Review article

Novel methodology to determine leakage power in standard cell library design

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ABSTRACT

In the most advanced technology nodes, leakage has become a major concern for integrated circuits designers. In addition, the leakage calculation using SPICE simulations takes a large amount of time for the entire library of standard cells for the different PVT (Process, Voltage, and Temperature) conditions. However IC Designers usually need a fast access to the leakage current estimation in order to validate their designs. In this context, the present paper proposes a new approach of the leakage estimation. The aim of this methodology is to predict the leakage of a standard cell accurately and in a short amount of time. This method is applied to all the cells of the used standard cell library and is based on mathematical models developed from the leakage physical equation. The results of the leakage calculated with this technique shows an average error of 5%. The context of this work is part of a fast generation of a full liberty file of a standard cell library using the curve fitting method.

1. Introduction

As the technology is shrinking, leakage is one major issue that faces chip designers especially in the most advanced nodes [1]. The total power consumption has two components: the dynamic power and the leakage power. Tompson et al. [2], in his paper explains that the leakage power is becoming as important as dynamic power in the coming technologies.

In sub-22nm technologies, Moore's law has been shaken as the gate size because it is not shrinking correctly due to the process limit [7]. In this context, FinFET technology has been introduced few years ago in production, as a solution for continuous scaling in order to respect Moore's law [3]. Indeed, Agostinelli et al. present a study that highlights the advantages of FinFET over CMOS technology [4]. From the electron devices prospective, FinFET which is a multigate FETs offers a good biasing flexibility [4]. In general, two types of transistors in the FinFET technology can be fabricated: a single gate (3T) or a two gates transistor that can be controlled independently. The 3T FinFET improves the DBIL (drain induced barrier lowering) and reduces random dopants fluctuation because of a better control of short channel effect (SCE). It is no more controlled by the channel doping but the thickness of the thin body [4].

From a circuit level perspective, reducing the leakage can be obtained by stacking transistor and controlling threshold voltage by back biasing technique [8, 9]. By having independent gates, these techniques take advantage of the flexibility given by the FinFET technology [4]. Even though the reduction of leakage in the multi gate FinFET technology in comparison with the bulk MOSFET, the focus remains on the same areas of the design [3] and predicting the speed and the energy of a design is an overriding concern. While Spice simulations remain the reference technique in estimating delay and energy consumption at logic level due its very high accuracy, it also takes a very long time for computation [10].

Many leakage power models during the last years have been introduced. However, two types of models can be distinguished; the first type is based on the physical model of leakage currents of the cells while the other models are an offline SPICE characterization of the leakage current in standard cells depending on the input logic values [11]. Recently, Zia et al propose a new leakage methodology based on logic level approximation model based on internal nodes characterization [10]. V. K. Sharma et al. proposes a methodology based on Boolean logic in order to reduce leakage current while taking into consideration PVT variations [23], whereas Z. Ning et al. proposes a test structure to model and characterize the leakage [24].

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The present work is a combined methodology based on characteriza-
tion of the standard cells in some few corners and the physical model of the leakage current. Few PVTs are first characterized in order to extract the fitting parameters of the leakage model. Once all the parameters are known, any other PVT can be generated with interpolation. The rest of this paper is organized as follow:

Section 2 presents the leakage physical variation on FET devices and the different data obtained by the characterization of the leakage in the standard cell. Section 3 explains the methodology and the flow followed while section 4 describes the proposed leakage model. Characterized data are compared to data extracted from the mathematical model while showing the accuracy in Section 5. Section 6 concludes this work.

2. Background and leakage physical model

2.1. Background

In digital circuits FET devices, many leakage phenomena are added up in the static dissipation of power for each technology: FinFET, MOS-FET [11] etc. No less than seven physical phenomena have been distinguished in MOS devices [12]. Yet, in technologies below 65nm node, subthreshold, gate and body leakage are the prevailing types [13] and represent the main targets of reduction techniques studies. Concerning the finFET devices, the drain-to-source subthreshold is dominant. This is due to the fact that the gate oxide tunnelling and source/drain conduction to body are considerably lessened [11]. In general, the different types of leakages in the FET devices show a different behaviour regarding temperature and the circuit level response. Yet, the most dominant leakage power components have an exponential variation regarding the voltage at the output nodes [12]. For this reason, the characterization of leakage current is not straightforward in digital cells as a consequence of two major effects: stacking transistors, the leakage is strongly impacted by the change in the voltage of the nodes [14]; the other effect happens when the gate leakage of a cell is strongly affected by an another cell and becomes important enough to cause the output voltage node to change state (drop or rise) [15, 16].

Several researches have been done in order to estimate the leakage power in the device and at digital circuit level. D’Agostino et al. introduces an analytical method in order to represent the static variations of the leakage currents in a circuit [17]. Mukhopadhyay et al. presents an accurate model of the leakage power in logic gates without considering the load effects of these [18].

