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ROBUST Dynamic System Design Simulation Study using Taguchi Method and MINITAB

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Abstract: This paper reports robust circuit design simulations of dynamic system based on Taguchi's orthogonal array method and data analysis with MINITAB. The simulation study emphasis was to minimize variations and/ or sensitivity to noise under unknown harsh noise. The systematic Taguchi method of DOE for designing electronic products operates consistently under the noise conditions discussed and implemented. OrCAD/ PSPICE an electronic circuit simulation and Minitab statistical tools were used to determine parameter values. The dynamic system circuit performance of a temperature controller using thermistor modeled and discussed. The predicted and confirmed results for the sensitivity of the before and after optimization of circuit parameters designed were in close agreement. The significant S/N Gain improvement in the circuit performance was observed in the early stage of design. Thus, discussed method of designing of electronic products saves time; energy and material cost of the product or-process avoid major loss to all stakeholders in the society.

Keywords:Dynamic characteristics, MINITAB, Orthogonal Array, Parameter Design, Robust design, Taguchi method.

I. INTRODUCTION

With the world becoming increasingly competitive in manufacturing sector, engineers are trying very hard to improve quality while lowering costs so as to enhance competitiveness. Robust design is one of the most effective ways to achieve these goals. This two–stage approach usually increases the time and money spent to find acceptable parameter and tolerance values. Furthermore, these values are not the optimal solutions [1].Delivering reliable, high quality products and process at low cost has become the key to survival in today's global economy. Designing in quality is cheaper than trying to inspect and re-engineer it in after a product hits the production floor or worse, after it gets to the customer [2].

A systematic approach to determining the optimum settings of process parameters. Parameters deemed to be important (usually by an ad hoc team of experts) are varied and the results observed. The simplest form is an experiment in which a high and low value is picked for each parameter and every possible combination is used. Quality engineers normally conduct parameter design followed by tolerance design. Parameter design mainly decides the parameter value for the product design or for the process planning so that the sensitivity toward the noise impact is minimized. If satisfactory quality and cost levels are achieved via parameter design, engineers turn to tolerance design. From viewpoint of quality engineering the downstream quality problems of a product are symptoms of its functional instability (lack of robustness).These problems can be estimated by the total quality loss after the product is shipped out of its manufacturing plant. The total Quality loss of a product is the sum of the total monetary loss and environmental effects the product contributes during its entire life. The quality loss function of a product is:

Quality Loss =' Cost due to functional variation'

+ 'operating cost' +'Cost due to environmental effects'

Of course, it is important to reduce operating cost. Warranty and cost due to environmental effects to reduce the quality loss. However, from the view point of quality engineering, the most efficient way to focus engineering resource of a company on technology research activities that enhances the functional robustness of their new product or process technology. Improving functional robustness of a product or process technology encompasses 3 steps. Therefore, significant cost savings and improvements in quality can be realized by optimizing product designs. The three major steps in designing quality products are:

- System design: selection of new technology systems or concept;
- Parameter design: selection of appropriate settings of control factors that maximizes the newly selected technology systems or concept;
- Tolerance design: selection of appropriate settings of tolerance specifications considering total cost, environmental effects, manufacturing capability etc.

Among the 3 steps, system design is related to the expertise engineering field and to the creativity of the engineers.

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Currently most technology development engineers focus their efforts on adjusting the objective functions of their new systems to meet various marketing requirements using traditional reliability engineering methodologies. These methods are marginally effective in reducing the failure rates of new products. They are insufficient in improving basic function (upstream quality characteristics) of the product or process technologies [3].

For cost effective production of integrated circuits, one important aspect is the accurate simulation of electronic circuits with regard to product/ process variation. Process variation is described as the range of simulation parameters. The statistical methods are validated by PSPICE simulation experiments of typical analog /mixed–signal circuit design. There are two methods

A. Research Approach: Every experimenter has to plan and conduct experiments to obtain enough and relevant data so that one can infer the science behind the observed phenomenon. He can do so by.

