Novel Photo Catalytic Sensor Output Calibration Technique

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Abstract

Many issues like large size, poor response time and accuracy which were plaguing the performance of the conventional Photo Catalytic Processes were overcome by Photo Catalytic Sensor (PCS) proposed by Whig and Ahmad in 2014. The continuing advancements in the field of sensor interface development are to calibrate and correct the inherent non-idealities present in transducers forced us to work in this area. The variations of various internal parameters based on the transfer characteristics of novel PCS resulting from Photocatalytic oxidation of organic compounds has been carried out by Whig and Ahmad in 2015 and it is found that the major contributors to non-idealness are typically the nonlinear response to stimulus (gain), the offset, and the temperature dependence of one or both of these factors. Conventionally the calibration of the sensor has been done manually in the laboratory prior to the actual deployment in the system. This requires a lot of manual computation highly skilled manpower. To make this tedious procedure easy and to make PCS sensor more accurate, a novel sensor calibration with built-in calibration registers using FPGAs is proposed.

Keywords - *PCS, CMOS, low power, simulation, sensor*

I. INTRODUCTION

This Chemical oxygen demand (COD) and biological oxygen demand (BOD) are two of the most widely recognized nonexclusive lists used to evaluate aquatic organic pollution. Biological oxygen demand (BOD) is frequently used to assess the biodegradable portion, and COD the aggregate organic pollution of water debased by reductive poison pollutants [1-2].

In the modern world, the constant checking of the organic load becomes necessary to agree with regulatory necessities. Therefore a rapid method for the measurement of various water quality parameters is needed. The method of semiconductor photo catalysis is employed while the radiations are used to create electron pairs/holes helps in the above phenomenon[3-4]. The electron produced as a result of the above phenomenon reacts with the oxygen in turn (with the sample) producing O_2 while the holes react with surface groups to form OH- radicals with the liberation of carbon dioxide and water upon further reacting with organic molecules [5-6].

The result of the photo catalysis leads to the formation of a positive role in the valence band. The excitation of electrons from the same band results in a reduction of the organic molecule. The hole reacts with water to form hydroxyl radicals which help in oxidizing the organic pollutants. Most of the photocatalytic processes apply TiO_2 as the catalyst due to its friendly properties with regards to the above. The COD of a given catalyst can be calculated by noticing the change of the dissolved oxygen concentration under photocatalytic conditions [7].

In the paper published by Whig and Ahmad, COMPEL 2014 [1] a novel SPICE model for PCS was presented. This concept was very powerful and simple which can be used to develop simulated models of bioelectronics. This accuracy of the proposed model depends on the coding and model used in SPICE model. The non-ideal behaviour due to temperature variations can also be modelled and included in order to remove overcome their effects. Also, similar macro models can be developed for other bio-electronic devices and can be implemented in different versions of SPICE.

The impact of different components on the output current of photocatalytic biosensors with variation in temperature is already published by Whig et. al in Electronics 2017 [8]. It is found that the major change occurs in the output current is due to a variation of threshold voltage component. In order to get the more accurate output, the effect of variation due to threshold voltage must be fixed.

The variations of internal parameters based on the transfer characteristics of novel PCS resulting from Photocatalytic oxidation of organic compounds has been done by Whig and Ahmad in 2015 and it is found that the major contributors to non-idealness are typically the nonlinear response to stimulus (gain), and the temperature dependence of one or both of these factors [9]. Also, the continuing advancements in the field of sensor interface development are to calibrate and reduce the inherent non-idealness present in transducers. To make this tedious procedure easy and to make PCS sensor more accurate, a novel sensor calibration with built-in calibration registers using FPGAs is proposed.

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II. MECHANISM OF PHOTO CATALYSIS PROCESS

There are various methods for degrading organic compound but photo catalysis is one of the efficient method which is easy and fast. Many research studies are available in the literature on different kind of mechanisms involved in this process. The mathematical equations are also involved in describing the process and for gaining a better knowledge [10]. The semiconductor material consists of two bands one over each other i.e valence and conduction band. The difference in between these two energy bands is denoted by E_g and termed as energy gap. When the light of suitable intensity fall into this energy gap results in the movement of the electrons from the valence band to conduction band. When electron excited from lower energy band to higher it leaves vacancy behind it and term as holes. The holes thus generated reached the surface of organic pollutants they oxidised the organic pollutants and released water and O_2. The dissolved oxygen in the molecular form acts as a scavenger of the photon-generated electrons and forms a superoxide radical ion[11]. Titanium dioxide (TiO_2) has the ability to cause a photo-oxidative destruction of the organic pollutants and is non-corrosive in nature due to which it is used as a catalyst in the process.

