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# Advanced Fault Tolerant Air-Fuel Ratio Control of Internal Combustion Gas Engine for Sensor and Actuator Faults

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**ABSTRACT** The reliability of a process machine can be significantly enhanced by introducing a fault-tolerant control system in it. Hardware redundancy is an important aspect to enhance fault tolerance capability and is studied in this paper. A novel modified triple modular redundancy (MTMR) approach is proposed for the sensors to avoid a shutdown in the case of simultaneous faults in more than one sensor, and dual redundancy is proposed for the actuators to avoid a single point of failure due to the single actuator fault. The performance of the control system is verified by simulation in MATLAB Simulink environment. The proposed MTMR fulfills the gap in conventional TMR by maintaining stability even in the case of simultaneous faults in two channels. Cost and benefit analysis (CBA) is carried out to determine the financial feasibility of the implementation of the proposed system. The results of the CBA demonstrate that the proposed system is financially feasible due to the positive net present value and small breakeven period.

**INDEX TERMS** Air-fuel ratio control, fault tolerant control, hardware redundancy, IC gas engine, triple modular redundancy.

## I. INTRODUCTION

A fault is defined as the deviation of a system parameter from its normal range. Faults in the system components such as sensors and actuators can cause failure of the complete system. A fault tolerant control system (FTCS) can continue to operate and maintain stability even in the events of faults in the sensors and actuators. There is great research being carried in the FTCS domain [1]–[3]. Faults in a system cause tripping of the machines and hence, production loss justifying the involvement of the FTCS in the production plants for increasing the reliability of machines for increased profits. An FTC is mainly classified into two types: active and passive. In the active FTCS (AFTCS), a dedicated unit named as fault detection and isolation (FDI) is used to identify and isolate the faulty components. After fault isolation, controller reconfiguration is performed to adapt to the new conditions. However, the AFTCS has a quite complex structure and is slow due to excessive computations. In the passive FTCS (PFTCS), no FDI is used rather faults are considered at the design stage. Time response of the PFTCS is fast as compared to the AFTCS but its operation is limited to the faults defined at the design stage [4]–[6].

Redundancy is one of the most important aspects of FTCS design in which two components perform the same action in parallel. In case of a fault in the primary component, other redundant or backup component comes into operation and maintain system continuity. Redundancy can be categorized into hardware and analytical. In the hardware redundancy, extra hardware is added to the system. In the analytical redundancy, no additional hardware is added rather software model is created to produce a virtual output of the actual measurement. This virtual output is used in the control system in case of a fault. The analytical redundancy can save cost and reduce the size and weight of the system but is strongly dependent on the accuracy of the software model [7], [8].

Single point of failure is an important aspect in reliable control systems which is a condition in which fault in a single component of a system can cause total system failure. Hardware redundancy eliminates a single point of failure and improves the availability of the system [9]. Dual redundancy and Triple Modular Redundancy (TMR) are the most widely used hardware redundancy techniques. In dual redundancy, normal operation is carried out with two similar components installed in parallel in which one is the primary component. In case of a fault in the primary component, secondary component comes into operation and faulty one is isolated which may then be replaced. In conventional TMR, three identical channels perform a similar function of producing output from the same input in parallel independently with one another. A voter then performs voting among the outputs to determine the single output from the system. If one channel gets faulty thereby giving erratic output, voter decides among the rest two healthy channels. This redundancy scheme is also called as 2 out of 3 logic (2oo3) as shown in Fig. 1 [7], [10], [11].

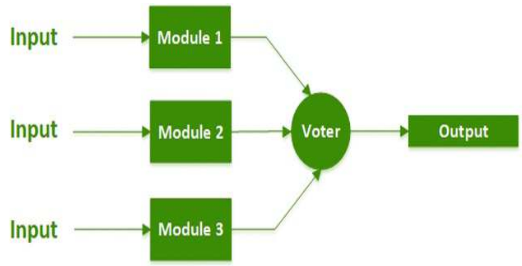


**FIGURE 1.** The architecture of the conventional TMR.

Let $R_1, R_2$ *and* $R_3$ denote reliabilities of the individual components and $R_{TMR}$ denotes the overall reliability of a TMR system. Mathematically, the reliability function of TMR can be determined as follows:

$$\begin{aligned} R_{TMR} &= R_1R_2R_3 + (1-R_1)R_2R_3 \\ &\quad + R_1(1-R_2)R_3 + R_1R_2(1-R_3) \qquad (1) \\ &= R_1R_2R_3 + R_2R_3 - R_1R_2R_3 + R_1R_3 - R_1R_2R_3 \\ &\quad + R_1R_2 - R_1R_2R_3 \\ &= R_1R_2 + R_2R_3 + R_1R_3 - 2R_1R_2R_3 \\ If\ R_1 &= R_2 = R_3 = R \\ R_{TMR} &= R^2 + R^2 + R^2 - 2R^3 \\ R_{TMR} &= 3R^2 - 2R^3 \\ If\ R &= 0.9, R_{TMR} = 0.972 \qquad (2) \end{aligned}$$

The conventional TMR has been widely used in the process and safety applications. In [12] TMR scheme has been proposed for four sensors in the chip architecture of the VLSI system. In [13] TMR is implemented for digital control systems. In [14] a TMR voter system is implemented at Nanoelectronic field level for CMOS circuits. In [15] TMR has been implemented for the operating systems. However, there is a major drawback in the conventional TMR that the system cannot produce output in case of a simultaneous fault in two channels [7]. In such a case, an alarm scheme is usually implemented to alert the operator to check for the faulty channel should a fault in a channel arise and get it repaired or replaced as soon as possible. Replacement or repair of the components can be performed online without interrupting the process.

