A 1.2µW SIMO Energy Harvesting and Power Management Unit with Constant Peak Inductor Current Control Achieving 83-92% Efficiency Across Wide Input and Output Voltages

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Abstract

This paper presents a single inductor energy harvesting and power management (EHM) unit for ultra-low power (ULP) systems. The proposed circuit harvests energy from solar cells from 0.38V input voltage (Vin) and provides 4 output voltages - storage at 5V and V_{DD}s at 3.3V, 1.5V and 1.2V. A peak inductor current control scheme enables high efficiency operation across wide input and output voltage range. The IC supports maximum power point tracking, battery management, and cold starts from 0.38V Vin.

Introduction

Energy harvesting from ambient sources such as solar or thermal can enable batteryless operation of wireless sensors, body sensor nodes (BSNs) [1], or the Internet of Things (IoT). The energy harvested from a solar cell depends on illumination level and can vary greatly. The energy harvesting system should harvest efficiently in varying condition to prolong the system life time. Further, BSNs, like most SoCs, need multiple supply rails to power core circuits, memories, and RF and IO cells. The existing solutions for BSNs use low drop out (LDO) regulators with low efficiencies [1]. ULP SoCs need EHM system that can efficiently harvest energy from ambient sources and also provide multiple regulated output voltages. Single inductor multiple output (SIMO) EHM systems have been proposed to provide low cost and efficient solution for ULP systems [2]. In this paper we present a SIMO EHM system that can harvest from a solar cell (0.38V to 3.3V i/p voltage) to a storage capacitor or a battery. It also provides multiple output voltages at 1.2V, 1.5V and 3.3V using the same inductor. It supports 0-5V output voltage for capacitive storage and 1.7-5V for a battery interface (Fig. 1). It has a maximum power point tracking (MPPT) circuit, an over-voltage and under-voltage protection scheme for battery management, and a cold start circuit operational at 0.38V. A peak inductor current (I_{PEAK}) control scheme helps in achieving high efficiency across varying input and output voltages.

EHM Architecture

The output power from solar cell cannot meet the peak power needed by the system for activities such as RF communication. Therefore, the energy from the solar cell is first stored on an energy accumulator (capacitor or battery) and used to supply the other V_{DD} rails [1]. Fig. 1 shows the concept of the switching scheme used in our EHM system. A single inductor (L_{SHR}) is shared to generate the V_{DD} rails and is also used for the boost converter for energy harvesting. The storage or battery is kept on the +ve side of L_{SHR} and PV module and the V_{DD} rails on the -ve side. The inductor current flows from the –ve of L_{SHR} to the +ve terminal for harvesting and from +ve to -ve for supply regulation (Fig. 2). Fig. 3 shows the complete architecture of the proposed EHM system. A SIMO control scheme operates all converters in the design in discontinuous conduction mode (DCM) using a pulse frequency modulation scheme (PFM) for higher efficiency at light loads. Each converter generates two output signals, Busy and Ready. Using the Busy and the Ready signal, the digital controller generates enable signals (ENs) based on priority to enable a particular converter which in turn controls the common shared switches MP and MN using signals for high side (HS) and low side (LS) switching controls (Fig. 3).

Control Circuit

Fig. 4 shows the control architecture of the EHM buck converter. It implements a PFM control scheme with peak inductor current (I_{PEAK}) control for HS switching and inductor zero current detection (ZD) for LS switching. A 70nA comparator is used for low power regulation (Fig. 5). The converter generates Busy and Ready signals for the digital controller. The comparator, I_{PEAK} control and ZD scheme enables high efficiency for the buck converter from 1µA to 30mA load current. I_{PEAK} control is necessary for efficiency optimization but the conventional R_{DS}-on method to control I_{PEAK} is sensitive to mismatch (+/-20%) and has large power overhead [3]. Fig. 6 shows the proposed I_{PEAK} control scheme which is less sensitive to mismatch and well suited for low power systems. A large resistor R sets the node A close to the threshold voltage of M_1. Therefore voltage at A (gate of M_2) equals $Vo-V_T$. M_2 is a long channel device (10µm long), so its current is given by,

$$I = K\mu C_{ox}(Vo - V_T - Vi + V_T)^2 = K\mu C_{ox}(Vo - Vi)^2 \quad (1)$$

The capacitor C_X is pre-charged to $V_O/2$ and it goes to Vi/2 during the switching cycle, so HS turn on time, T_H is given by,

$$T_H = C_X(Vi - Vo)/2I = C_X/2K\mu C_{ox}(Vo - Vi) \quad (2)$$

Peak Inductor current is approximately given by,

$$I_{PEAK} = (Vi - Vo)T_H/L_{SHR} = C_X/2K\mu C_{ox}L_{SHR} \quad \{\text{Using (2)}\} \quad (3)$$

The expression in (3) is independent of input voltage Vi, output voltage Vo, and the V_T of the transistor enabling a constant peak current for wide input and output voltage range, controllable with the size of on-chip capacitor C_X. Fig. 7 shows the measurement of I_{PEAK} from 3.5V to 5.5V Vi achieving less than 3% variation. Monte-carlo simulation show +/-6% variation for mismatch (Fig. 8). The process variation in I_{PEAK} can be controlled by trimming C_X. A similar I_{PEAK} control scheme is used for boost converter as well for higher efficiency.

