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LQR Based Optimal Control Techniques As Applied to Air Path of Diesel Engines

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Abstract**: *The selection of best optimal control technique for air path of diesel engines is a challenging task in the present scenario. Control inputs of air dynamics such as Exhaust Gas Recirculation (EGR), Variable Geometry Turbine (VGT) & Fuelling have different properties with respect to their different applications. Hence, in this paper different optimal LQR control techniques are proposed for all three control inputs of air dynamics in diesel engine. The proposed controllers have been implemented using MATLAB/SIMULINK@ platform and the results are compared with the individual, coordinated & switching control inputs.***

Index Terms**: *LQR, Optimal Control, Switched Linear Systems, EGR & VGT.***

I. INTRODUCTION

Air path is used in the diesel engines because it provides fresh air with necessary oxygen into the cylinders. To achieve this, a compressor, charge air cooler, intake and exhaust valves, Variable Geometry Turbine (VGT), Exhaust Gas Recirculation (EGR) valve, EGR cooler, Back Pressure Valve (BPV) and intake throttle can be used. Fig.1 shows the basic layout of an EGR engine (Chris Criens et al. 2014).

Exhaust Gas Recirculation (EGR) is a well known strategy to control NOx emissions in diesel engines. The EGR reduces NOx by reducing the oxygen concentration in the combustion chamber, as well as through temperature reduction.Variable Geometry Turbocharger (VGT) is designed such that the effective aspect ratio of the turbo to be varied as and when conditions change. In today's highly complex automotive system, selecting the better control input, controlling of overshoots, etc., for air path of diesel engines is very challenging.This has been a challenging research for the automotive control system community from last few decades. A brief literature survey of latest works in this area of research as below is motivation for the proposed work.

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(Peter Ortner and Luigi del et al. 2007), describes the model based advanced control for the air path of diesel engines. The optimization problem is considered with input constraints and solved using model predictive algorithms. In (Stephan Zentner & Erika et al. 2014), the authors designed the control strategy to handle cross couplings of the system and the results are compared with a conventional controller of equal tuning.

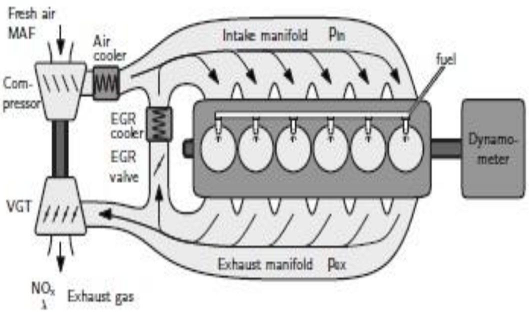

Fig 1: Layout of EGR Engine

For comparison, a single stage turbocharged diesel engine equipped with a HP EGR and VGT was used. (Mohamed Guermouche and Sofiane Ahmed Ali et al. 2014), developed a higher order sliding mode control technique for the internal combustion engine air path and the simulation results of air path engine model shows good results even under actuator faults conditions and in presence of parametric uncertainties. In (Peter Langthaler & Luigi del Re et al.2014) the authors provide comparison of different robust predictive control strategies as applied to a Diesel engine airpath and the results conclude that the Robust Model Predictive Control (RMPC) technique provides better strategy than the standard engine control strategies which are tuned by system engineers. (Xiukun Wei and Luigi del Re et al. 2006), the authors proposed a pole placement method for Linear Parameter Varying (LPV) for the dynamics of the air path system and the simulation results show that the controller can achieve a performance which is satisfactory.

(M. Sassano & T. E. Passenbrunner et al. 2012), considered the problem of regulating fresh mass-air-flow and the absolute pressure in the intake-manifold in the air

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path of a turbocharged Diesel engine to set point references and the performances of the proposed control law have been validated by the simulation results. In (Tianpu Dong & Fujun Zhang et al. 2015), the authors proposed a novel approach for the control of diesel engine EGR system. The results are compared with the PID controller and it reveals that the proposed control for EGR engine system meet the well control requirements in steady and transient conditions.

In summary, a single optimized control input (EGR,VGT & Fuelling) will not be suitable at all over entire dynamic range of applications of today's complex automotive systems, particularly, in dynamics of air path system.

