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Architecture of Ultra-Low-Power Micro Energy Harvester Using Hybrid Input for Biomedical Devices

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ABSTRACT

This research work presents an Ultra-Low-Power (ULP) Hybrid Micro Energy Harvester (HMEH) for biomedical application. This architecture uses the inputs of Thermoelectric Generator (TEG) and body vibration. TEG is based on temperature gradient between the ambient environment and human body. While vibration is based on the vibrate sources like motor that is able to generate an AC voltage. Having two sources overcome the issue of limitation caused by single source harvester but will result in impedance mismatching among the desired sources. The proposed of HMEH architecture consists of a control manager with Asynchronous Finite State Machine (AFSM) to grab the proper input value, a rectification to convert vibration input from AC to DC, a start-up to initialize the desired input, a Maximum Power Point Tracking (MPPT) to achieve maximum power extraction, a boost converter to boost up the input voltage, energy storage to keep the energy and voltage regulator to fix or produce the desired output voltage. A single power management circuit is used to reduce the number of components used and power losses. The HMEH will be modeled, designed and simulated using PSPICE software and then implement in 0.13 µm CMOS technology. Next, the developed HMEH will be coding using Verilog Hardware Description Language (VHDL) under mentor graphics and then download to Field Programmable Gate Array (FPGA) for real time implementation. The expectation from this ULP HMEH is to achieve 2.0-4.0 V of regulated voltage output from input sources range of 80-600 mV at start-up with an efficiency of 93%.

Key words: Ultra low power, hybrid micro energy harvester, thermoelectric generator, vibration, biomedical device

INTRODUCTION

Energy harvesting is known as energy scavenging has become a popular source in recent years for low power electronic systems like biomedical implants and wireless sensor network. Energy can be scavenged from external sources like thermal, water, solar, vibration and wind (Yao *et al*., 2009). This study focuses on the hybrid input sources which are TEG and vibration to be applied in biomedical devices. Energy harvesting would be perfect for biomedical application because it is able to supply the electrical energy without battery. The choice of the energy harvesting sources depends on the nature of the application and power requirements of the particular electronic load

(Dayal *et al*., 2013). Macro-energy harvester mainly focuses for oil dependency and to reduce carbon emission. The sun, wind, tides and waves are the most suitable energy sources for the macro-energy harvesters. Typical power ranges from kilowatts to megawatts produce by macro-energy harvester. While micro-energy harvester, energy is limited in the range of nanowatts to milliwatts from thermal, vibration and solar (Colomer-Farrarons *et al*., 2011) with the goal is for wearable devices and to power up wireless sensor network (Nimbalkar and Kshirsagar, 2013).

Thermal based energy harvester is one of the most eco-friendly energy sources and particularly useful in biomedical application due to zero emission, compactness, high reliability, inferior noise, cleanness of energy production and zero fuel consumption (Han *et al*., 2010). TEG can generate a voltage which is proportional to the temperatures difference applied to each side. TEG uses seebeck effect which is converting heat (temperature difference) directly into electrical energy. The free charge carriers will drive to the cold end as the heat flows from hot side to cold side. When the temperature difference across the module increases and the efficiency of converting heat energy into electric energy also increases, the more electricity will be generated. TEG exploits temperature gradients to generate power. The advantages of TEG from human body heat are steady and large (Jo *et al*., 2012). But with limited physical dimension of the TEG device and the difference of temperature between the ambient and the human body will make the induced voltage from TEG could be as low as 10 mV (Weng *et al*., 2013).

Energy harvester has approaches three methods for vibration which are piezoelectric (PZT), electrostatic (capacitive) or electromagnetic (inductive). Vibration source will transfer mechanical energy and convert into electrical energy. The major limitation of existing vibration harvester is in the interface mechanism. Generally, by using full wave rectifier and voltage doubler in the circuit will control and fix the power generated from a vibration substrate. The power used from the control mechanism will reduce the total of usable electrical power. Ramadass and Chandrakasan (2010) used a bias-flip rectifier to recover the potential power extraction from PZT over existing full bridge rectifier by increasing it 4 times. The filter inductor with the bias flip rectifier will be used in DC-DC converter with an efficient control circuit to reduce the total of component count.