The conventional TMR possesses a major flaw that in case of more than one channels failure, it ceases to generate an output causing system failure. Therefore, an advanced version of TMR is necessary which can continue operation even in case of failure of two channels. This research gap is fulfilled in this research work by proposing a new MTMR technique. The architecture of the proposed MTMR is similar to the conventional TMR, as shown in Fig. 1, but with some additional control features. Since the conventional TMR cannot provide output in case of a fault in two channels, the MTMR will be able to provide output in this condition with the only single healthy channel. Thus, proposed MTMR is an advanced version and more reliable than the conventional TMR. This has been implemented in this paper for the sensors in the AFR control system and its performance has been verified through simulation in MATLAB by introducing faults in the sensors one by one.

In this paper, our contribution is the application of advanced FTC hardware redundancy techniques for reliability enhancement of the engine AFR control system. We have proposed an advanced version of existing mostly used technique i.e., TMR by fulfilling its gap. The novelty of the work is proposing new hardware redundancy approach MTMR for sensors in combination with dual redundancy in the actuator. The proposed approach is highly reliable and not found in the literature so far up to our best knowledge for the IC engine AFR control and any other similar process application. Proposed hardware redundancy approach to the AFR control is quite significant for further research and automotive industry for manufacturing highly reliable gas engines. This control system can also be introduced in current installations in the industry as well as new upcoming models of gas engines to avail greater reliability benefits. Since it involves costs of adding extra hardware, CBA is performed to determine the financial feasibility of extra cost.

Following contents of the paper include background and literature review of the air-fuel ratio control of IC engines in section 2. Section 3 includes details of the cost and benefit analysis. The research methodology is discussed in section 4 and the results with discussions are presented in section 5. The conclusion is presented in the last section.

## II. AIR FUEL RATIO (AFR) CONTROL SYSTEM

An internal combustion gas engine is an extensively used equipment as the prime mover in the process industry for power generation and gas compression systems. It converts chemical energy of the fuel to mechanical rotational energy. This rotational energy is further applied to the alternator to produce electricity or a gas/air compressor for the compression process [16]. In a four-stroke IC engine, fuel is combined with air to produce an air-fuel mixture and is burnt in the cylinders to produce high-pressure gases causing mechanical movement of the camshaft and crankshaft [17].

Air-fuel ratio (AFR) or Lambda ($\lambda$) optimization is of great importance in the performance and energy efficiency of the gas engines. The AFR is defined as the ratio of the mass of air to that of fuel (solid, liquid, or gaseous) and is mathematically written as follows:

$$AFR = \frac{m_{air}}{m_{fuel}} \qquad (3)$$

Combustion takes place according to the following chemical equation:

$$25O_2 + 2C_8H_{18} \rightarrow 16CO_2 + 18H_2O + Energy$$

The mixture with the optimized air-fuel ratio is also called as a stoichiometric air-fuel mixture. The stoichiometric mixture forms the ideal ratio of air to fuel that burns all fuel with no excess air. For gasoline fuel, the stoichiometric air-fuel mixture is about 14.6:1. If the ratio is greater than 14.6, there is excess air than the fuel and the mixture would be termed as a lean mixture. If the ratio is less than 14.6, there are more fuel contents and the mixture is termed as a rich mixture. Both lean and rich mixtures do not offer optimum combustion and cause leftover of unburnt carbon particles and carbon monoxide which cause environmental and health problems. Moreover, these also decrease the engine efficiency and cause more fuel cost. Therefore, in an AFR fuel control system, the primary objective is to achieve this ratio [18], [19].

Block diagram of an air-fuel system of a practical spark ignition (SI) IC gas engine is shown in Fig. 2. Fuel is first filtered to remove foreign particles and then regulated by a pressure regulator at specific pressure as per the design requirement of the engine. It is then passed through a throttle valve for the AFR adjustments. Atmospheric air is filtered and passed through the air throttle valve for airflow adjustments. Both air and fuel are then mixed and sent to engine cylinders for combustion [20].

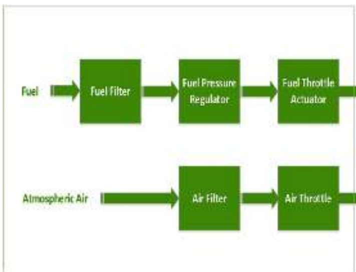


**FIGURE 2. Air-Fuel system of SI IC gas engine.**

Faults in the sensors and actuators of the AFR control system cause engine shutdown, thereby, causing production loss. Therefore, a highly reliable AFR control system is very important for IC engines. Various techniques have been used for the design of the AFR control system. The AFR control by sliding mode control technique is reported in [21] in which MIMO controller is designed for various flow disturbances in the engine. A nonlinear approach for AFR control Takagi–Sugeno's model is reported in [22] that takes into account the variable time delay. In [23] a Smooth Super-Twisting Algorithm (SSTA) is reported for the AFR control using the Mean Value Engine Model (MVEM) that has reduced chattering effect. In [24] Fuzzy Sliding-mode Strategy is reported which is model-free without requiring any system characteristics and has superior regulation performance. In [25] a PI-like fuzzy knowledge-based controller is reported that has self-tuning capability and is highly robust.

