

# Efficient Adaptive Switch Design for Charge pumps in Micro-scale Energy Harvesting

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**Abstract**— The performance of Micro-scale energy harvesting unit depends on the efficient design of charge-pump. Optimization of the dimension of MOSFET switches in charge pump is one of the techniques to improve the efficiency. In this work, a new optimization technique for transistor sizing and a concept of reconfigurable adaptive switches has been introduced to maximize the extracted power. A control unit is designed for adaptive reconfiguration of the switches. These proposed techniques are validated for linear charge-pump topology in UMC 180nm technology. Combined effect of size optimization of switch along with reconfigurable switch offers an improvement up to 23.5% in the net harvested power with 6% less silicon area.

**Keywords**-component; Charge pump, Micro scale energy harvesting, Reconfigurable switches, Ultra low power systems.

## I. INTRODUCTION

Ultra-low power systems such as Wireless sensor network (WSN) nodes, biomedical implants etc. have emerged as an active research topic due to their vast application areas [1] [2]. Such system would be able to perform their sensing functions and wireless communication without any supervision or maintenance. These systems have to cope with severe power supply constraints. The need shared by most of these systems for long lifetime does not match up well with available battery technology, thus limits their use [3]. Energy harvesting is becoming more and more popular for micro-power applications so that mini-electronics system can be completely autonomous and could enable widespread use.

In most of the micro-scale systems, the area dedicated to the transducer is very small and as a result, the voltage and power obtained is also much less ( $\sim$ mV and  $\sim$  $\mu$ W). Moreover in micro-scale systems, the power harvested from the transducer is comparable with the losses in the power converter circuit. The effective harvested power is calculated by subtracting the power losses in the charge pump from the power harvested by transducer [4]. Thus, to deliver maximum power for storage, we have to increase the harvested power and decrease the losses. Efforts are made to improve the net output power of charge pumps through topology optimization [5] [6], transistor sizing [7] [8] and stage number optimization [9].

In the charge pump based power converter, most of the losses occur in the charge pump switches. These losses are

directly related to the size of the switches. For small switches, the loss is high due to high conduction loss and for big switches the loss is again high because of high switching power loss. There will be an optimum value of the switch size for minimal loss that results in maximum harvested power. In this context, an optimization technique [7] is proposed by equating total conduction power loss to switching power loss. In [8] optimization of transistor sizes based on constant V-A capacity was introduced.

These methods have two drawbacks when used for micro scale energy harvesting. First, these optimizations are done by considering all the switches in the charge pump are of same characteristics. But the parameters like threshold voltage, ON resistance and hence the losses will be different for MOSFET switches depending on the voltage level across the switch even if they are of same size. Hence, the selection of equal sizes for all the switches will not able to provide efficient performance as switches in different position (of charge pump) have different voltage level. Secondly, the optimum transistor size depends on the current, voltage and switching frequency of the charge pump. These parameters varies significantly with environmental conditions (like light intensity in solar) when charge pump is used for energy harvesting. So the optimum transistor size should be different for different light intensities.

Hence there is a need for new optimization technique that sizes each MOSFET according to the requirement. To address the light intensity dependency on optimum switch size, the concept of reconfigurable switch that can dynamically adapt the switch size is presented. Applying both techniques offers substantial performance enhancement in charge pump.

## II. PROPOSED SYSTEM

Typical micro scale energy harvesting system consists of an energy transducer, power converter (charge pump), Maximum power point tracking (MPPT) unit, energy buffer (battery) and load [4][10]. The transducer converts environmental energy such as light, heat, vibration etc. to electrical signals. The proposed energy harvesting system (solar based) is shown in Fig. 1. In this system, a single solar cell is used as energy transducer. MPPT unit is interfaced between battery and charge-pump to extract optimum power [11] [12]. The function of the MPPT unit is to adjust the operating point of the power

converter with the change in the transducer output with environmental condition variations. In our proposed harvesting units, the charge-pump efficiency improvement is achieved through switch optimization and using reconfigurable switches. A control unit is designed to reconfigure the switches in adaptive manner to maximize the extracted power under the variation of solar light intensity.