2.2. Leakage physical model

As previously mentioned, the drain-to-source subthreshold leakage is dominant in finFET devices because the gate oxide tunnelling and source/drain conduction to body are considerably lessened [11]. The subthreshold leakage current of transistor when \( V_{ds} = V_{dd} \) and \( V_{gs} = 0 \) is represented in [19] as follow:

\[
I_{\text{leak}} = \left( \frac{W}{L} \right) I_s \left( 1 - e^{-V_{ds}/V_{th}} \right) e^{\frac{V_{gs} - V_{th}}{nV_{th}}}
\]

where \( L \) and \( W \) are the transistor geometries, \( I_s \), \( n \), and \( V_{th} \) are constants to be determined for each process, and \( V_T \) represents the thermal voltage [20]. It should be noted that the variation of \( I_{\text{leak}} \) with the temperature is...
following an exponential tendency \[5\]. In Figure 1, this variation is illustrated for an Inverter cell and for different voltages. Also, \(I_{\text{leak}}\) has also an exponential dependence with threshold voltage \(V_t\). As \(V_{\text{off}}\) is very small and \(1 - \exp\left(-\frac{V_t}{V_{\text{off}}}\right)\) is approximately 1 for all \(V_{\text{dd}}\), the Eq. (1) becomes:

\[
I_{\text{leak}} = K_1 e^{-K_3 V_t}
\]

2.3. Leakage characterisation

Three different kind of power are calculated by characterization tools in a circuit: leakage power, hidden power and finally active power. All combinations of inputs are taken into account when the leakage power is calculated which means that a different power value is reported for each combination in the liberty file. Figures 2, 3, and 4 give examples of leakage values in the liberty file for an Inverter and NAND gates. In addition, the leakage power depends on the state of the transistors of the given standard cell. For instance, in the first scenario of Figure 2, the input has a value of \(0\) which means it’s the pmos which is activated. The leakage in this case will be the leakage of the nmos of the transistor. As the number of the standard cells increments, combinations also increments and leads to drastic increase in characterization time.

3. Flow and methodology overview

3.1. Overview of curve fitting methodology

For a better understanding of the developed methodology, it seems judicious to address the concept of the curve fitting.

The mathematical models representation of various systems, constitute a mandatory step in the behavioural evaluation process. However, the main issue of using this method is that the mathematical formulation can be very complicated. As a consequence, empirical correlation is usually used in order to represent a system which is based on data extracted from experimentation \[25\].

The aim of using curve fitting methodology is to analyse in theory the results of experimentations with a model (function or equation), the related parameters to the model (called fitting parameters later in this paper) are calculated using the function or the equation elaborated \[26\].

In a number of fields of engineering and applied mathematics, the experimentations and the issues interfere which implicate two variables \[27\]. If \(v\), the speed of a vehicle varies with \(p\), the horsepower of the motor following the equation \(\rho = a + bv^3\) where \(a\) and \(b\) are the parameters to extract. In this optic, various values of speeds with their respective horsepower are observed. The idea is to determine the best fitting values for parameters \(a\) and \(b\) using the taken values of \(v\) and \(p\). Consequently, the main issue is to determine the relationship that exists between variables \(x\) and \(y\) from a set of experimental values from empirical models \((x_i, y_i), i = 1, 2, \ldots, n\). The whole procedure or steps in order to find the best fitting model or the curve that fits the best in order to determine or predict the unknown values is called curve fitting. The different steps of a curve fitting and modelling methodology used in this work are summarized in the Figure 5.

3.2. Proposed methodology and flow

The method presented in this work consists of developing leakage mathematical equations in order to model leakage variations with the temperature and the voltage. More specifically, in the present work, the initial experimental models come from an initial characterization of cells in some initial PVTs.

Using a reduced number of pre-characterized corners of the standard cells, the fitting parameters are first calculated. The idea in the present work is that independently of the technology, the leakage variation with the physical metrics (temperature and voltage) follow the same tendency.

Figure 4. Example of leakage in liberty files for NAND2_X1N cell (ssgnp_cworstccworstt_max_0p54v_m40c).
The first step consists of a validation of the model on a reduced set of cells. Then the model is deployed on all cells of the library following the steps illustrated in the Figure 5 where the detailed flow used in this work is presented.

Once the fitting parameters are determined, any additional corner is generated using the interpolation based on the developed models. In the objective of achieving an acceptable accuracy of the results, a minimum of eight corners have to be pre-characterized: two different temperature values and four different voltage values. In this context, a script in JAVA has been developed to automate the calculation and the generation of additional corners.

A similar methodology has already been applied in previous work to the timing and the internal power [21, 22] but with different mathematical equations.