The oxygen content in any given example can be dictated by watching the change in dissolved oxygen concentration during the procedure of photocatalysis as shown in Figure 1.

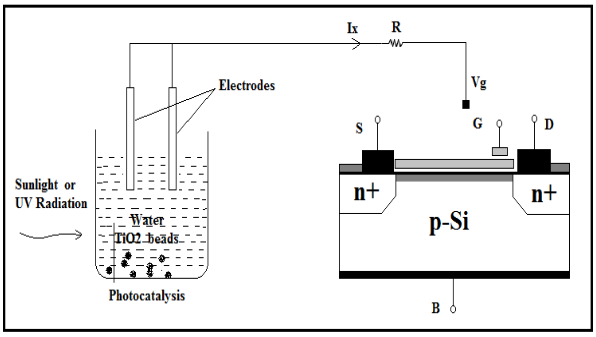


Fig.1. Mechanism of photo catalysis process

In photo catalysis process a floating gate electrode is utilized the sunlight or UV radiations fall on TiO_2 which additionally act as a catalyst to accelerate the photocatalysis process. PCS detects the adjustments in the oxygen concentration and its voltage levels change as a sign [12].

III. THE PHOTO CATALYSIS PROCESS

The SPICE model for PCS is given in [1]. It is basically a MOSFET having a structural difference in which the gate terminal is kept inside the solution and diffusion and quantum capacitances are added to overcome the effect of Helmholtz and diffusion layer. The cross-section of PCS is shown in Figure 2.

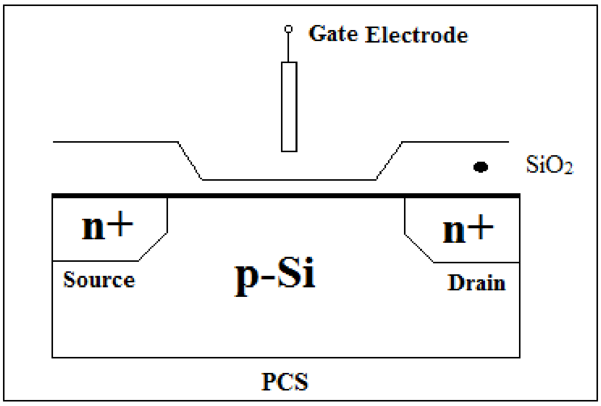


Fig. 2. cross-section of PCS

The threshold voltage equation for the PCS model is given as:

$$V_{th}\,(PCS) = E_{Ref} - \Psi_{sol} + \chi^{sol} + \frac{-\Phi_S}{q} - \frac{Q_{ox}+Q_{ss}+Q_B}{C_{ox}} + 2\phi_f \quad (1)$$

Ψ^{Sol} is an input parameter of the condition which is subject dependent on the concentration of O_2 in the solution and surface dipole potential χ^{sol}. Here E_{Ref} is the constant reference electrode potential.

For different convergences of O_2, particular V-I bends for PCS can be plotted .Ψ_{sol} is a component of O_2 and as the saturation cut-off, current I_{ds} extends the estimation of the oxygen concentration level reductions. The circuit for PCS as given in is shown in Figure 3.

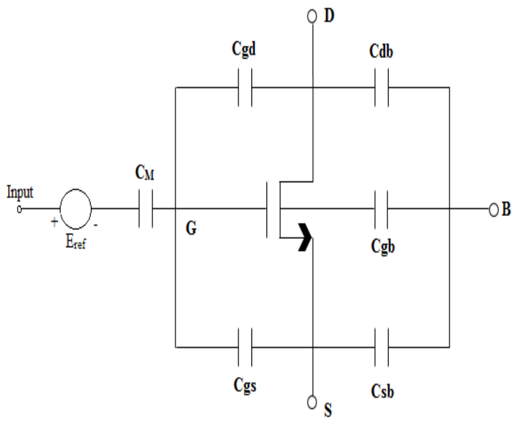


Fig.3 Circuit for PCS

Here is the resultant capacitance of and which are oxide and quantum capacitances respectively [13]. The equivalent capacitance is given as:

$$\frac{1}{C_M} = \frac{1}{C_q} + \frac{1}{C_{ox}} \quad (2)$$

The drain current equation in the non-saturation mode for PCS is given as:

$$I_{ds} = Cox\mu \frac{W}{L}\left[(V_{gs} - V_t)V_{ds} - \frac{1}{2}V_{ds}^2\right] \qquad (3)$$

