the typical threshold voltage of the rectifier. [38] used Schottky diodes with zero bias taking advantages of the low substrate losses, fast switching, and low forward voltage and used the non-symmetric properties that typically allow unidirectional flow of the current. [46] presented a self–biasing method to enhance the efficiency of AC-DC conversion with no outside source is applied. Unlike traditional Schottky and diode connected MOS transistor rectifier, [41] used a passive Voltage Boosting Network (VBN) and an orthogonally switching charge pump rectifier, CPR (OS-CPR) contains MOS transistors as voltage controlled switches. [43] introduced the rectifier without any external bias, so that each alternate transistor is biased by using the node voltage from the next transistor. [40] proposed an improvement on multi stage rectifier by organizing a fully passive threshold self-compensation scheme to solve the case on the input dead zone.

Low power voltage boosting is another important feature that used to switch on the MOSFETs, especially when dealing with CMOS. [46] focused on this part by implementing the basic concept of voltage boosting which uses LC resonant circuit to produce a valuable voltage across the MOSFET, so it can be turned on even though the input voltage is very low. At the resonant frequency, the voltage boosting produces large voltage and consequently the diode gets high current. There is an ideal point to get the maximum conversion efficiency as proposed by [45] by passively boosting the voltage.

According to [47], sensitivity and per-operation energy are two serious components effect on the effectiveness of the RF harvesting sensor node. [48] stated that the low harvested power is one of the limitations that require the use of low power on chip circuitry, including the data transceiver, controller, and auxiliary circuitry. To increase power extraction, [49] presented an ideal two stage design to reach nearly 100% enhancement over other current designs in the power range -20 to 7dBm. [50] applied charge pump rectifier which is used to increase the battery voltage and deliver a controlled output in spite of large load variation in the same time. This charge pump is able to boost the voltage up to 3.7 times of the input voltage. They also proposed a technique of frequency regulation to deliver stable efficiency with all different loads.

3. PROPOSED LOW POWER HYBRID ENERGY HARVESTER

Hybrid Energy Harvester system connect input sources of the energy harvesting into single system to improve system functionality and reliability [51] by producing sufficient power supply for wide range of environmental situations [52]. Using hybrid input increases the number of in demand materials, therefor, cost and volume of the system, especially for the passive component such as inductor, will be increased [53]. As presented in [36] to produce maximum power, various inputs boost converters with a single inductor are compound with a digital control unit while [11] have reduced the number of components regarding the output level and time sharing inductor.

In this work, the proposed Ultra Low Power Hybrid Energy Harvester (ULP HEH) system is designed to simultaneously capture and merge energies from input sources of Thermoelectric Generator (TEG), vibration and radio frequency (RF) waves and then convert them into an overall of electrical energy. Furthermore, the design supposed to have a low power consumption regarding on the conditioning circuits and control module. As a result of the ULP HEH system which deals with low voltage application and self-powered device, the circuits require low consumption of power to achieve higher efficiency operation. Thus, low power architectures need to be considered when ULP HEH circuits are designed.

Another task in the interface circuit is starting its process with the problem comes from the fact that the output voltage (input to the interface) is really different for the three sources. Start-up mechanism is needed to be implemented for getting a proper voltage.

Process, Voltage and Temperature (PVT) differences are the most significant challenges in CMOS technology of the circuit design. It

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demonstrates that all the circuit standards work through PVT combinations such as the efficiency of the conversion circuit which vary according to PVT variations. The output voltage of the generator is the most challenging part in designing a power management unit for the sources [54].

ULP HEH sources from TEG, RF and vibration are integrated in this work to competently achieve ULP consumptions. ULP HEH uses DC-DC converter to extract power from an inadequately controlled low-voltage power source. The system is capable of efficiently gathering the energy around it in order to overcome the limitation of the environment with energy management interface presented in [55] with high efficiency of PFM switching regulator and very useful in low power system like wireless communication system. Multiple-input boost (MIB) to execute MPPT in developing module integrated microconverters and microinveters is suggested.

The objective of this research is to overcome the problem of low ambient input due to a low single source power. The most significant design concern is to elevate the power obtained from ambient input and exploit it at a time of necessity to charge the mobile phone. Table 1 shows the proposed ULP HEH compared with the previous work in the same area. Input source will vary depending on each source minimum voltage of 20 mV to 500 mV. As a result of that, the minimum input power will vary from 1µW to 200 µW. The expected output voltage is 4.2 V and the output power is around 180 µW. All these expectation have not borne out yet because no one has combined TEG, Vibration and RF in one Hybrid Energy Harvester system. We are looking forward to achieve these expectations and applied for charging mobile phones successfully.

