ROBUST FUZZY CONTROL DESIGN USING GENETIC ALGORITHM OPTIMIZATION APPROACH: CASE STUDY OF SPARK IGNITION ENGINE TORQUE CONTROL

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Abstract. In the case of widely-uncertain non-linear system control design, it was very difficult to design a single controller to overcome control design specifications in all of its dynamical characteristics uncertainties. To resolve these problems, a new design method of robust fuzzy control proposed. The solution offered was by creating multiple soft-switching with Takagi-Sugeno fuzzy model for optimal solution control at all operating points that generate uncertainties. Optimal solution control at each operating point was calculated using genetic algorithm. A case study of engine torque control of spark ignition engine model was used to prove this new method of robust fuzzy control design. From the simulation results, it can be concluded that the controller operates very well for a wide uncertainty.

1. Introduction

In designing of fuzzy logic based control system, changing the dynamics of plant (plant uncertainties) becomes a troublesome issue until later developed the concept of fuzzy control design modifications, which are generally grouped into three major methods: (i) adaptive fuzzy [4] [8], (ii) adaptive neural network based fuzzy inference system (ANFIS) and neuro-fuzzy [11], and (iii) robust fuzzy [9] [14] [3]. Each group has its own advantages and disadvantages.

Adaptive fuzzy control, adopted the concept of adaptive control to change the parameters of fuzzy follow the changes of the plant, thereby resulting control process that is able to follow the changes of plant characteristics. It is quite successful for simple fuzzy inference systems. For a complex and large multi-input multi-output fuzzy inference system, neural network planning tasks similar to it being very difficult and so complicated. An alternative approach is to use robust control applications for fuzzy systems, which are known as robust fuzzy control system. This control system does not use adaptive applications that require fast computing systems and wasteful computer memory. Robust control approach is needed to ensure that the designed fuzzy control system could anticipate the presence of uncertainties in the plant dynamics within certain limits (under-bound). This approach is successful enough to avoid long time-consuming computer works in the

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process of control actions calculating. However, it gives controller designers additional work to calculate analytically robust control problems. This is not an easy task, because of the complexity of the fuzzy controller.

Similarly, in the case of a robust fuzzy state-feedback controller [3], plant state feed-back will be ineffective if there are more than three plant states. This is due to the number of inputs of a fuzzy controller equal to the state of the plant; so that the rule should be made to the fuzzy controller becomes very complex and many [14]. Repairs carried out by the study after that [14], by reducing the plant being only a second order plant, but is equipped with a reliable optimal control system; Linear Quadratic Integral Tracking (LQIT) optimal control system [1]. This modified robust fuzzy control is so powerful, but there is a weakness that the control action will discontinue over transient state of operating conditions.

Based on robust fuzzy control method previously [14], this research focused to repair control action discontinuing over transient state behavior by developing an iterative based optimization programming as genetic algorithm (GA) method [5] to produce more accurate gains appropriate to gains that calculate using LQIT optimal control design [1] [15]. This method combination yields a novel formulation for robust fuzzy control structure optimized by GA. A simulation case study of controlling engine torque of spark ignition engine model [12] applied to this design method; since spark ignition engine is a non-linear system that has very wide uncertainties. Spark ignition engine modeled by identification process for modified Mitsubishi Eterna engine (4 stages, automatic/manual transmission, 4 engine cylinders).

The rest of this paper is organized as follows. Section 2 is the method; including robust fuzzy control proposed method and spark ignition engine modeling method. In sections 3, robust fuzzy with genetic algorithm optimization method is investigated and well-proved by case study of engine torque control of spark ignition engine simulation in various operation schedules. The results are compared with others and are analyzed well. Section 4 concludes this paper.