Where

Cox = Oxide capacitance per unit area,
μ = Mobility of electrons in the channel,
W = Channel width
L = Length of the Channel

Various Process Parameters including a length of the channel and channel width are chosen according to the 70nm CMOS process model.

According to the characteristics of the MOSFET gate to source voltage, V_{gs} (Reference Voltage) and drain current is allowed to vary with drain to source voltage V_{ds}.

Differentiating PCS and MOSFET, keeping the grouping of O_2 = 1mg/l is founded that the bend looks like with the trademark V_{ds}/I_{ds} bend of MOSFET keeping V_{gs} steady. For different concentration level of O_2 and for a fixed value of source to gate voltage (V_{gs}) V_{ds}/I_{ds} curves are obtained and shown in Figure 4.

From the Figure 4, it is observed that as the oxygen concentration level decreases saturation cut off current I_{ds} increases. Therefore it is concluded that PCS can be treated as MOSFET on the basis that the chemical input parameter Ψ_{sol} is a function of O_2 (Ψ_{sol} = f (Oxygen)).

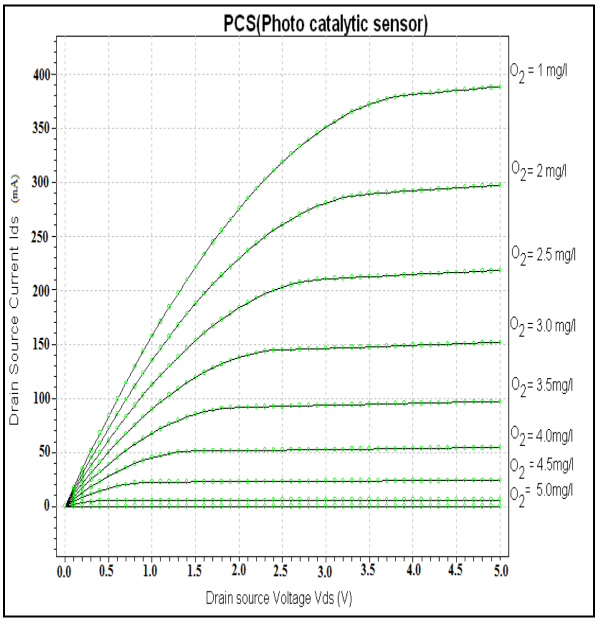


Fig. 4. characteristics curves for different value of oxygen content

WHY CALIBRATION?

Many external factors such as temperature, pressure, humidity and fabrication process etc. will affect the sensitivity of almost all kinds of sensors [14-15]. To clean the output from the variation of these factors calibration of the sensor is a must.

There are many techniques available for calibration of sensors. In this research work, a novel calibration method using Finite State Machine and Scan Path Technique is presented. Both techniques have been simulated and their comparative analysis is included in the subsequent sections.

IV. FINITE STATE MACHINE

A finite-state machine (FSM) is a mathematical model of computation. It is an abstract machine that can be exactly in one of a finite number of states at any given point of time. The FSM can change starting with one state then onto the next in response of some external inputs; the change starting with one state then onto the next is called a transition [16-17]. An FSM is characterized by a list of its states, its initial state, and the conditions for each transition. The block diagram of the finite state machine is shown in Figure 5. This diagram indicates that there is a set of n flip-flops that represent the state. There is likewise some logic that uses the output of the flip-flops and the inputs to the system to decide the next following state. At last, there is some logic that decodes the output values of the flip-flops to make the output signals. In this research studies to calibrate the output of Photo Catalytic sensor using finite state machine has been presented. The output Oxygen concentration of PCS is categorized into three standards like Low O_2, Mid O_2, and high O_2. These values are further cleaned through FSM. The output obtained through two logic proposed in different methods are presented in the next section.