In [26] Fault-Tolerant fuel control system available in Matlab for IC gas engine model is reported with a complete description of fault detection and isolation, AFR control and analytical redundancy. In this model, the analytical redundancy has been used for sensors using the look-up tables that provide estimated values of the sensors in case of a fault in the sensors. This model is used in this research study for reliability enhancement of the AFR control system.

In this model, the following four sensors play a major role in the air-fuel ratio control system of the gas engine [26].

- Throttle Position Sensor: provides feedback of the air throttle physical position to the engine controller.
- Engine Speed Sensor: provides feedback of the engine speed in RPM to the controller.
- Exhaust Gas Oxygen (EGO) Sensor: provides the oxygen content in the exhaust gas of the engine to adjust the fuel supply.
- Manifold Air Pressure (MAP) Sensor: provides suction pressure of the air flow at intake manifold of the engine. The sensor value is used to calculate air density and air mass flow rate.

In this model, an integral feedback ratio control is implemented to maintain the AFR to 14.6 with a reduced steady-state error in normal operation. Fault detection and isolation are performed by the engine control unit built with the state flow diagram in which look-up tables are used to provide estimated values of the faulty sensors for the analytical redundancy [26]. In case of a fault in any one sensor at a time, the estimated value of that sensor is provided by the look-up table to avoid engine shut down but AFR gets degraded to 11.7. The model suffers from some very important deficiencies. First of all, the existing model only presents FTC for sensors without considering actuator faults. We have proposed a highly reliable solution for both sensor and actuator faults. Secondly, fuel actuator is not incorporated in the fuel supply line but it is an important component in the practical gas engines in providing regulated fuel gas supply to the engine as per load demand and AFR control. We have incorporated this actuator in our model and fault tolerance is achieved for it. Thirdly, analytical redundancy of engine control is designed such that it can tolerate only one fault at a time in any one sensor. Simultaneous faults in any two sensors cause engine shutdown which is a highly undesirable feature in the existing model. We have proposed hardware redundancy to prevent engine shutdown in case of simultaneous faults in any two sensors at a time.

Our assumption in this model is the zero switching time for the redundant sensors and actuators. Practically, a time delay occurs during the changeover of the components. The limitations of the study are as follows: 1) Partial faults in the sensors and actuators are not considered in the model; sensors and actuators are fully functional or fully faulty. 2) An advanced robust AFR controller with fuel actuator is not implemented in this research study. Rather existing integral feedback control of the original MATLAB model is used for

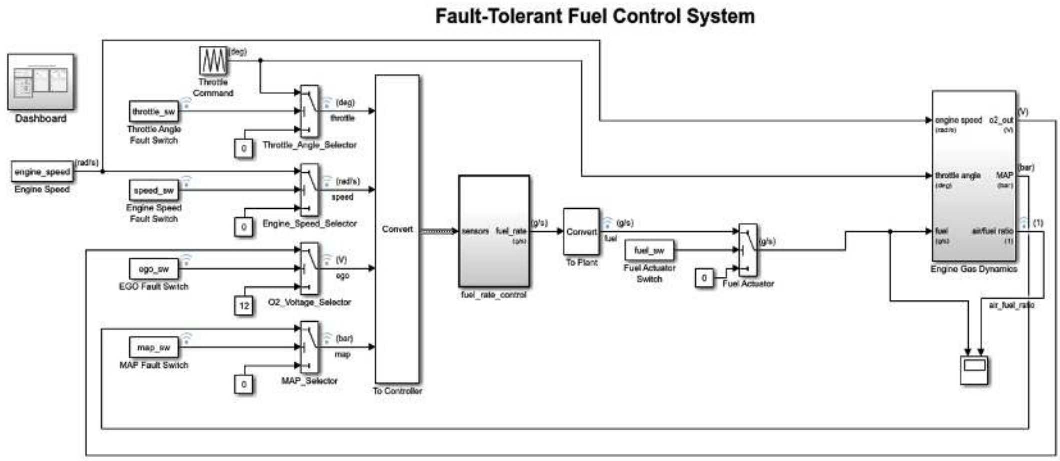


**FIGURE 3.** Incorporation of the fuel actuator in the fuel supply line.

AFR control. 3) Only simulation and cost perspective are considered in this study for adding extra hardware. Effects on the size increase of the engine are not considered in this study. 4) Fault detection and isolation (FDI) process based on the state flow logic diagram in the original MATLAB model is used in our new model with the main focus on the advanced hardware redundancy simulation and cost analysis.

