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Design and Verification of a Flexible Sensor Interface Module for Engine Control Unit

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Abstract : Over the last two decades the electronic content in automobiles, busses and lorries has significantly increased. In contemporary cars it has reached a value of about 15–20% and it is expected to further increase to 35–40% due to legislation and environmental requirements resulting in violation of emission standards and fuel economy standards. The electromechanical system helps system controls to improve fuel economy and reduce pollutant emissions and in improving the comfort and safety of vehicle users. With the recent advances in microelectronics, many sensors are being used in wide variety of applications, particularly in automotive industries and can be considered as preferable choice for signal conditioning accuracy and integration. The sensor functioning becomes sophisticated as market trends and customer requirements increase, this leads to the requirement of more accurate and reliable sensing element. The flexible sensor interfacing circuit is an automotive grade IC designed to be used as a sensor interfacing equipment that can overcome such problem. L9966 IC is one such type of dedicated integrated chip. The work proposes the design of a flexible sensor interfacing module that can interface different sensors without modifying PCB Hardware.

Keywords : Sensor Interface, Flex Input, L9966 IC, Electrostatic Discharge, Engine Control Unit, Electronic Control Unit, Electromagnetic Interference, Electromagnetic Compatibility.

I. INTRODUCTION

The growing demand for new technological solutions in automobiles has led to the replacement of mechanical system with electromechanical solutions. Over the last two decades the electronic content in automobiles, busses and lorries has significantly increased. In contemporary cars it has reached a value of about 15–20% and it is expected to further increase to 35–40% due to legislation and environmental requirements. The electromechanical system helps system controls to improve fuel economy and reduce pollutant emissions and improving the comfort and safety of vehicle users. With the recent advances in microelectronics, many sensors are being used in wide variety of applications, particularly in automotive industries and can be considered as preferable choice for signal conditioning accuracy and integration which is increasingly used in vehicles due to their ease of application. One key element in automotive electronics field is sensor and thus sensor interface circuits beside the actuators. The sensor functioning becomes sophisticated as market trends and customer requirements increase, this leads to the requirement of more accurate and reliable sensing element. The new flexible sensor interfacing circuit can help in improving the accuracy and can be considered as the suitable choice for sensor interfacing. The flexible sensor interfacing circuit is an automotive grade IC designed to be used as parameter sensing interface equipment. L9966 IC is one such type of dedicated integrated chip. The flexible sensor interfacing circuit is a part of an electronic control unit of an automotive and acts as a functional block that receives the electrical signals from sensor output and processes it and compares the received signal with the reference signal. By the comparator action, rectangular pulses are generated. The generated digital pulses are fed into a microcontroller. The microcontroller drives the actuator and an alarm signal is generated. The generated alarm signal controls the engine control unit.

II. METHODOLOGY

The flowchart for the proposed methodology is shown in Fig 1. The requirements are taken from customers and budget is planned accordingly. The components are selected such that they satisfy the design requirements. The circuit is designed and simulated for functionality testing. Matlab/Simulink is used for simulation. The developed circuit is verified and validated through Monte Carlo Analysis technique and Sensitivity Analysis. The simulated results are analysed.

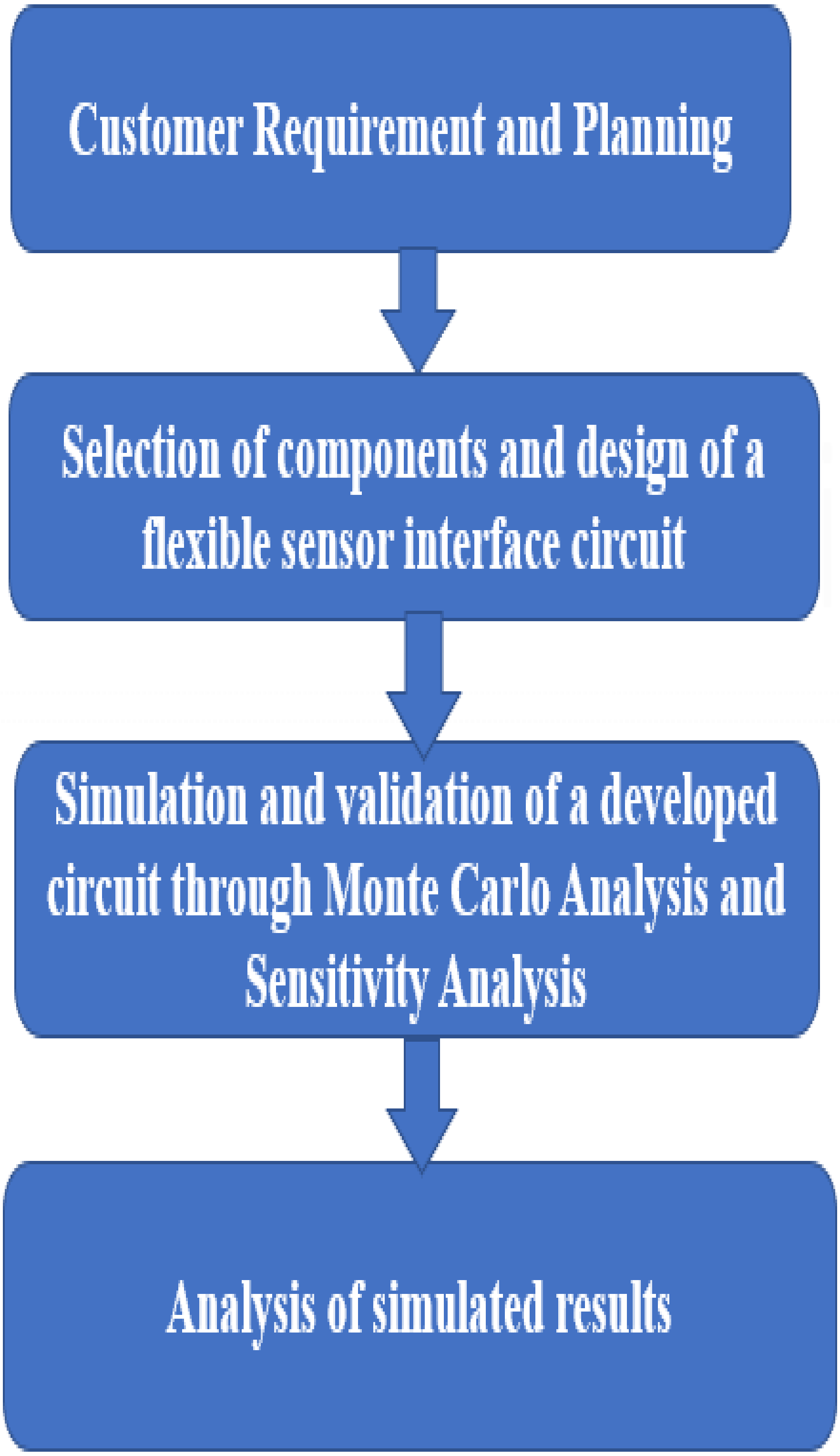


Fig 1 Flowchart for proposed methodology

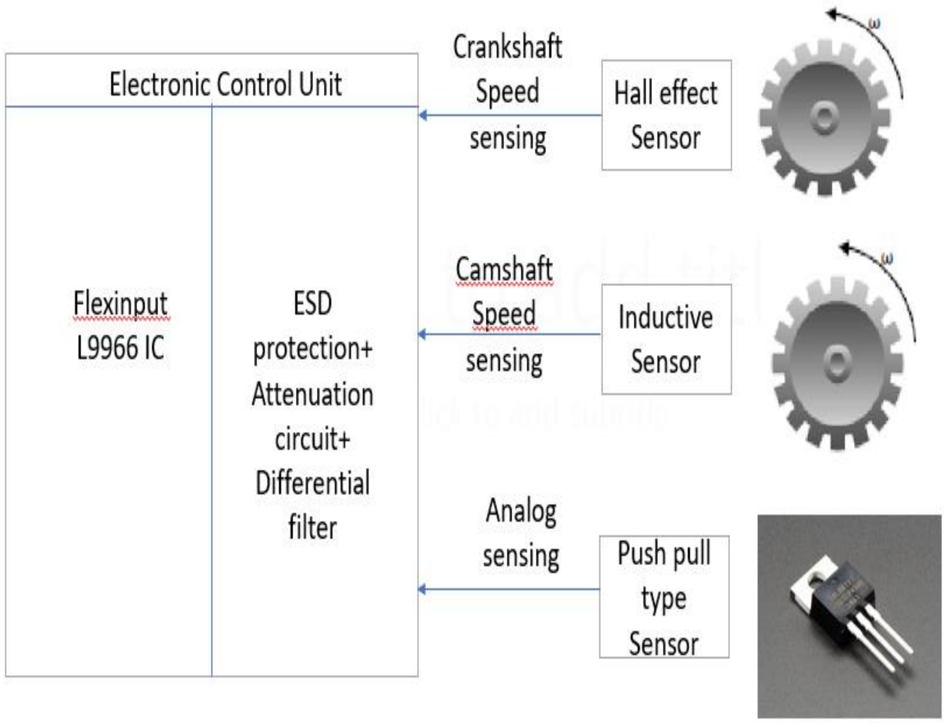


Fig 2 Block diagram for proposed methodology

Fig 2 shows the basic block diagram of proposed methodology. The input system forms the interface to which various field devices taken from engine are connected to the sensor interface. The purpose of the interfacing is to condition the various signals received from or sent from engine. Input devices from different parts of the engine such as crankshaft wheel, camshaft position are hardwired to the input terminals of an ECU. The ECU acts as a transfer block for sensor and actuator. An ECU is basically an electronic control unit consists of a flexinput IC and a sensor interface block and the processor. Here hall effect Sensor, inductive sensor, push pull type sensor are used for measuring crank speed, camshaft speed and analog parameters such as temperature, pressure. The sensors are interfaced to an ECU block and are tested for the functionality. The signals received from sensors are hardwired to the ECU input terminals. The common mode capacitors located at the input side of an ECU provide protection against electrostatic discharge. The differential capacitor located between pull up and pull down resistor shunts high frequency components into the ground and hence protects the circuit from EMC/EMI issues. A passive attenuator is a special type of electrical circuit made up of entirely resistive network designed to weaken or attenuate the power supplied by a source to a level that is suitable for the connected load. The lowpass RC filter helps in shunting high frequency components into the ground. The signal from the RC filter is fed to a flex input L9966 IC. L9966 IC acts as a comparator and hence generates the output in the form of rectangular pulses. The rectangular pulses are fed into microcontroller.