2. Method

2.1. Robust Fuzzy Control Design Method. Assumed a non-linear plant with uncertainty can be expressed by linear state space model at each different operating point, and then we will get a group of state equations that express the dynamic character of each individual plant operations. By using the Takagi-Sugeno fuzzy models [13], the general model can be derived from the state equation as equation 1.

$$R^i : IF\ x_1\ is\ F_1^i\ AND\ x_2\ is\ F_2^i ......AND\ x_n\ is\ F_n^i$$
$$THEN\left\{{}^{\dot{x}=A_i x+B_i u}_{y=Cx}\right.\ i = 1, ..., L \quad (1)$$

where R_i is the rule appropriate to the i^th operating condition, L is the sum of operating conditions, and Fij are fuzzy sets of state variables.

Nominal model can be expressed analytically by equation 2.

$$\dot{x} = A_0 x + B_0 u \quad (2)$$

with

$$A_0 = \Sigma_{i=1}^{L} \mu_i A_i \ and \ B_0 = \Sigma_{i=1}^{L} \mu i B_i \tag{3}$$

where u_i is the membership factor for i^th rule by using sum-prod inference method.

The first idea was to create a state-feedback control of each rule by using the classical method of pole-placement topology. Local controllers will be distributed on each rule into a single global controller fuzzy state-feedback that includes all the operating point of the plant. State-feedback control system is given by equation 4 [3] [10] [2].

$$\begin{gathered} R^i : IF \ x_1 \ is \ F_1^i \ AND \ x_2 \ is \ F_2^i ......AND \ x_n \ is \ F_n^i \\ THEN \{ {}^{\dot{x}=A_i x + B_i u}_{u=-K_i x} \ i = 1, ..., L \end{gathered} \tag{4}$$

where K_i is gain vector of state-space model for i^{th} rule which determined by using closed loop pole placement method. Gain vector of nominal model is given by equation 5.

$$K = \Sigma_{i=1}^{L} \mu_i K_i \tag{5}$$

Some developments have been done to improve the control quality by using Linear Quadratic Integral Tracking (LQIT) problem optimal control [1] to calculate the control action (u) and adding some operating conditional inputs as soft-switch selector input [14]. Equation 6 describes this idea clearly.

$$\begin{gathered} R^i : IF \ c_1 \ is \ O_1^i \ AND \ c_2 \ is \ O_2^i ......AND \ c_q \ is \ O_q^i \\ AND \ x_1 \ is \ F_1^i \ AND \ x_2 \ is \ F_2^i ......AND \ x_n \ is \ F_n^i \\ AND \ w_1 \ is \ G_1^i \ AND \ w_2 \ is \ G_2^i ......AND \ w_m \ is \ G_m^i \\ AND \ r_1 \ is \ H_1^i \ AND \ r_2 \ is \ H_2^i ......AND \ r_k \ is \ G_k^i \\ THEN \{ {}^{\dot{x}=A_i x + B_i u}_{u=-K_x x - K_w w + K_r r + K_c c} \ i = 1, ..., L \end{gathered} \tag{6}$$

where R_i is the rule appropriate to the i^th operating condition, L is sum of operating conditions, F_j^i are fuzzy sets of state variables (x), G_j^i are fuzzy sets of integral error between output and reference (w), H_j^i are fuzzy sets of reference signal as tracking trajectory (r), O_j^i are fuzzy sets of conditional signal, n is the sum of state variables, m is the sum of integral error variables, k is the sum of reference signals as tracking trajectory, q is the sum of conditional signals, K_x is the gain of state variables, K_w is the gain of integral error variables, K_r is the gain of reference signals, Kc is the gain of conditional signal (as triggering signal only, proposed $K_c = 0$).

Those above robust fuzzy control design method proposed previously has a weakness in the form of discontinuities during a transition between two operating conditions. This research aimed to fix this problem by replacing the optimal control solution by LQIT with genetic algorithm (GA) optimal solution [5]. Its mean that the gain of state variables (K_x), the gain of integral error variables (K_w), and the gain of reference signals (K_r) in equation 6 will be calculated using GA optimal solution. Figure 1 describes GA solution flowchart to optimize those gains.

