# Ultra-Low Voltage Power Management Circuit and Computation Methodology for Energy Harvesting Applications

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**Abstract- A power management and computation methodology is proposed for ultra-low power energy harvesting applications. An integrated exponential charge pump that accepts an input voltage of around 150mV and provides an unregulated output voltage of more than 1.5V serves as the power supply. To cater with the fluctuated energy source and unregulated power supply, a supply side charge-based computation methodology is proposed, of which the computation activity tracks with the fluctuation of the available energy. The idea is demonstrated in a test chip fabricated using a 0.35µm technology.**

## I Introduction

Recently, new emerging applications such as RFID and wireless sensors network, which consume very low power and utilize the energy harvested from the environment, are gaining more attention[1][2]. In these applications, the energy are collected from solar, vibration, heat or radioactive decay of matters and at the same time the amount of energy available is limited and the source is unstable.

Previous researches on energy harvesting systems assume that a voltage source of at least 1V is available [3][4]. However for some environment, such as inside a human body, the harvested voltage source may be much lower. At the same time in order to reduce the cost of the device, expensive voltage regulator should be avoided. Unstable low voltage source poses new challenges in the design of the power management circuit and computation paradigm for the applications.

In this work, we propose a novel power management system for energy-limited source applications which can pump the input voltage of ~150mV, a value much lower than the threshold voltage of CMOS transistor, to several volts. We also present the design of the computation module that can operate under the unregulated voltage supply. We propose a supply-side charge-based computation paradigm where computation is carried out only when the energy from the environment is enough to execute a specified atomic operation of the computation. An experimental chip was designed, fabricated and measured to demonstrate the idea.

## II. System Design Description

Fig. 1 shows the block diagram of our target system. It contains of 4 blocks, the energy harvesting mechanism, the power management system, the computation module and the charge-based control unit.

A generic energy harvesting mechanism scavenges the energy from the environment and gives out an unregulated source voltage. The voltage is inputted to the power management system where a high conversion ratio charge pump steps up the voltage. The unregulated voltage ($V_{out}$) is then fed directly to the computation module. The charge-based control unit will make sure the energy available is enough for the atomic operation before triggering the computation.

### *A. Power Management System*

The power management system contains a 4-stage 16x exponential charge pump and a clock generator for control. Figure 2 shows the circuit diagram. Since the voltage source $V_s$ is around 100mv~200mv, the circuit needs a start up circuit, which only functions at the beginning of the circuit running. Once the circuit is started, the generated high voltage source $V_{out}$ will provide the energy to the clock generator and cut the switch between the start-up voltage and the circuit.

This charge pump has a cross-coupled structure that employs a 2-phase non-overlapping clock. The cross-coupled structure consists of two symmetrical branches A and B. When $\phi_1$=1, the $k^{th}$ stage capacitor of Branch A is charged to $2^{k-1}$ Vs by the $k-1^{th}$ stage capacitor of Branch B. When $\phi_2$=1, the positive plate of the $k^{th}$ stage capacitor of Branch A is pushed by the $k-1^{th}$ stage capacitor of Branch A to $2^k$Vs and charges the $k+1^{th}$ stage capacitor of Branch B to $2^k$Vs at the same time. A similar mechanism occurs to the capacitors in Branch B. If the charge pump has 4 stages, an ideal voltage conversion of 16 is obtained.

### *B. Computation Module*

The power supply becomes unstable due to the absence of the voltage regulator, and this will affect the delay of the circuit and may cause timing problems. In order to track the change of the supply and automatically adjust the circuit's performance, we propose to use self-time asynchronous pipeline design to implement the computation module [5]. In this case the operation of a pipeline stage gets more robust over various operating conditions for its locally-generated timing signal and it is more suitable for the design to track with the unstable supply voltage

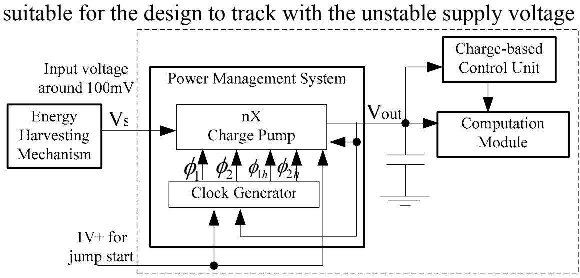


Fig. 1. Targeted system using energy harvesting

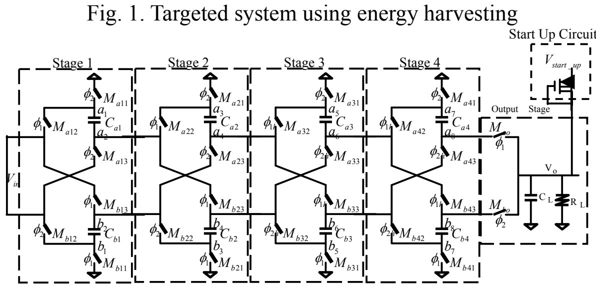


Fig. 2. 16x charge pump with startup circuit

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### C. *Charge-based Control Unit*

Due to the unpredictable nature of the energy source, the energy available at a particular time interval may not be enough for the computation and if we carry it out, the computation may not be able to finish and even worse the voltage may drop to a level that some of the stored data will be lost. Here, we propose a supply side charge-base computation methodology. The charge required at different voltage for a certain atomic computation is estimated and stored in the device. The computation will only be triggered when the harvested energy can provide the charge for it. Moreover, the computation can be further prioritized, both in task level and bit level. Depending on the energy available and priority, different computations will be executed.