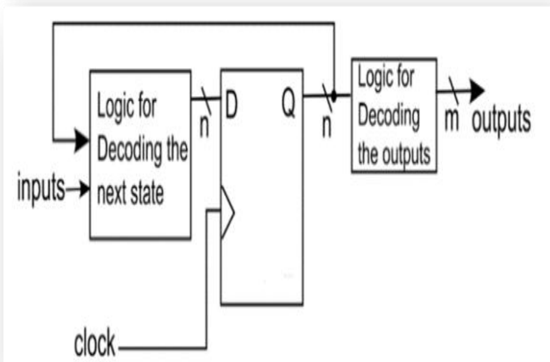


Fig 5. Finite State block diagram

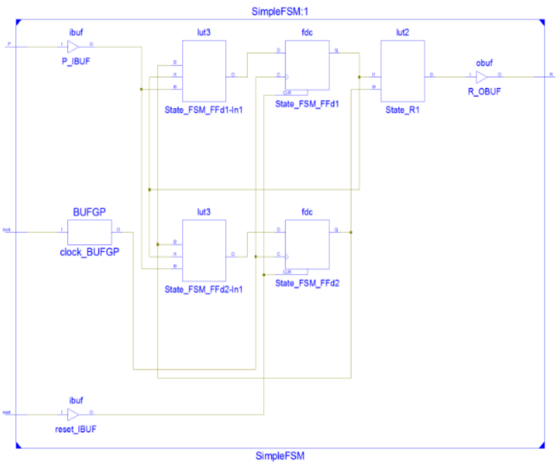


Fig. 6 .RTL of finite state Machine

V. MATHEMATICAL MODELLING USING THE TWO-POINT TECHNIQUE

In this method, two measurements of Photocatalytic Sensor is taken. One near the low end of the measurement range and another from the high end of the measurement and called the specific values as O_2 low and O_2 high. Repeat these measurements using FSM Model using semi-custom design. And record the output readings. The normal and reference ranges are calculating $In_1 - In_2$ using and $Out_1 - Out_2$.

Then the gain is calculated as

$$\text{Gain} = \frac{In_1 - In_2}{Out_1 - Out_2}$$

The value of the offset is calculated using below relation

$$\text{Offset} = \frac{In_1}{Gain} - Out_1$$

The corrected measured output value is given by equation

Corrected value = Gain * (Input + Offset)

The method is checked and verified using following readings and it is observed that the output is consistent with input. The verification table is shown in Table 1.

The working of an algorithm is shown in given Figure 7.

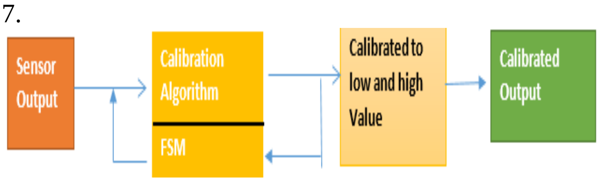


Fig.7 . Diagram represents algorithm used in two point technique

Table 1: Verification of the two point technique

Maximum Current Decrease (Calculated)	Maximum Current decrease (Observed)	error	Gain	Offset	Corrected Output
-0.054	0	-0.054	1.641	-0.032	-0.053
0.094	0.09	0.004	3.545	-0.06	0.094
0.130	0.1	0.030	0.905	0.043	0.129
0.247	0.23	0.017	2.77	-0.140	0.247
0.303	0.25	0.053	-0.097	-3.360	0.302
0.296	0.32	-0.024	0.924	0.022	0.295
0.324	0.35	-0.026	0.92	0	0.323

VI. MATHEMATICAL MODELING USING THE THREE-POINT TECHNIQUE

The same processor has been done by taking three points and it is observed that the output is more consistent with input.

Corrected Value = a*$(\text{Observed value})^2$ + b

* $\text{Observed value})$ + c

Where

$$a = \frac{\frac{In_1 - In_2}{Out_1 - Out_2} - \frac{In_1 - In_3}{Out_1 - Out_3}}{Out_2 - Out_3}$$

$$b = \frac{In_1 - In_2}{Out_1 - Out_2} - a\,(Out_1 + Out_2)$$

$$c = In_1 - a * Out_1^2 - b\,Out_1$$

The working concept of a three-point technique is same as two points the only difference is that the output is more significant and accurate. From Figure 8 below using a 3-d bar chart, it is shown that the corrected output after using method 1 is same as the standard output.