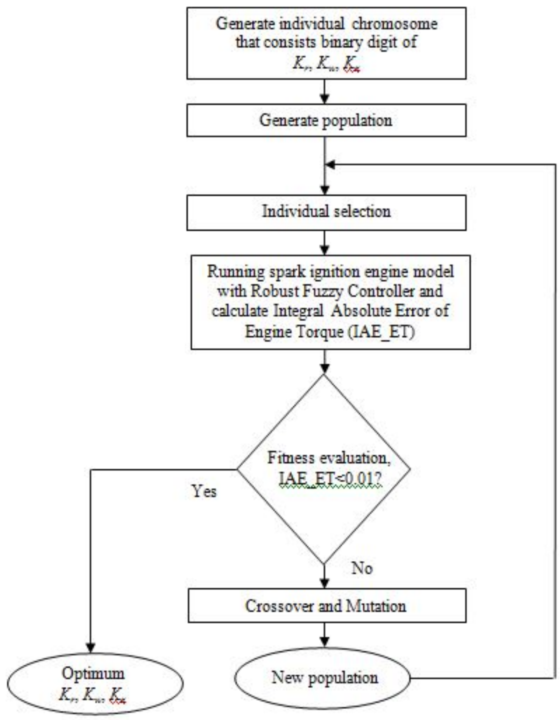

Figure 1. Genetic Algorithm Solution Flowchart to Optimize Gain of State Variables (K_x), Gain of Integral Error Variables (K_w), and Gain of Reference Signals (K_r) of Proposed Robust Fuzzy Controller

To perform good and quick GA solution, we choose the number of population and iteration by trial and error (as best result in 30 populations and 30 iterations), mutation probability about 0.25 by using differential evolution, and crossover probability about 0.9. To optimize this process, we used minimum Integral Absolute Error of Engine Torque (IAE-ET, as sum of absolute error between desired engine torque and actual engine torque) as fitness function.

The optimum result of gains (K_x, K_w, and K_r) generating using genetic algorithm are shown in Table 1. All of those gains are distributed to Takagi-Sugeno fuzzy membership function for each condition described in fuzzy rules base.

2.2. **Spark Ignition Engine Model and Engine Torque Management Strategy.**

In this research, to prove and validate our model identification, we use spark ignition engine model as described in [7]. The rate of air into the intake manifold can be expressed as the product of two functions; i.e. an empirical function of the throttle plate angle and a function of the atmospheric and manifold pressures, as shown in equation 7.

$$\dot{m}_{ai} = f_1(\theta) f_2(P_m) \tag{7}$$

where
$\dot{m}_{ai}$ = mass flow rate into manifold (g/s), with
$f_1(\theta) = 2.821 - 0.05231\theta + 0.10299\theta^2 - 0.00063\theta^3$
θ = throttle angle(deg)

$$f_2(P_m) = \begin{cases} 1, & P_m \le \frac{P_{amb}}{2} \\ \frac{2}{P_{amb}}\sqrt{P_m P_{amb} - P_m^2}, & \frac{P_{amb}}{2} \le P_m \le 4P_{amb} \\ \frac{-2}{P_m}\sqrt{P_m P_{amb} - P_m^2}, & P_{amb} \le P_m \le 2P_{amb} \\ -1, & 2P_m \ge 2P_{amb} \end{cases}$$

P_m = manifold pressure (bar)
P_{amb} = ambient (atmospheric) pressure (bar), 1 bar