Further, the design also supports 5V storage for various battery chemistries using 5V drain extended (DE), 3.3V gate oxide transistors. A specialized level converter insures high gate oxide reliability for 5V operation. The boost converter uses a constant voltage MPPT scheme set at 0.76 of PV's open circuit voltage which was verified in measurements. A cold-start circuit enables start-up from 0.38V (Fig. 9). It also provides over-voltage, under-voltage, and a power good signal for storage voltage.

Measurements

The proposed EHM system is implemented in 130nm CMOS process with drain extended devices to support 5V operation. It has an area of $1.5x1.5mm^2$. Fig. 10 shows the measurement result of the multiple regulated EHM output voltage starting from 0.38V Vin. The system can support peak load of 30mA on 3.3V V_{DD} with other rails lightly loaded or peak of 10mA on each V_{DD} (max 30mA/100mW total). The maximum ripple on the V_{DD} rails is ~3% at high load (Fig. 5 and Fig. 11). Peak measured efficiency (η) of 92% is achieved on 3.3V rail at high load and 83% at 1µA load (Fig. 12). The 1.2V and 1.5V V_{DD} have peak efficiency of 83% and 82% respectively. The boost converter has efficiency of 81% at 0.4V PV module supplying 10µA short circuit current and 92% at 3.3V (Fig. 12). Fig. 13 shows the die photo. Fig. 14 shows the comparison of the proposed EHM system with state-of-the-art energy harvesters. Among the reported work, this work is the first complete EHM system with energy harvester, multiple regulated voltages, battery management, a cold start circuit, a wide input (0.38-3.3V Vin) and output voltage (5V) support. The solution in [2] has energy harvester and two regulated output voltage but it doesn't support wide input voltage range, battery management or cold-start. The solution in [6] provides battery management but doesn't support voltage regulators. We also support maximum output power of 100mW, 4X more than [5] and 10X more than [2]. The use of SIMO for energy harvesting and voltage regulation with I_{PEAK} control enables complete and efficient energy management system for WSNs or IoT.

References

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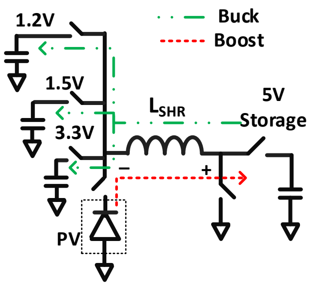