## III. COST AND BENEFIT ANALYSIS (CBA)

Cost and benefit analysis (CBA) is a popular technique to determine the profitability of investment for decision making regarding investment in a project. CBA helps in establishing that the investment benefits would be much greater than initial and maintenance costs incurred on the system. In this method, the net present value (NPV) is calculated which is the difference between current investment and all the future discounted cash inflows or benefits. If the NPV is positive, the investment is recommended [27].

The Net Present Value (NPV) is calculated as follows:

$$NPV = \sum_{t=0}^{n} \frac{(Future\ Cash\ Benefits - Costs)_t}{(1+r)^t} - H \qquad (4)$$

where "H" is the initial investment, "r" is the discount rate such as the inflation rate, "t" is the number of years and "n" is the time horizon.

If the NPV turns out to be positive or greater than the desired profitability limit, the investment is considered as profitable and recommended. The breakeven period can also be calculated from this study, which is defined as the time in which cash inflow or profit would be equal to the cost incurred [28].

## IV. RESEARCH METHODOLOGY

The Fault tolerant fuel control model of the IC gas engine available in the Simulink is used in this study for implementation of advanced hardware redundancy schemes. The control system in the original model is designed to tolerate faults in the sensors without considering actuator faults. The detailed functionally of the control system both in normal and faulty sensor conditions is already explained in [26]. The limitation of this model is that engine can tolerate faults in only one sensor at a time and gets shut down in case of simultaneous failure of more than one sensor. Fuel actuator is also missing in the model and is introduced in our new model as per practical air-fuel model of the engine to provide regulated fuel supply. A fault is introduced in this actuator and its effect on the AFR is observed. Single actuator failure will cause a shut down of the engine cutting the fuel supply, therefore, the redundancy is proposed for it to avoid a single point of failure. However, no time delay is assumed in the switching of the actuators. Only full sensor and actuator fault types are considered in this study. Partial sensor and actuator faults are not considered.

An advanced version of FTC technique, MTMR, is implemented for the sensors for enhanced reliability and to avoid shut down due to simultaneous faults in more than one sensor. As discussed in section 1, the MTMR can provide an output with a single channel in case of simultaneous faults in two channels. A financial tool cost and benefit analysis (CBA) is used to determine the feasibility for the addition of the hardware redundancy in the model.

## V. RESULTS AND DISCUSSIONS

### A. SIMULATION OF ACTUATOR FAULT

The fuel actuator is added in the fuel supply line of the engine as shown in Fig. 3. Full ON/OFF type actuator is considered for simplicity without considering partial actuator fault.

The dashboard of the control system in MATLAB is also updated accordingly to simulate faults in the fuel and throttle actuators as shown in Fig. 4.

Fuel flow, air flow and AFR in the normal running condition are shown in Fig. 5.

Now the fault is simulated in the fuel actuator. The effect of fuel actuator fault on the AFR is shown in Fig. 6. The results

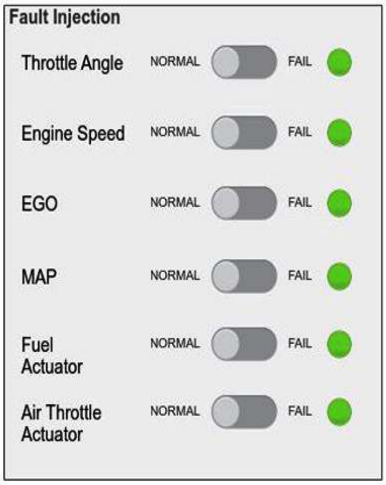


**FIGURE 4.** Incorporation of actuators in the dashboard.

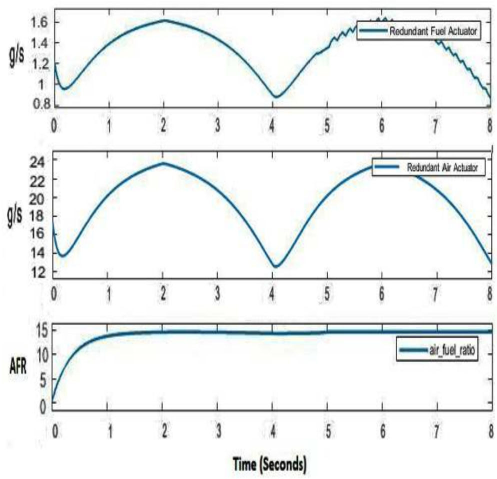


**FIGURE 5.** Fuel, air flow, and AFR in normal conditions.

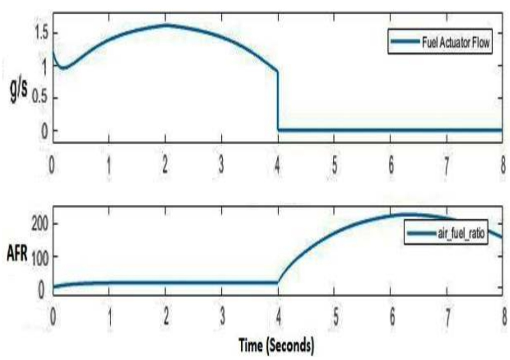


**FIGURE 6.** Effect of the fuel actuator failure on AFR.

show that the AFR ratio increases drastically due to cutting off of the fuel flow by the fuel actuator's fully closed position.

The effect of air throttle actuator failure is shown in Fig. 7. The AFR reduces to zero due to the air cut off by fully closing of the actuator.