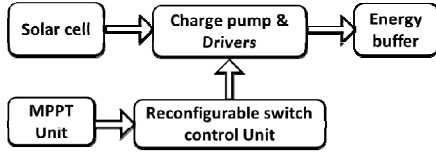


Figure 1. Energy harvesting system with reconfigurable switches

The design methodologies including circuits are described in the following sections.

### A. MOSFET size Optimization

In order to reduce the losses and to develop the optimization technique, better understanding of the losses in charge pump is required. Two major losses in charge pump are switching power loss and conduction power loss. Loss due to leakage is ignored in this analysis because it is independent of switch size. The expression for switching power loss and conduction power loss are given [7] respectively as

$$P_{swt\_loss} = C_{ox} V_O^2 F_{CLK} L \frac{WR}{(R-1)} \quad (1)$$

$$P_{con\_loss} = \frac{I_{on}^2}{\mu C_{ox} \left( \frac{W}{L} \right) \left[ V_G - \left( V_{TH} + \frac{1}{2}(V_S + V_D) \right) \right]} \quad (2)$$

Where  $C_{ox}$  is the gate capacitance per unit area and  $V_O$  is the storage battery voltage.  $F_{CLK}$  is the charge pump clock frequency.  $R$  is the ratio of inverter sizes used in the driving buffer.  $I_{ON}$  is the current in the ON state of MOSFET.  $W$  and  $L$  are the width and length of the MOSFET.  $V_{TH}$  is the threshold voltage.  $V_G$ ,  $V_S$  and  $V_D$  are the gate, source and drain voltages of the MOSFETs used.

The switching power loss ( $P_{swt\_loss}$ ) increases with the size of the MOSFET as it increases the gate capacitance, whereas the conduction loss ( $P_{con\_loss}$ ) decreases with the size of the MOSFET. The optimum size of switch will be determined through the minimization of sum of  $P_{swt\_loss}$  and  $P_{con\_loss}$  and the optimum switch width ( $W_{opt}$ ) is estimated in [7] as

$$W_{opt} = \frac{I_{ON}}{V_O C_{ox}} \sqrt{\frac{(R-1)}{R \mu F_{CLK} (V_{GS} - V_{TH} - \frac{1}{2} V_{DS})}} \quad (3)$$

In this method, all the switches are made up of equal size and hence, the conduction power loss and switching loss are considered as equal for all the MOSFETs. But from the Eq. (2) it is clear that  $P_{con\_loss}$  depends on  $V_S + V_D$  and  $V_{TH}$  of the MOSFET. Just before charge sharing, the voltages  $V_S$ ,  $V_D$  across the switches of a linear charge pump (Fig. 2) are tabulated in Table.1 in terms of input voltage ( $V_{IN}$ ) and a battery of voltage ( $V_O$ ). Even after the complete charge sharing the term  $V_S + V_D$  remains unchanged (although there will be increment / decrement on  $V_S / V_D$ ) [13]. It is clear that  $V_S + V_D$  and  $V_{TH}$  are not same for the switches. Such as  $V_D + V_S$  for  $S_5$ ,  $S_7$  and  $S_9$  are very low and they do not suffer with body effect and hence their  $V_{TH}$  is low. Similarly we can observe that the

$V_D + V_S$ , and  $V_{TH}$  are different for the MOSFETs depending on their position. As a result, ON resistance of the switches have different values as per Eq. (2).

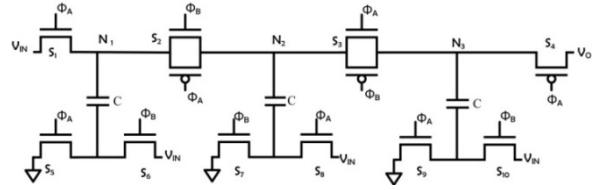


Figure 2. Linear charge pump [4].