4. PROPOSED ARCHITECTURE OF ULP HEH

The proposed conventional architecture is shown in Figure 1**Error! Reference source not found.**. It consists of eleven sub-blocks which are: Hybrid input sources, Voltage boosting & tuning, Rectifier, Control loop, ULP Control Unit with AFSM, Start-up circuit, MPPT, Boost Converter, Energy Storage, Regulator and Load. All the blocks are integrated to work together in order to enhance the efficiency and sensitivity of the micro energy harvester. Each block is described as following:

Firstly, Block 1 presents the ULP HEH input sources from TEG, Vibration and RF to be implemented for wireless devices (mobile phones). The purpose of hybrid inputs is to avoid the insufficiency of single input sources that have many restrictions of robustness, energy efficiency and output power.

Secondly, Block 2 represents Voltage boosting and tuning. Voltage boosting will be similar to the design of [45] in which the inductive behavior of a high Q loop antenna is combined with the capacitive input impedance. When resonance happened, high current will flow across the inductor and consequently boosts voltage. To make a resonance happen, a parallel capacitor is connected. However, high Q networks are very sensitive to any mismatch process, input power level or environmental changes. Thus, a tuning is needed to compensate these variations.

Thirdly, Block 3 represents a rectifier. Vibration and RF sources generate AC signal and cannot be directly supplied to the load, therefore, they need rectification stage to convert the AC signals to DC. Once voltage boosted, rectifier will be switched on.

Fourthly, Block 4 represents a control loop. The nonlinear input impedance of the rectifier changes according to the frequency and input power. This makes the high Q interface vary with impedance variation. To solve this problem, a control loop is used to adjust the impedance that occurs when a resonance is made with the antenna. The reactance of the rectifier and the antenna at the interface effects on both the resonance frequency and the passive voltage boost, thus, the compensating will be only for reactive variations. In addition, the robustness of the harvester is improved by the loop with getting benefits of the passive voltage boost gotten from the high Q resonator.

Fifthly, Block 5 represents Ultra Low Power (ULP) Control Unit with Asynchronous Finite State Machine (AFSM) that the three hybrid sources are connected to in order to share the resources and control power supplies individually or totally [36]. The AFSM is to choose the proper source when they are simultaneously activated. In cases that the source is insufficient and cannot operate the AFSM block, an amplifier or kick start circuit must be used to obtain more signal of the input.

Sixthly, Block 6 represents the Start-Up circuit that works as voltage detecting switch. It will be joined when getting the preferred input from AFSM as a kick start signal. [33] utilized Start-Up technique to generate higher auxiliary voltage (>VTH).

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Seventhly, Block 7 represents a Maximum Power Point Tracking (MPPT) algorithm which is modeled to get and improve maximum power extraction before boost up the voltage. Impedance mismatch caused by hybrid input sources must be considered.

Eighthly, Block 8 represents a Boost Converter mechanism to boost the voltage that has been determined by control unit.

Ninthly, Block 9 represents an Energy Storage unit. Once the voltage is boosted up to the required level of input, Energy Storage is started and the energy is stored in a storage capacitor.

Tenthly, Block 10 represents the regulator which controls and maintains the storage voltage to a certain voltage value [9].the regulated voltage must be around 4.2 volts which is required to charge mobile phone battery [3].

Lastly, Block 11 represents the load. The load in current case will be a mobile phone.

5. METHODOLOGY

This research which is working on the title "Ultra Low Power Energy Harvester using hybrid input for wireless communication devices" will be performed by using the design-flow as shown in Figure 2. To accomplish this work, firstly investigation on the literature background on Hybrid Energy Harvesting based on previous researches has been done. From there, a scope of work is assigned and the new ULP HEH architecture is proposed. Then, each block of the ULP HEH is modeled, designed and then simulated using Pspice Software. If there are no errors and the simulation result achieves the expected result, continue to next step. If negative results obtained, the design is modified. Next, by using Mentor Graphics Design Architecture and IC station the circuit design is ported over as a gate level model on the 0.13µm process technology. When the layout is ready, testing and analysis will be performed and multiple of validations will be achieved by CALIBRE tool to check either any enhancement or back annotation is needed before the final implementation. This is important to avoid any deviation in terms of parasitic, timing or power issues. Once the verification on the final layout completed, the tape-out ready Graphic Database System GDSII format can finally be generated.

