Energy Efficient Ultra low power Solar Harvesting System Design with MPPT for IOT Edge Node Devices

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Abstract—**Towards designing an on-chip harvesting system design for IoT, an inductor free methodology is proposed. The solar system behavior is analyzed and proper control algorithm for maximum power point tracking (MPPT) is adopted. The control section monitors the computational circuit and recharging of the battery. Capacitor value modulation (CVM) is used for impedance matching. The conversion efficiency of the DC-DC converter is from 87% to 97%. The resulting output is in the range of 3-3.55V.**

Keywords— Maximum Power Point (MPP), Energy Harvesting System (EHS), Solar Cell, Capacitor Value Modulation (CVM), Charge Pump, IOTs.

I. INTRODUCTION

Most of the edge devices (sensors) are battery powered and are always active, which puts the stress on battery-based power supply. The researchers are working to harness the renewable energy sources to power the IoT edge nodes [1]. In this connection, we can find the literature on harnessing solar, thermal, microbial, vibration and RF (radio frequency) to charge the batteries and manage uninterrupted quality power supply to IoT edge nodes [2]. Solar energy is preferred over other renewable schemes because of several advantages like wide availability, improved power density and dc output. The solar cell output depends on the temperature and irradiance level. The MPPT (maximum power point tracking) in solar energy harvesting applications extract maximum power from ambient energy source under different environmental conditions [3]. To power IoT edges, small PV cells are used and power delivery is in the range of microwatts to mili watt [4-5]. The early attempts were made by Raghunathan et al [6], in which a small solar cell was directly connected to a rechargeable battery without MPPT. Another significant early endeavor by Simjee et al in [7], discuss the linear relationship between maximum power point (MPP) voltage and open circuit voltage. The technique described results in reduced conversion efficiency. Afterward, the most of the researchers adopt hill-climbing and perturb and observe (P&O) methods [8]. In this paper, we presented a solar energy harvesting system (EHS) for IoT edge nodes using inductor less dc-dc converters. In the proposed scheme, the impedance tuning method will tweak the capacitors with a fixed switching frequency, which significantly improves the MPPT. The EHS is self- sustainable and use of supercapacitor makes it more preferable [4]. The next section describes the proposed solar EHS. Section III describes the MPPT decision mechanism. Section IV presents the current sensing scheme. Section V present the simulation setup and analyze the results. Finally, section VI concludes the paper.

II. PROPOSED PV HARVESTING SYSTEM

The block diagram of proposed EHS is shown in Fig. 1. For a monolithic implementation of a DC-DC converter, Charge pump is used [4]. The feedback path comprises of (a) current sensing circuit, (b) MPPT Unit and (c) finite state machine (FSM).

1. Auxiliary Charge Pump, Level Shifter and Charge Pump as a Nested Voltage Tripler

The Charge pump (CP) [5] switches should be made small such that the reverse current is prevented. The threshold voltage of a MOSFET plays a crucial role during charge transfers. An auxiliary CP and level shifters are used for generation of high voltage switching signals for the tripler as shown in Fig. 2 and Fig. 3. To boost the output of the PV cell, nested voltage tripler is used as shown in Fig. 4. The transistors M_1 and M_2 are connected in a cross-coupled manner, which restricts the turn-on voltage of the NMOS transistor and is less than V_{solar}. The conduction resistance is increase by the low turn-on voltage and degrades the efficiency of the device. Separate higher voltages drive the gates by avoiding the cross coupled methodology then enough gate overdrive voltage can be generated and parasitic reduced. The MN_1 and MN_2 transistors have a gate drive signal of higher amplitudes. The clock pulses are boosted by the level shifter, which improves the efficiency of the converter thereby reducing the shoot-through current.

The frequency chosen for the overall operation is 150 KHz.

The impedance of the charge pump is given by

$$Z_{cp} = \frac{V_{solar}}{I_{in}} = \frac{1}{2 f_s C_u} \frac{1+\alpha}{\left(3-\frac{V_{out}}{V_{solar}}\right)\alpha} \quad (1)$$

Where α is the Capacitor ratio of various stages of charge pump.