Hybrid Micro Energy Harvester (HMEH) is suggested to produce a suitable input that can be implemented to micro biomedical devices. TEG will produce low input compare to vibration in a realistic case. Hence, HMEH system will specify the proper input to be connected to the load. For replacing the existing battery, Micro Electro Mechanical Systems (MEMS) able to generate electrical power for implantable biosensors (Lueke and Moussa, 2011). MEMS technology has been used to design a variety of integrated bio-analytical devices with the batch fabrication and integration of miniaturized devices at low cost (Wang *et al*., 2008). In biomedical applications, MEMS based micro power generator gaining notoriety due to the nature of small size and low power consumption. In upgrading the performance of the biosensor's mechanism, additional components like computational and wireless need to be added (Chandrakasan *et al*., 2008). For this study, the low voltage energy harvesting systems will be focused on ULP HMEH by using TEG and vibration. Then, the HMEH system will be used for micro bio-medical devices.

Most of the energy harvesters in practically able to supply 10-100 μW of an output power, by adjusting a restriction on the moderate power that able to be used for self-powered operation of the load circuitry (Chandrakasan *et al*., 2008). The human body heat proposes a simple source of energy for healthcare applications. Base on seebeck effect, energy can be harvested using TEG which converts thermal energy into electricity directly. A simple TEG is a device that consists of an array thermoelectric couple (thermocouple) composed of two elements p-type and n-type semiconductors. They are attached thermally in parallel and electrically in series to form a thermoelectric module (Abdul Rahman *et al*., 2013). Besides TEG, vibration also can be converted into electrical energy. Generally, the voltage used in vibrational energy harvesting is an AC but in ubiquitous loads always use a DC voltage for their operational. Therefore, a rectification stage is needed in order to convert AC to DC voltage (Rao and Arnold, 2011). It has a competent control circuit to adjust the output voltage generated from rectifier. In PZT, the direct connection to the load is not recommended to increase the power harvested (Mehraeen *et al*., 2010). Therefore, they suggested an efficient stand-alone of energy harvesting circuit consist of a PZT cantilever beam, rectifier, voltage inversion circuitry and power converter.

Hybrid energy harvester combines input sources into a single system to enhance system reliability and functionality (Calhoun *et al*., 2010). It provides more and enough power delivery for variety environmental conditions (Hamilton, 2012). When using hybrid inputs system, the amount of required components will increase in terms of cost and volume specifically for the passive component like inductor (Dhople *et al*., 2010). Tan and Panda (2011) have presented the idea of energy harvesting from ambient thermal and light to solve the limitation of the single source. They used one power management circuit to prolong the lifespan of the wireless sensor node besides reduce the power losses and cost. They performed a good efficiency of 90% for the power management with the power consumption around 135 μW. Kadirvel *et al.* (2012) inspired one power management unit as well with the charger efficiency of >80% at 330 mV start-up voltage. While Bandyopadhyay and Chandrakasan (2012) have been involved in a dual path architecture which consists of a reconstruct multi input and output with an improvement in peak efficiency equal to 11-13%. Utilizing only a single inductor, the system can harvest the input voltages from 20 mV to 5 V and produce maximum output power. Lim *et al.* (2014) combine three input sources; thermal, motion and indoor light in parallel using a DC-DC boost converter. The circuits can harvest input voltage from 18 to 907 mV and produce output voltage of 310 mV-27.9 V. In the case of boost converter, it is pivotal to match these inputs impedances to its load for getting the maximum harvested power.

Weng *et al.* (2013) reported that the energy harvester circuits achieved the efficiency up to 73% and Carlson *et al.* (2010) presented 75% of the efficiency for higher conversion ratio inferior power boost converters. However, the number is considered inferior for human body energy harvesting application due to the total of power is very limited. Carlson *et al*. (2009) and Richelli *et al.* (2009) used DC-DC converter to expeditiously take out power from a deficiently controlled low-voltage power source. The system can collect energy around it efficiently and break the limitation of the environment with energy management interface (Chou *et al*., 2014). The system achieves efficiency up to 73% of Pulse Frequency Modulation (PFM) switching regulator and quite useful in low power system like biomedical sensing system. To minimize the power consumption and maximize the efficiency of 61.5%, the boost converter works in discontinuous conduction mode as the inductor current is forbidden to flow from negative side (Carreon-Bautista *et al*., 2014). Dayal *et al.* (2013) had implemented the discontinuous conduction mode allowing the technique of synchronous rectification. It is able to produce a switched mode DC-DC boost converter which is efficient to generate 1 V output from the lowest input voltages of 20 mV (Carlson *et al*., 2010). Wahab *et al.* (2014) presented a parametric analysis with passive components for boost converter from PZT and the result shows the input voltages increase from 0.1-0.5 and 7.0-35 V. As shown by Shi *et al.* (2011) for delivering maximum power, multiple input boost converters using a single inductor is merged with an automatic digital control technique. While Bandyopadhyay and Chandrakasan (2012) reduced the components count by the output level and time sharing inductor.