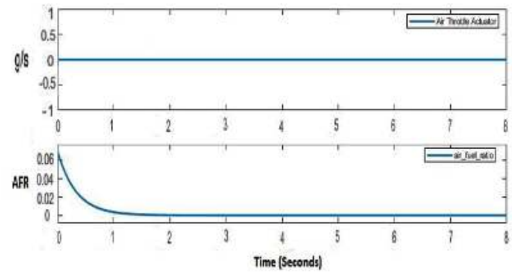


**FIGURE 7.** Effect of the air actuator failure on AFR.

Single actuator failure will be a single point of failure for the system. Therefore, the redundant actuator assembly is proposed to avoid a single point of failure as shown in Fig. 8. Both actuators are installed in parallel with one as primary in service and other as standby. In case of a fault in the primary actuator, secondary comes into operation to avoid process interruption and the faulty one is isolated.

The superior performance of the redundant actuator assemblies on the AFR by simulating faults is shown in Fig. 9. The results show that the AFR remains unaffected by the single actuator failure and the system remains stable.

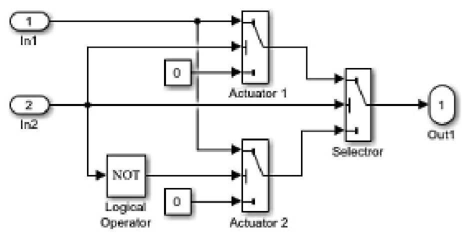


**FIGURE 8.** Redundant actuator assembly.

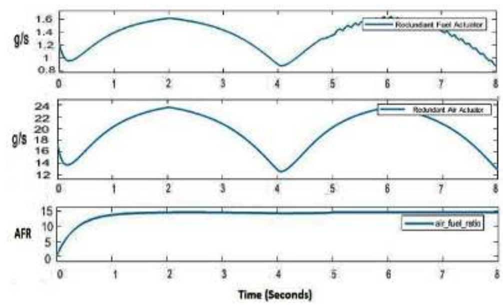


**FIGURE 9.** Effects of the redundant actuator assemblies.

In this simulation, ideal switching of the actuators is assumed with no time delay, however, in practice, there is a certain time delay in the switching operation.

### B. SIMULATION OF SENSOR FAULTS

Fault in each of the four sensors is simulated one by one considering one fault at a time and the corresponding effect

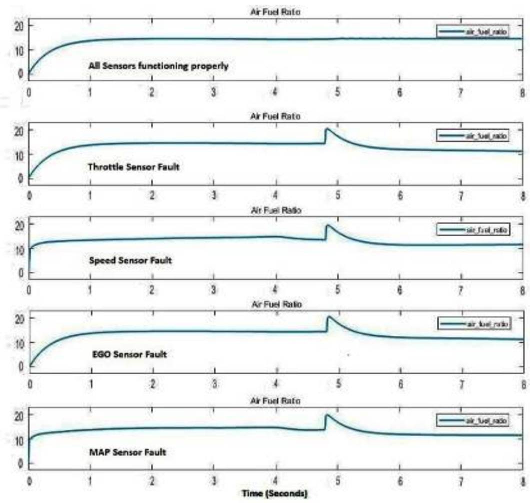


**FIGURE 10.** Effect of the sensor faults on the air-fuel ratio.

on AFR is shown in Fig. 10 for each sensor. The system maintains stability with one sensor fault due to already implemented analytical redundancy scheme, explained in [26] but AFR gets degraded to 11.7 from 14.6 in faulty conditions as per graceful degradation. The system is shut down in case of simultaneous faults in case of more than one sensor.

The MTMR scheme is implemented for the sensors in the model and is shown in Fig. 11.

The dashboard of the model is updated to simulate faults in the individual sensors in the MTMR assemblies as shown in Fig. 12.

The internal architecture of the MTMR block is shown in Fig. 13 which consists of the control block, port selector block, and the voter block.

The control block of the MTMR is shown in Fig. 14. This block performs the function of the conventional TMR to produce an output from all three healthy sensors and two healthy sensors in case of a fault in one sensor.

Four AND gates are installed, first one is for all working sensors and the other three are for two working sensors in case of one faulty sensor.

Logic chart of the control block is shown in table 1.

Port selector block of the MTMR is shown in Fig. 15. It generates the port number of the voter depending upon the available sensor information to produce a single output from the MTMR block.

The control chart of the port selector block is shown in Table 2. An additional feature of the MTMR is achieved by this block in which a single sensor also provides an output with other two failed sensors whereas in conventional TMR output is not generated in case of a fault in two sensors. In case