III. MONTE CARLO ANALYSIS

Monte Carlo analysis is defined as a simulation process that generates probabilities of risk using a mathematical model. The method provides a range of possible results based on the varying parameters that are measured in the analysis. The method was developed by a scientist developing the atomic bomb during World War II.

Monte Carlo Analysis generates predictive situational results based on distributing factors that influence the outcome of the process. It takes into account the maximum and minimum threshold of each parameter and randomly iterates the simulation with different values. There are **v**arious types of probability distributions used in Monte Carlo analysis. They represent how the possible outcome values are distributed and give a good picture of the risk when presented in a histogram chart. Commonly used probability distributions are the Gaussian and uniform models. Depending on the parameters involved, completing a Monte Carlo analysis simulation may take hundreds or thousands of iterations. Monte Carlo gives a better picture of what may go wrong in terms of probability.

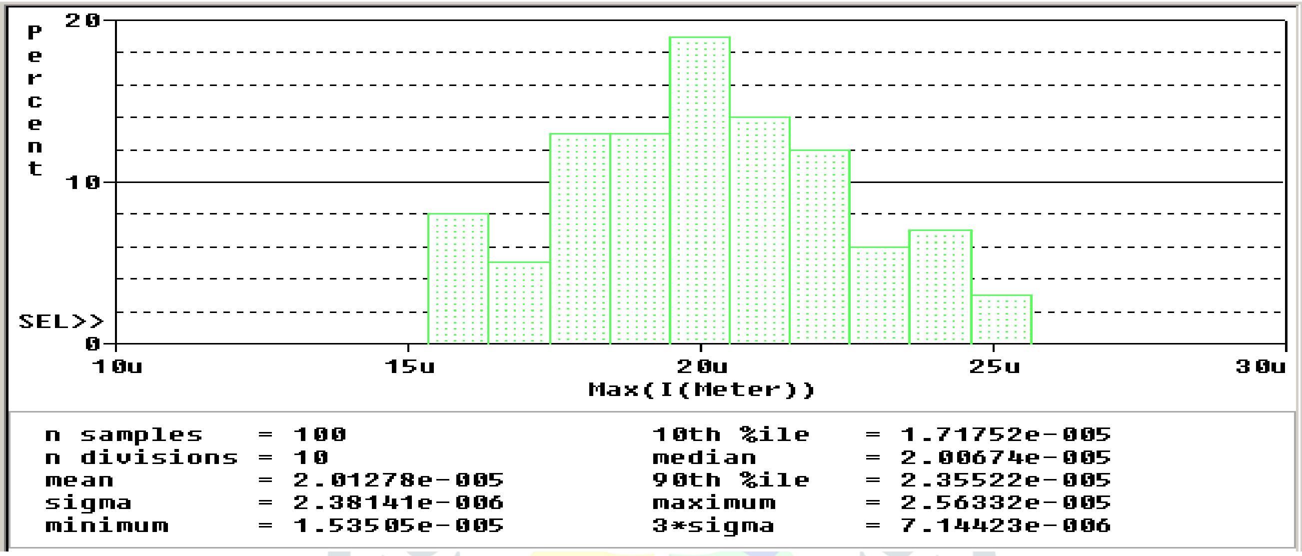


Fig 3 Monte Carlo Histogram Distribution

IV. SENSITIVITY ANALYSIS

A simple definition of sensitivity is how much specific system behavior/characteristic changes as individual component value changes. The general equation for sensitivity analysis is given as

$$S_x^y = \lim_{\Delta x \to 0} \frac{\frac{\Delta y}{y}}{\frac{\Delta x}{x}} = \frac{x}{y}\frac{\partial y}{\partial x} \qquad \textbf{(4.1)}$$

Equation (2.23) is the general mathematical definition of circuit sensitivity.

Where S represents sensitivity, X represents changing element/component and

Y is the characteristic of circuit which one want to evaluate as component value is varied.

The middle part of the equation shows that the percentage that the dependent variable Δy/y changes, relative to the percentage that the independent variable Δx/x changes. Sensitivity analysis of analog circuit provide us the information about various component present in the circuit. The design engineer needs to choose as many inexpensive components as possible, by keeping the circuit performance stable, engineer needs to decide which elements are sensitive and how much value they required for the tolerance. With the help of sensitivity analysis we also know about the component characteristics variation in circuit and its effect on performance of system output.

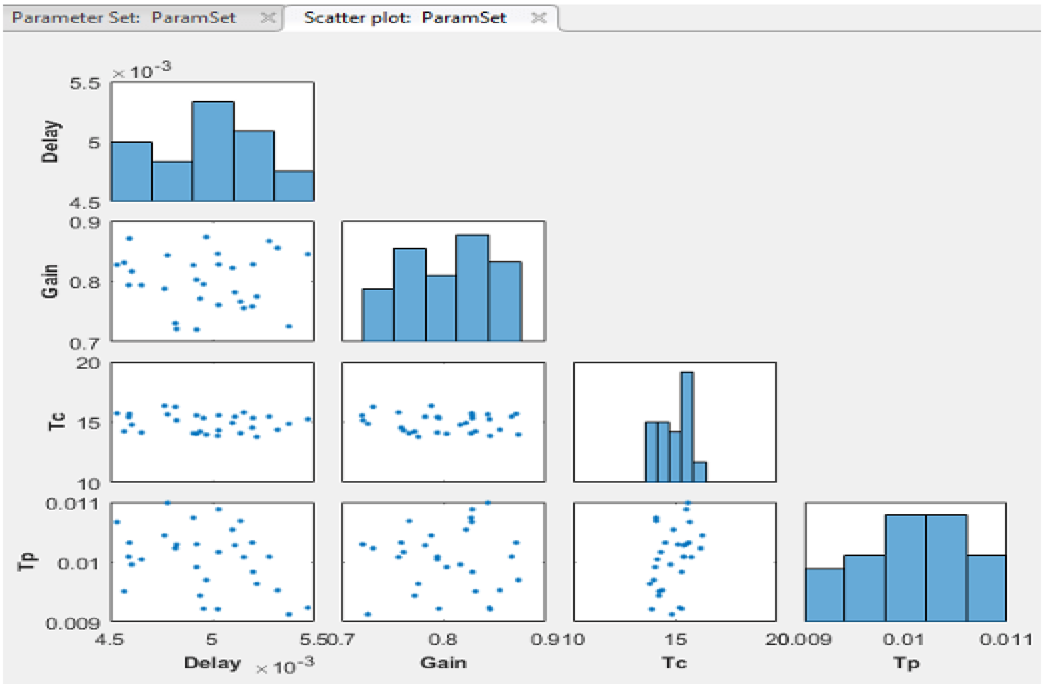


Fig 4 Scatter plot view of Sensitivity Analysis

V. DESIGN SPECIFICATIONS OF SENSOR INTERFACE CIRCUIT

Table 1 Specifications of Sensor Interface circuit

Components	Description	Values
CSTvrsp	Common mode capacitor for electrostatic discharge protection	4.7nF
CSTvrsn	Common mode capacitor for electrostatic discharge protection	4.7nF
Rpu	Pull up resistor	10kohm
Cvrspn	Differential noise capacitor filter for EMC/EMI protection	1nF
Rpd	Pull down resistor	10kohm

RIN1,RIN2,RIN3,RIN4	Parallel resistances for signal attenuation	31.6kohm
Rsrup1,Rsrup2	Series up resistances for signal attenuation	46.4kohm,68.1kohm
Rsrlo1,Rsrlo2	Series low resistances for signal attenuation	46.4kohm,68.1kohm
Radj	Resistance used for signal attenuation	26.1kohm
Cvrsp	Common mode capacitor for EMC/EMI protection	470pF
Cvrsn	Common mode capacitor for EMC/EMI protection	470pF
VDD5	Supply Voltage	5 V
Vgndshift	Ground shift voltage	1 V
Vposmax	Input signal high clamping voltage	3.3 V
Vnegmax	Input signal low clamping voltage	-0.6 V
V3V3	Internal 3V3	3.3 V