A new method for implementing maximum power scheme is presented by dominating the duty cycle of the converter to maximize the power system output (Dayal *et al*., 2013). The control system uses only simple mixed signal components and can be applied for low power systems. The controller utilizes two different systems; electromagnetic micro generator with an AC-DC boost converter and a miniature solar cell array. The voltage regulation for single stage conversion can be achieved by employing a linear regulator after the power converter design (Doms *et al*., 2009a). Power converter for TEG harvester require one time impedance tuning during installation with inductor sharing which has 58% peak efficiency (Bandyopadhyay and Chandrakasan, (2012). As the power input is also varying, an additional energy management stages are needed for the system. These power circuits have the ability to provide impedance matching to attain maximum energy potential of the sources and also responsible for relevant step-up or down conversion.

Ramadass and Chandrakasan (2011), Carlson *et al*. (2010) and Chen *et al*. (2012) addressed a low voltage issue from thermal harvester. Hence, the start-up circuit used an array of discrete MOSFETs which is worked with appropriate gate threshold to kick start the system operation. Doms *et al*. (2009b) and Carlson *et al*. (2009) have used storage or starting high voltage input to initialize and start the system operation from low voltage. Basically, a start-up circuit consists of energy storage, a regulated DC-DC buck converter and inductive boost converter. Chen *et al*. (2012) presented a start-up voltage DC-DC converter without using additional off-chips components, the capacitor pass-on technique allow the system operation under the low power voltage. Ramadass and Chandrakasan (2011) recommended the start-up circuit for TEG harvester due to an extremely low input voltage. The load and harvester needs to be isolated due to a start-up failure mechanism reported from Torah *et al*. (2007). Figure 1 shows the diagram of micro power management for controlling the burst powering on the load (Stark *et al*., 2010). The voltage detector circuit near to the segregation switch will power up the boost converter.

Carreon-Bautista *et al*. (2014) recommended the Maximum Power Point Tracking (MPPT) system operating in a discontinuous conduction mode with Pulse Frequency Modulation (PFM). It is also implemented to a boost converter by a Pseudo Zero Current Switching (P-ZCS) scheme to achieve high efficiency. The matching impedance is achieved through the MPPT system via PFM to reduce losses and improve efficiency (Mi *et al*., 2013). The internal impedances can range from S sec to kS sec. Pulse Counting Control (PCC) is suggested in Shi *et al*. (2011) as an adaptive method so that the imitated resistance of the converter drives to maximum power extraction for every source. Dhople *et al*. (2010) proposed a Multiple-Input Boost (MIB) to carry out MPPT in emergent module combined with micro-converters and micro-inverters. The result showed the MIB converter achieved up to 9.6% more power contrasted to an individual boost converter.

The Complementary Metal Oxide Semiconductor (CMOS) technology dissipates low power due to the flow of leakage currents. The static power dissipation is 10 nW per gate. A lot of works

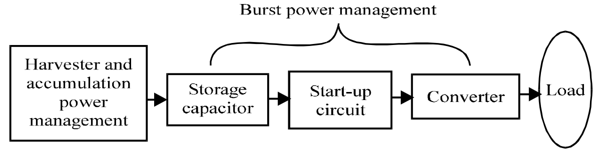

Fig. 1: Micro power management (Stark *et al*., 2010)