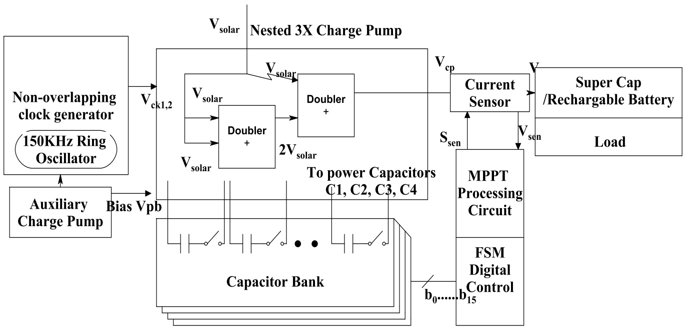

Fig. 1. Block Diagram of Energy Harvesting System

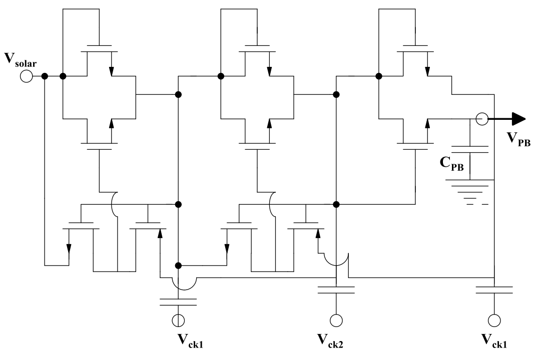

Fig. 2. Circuit Diagram of Auxiliary Charge Pump for Bias generation

2. Modified MPPT with Hill Climbing Algorithm

The hill climbing algorithm for MPPT is shown in Fig. 5. The impedance tuning for MPPT is a significant part of harvesting system [5] [8]. The product of the f_s and C_u gives the input impedance of charge pump as per equation (1). The MPPT unit compares the old and new power information (Φ_1 and Φ_2). An enable signal S (environmental sensor) starts the MPPT procedure. This S is either an enable produced by a timer or an environmental sensor of WSN as shown in Fig. 5.

3. Capacitor Value Modulation (CVM)

The converter charges the solar voltage across the capacitor C_u and then equals the negative plates by the same voltage [4]. The small signal analysis of the tripler of Fig. 4 gives the associated equations as

$$\left[2V_{solar} - \left(V_{out} - V_{solar}\right)\right] \times \alpha C_u = \frac{1}{2} \times \frac{T \times V_{out}}{R_L} \qquad (2)$$

Where T and R_L are the switching period and load of the SOC respectively.