B. Trial-and-Error Approach: By performing a series of experiments each of which gives him some understanding. This requires making measurements after every experiment. so that analysis of observed data will allow him to decide what to do next "Which parameters should be varied and by how much". Many a times such series does not progress much as negative results may discourage or will not allow a selection of parameters which ought to be changed in the next experiment. Therefore, such experimentation usually ends well before the number of experiments reaches a double digit! The data is insufficient to draw any significant conclusions and the main problem of understanding the science remains unsolved.

II. METHODOLOGY

A Taguchi design is a designed experiment that lets you choose a product or process that functions more consistently in the operating environment. Taguchi designs recognize that not all factors that cause variability can be controlled. These uncontrollable factors are called noise factors. Taguchi designs try to identify controllable factors (control factors) that minimize the effect of the noise factors. During experimentation, you manipulate noise factors to force variability to occur and then determine optimal control factor settings that make the process or product robust, or resistant to variation from the noise factors. A process designed with this goal will produce more consistent output. A product designed with this goal will deliver more consistent performance regardless of the environment in which it is used. Taguchi designs use orthogonal arrays, which estimate the effects of factors on the response mean and variation. An orthogonal array means the design is balanced so that factor levels are weighted equally. Because of this, each factor can be assessed independently of all the other factors, so the effect of one factor does not affect the estimation of a different factor [4]-[5]. This can reduce the time and cost associated with the experiment when fractionated designs are used.

Dr. Taguchi of Nippon Telephones and Telegraph Company, Japan has developed a method based on "Orthogonal Array" experiments, which gives much-reduced "variance" for the experiment with "optimum settings "of control parameters. Thus, the marriage of Design of Experiments with optimization of control parameters to obtain BEST results is achieved in the Taguchi Method. "Orthogonal Arrays" (OA) provide a set of well balanced (minimum) experiments and Dr. Taguchi's Signal-to-Noise ratios (S/N), as objective functions for optimisation, help in data analysis and prediction of optimum results [6].

MINITAB provides two types of Taguchi designs that let you choose a product or process that functions more consistently in the operating environment. Both designs try to identify control factors that minimize the effect of the noise factors on the product or service. **Static response-**In a static response design, the quality characteristic of interest has a fixed level **Dynamic response-** In a dynamic response design, the quality characteristic operates along a range of values and the goal is to improve the relationship between a signal factor and an output response.

Taguchi Method treats optimization problems in two categories:

A. STATIC PROBLEMS: Generally, a process to be optimized has several control factors, which directly decide the target or desired value of the output. The optimization then involves determining the best control factor levels so that the output is at the target value. Such a problem is called as a "STATIC PROBLEM"[7].

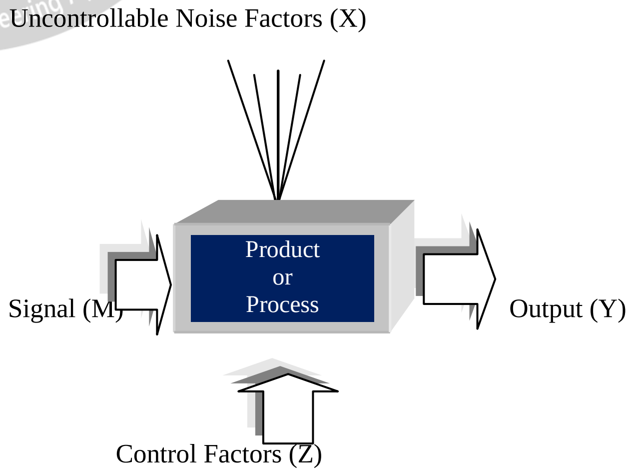

Figure 1: P–Diagram for DYNAMIC Problems

B. DYNAMIC PROBLEMS: If the product to be optimized has a signal input that directly decides the output, the optimization involves determining the best control factor levels so that the "input signal / output" ratio

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is closest to the desired relationship. Such a problem is called as a "DYNAMIC PROBLEM". This is best explained by a P-Diagram, is as shown in figure1. Again, the primary aim of the Taguchi experiments - to minimize variations in output even though noise is present in the process- is achieved by getting improved Linearity in the input-output relationship. In dynamic problems, we come across many applications where the output is supposed to follow input signal in a predetermined manner. Generally, a linear relationship between "input" "output" is desirable. The Signal-to-Noise ratio for these two characteristics have been defined as sensitivity(η) i.e. slope and best fit straight-line(linear regression) is the linearity(β) defined in detail in the next section.

