A Reconfigurable Fractional-Conversion-Ratio Charge Pump for Energy Harvesting Applications

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***Abstract*—In this paper, a fully integrated reconfigurable charge pump (CP) is presented. In energy harvesting applications, the input voltage can have large variations due to change in the environmental conditions, thus the CP has to be highly reconfigurable to support a wide range of input voltages together with expected load current variations. The proposed CP offers a fractional conversion ratio in order to optimize the overall system efficiency. The analysis of the CP in terms of output resistance, optimum number of stages for a given output voltage, and efficiency is performed. A design example is shown for a 5-stage CP using a UMC 180nm CMOS technology. The CP has a programmable conversion ratio from 1.25 to 5 in steps of 0.25 to support an input voltage from 0.3V to 1.2V and an output voltage of 1.5V. The implementation uses a total on-chip pumping capacitor of 2.5nF and achieves an efficiency of more than 73% across the whole input range at a load current of 1mA.**

Keywords—charge pump, fractional conversion ratio, energy harvesting, reconfigurable, fully-integrated

I. INTRODUCTION

Energy harvesting sources have been recently emerging as a promising power source that can be used in low power portable systems such as Internet of Things (IoT) and biomedical implanted devices. In such systems, these sources after proper signal conditioning can be either used to directly power the circuits of the application or to recharge small batteries that can be later used for the same purpose. A system-on-chip (SoC) provides the key for cost and size reduction of these systems. Therefore, harvesting sources have to be sufficiently small in size to provide the capability of full integration inside an SoC. Due to this area constraint, used energy harvesting sources such as thermoelectric generators, solar cells, and wirelessly transmitted power can only produce a few tens to hundreds of millivolts. Such low voltage is usually inadequate to power the circuits directly until it is raised to a well-regulated voltage suited for the technology of implementation used in the SoC. This triggers the need for boosting converters in such systems.

Charge pumps have desirably served the need for the voltage boosting needed in energy harvesting systems. Unlike inductor-based converters that usually require off-chip inductors, charge pumps have served the way for fully-integrated solutions due to their capacitive nature. When a charge pump is used inside an energy harvesting system, it is often followed by a voltage regulator as shown in Fig. 1. Such voltage regulator is usually implemented as a low-dropout regulator (LDO) [1], or using a simple regulation loop that turns the charge pump on or off upon load demand [2]. In both scenarios, the charge pump is required to produce an output voltage that lies within a certain window to either improve the efficiency of the LDO in the former case, or reduce the output ripple in the latter case. One of the charge pumps that have been in wide use is the Dickson charge pump [3]. This is mainly due to its lower output resistance and resilience to stray capacitance compared to other topologies [4]. Despite the desirable properties of the Dickson topology, the fact that it only provides integer conversion ratios may not be optimum in terms of power efficiency. This calls the need for charge pump topologies that provide fractional conversion ratios in addition to being reconfigurable to adopt to possible input voltage and load current variations present in today's energy harvesting systems.

Several reconfigurable fractional charge pumps have been recently reported in literature [5]-[7]. Despite serving the need for fractional conversion ratios, [5] and [7] implementations suffer from a large output resistance due to not utilizing the whole flying capacitance effectively. This in turn increases the conduction losses and degrades the efficiency of the system for a given flying capacitance in use. On the other hand, the implementation of [6] utilized a large off-chip capacitance which is not acceptable in most energy harvesting systems. This paper presents a reconfigurable fractional charge pump that is both fully integrated and offers better output resistance than [5] and [7] implementations. Such charge pump could be optimized for a specific output voltage needed by the voltage regulator inside an energy harvesting system. In Section II, the fractional charge pump is introduced and the analysis of its output resistance is conducted. Expressions for the optimum conversion ratio that minimizes the input current at a given output voltage and the optimum efficiency at such condition are derived in Section III. Section IV provides a design example for a 5-stage charge pump implemented using the proposed architecture, while Section V concludes the paper.

