Design of 45nm Switched Inverter Scheme (SIS) ADCs for Low Power and High Speed Applications

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ABSTRACT

The Analog to Digital converters (ADC) play a very important role in today's world of electronic systems. The requirement of present applications demands high speed, low power dissipation, minimum area, low noise and application specific resolution. Out of the various types of ADCs available the flash ADC is most popular for its highest conversion rate and its wide applications. On the down side the flash ADC dissipates high power due to the presence of resistance ladder. The power dissipation further increases with increase in resolution. In this research two different approaches are presented which eliminates the resistor ladder completely and hence reduce the power demand drastically. The first approach is Switched Inverter Scheme (SIS) ADC; it is realized for 3 bits using 7 comparator circuits of varying size in CMOS 45nm technology with Predictive Technology Model (PTM). The test result obtained indicates an offset error of 0.014 LSB. The full scale error is of -0.112LSB. The gain error is of 0.07 LSB, actual full scale range of 0.49V, worst case DNL & INL each of -0.3V. The power dissipation for the SIS ADC is 207.987 μ watts; Power delay product (PDP) is 415.9 fWs, and the area overhead is 1.89 μ m². The second approach is Sleep transistor SIS ADC. This approach shows 71% improvement in power dissipation. Whereas PDP is found to be 107.3 fWs and area overhead is 1.94 μ m² for Sleep transistor SIS ADC.

General Terms

ADC, Switched Inverter Scheme (SIS)

Keywords

CMOS 45nm, flash analog to digital converter, low power, resistor less, switched inverter scheme (SIS), sleep transistor

1. INTRODUCTION

Recent advances in the field of electronics require data converters for interfacing the signals of real world and then processing the obtained information in digital domain [10], [20]. In present scenario an ADC became an unavoidable component and it is also required to be fabricated on the same chip instead of a separate circuit for data conversion.

Since a few years lot of research is done on data converters to achieve maximum speed and minimum power consumption [8]. As technology scaling continues the demand of minimum power dissipation further increases in various modern battery powered applications [25].

The research is continuing in various types of data converters like flash, semi flash, sigma delta, pipeline, folding, and successive approximation register (SAR) ADCs to optimize their performance [1]. The insatiable demand of high performance data converters attracts researchers due to their wide usage in digital signal processing. In various applications data converters repress the performance severely if not designed optimally. Investigation of new design techniques for an ADC is in progress in order to reduce power dissipation, increase operating speed and decrease chip area [3].

High speed data converters are the key building blocks in many applications including high data rate serial links [2], [11]. Ultra wide band systems [4], magnetic and optical data storage devices [5], high speed instrumentation, wideband radar and optical communications [8], [12], 3G telecommunication systems, wireless wide area networks, broadband wireless communication network, radio astronomy, optical communication systems [6]. ADCs with high speed and resolution in the range of 6-8 bits are used in digital telecommunications, cryptography, high performance image sensing and processing, digital signal oscilloscopes and gigabit Ethernet. ADCs with low power dissipation are especially required for system on chip (SOC) applications, cellular phones, Digital TVs, & spectrum monitoring systems [7].

Out of various ADC architectures available, the design of flash ADC becomes quite more important as it is used in other ADC architectures like two step ADC and multi bit sigma delta ADC. The block diagram of a flash ADC is as shown in Fig.1. [26], [38].

Due to increase in number of resistors and comparators required in designing of fully parallel flash ADCs having resolution 8 bits and above, the layout area & power dissipation also increases. Therefore in recent years the research is carried with resistor less flash ADC architecture.

New methods developed to reduce the power consumption of flash ADCs are [5].

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Fig.1. Block Diagram of a Flash ADC

- Use of interpolation and voltage to current converters that operate as preamplifier stage of latches.
- Extension in the input range.
- Use of bisection method to let only half of the ADCs working in every clock cycle.

The aim of this work is to design the ADCs required for battery operated devices. The ADCs are designed and simulated with two different power saving schemes. The main improvements for various schemes are envisaged in power dissipation, differential and integral non linearity. The specifications of the design prototype are selected as 3 bit, for 500 MHz signal, and 0.5 V full scale range, with a supply voltage of 1V. The simulation is carried out in 45nm PTM [39] on LT Spice IV platform.

In section II two different types of flash comparator architectures are discussed along with the mathematical relations for sizing the transistors of comparator. The design issues of complete design along with component blocks like gain booster, encoder are given in section III. In section IV results and discussions are presented. Section V concludes the work.