No	Operating Condition	Gain		
		K_x	K_w	K_r
1	1^{st} Gear, Throttle about 10 degree	$[9.62\ 1.405]^T$	-1.24	-0.11
2	2^{nd} Gear, Throttle about 10 degree	$[6.10\ 0.77]^T$	-0.06	0.08
3	3^{rd} Gear, Throttle about 10 degree	$[-0.39\ 1.99]^T$	-1.11	0.11
4	4^{th} Gear, Throttle about 10 degree	$[3.84\ 1.13]^T$	-4.29	-0.78
5	1^{st} Gear, Throttle about 50 degree	$[2.97\ 0.29]^T$	-0.40	-0.85
6	2^{nd} Gear, Throttle about 50 degree	$[3.27\ 0.17]^T$	-0.64	0.39
7	3^{rd} Gear, Throttle about 50 degree	$[4.78\ 4.82]^T$	-1.50	-0.14
8	4^{th} Gear, Throttle about 50 degree	$[3.15\ 7.27]^T$	-1.71	0.19
9	1^{st} Gear, Throttle about 90 degree	$[4.33\ 3.76]^T$	-2.64	0.19
10	2^{nd} Gear, Throttle about 90 degree	$[-0.40\ 1.89]^T$	-0.30	0.24
11	3^{rd} Gear, Throttle about 90 degree	$[5.08\ 6.01]^T$	0.11	0.06
12	4^{th} Gear, Throttle about 90 degree	$[1.14\ 4.56]^T$	0.85	0.90

Table 1. Optimum Gain (K_x, K_w, and K_r) Using Genetic Algorithm

The intake manifold can be modeled as a differential equation for the manifold pressure, as shown in equation 8.

$$\begin{aligned} \dot{P_m} &= \frac{RT}{V_m}(\dot{m_{ai}} - \dot{m_{ao}}) \\ &= 0.41328(\dot{m_{ai}} - \dot{m_{ao}}) \end{aligned} \tag{8}$$

where
R = specific gas constant
T = temperature ($^\circ K$)
V_m = manifold volume (m^3)
$\dot{m_{ao}}$ = mass flow rate of air out of the manifold (g/s)
$\dot{P_m}$ = rate of change of manifold pressure (bar/s), with $P_0 = 0.543$ bar

The mass flow rate of air that the model pumps into the cylinders from the manifold is described in equation 9 by an empirically derived equation.

$$\dot{m_{ao}} = -0.366 + 0.08979NP_m - 0.0337NP_m^2 + 0.0001N^2P_m \tag{9}$$

where
$\dot{m_{ao}}$ = mass flow rate of air out of the manifold (g/s)
N = engine speed (rad/s) P_m = manifold pressure (bar)

The torque developed by the engine is described as in equation 10.

$$T_e = -181.3 + 379.36m_a + 21.91(A/F) - 0.85(A/F)^2 + 0.26\sigma$$
$$-0.0028\sigma^2 + 0.027N - 0.000107N^2 + 0.00048N\sigma$$
$$+2.55\sigma m_a - 0.05\sigma^2 m_a \quad (10)$$

where
m_a = mass of air in cylinder for combustion (g)
A/F = air to fuel ratio
σ = spark advance (degrees before top-dead-center/TDC)
T_e = torque produced by the engine (Nm)

Fuel consumption can be estimated with air-to-fuel ratio estimation (A/F) and mass of air in cylinder for combustion ($m_a \approx m_{ao}$) in equation 9; as shown in equation 11.

$$Fuel = \frac{m_a}{A/F} \quad (11)$$

where
$Fuel$ = fuel consumption (g)
m_a = mass of air in cylinder for combustion (g)
A/F = air to fuel ratio

The engine torque less the impeller torque results in engine acceleration; as in equation 12.

$$I_{ei}\dot{N} = T_e - T_L \quad (12)$$

where
I_{ei} = engine rotational + impeller moment of inertia ($kg - m^2$) = $0.14kg - m^2$
$\dot{N}$ = engine acceleration (rad/s^2), with initial engine speed N_0 = 209.48 rad/s
T_e = torque produced by the engine (Nm)
T_L = load torque (Nm)

Load torque (T_L) generally produced by vehicle dynamics. The vehicle model with 4-step automatic gear transmission that used in this engine model application is derived based on state-flow model as in [7].