C. SENSITIVITY (Slope): The slope of Input and Output characteristics should be at the specified value (usually 1). It is often treated as Larger-The-Better when the output is a desirable characteristic as in the case of Sensors, where the slope indicates the sensitivity:

$\eta = 10 \, \mathrm{Log}_{10}$ [Square of Slope or Beta of the I/O Characteristics]

D. LINEARITY(Larger-The-Better): Most dynamiccharacteristics are required to have direct proportionality between the input and output. These applications are therefore called as TRANSFORMATIONS". The straight-line relationship between I/O must be truly linear i.e. with as little deviations from the straight line as possible.

$$\eta = 10 \, \mathrm{Log}_{10} \{\text{Square of Slope or Beta /Variance}\}$$

Variance in this case is the mean of the sum of squares of deviations of measured data points from the best-fit straight-line i. e linear regression.

E. MINITAB TAGUCHI DOE

For 2-level designs based on L8 (3 or 4 factors), L16 (3-8 factors), and L32 (3-16 factors) arrays, Minitab will choose a full factorial design if possible. If a full factorial design is not possible, then Minitab will choose a Resolution IV design. For all other designs, the default designs in Minitab are based on the catalog of designs by Taguchi and Konishi. Minitab takes a straightforward approach in determining the default columns that are used in any of the various orthogonal designs. Say you are creating a Taguchi design with k factors. Minitab takes the first k of columns of the orthogonal array. Taguchi designs use orthogonal arrays, which estimate the effects of factors on the response mean and variation. An orthogonal array means the design is balanced so that factor levels are weighted equally. Because of this, each factor can be assessed independently of all the other factors, so the effect of one factor does not affect the estimation of a different factor. This can reduce the time and cost associated with the experiment when fractionated designs are used.

Orthogonal array designs concentrate primarily on main effects. Some of the arrays offered in Minitab's catalog let a few selected interactions to be studied. We can also add a signal factor to the Taguchi design in order to create a dynamic response experiment. A dynamic response experiment is used to improve the functional relationship between a signal and an output response.

Output Plots for a Taguchi design: Minitab calculates response tables, linear model results, and generates main effects and interaction plots for:

1. Signal-to-Noise ratios (S/N ratios, which provide a measureof robustness) vs. the control factors

2. Means (static design) or Slopes (Taguchi dynamic design) vs. the control factors.

3. Standard deviations vs. the control factors natural log of the standard deviations vs. the control factors

Use the results and plots to determine what factors and interactions are important and assess how they affect responses. To get a complete understanding of factor effects, we should usually assess signal-to-noise ratios, means (static design), slopes (Taguchi dynamic design), and standard deviations[4]-[5].

Ensure that you choose a signal-to-noise ratio that is appropriate for the type of data you have and your goal for optimizing the response.

III. DYNAMIC SYSTEM CIRCUIT DESIGN

Circuit design is one of the most important design activities in electronic manufacturing. Circuit design is the search for a circuit with a specific input-output behaviour. Generally, an electronic circuit is subjected to input variables in the form of a voltages or currents associated with some components in the circuit. These may be more than one input variable or more than one output variable. The components that are commonly used are resistance capacitance and inductance. The quality functions betweens between input variables and output variables are generally called the transfer functions in a circuit design. The function of a temperature control system is to maintain the temperature of a room, bath or some object at a target value. The temperature effects that may prove most damaging are those of rapid temperature cycling. Where the ambient temperature varies between a low temperature and a relatively high value during a day or part of a day, the continual expansions and contraction of materials and components will accelerate failure[11}-[12]-[13].