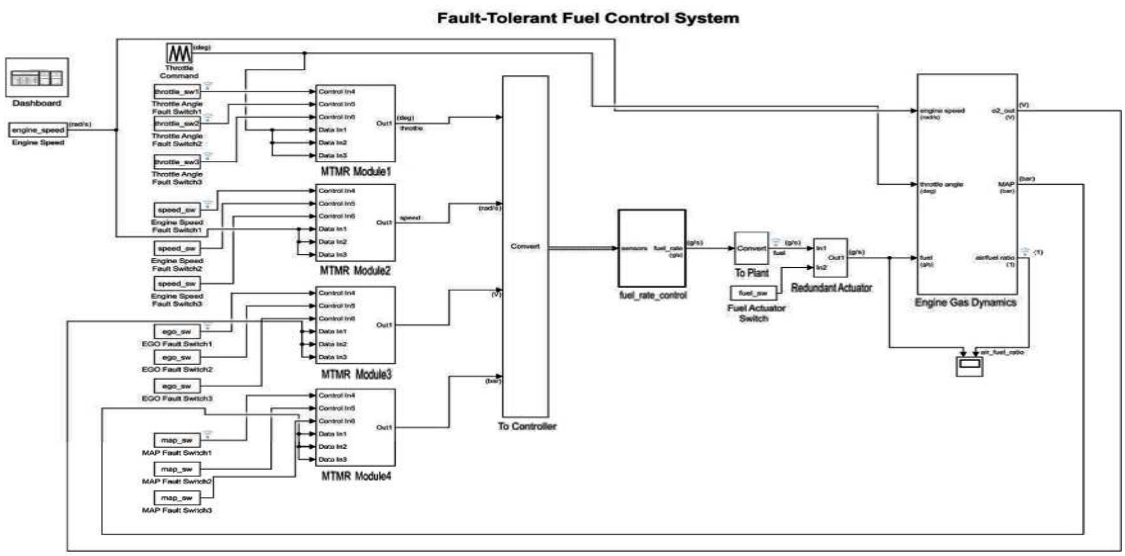


**FIGURE 11.** Implementation of the MTMR on sensors.

**TABLE 1.** MTMR control block logic chart.

| Sensor 1 | Sensor 2 | Sensor 3 | Action |
|---|---|---|---|
| 1 | 1 | 1 | Out 1 |
| 1 | 1 | 0 | Out 2 |
| 0 | 1 | 1 | Out 3 |
| 1 | 0 | 1 | Out 4 |

$1 \rightarrow Healthy\ Sensor$

$0 \rightarrow Faulty\ Sensor$

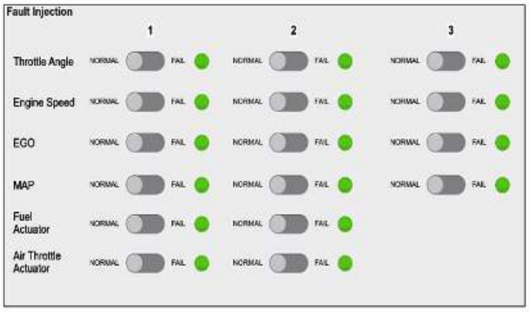


**FIGURE 12.** Dashboard for MTMR fault simulation.

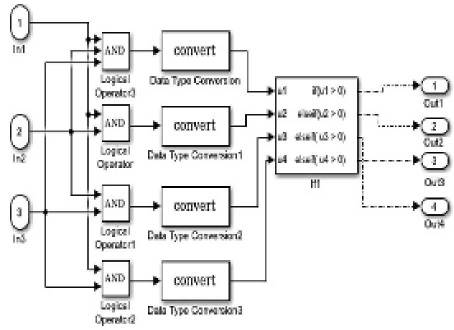


**FIGURE 14.** MTMR control block.

of all sensor failures in one MTMR block, the system still remains stable due to analytical redundancy already implemented in the model and continues operation with degraded performance i.e., reduced AFR ratio of 11.7.

Performance of the MTMR for fault in one sensor of a single MTMR assembly is shown in Fig. 16. It shows that the fault in one sensor does not affect the system performance.

Performance of the MTMR for simultaneous faults in two sensors of the same block is shown in Fig. 17 which indicates that fault in two sensors do not affect system performance as the system reverts to the last healthy sensor. This property is not available in conventional TMR.

Worst case of a fault in all three sensors of the same assembly is shown in Fig. 18 in which all three sensors become faulty at a time. In such a situation, the system will go on analytical redundancy method of generating estimated sensor value and keep the system stable but with degraded performance level i.e., AFR of about 11.7 as designed in the model.

The proposed highly redundant system can tolerate simultaneous faults in sensors and actuators except for the worst case of failure of any two complete MTMR sensors or redundant fuel or air throttle actuators which will lead to engine shutdown.