TABLE 1. VOLTAGE LEVELS IN LINEAR CHARGE PUMP

MOS Switches	Voltages before the charge sharing		
	$V_D$	$V_S$	$V_S + V_D$
$S_1, S_6, S_8, S_{10}$	$V_{IN}$	$(V_O - V_{IN})/3$	$(V_O + 2V_{IN})/3$
$S_2$	$2V_{IN}$	$2(V_O - V_{IN})/3$	$2(2V_{IN} + V_O)/3$
$S_3$	$(V_O + 5V_{IN})/3$	$V_O - V_{IN}$	$2(V_{IN} + 2V_O)/3$
$S_4$	$(2V_O + 4V_{IN})/3$	$V_O$	$(5V_O + 4V_{IN})/3$
$S_5, S_7, S_9$	$V_{DS}$	0	$V_{DS}$

This suggests that the optimization method considering equal losses and equal sizing [7] in all the switches will result in sub optimal performance. Therefore, switch size has to determine based on their effective  $V_S + V_D$  voltage (according to the voltage levels of that particular switch). For example, we can reduce the sizes of  $S_5$ ,  $S_7$  and  $S_9$  considerably because their  $R_{ON}$  is much less compared to others ( $S_1$ ,  $S_2$  etc.). Similarly we have to increase the width of  $S_2$  and  $S_3$  as they have high  $V_S + V_D$  i.e. high  $R_{ON}$ .

The proposed optimization technique is to optimize the switching loss and conduction loss for each switch. The optimum design is to use bigger MOSFETs where ON resistance is higher and smaller one where ON resistance is lower. This method will enhance the performance of the charge pump and save silicon area. Moreover to optimize the charge pump efficiency under different light intensity, the switch size should be variable that leads to the design of reconfigurable switches.

### B. Reconfigurable switch

The Eq. (3) shows that the optimum width of the MOSFET depends on the current through the switch. In certain type of energy transducer, the ratio of maximum current to minimum current is very high (as in the case of solar cell energy harvesting). That means during their operation, the charge pump has to expect a wide range of current [14]. Therefore the corresponding optimal switch size is not a constant. In these situations, if we optimize the  $W$  for higher current, that result in large  $W_{OPT}$ , the efficiency will be inferior at lower current because of excess switching power loss. In the other hand, if we optimize for lower current (small  $W_{OPT}$ ), at high current mode, it will face excessive conduction loss and performance is again degraded. In micro power systems, the switch sizes are often optimized and fixed for worst case (less current). However in practice the harvested power and hence the current significantly varies with environmental change. So most of the time efficiency of charge pump will be away from the maximum value. As a result adaptively adjusting the switch size is an attractive and viable option to maintain high efficiency.

One effective method is to use different switches for these conditions and a control unit to select the switch. Smaller switches for lower current and bigger switch for higher current. But this method will increase the area of the total circuit and hence the cost. Instead we can think about reconfigurable switches and a control unit that assigns the switch size dynamically according to the requirement. This can be done by dividing the total switch and then connect them parallel only when large size is needed.