The temperature control system[14] shown in figure 2 can be divided in to three main modules:

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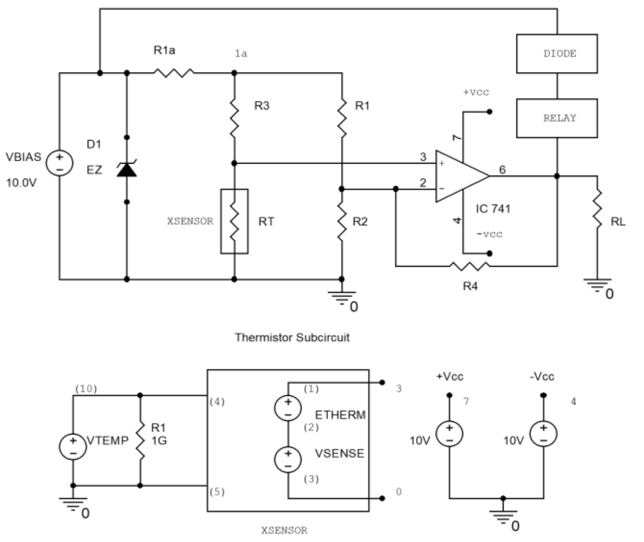

Figure 2: Temperature Controller with Sensing Model

Module 1: A temperature sensor XSENSOR, is a subcircuit referred as "THERMISTOR SPICE MODEL": Thermistor resistance (R) versus temperature (T) is described by the exponential equation by (1).

$$R = R_0 \exp(Beta/T - Beta/T_0) \quad (1)$$

Where R=Thermistor resistance at T(K),T=Thermistor Temperature(K),R_0=Nominal resistance at T_0 (K), T_0 = Temperature where R_0 is measured. Beta = Thermistor material constant.

It is a very nonlinear curve that decreases with increasing temperature referred to as Negative Temperature Coefficient (NTC) device. An important step is in modeling a Thermistor is created a model of resistor without using a resistor in the subcircuit of Thermistor model as shown in figure 3. to sense current SPICE uses a voltage source VSENSE (0V). It is set to 0V so there is no effect on the output voltage. The R Vs T equation is included in the ETHERM statement in the PSpice circuit file to create our compact but powerful sensor model. Note that the temperature V(4,5) included in this equation as a sensor's input temperature.

The voltage source VTEMP generates the sensor's temperature. It contains a Piece-Wise–Linear (PWL) statement that creates a voltage ramping linearly form -15V to 65V with respect to time in the spice simulation program.

Module 2: A temperature control circuit and heating element RT. The temperature for example of a bath, is sensed by a thermistor has a negative temperature coefficient. This means that as the bath temperature increases the value of RT decreases and vice a versa. When bath temperature rises slightly above a certain value, the resistance RT drops below a threshold value so that the difference in the voltage between the input terminals 2 and 3 of the amplifier becomes negative.

Module 3: Relay: This actuates the relay and turns the heater off. Like wise, when the temperature drops below a certain value, then the difference in voltages between the terminals 2 and 3 becomes positive so that the relay is actuated, and heater is turned on. The temperature control circuit (figure 3) provides a way of setting the threshold value of the resistance RT and thus setting a temperature. As this research paper attempts to demonstrate the proposed concepts through a simulation-based approach, attention must be given to the setting of the threshold value of RT when the heater is turns ON. Hence the resistance of RT is used as the performance characteristics. The resistance value of RT can change due to degradation in the values of the various circuit components.