4. Proposed leakage model

From previous works of literature and the physical model of the leakage, it is known that the leakage power increases with the increase of temperature and voltage. The first step in order to determine the model of leakage consisted on characterizing the leakage of a set of cells in order to validate the exponential behaviour of leakage current regarding the
voltage. Figure 6 shows an example of leakage current variation with voltage for a NAND cell based on characterized data for two different temperatures. The curve shown in this figure validates the exponential behaviour of the leakage regarding the voltage.

In the developed model, the two major components are kept which are: the subthreshold current ($I_{sub}$) and gate–source/drain current ($I_{gate}$) represented by the following equations:

$$ I_{leak} = I_{sub} + I_{gate} $$  \hspace{1cm} (3)

$$ I_{sub} = I_1 \exp(\alpha_1 V_{dd}) $$  \hspace{1cm} (4,5)

$$ I_{gate} = I_2 \exp(\alpha_2 V_{dd}) $$  \hspace{1cm} (6)

where $I_1$ and $\alpha_1$ represent parameters of drain/source leakage current and $I_2$, $\alpha_2$ represents parameters of gate to drain/source leakage current.

The gate current isn’t sensitive to the variation of temperature which means that its effect will be visible on small temperatures only. As it’s under the effect of the gate oxide tunnelling, the gate leakage remains negligible until a sufficient high voltage is reached [28]. On the other hand, the subthreshold leakage has a very high dependence with temperature as shown in the section of physical model [6]. Hence, the parameters $I_2$, $\alpha_2$ are extracted at minimal temperature.

On the other hand, the temperature model is assumed to be linear as only two points of temperature are initially characterized.

4.1. Equation’s parameters extractions

4.1.1. Voltage model parameter’s extraction

In order to determine the parameters of the voltage model, leakages of four different voltages are simulated across the platform as shown in Figure 7. These data should contain leakages values at the minimal and the maximal voltages allowed by the technology platform as the extrapolation outside the platform range is not possible. The extraction of the fitting parameters of the equation is done at different steps.

As explained previously, the gate current is very small at the minimal voltages, so the Eq. (6) becomes:

$$ I_{leak} = I_1 \exp(\alpha_1 V_{dd}) $$  \hspace{1cm} (7)

The parameters $I_1$ and $\alpha_1$ are then extracted at the minimal temperature. Only leakages at the two lower values of the voltage are used here.

Now that $I_2$ and $\alpha_2$ are known, $I_1$ and $\alpha_1$ are determined using the two remaining leakages at $V_{dd3}$ and $V_{dd4}$ (the higher voltages).

4.1.2. Temperature model parameters extraction

In order to complete the leakage model and determine temperature model’s parameters, two temperatures are used when computing the variation of the parameters $I_2$, $\alpha_2$, $I_1$ and $\alpha_1$ w.r.t the temperature. Only the minimum and the maximum temperature values allowed by the platform are taken.

The parameters $I_2$ and $\alpha_2$ are considered not variable with the temperature as the gate leakage variation with temperature is very slow. As represented in the Eqs.(8) and (9), parameters $I_1$ and $\alpha_1$ are assumed to follow a linear variation as the temperature increases:

$$ \alpha_1 = a_1 * T + b_1 $$  \hspace{1cm} (8)

$$ \ln(I_1) = c_1 * T + d_1 $$  \hspace{1cm} (9)

4.2. Correction function

Figure 8 shows the correlation of the temperature fitting parameter ($a_1_{\text{model}}$), in comparison with the value of this parameter calculated from characterized leakage data ($a_1$). The curve representing $a_1_{\text{model}}$ is linear as assumed before, while $a_1$ calculated based on characterized data shows a nonlinear behaviour. More temperatures have been
characterized for verification purpose only. This divergence between the two curves is explained by the fact that we worked with two values of temperatures only.

Table 1 compares leakage values of modelled data with characterized leakage data. From that, we can deduce that the linear model is not accurate enough and impacts the leakage model's precision. This is the consequence of the temperature models that are assumed to be linear as explained previously.

To achieve a better accuracy, a correction function has been developed and applied on the proposed model. This correction function adds some inflections to the temperature's linear model to match the best curve representing the evolution of the leakage w.r.t. temperature (Figure 8). The correction terms are computed on the INVERTER cell and then deployed for the rest of cells. The complete model of the leakage is given by the Eq. (10):

$$I_{\text{leak}} = F_{\text{corr}} \times \left( \exp(c_1 T + d_1) \exp\left(\alpha T + b_1\right) V_{dd} \right) + I_1 \exp(\alpha V_{dd})$$ (10)

$$F_{\text{corr}} = 1 + f_{\text{max}} \times \left(1 - \frac{(T - T_0)^2}{R^2}\right)$$ (11)