Fig. 1 Switch arrangement for EHM system

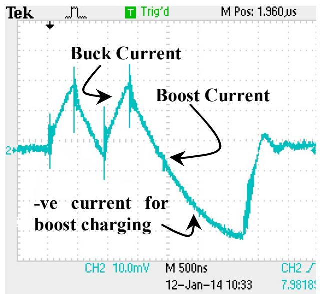

Fig. 2 Measured Inductor current waveform for EHM

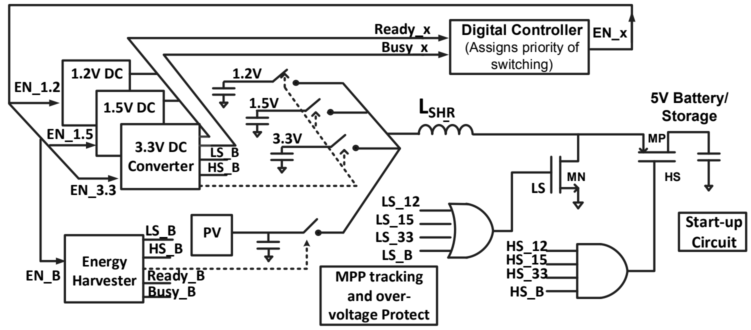

Fig. 3 Complete architecture of the EHM System

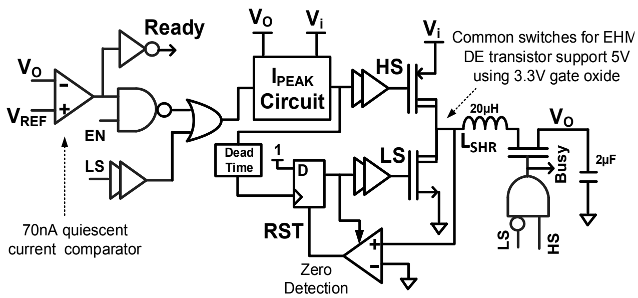

Fig. 4 Architecture of the buck converter used in EHM

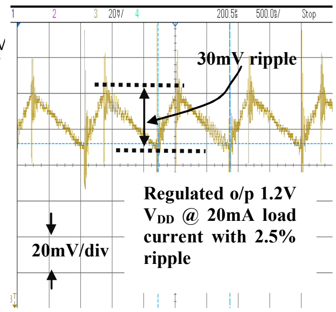

Fig. 5 Measurement of 1.2V V_{DD}

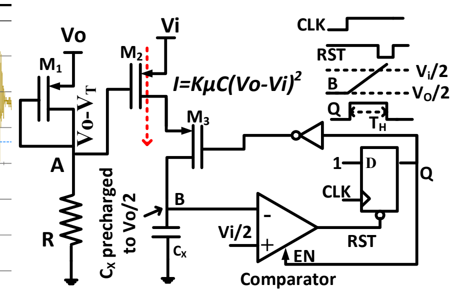

Fig. 6 I_{PEAK} control scheme

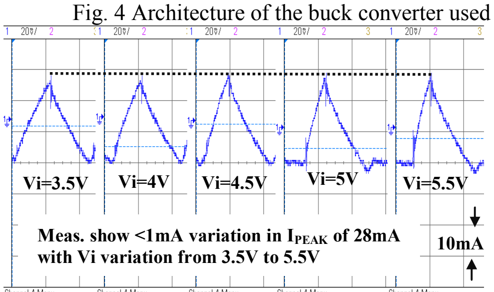

Fig. 7 Measurement of I_{PEAK} with Vi=3.5V-5.5V

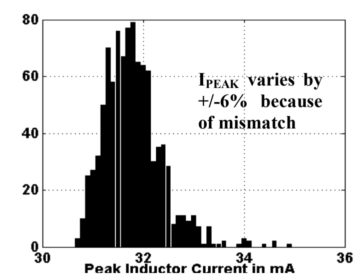

Fig. 8 Monte-carlo variation of I_{PEAK}

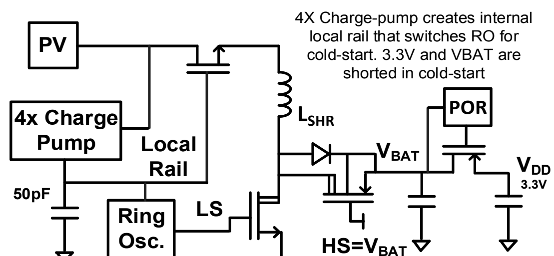

Fig. 9 Cold start circuit to start from 380mV

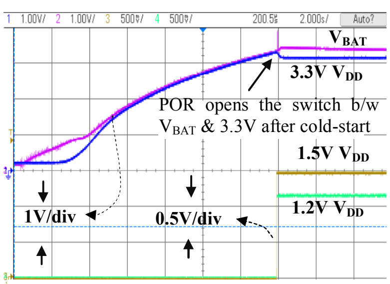

Fig. 10 Cold-start of EHM from 380mV

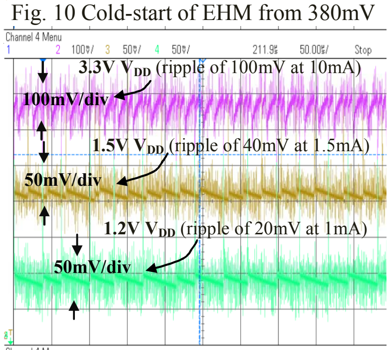

Fig. 11 EHM o/p voltages at high load

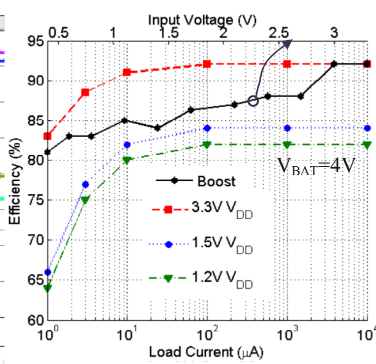

Fig. 12 Efficiency measurements

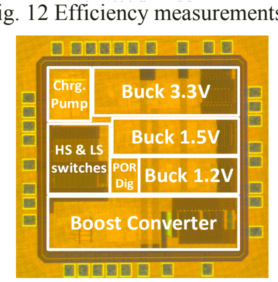

Fig. 13 die photo of EHM IC

	[2]	[4]	[5]	This Work
Process	0.18µm	0.25µm	0.35µm	0.13µm
# of o/p	3	1	1	4
o/p Voltages	1V, 1.8V &3V	5V	0-3.3V	5V, 1.2V,1.5V & 3.3V
Efficiency	83% max @100µW, 67% @ 1µW, 70% @10mW	87%	80% @0.5V 95% @ 3V for boost	81% @ 0.4V, 92% @ 3.3V for boost* 92% @ high load, 83% @1µA for 3.3V buck * *(in SIMO)
Idle Power	0.4µW	2.4µW	1µW	1.2µW
Start-up	-	1V	0.33V	0.38V
Max. o/p V	3V	3V	3.3V	5V
Area (mm^2)	4.625	11.56	-	2.25
Max. Load	10mW	10mW	25mW	100mW
SIMO Reg.	✓	×	×	✓
Bat. Mgmt.	×	×	✓	✓
Cold start	×	×	✓	✓

Fig. 14 Comparison of EHM with recent work