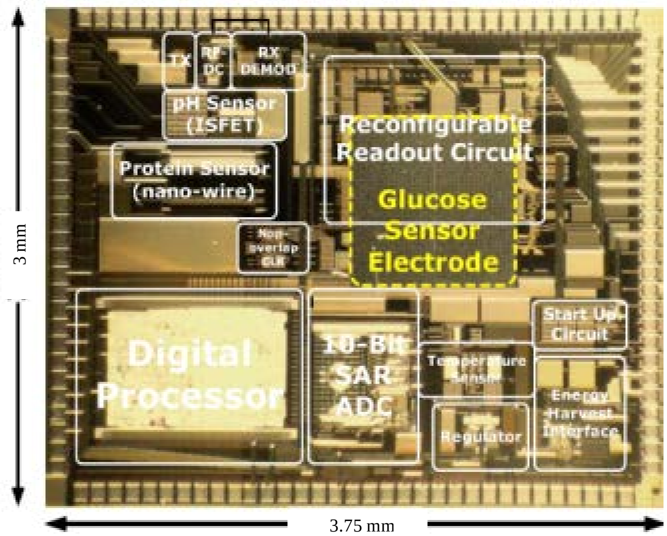

Fig. 2: Micrograph chip photo (Huang *et al*., 2014)

reported that CMOS process is based on doped polysilicon materials. Abdul Rahman *et al.* (2013) presented the CMOS TEG design consists of 220 thermocouples in series. Phosphorus and boron doped polysilicon are used to produce n-type and p-type semiconductor element. Its work based on seebeck effect and occupies a dimension of 1300×3000 μm with output voltage and power generated is 301 mV and 45 μW, respectively. Huang *et al.* (2014) fabricated a 0.35 μm CMOS process followed by post-IC process for real time biomedical monitoring. Figure 2 represents a micrograph chip photo for die area of 3×3.75 mm with efficiency of 73%. The chip comes together with a part of Micro Electro Mechanical System (MEMS) glucose sensor as a physiological parameter including start-up circuit, energy harvest interface, digital processor and regulator which is similar with the architecture that we proposed in term of sub modules implementation.

In our proposed work, the HMEH mechanism is designed to pick up and combine energy from input sources of TEG and vibration simultaneously, then transform it into electrical energy. The key point for our ULP based HMEH system is the way to enhance efficiency of acquiring energy from the surrounding. Among them, the TEG is well-established in physical theory and be the first one to appear on the market with solid state technology and low temperature gradients. HMEH sources from TEG and vibration are combined in this work to efficiently achieve ULP consumptions and increase the power efficiency.

METHODOLOGY

The aim of this work is to point the drawbacks faced by previous researchers in finding the suitable input from energy harvesters. Figure 3 shows a conventional block diagram for hybrid energy harvester topology with an individual ULP control unit. Colomer-Farrarons *et al.* (2011) has option to sum the sources together or use them individually, but this approach will increase the cost and power losses. Furthermore, the parasitic resistance and capacitance will cause conduction and switching losses, respectively. Besides that, leakage current and power used in the control circuit also contributed in decreasing the capability of the hybrid energy harvester sources.

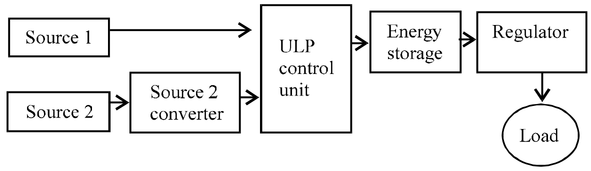

Fig. 3: Conventional architecture of hybrid energy harvester (Tan and Panda, 2011; Sarker *et al*., 2011)

The major challenge comes from the voltage side. It is extremely low and high input voltages for TEG and vibration, respectively in micro device inside the human body. The voltage range around 20-50 mV cannot be utilized directly to operate the interface circuit. The generator output voltage is the main difficulty in designing a power management unit for both sources (Alhawari *et al*., 2013). It will use to supply the remaining energy into storage like a capacitor or a battery. Mateu *et al.* (2007) reported that the TEG utilizing heat from human hand have a maximum current of 18 mA with voltage range generated from 150-250 mV. While for human hand vibration capable to harvest 24 mW maximum power with an output voltage of 3 V from low ambient source of 0.5 V (Rahaman *et al*., 2015). Alhawari *et al.* (2013) highlighted that Process, Voltage and Temperature (PVT) variations considered as the main challenges in CMOS technology of the circuit design. It shows that all the circuit metrics are function across PVT combinations as the efficiency of the conversion circuit will change with PVT variations.