In the present work, Optimal Linear Quadratic Regulator (LQR) feedback control techniques are applied for EGR (B_1), VGT (B_2) & Fuelling (B_3) control inputs in various capacities such as individually, coordinated & switching between individual control inputs. The proposed optimal control techniques are simulated using MATLAB/SIMULINK @ platform. Finally, the results are compared with respect to optimization (performance index $J = \int_0^{\infty} y^2 dt$) peak overshoots & settling time to draw the conclusion to apply best optimal LQR control techniques in future.

The organization of remainder of the paper is as follows. Section II describes Linear Time Invariant (LTI) model investigation, plant properties of air path of diesel engines. Optimal control theory and the switched linear control theory are discussed in Sections III and IV respectively. Simulation results and discussions are presented in Section V and Section VI. Section VII concludes the paper.

II. DYNAMIC MODEL: THE AIR PATH OF DIESEL ENGINES

The third order nonlinear mean value model parametrized for low and medium speed load points, covers the New European Drive Cycle (NEDC), was proposed by (Jung M et al. 2003) for robust control purposes. The System's basic structure is as shown in Fig. 2.

Parameter	Name
τ	time constant of turbocharger
η_m	mechanical efficiency of turbocharger
V_i	Intake Manifold Volume
V_x	volume of the Exhaust Manifold
η_c	compressor efficiency
T_a	ambient temperature
C_p	Specific heat at constant pressure
C_v	Specific heat at constant volume
μ	Specific heat ratio
p_a	ambient pressure
T_x	temperature of exhaust gas
R	gas constant
n_v	volumetric efficiency of engine
T_i	Intake Manifold gas temperature
V_d	total engine displacement volume
p_{ref}	reference pressure
T_{ref}	reference temperature
η_t	turbine efficiency
n	number of cylinders

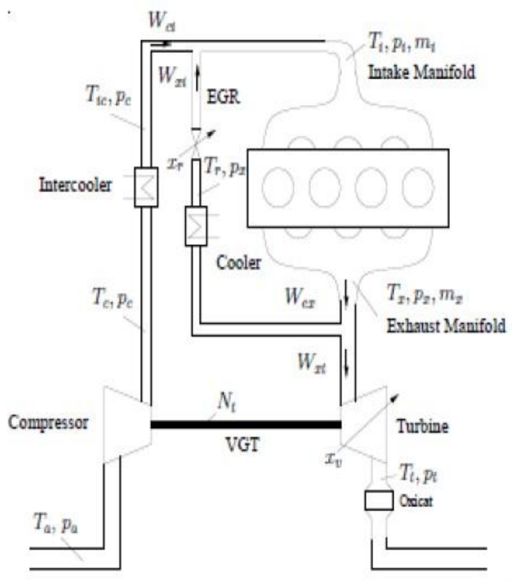

Fig 2: Structure of Turbocharged Diesel Engine

$$\dot{p}_i = \frac{RT_i}{V_i}\left(\frac{n_c}{C_p T_a}\frac{P_c}{(\frac{p_i}{p_a})^{\mu} - 1} + \frac{A_{egr}(x_{egr}p_x}{\sqrt{RT_x}}\sqrt{\frac{2p_i}{p_x}(1-\frac{p_i}{p_x})} - n_v\frac{p_i N V_d}{120 T_i R}\right)$$

$$\dot{p}_x = \frac{RT_x}{V_x}\left(\frac{n_v p_i N V_d}{120 T_i R} + \frac{A_{egr}(x_{egr})p_x}{\sqrt{RT_x}}\sqrt{2\frac{p_i}{p_x}(1-\frac{p_i}{p_x})}\right)$$

$$(-(ax_{vgt}+b)(c(\frac{p_x}{p_a}-1)+d)\frac{p_x}{p_{ref}}\sqrt{T_{ref}T_x}\sqrt{2\frac{p_a}{p_x}(1-\frac{p_a}{p_x})}+w_f)$$

$$\dot{p}_c = \frac{1}{\tau}(-p_c + \eta_m(ax_{vgt}+b)(c(\frac{p_x}{p_a}-1)+d))$$