This research used Mitsubishi Eterna engine (4 stages, automatic/manual transmission, 4 engine cylinders) to yield spark ignition engine model, as shown in Figure 2. Throttle position (in degree) and gear position (from 1^{st} to 4^{th} gear position) were taken as engine model input (u). Engine speed (in rpm) and engine torque (in Nm) were taken as engine model output (y). Some engine models are presented in state space equation, as shown in equation 13, as result of identification process using Matlab Identification Toolbox from some engine operating conditions (L operating condition) input-output data.

$$\dot{x} = A_i x + B_i u$$
$$y = C_i x \ , i = 1, ..., L \quad (13)$$

where x is state of the model, u is input of the model, y is output of the model, A_i is A matrices for ith model, B_i is B matrices for i^{th} model, C_i is C matrices for the ith model, and L is the number of engine operating point. All of the identification models were validated with real spark ignition engine data (from data acquisition process) and engine simulation model data [7].

Figure 2. Mitsubishi Eterna Engine 4 Stages to Yield Model Data

To describe uncertainty of the spark ignition engine model [12], the operating condition of the engine, i.e. throttle input and gear position, were varied and combined along determined interval. Figure 3 describe variation of eigen values for each model every operation condition variation (plotted in real-imaginary axis or s-plane). From this figure, it shown that there were many variation characteristic of the entire model (model uncertainties) since its eigen value spread widely. Due to this reason, it is needed to perform a controller that overcome control specification for all operating condition.

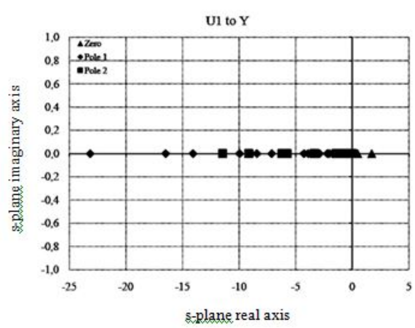

Figure 3. Eigen Values for the Models for Each Operating Condition That Show Model Uncertainties

Basically, the engine torque management strategy use throttle opening control function, air to fuel ratio (AFR), and ignition timing simultaneously to produce desired engine torque [7]. In this research, air to fuel ratio and ignition timing were determined constant, so that the controller will vary only electronic (secondary) throttle to modify throttle movement (from the driver command) to perform appropriate desired engine torque. In practical reality, desired engine torque does not exist, because the input given by the driver on the system is the position of the accelerator pedal (pedal position). For that reason, the engine torque control strategy known as the mapping between the position of throttle opening (pedal position) and engine speed with engine torque command [6]. Figure 4 shows the mapping for economical vehicle feel. Desired engine torque as output reference in engine torque control system is determined using this mapping.

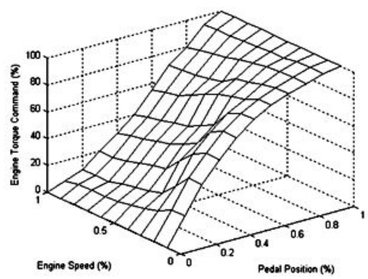

FIGURE 4. Mapping of Pedal Position and Engine Speed with Engine Torque Command for Economical Vehicle Feel [6]

Figure 5 describe structure of robust fuzzy control optimized by genetic algorithm for spark ignition engine model. This proposed robust fuzzy has five inputs, there are engine torque output (as feedback), desired engine torque (as reference), state variables (estimated using fuzzy T-S state estimator [16]), throttle position (from driver), and gear position (as operating condition). The output of controller are actual electronic throttle position and secondary throttle (to compensate primary electronic throttle position, with value range about 0 to 1). Economical engine torque mapping is used to generate desired engine torque based on throttle position and engine speed input, as described in Figure 4 [6]. As described before in equation 6, controller simulation was performed with Matlab Simulink as shown in Figure 6.