6. CONCLUSION

Architecture of Ultra Low Power Hybrid Energy Harvester (ULP HEH) has been proposed with the sources from TEG, RF and vibration. This combination of the three sources has not been utilized before. Furthermore, using HEH to charge mobile phone is a new idea that we expect to open wide area of research. The proposed architecture will be designed, modeled and simulated in PSPICE software. Then, the proposed ULP HEH will be downloaded into a FPGA board using 0.13 µm CMOS technology for real time verification. The expected result is to achieve an efficiency of 90% with an input voltage ranges between 20 mV to 500 mV and output voltage of 4.2 V to be used for charging the mobile phone. The minimum input power will vary from 1µW to 200 µW and the expected output power is around 180 µW.

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Table 1: Comparison of Previous Researchers Works on Hybrid Energy Harvesters and This Work

Source	architecture	V_{in} (V)	V_{out} (V)	P_{in} (µW)	P_{out} (µW)	MPPT	Start-up	η (%)	Process Tech.	Application	Reference
RF, PZT, PV	LDO regulator, charge pump, external SD	1.0 – 1.89	1.2 – 2.5	7529 - 11636	6400	Yes	No	55 - 85	ASIC 0.13 µm	Low power loads, WSN	[56]
PZT, Heat, PV	Dual path approach, inductor sharing	0.02 - 5	1.88 – 2.3	----	200 - 2500	Yes	No	58 - 83	CMOS 0.35 µm	DSP, sensors	[11]
PZT, Heat, PV	Resources sharing Arbiter, AFSM, UULP f/b, fuzzy charger, DC/DC converter, ZCS	0.1 – 0.3	3.0 – 5.0	722	650	Yes	Yes	90	CMOS 0.13 µm	Body worn devices cum charger	[57]
TEG, PV, PZT	Transformer boost, shunt regulator	0.071 – 0.086	1.0 – 3.0	11 - 26	14.8	No	----	57	CMOS 0.13 µm	WSN	[58]
TEG, PV, PZT	Resources sharing Arbiter, Boost converter, PMOS transistor	0.018 – 0.907	0.31 – 27.9	14 - 187	9.61 – 78000	Yes	----	----	----	Quartz watches, medical devices, WSN	[59]
TEG, Vibration	Boost converter, MPPT control, resource sharing arbiter	0.08 – 0.6	2.0 – 4.0	750	690	Yes	Yes	93	CMOS 0.13 µm	Micro biomedical	[60]
RF, TEG, Vibration	Boost converter, control circuit, rectifier, control loop, regulator	0.020 – 0.5	4.2	1 - 200	180	Yes	Yes	90	CMOS 0.13 µm	Mobile phone battery charger	(This work 2016)

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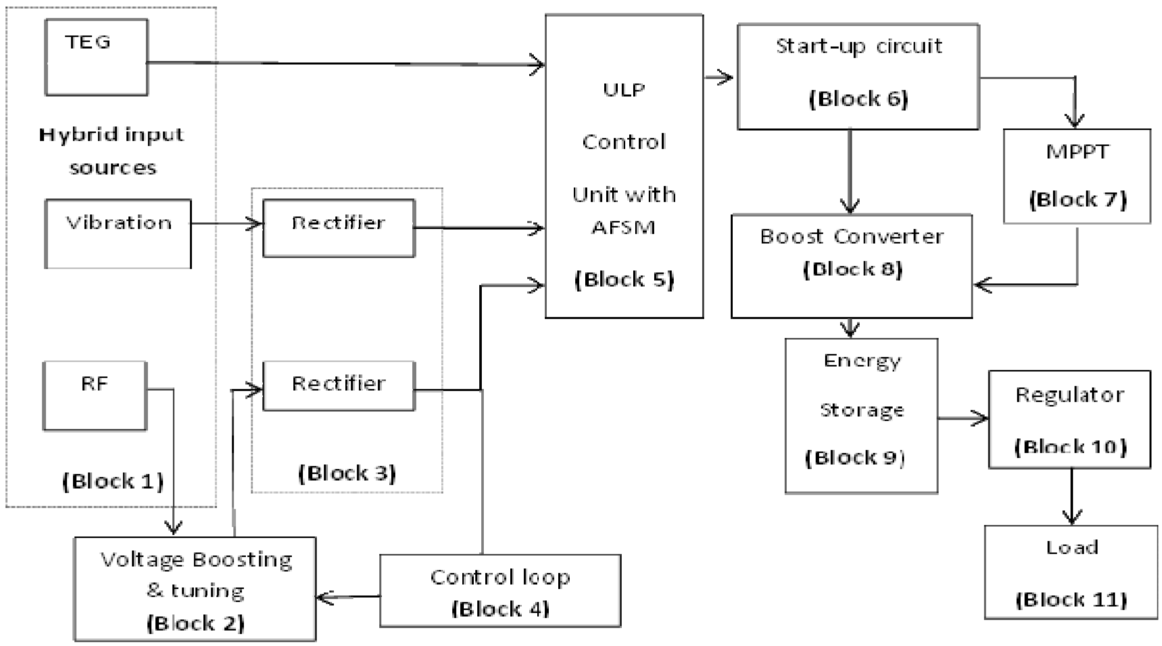