2. DIFFERENT TYPES OF FLASH COMPARATORS

2.1 switched inverter scheme (SIS) comparator

The SIS comparator has very simple architecture as shown in Fig.2. It is quite different than the conventional operational amplifier based differential input voltage (DIV) comparator [9], [29], [34]. The key difference between the DIV comparator and the switched inverter scheme (SIS) comparator scheme lies in the way the reference voltage is generated for each level. In DIV comparator conventional method of using resistor ladder is utilized for externally generating the reference voltage. Where as in the SIS comparator scheme all $2n-1$ reference voltage for a n bit ADC are set internally by adjusting the threshold voltage of each voltage comparator separately by sizing the transistor properly. All DIV comparators are identical and duplicated for $2n-1$ times but each SIS comparator is altogether different from others and obtained by varying the β ratio of the inverters.

The SIS comparator design consists of two pairs of inverters connected back to back. Each of the inverter is sized separately to get a unique switching voltage [13], [17].

The cascaded inverters then work as voltage comparator. The full scale voltage range (VFSR) is equally divided by $2n-1$ SIS comparators, to obtain the switching point voltage for each comparator separately.

Fig.2. SIS Comparator

Achieving optimal sizing for each transistor in SIS comparator scheme is very much time consuming. The analytical expression for (W_p/W_n) of each comparator is determined by equating the pull up and pull down saturation currents as equation (1) [14], [15], [16], [18].

$$K_p V_{DSATp} \left(V_m - V_{DD} - V_{tp} - \frac{V_{DSATp}}{2} \right) \quad (1) \quad \text{The}$$

expression for switching voltage V_m is thus obtained for a short channel CMOS inverter in 45nm as equation (2) [19], [21], [22], [30].

$$V_m = \frac{V_{DD} - |V_{tp}| + V_{tn} \sqrt{1/r}}{1 + \sqrt{1/r}} \quad (2)$$

Where,

$$r = \frac{K_p V_{DSATp}}{K_n V_{DSATn}} = \frac{v_{satp} \cdot W_p}{v_{satn} \cdot W_n} \quad (3)$$

$$r = \frac{\mu_p (W_p/L_p)}{\mu_n (W_n/L_n)} \quad (4)$$

$$K_p = K_p \left(\frac{W}{L} \right) = \beta_p \quad (5)$$

$$K_p = \mu_p \cdot C_{oxp} \quad (6)$$

$$K_n = K_n \left(\frac{W}{L} \right) = \beta_n \quad (7)$$

$$K_n = \mu_n \cdot C_{oxn} \quad (8)$$

The above equations are realized on MATLAB 7.3.0 R2006b for switching voltage calculations. The program is given in Fig.3.

```
>> un= 0.032;
up = 0.0095;
vm = 0.3:0.071:0.801;
vdd = 1;
vtn = 0.22;
vtp = 0.22;
b = sprintf('%4f', W);
W = (un/(up))*((vm-vtn)./(vdd-vtp-vm)).^2;
```

Fig.3. MATLAB code for switching voltage calculation

The main advantage of the SIS comparators is that it does not use any resistor ladder and so it is suitable for low voltage, low power and high speed applications such as cellular mobile phones and touch screen display devices. On the other hand the process parameter variations may cause offset and gain errors to vary considerably when the design is used for higher resolution ADCs. Also noise can be a big challenge for the single ended SIS comparator scheme.

2.2 SIS comparator with sleep transistor

The circuit of SIS comparator is modified by addition of high threshold PMOS and NMOS near the supply rails as shown in Fig.4. The addition of header & footer reduces the static power dissipation to a great extent due to increased resistance of the high threshold PMOS and NMOS transistors [27], [31], [36]. During the period of no activity the section not in use remains completely off. Whereas, the components are invoked again when any activity is detected.

A Local sleep transistor network is used here as opposed to global level network, because every comparator is differently sized and hence the current through each comparator section is also different. The sizing of a sleep transistor is calculated using equation (9).

$$\left(\frac{W}{L}\right)_{\text{Sleep}} = \frac{I_{\text{Sleep}}}{0.0281\mu_n C_{\text{ox}}(V_{\text{DD}} - V_{\text{TL}})(V_{\text{DD}} - V_{\text{TH}})} \quad (9)$$

Where, I_{Sleep} is calculated by simulating the circuit without sleep transistor network and finding maximum current that flows through ground or VDD.

$$C_{\text{ox}} = \frac{\epsilon_0 \epsilon_r}{t_{\text{ox}}} \quad (10)$$

$$C_{\text{ox}} = \frac{\epsilon_{\text{ox}}}{t_{\text{ox}}} \quad (11)$$

$$C_{\text{ox}} = \frac{\epsilon_0 \epsilon_{\text{ox}}}{t_{\text{ox}}} \quad (12)$$

$$C_{\text{ox}} = C_{\text{ox}} \cdot A \quad (13)$$

$$A = W \cdot L \quad (14)$$

All the symbols used in equation (1) to (14) have usual meaning and are also universally known.