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$$\left(\frac{p_x}{p_{ref}}\sqrt{\frac{T_{ref}}{T_x}}\sqrt{2\frac{p_a}{p_x}(1-\frac{p_a}{p_x})c_pT_x\eta_t(1-(\frac{p_a}{p_x})^{\mu})}\right)$$

Table 1: Parameters of Nonlinear model

After linearization, the Linear Time Invariant (LTI) model can be written in state space as:

$$\Delta\dot{x} = A.\Delta x + B.\Delta u$$
$$\Delta y = C.\Delta x + D.\Delta u$$

where, $\Delta x = x - x_0$, $\Delta u = u - u_0$, and $\Delta y = y - y_0$; A, B, C, D are the coefficient-matrices of the state space model. The Numerical values of A and B matrices used in the experiment are as follows:

$$A = \begin{bmatrix} -5.2643 & 4.7316 & 28.5021 \\ 50.7697 & -156.9827 & 0 \\ 0 & 0.4287 & -9.0909 \end{bmatrix}$$

$$B = \begin{bmatrix} 1.6111 \times 10^{9} & 0 & 0 \\ -1.5720 \times 10^{10} & 8.3514 \times 10^{4} & 1.46083 \times 10^{8} \\ 0 & -141.6484 & 0 \end{bmatrix}$$

III. OPTIMAL CONTROL THEORY

Optimal control theory is defined as control law searching for the given optimization problem which is in the quadratic form to obtain some optimization solution for that particular system. The advantage gained by using optimal control technique when compared to conventional pole placement technique is that the optimal control technique provides a coherent method of evaluating the closed loop control gain matrix. The optimized feedback controllers for this research are obtained from the LQR technique. A brief explanation of LQR is as follows (Yathisha L and S Patil Kulkarni et al. 2013; Yathisha L and S Patil Kulkarni et al. 2015; Yathisha L and S Patil Kulkarni et al. 2017):

A. Linear Quadratic Regulator: Individual & Coordinated Control Inputs

The minimization of performance index J can be achieved by optimal LQR state feedback control and also that guarantees the stability of the system.

Linear time invariant system

$$\dot{x}(t) = A.x(t) + B.u(t)$$
$$y(t) = C.x(t)$$

The negative feedback system is given by

$$\dot{x}(t) = (A - BK).x(t)$$

Where K is the feedback controller gain. The performance index J is given by,

$$J(x,u,Q,R) = \int_0^{\infty} (x^T.Qx + u^T.Ru).dt, \quad Q \geq 0, R \geq 0$$

The aim of the LQR problem is to design a control law u=-Kx by minimizing the objective function J with the solution given by,

$$K = -R^{-1}.B^T.P \quad (2)$$

Thus the control law is

$$u(t) = -K.x(t) = -R^{-1}.B^T.P \quad (3)$$

In which P must satisfy the reduced Riccati equation,

$$P.A + A^T.P - P.B.R^{-1}.B^T.P + Q = 0$$

By using the MATLAB command lqr, the algebraic Riccati equation is computed.

$$[K, P, E] = lqr(A, B, Q, R)$$

B. Linear Quadratic Regulator: Switching Control

Switched systems are the combination of two or more control inputs to combine the properties of all the control inputs and it is guided by a switching law.

Advantages of Switching Control

- Switching between two feedback control structure is to select the best control structure for the particular application.
- If any of the component failure in one of the control structure, the switching supervisor will take care of the same and alternate control will be in place.

A switched linear system model for this research is as follows:

$$\dot{x} = A_{\sigma}x(t)$$

The switching signal $\sigma(t)$ indicates

$$\dot{x}(t) = A_{\alpha}x(t) = if, \quad \sigma = \alpha$$
$$= A_{\beta}x(t) = if, \quad \sigma = \beta$$
$$= A_{\gamma}x(t) = if, \quad \sigma = \gamma$$

Where,

$$A_{\alpha} = A - B_1K_1$$
$$A_{\beta} = A - B_2K_2$$
$$A_{\gamma} = A - B_3K_3 \quad (4)$$

Here, B_1= EGR , B_2= VGT & B_3= Fuelling control inputs and the feedback controllers K_1 , K_2 & K_3 are derived from the optimal LQR theory by tuning of the weighting matrices.