Therefore, our proposed design will have two input sources, TEG and vibration to provide suitable threshold input voltage that can be applied in micro biomedical devices. The sources can be combined or used them separately. Basically, vibration energy circuit required converter stage which is rectifier part to convert output voltage from AC-DC (Sarker *et al*., 2013). In determining the proper input voltages, a start-up circuit will be implemented. Many start-up circuits have been proved in previous reviews like a motion activated switch (Ramadass and Chandrakasan, 2011) and fully electrical method (Chen *et al*., 2012). DC-DC converter will be used to boost up the input voltage to a desired value. It is a challenge to address impedance mismatching among the integration of the energy sources as stated by Tan and Panda (2011). Hence, the proposed HMEH system will have MPPT to produce maximum power and solve this impedance mismatch issue. The aim for the proposed design is also to have as low power consumption as possible to achieve maximum efficiency of 93% with minimal losses. Thus, the components using will be selected properly based on their power consumption. The target inputs and outputs are in range of 80-600 mV and 2.0-4.0 V, respectively. The proposed HMEH system will be applied on a 0.13 μm CMOS process technology and downloaded into Field Programmable Gate Array (FPGA) for real time verification.

Design of flow chart to proposed method: The design flow chart for the proposed research with title “An Architecture of Ultra Low Power Micro Power Generator Using Hybrid Input Micro Energy Harvester for Biomedical Devices” is performed as in Fig. 4.

To carry out this research work, firstly it is starting with a comprehensive literature reviews and finishing up with the implementation of the develop ULP HMEH in biomedical devices. To perform this work, we will explore the review survey from literature on the HMEH architectures and also the behaviour of the MPPT algorithm and charging techniques. Then, HMEH sub-blocks will be designed, modelled and simulated in PSPICE software. The initial voltage from 80-600 mV will be