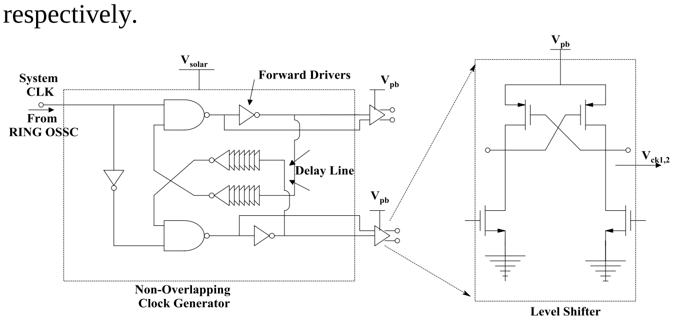

Fig. 3. Circuit diagram of Non-overlapping Clock generator with Level Shifter

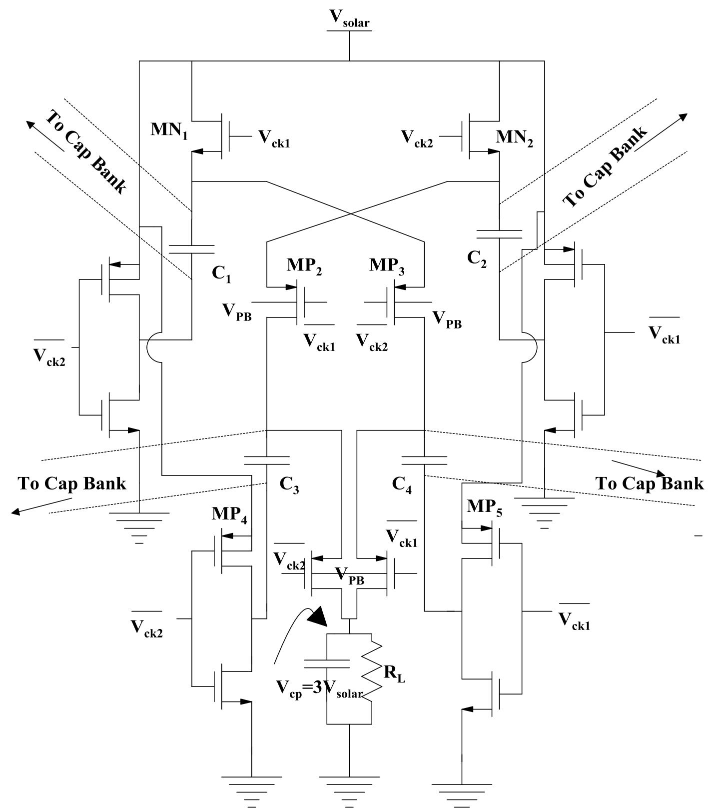

Fig. 4. Circuit diagram of Charge Pump as a Voltage Tripler

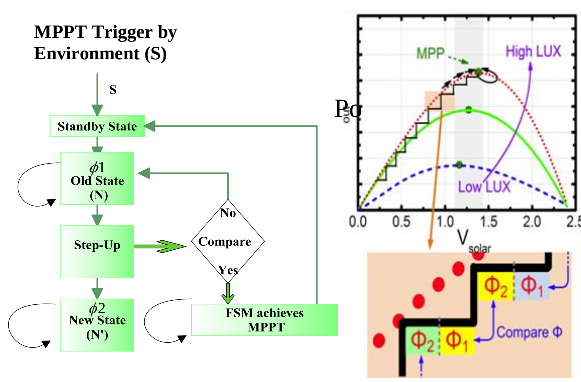

Fig. 5. Flow chart of Hill-Climbing Algorithm with procedure

To match the MPP when the load is variable, the input PV voltage is tune by switching frequency (f) and Capacitor C_u. Here the C_u is programmable, that can be varied for impedance tuning to achieve the MPP [6]. The capacitor bank is digitalized as shown in Fig. 6. MIM capacitors are used for the on-chip implementation. The power conversion efficiency of the charge pump can be determined by the formula

$$PCE = \frac{V_{out}}{V_{solar} \times CR} \times 100\% \qquad (3)$$

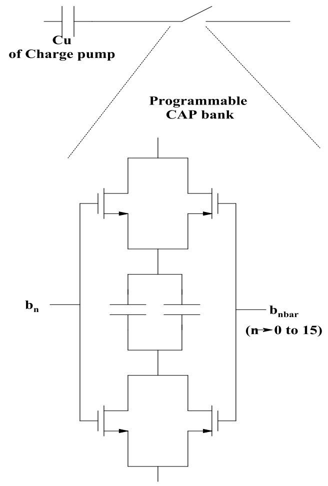

Fig. 6. Digitally programmable capacitor bank

III. MPPT AND FSM DESIGN

The MPP [5] mechanism is implemented by using a 5-bit counter, logic gates, S/H circuits, and capacitor banks as shown in Fig. 7. One cycle of MPPT needs 32-clock cycles. At the beginning of MPPT, all capacitor banks are connected. The FSM will disconnect them one by one, using an algorithm in each MPPT cycle. The FSM releases S_1 and S_2 at different intervals, which are the enabling signal for sample and hold circuits S/H_1 and S/H_2 to store the old and new power information. The power information for N and N' capacitors in CAP bank are stored [4]. The FSM releases S_3 for comparison. With S_4 becomes high gives the decision of comparison [9]. Once MPP achieved, the FSM stops and S_{sen} becomes low and other control signals are also disabled. This leads to the charging of supercapacitor. The signal S_5 initiates the I/O communication for IoT smart nodes with other wireless sensor networks (WSNs) [1].