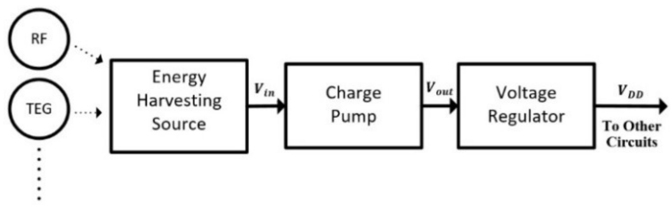
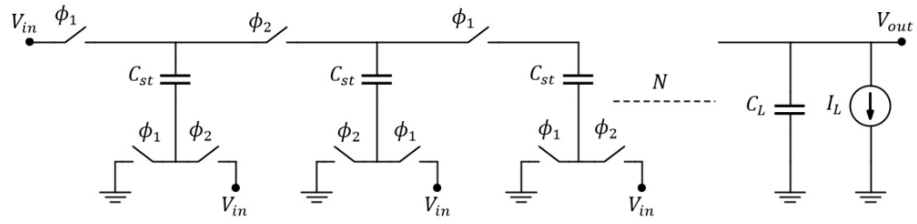


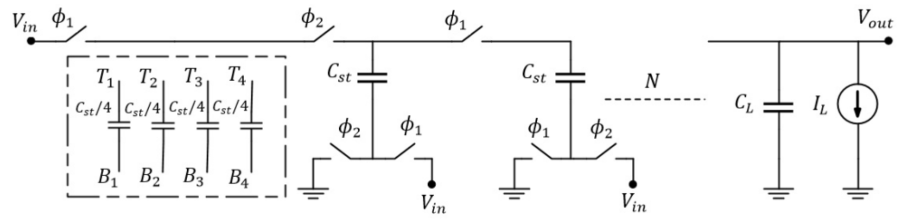
Fig. 1. A conventional energy harvesting system

II. PROPOSED CHARGE PUMP

The classical N-stage Dickson charge pump is shown in Fig. 2(a) with a capacitance per stage C_{st}, a load capacitance C_L, and two non-overlapping clocks ϕ_1 and ϕ_2. The charge pump has an input voltage V_{in} and an output voltage V_{out}, while delivering a load current I_L.

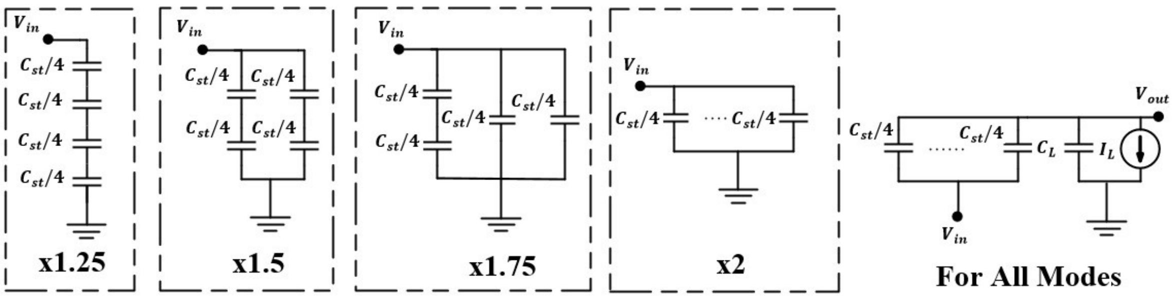


(a)



(b)

Fig. 2. (a) Dickson charge pump using switches, (b) Proposed fractional charge pump



(a) (b)

Fig. 3. Reconfiguration of the 4 first stage capacitors in the proposed charge pump for different conversion ratios during: (a) ϕ_1, (b) ϕ_2