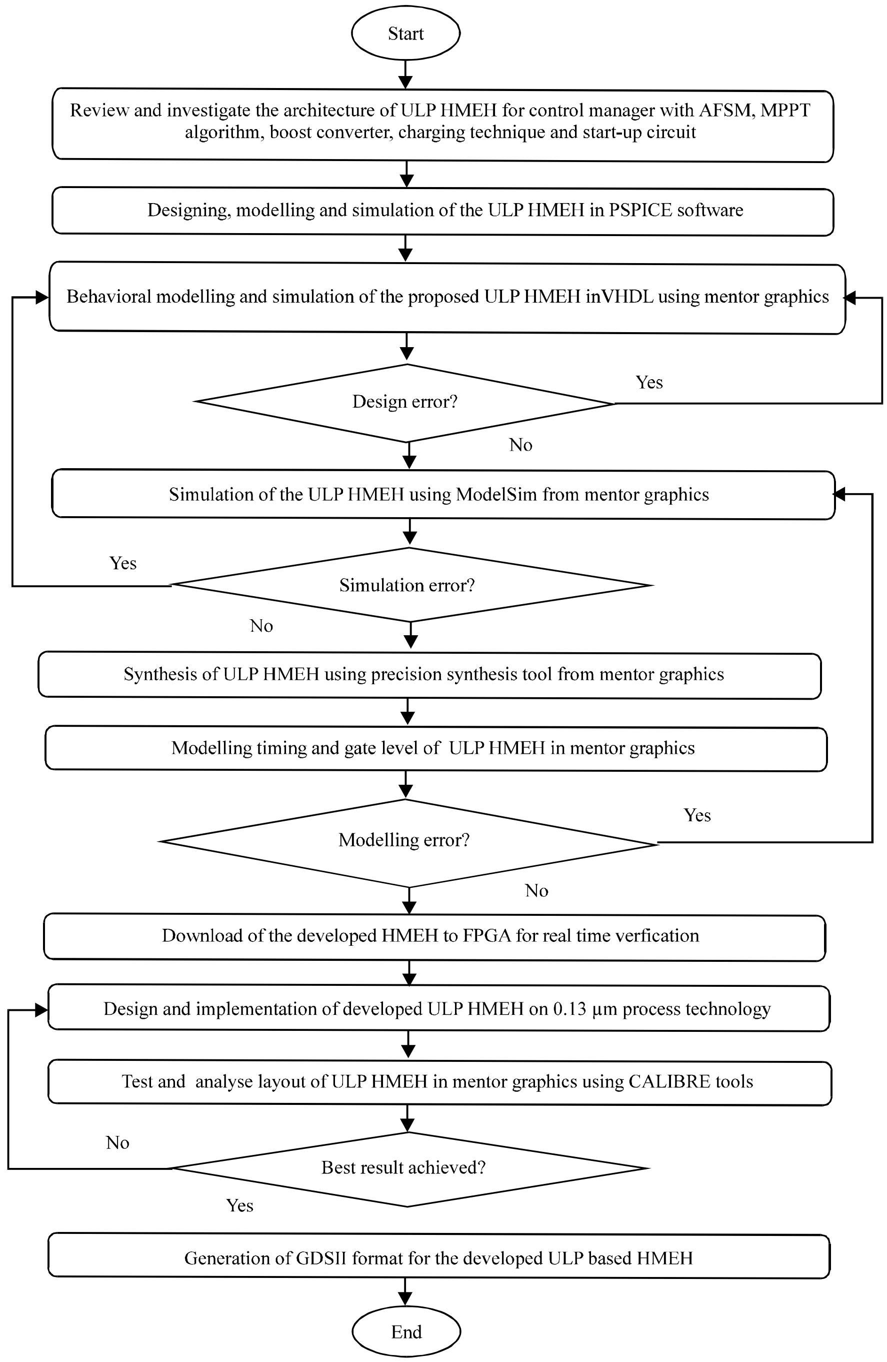

Fig. 4: Design flow chart of ultra low power hybrid micro energy harvester architecture

achieved from HMEH. The literature survey and design stage will be done again if any erroneous or undesirable simulations results happen especially on power consumption, efficiency, input and output voltage. After completing simulation of the proposed ULP HMEH in PSPICE, VHDL based mentor graphics will be used to write coding for controller manager with AFSM and also for MPPT algorithm. The ModelSim will be used to simulate the proposed design of ULP HMEH and if any contradictory in design or simulation in this level will be redesigned using mentor graphics. Then, by using precision synthesis tool the behavioral model of ULP HMEH is synthesized to allow a gate level simulation. If there is any simulation error for the gate level and timing, the synthesis stage will be done again before downloading into the FPGA for real time verification. Next, the ULP HMEH will be designed on the 0.13 µm CMOS technology implementation. The completed layout of ULP HMEH then will be tested and analysed using CALIBRE tools under mentor graphics. Finally, the developed ULP HMEH will be generated the GDSII format for real life implementation after successful in testing and analysing stage.

RESULTS AND DISCUSSION

Table 1 summarized the specification work on hybrid energy harvester from past researchers. The proposed block diagram for ULP HMEH system is shown in Fig. 5. It consist of 8 blocks which are hybrid input sources of Thermoelectric Generator (TEG) and vibration, rectifier, control manager, start-up or kick start input, boost converter, MPPT algorithm, energy storage and voltage regulator, respectively. All of the blocks will be integrated and then implemented to a biomedical device (load).

Firstly, Block 1 represents the HMEH input sources from TEG (human temperature gradient) and vibration from body to be applied for biomedical devices. The main proposed why hybrid input is introduced due to single input sources has many limitations of robustness, energy efficiency and output power. TEG harvesting has limited physical dimension and will be induced a low voltage. Only vibration source produce AC signal and not suitable supply directly to the load. Therefore, body vibration source require rectification stage (Block 2) from voltage doubler (Rahaman *et al*., 2015; Tabesh and Frechette, 2010; Mi *et al*., 2013) to produce DC signal before interfacing with TEG input and operate the whole system. To achieve a proper DC voltage, MOSFET will be used in designing AC-DC full wave rectifier circuit without facing loss voltage.

Secondly, both hybrid input sources will be connected to a control manager with an Asynchronous Finite State Machine (AFSM) as in (Block 3) to expeditiously share the resources and supervise single or total of the power supplies (Mi *et al*., 2013; Shi *et al*., 2011). The AFSM is to arrange preference between the hybrid sources when they perform at the same time. If the source is limited which is only the minimum input of TEG source is available and not capable to operate the AFSM block, a pre amplifier or kick start circuit will be added to gain more signal of the TEG input. Thirdly, the start-up circuit which acts as voltage detecting switch (Block 4) will be integrated after getting the desired input of 80-600 mV from AFSM as a kick start signal. Chen *et al.* (2012) used start-up mechanism like an external voltage or another power management circuit to generate higher auxiliary voltage ($>V_{TH}$).