The nominal values of the circuit parameters and their initial conditions are listed in Table 1. To formulate the system as a robust design problem, we classify R3 as the signal factor, and RT- ON and RT- OFF as the output responses. The potential control factors are the nominal values of R1, R2, R4 and EZ. The noise factors are always challenging an uncontrollable factor i.e. an ambient temperature. When such temperature control system is exposed to work under harsh environment temperature variations the dynamic response experiments are used to predict the functional relationship between input signal and output where the response is questionable. The ideal relationships between the signal and each of the two responses are linear through the origin. Through standard circuit analysis techniques, the values of RT- ON and RT-OFF can be expressed as:

$$RT_{ON} = R3R2\,(EZR4 + E0R1)\,/[R1(EZR2 + EZR4 - E0R2)] \quad (2)$$

$$RT_{OFF} = R3R2R4/[R1\,(R2 + R4)] \quad (3)$$

Where R1, R2, R3 and R4 are the resistance values of the four resistors, E0 is the power supply voltage and Ez the nominal voltage of the Zener diode D1. The simulation experiments were performed for verification and the results support the optimal solutions. In practice, for more complicated circuits, complex circuit simulators are developed to evaluate the values of the output responses since simple equations are usually not available. Alternatively, hardware experiment s could be used to measure the values of the output responses by building prototype circuits. In both cases, design of experiments would be needed to understand and model the relationships between output and control and noise factors.

The four control factors and their starting levels and the alternate levels are listed in Table 1. For the three resistances (R1, R2 and R4) and for the Power Supply a

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(Zener diode EZ, fixed), level _2 is the starting level, level_ 3 is the 1.2 times level_ 2 while level_1 is 0.8 times level_ 2. A Zener diode D1 is connected between points 1a and 0 and it maintains a constant voltage to the Wheat-stone Bridge, despite fluctuations of E0.

Table 1: Setting of Control, Noise and Signal Factors

Control Factors		Level		
		1	2	3
A	R1(KΩ)	3.2	4.0	4.8
B	R2(KΩ)	6.4	8.0	9.6
C	R4(KΩ)	72.0	40.0	88.0
D	EZ (V)	4.8	6.0	7.2
M	R3 (Signal)	0.5 KΩ	1.0 KΩ	1.5 KΩ
N	Noise Factor Ambient	0 25 50 75 100		

IV. WORST CASE CIRCUIT OPTIMIZATION

The objective of the Taguchi parameter method is to determine a setting of design parameters at which the characteristics is robust against the noise. For this purpose, Taguchi proposed an experimental method in which orthogonal arrays (OA) are used as experimental design and performance measure called the SNR (Signal-to Noise Ratio) is employed for analyzing the experimental data. We studied the effect of an ambient temperature as a environmental noise factor on a temperature control circuit for sensitivity optimizations. The optimized values are then used as control factors for the parameter design followed by statistical analysis. We aimed to improve sensitivity and robustness under the influence of uncontrolled ambient temperature variations of noise factor. The systematic circuit simulation experiments were performed using PSPICE (PC version of Simulation Program with Integrated Circuit Emphasis) a powerful circuit simulation tool. It is industry standard tool and due to its wide use all over the world wide because of the facts: easy to use, highly accurate and reliable results. Which leads to saves time, efforts and cost of the electronic product, system or process at their early design stage.

The thermistor resistance RT_ON is the characteristic response simulated by writing either circuit file or drawing a schematic in OrCAD for each of the row of L_{18} orthogonal array layout as shown in Table 2. The resistance R3 is signal factor with 1kΩ nominal value at their 3 levels is used to perform the 54 experiments.

The thermistor resistance RT-ON response is tabulated to find the sensitivity and S/N Ratios for each experiment. The worst-case circuit performance for A1B1C1D1 is simulated as an initial design for the measurement of RT-ON (thermistor resistance) characteristics for a set temperature shown in figure 3.

