Multi-Source Energy Harvesting Management and Optimization for Non-volatile Processors

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***Abstract*—Due to size, longevity, safety, and recharging concerns, energy harvesting is becoming a better choice for many wearable embedded systems. However, harvested energy is intrinsically unstable. In order to overcome this drawback, non-volatile processor (NVP) was proposed to bridge intermittent program execution. However, even with NVP, frequent power interruption will severely degrade system performance. In this paper, we will propose a multi-source energy harvesting system to combine multiple harvesting sources to provide a more stable power supply. Maximum power extraction and converter parameter optimization techniques will be discussed. Preliminary experimental results show the proposed architecture is very promising in providing a stable energy source for NVPs.**

I. Introduction

The vision for wearable devices is to interweave embedded system technologies into our everyday life and improve the quality of life. While the vision is promising and exciting, there are several challenges in achieving this goal. One of the imminent challenges is how to power these embedded devices. While battery power has been the energy source for most embedded systems nowadays, it is not a favorable solution for wearable devices due to size, longevity, safety, and recharging concerns. Therefore, researchers are actively pursuing power alternatives. Out of all possible solutions, energy harvesting is one of the most promising techniques to meet both the size and power requirements of wearable devices.

Energy harvesting devices generate electric energy from their ambient environment using direct energy conversion techniques. Examples of power sources include kinetic, light, RF, and thermal energy. The obtained energy can be used to power the electronics. However, there is an intrinsic drawback with harvested energy. They are all unstable. With an unstable power supply, the whole computer system will be interrupted frequently. What is worse, large tasks could possibly never finish since the intermediate results cannot be saved.

In order to attack this problem, NVP has been proposed to enable instant on/off for these devices. In NVP, a non-volatile FRAM is attached to the processor's volatile registers. Every time there is a power outage, the processor's state will be saved to the NV FRAM. Then the next time the power comes back on, the processor's state is copied back to the volatile registers and program execution resumes. In this way, we can make sure the program execution is "accumulative" and resistant to frequent power outage.

However, even with NVP, frequent power interruption will cause severe performance degradation. NVP mainly operates in-door and relies on in-door energy harvesting techniques. A single in-door source energy harvesting is variable and often sporadic due to its high dependency on environmental conditions and energy flow fluctuation. In addition, the available harvested power is limited to few mWs. Hence, relying on single-source energy harvesting will limit the system performance. In this paper, we aim to combine multiple energy sources (e.g., Thermoelectric Generator (TEG), Photovoltaics (PV), Piezoelectric (PZ)) to compensate the limitations and increase overall power extraction efficiency to provide a sufficient and stable power source.

II. Related Works

Energy harvesting extracts power from the ambient environment and can be used to deploy long lifetime battery-less devices. Solar [1], wind [1], footfalls [2], [3], breathing [2], blood pressure [2], and body heat [4] are all promising sources of energy. They have different characteristics of predictability, controllability, and magnitude. For ultra low power devices, the sources of low power densities, such as micro-solar, breathing ($0.42W$), and body heat ($2.4{\sim}4.8W$) are able to provide sufficient power to drive the devices at low duty cycles [5], [6].

III. Multi-Source Energy Harvesting

Multi-source energy harvesting devices face three important challenges which include: 1) Wide range of input voltages (20 mV to 5 V); 2) Wide range of harvester impedances (ohms to kilo-ohms) and hence different maximum power extraction techniques need to be used; 3) Circuit component sizing. Also there is a need for an efficient architecture of multi-source energy harvesting system for NVPs, which exploits all energy harvesting sources without the battery storage element.

Figure 1 illustrates the proposed system architecture of the multi-source energy harvesting system for NVPs, with three harvesting sources: in-door PV, TEG, and PZ devices. Unlike traditional cascade connection of two stages of DC-DC converters, single DC-DC converter is utilized between the in-door PV and NVP and between the TEG and NVP, due to the elimination of battery. On the other hand, cascade connection of AC-DC rectifier and DC-DC converter is used between PZ and NVP since the harvested power from PZ devices is AC by nature. Since the operating voltage of NVP is around 1V, buck converters are needed for PV and PZ devices (due to their relatively high output voltage) while boost converter is

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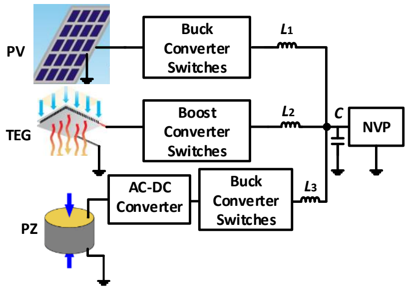

Fig. 1. System architecture of multi-source energy harvesting for NVPs.