After determining the desired input from control manager with AFSM, the voltage requires to be boosted by a boost converter mechanism (Block 6). There is a condition for the voltage to come out from start-up circuit which is not suitable to boost the voltage. So, MPPT algorithm (Block 5)

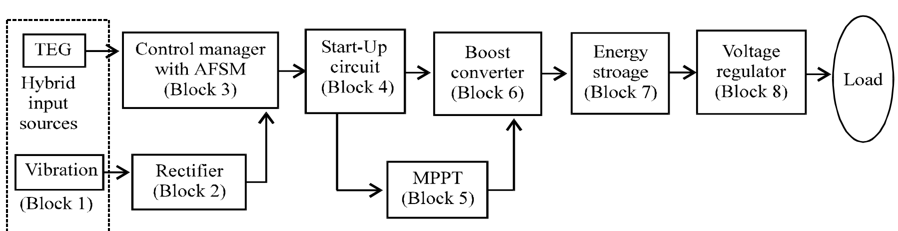

Fig. 5: Proposed architecture of hybrid micro energy harvester (HMEH)

Table 1: Summary performance of the hybrid energy harvester circuit from past researches

Sources	Architecture	V_{IN} (V)	V_{OUT} (V)	PIN (μW)	POUT (μW)	Boost converter	MPPT	Start-up	Peak 0 (%)	Process Tech.	Application	Researcher (Year)
TEG	Charge pump, Pmc with DC/DC	Not stated	1.508	3.95	2.29	Yes (charge pump)	No	Yes	58	0.35 μm	Buffer	Doms *et al*. (2009a)
TEG	Boost converter, synchronous rectification	0.020	1.0	233.33	175	Yes	No	Yes	75	0.13 μm	Thermo harvesting	Carlson *et al*. (2010)
Magnetic	AC AC, DC DC converter, active diode, boost converter, rectifier	0.6	3.0	6500	3900	Yes	No	No	60	0.5 μm	Electro-dynamics (magnetic) vibrational	Rao and Arnold (2011)
TEG, Light	Boost converter with MPPT, PWM generation, energy storage and regulating buck converter	3.6	5.5	756	621	Yes	Yes	No	90	H/W prototype	WSN	Tan and Panda (2011)
PV, TEG	Charger, MPPT, oscillator, charge pump	0.5	3.0	Not stated	Not stated	Yes (Charge pump)	Yes	No	80	IC fabricate	Battery and super capacitor charger	Kadirvel *et al*. (2012)
PZT	Power conditioning circuit, MPP algorithm	0.5	3.0	26667	24000	Yes (Charge pump)	Yes	No	90		WSN	Rahaman *et al*. (2015)
TEG, Vibration	Boost converter, MPPT control, low voltage start- up, resource sharing arbiter	0.08-0.6	2.0-4.0	>750	>690	Yes	Yes	Yes	>93	0.13 μm	Micro bio Medical	This work Author (2015)

will be modelled to achieve and enhance maximum power extraction before boost up the voltage. At the same time, impedance matching is also considered from hybrid input to overcome the probability of impedance mismatch. When the voltage is boosted to the desire input, all operation consider done for the half way and the Energy Storage block (Block 7) is operated and the energy is kept in a storage capacitor. Kim and Kim (2012) used the storage capacitor with ZCS for semi-lossless. For the final stage before connecting to the load, a voltage regulator (Block 8) is activated to fix the value of the output voltage which is 2.0-4.0 V. This architecture will be implemented on the 0.13 µm CMOS technology with minimal losses and achieve efficiency of about 93%.

CONCLUSION

Architecture of ULP HMEH has been proposed with the sources from TEG and body vibration. The main target in this study is to achieve maximum conversion efficiency with minimal power losses. The proposed of ULP HMEH will be designed, modelled and simulated in PSPICE software while the MPPT algorithm and charging technique will perform in VHDL using Mentor Graphics. Next, the proposed ULP HMEH will be downloaded into a FPGA board using 0.13 µm CMOS technology for real time verification. Finally, the expected result is to achieve an efficiency of about 93% with an input voltage range between 80-600 mV and output regulated voltage ranging from 2.0-4.0 V. Furthermore, the ULP based HMEH will reduce power consumption to 60 µW compare to the others HMEH conventional approaches with expected output power of 690 µW to be used in biomedical application.

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