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Switching Control Algorithm

The existing switching algorithm by (Lalitha S Devarakond et al. 2006; Yathisha L et al. 2018) is as follows (Ex: For B_1 & B_2 control inputs):

- Initialize the two closed loop systems A_α & A_β.
- Determine T_0 by solving the Lyapunov Equation:

$$A_\alpha^T T_0 + T_0 A_\alpha = -C^T.C$$

- Using, A_2 the switching matrix is defined as:

$$S = -(A_\beta^T T_0 + T_0 A_\beta + C^T C)$$

- Now, the switching rule is that,

$$\begin{aligned} \sigma &= \beta \quad if < x, Sx >> 0 \\ &= \alpha \quad otherwise \end{aligned}$$

IV. EXPERIMENTAL SETUP

The proposed novel optimal LQR control techniques for all the control inputs are investigated by considering the following cases:

Case I.(i): Optimal LQR feedback controller K_1 is designed for the control input B_1.

Case I.(ii): Optimal LQR feedback controller K_2 is designed for the control input B_2.

Case I.(iii): Optimal LQR feedback controller K_a is designed for the coordinated control input $B_a = [B_1 \quad B_2]$.

Case I.(iv): Switching between the control inputs B_1 and B_2 is considered for this case. K_1 & K_2 corresponding to their B_1 & B_2 are updated and defined as shown in Table 3.

Table 3: Updated controller gains for switching

B	K_1	K_2
$[B_1 \quad B_2]$	$k_1' = \begin{bmatrix} K_1 \\ 0 \end{bmatrix}$	$k_2' = \begin{bmatrix} 0 \\ K_2 \end{bmatrix}$

Case II.(i): Optimal LQR feedback controller K_2 is designed for the control input B_2.

Case II.(ii): Optimal LQR feedback controller K_3 is designed for the control input B_3.

Case II.(iii): Optimal LQR feedback controller K_b is designed for the coordinated control input $B_b = [B_2 \quad B_3]$.

Case II.(iv): Switching Between the control inputs B_2 and B_3 is considered for this case. K_2 & K_3 corresponding to their B_2 & B_3 are updated and defined as shown in Table 4.

Table 4: Updated controller gains for switching

B	K_2	K_3
$[B_2 \quad B_3]$	$k_2' = \begin{bmatrix} K_2 \\ 0 \end{bmatrix}$	$k_3' = \begin{bmatrix} 0 \\ K_3 \end{bmatrix}$

Case III.(i): Optimal LQR feedback controller K_3 is designed for the control input B_3.

Case III.(ii): Optimal LQR feedback controller K_1 is designed for the control input B_1.

Case III.(iii): Optimal LQR feedback controller K_c is designed for the coordinated control input $B_c = [B_3 \quad B_1]$.

Case III.(iv): Switching Between the control inputs B_3 and B_1 is considered for this case. K_3 & K_1 corresponding to their B_3 & B_1 are updated and defined as shown in Table 5.

Table 5: Updated controller gains for switching

B	K_2	K_3
$[B_3 \quad B_1]$	$k_3' = \begin{bmatrix} K_3 \\ 0 \end{bmatrix}$	$k_1' = \begin{bmatrix} 0 \\ K_1 \end{bmatrix}$

Case IV.(i): Optimal LQR feedback controller K_a is designed for the coordinated control input $B_a = [B_1 \quad B_2]$.

Case IV.(ii): Optimal LQR feedback controller K_b is designed for the coordinated control input $B_b = [B_2 \quad B_3]$.

Case IV.(iii): Switching Between the coordinated control inputs $B_a = [B_1 \quad B_2]$ & $B_b = [B_2 \quad B_3]$ is considered for this case. K_a & K_b corresponding to their B_a & B_b are updated and defined as shown in Table 6.

Table 6: Updated controller gains for switching

$B = [B_1 \quad B_2 \quad B_3]$	K_a / K_b
$B_a = [B_1 \quad B_2]$	$k_a' = \begin{bmatrix} K_{11} \\ K_{21} \\ 0 \end{bmatrix}$
$B_b = [B_2 \quad B_3]$	$k_b' = \begin{bmatrix} 0 \\ K_{11} \\ K_{21} \end{bmatrix}$

Case V.(i): Optimal LQR feedback controller K_b is designed for the coordinated control input $B_b = [B_2 \quad B_3]$.