Vcm	Common mode Voltage	1.6 V
Vhyst	Hysteresis Voltage	6uV

VI. SIMULATION ANALYSIS AND DISCUSSION

6.1. Hall Effect Sensor Interfacing

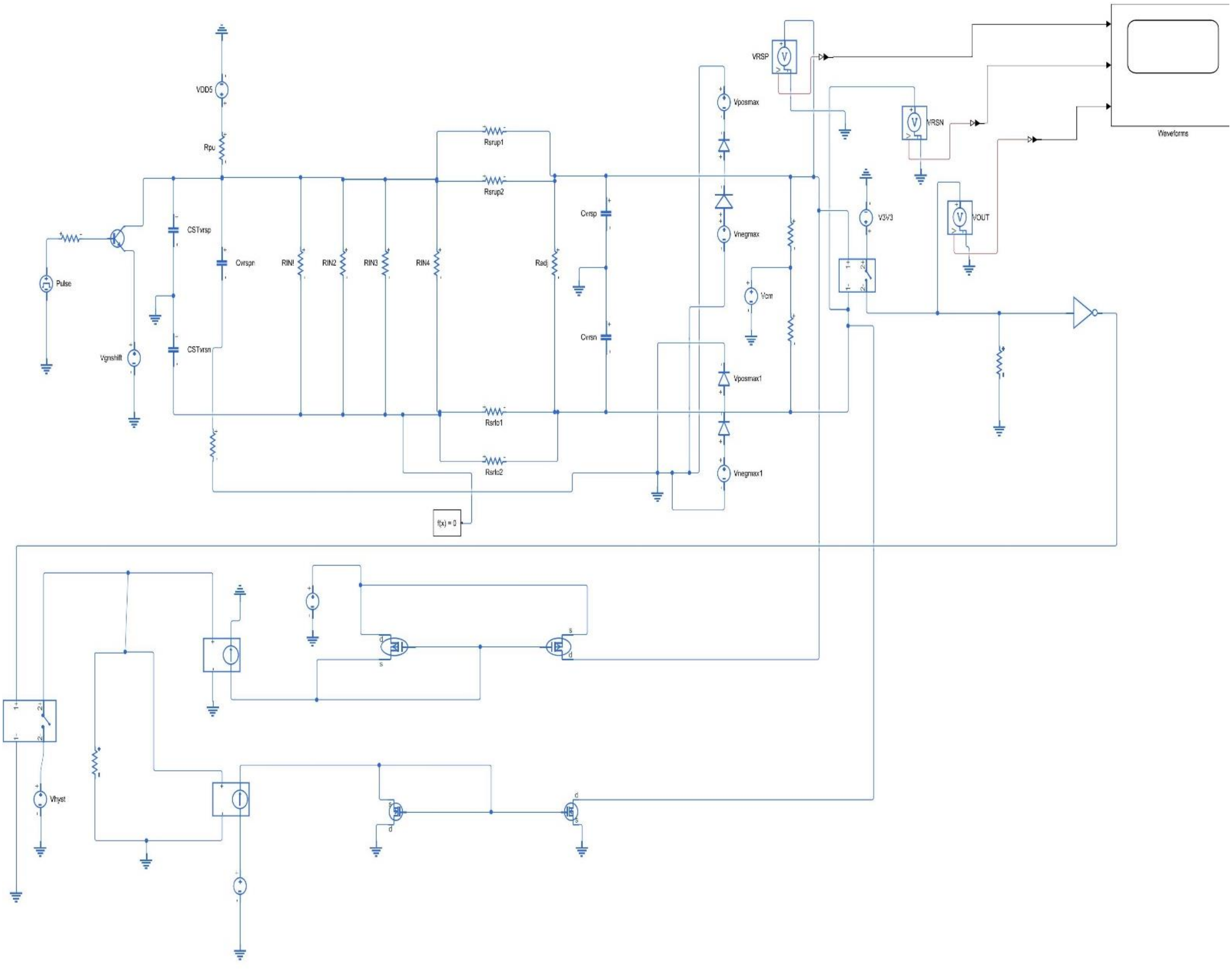


Fig 5 Hall Sensor Interfacing Circuit

The circuit diagram for Hall sensor interfacing is shown in Fig 5. Here the MOSFET is modelled as "Hall Effect Sensor". The sensor senses the signal and is converted into electrical quantity. The signal is fed into input interface of a sensor interface block. The ESD capacitors at the input side prevents the circuit from electrostatic discharge phenomenon by shunting high frequency components into the ground. The pull up resistor pulls the voltage level equivalent to supply voltage level. The pull down resistor pulls down the voltage level equivalent to ground. The differential capacitor filter protects the circuit from electromagnetic interference. The resistive network acts as a pi attenuator helps in signal attenuation such that desirable amount of power is delivered to load. The signal passes to the next stage. Here the RC low pass filter passes the low frequency signals at VRSP pin and VRSN pin of L9966 IC and rejects high frequency signals.

The integrated circuit consists of 2 comparators. The difference between the two signals VRSP and VRSN is considered as the control voltage. A comparator1 compares the control voltage with the reference voltage. If the control voltage is greater than the sum of hysteresis voltage and threshold voltage, the output will be 3.3V of logic high state. If the control voltage is less than difference between threshold voltage and hysteresis voltage, the output will be logic low state. The overall voltage VRS_OUT is inverted with the help of a NOT gate and is sent to comparator 2. A comparator2 compares the control voltage. Here the control voltage will be the difference between complement of VRS_OUT and 0V. The control voltage is compared. If the control voltage is greater than the sum of hysteresis voltage and threshold voltage, the output will be logic low state. If the control voltage is less than difference between threshold voltage and hysteresis voltage, the output will be logic high state of 6uV. The overall output voltage signal is sent to 2 voltage controlled current source blocks. Voltage controlled current source 1 generates the hysteresis current 1 of 6uA and is sent to the current mirror circuit 1. Similarly voltage controlled current source 2 generates the hysteresis current 2 of 6uA and is sent to the current mirror circuit 2. In current mirror circuit 1, MOSFET MbreakP1 acts as current to voltage converter and MOSFET MbreakP2 acts as voltage to current converter and there by generating the copy of the reference circuit and same current is sinked (-6uA) at VRSN pin of L9966 IC. In current mirror circuit 2, MOSFET MbreakN1 acts as current to voltage converter and MOSFET MbreakN2 acts as voltage to current converter and there by generating the copy of the reference circuit and same current is sourced (6uA) at VRSP pin of L9966 IC. The resultant rectangular digital output from VRS_OUT pin of L9966 IC is fed to a microcontroller. The signal from the microcontroller produces an alarm signal and actuates the actuator. This is the process of signal conditioning of flex input L9966 IC.

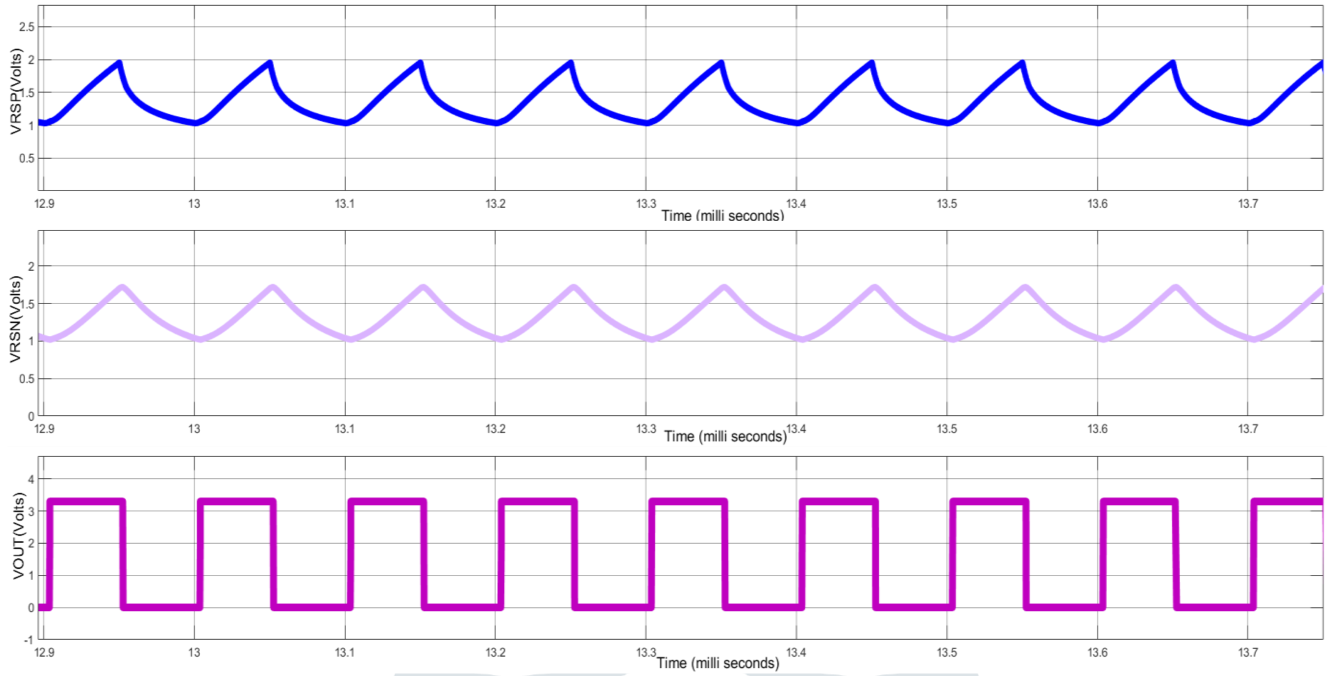


Fig 6 Simulated Result for Hall Effect Sensor Interfacing

The waveforms of VRSP, VRSN and VRS_OUT are shown in Fig 6. In VRSP and VRSN waveforms, the signal charges to 6uA pull up and discharges to 6uA pull down and both the waveforms are triangular in nature. The signals VRSP and VRSN are compared with the reference signal, there by rectangular digital pulses are generated at VRS_OUT pin. The average output voltage obtained was 3.3 V.