## III. Experimental Results

To demonstrate the proposed idea, a test chip was designed and fabricated using AMS 0.35μm CMOS technology. A 16x exponential charge pump is used for the power management system with an output capacitance of 0.47μF. For the computation module, we use a self-timed pipelined 4-tap FIR filter as an example where bundle delay is used to generate the local timing signals. An on-chip linear feedback shift register is used to generate the input data to the filter. A simple start-stop control is used to demonstrate the charge-based control where a hysteretic comparator is implemented. The charge required for an atomic computation is converted as a voltage level at the output of the charge pump given the output capacitance. A voltage comparator is used to compare the output voltage with this voltage level for the stopping of the computation. Table 1 shows the chip summary and the die photo is shown in Fig.3.

Experiments were carried out on the chip. First we varied the input voltage to the charge pump between 169mV and 190mV to mimic the unstable harvested energy source. Fig.4 shows the waveform of $V_s$ (input voltage to the charge pump), $V_{out}$ (output voltage at the charge pump), stop signal from the charge based control unit and output data from computation module. Here $V_{out}$ is not regulated when stop signal is disabled and it drops as the computation consumed energy is larger than the converted energy from the power management system. The charge based control unit will stop the computation when the available energy is not enough and activate it again when energy recovers. What's more, the duty cycle under small input voltage is longer due to the lower input power value. Another experiment was conducted using the energy converted from a solar cell as the energy source. The input voltage varies from 80mV to 143mV while the solar cell is under weak light and strong light condition, respectively. Fig.5 shows the corresponding waveforms where Vs is the voltage output from the solar cell. It is shown that under weak light condition, the charge based control unit stops the computation because of small amount of energy available. When the light intensity increases, the computation will be triggered if the available energy can support the atomic operation. To show the reliability of the computation under the unstable energy source and the unregulated power supply, we ran the test chip for days and collect the sample error. About $10^{12}$ output samples were collected and no error was found when comparing with the correct samples.

## IV. Conclusion

A power management circuit and a supply side charge-based computation methodology for energy harvesting applications were proposed. A test chip was designed and fabricated to demonstrate the idea. Future work includes the development of more complicated charge-based control for real applications.

## References

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TABLE I Chip Performance Summary

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|---|---|
| Technology | 0.35μm CMOS 4-Metal 2-Poly |
| Size of power management system | 0.29mmx0.33mm |
| Switching frequency | 100kHz~2MHz |
| Input voltage range | 80mV~200mV |
| Output voltage | 1.12V~2.31V |
| Maximum Output Current | 200μA |
| Output capacitance | 0.47μF |
| Size of computation module | 0.93mmx0.40mm |
| Size of charge based control unit | 0.15mmx0.29mm |

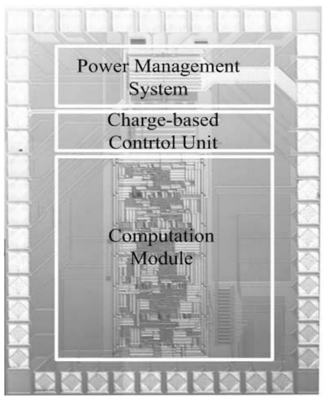

Fig. 3. Die photo of the test chip

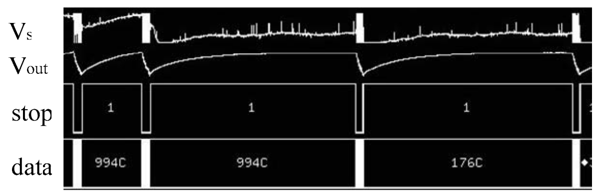

Fig. 4. Measurement result for fluctuated input voltage

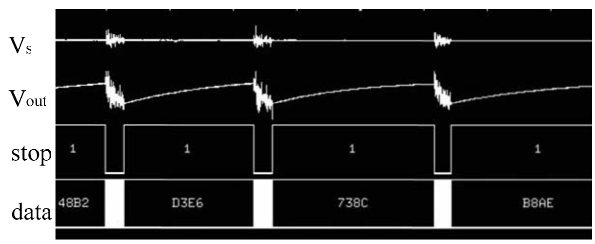

Fig. 5. Measurement result with energy from the solar cell