PSPICE tool provides a powerful graphical post-processor facility known as PROBE, which allows user to display graphical waveforms. The output voltage response for RT-ON corresponding to the SET temperature value is also traced and displayed when the control circuit turns ON is shown in the figure 4. The nodal voltage trace at circuit node 2 is evaluated as V(2)/ I(XTHERM) for getting thermistor resistance value RT-ON corresponding to sensor temperature that is already a set point by using R3 signal. The output voltage V(5) at node 5 is simultaneously referred to note the exact value of thermistor resistance RT-ON for ON time of response as shown in figure 3

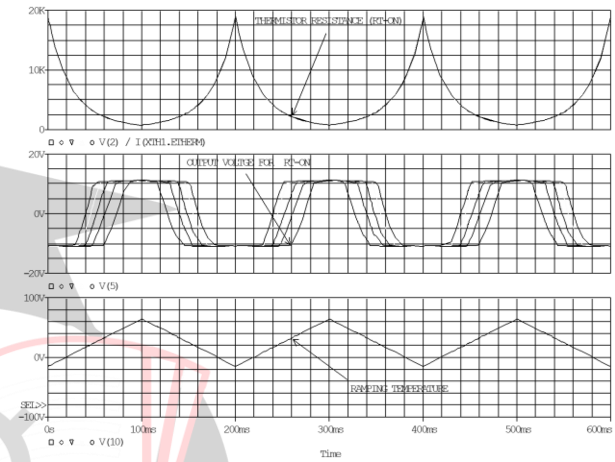

Figure 3: Worst-Case Circuit Performance

Table 2: Orthogonal Array (L_{18}), S/N Ratios, Sensitivities

⇨ Factors Sr. No	e1	e2	A3	B4	C5	E6	D7	E8	S/Nη (dB)	Sensitivity
1.	1	1	1	1	1	1	1	1	2.05334	1.93134
2.	1	1	2	2	2	2	2	2	2.36680	1.60862
3.	1	1	3	3	3	3	3	3	2.58953	1.54283
4.	1	2	1	1	2	2	1	1	2.36019	1.59316
5.	1	2	2	2	3	3	1	1	2.44143	1.55812
6.	1	2	3	3	1	1	2	2	2.28547	1.72456
7.	1	2	1	2	1	3	2	3	2.08870	2.31210
8.	1	2	1	1	2	2	1	1	2.27046	1.99821
9.	1	2	1	1	2	2	1	1	2.87229	0.98678
10.	2	1	1	3	3	2	2	1	2.37358	2.51902
11.	2	1	2	1	1	3	3	2	2.49264	1.28586

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12.	2	1	3	2	2	1	1	3	2.33992	1.31977
13.	2	2	1	2	3	1	3	2	2.43022	1.98201
14.	2	2	2	3	1	2	1	1	2.12000	2.23168
15.	2	2	3	1	2	3	2	1	2.62318	1.01459
16.	2	3	1	3	2	3	1	2	1.99788	2.75633
17.	2	3	2	1	3	1	2	3	1.99788	1.19949
18.	2	3	3	2	1	2	3	1	2.19248	1.36746
Note that e is assigned as dummy column treatments										

The simulated circuit performance is optimized as shown in the following figure 4.

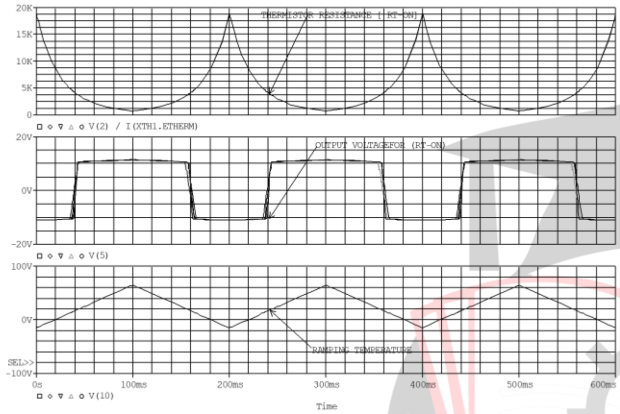


Figure 4: Optimized Circuit Performance

Taguchi's two-step optimization procedure with the suggested S/N ratio for dynamic problems is implemented. The graphical data analysis and prediction of optimum design and other results are calculated by using a very powerful statistical software MINITAB. The response data is used to generate plots of main effects for the slopes and plot of main effects for the S/N ratios for the selected control factors are plotted in figure 5 and 6 respectively. The response Vs signal scatter plots for S/N ratio, Slope and standard deviation are plotted in descending values of order in figure 7. After having examined the response tables and main effects plots to determine which factor setting should maximizes the S/N ratio for predicting the Optimum setting for achieving the system functional robustness.