Fig.4. SIS Comparator with Sleep Transistor

Table I

Truth table for one out of n code

Input Thermometer code							Output "01" code						
T7	T6	T5	T4	T3	T2	T1	G7	G6	G5	G4	G3	G2	G1
0	0	0	0	0	0	0	0	0	0	0	0	0	1
0	0	0	0	0	0	1	0	0	0	0	0	1	0
0	0	0	0	0	1	1	0	0	0	0	1	0	0
0	0	0	0	1	1	1	0	0	0	1	0	0	0
0	0	0	1	1	1	1	0	0	1	0	0	0	0
0	0	1	1	1	1	1	0	1	0	0	0	0	0
0	1	1	1	1	1	1	1	0	0	0	0	0	0
1	1	1	1	1	1	1	0	0	0	0	0	0	0

3. DESIGN OF ADCs

For the complete realization of any flash ADC the blocks required other than comparator are gain booster and thermometer to binary encoder. The design of these blocks is given here.

3.1 Gain Booster

The gain booster is used to increase voltage gain of the output of a comparator so that it provides a full digital output voltage swing, without which the output of the comparator circuit is unable to drive the next stage, it also makes thresholds sharper for comparator outputs and provide full digital output voltage swing. The gain booster block is designed for lowest switching voltage.

Each gain booster consists of two identical cascaded inverters with the same circuit as that of comparator, but the transistors are sized for minimum aspect ratio for each gain booster [23].

3.2 Thermometer code converter

The encoder converts the thermometer code to binary code in two steps. In the first step the thermometer code is converted into one out of n code by using the truth table as shown in Table 1. The one out of n codes is then converted to binary code d_2, d_1, d_0 by Read only memory (ROM) encoder, as shown in Fig.5. [35]. The ROM encoder is a common and straight forward approach to encode the one out of n code to binary bit. The appropriate row m in the ROM is selected by using a row decoder that has the output of comparator m and the inverse of comparator $m + 1$ as inputs. The output m of the row decoder, connected to memory row m , is high if the output of comparator m is high and the output of comparator $m + 1$ is low. The row decoder can be realized by, a number of 2-input NAND gates, where one input to each NAND gate is inverted. The main advantage of the ROM decoder approach is its regular structure that is easy to design [34].

Fig.5. ROM Encoder

4. RESULTS AND DISCUSSION

The proposed technique is applied in the design of 3 bit ADC with chosen specifications as given in Table II and the implementation is as shown in Fig.6 for SIS ADC & Fig.8 for sleep transistor ADC [23], [24].

The design consists of comparator chain, gain booster circuit and a thermometer to binary encoder block and finally a buffer circuitry to reduce the loading effects.

Conventional voltage comparators use a resistor ladder circuit to generate $2n-1$ reference voltages (V_{ref}) for comparators, ranging from $V_{ref}(\max)$ to $V_{ref}(\min)$. Generating equally spaced reference voltages determines the quantization performance of ADCs [9], [21]. The SIS comparator eliminates the use of the resistor ladder circuit by generating the reference voltages internally. The SIS comparator uses two cascaded inverters to generate the range of internal reference voltages. At the first inverter, the analog input quantization is determined by adjusting the ratio of the PMOS and NMOS transistors. The second inverter is used to increase the voltage gain and prevent unbalanced propagation delays of all comparators.

The results for SIS Comparator are shown in Fig. 7 and for the modified Sleep transistor version in Fig.9.

The total power consumption here is determined by summing up the power dissipation of each circuit separately. The various blocks used to realize the design are comparator section, gain booster, XOR gate, ROM Encoder and buffers. The comparison results are shown in Table III for both types of ADCs [17], [31], [41], [42].

TABLE II
ADC SPECIFICATION

S No.	Specification	Value
1	Resolution	3 Bit
2	CMOS tech.	45nm
3	Model File	PTM
4	$L_p = L_n = L_{min}$	45 nm
5	t_{ox}	14 Å
6	C_{ox}	25 fF/ μm^2
7	Max. Speed	500 MSPS
8	V_{FSR}	0.3 V-0.8 V
9	V_{LSB}	0.0714 V
10	$(W_p/W_n)_{Min}$	0.55
11	$(W_p/W_n)_{Max}$	266
12	V_{DD}	1 V
13	V_{TP}	-0.22V
14	V_{TN}	0.22V
15	$V_{m min}$	0.371 V
16	$V_{m max}$	0.8 V
17	μ_n	320 $cm^2/v\text{-sec}$
18	μ_p	95 $cm^2/v\text{-sec}$
19	C_L (Load Capacitance)	0.01fF

Fig.6. SIS ADC with ROM Encoder

The power dissipation is calculated and is compared for both the designed ADCs. The finding for saving in power dissipation is shown in Table IV.

The various dynamic parameters for all ADCs are also calculated using the equations (15) – (22) [30], [40] and are tabulated in Table V.