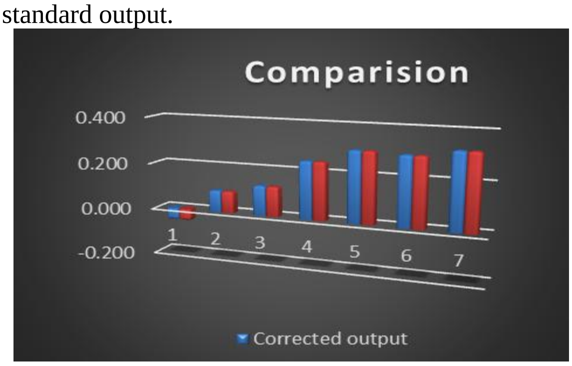


Fig. 8.Comparison among corrected output and standard outputs.

A. Hardware Description

Hardware description of the system is shown in the following schematic diagram in Figure 9. The output from the PCS along with the calibration signal is feed to the FSM which in turn generates the corrected output

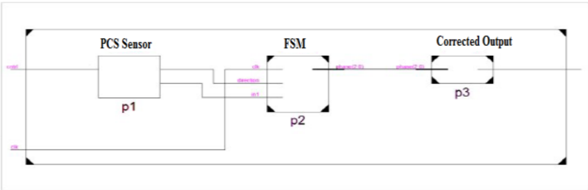


Fig 9.Schematic diagram of sensor system

B. Scan Path Technique (SPT)

The scan path is a method that is used to increase the overall controllability and observability of the combinational circuits with the help of scan register into the circuit design. These registers normally act as a flip-flop but we can switch them into the test mode where they all become a long shift register this help us to make the data to be clocked serially and pass through all scan registers and get an output through output pin as the same time new data is clocked as input to it.

Steps1: Set the mode to test and let latches accept data from a scan-in input.

Step2: Verify the scan path.

Step3: Scan in the desired state vector into a shift register

Step4: Apply the test pattern to primary input pins.

Step5: Set the mode the normal and observe the primary output of the circuit after sufficient time for propagations.

Step6: Assert the circuit clock for one machine cycle.

Step7: Repeat steps 3-6.

The RTL view after scan path technique is shown in Figure 10.