The optimum value of N that minimizes the input current for a given output voltage was derived as [8]:

$$N_{opt} = (1 + \sqrt{\frac{\alpha}{1+\alpha}})\left(\frac{V_{out}}{V_{in}} - 1\right) \quad (1)$$

where α is the ratio between the parasitic capacitance of the bottom plate of a stage capacitance and the stage capacitance itself. This value of N_{opt} is generally fractional and cannot be implemented using the topology shown in Fig. 2(a). To tackle this issue, the charge pump shown in Fig. 2(b) is proposed. The capacitance of the first stage is divided into 4 equal capacitors, each having reconfigurable top and bottom plates. Other stages are maintained the same as Dickson. Such capacitance division in the first stage helps in achieving a resolution of 0.25, and therefore achieves better approximation for N_{opt} than taking the integer value. The method of connecting the 4 capacitors for different conversion ratios during ϕ_1 and ϕ_2 is clarified in Fig. 3(a) and (b) respectively, under the assumption of configuring only the first stage. If this is not the case and more than one stage needs to be configured, the capacitors of the first stage will be connected to the capacitor of the second stage during ϕ_2 instead of being connected to the load.

A big advantage of the proposed charge pump is that its output resistance (R_{out}) depends on the number of stages in use and do not degrade in some fractional modes as in [5] and [7]. This is qualitatively due to utilizing the whole effective capacitance of the first stage by avoiding any series connections of capacitors when the first stage delivers charge to the next stage or load. Without loss of generality, this conclusion can be deduced by analyzing the steady-state behavior of the x1.25 mode shown in Fig. 3. The same procedure can be then readily applied to other fractional modes. Assuming that the charge pump operates with a switching frequency f_{sw} and that V_{out} has a ripple ΔV that swings between V_L and V_H, ΔV can be expressed as:

$$\Delta V = \frac{I_L}{2C_L f_{sw}}. \quad (2)$$

By applying conservation of charge during ϕ_2, we can write

$$\frac{C_{st}V_{in}}{4} + C_L V_L = C_{st}(V_H - V_{in}) + C_L V_H + \frac{I_L}{2f_{sw}}. \quad (3)$$

Also, V_L can be written in terms of V_H and ΔV as:

$$V_L = V_H - \Delta V. \quad (4)$$

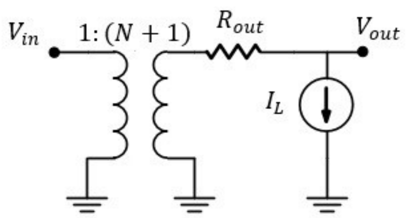


Fig. 4. Conventional charge pump model

By substituting (4) and (2) in (3), and simplifying for V_H, we obtain:

$$V_H = 1.25V_{in} - \frac{I_L}{C_{st} f_{sw}}. \quad (5)$$

If ΔV is small, $V_{out} \cong V_H$ and after comparing the expression of V_H with the conventional charge pump model in Fig. 4, we conclude that $N = 0.25$ and $R_{out} = \frac{1}{C_{st} f_{sw}}$. This analysis implies that the output resistance of the first stage depends on the effective stage capacitance that appears during ϕ_2 and is therefore the same as the output resistance of a conventional Dickson stage.

III. Charge Pump Optimization

The expression of N_{opt} given by (1) cannot be directly applied on the proposed charge pump topology. This is because it was derived assuming that R_{out} depends on the fractional N, not on the number of stages. In order to determine N_{opt} for the proposed charge pump, the output voltage can be expressed as:

$$V_{out} = (N+1)V_{in} - \frac{N_o I_L}{f_{sw} C_{st}} \quad (6)$$

where $(N+1)$ is the conversion ratio that could be fractional and N_o is the number of stages and is also equal to ceil (N). Considering the switching losses of the charge pump due to the bottom plate parasitic capacitance associated with each stage capacitor, the input current is given by [8]:

$$I_{in} = (N+1)I_L + \alpha N_o C_{st} f_{sw} V_{in} \quad (7)$$

From (6), the switching frequency can be expressed as:

$$f_{sw} = \frac{N_o I_L}{C_{st}[(N+1)V_{in} - V_{out}]} \quad (8)$$

By substituting (8) in (7), the input current can be rewritten as:

$$I_{in} = (N+1)I_L + \frac{\alpha N_o^2 V_{in} I_L}{(N+1)V_{in} - V_{out}} \quad (9)$$