- **Monte Carlo Result**

Various factors such as resistance positive or negative temperature coefficient, thermal conditions such as soldering or extended high or low-temperature, operating conditions such as humidity, pressure, and exposure to vibration or shock will affect the tolerance value of resistors and hence the tolerance value of resistors is set as +3.5% and -3.5% . Various factors such as capacitor ageing rate, ESD/EMI protection tolerance, conductive tolerance will affect the tolerance value of capacitors and hence the tolerance value of capacitors is set as +20% and -20%.

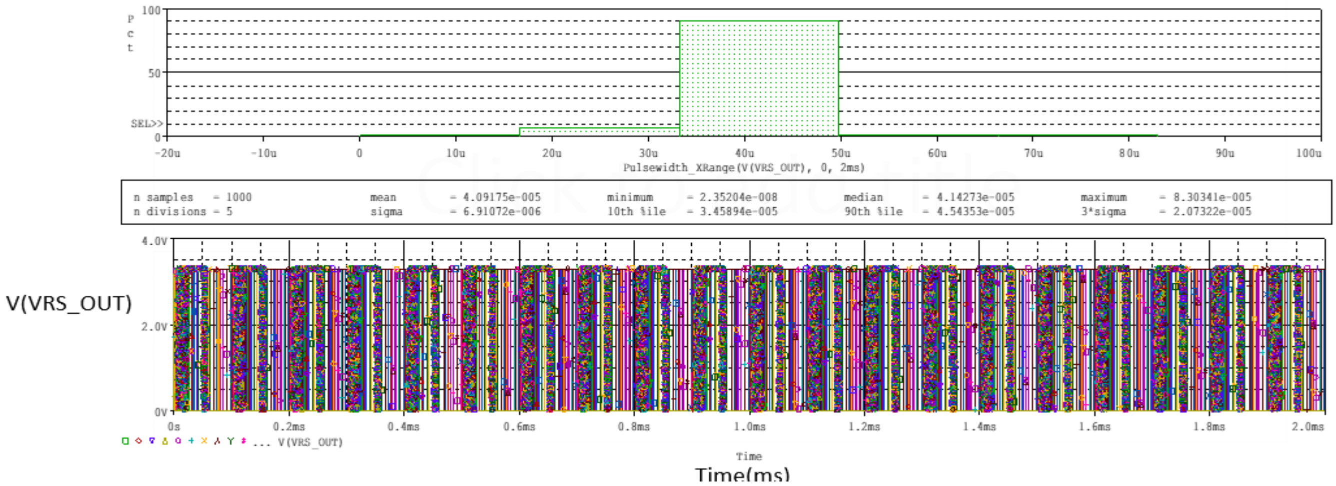


Fig 7 Histogram View of Monte Carlo Run

The Hall sensor measures the speed of the crank wheel. The measured pulse width from Monte Carlo histogram is a measure of engine rpm (crank speed). The histogram indicates the boundary values. The measured engine speed lies between minimum and maximum value. From histogram distribution, it can be understood that the average pulse width is 40.91 usec which implies that average rpm of the engine would be equivalent to 40.91 usec. The pulse width is also a measure of life cycle of engine rpm. The measured 3 sigma value indicates that 99.7% of the values will lie within three standard deviations from the average pulse width value which means that for all 1000 runs, the resulted output is 99.7% accurate under this region.

- **Sensitivity Analysis Result**

Sensitivity Analysis tool examines how much each component affects circuit behaviour by itself and in comparison to other components.

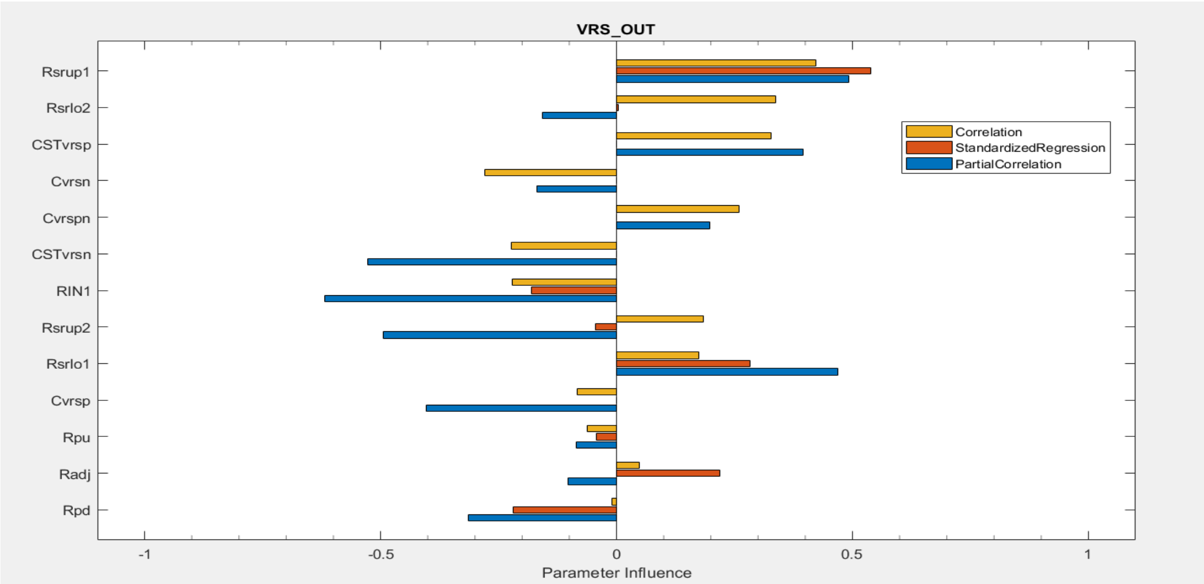
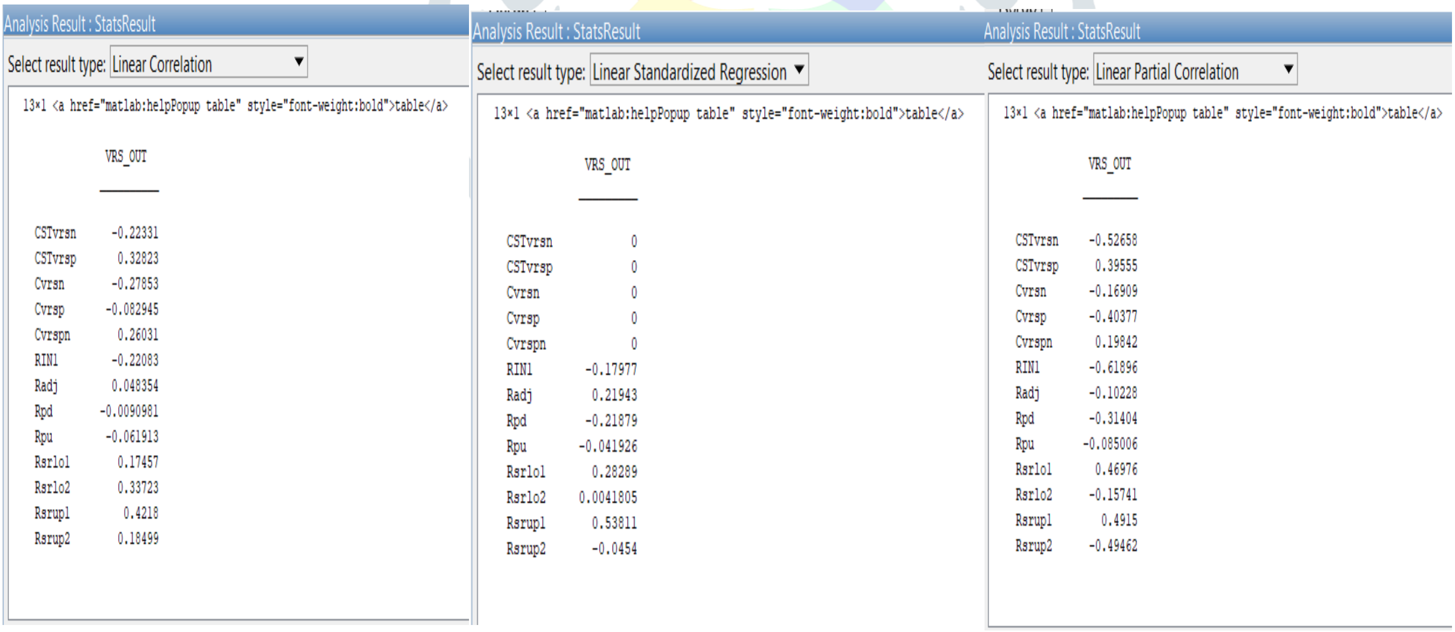