Where: $F_{\text{corr}}$ represents the correction function,

| Voltage | Temperature | -40 | 0  | 40  | 85  | 125 |
|---------|-------------|-----|----|-----|-----|-----|
| 0,54    | 0,0 %       | 44,3 % | 53,1 % | 40,0 % | 0,0 % |
| 0,59    | 0,1 %       | 42,8 % | 52,3 % | 40,0 % | 1,5 % |
| 0,61    | 0,2 %       | 42,1 % | 51,8 % | 39,8 % | 1,9 % |
| 0,63    | 0,4 %       | 41,3 % | 51,3 % | 39,6 % | 2,2 % |
| 0,67    | 0,7 %       | 39,5 % | 50,2 % | 39,0 % | 2,4 % |
| 0,7     | 0,9 %       | 38,0 % | 50,0 % | 38,3 % | 2,3 % |
| 0,74    | 1,2 %       | 35,8 % | 47,7 % | 37,1 % | 2,0 % |
| 0,81    | 0,0 %       | 32,0 % | 44,8 % | 35,1 % | 0,8 % |
| 0,9     | 9,1 %       | 30,0 % | 41,6 % | 32,3 % | 1,3 % |
| 0,95    | 14,4 %      | 32,1 % | 41,1 % | 31,3 % | 2,0 % |
| 1,05    | 0,0 %       | 33,0 % | 43,5 % | 32,9 % | 0,0 % |

| Voltage | Temperature | -40 | 0  | 40  | 85  | 125 |
|---------|-------------|-----|----|-----|-----|-----|
| 0,54    | 0,0 %       | 3,0 % | 1,2 % | 11,0 % | 0,0 % |
| 0,59    | 0,1 %       | 3,5 % | 0,3 % | 8,7 % | 1,5 % |
| 0,61    | 0,2 %       | 3,9 % | 0,2 % | 8,0 % | 1,9 % |
| 0,63    | 0,4 %       | 4,4 % | 0,1 % | 7,4 % | 2,2 % |
| 0,67    | 0,7 %       | 5,6 % | 0,3 % | 6,6 % | 2,4 % |
| 0,74    | 1,2 %       | 8,4 % | 1,3 % | 5,9 % | 2,0 % |
| 0,81    | 0,0 %       | 11,0 % | 2,7 % | 5,9 % | 0,8 % |
| 0,9     | 9,1 %       | 9,2 % | 3,0 % | 5,7 % | 1,3 % |
| 0,95    | 14,4 %      | 3,2 % | 0,6 % | 4,5 % | 2,0 % |
| 1,05    | 0,0 %       | 3,5 % | 9,7 % | 3,4 % | 0,0 % |

Table 1. Leakage errors of modelled leakage Vs characterized leakage before applying the correction function for a NAND3_X2N.

Table 2. Leakage errors of modelled leakage Vs characterized leakage after applying the correction function for a NAND3_X2N.

![Figure 9. Characterized Leakage Vs Modelled leakage for the NAND3_X2N cell.](image)
\(a_3, b_1, c_1, \) and \(d_1\) are the temperature variation parameters
\(I_2\) and \(\alpha_2\) are the voltage model parameters
\(T\) is the temperature
\(R\) and \(T_0\) are the parameters to be calculated

As previously explained, the aim of the correction function is to add a quadratic dimension to the linear model of the temperature. When the temperature is equal to the minimal or the maximal, no correction function is applied, hence:

### Table 3. Leakage errors of modelled leakage Vs characterised leakage for the different input combination for MXIT2_X4N.