By computing the derivative of I_{in} with respect to N and setting such derivative to 0, the optimum value of N that minimizes I_{in} for a given output voltage is:

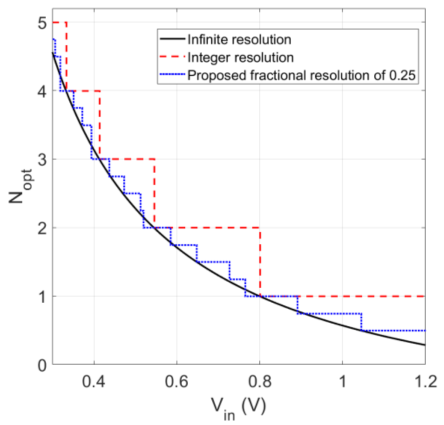


Fig. 5. Optimum N of charge pump for 1.5V output voltage at $\alpha = 0.02$

$$N_{opt} = \left(\frac{V_{out}}{V_{in}} - 1\right) + \sqrt{\alpha} N_{o,opt} \quad (10)$$

where $N_{o,opt}$ is the optimum number of stages and is equal to ceil (N_{opt}). This value of $N_{o,opt}$ is equal to the integer that satisfies:

$$(N_{o,opt} - 1) < \left(\frac{V_{out}}{V_{in}} - 1\right) + \sqrt{\alpha} N_{o,opt} < N_{o,opt}. \quad (11)$$

It is worth noting that the derivative $\frac{dN_o}{dN}$ has been set to 0 during the analysis to consider the fractional range of N which is the primary focus. However, if there happens to be an integer value between $\left(\frac{V_{out}}{V_{in}} - 1\right)$ and the value of N_{opt} computed from (10), such value could prove optimum and shall be considered. Also, it is important to observe that the value of N_{opt} computed from (10) will be rounded to the closest value within the 0.25 resolution of the charge pump. By substituting for N_{opt} from (10) in (8), the optimum switching frequency can be computed for a given C_{st}. Also, by taking the ratio between the delivered output power to the input power while substituting for I_{in} from (9) at N_{opt}, the optimum efficiency can be derived as:

$$\eta_{opt} = \frac{(V_{out}/V_{in})}{(N_{opt}+1) + \frac{\alpha N_{o,opt}^2}{(N_{opt}+1) - (V_{out}/V_{in})}} \quad (12)$$

Fig. 5 shows N_{opt} of the proposed charge pump (at $V_{out} = 1.5$V and $\alpha = 0.02$) after rounding the values to comply with the 0.25 resolution. Such N_{opt} is compared to: (a) the value of N_{opt} computed from (1) assuming infinite resolution and R_{out} dependence on the fractional N, and (b) the integer version of (1) that is usually implemented using integer charge pumps.

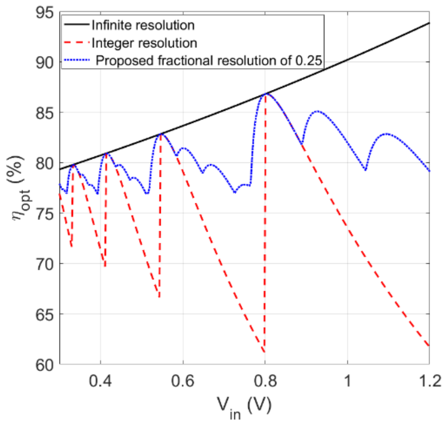


Fig. 6. Optimum efficiency of charge pump for 1.5V output voltage at $\alpha = 0.02$

The efficiency of the 3 cases at the same conditions is shown in Fig. 6. Clearly, the proposed fractional charge pump outperforms its integer counterpart, especially in the cases when N_{opt} happens to be fractional and far away from the integer value.