Fig 8 Components influence on Output Voltage



Analysis Result : StatsResult

Select result type: Linear Correlation

13×1 table

	VRS_OUT
CSTvrsn	-0.22331
CSTvrsp	0.32823
Cvrsn	-0.27853
Cvrsp	-0.082945
Cvrspn	0.26031
RIN1	-0.22083
Radj	0.048354
Rpd	-0.0090981
Rpu	-0.061913
Rsrlo1	0.17457
Rsrlo2	0.33723
Rsrup1	0.4218
Rsrup2	0.18499

Analysis Result : StatsResult

Select result type: Linear Standardized Regression

13×1 table

	VRS_OUT
CSTvrsn	0
CSTvrsp	0
Cvrsn	0
Cvrsp	0
Cvrspn	0
RIN1	-0.17977
Radj	0.21943
Rpd	-0.21879
Rpu	-0.041926
Rsrlo1	0.28289
Rsrlo2	0.0041805
Rsrup1	0.53811
Rsrup2	-0.0454

Analysis Result : StatsResult

Select result type: Linear Partial Correlation

13×1 table

	VRS_OUT
CSTvrsn	-0.52658
CSTvrsp	0.39555
Cvrsn	-0.16909
Cvrsp	-0.40377
Cvrspn	0.19842
RIN1	-0.61896
Radj	-0.10228
Rpd	-0.31404
Rpu	-0.085006
Rsrlo1	0.46976
Rsrlo2	-0.15741
Rsrup1	0.4915
Rsrup2	-0.49462

Fig 9 Numerical data for components influence

6.2. Inductive Sensor Interfacing

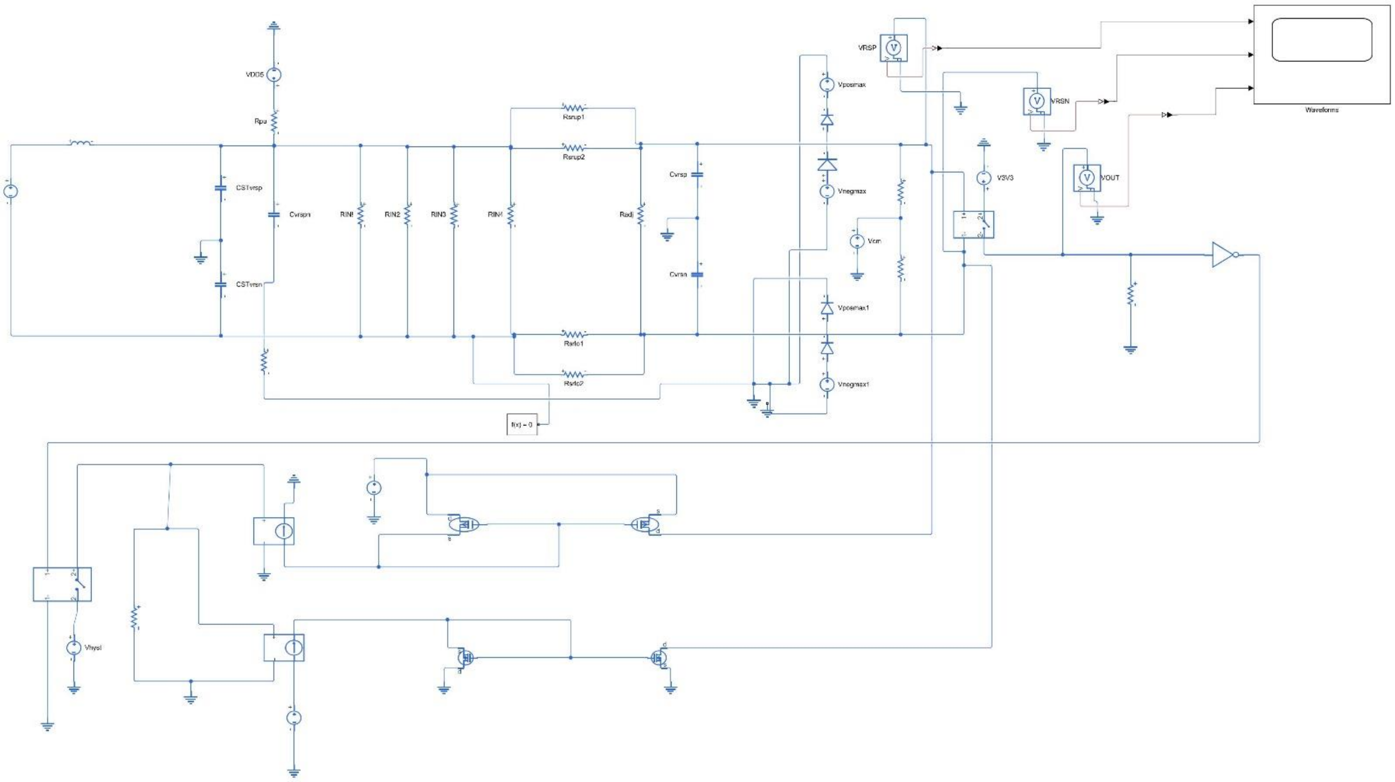


Fig 10 Inductive Sensor Interfacing

The circuit diagram for inductive sensor interfacing is shown in Fig 10. The circuit consists of an AC voltage source and inductor of 10 uH. The inductive sensor senses the speed of the crankwheel and the signal is fed to a sensor interface block and the signal output from the sensor interface block is fed to a flexible input L9966 IC. Similarly like Hall Effect Sensor, by the comparator action located inside L9966 IC, rectangular pulses are obtained and are sent to a microcontroller. The microcontroller activates the actuator and there by completing the mechanism.

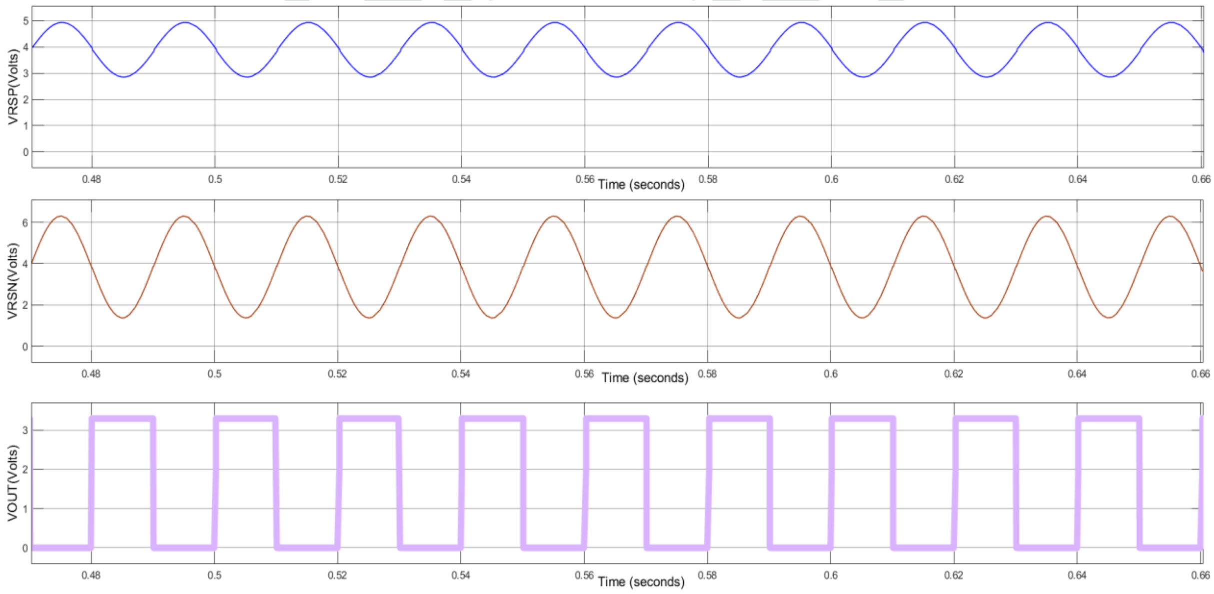


Fig 11 Simulated Result for Inductive Sensor Interfacing

The waveforms of VRSP, VRSN and VRS_OUT are shown in Fig 11. In VRSP and VRSN waveforms, the current source is charged to 6uA pull up and discharges to 6uA pull down and both the waveforms are sinusoidal in nature. The signals VRSP and VRSN are compared with the reference signal, there by rectangular digital pulses are generated at VRS_OUT pin. The average output voltage obtained is 3.3 V.