Case V.(ii): Optimal LQR feedback controller K_c is designed for the coordinated control input

$B_c = [B_3 \quad B_1]$.

Case V.(iii): Switching Between the coordinated control inputs $B_b = [B_2 \quad B_3]$ & $B_c = [B_3 \quad B_1]$ is considered for this case. K_b & K_c corresponding to their B_b & B_c are updated and defined as shown in Table 7.

Table 7: Updated controller gains for switching

$B = [B_1 \quad B_2 \quad B_3]$	$K_a\ /K_b$
$B_b = [B_2 \quad B_3]$	$k_b' = \begin{bmatrix} 0 \\ K_{11} \\ K_{21} \end{bmatrix}$
$B_c = [B_3 \quad B_1]$	$k_c' = \begin{bmatrix} K_{11} \\ 0 \\ K_{21} \end{bmatrix}$

Case VI.(i): Optimal LQR feedback controller K_c is designed for the coordinated control input $B_c = [B_3 \quad B_1]$.

Case VI.(ii): Optimal LQR feedback controller K_a is designed for the coordinated control input $B_a = [B_1 \quad B_2]$.

Case VI.(iii): Switching Between the coordinated control inputs $B_c = [B_3 \quad B_1]$ & $B_a = [B_1 \quad B_2]$ is considered for this case. K_c & K_a corresponding to their B_c & B_a are updated and defined as shown in Table VII.

Table 8: Updated controller gains for switching

$B = [B_1 \quad B_2 \quad B_3]$	$K_c\ /K_a$
$B_c = [B_3 \quad B_1]$	$k_c' = \begin{bmatrix} K_{11} \\ 0 \\ K_{21} \end{bmatrix}$
$B_a = [B_1 \quad B_2]$	$k_a' = \begin{bmatrix} K_{11} \\ K_{21} \\ 0 \end{bmatrix}$

V. SIMULATION RESULTS

To do the comparison of all the proposed optimal LQR control techniques, simulations are carried out for all the state space variables, Intake manifold presuure (p_i), Exhaust manifold pressure (p_x) & Turbine power (p_c) deviations. The numerical values of the optimized LQR feedback controller gains K_1, K_2, K_3, K_a, K_b & K_c are as follows:

$$K_1 = [0.2883 \quad -0.9757 \quad 0.0527 \quad]$$

$$K_2 = [0.4080 \quad 0.9994 \quad 0.7540 \quad]$$

$$K_3 = [0.4245 \quad 1.0000 \quad 0.8033 \quad]$$

$$K_a = \begin{bmatrix} -3.2296 \times 10^{-9} & -7.3747 \times 10^{-7} & -0.9998 \\ 4.1696 \times 10^{-7} & -8.9701 \times 10^{-9} & -0.0024 \end{bmatrix}$$

$$K_b = \begin{bmatrix} 8.9321 \times 10^{-11} & -9.2463 \times 10^{-7} & -0.0247 \\ 3.4753 \times 10^{-7} & 7.5465 \times 10^{-5} & 0.9981 \end{bmatrix}$$

$$K_c = \begin{bmatrix} 1.1474 \times 10^{-9} & 6.8645 \times 10^{-8} & 0.0093 \\ -3.2189 \times 10^{-9} & -7.3742 \times 10^{-6} & -0.9998 \end{bmatrix}$$

The dynamic response of the state variables p_i, p_x & p_c for all the cases are shown in Figures 3-13.