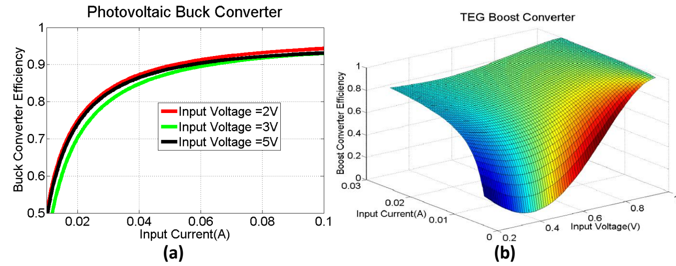

Fig. 2. Energy efficiency of (a) PV converter and (b) TEG converter as function of input voltage and current.

needed for TEG (due to its low output voltage). We use shared filter capacitor of DC-DC converters in order to simplify the multi-source harvesting structure. Compared with [7] (which shares inductor in DC-DC converters), our structure simplifies the system control methodology and provides more flexibility of utilizing separate maximum power extraction methods for different energy harvesting sources, thereby improving overall efficiency.

We further propose to address two main issues in the design and control of multi-source energy harvesting system: maximum power extraction and converter optimization.

A. Maximum Power Extraction

Most of energy harvesting sources, e.g., in-door PV, TEG, PZ, can be modeled as a time-variant voltage or current source and a circuit element (e.g., resistor) limiting the maximum extractable power. In order to extract the maximum power from each energy source, the switching duty ratio of DC-DC converter needs to be dynamically adjusted such that the input impedance of converter matches the internal impedance of the harvesting energy source. Since our proposed system comprises three intermittent energy harvesting sources with distinct characteristics, efficient maximum power extraction technique is required for each type of harvesting source to take advantage of its unique characteristics. These techniques are integrated in the harvesting system controller.

For PV energy harvesting, *maximum power point tracking* (MPPT) techniques such as perturb and observe (P&O) or hill climbing methods [8] are utilized to maximize the power extraction. However, they require voltage/current sensing at the output and a feedback loop to dynamically adjust the switching duty ratio of DC-DC converter, and thus may not be appropriate for in-door usage where the harvesting energy is highly intermittent. An important observation of PV energy harvesting is that the voltage at maximum power point (MPP) is close to a constant value (around 70%-80% of the open-circuit voltage) even at different irradiance levels. Hence we find the optimal switching duty ratio offline such that the PV panel voltage is fixed around 70%-80% of the open-circuit voltage (or using a set of duty ratios if DVFS is supported in NVP). In this way we can approximately extract the maximum amount of power with minimum overhead of controlling technique. For the TEG and PZ, traditional MPPT techniques such as P&O or hill climbing are still required because of the highly variable terminal voltage at MPP for TEG and PZ devices.

B. Converter Parameter Optimization

In order to maximize the overall energy efficiency, converter parameters need to be optimized separately for each energy source. Since the inductance and capacitance values in a converter are largely determined by the ripple magnitude constraint, we propose to optimize for the best-suited MOSFET switch size inside each converter based on the input energy source characteristics. A wide MOSFET switch will increase the energy consumption of turning ON/OFF the switch whereas a narrow MOSFET switch will increase its internal resistance. Based on our power converter modeling from actual measurements [9], we derive the optimal MOSFET switch size in converters connected to the PV and TEG, such that the average energy efficiency can be optimized over the whole operating range. Figure 2 (a) illustrates the resultant energy efficiency for the PV converter as a function of input voltage and current (with output voltage fixed at 1V), and Figure 2 (b) illustrates energy efficiency for TEG converter.

IV. Conclusion and Future Works

In this work, we briefly describe the proposed architecture with maximum power extraction and converter parameter optimization techniques. In the future, we will propose a detailed framework and optimization techniques to achieve more stable harvested energy supply for NVPs.

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