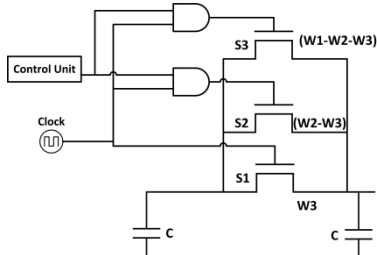


Figure 3. Reconfigurable switch with control unit

The model of a reconfigurable switch is shown in Fig 3. This is basically three switches ( $S_1$ ,  $S_2$  and  $S_3$ ) connected in parallel. Assume we optimized the width (as per Eq.3) for three current levels ( $I_1, I_2$  and  $I_3$ ) and  $W_1$ ,  $W_2$  and  $W_3$  are the three optimum widths such that  $W_1$  is for maximum current ( $I_1$ ) and  $W_3$  for minimum ( $I_3$ ). This switch is divided to three parts having widths  $W_3$ ,  $W_2-W_3$  and  $W_1-W_2-W_3$  such that for minimum current  $S_1$  is used, for intermediate current both  $S_1$  and  $S_2$  are connected in parallel (effectively  $W_2$ ) and for maximum current all the switches are used (effectively  $W_1$ ). The control unit automatically decides how many switches should be connected based on the current.

### C. Control unit

The control unit has to design such a way that it can configure the switches according to light intensity variations (charge pump current variation). The control information can be obtained from input voltage/ current or charge pump clock frequency. The voltage and current sensing are avoided to minimize the circuit complexity. However, the sensing the charge pump frequency will a better choice since it is easy to measure and provides information about charge pump current [13] [15]. In our design the control unit analyses the clock frequency coming from MPPT unit and adaptively determines the number of switches, that to be connected in parallel.

The first step in the control unit design is to empirically identify the clock frequencies (CLK\_MPP) corresponding to  $I_1$ ,  $I_2$  and  $I_3$ . The clock frequency has chosen above 12 MHz under high light intensity ( $I_1$ ) and above 8 MHz for medium light intensity ( $I_2$ ). All the switches are enabled for high light intensity and for medium light intensity only two switches are enabled, whereas switch 1 is always enabled.

This approach has transferred in circuit level (Fig 4) using digital counters and logic gates. The counter is used to count the pulses in the charge pump clock (CLK\_MPP) for fixed time duration and frequency information is obtained. This is achieved by enabling the counter using the signal Control\_sig which is high only for  $1\mu$  second. Logic gates designed to identify whether the count goes above 8 or 12. If count goes above 8 switch 2 is enabled and if it goes above 12 both

switches are enabled. The value is stored in a Flip Flop using a Hold signal and the counter is set to zero using a clear signal after each Control\_sig pulse.

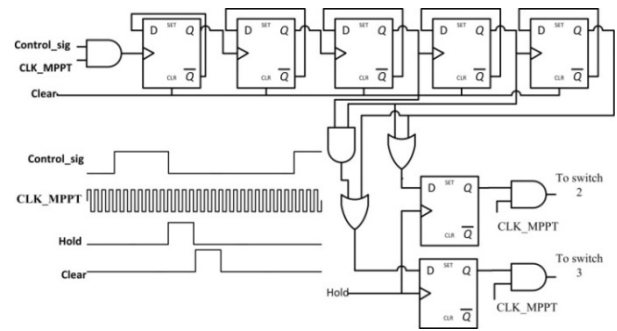


Figure 4. Control unit and signals of reconfigurable switch

## III. SIMULATION RESULTS AND DISCUSSION

The proposed optimization technique, reconfigurable switch and control unit are designed and simulated in UMC 180nm technology. A micro scale solar cell model [4] is used for the simulation. The light generated current ( $I_L$ ) is varied to mimic the light intensity variation. The output battery voltage is set to 1V. Capacitance of 500pF was used in the charge pump. Lengths of all the MOSFETs are set to 180nm.

Our first simulation experiment verified the necessity of reconfigurable switches in charge pump. To illustrate that, we designed a linear charge pump with optimized switches as per [7]. The switch dimensions (optimized based on [7]) are listed for 3 different solar intensity in first row of Table.2.

TABLE 2. PERFORMANCE IMPROVEMENT THROUGH RECONFIGURABLE SWITCHES.