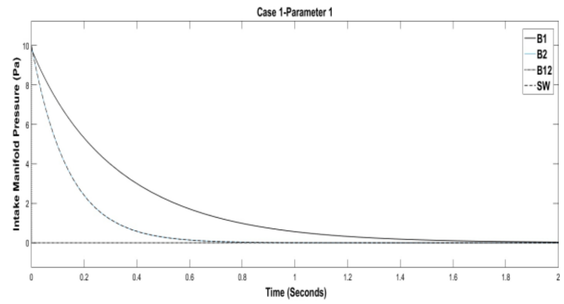

Fig 3: p_i Case I response

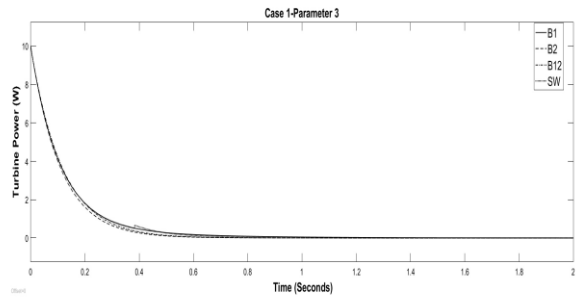

Fig 4: p_c Case I response

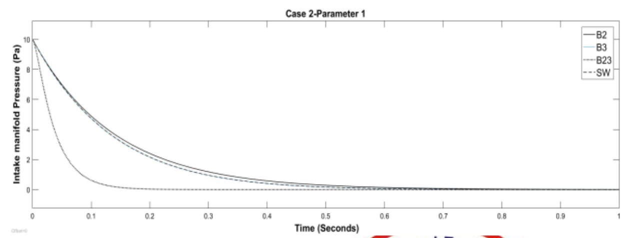

Fig 5: p_i Case II response

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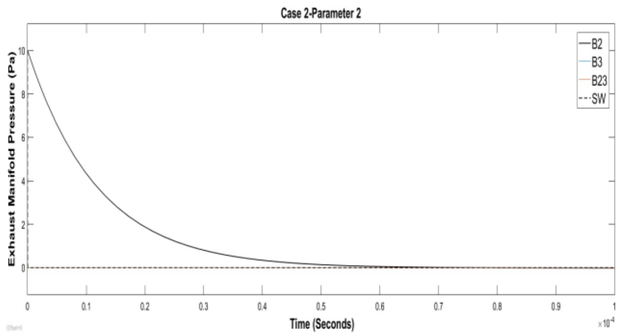