| State | Voltage(V) | Temperature (°C) | Temperature (°C) |
|-------|------------|------------------|------------------|
|       | 40         | 0                | 40               |
|       | 85         | 125              | 40               |
| 111   | 0.54       | 0.0%             | 2.4%             |
|       | 0.59       | 0.1%             | 1.4%             |
|       | 0.61       | 0.0%             | 1.2%             |
|       | 0.63       | 0.0%             | 1.1%             |
|       | 0.67       | 0.2%             | 1.1%             |
|       | 0.74       | 0.7%             | 1.9%             |
|       | 0.81       | 1.0%             | 3.4%             |
|       | 0.90       | 1.0%             | 6.1%             |
|       | 0.95       | 0.7%             | 7.9%             |
|       | 1.05       | 0.0%             | 11.8%            |
|       |            | Average Error   |                  |
| 2.7%  |            |                  |                  |
| State | 110        | Temperature (°C) | Temperature (°C) |
|       | 40         | 0                | 40               |
|       | 85         | 125              | 40               |
| 101   | 0.54       | 0.0%             | 1.4%             |
|       | 0.59       | 0.4%             | 3.5%             |
|       | 0.61       | 0.4%             | 4.1%             |
|       | 0.63       | 0.3%             | 4.7%             |
|       | 0.67       | 0.1%             | 5.5%             |
|       | 0.74       | 1.0%             | 6.2%             |
|       | 0.81       | 0.0%             | 6.8%             |
|       | 0.90       | 13.0%            | 9.9%             |
|       | 0.95       | 22.7%            | 14.1%            |
|       | 1.05       | 0.0%             | 12.2%            |
|       |            | Average Error   |                  |
| 5.2%  |            |                  |                  |
| State | 011        | Temperature (°C) | Temperature (°C) |
|       | 40         | 0                | 40               |
|       | 85         | 125              | 40               |
| 010   | 0.54       | 0.0%             | 1.4%             |
|       | 0.59       | 0.3%             | 3.3%             |
|       | 0.61       | 0.3%             | 3.9%             |
|       | 0.63       | 0.2%             | 4.3%             |
|       | 0.67       | 0.1%             | 5.0%             |
|       | 0.74       | 0.8%             | 5.5%             |
|       | 0.81       | 0.0%             | 5.6%             |
|       | 0.90       | 10.5%            | 9.9%             |
|       | 0.95       | 18.9%            | 11.1%            |
|       | 1.05       | 0.0%             | 10.3%            |
|       |            | Average Error   |                  |
| 4.7%  |            |                  |                  |
| State | 001        | Temperature (°C) | Temperature (°C) |
|       | 40         | 0                | 40               |
|       | 85         | 125              | 40               |
| 000   | 0.54       | 0.0%             | 0.2%             |
|       | 0.59       | 0.3%             | 1.5%             |
|       | 0.61       | 0.2%             | 1.9%             |
|       | 0.63       | 0.0%             | 2.3%             |
|       | 0.67       | 0.8%             | 2.7%             |
|       | 0.74       | 2.7%             | 2.8%             |
|       | 0.81       | 19.5%            | 12.3%            |
|       | 0.90       | 25.4%            | 20.6%            |
|       | 1.05       | 0.0%             | 20.0%            |
|       |            | Average Error   |                  |
| 5.3%  |            |                  |                  |
\[ F_{corr} = 1 \text{ if } T = T_{\text{min}} \text{ or } T = T_{\text{max}} \] (12)

From that, we can extract the parameters \( T_0 \) and \( R \) as follow:

\[ R = \frac{(T_{\text{max}} - T_{\text{min}})}{2}, \quad T_0 = \frac{(T_{\text{max}} + T_{\text{min}})}{2} \] (13,14)

Table 2 and Figure 9 show the leakage values of the model in comparison with leakage values from the characterization after applying the correction function. We can see that the results are more accurate after applying the correction function.

5. Validation and accuracy

A “Cell-by-cell” comparison approach has been used in order to compare the liberty file generated from the developed models and the characterized ones. It is a mandatory first check to validate the results obtained because it gives a representation of the results at circuit level.

For each cell, once the fitting parameters are calculated using data in the initial liberty files, intermediate corners are generated using the script developed for this purpose. It is to note that intermediate corners are not used in the initial parameters’ extraction. After this step, the same corners are characterized for the same cells and the corresponding leakage values are finally compared for each case. Two types of errors are hence represented in the table of results below: the relative error and the average error where relative error calculation is:

\[ \text{error}_{\text{relative}} = \frac{\text{data}_\text{modelled} - \text{data}_\text{characterized}}{\text{data}_\text{characterized}} \] (15)

while the average error is the average of the errors of all the different conditions in the same table.

The results of this validation tests are illustrated in the tables below for some representative cells for different voltages and temperatures. These tables summarize the absolute values of errors of modelled leakage compared to the characterized ones. All different inputs combinations for the cells are taken into account. After applying the correction function, the average errors on each leakage table reaches up to 5% of average errors on the table. Indeed, error values are more significant for the largest voltage values. However the error values presented in the tables are absolute values. In a full circuit, we are expecting an averaging phenomenon that will improve the results of the proposed Leakage models.

Table 3 presents the correlation results of the leakage currents for the MXIT2 cell for 5 values of temperature and 10 different voltage values. The MXIT2 cell is a multiplexer with 3 inputs: two inputs \( A \) and \( B \) for the signal and an input \( S_0 \) for selection. All combinations of input pins are presented: the cell is having 3 input pins with two possible states (1 or 0), the six different combinations are considered. The largest errors are noted for the highest voltages and especially for those that correspond to the intermediate temperatures.