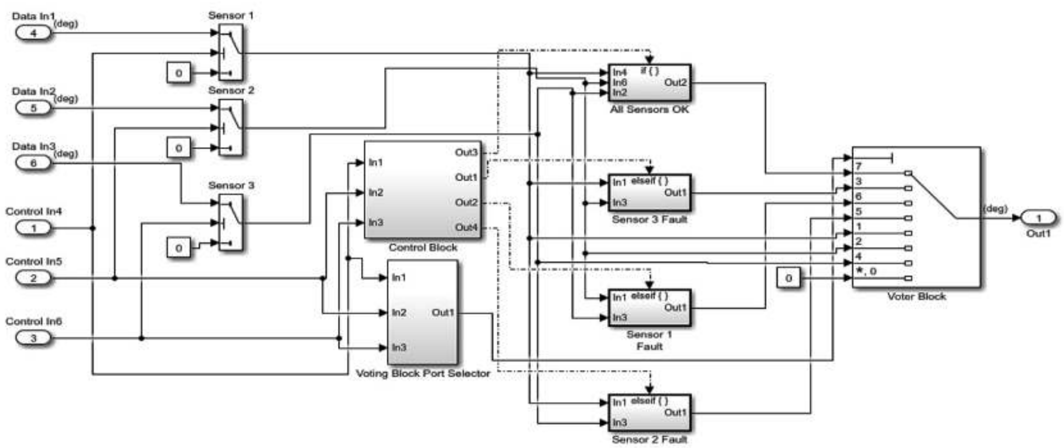


**FIGURE 13.** The architecture of the proposed MTMR.

**TABLE 2.** MTMR voter port selector logic chart.

| Sensor 1 | Sensor 2 | Sensor 3 | Calculation | Voter Port | TMR Performance |
|---|---|---|---|---|---|
| 1 | 1 | 1 | 1+2+4 | 7 | System Stable and Available |
| 1 | 1 | 0 | 1+2 | 3 | System Stable and Available |
| 0 | 1 | 1 | 2+4 | 6 | System Stable and Available |
| 1 | 0 | 1 | 1+4 | 5 | System Stable and Available |
| 1 | 0 | 0 | 1 | 1 | System Stable and Available |
| 0 | 1 | 0 | 2 | 2 | System Stable and Available |
| 0 | 0 | 1 | 4 | 4 | System Stable and Available |
| 0 | 0 | 0 | 0 | 0 | System Available on Estimation |

$1 \rightarrow Healthy\ Sensor$

$0 \rightarrow Faulty\ Sensor$

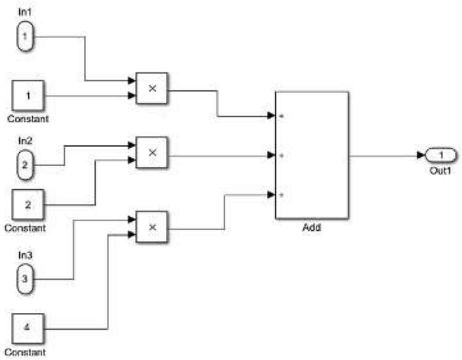


**FIGURE 15.** MTMR voting block port selector.

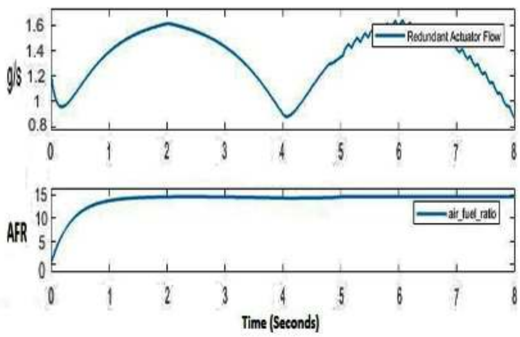


**FIGURE 16.** MTMR performance for one faulty sensor.

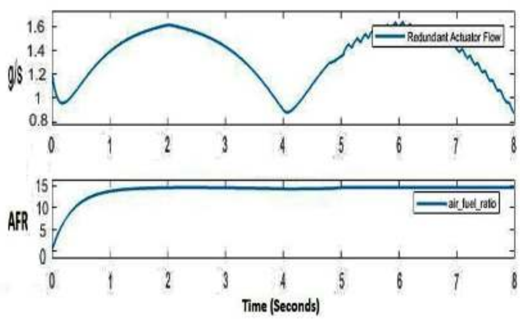


**FIGURE 17.** MTMR performance for two simultaneous faulty sensors.

### C. COST AND BENEFIT ANALYSIS

Cost and benefit analysis (CBA) of adding extra actuator and sensors for the redundant and MTMR schemes is carried out. The market-based prices are taken in the analysis [29]–[31]. Total cost includes one-time installation cost and annual operational costs incurred on the system. Installation costs include costs of additional actuators, sensors, controller and commissioning costs. Annual operational costs include maintenance / repair / replacement costs of faulty components in a year time interval with labor costs. Future benefit is taken from the cost saved due to the prevention of shut down or production loss as shown in table 3.

The results of the CBA are shown in table 4 which demonstrate that the NPV becomes positive after 2$^{nd}$ year, making this investment feasible to increase the reliability of the process plant with FTC.

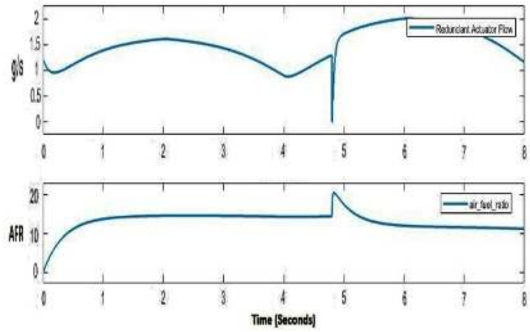


**FIGURE 18.** MTMR performance for all three faulty sensors in one assembly.

**TABLE 3.** Input data for cost and benefit analysis.

| Component | Unit Cost | Quantities | Total Cost |
|---|---|---|---|
| Installation Costs | | | |
| Actuators | $1,000 | 2 | $2,000 |
| Sensors | $500 | 12 | $6,000 |
| Controller | $20,000 | 1 | $20,000 |
| Commissioning | $10,000 | 1 | $10,000 |
| Total Investment Cost | | | $38,000 |
| Maintenance and Operation Costs | | | |
| Actuators | $1,000 | 1 | $1,000 |
| Sensors | $500 | 2 | $1,000 |
| Controller | $20,000 | 0.2 | $4,000 |
| Labor | $2,000 | 1 | $2,000 |
| Total Maintenance Cost | | | $8,000 |
| Shut down / Tripping Costs | | | |
| One Shut down / Tripping Cost | $5,000 | 5 | $25,000 |