IV. Design Example

The proposed fully integrated CP is designed and simulated using UMC 180nm CMOS technology. The total pumping capacitance of the CP is 2.5nF divided into 5 stages such that each stage has a 500pF capacitance. This is implemented using metal-insulator-metal (MIM) capacitor occupying an area of 2.5mm^2. The load capacitor C_L is 10nF and this is implemented as a MOS capacitor placed under the MIM capacitor to save silicon area. The 1st stage is divided into 4 unit capacitors each of 125pF. The switches of the CP are implemented using bootstrapped technique [9] to reduce the ON resistance with switch dimensions (W/L) of (40µm/0.18µm). Bypass switches are included across the 5 stages for reconfigurability. The optimum values N_{opt}, $N_{o,opt}$, and switching frequency are calculated using (8) and (10) for a load current of 1mA. For V_{in} = 0.3V, N_{opt} = 4.75 (f_{sw} = 44 MHz), while N_{opt} = 0.5 (f_{sw} = 6.6 MHz) for V_{in} = 1.2V. Fig. 7 shows the transient output voltage of the CP while varying V_{in} from 0.3V to 1.2V. The proposed CP can control V_{out} within a range of ~50mV from 1.45V to 1.5V all over the V_{in} range. The efficiency of the proposed CP is simulated and shown in Fig. 8. It can provide efficiency higher than 73% all over the V_{in} range. The simulated efficiency is degraded from the ideal efficiency (proposed fractional resolution), shown in Fig. 6, mainly due to the additional switching losses contributed by the gate capacitance of the bootstrapped switches.

V. Conclusion

A fully integrated reconfigurable fractional conversion ratio charge pump (CP) is proposed. The optimum number of stages, switching frequency, and efficiency are derived for a given input and output voltages. A design example for a 5-stage CP is implemented in a 0.18µm CMOS technology with a programmable conversion ratio from 1.25 to 5 in steps of 0.25 and an output voltage of 1.5V. It achieves efficiency greater than 73% for input range from 0.3V-1.2V and load current of 1mA. Simulations results show that the proposed CP is a good candidate for energy harvesting applications. Circuit simulation results are in good agreement with the theoretical analysis.

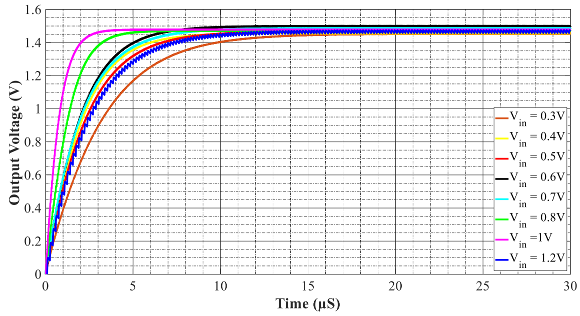


Fig. 7. Simulated output voltage of the proposed CP

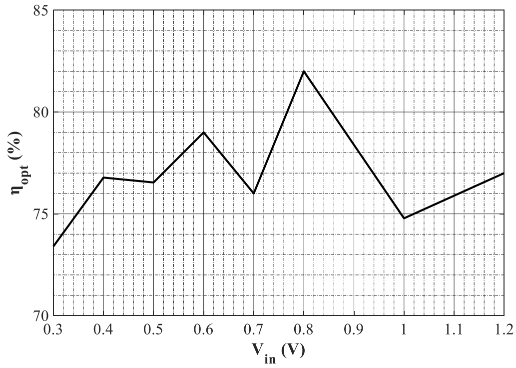


Fig. 8. Simulated efficiency of the proposed CP

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