V. RESULTS AND DISCUSSION

A well-planned set of experiments in which all parameters of interest are varied over a specified range is a much better approach to obtain systematic data. Mathematically speaking such a set of experiments is complete and ought to give desired results. However, it does not easily lend itself to understanding of science behind the phenomenon.

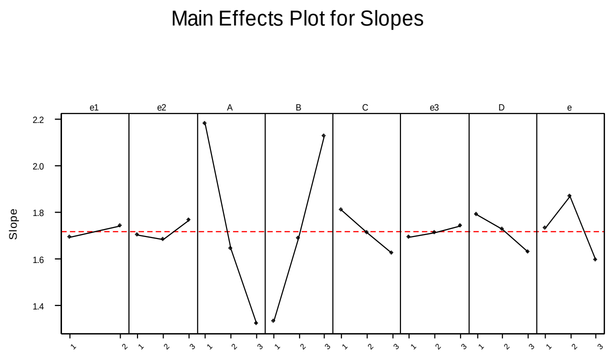


Figure 5: Main Effects Plot for Slopes

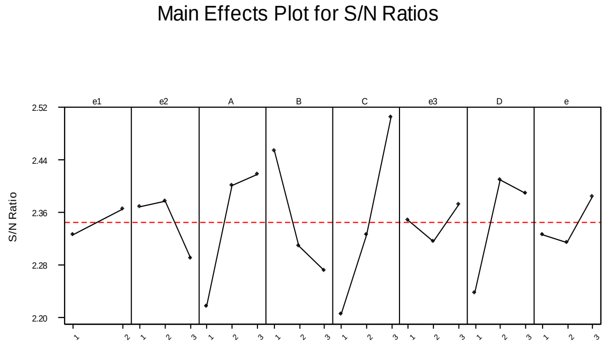
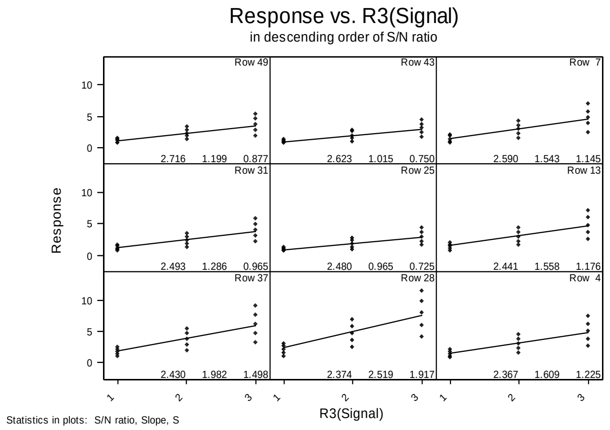


Figure 6: Main Effects Plot for S/N Ratios

The data analysis and the main effect plots were plotted using MINITAB were as shown above figures. To minimize variations i.e. Sensitivity to noise for ambient temperature using systematic Design Of Experiments Orthogonal (DOE) Array (L_{18}). The scattered plots explore required data of Statistics of S/N Ratios, Slopes and Std. Deviation. A careful statistical data analysis ravels us to formulate combination of the control factor levels that maximizes the functional robustness of a temperature control circuit against the ambient temperature noise.