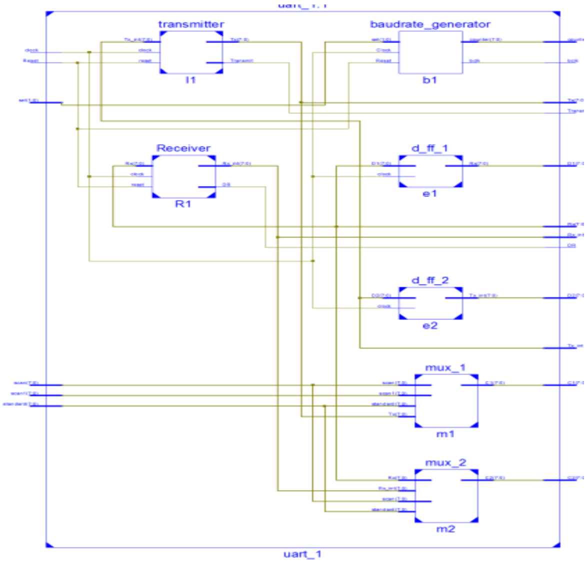


Fig.10 RTL view of Scan Path Technique

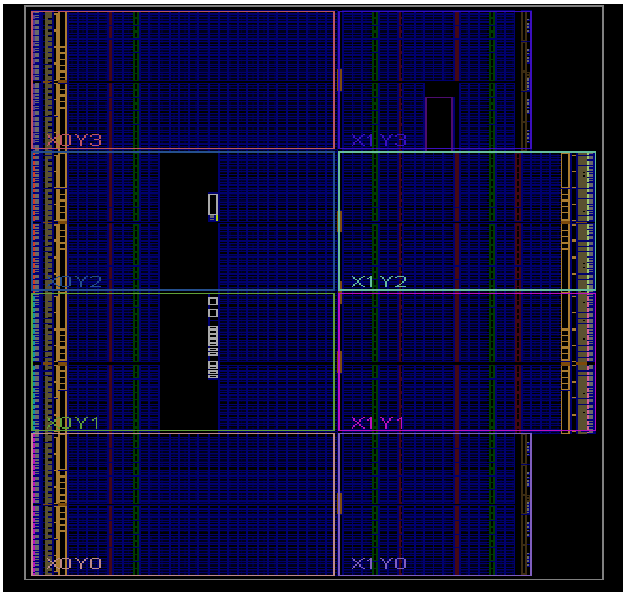


Fig 11.FSM using (SPT) On FPGA kit Implementation

C. Register-transfer Logic

It shows the blueprint image of a design in which the modeling of the universal asynchronous receiver and transmitter digital circuits is done through the combinational use of logic gates, multiplexer, encoder, decoder, and various other flows of digital circuits and signals between hardware registers.

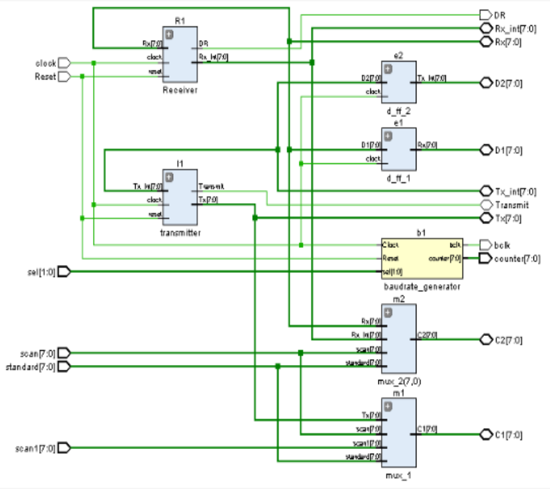


Fig.12.Inter relation between FSM chip and sub module.

The above Figure12 represents the combination of the three sub-modules to form an FSM on a chip, this shows inter-relation between these three sub-modules.