Table 4 presents the correlation results of the leakage currents for the INVERTER cell for 5 temperature values and 10 different voltage values. Since the cell has an entry, only two states are possible (1 or 0), the two different combinations are presented. As explained previously when the input of the inverter is at state 1, it is the leakage current of the pmos which is calculated and when the state of the input is at 0, it is the leakage current of the nmos which is calculated. The most important errors are...
| Voltage (V) | Temperature (°C) | State 1111 1110 | Temperature (°C) | Average Error |
|------------|-----------------|-----------------|-----------------|---------------|
| 0.54       | 0.0%            | 1.3%            | 0.5%            | 10.9%         | 0.0%          |
| 0.59       | 0.2%            | 1.8%            | 7.4%            | 2.2%          | 0.3%          |
| 0.61       | 0.2%            | 2.6%            | 6.2%            | 2.9%          | 0.3%          |
| 0.63       | 0.2%            | 3.2%            | 5.2%            | 3.4%          | 0.2%          |
| 0.67       | 0.1%            | 4.1%            | 3.5%            | 4.2%          | 0.1%          |
| 0.74       | 0.5%            | 5.1%            | 1.3%            | 4.7%          | 0.7%          |
| 0.81       | 0.0%            | 5.4%            | 0.0%            | 4.4%          | 0.0%          |
| 0.90       | 5.7%            | 5.6%            | 1.1%            | 2.9%          | 8.0%          |
| 0.95       | 11.2%           | 6.2%            | 1.6%            | 1.9%          | 15.1%         |
| 1.05       | 0.0%            | 8.0%            | 3.7%            | 0.0%          | 0.0%          |
| Average Error | 2.6%      | 2.9%            | 0.0%            | 0.0%          |               |

| Voltage (V) | Temperature (°C) | State 1110 1110 | Temperature (°C) | Average Error |
|------------|-----------------|-----------------|-----------------|---------------|
| 0.54       | 0.0%            | 1.2%            | 0.4%            | 10.8%         | 0.0%          |
| 0.59       | 0.3%            | 2.0%            | 7.4%            | 2.1%          | 0.3%          |
| 0.61       | 0.2%            | 2.7%            | 6.2%            | 2.7%          | 0.3%          |
| 0.63       | 0.2%            | 3.3%            | 5.2%            | 3.2%          | 0.2%          |
| 0.67       | 0.1%            | 4.3%            | 3.6%            | 3.9%          | 0.1%          |
| 0.74       | 0.7%            | 5.2%            | 1.5%            | 4.3%          | 0.7%          |
| 0.81       | 0.0%            | 5.6%            | 0.2%            | 3.8%          | 0.0%          |
| 0.90       | 7.7%            | 6.2%            | 1.0%            | 2.3%          | 8.3%          |
| 0.95       | 14.4%           | 7.3%            | 1.7%            | 1.3%          | 15.6%         |
| 1.05       | 0.0%            | 9.8%            | 4.9%            | 0.0%          | 0.0%          |
| Average Error | 2.9%      | 3.0%            | 0.0%            |               |               |

| Voltage (V) | Temperature (°C) | State 1101 1100 | Temperature (°C) | Average Error |
|------------|-----------------|-----------------|-----------------|---------------|
| 0.54       | 0.0%            | 1.3%            | 0.5%            | 10.9%         | 0.0%          |
| 0.59       | 0.3%            | 1.9%            | 7.3%            | 2.2%          | 0.3%          |
| 0.61       | 0.2%            | 2.6%            | 6.2%            | 2.9%          | 0.3%          |
| 0.63       | 0.2%            | 3.3%            | 5.2%            | 3.2%          | 0.2%          |
| 0.67       | 0.1%            | 4.3%            | 3.4%            | 4.2%          | 0.1%          |
| 0.74       | 0.6%            | 5.3%            | 1.2%            | 4.7%          | 0.7%          |
| 0.81       | 0.0%            | 5.7%            | 0.2%            | 4.4%          | 0.0%          |
| 0.90       | 6.4%            | 6.1%            | 1.3%            | 2.9%          | 8.6%          |
| 0.95       | 12.5%           | 6.7%            | 1.9%            | 1.9%          | 16.3%         |
| 1.05       | 0.0%            | 8.7%            | 4.0%            | 0.0%          | 0.0%          |
| Average Error | 2.7%      | 3.1%            | 0.0%            |               |               |

| Voltage (V) | Temperature (°C) | State 1011 1010 | Temperature (°C) | Average Error |
|------------|-----------------|-----------------|-----------------|---------------|
| 0.54       | 0.0%            | 1.4%            | 0.5%            | 10.9%         | 0.0%          |
| 0.59       | 0.3%            | 1.9%            | 7.4%            | 2.1%          | 0.3%          |
| 0.61       | 0.3%            | 2.6%            | 6.2%            | 2.9%          | 0.3%          |
| 0.63       | 0.2%            | 3.3%            | 5.2%            | 3.2%          | 0.2%          |
| 0.67       | 0.1%            | 4.3%            | 3.5%            | 3.8%          | 0.1%          |
| 0.74       | 0.8%            | 5.4%            | 1.4%            | 4.2%          | 0.9%          |
| 0.81       | 0.0%            | 5.9%            | 0.1%            | 3.6%          | 0.0%          |
| 0.90       | 9.8%            | 6.9%            | 1.1%            | 2.1%          | 10.4%         |
| 0.95       | 17.2%           | 8.3%            | 2.0%            | 1.1%          | 18.4%         |
| 1.05       | 0.0%            | 13.1%           | 5.8%            | 0.0%          | 0.0%          |
| Average Error | 3.2%      | 3.3%            | 0.0%            |               |               |