Offset error = real transition - ideal transition (15)

Offset in LSB = offset error/ One LSB (16)

4.1 Design of SIS ADC

Fig.7. Simulation Results of SIS ADC

4.2 Design of Sleep Transistor SIS ADC

Fig.8. Sleep Transistor SIS ADC with ROM Encoder

Fig.9. Simulation Results of Sleep Transistor SIS ADC

Full Scale Error = real last transition - ideal last

transition (17)

Gain error = Average code width (LSB size)

= $\frac{\text{Real last transition} - \text{first transition}}{2^{(N-1)} - 1}$ (18)

DNL= DNL [k] = Width[k] -1 (19)

TABLE III
COMPARISON OF COMPONENT POWER DISSIPATION IN μW

S.No.	Blocks	SIS ADC [17], [31], [41], [42]	Sleep SIS ADC
1	Comparator	167.087	37.88
2	Gain Booster	35.18	18.48
3	One out of n coder	3.1357	1.8
4	ROM encoder	2.153	1.09
5	Buffers	0.437	0.31
6	Total Power	207.987	59.64
7	Delay	2ns	1.8ns
8	Power Delay Product	415.9 fWs	107.3 fWS
9	Area	1.89 μm^2	1.94 μm^2

TABLE IV
BLOCK WISE PERCENTAGE SAVING IN POWER
DISSIPATION AS COMPARED TO SIS ADC

S.No.	Blocks	Sleep SIS ADC
1	Comparator	77.3 %
2	Gain Booster	47.47 %
3	One out of n coder	42.6 %
4	ROM encoder	49.37 %
5	Buffers	29.06 %
6	Total Power	71 %

Where,

Width [k] = Transition [k+1] - Transition [k] (20)

INL=

INL (m) = $\frac{\text{Transition [m]} - \text{Transition[ideal]}}{\text{Transition[ideal]}}$ (21)

Step Width [Ideal]

Table V
DYNAMIC PARAMETERS FOR ADCs IN LSB

Parameter	SIS ADC	Sleep Transistor SIS ADC
Offset Error	0.014	-0.084
Full Scale Error	-0.112	-0.36
Gain Error	0.07	0.021
DNL	-0.3	-0.6
INL	-0.3	-0.4

$$INL = \frac{\sum_{i=1}^m DNL[i]}{m} \quad (22)$$

DNL is Differential non linearity error and INL is Integral non linearity error. The quantization error in each case is less than 0.5 LSB.

Comparison of this work with existing ADCs is shown in Table VI.

Table VI
COMPARISON WITH EXISTING ADCs

S.No	Publication	Year	Type	No. of Bits	Sampling Frequency (SPS)	Supply Voltage	Technology	DNL (LSB)	INL (LSB)	SNR	Power Dissipation
1.	This Work	-	Flash (SIS ADC)	3	500 M	1 V	45 nm	+/-0.3	+/-0.3	-	207.98 μ W
2.	This Work	-	Flash (Sleep Transistor SIS ADC)	3	500 M	1V	45nm	+/-0.6	+/-0.4	-	59.64 μ W
3.	[12]	2011	SAR	6	50 M	1V	90 nm	<0.64LSB	<0.54LSB	32 dB	240 uW
4.	[13]	2011	Flash	4	200 M	3.3v	0.35 um	0.2LSB/-0.9LSB	0.2	20dB	12.4mW
5.	[26]	2010	Flash	4	1.9 G	1.8 V	0.5um	+0.16/-0.16 LSB	+0.16/-0.104	-	0.28573 mW
6.	[28]	2010	SAR	9	80 M	1V	65 nm	0.37	0.40	50.71 dB	3.4 mW
7.	[31]	2009	Flash	3	-	3.3V	130nm	-	-	-	-
8.	[33]	2008	Folding	9	1G	3.3V	0.35 um	-	-	-	375 mW
9.	[32]	2008	Flash	3-6	200 M	3.3v	0.35um	0.519LSB	0.423LSB	-	-
10.	[35]	2007	Pipelined Flash	4	2.5 G	1.2V	130 nm	0.26	0.296	-	23.778 mW
11.	[37]	2006	Flash	6	500 M	3.3V	0.35um	+0.2	-0.2	37.2dB	-

5. CONCLUSION

Low power architecture for a 3-bit CMOS SIS based flash ADC is presented using PTM 45 nm. The modified versions of SIS ADC can further achieve very low power dissipation; this proposed method can reduce power dissipation upto 71%. It uses smaller silicon area of $1.94\mu\text{m}^2$. The DNL of the proposed ADC is within -0.3LSB and INL is also within -0.3LSB . The proposed ADC chip so designed can be used for capacitive pressure sensor, video systems as well as it can be used in a low power two-step ADC, pipelined ADC and multi-bit sigma delta ADC. A disadvantage is that for higher no of bits the increased complexity of the circuit consumes more chip area and will likely consume more power.

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