Figure 1: Proposed Block Diagram of Hybrid Energy Harvester (ULP HEH)

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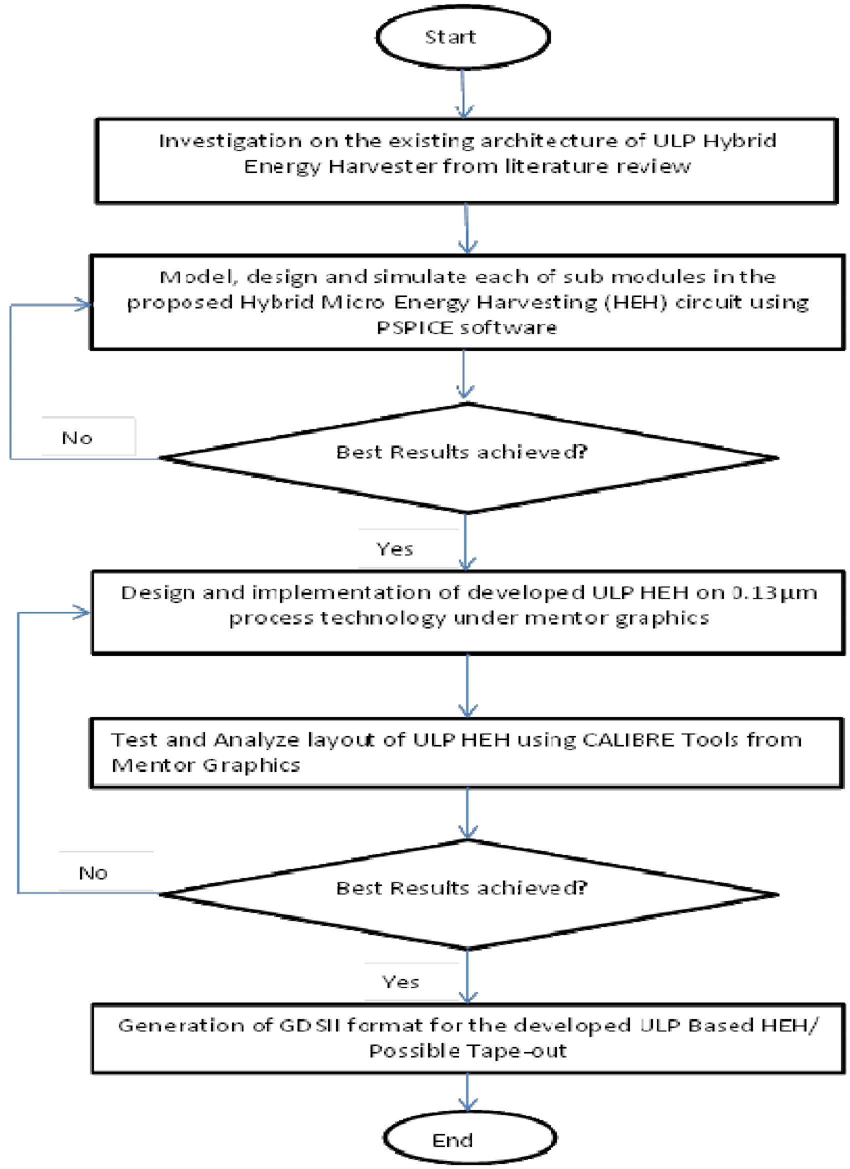

Figure 2: Design-Flow of the Proposed Hybrid Energy Harvester (ULP HEH)