Fig 6: p_x Case II response

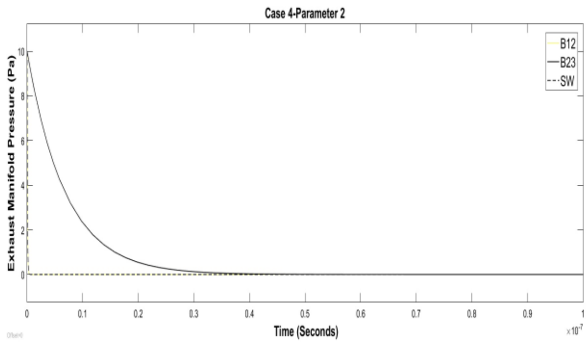

Figure 10: p_x Case IV response

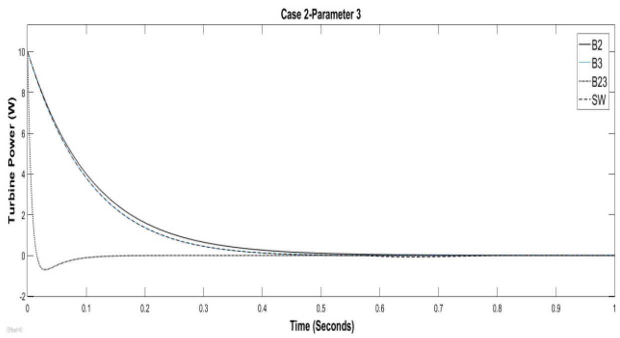

Figure 7: p_c Case II response

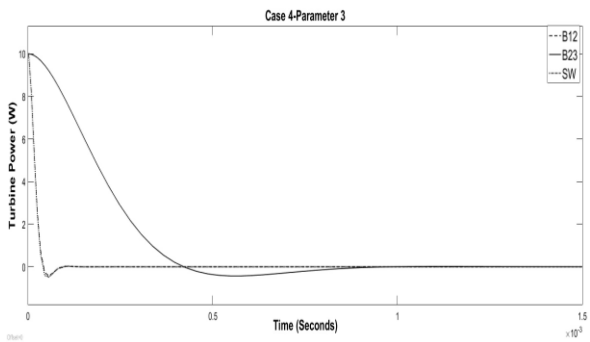

Figure 11: p_c Case IV response

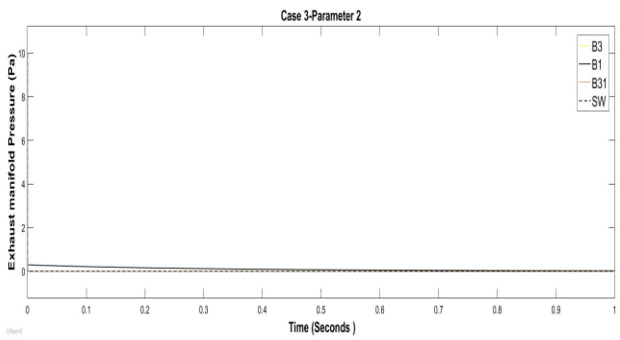

Figure 8: p_x Case III response

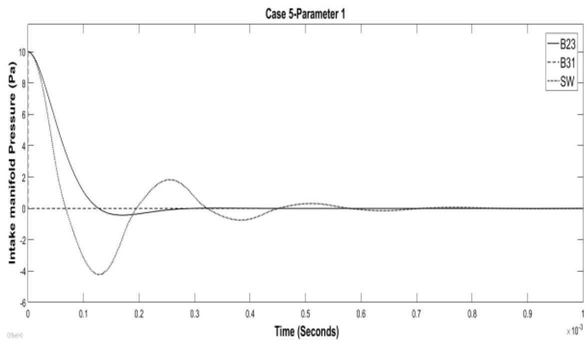

Figure 12: p_i Case V response

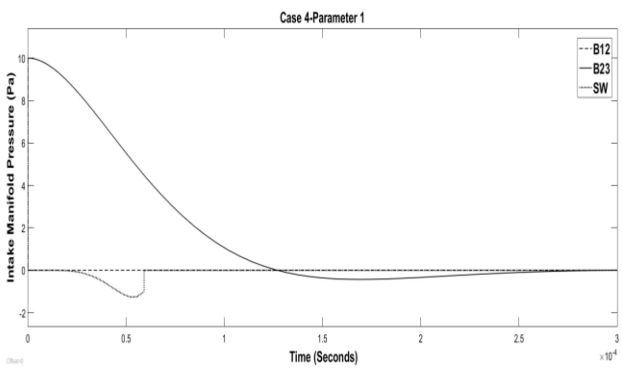

Figure 9: p_i Case IV response

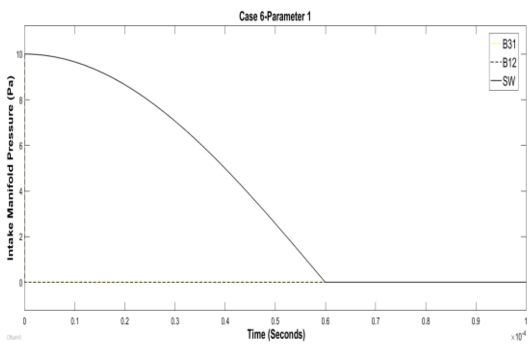

Figure 13: p_i Case VI response

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Table 9: performance index ($J = \int_0^\infty y^2 dt$) Comparison for Case I

State Variables	$B_1\ K_1$	$B_2\ K_2$	$B_a\ K_a$	Switch $B_1\ K_1$ / $B_2\ K_2$
p_i	15.92	6.984	0.005746	6.984
p_x	1.382×10^{-5}	0.00059 62	6.071×10^{-7}	0.0005 962
p_c	5.697	5.451	5.791	5.697

Table 10: Performance index ($J = \int_0^\infty y^2 dt$) Comparison for Case II

State Variables	$B_2\ K_2$	$B_3\ K_3$	$B_b\ K_b$	Switch $B_2\ K_2$ / $B_3\ K_3$h
p_i	6.984	6.635	2.181	6.635
p_x	0.0005 962	3.517×10^{-7}	3.517×10^{-7}	3.517×10^{-7}
p_c	5.451	5.158	0.2981	5.158