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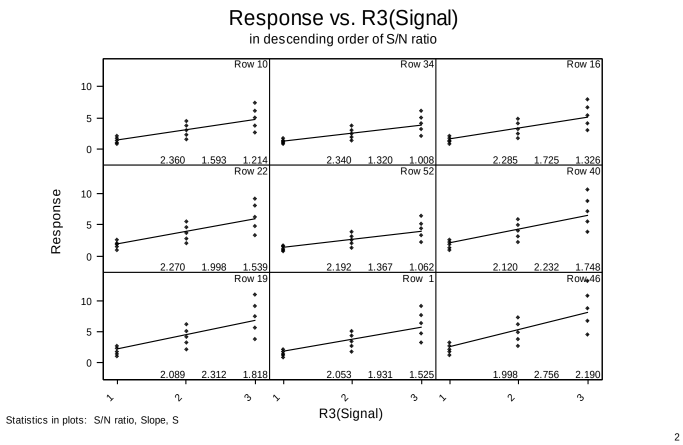

Figure 7(a) and (b): Scatter Plots and Statistics of S/N Ratios,

Slopes and Std. Deviation

We selected a combination of the control factor levels that maximizes the functional robustness of a temperature control circuit. Figure 4 shows the main effect plots of the control factors. From the figure 5 it is obvious that (A3 B1 C3 D2) is the optimal combination because this combination maximizes S/N ratio. In other case studies, the sensitivities of the objective systems can be as important as the S/N ratio. However, in this present study of control circuit functional robustness is more important than sensitivity. still the details of sensitivity analysis is linearly varying with the signal input R3 as shown in the scatter plots as well as statistically verified from the figure 7(a) and (b).

VI. DATA ANALYSIS

The purpose of a combination test is simulated to ensure that S/N ratio and sensitivity of the optimized circuit can be reproduced under the downstream, realistic, operating conditions. If S/N ratio and sensitivity of the confirmation test is close to those of optimized circuit technology, we can be sure that the functional robustness and sensitivity of the optimized circuit technology are reliable to reproduce under realistic operating environment that is operation of system in stated ambient temperature.

Let the initial design of the 4 control factors be A1B1C1D1. The prediction of S/N ratio for the initial design and the optimal design is now presented as follows. Predicted S/N ratio of the optimal design A3 B1 C3 D2 is:

$$\hat{\eta} = \overline{A3} + \overline{B1} + \overline{C3} + \overline{D2} - 3.\overline{T}$$
$$= 2.483812 + 2.519537 + 2.570445 + 2.40889 + 3.2.38813$$
$$= 2.818297$$

Predicted S/N ratio of the initial design A1B1C1D1 is:

$$\hat{\eta} = \overline{A1} + \overline{B1} + \overline{C1} + \overline{D1} - 3.\overline{T}$$
$$= 2.217312 + 2.519537 + 2.267539 + 1.79734 + 3.2.38813$$
$$= 1.637338$$

Thus, the predicted difference in gain in S/N ratio between the initial design and the optimum design and confirmation test is obtained 81.9%. Hence the circuit quality performance is sufficiently improved using the simulation techniques along with Taguchi OA method.

Table 3 extract the predicted and confirmed S/N ratio of the optimum and initial designs; and shows that the gain of optimal design setting highly improved in S/N ratio and is reproducible. This validates that the functional robustness of the optimized circuit is now robust against downstream harsh operating conditions such as an ambient temperature variation.

Table 3: S/N ratio (η) of prediction and Confirmation

Sr.No.	S/N ratio (η) dB	
	Predicted	Confirmation
1. Optimal design setting	2.818297	2.87229
2. Initial design	1.637338	2.05334
3. Improved Gain in S/N Ratio	1.180962	0.81895

VII. CONCLUSION

The Simulation study of dynamic system based on Taguchi's Orthogonal Array (OA) methodTaguchi parameter designed method with the help of MINITAB tool applied. The optimum parametersof design setting against insensitivity to noise for dynamic system circuit performance was PSPICE modeled. The predicted and confirmed results for the sensitivity of circuit performance before and after optimization of parameters design were calculated. It reveals that Gain in S/N ratio between the initial design and confirmation test is obtained 81.9%. Hence the dynamic system circuit is robust against the noise. The significant S/N Gain improvementcircuit performance was useful in the early stage of system design. Thus, presented simulation method of designing of electronic products saves time; energy and material cost of the product or-process and avoid major loss to all stakeholders in the society.

VIII. ACKNOWLEDGEMENT

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