➢ Monte Carlo Result

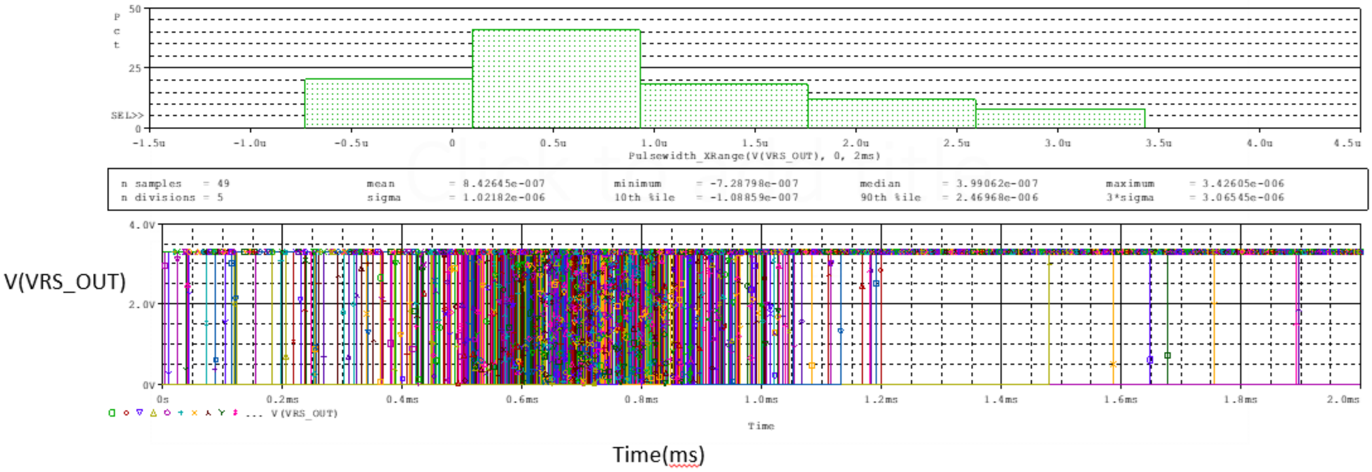


Fig 12 Histogram View of Monte Carlo Run

The Inductive sensor measures the speed of the camshaft. The measured pulse width from Monte Carlo histogram is a measure of camshaft speed. The histogram indicates the boundary values. The measured engine speed lies between minimum and maximum value. From histogram distribution, it can be understood that the average pulse width is 84.26*10^(-8) sec which implies that average rpm of the camshaft would be equivalent to 84.26*10^(-8) sec. The pulse width is also a measure of life cycle of camshaft rpm. The measured 3 sigma value indicates that 99.7% of the values will lie within three standard deviations from the average pulse width value which means that for all 1000 runs, the resulted output is 99.7% accurate.

➢ Sensitivity Analysis Result

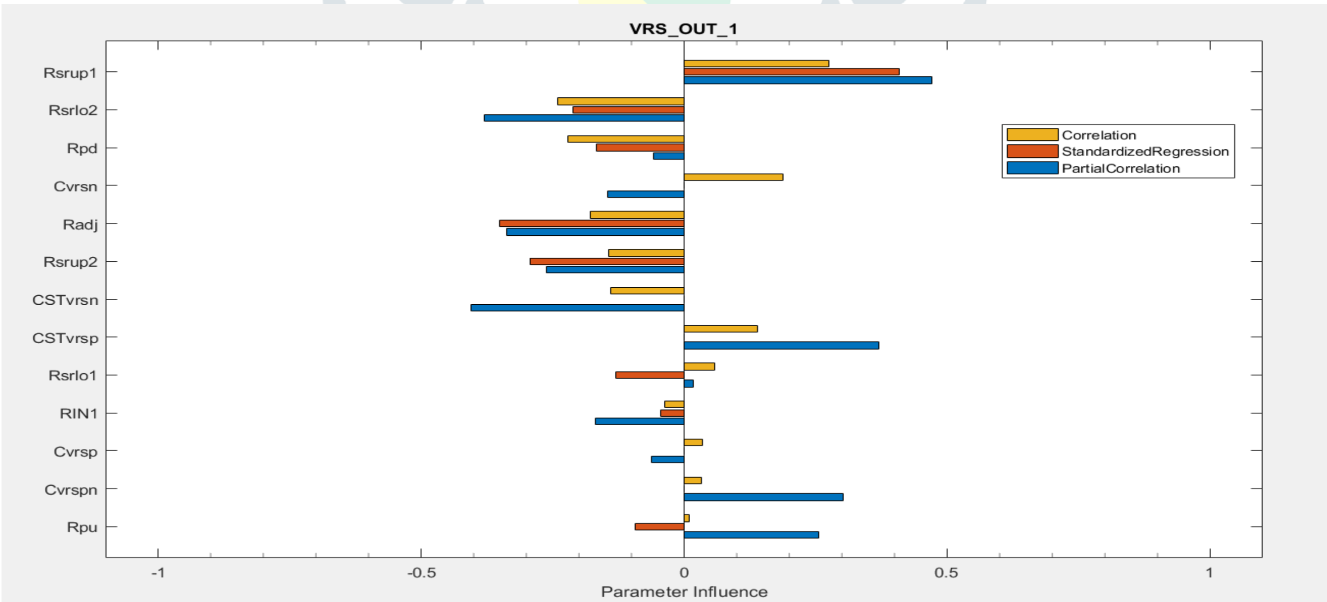
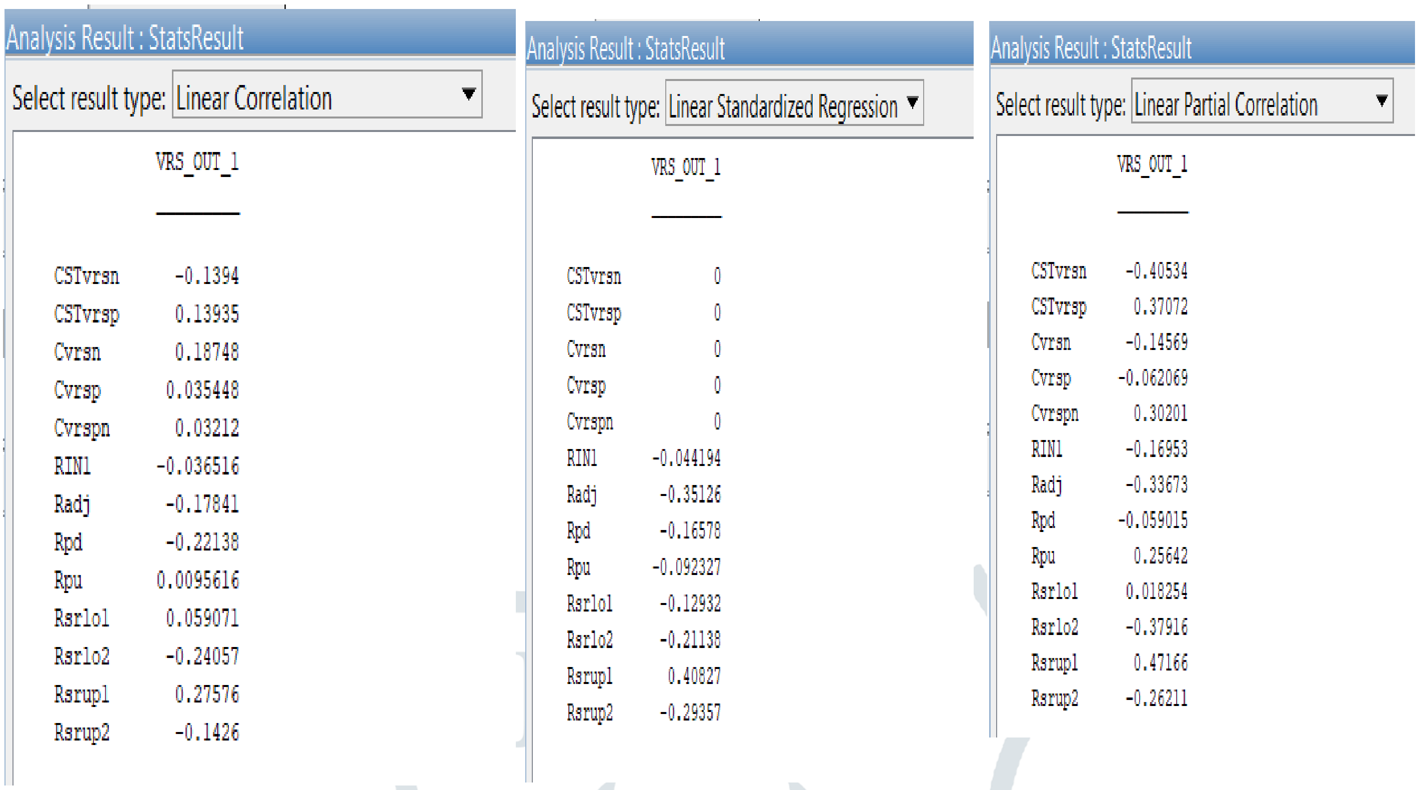


Fig 13 Components influence on Output Voltage



Analysis Result : StatsResult

Select result type: Linear Correlation

	VRS_OUT_1
CSTvrsn	-0.1394
CSTvrsp	0.13935
Cvrsn	0.18748
Cvrsp	0.035448
Cvrspn	0.03212
RIN1	-0.036516
Radj	-0.17841
Rpd	-0.22138
Rpu	0.0095616
Rsrlo1	0.059071
Rsrlo2	-0.24057
Rsrup1	0.27576
Rsrup2	-0.1426