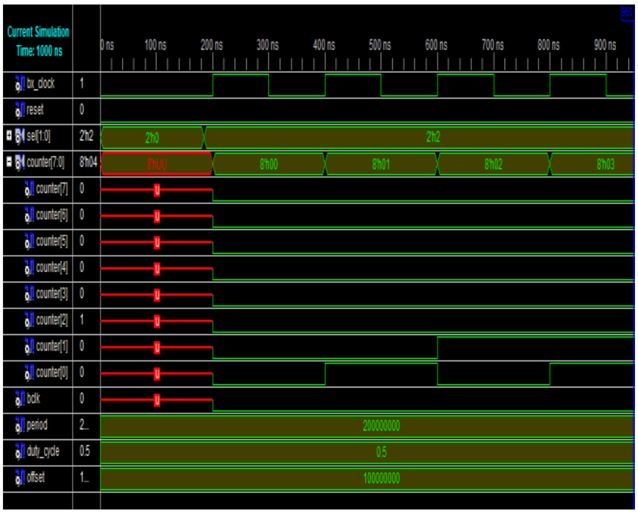


Fig.13. Output Waveforms

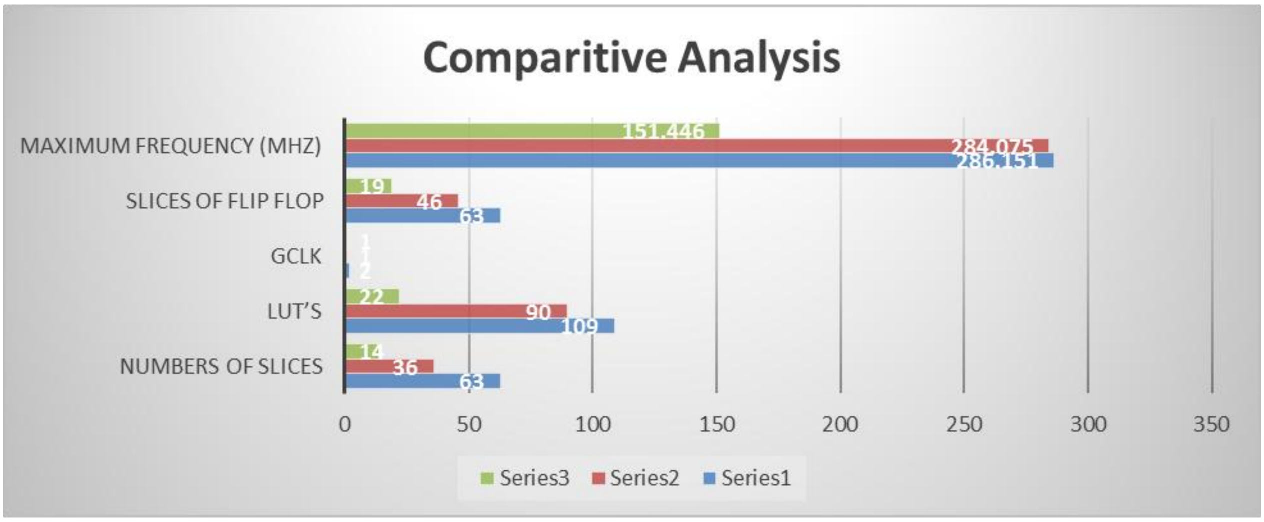
Simulation: The verification of above design has been done through Xilinx v14.1and the test bench waveform has been done through Xilinx software v 14.1. Realization of output waveform has been done through various gates, logic gates, LUTs are shown in above Figure 13. Simulation result with the different methods is shown in Table 2.

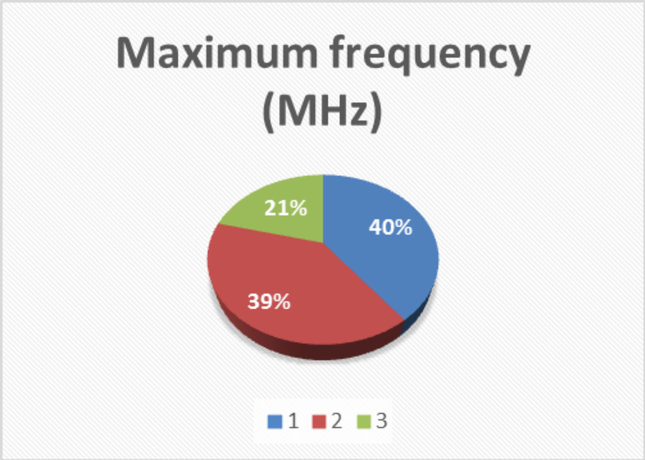
Table 2: Simulation result with different methods

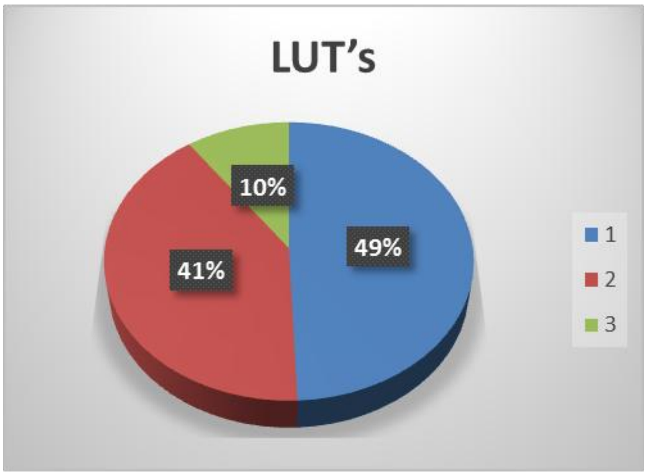
Maximum Current Decrease (Calculated)	Corrected Output using Method 1	Corrected Output using Method 2
-0.054	-0.053578431	-0.053978413
0.094	0.094150327	0.094024235
0.130	0.129607843	0.129996778
0.247	0.247336601	0.247011244
0.303	0.302794118	0.303134245
0.296	0.295980392	0.296123432
0.324	0.323709156	0.324129832