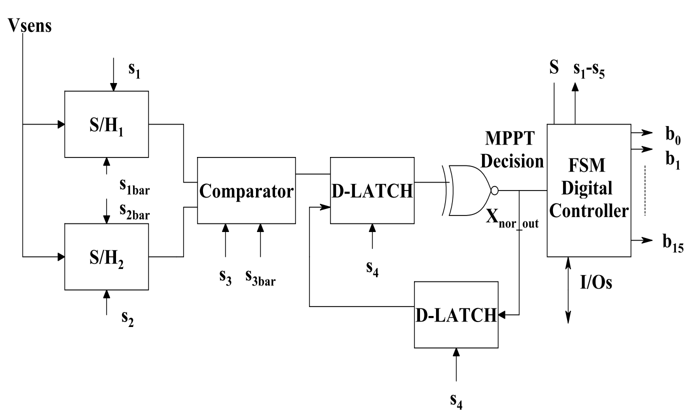

Fig. 7. MPPT procedure with FSM

IV. CURRENT SENSOR

The current sensor as shown in Fig. 8 is used to monitor the power information from the output of the dc-dc converter. To allow total current during sensing, control signals are issued by FSM as S_{sen} and S_{senbar}. When S_{senbar} is a low total current of the tripler is used for sensing and the super capacitor provides the reference current. The sensing voltage V_{sens} is obtained across R_{sen} resistor [4]. The transfer function (Closed loop) from the output of tripler to current sensor is obtained as

$$\frac{V_{sen}}{I_{cp}} = \frac{R_{sen}}{1 + \frac{1}{gMCP3} T_{FB}} \tag{4}$$

Where T_{FB} is the open loop Trans conductance and is given by

$$T_{FB} = \frac{i_2}{V_{cp} - V_Y} = \frac{1}{\frac{1}{gMCN2 * (-gMCP1) * Z_{CN1}} + Z_{CP2} - \frac{1}{gMCN2}} \tag{5}$$

V. EXPERIMENTAL RESULTS

The proposed EHS uses on-chip capacitors and is suitable for monolithic integration. The input voltage from the PV cell is in the range of 1 to 1.5V. The complete system is designed and simulated in Cadence Virtuoso environment with Spectre simulator with CMOS 180nm technology library. The simulation shows that the CVM scheme is more sensitive to a dynamically changing lighting environment and temperature. The capacitors used in the tripler and capacitor banks are MIM (Metal-Insulator-Metal) Capacitors. The load was designated with a resistor in range 200Kohm to 10Mohm in parallel with a supercapacitor having 33mF value.