| Voltage (V) | Temperature (°C) | State 0111 0110 | Temperature (°C) | Average Error |
|------------|-----------------|-----------------|-----------------|---------------|
| 0.54       | 0.0%            | 0.8%            | 10.1%           | 0.0%          |
| 0.59       | 0.3%            | 3.2%            | 6.8%            | 2.0%          | 0.5%          |
| 0.61       | 0.2%            | 3.9%            | 5.7%            | 2.5%          | 0.5%          |
| 0.63       | 0.1%            | 4.6%            | 4.7%            | 3.0%          | 0.4%          |
| 0.67       | 0.2%            | 5.6%            | 3.0%            | 3.6%          | 0.1%          |
| 0.74       | 0.9%            | 6.7%            | 1.0%            | 3.8%          | 1.1%          |
| 0.81       | 0.0%            | 7.2%            | 0.3%            | 3.2%          | 0.0%          |
| 0.90       | 9.4%            | 8.3%            | 1.6%            | 1.6%          | 14.0%         |
| Average Error | 3.2%      | 3.3%            | 0.0%            |               |               |

(continued on next page)
noted for the highest voltages and especially those which correspond to the intermediate temperatures when the input state is at 0. Figures 10 and 11 show the correlation of the leakage current between the characterized values and the modelled ones for an Inverter for a voltage of 1.05V when the input is 1 and 0 respectively. These figures show that the correlation when the state of the input is 1 is much better than the correlation when the state of the input is 0. In the latter case, the offset between the two curves is clearly visible, hence larger errors are noted on one side rather than the other.

Table 5 presents the correlation results of the leakage currents for the SDDFQA cell for 5 temperature values and 10 different voltage values. The SDDFQA cell is a flip flop with 4 inputs: two inputs A and B for the signal and an input S0 for selection. All combinations of input pins are presented: the cell having 4 input pins with two possible states (1 or 0), the 16 different combinations are presented. The most important errors are observed for the highest voltages and especially for those that correspond to the intermediate temperatures. The same behaviour have been noted for the case of the Inverter and the MXIT cell. The highest errors are noted when all the input states are at zero. This suggests that the model to be developed corresponds better to modelling the leakage currents of pmos rather than nmos.

The accuracy of the developed model has been tested against the characterization methodology. Cells has been tested for all possible input pattern cases. Tables 3, 4, and 5 report the relative errors of the model with an average error between 2% and 5%. For all the cases, the maximal values errors corresponds to the highest voltage values which suggests that the model developed under fit these values. Especially if we look into the Tables 1 and 2 representing the errors of modelled values for a NAND cell before and after applying the correction function, we note that errors are sensibly the same especially for intermediate temperatures. From that we can say that adjusting the correction function to fit better these values can solve the problem.

### Table 5 (continued)

| State | 1111 | Voltage (V) | Temperature (°C) | Temperature (°C) |
|-------|------|-------------|-----------------|-----------------|
|       |      | -40 0 40 85 125 |                  |                  |
| 0.95  | 15.2% | 7.9% 9.9% 2.7% 0.6% | 24.0% 14.4% 14.4% 4.8% 0.5% |
| 1.05  | 0.0%  | 4.5% 14.3% 7.0% 0.0% | 0.0% 13.5% 20.2% 9.8% 0.0% |
| Average Error | 3.5% |                          | 5.1% |

| State | 1110 | Voltage (V) | Temperature (°C) |
|-------|------|-------------|-----------------|
|       |      | -40 0 40 85 125 |                  |
| 054   | 0.0%  | 0.1% 0.7% 10.2% 0.0% | 0.0% 0.3% 0.9% 10.1% 0.0% |
| 0.59  | 0.3%  | 1.5% 3.1% 6.8% 1.9% | 0.3% 1.9% 3.4% 6.7% 1.9% |
| 0.61  | 0.2%  | 1.9% 3.9% 5.8% 2.4% | 0.3% 2.3% 4.2% 5.6% 2.5% |
| 0.63  | 0.1%  | 2.2% 4.5% 4.8% 2.8% | 0.2% 2.7% 4.9% 4.6% 2.9% |
| 0.67  | 0.2%  | 2.5% 5.5% 3.2% 3.4% | 0.2% 3.1% 6.0% 2.9% 3.5% |
| 0.74  | 1.0%  | 2.3% 6.7% 1.1% 3.5% | 1.0% 3.1% 7.3% 0.8% 3.6% |
| 0.81  | 0.0%  | 2.1% 7.3% 0.1% 2.7% | 0.0% 3.1% 8.0% 0.6% 2.9% |
| 0.90  | 10.8% | 4.7% 8.7% 1.5% 1.0% | 11.2% 5.8% 9.5% 2.0% 1.2% |
| 0.95  | 17.0% | 8.7% 10.7% 2.7% 0.1% | 18.0% 9.8% 11.5% 3.2% 0.3% |
| Average Error | 3.7% |                                 | 4.0% |