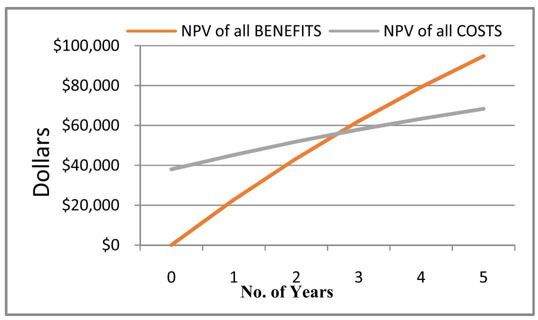


**FIGURE 19.** Graph of the breakeven point.

The breakeven period of the investment is shown in Fig. 19 which demonstrates that the cost becomes equal to benefit in almost 2.5 years. Hence the investment by adding extra hardware for making system more reliable and available is justified.

This study validates the incorporation of the proposed control system, both from the simulation study results and the financial analysis.

**TABLE 4.** Cost and benefit analysis for advanced FTC redundancy.

Project Cost and Benefit Analysis

| | |
|---|---|
| *Discount Rate Used* | *10.00%* |
| *Annual Benefits* | *$25,000.00* |
| *Annual Operational Costs* | *$8,000.00* |
| *One-Time Development Cost* | *$ 38,000.00* |

| | Year of Project | | | | | | |
|---|---|---|---|---|---|---|---|
| | 0 | 1 | 2 | 3 | 4 | 5 | TOTALS |
| Economic Benefit | $0.00 | $25,000.00 | $25,000.00 | $25,000.00 | $25,000.00 | $25,000.00 | |
| Discount Rate | 1.0000 | 0.9091 | 0.8264 | 0.7513 | 0.6830 | 0.6209 | |
| PV of Benefits | $0.00 | $22,727.27 | $20,661.16 | $18,782.87 | $17,075.34 | $15,523.03 | |
| NPV of all BENEFITS | $0.00 | $22,727.27 | $43,388.43 | $62,171.30 | $79,246.64 | $94,769.67 | $94,769.67 |
| One-Time COSTS | $(38,000.00) | | | | | | |
| Recurring Costs | $0.00 | $ (8,000.00) | $ (8,000.00) | $ (8,000.00) | $ (8,000.00) | $ (8,000.00) | |
| Discount Rate | 1.0000 | 0.9091 | 0.8264 | 0.7513 | 0.6830 | 0.6209 | |
| PV of Recurring Costs | $0.00 | $ (7,272.73) | $ (6,611.57) | $ (6,010.52) | $ (5,464.11) | $ (4,967.37) | |
| NPV of all COSTS | $(38,000.00) | $ (45,272.73) | $ (51,884.30) | $ (57,894.82) | $ (63,358.92) | $ (68,326.29) | $ (68,326.29) |
| Overall NPV | | | | | | | $ 26,443.38 |

Break-even Analysis

| | | | | | | |
|---|---|---|---|---|---|---|
| Yearly NPV Cash FLOW | $(38,000.00) | $ 15,454.55 | $ 14,049.59 | $ 12,772.35 | $ 11,611.23 | $ 10,555.66 |
| Overall NPV Cash FLOW | $(38,000.00) | $ (22,545.45) | $ (8,495.87) | $ 4,276.48 | $ 15,887.71 | $ 26,443.38 |

## VI. CONCLUSIONS

In this paper, advanced FTC hardware redundancy techniques were proposed and simulated for the gas engine AFR fuel control system. The redundant assemblies were proposed for the actuators to avoid a single point of failure and a novel MTMR approach was proposed for the sensors which can continue operation in case of even one healthy sensor. Finally, cost and benefit analysis (CBA) was performed to justify the extra cost of the hardware implementation for an increased amount of sensors, actuators, and MTMR implementation. The results of the CBA showed that the proposed modifications were financially feasible due to the positive net present value (NPV) and a breakeven period of 2.5 years.

Further work includes the implementation of the proposed technique in the hardware to assess its practical performance and determine its effect on the overall increase in the size of the engine for space optimization. These additions will make these engines highly reliable for production-critical applications. Moreover, partial faults in the actuator and maintaining AFR up to 14.6 in faulty conditions may also be considered in the future work. Another future work direction could be the implementation of the FDI unit using advanced analytical redundancy techniques such as Kalman Filters (KF), Linear Parameter Varying (LPV), Fuzzy Logic (FL), Artificial Neural Networks (ANN) etc. with the advanced hardware techniques.

## CONFLICT OF INTEREST

The author(s) declare no conflict of interest in preparing this paper.

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