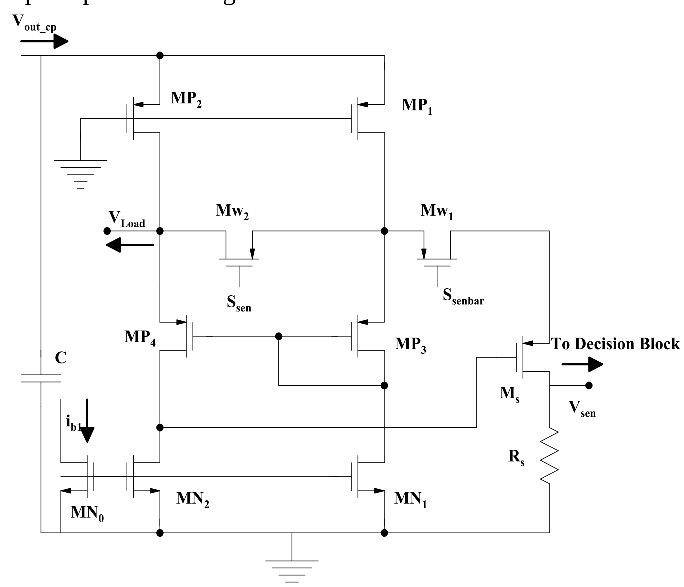

Fig. 8. Energy efficient Current Sensor

The V_{solar}, V_{out}, S_1, and S_2 are shown in figure 9. During the MPPT procedure, the capacitor value is changed in the programmable capacitor bank by the FSM using thermometer codes as shown in Fig. 9 as b_0, b_1 etc. The current sensor is ON during MPPT cycle only to save the power consumption. The MPPT process takes some steps for refinement of the solar voltage. Once the MPPT is achieved through tuning of the capacitor bank, the MPP is locked. Here, after 8 MPPT cycles maximum power point is achieved as shown in Fig. 10. The FSM releases control signals to charge the supercapacitor (Scap), once MPPT achieved as depicted in Fig. 9. The comparison between the different harvesting schemes is presented in Table I.

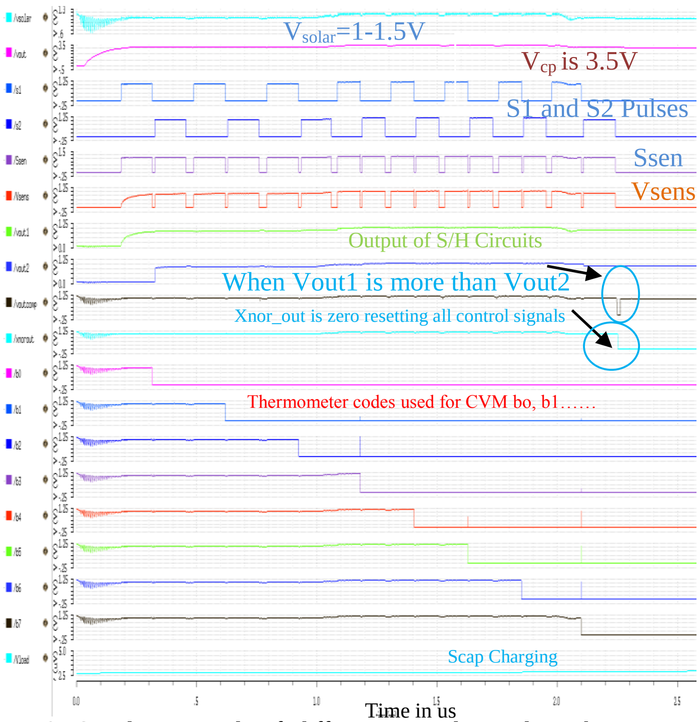

Fig 9. Simulation result of different control signals with MPPT achievement

Table I comparison between the different harvesting schemes

Design Parameters	DICM [6]	FOCV [7]	HC [5]	NFC [3]	Proposed
Sensors Required	No	Yes	Yes	No	No
Microcontroller Required	No	Yes	No	No	No
Adaptive MPPT	No	No	Yes	Yes	Yes
Impedance Matching Varied by?	NA	Duty ratio	Clock Frequency	Clock frequency	CVM
Switching Converter type	NA	Inductor	Capacitor	Capacitor	Capacitor
Hardware cost	NA	Low	Medium	Low	Low
Self-Startup	NA	No	Yes	Yes	Yes
Technology	NA	NA	.35um	.18um	.18um

VI. CONCLUSION

The IoT sensor nodes need a continuous power supply to provide an uninterrupted service. The solar EHS designed is well suited for a minimum voltage of 1.22V as MPP in the range of 1-1.5V. The resulting output is in the range of 3-3.55V (with an efficiency of 87% to 97%), which is a requirement of IoT edge node devices. The entire modules are powered by the solar cell and the auxiliary charge pump generates the higher bias voltages. By adopting the state of art technologies the entire EHS is self-sustainable and no external power supplies are needed. The energy harvesting system proposed is consuming power in the range of ultra-low power range and is within microwatt range.

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