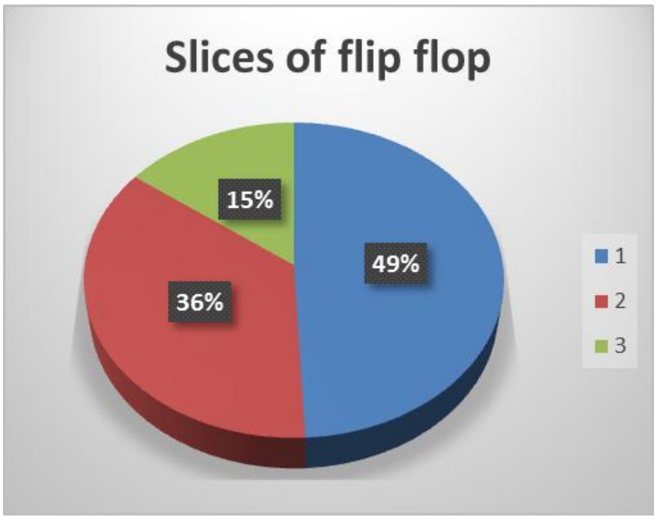
Table 3. Comparison between different methods

Serial no.	Parameter	One Point Method	Two Point Method	Scan Path Technique (Dynamic Method 2)
1.	Numbers of slices	63	36	14
2.	LUT's	109	90	22
3.	GCLK	1	1	1
4.	Slices of flip flop	63	46	19
5.	Maximum frequency (MHz)	286.151	284.075	151.446
6.	complexity	High	High	Low
7.	size	Large	Large	Medium









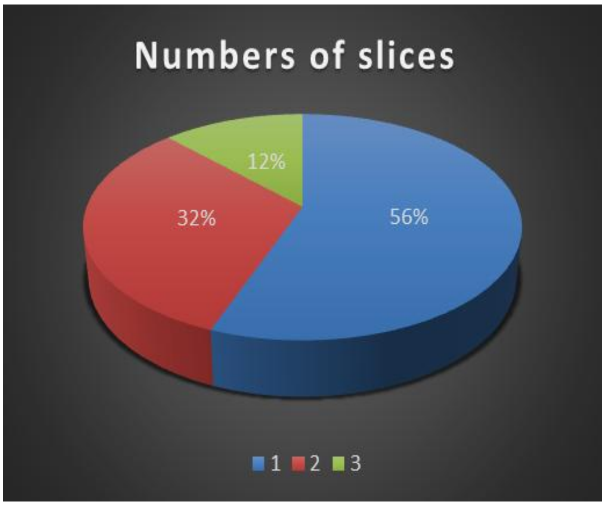


Fig. 14. Comparative Analysis shown by various charts

V. RESULTS AND DISCUSSION

The circuit simulation of the device using PCS involving various components has been done on tanner simulator, further, the algorithm used in the various methods has been realized on Xilinx. Various parameters of interest are shown in Table 3. In this table, the detailed description of various parameters from all the three techniques used is presented.

Considering the same technology parameters of PCS but using different techniques, we arrive at the following comparative results

a) Number of Slices used is 63 in two-point technique, 36 is in three-point technique and 14 in using Scan Path Technique (SPT) i.e SPT deploys the least number of slices whereas two-point technique keeps it to maximum.
b) Numbers of LUTs required are as follows 109 in two-point technique, 90 in three-point technique and 22 in SPT i.e least in SPT.
c) GCLK remains constant in for all other techniques.
d) Slices of Flip flops is 63(Max.) 46 and 19 (min). From these numbers we figure out that least number of flip-flops are required in SPT
e) Frequency (MHz) i.e least in SPT and Max. in two-point technique.
f) In terms of complexity and size, the SPT is least complex and having the comparatively small size from other techniques.
From the above points discussed we came down to the conclusion that in terms of complexity, size, number of components and other parameters the SPT technique is best in all respect.

V. CONCLUSION

The scan path is a method that is used to increase the overall controllability and observability of the combinational circuits with the help of scan register into the circuit design. After the comparative analysis of various calibration techniques namely two points, three points and SPT we come to the conclusion that Scan path technique is better than Two point Technique and Three Point Technique in terms of number of component used cost and complexity of system. Results of computer simulations and its composition with experimental data demonstrated an accuracy of the approach.

FUTURE SCOPE

This study may be extended and more improvement in terms of power and size can be achieved at layout level and thus more effective results may be obtained.

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AUTHOR CONTRIBUTIONS

The authors contributed equally to this work.

Conflicts of Interest: No conflict of interest is declared by the author.

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