3. Results and Discussion

The application of robust fuzzy controller design optimized by genetic algorithm results will be compared with the results application of LQIT control method [15]. Qualitative comparison observed by calculating the Integral Absolute Error (IAE an absolute error calculation between desired torque and actual engine torque) of both methods: IAE_{RFProp} (IAE for proposed robust fuzzy) and IAE_{LQIT} (IAE for linear quadratic integral error tracking)

To examine this proposed robust fuzzy controller performance, simulations were done by varying all available engine operating conditions. Throttle input was varied among 0 to 90 degree (simulated by sinusoidal signal with determined amplitude, frequency, and bias) and gear position was varied among 1 to 4 (simulated by an integer as 1, 2, 3, or 4). Engine torque was observed for all simulation results.

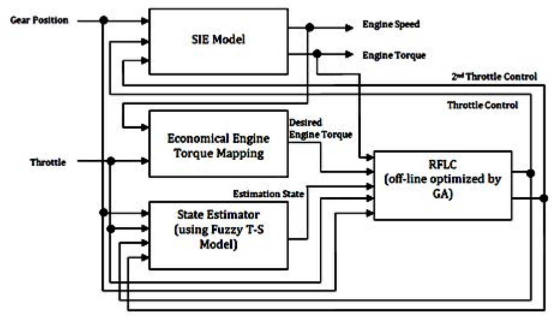

FIGURE 5. Block Diagram of Robust Fuzzy Control Optimized by GA Simulation for SIE Model

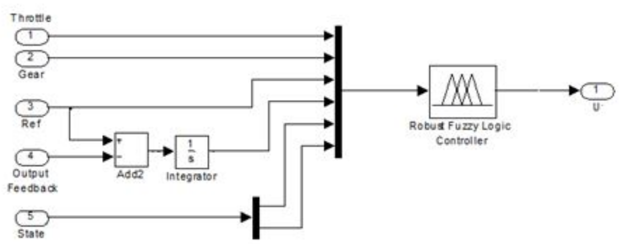

FIGURE 6. Proposed Robust Fuzzy Logic Controller for SIE Model

Figure 7 and Figure 8 are some simulation result samples. The result comparisons for more simulation of engine operating conditions are described in Table 2.

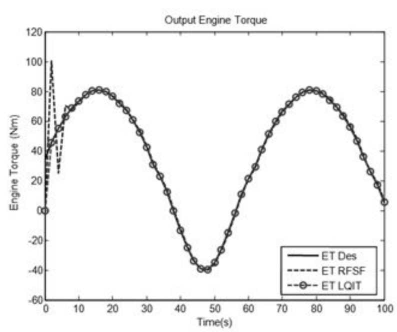

FIGURE 7. Engine Torque Produced from Application of Proposed Robust Fuzzy (ET RFProp) vs Linear Quadratic Integral Error Tracking (ET LQIT) - (gear position = 2, Throttle Input $d(t) = 10\sin(0.1t) + 10$)

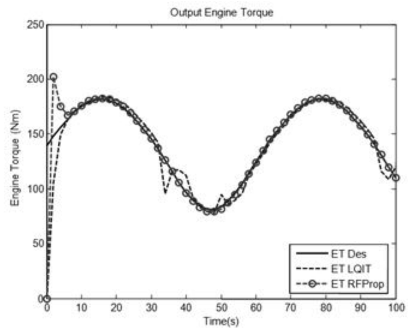

FIGURE 8. Engine Torque Produced from Application of Proposed Robust Fuzzy (RFProp) vs. Linear Quadratic Integral Error Tracking (ET LQIT) - (gear position = 2, Throttle Input $d(t) = 10\sin(0.1t) + 30$)

From all simulation results, it showed that proposed robust fuzzy controller can perform good control action for all operating condition since the engine torque output can follow the desired engine torque appropriate with its throttle input. It cannot be performed by single controller as LQIT based controller.

From Table 2, it shown that robust fuzzy controller (ET RFProp charts, with an average IAE = 155.2) which was designed in this research is much better than the LQIT based controller (ET LQIT charts, with an average IAE = 756.8). Even in some of the operating point, the LQIT based controller was unable to work (unstable). This can happen because the LQIT based controller designed by nominal model (single model), and when the model parameters were change, this controller cannot perform control system requirement well anymore.