Analysis Result : StatsResult

Select result type: Linear Standardized Regression

	VRS_OUT_1
CSTvrsn	0
CSTvrsp	0
Cvrsn	0
Cvrsp	0
Cvrspn	0
RIN1	-0.044194
Radj	-0.35126
Rpd	-0.16578
Rpu	-0.092327
Rsrlo1	-0.12932
Rsrlo2	-0.21138
Rsrup1	0.40827
Rsrup2	-0.29357

Analysis Result : StatsResult

Select result type: Linear Partial Correlation

	VRS_OUT_1
CSTvrsn	-0.40534
CSTvrsp	0.37072
Cvrsn	-0.14569
Cvrsp	-0.062069
Cvrspn	0.30201
RIN1	-0.16953
Radj	-0.33673
Rpd	-0.059015
Rpu	0.25642
Rsrlo1	0.018254
Rsrlo2	-0.37916
Rsrup1	0.47166
Rsrup2	-0.26211

Fig 14 Numerical data for components influence

6.3. Push Pull type Sensor Interfacing

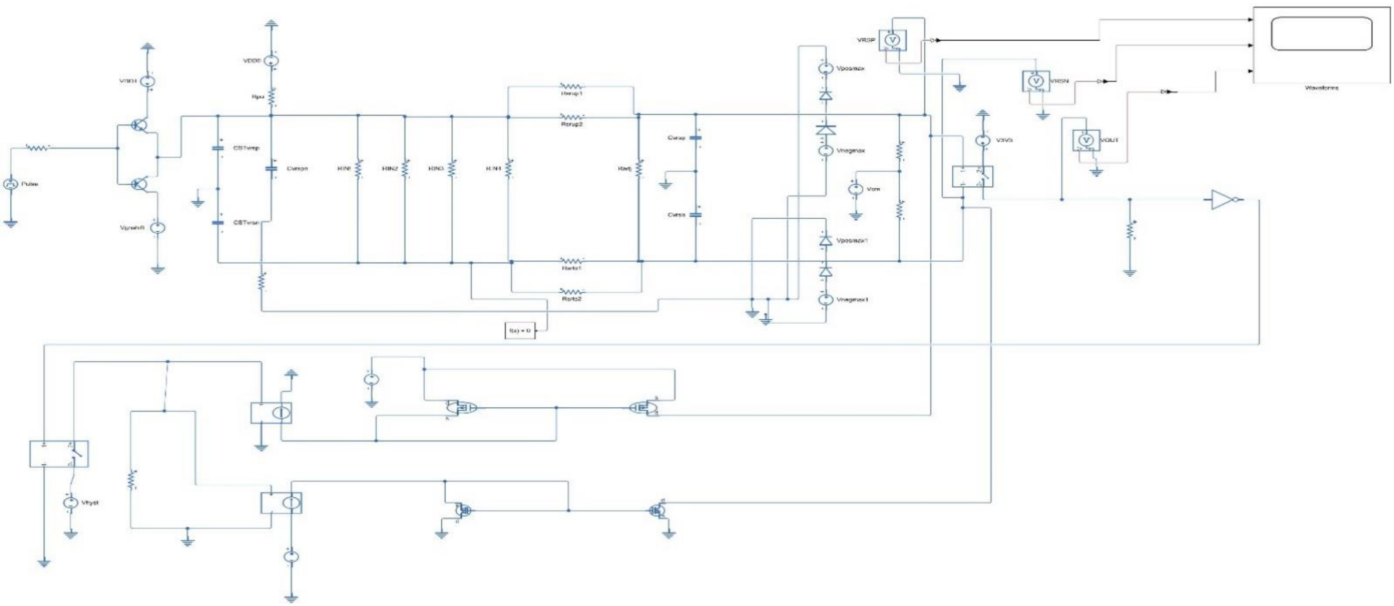


Fig 15 Push Pull type Sensor Interfacing

The push-pull sensors are the combination of P-N-P and the N-P-N transistors. It acts as a dual-stage sensor. The N-P-N transistor here acts as a push sensor during turn on time. P-N-P transistor acts as a pull senso during turn off time. The push pull type sensor is capable of sensing any analog parameter from engine control section, The sensed signal is processed to a sensor interface block. The sensed signal is converted to a undistorted signal by sensor interface block. During next stage, the signal is processed to a flexible input L9966 IC. The comparator located inside L9966 IC generates the digital rectangular pulses and are fed to a microcontroller. Microcontroller generates an actuating signal and there by drives an actuator and there by completing the mechanism.

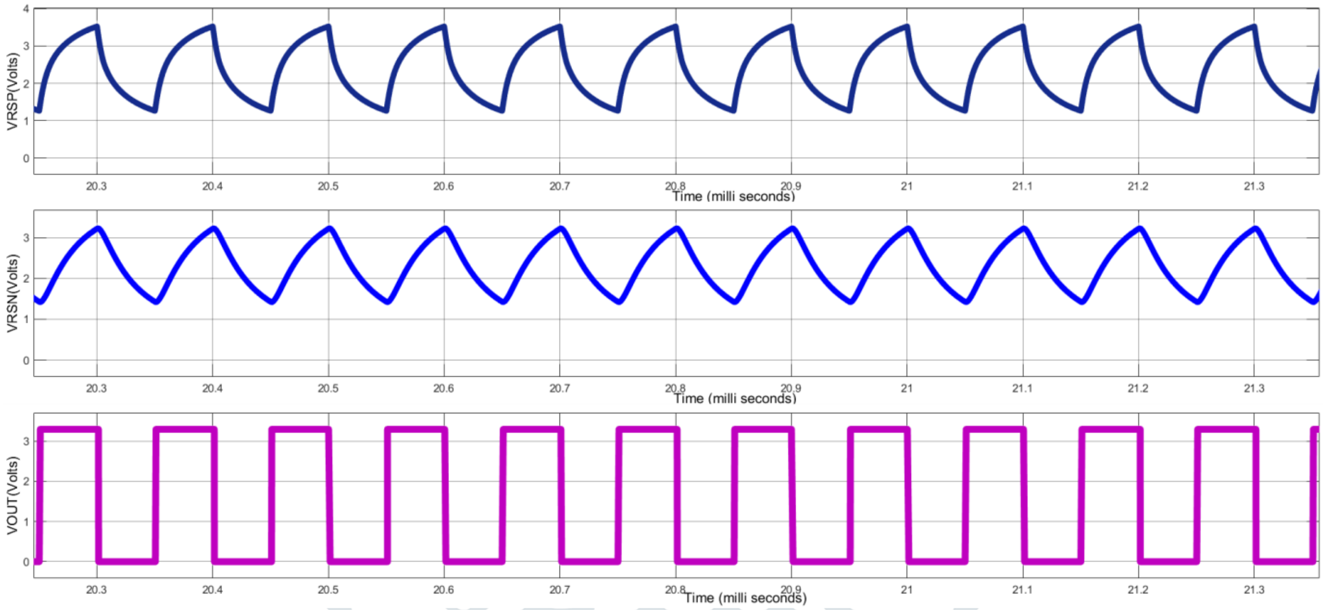


Fig 16 Simulated Result for Push Pull type Sensor Interfacing

The waveforms of VRSP, VRSN and VRS_OUT are shown in Fig 16. In VRSP and VRSN waveforms, the current source is charged to 6uA pull up and discharges to 6uA pull down and both the waveforms are pulsating in nature. The signals VRSP and VRSN are compared with the reference signal, there by rectangular digital pulses are generated at VRS_OUT pin. The average output voltage obtained is 3.3 V.

- **Monte Carlo Result**

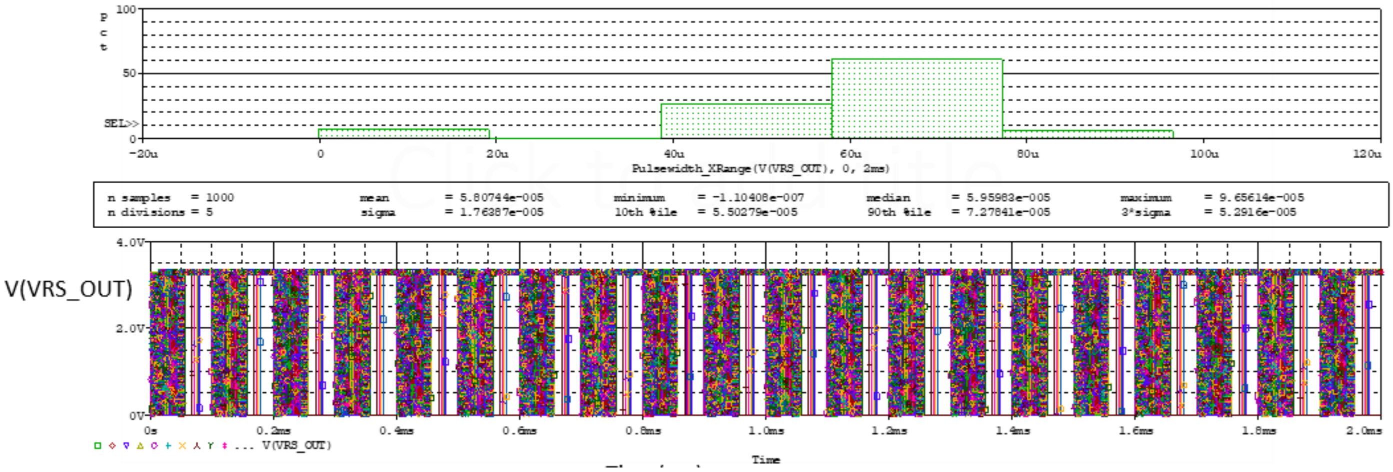


Fig 17 Histogram View of Monte Carlo Run

The Push pull type sensor measures the analog parameter such as temperature. The measured pulse width from Monte Carlo histogram is an implication of healthiness of the sensor. The histogram indicates the boundary values. The measured temperature lies between initial and final value. From histogram distribution, it can be understood that the average pulse width is 58.07 usec which implies that average feasible temperature at which the engine would operate would be equivalent to 58.07 usec. The pulse width is also a measure of life cycle of engine. The measured 3 sigma value indicates that 99.7% of the values will lie within three standard deviations from the average pulse width value which means that for all 1000 runs, the resulted output is 99.7% accurate.