Table 11: performance index ($J = \int_0^\infty y^2 dt$) Comparison for Case III

State Variables	$B_3\ K_3$	$B_1\ K_1$	$B_c\ K_c$	Switch $B_3\ K_3$ / $B_1\ K_1$
p_i	6.635	15.92	3.276×10^{-6}	6.635
p_x	3.517×10^{-7}	1.382×10^{-5}	3.695×10^{-9}	3.517×10^{-7}
p_c	5.158	5.697	5.492	5.158

Table 12: performance index ($J = \int_0^\infty y^2 dt$) Comparison for Case IV

State Variables	$B_a\ K_a$	$B_b\ K_b$	Switch $B_a\ K_a$ / $B_b\ K_b$
p_i	0.005746	2.181	2.41×10^{-5}
p_x	6.071×10^{-7}	3.517×10^{-7}	3.281×10^{-9}
p_c	5.791	0.2981	0.001284

Table 13: performance index ($J = \int_0^\infty y^2 dt$) Comparison for Case V

State Variables	$B_b\ K_b$	$B_c\ K_c$	Switch $B_b\ K_b$ / $B_c\ K_c$
p_i	2.181	3.276×10^{-6}	0.0004306
p_c	0.2981	5.492	15.06

Table 14: performance index ($J = \int_0^\infty y^2 dt$) Comparison for Case VI

State Variables	$B_c\ K_c$	$B_a\ K_a$	Switch $B_c\ K_c$ / $B_a\ K_a$
p_i	3.276×10^{-6} 46	0.0057	0.002992
p_c	5.492	5.791	173.5

VI. DISCUSSION

Figures 3-13 and Tables IX -XIV shows the dynamic response plots of p_i, p_x & p_c and comparison of performance index J for all the cases defined in the experimental set up. The discussions of the experimental results are as follows:

Case I: The simulation results of individual controllers B_1K_1, B_2K_2, coordinated control inputs (B_aK_a) and switch between individual controllers (B_1K_1/ B_2K_2) reveals that for the state space variables p_i & p_x the cordinated control design (B_aK_a) provides better performance and for the state variable p_c the individual control input B_2K_2 gives good results with respect to the optimization.

Case II: For all the three state variables (p_i, p_x & p_c) the coordinated control inputs of VGT & Fuelling (B_bK_b) has better response compared to other proposed control techniques.

Case III: The simulation results for this case shows that for the deviations in intake and exhaust manifold pressures (p_i & p_x) the coordinated control design (B_cK_c) provides better results and for the turbine power deviation (p_c) the switching between two individual control inputs (B_3K_3/ B_1K_1) has lesser performance index(J) compared to other control input techniques.

Case IV: In this case, the experiment set-ups are conducted for the coordinated control inputs and the simulation results indicate that for all the three state variables (p_i, p_x & p_c), the switching control technique between two coordinated control inputs (B_aK_a/ B_bK_b) provide better output performance in comparison to without switching (Individual coordinated control inputs (B_aK_a) & (B_bK_b).

Case V: The simulation results in this case reveals that for the state variable p_i the coordinated control inputs B_cK_c and for p_c the coordinated control inputs B_bK_b provides better performance. The simulation result for the state variable p_x introduces error in plots.

Case VI: The coordinated control inputs B_aK_a provides good results compared to other control techniques for the state variables p_i & p_c and for the state variable p_x introduces error in plots.

VII. CONCLUSION

The summary of the literature survey indicates that the control techniques proposed by different authors in most of the papers are briefed on stability of the system by applying faults for the existing air dynamics state space model at different times. In this paper the different optimal LQR control techniques are applied for the three control inputs EGR, VGT & Fuelling of air dynamics in existing state space model in various combinations by developing six cases of different experimental set ups.

All the proposed six cases are simulated using MATLAB/SIMULINK@ platform and the results are compared with respect to the optimization level of output performance ($J = \int_0^\infty y^2 dt$). Since, the proposed control techniques combine more than one controller, hence concentrating only on the minimization of output energy by neglecting the control energy. The ouput performance is very much essential for the air path of diesel engines.

Figures 3-13 and Tables IX -XIV, for different control technique simulation results conclude that case IV result of switching control techniques between the coordinated control inputs (B_aK_a/ B_bK_b) provides very good respone and also the performance index (J) is minimized in comparison with all other control techniques of different cases. In future, the proposed control technique can be applied for the system with disturbances or by applying different faults.

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16.

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