Another simulation result that shown from Table 1 was: every gear position operating engine has critical characteristic (since throttle variation) that need more control reaction due to its unstable trend behavior. The proposed robust fuzzy controller can perform good reaction control to handling this situation because actually this situation has been considered before, actually when choosing all gain in equation 6 for each model. This consideration cannot be performed by LQIT based controller, so discontinuities will appear in this case.

Another simulation result shown in Figure 9 that compares this proposed robust fuzzy control method (as RF GA) with our previous robust fuzzy control method (as RF Prev) [17]. It shown that in transient response behavior that represent engine operation engine change behavior, our proposed controller performs more smooth reaction without any overshoot. This result represents that transient error can be reduced by choosing more optimal gains (K_x, K_w, and K_r) in this proposed robust fuzzy controller using genetic algorithm optimization.

Operating Condition		IAE_{RFProp}	IAE_{LQIT}
Gear Position	Throttle		
G1	$d1(t)$	0,1192	48,46
	$d2(t)$	169,9	Unstable
	$d3(t)$	483,5	1255
	$d4(t)$	133,6	Unstable
	$d5(t)$	1378	Unstable
G2	$d_1(t)$	0,4825	263,6
	$d_2(t)$	369	693,8
	$d_3(t)$	13,46	Unstable
	$d_4(t)$	17,78	Unstable
	$d_5(t)$	24,73	Unstable
G3	$d_1(t)$	0,3845	74,8
	$d_2(t)$	5,351	634,5
	$d_3(t)$	38,49	2345
	$d_4(t)$	11,75	Unstable
	$d_5(t)$	28,15	Unstable
G4	$d_1(t)$	175,3	891,8
	$d_2(t)$	80,63	648,6
	$d_3(t)$	29,36	Unstable
	$d_4(t)$	24,78	653,2
	$d_5(t)$	119,3	815,5
Mean of IAE :		155,2	756,8

Note :

(1) *Gi indicate gear position of spark ignition engine operation with i indicate i^{th} gear position.*
(2) $d_i(t)$ *indicate throttle degree schedule with* $d_i(t) = 10\sin(0.1t) + 10 * i, i = 1, 2, 3, 4, 5.$

(3) *Mean of IAE calculated from stable simulation only.*

TABLE 2. Comparison of Engine Torque Integral Absolut Error (IAE) with Application of Proposed Robust Fuzzy (IAE_{RFProp}) vs. Linear Quadratic Integral Error Tracking (IAE_{LQIT})

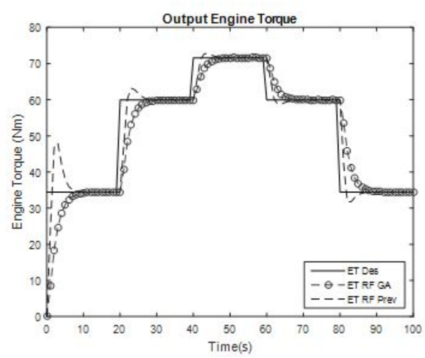

FIGURE 9. Engine Torque Produced from Application of Proposed Robust Fuzzy (RF GA) vs. Our Previous Robust Fuzzy Control [17] (RF Prev) Over Transient Behavior, with ET Des as Desired Engine Torque

4. **Conclusion**

To solve the problem control on wide non-linear uncertain plant as engine torque control in spark ignition engine plant, it is very difficult to get a single controller that can accommodate all its dynamic characteristics. Robust fuzzy control method as a design results of this research proved able to overcome these problems with a fairly simple design method. From simulation results, it is evident that the proposed robust fuzzy control system can work well with a satisfactory performance for all operating conditions that have been previously planned by changes in throttle input degree and gear position. This can be seen from the results of simulations, robust fuzzy control application has average IAE = 155.2 and works well for all operating conditions, since the LQIT based control application has average IAE = 756.8 and in some operating conditions becomes unstable. From simulation results it can be concluded that the proposed robust fuzzy controller guarantee continuity of stability over all operating point.

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