Light generated current ( $I_L$ ) for different light intensities	4.2 mA	2.5 mA	1 mA
$W_{OPT}$ according [7] ( $\mu m$ ) (for all switches)	400	290	180
Harvested Power ( $\mu W$ ) for keeping $W_{all\ switches} = 400\ \mu m$	711	425	138
Harvested Power ( $\mu W$ ) with keeping $W_{all\ switches} = 290\ \mu m$	703	434	150
Harvested Power ( $\mu W$ ) with keeping $W_{all\ switches} = 180\ \mu m$	613	420	156
Harvested Power ( $\mu W$ ) Using Reconfigurable switch (Sizing according the incident light intensity)	711	434	156

From Table.2 it is clear that fixing all the switch sizes to one of the optimized value (400um/290um/180um), will not provide the maximum harvested power. We observed that optimization for higher light intensity ( $I_L=4.2mA$ ) will degrade the system performance when the light intensity is less ( $I_L=1mA$ ) and optimization for lower light intensity will degrade the system performance when the light intensity is high. This indicates that for a fixed switch size, the performance is maximum for a particular light intensity. To overcome this problem we designed the charge pump with reconfigurable switches which is optimized for three (high, medium and low) light intensities. Table.2 indicates that reconfigurable switches ensure best performance of charge pump irrespective of light intensity.

Further improvement has been archived through our proposed non uniform switch sizing technique and performance summary is tabulated in Table. 3. Each switch is optimized according to the voltage level across it. Our optimization technique provides an additional efficiency improvement of 4.5 % to 6.4% compared to [7] with 9% less silicon area.

TABLE 3. IMPROVEMENT IN HARVESTING POWER THROUGH PROPOSED OPTIMIZATION

<b>Light generated current (<math>I_L</math>)</b>		<b>4.2 mA</b>	<b>2.5 mA</b>	<b>1 mA</b>
Harvested Power ( $\mu W$ ) Using Reconfigurable switch (Sizing according the incident light intensity)		711	434	156
$W_{all\ switches}$ ( $\mu m$ )		400	290	180
Harvested Power ( $\mu W$ ) using proposed optimization		757	458	162
Switches Size	$S_1, S_6, S_8, S_{10}$	410	290	180
	$S_2$	1220	900	550
	$S_3$	400	290	180
	$S_4$	400	290	180
	$S_5, S_7, S_9$	230	180	110
Improvement in power		6.46 %	5.5 %	4.5 %
Area reduction		9.3 %	8.6 %	9.2 %

Finally, we have summarized the effective improvement in Table.4 using proposed optimization technique and adaptive re-configurability. The reconfigurable switch control unit consumes a very small amount of power as it consists of only digital logic and its duty ratio is very small. Our combined approach provides an efficiency improvement up to 23.5 % in the harvested power.

TABLE 4. OVERALL IMPROVEMENT IN HARVESTED POWER WITH PROPOSED TECHNIQUES AND CIRCUITS

<b>Light generated current (<math>I_L</math>) for different light intensities</b>	<b>4.2 mA</b>	<b>2.5 mA</b>	<b>1 mA</b>
Harvested Power ( $\mu W$ ) for keeping $W_{all\ switches}=400\ \mu m$	613	420	156
Harvested Power ( $\mu W$ ) with keeping $W_{all\ switches}=180\ \mu m$	711	425	138
Harvested Power ( $\mu W$ ) (Including proposed optimization technique and adaptive re configurability)	757	458	162
<b>Overall Improvement in Harvested Power</b>	23.5%	9%	17.3%

#### IV. CONCLUSION

Environmental energy harvesting has emerged as a feasible option to improve the life time of ultra-low power systems. Maximizing the transferred power from energy transducer to the storage cell is a major design objective. In this paper a switch size optimization technique, concept of reconfigurable switches and a control unit for adaptive reconfiguration are presented. We designed and implemented charge pump circuits and control unit in UMC 180nm process to demonstrate proposed methods. Simulation results shows that our proposed reconfigurable switch results in an improvement up to 23.5 % in the net harvested power with 6% less area (including the control unit) when compared with existing approaches.

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