| State | 0101 | Voltage (V) | Temperature (°C) |
|-------|------|-------------|-----------------|
|       |      | -40 0 40 85 125 |                  |
| 0.54  | 0.0%  | 0.6% 1.1% 10.0% 0.0% | 0.0% 0.8% 1.3% 9.9% 0.0% |
| 0.59  | 0.3%  | 2.2% 3.6% 6.5% 2.0% | 0.4% 2.8% 4.1% 6.3% 1.9% |
| 0.61  | 0.3%  | 2.6% 4.4% 5.4% 2.6% | 0.4% 3.3% 5.0% 5.1% 2.5% |
| 0.63  | 0.2%  | 2.9% 5.1% 4.3% 3.1% | 0.3% 3.8% 5.8% 4.1% 2.9% |
| 0.67  | 0.2%  | 3.3% 6.2% 2.6% 3.7% | 0.1% 4.5% 7.1% 2.3% 3.5% |
| 0.74  | 0.9%  | 3.3% 7.5% 0.5% 3.9% | 1.1% 5.0% 8.7% 0.0% 3.6% |
| 0.81  | 0.0%  | 3.1% 8.2% 0.9% 3.3% | 0.0% 5.4% 9.8% 1.5% 2.9% |
| 0.90  | 9.9%  | 5.1% 9.4% 2.3% 1.7% | 14.0% 9.0% 11.7% 3.1% 1.2% |
| 0.95  | 16.2% | 8.4% 11.1% 3.3% 0.8% | 23.6% 14.0% 14.0% 4.4% 0.3% |
| Average Error | 3.9% |                                 | 4.9% |

| State | 0011 | Voltage (V) | Temperature (°C) |
|-------|------|-------------|-----------------|
|       |      | -40 0 40 85 125 |                  |
| 0.54  | 0.0%  | 0.9% 1.4% 9.8% 0.0% | 0.0% 0.7% 1.3% 9.9% 0.0% |
| 0.59  | 0.4%  | 2.8% 4.1% 6.3% 1.9% | 0.4% 2.6% 4.0% 6.4% 1.8% |
| 0.61  | 0.4%  | 3.3% 5.0% 5.2% 2.4% | 0.4% 3.2% 4.8% 5.3% 2.3% |
| 0.63  | 0.3%  | 3.8% 5.7% 4.2% 2.8% | 0.3% 3.6% 5.6% 4.3% 2.7% |
| 0.67  | 0.1%  | 4.4% 7.0% 2.4% 3.3% | 0.1% 4.3% 6.9% 2.5% 3.2% |
| 0.74  | 1.2%  | 4.8% 8.5% 0.2% 3.4% | 1.2% 4.7% 8.4% 0.3% 3.3% |
| 0.81  | 0.0%  | 5.2% 9.5% 1.2% 2.6% | 0.0% 5.1% 9.4% 1.1% 2.4% |
| 0.90  | 13.9% | 8.8% 11.4% 2.8% 0.9% | 14.5% 9.1% 11.5% 2.7% 0.7% |
| 0.95  | 22.9% | 13.9% 13.9% 4.2% 0.0% | 23.5% 14.5% 14.1% 4.2% 0.2% |
| 1.05  | 0.0%  | 13.4% 20.5% 9.9% 0.0% | 0.0% 14.0% 21.1% 10.3% 0.0% |
| Average Error | 4.8% |                                 | 4.9% |
6. Conclusion

A new accurate method for a fast estimation of leakage in standard cells has been developed. This approach is based on a number of characterized leakage current of the cells and the leakage estimation is calculated based on mathematical modelling. A “cell-by-cell” approach is used to validate the models. However, the error on the leakage of cells can be positive or negative. In the full circuit, the averaging of these errors may give better results than the cell by cell validation. Future work will be focused on enhancing the proposed model and making a comparison at circuit level.

Declarations

Author contribution statement

Kenza Charafeddine: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Faisal Ouardi: Conceived and designed the experiments; Contributed reagents, materials, analysis tools or data.

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The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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