- **Sensitivity Analysis Result**

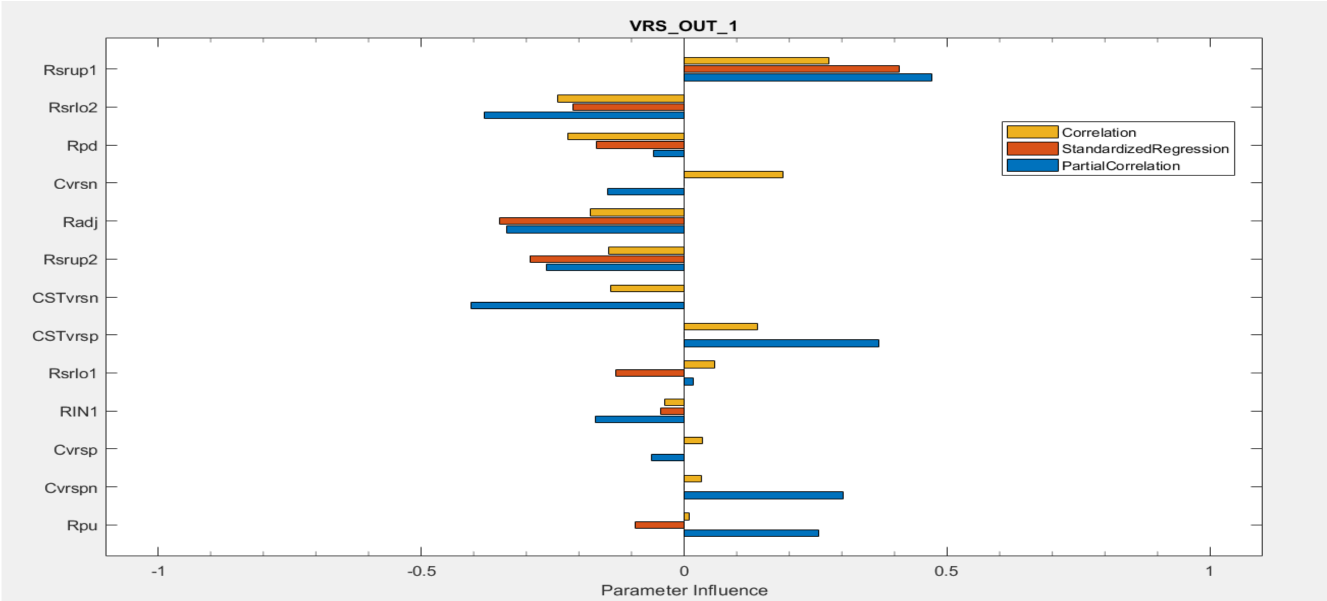
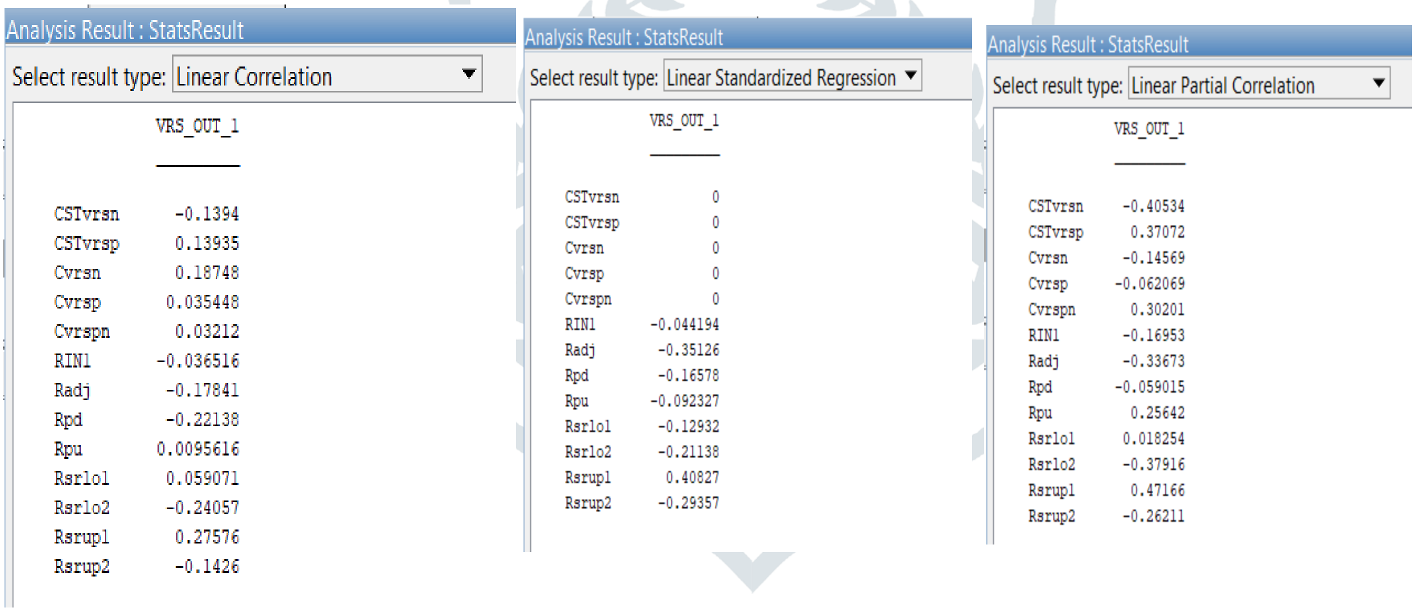


Fig 18 Components influence on Output Voltage



Analysis Result : StatsResult — Select result type: Linear Correlation

	VRS_OUT_1
CSTvrsn	-0.1394
CSTvrsp	0.13935
Cvrsn	0.18748
Cvrsp	0.035448
Cvrspn	0.03212
RIN1	-0.036516
Radj	-0.17841
Rpd	-0.22138
Rpu	0.0095616
Rsrlo1	0.059071
Rsrlo2	-0.24057
Rsrup1	0.27576
Rsrup2	-0.1426

Analysis Result : StatsResult — Select result type: Linear Standardized Regression

	VRS_OUT_1
CSTvrsn	0
CSTvrsp	0
Cvrsn	0
Cvrsp	0
Cvrspn	0
RIN1	-0.044194
Radj	-0.35126
Rpd	-0.16578
Rpu	-0.092327
Rsrlo1	-0.12932
Rsrlo2	-0.21138
Rsrup1	0.40827
Rsrup2	-0.29357

Analysis Result : StatsResult — Select result type: Linear Partial Correlation

	VRS_OUT_1
CSTvrsn	-0.40534
CSTvrsp	0.37072
Cvrsn	-0.14569
Cvrsp	-0.062069
Cvrspn	0.30201
RIN1	-0.16953
Radj	-0.33673
Rpd	-0.059015
Rpu	0.25642
Rsrlo1	0.018254
Rsrlo2	-0.37916
Rsrup1	0.47166
Rsrup2	-0.26211

Fig 19 Numerical data for components influence

VII. CONCLUSION

The flexible sensor interface was designed for engine control unit section in automotives. The flexible sensor interfacing circuit was simulated using Matlab/Simulink. The circuit was tested for functionality. The designed circuit comprised of sensor block, sensor interface block and flex input L9966 IC. The sensor block comprised of Hall Effect Sensor, Inductive Sensor and Push pull type Sensor. Each sensor was interfaced to sensor interface block and L9966 IC. The L9966 was able to condition all the three sensors to its input terminals resulting in digital rectangular pulses. The average voltage obtained was 3.3 V in all the three cases. Without modifying sensor interface, flex input L9966 IC was able to convert any signal into rectangular pulses, resulting in increased flexibility. The increased flexibility resulted in variant reduction and overall cost of the system. The developed circuit was validated using Monte Carlo Analysis and Sensitivity Analysis. The 3 sigma in Monte Carlo simulation implies that the circuit design was 99.7% accurate considering all boundary conditions. The view of Sensitivity analysis gives an idea how to optimize the circuit as per the design requirements.

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