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Control and Optimization of Torque Response in Spark Ignited Engines Using NSGA Algorithm

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Abstract: Increasing demands for lower carbon dioxide emissions and fuel consumption drive technological developments for car manufacturers. One trend that has shown success for reducing fuel consumption in Spark Ignited engines is downsizing, where the engine size is reduced to save fuel and a turbocharger is added to maintain the power output. Even though many downsized turocharged engines matches the larger engines in terms of power and fuel consumption, they still cannot match the natural aspirated engine in the transient torque response. Recent hardware improvements have facilitated the use of Variable Geometry Turbochargers (VGT) for spark ignited engines, which can improve the transient torque response. In the present techniques the optimal control of the valve timing and VGT are preferred for a fast torque response. Optimal open-loop control signals are found by maximizing the torque integral. Here, a control strategy to improve the combustion efficiency of Spark Ignited engines is presented. To reduce fuel consumption and to achieve high performance, multi-objective genetic optimization algorithm is proposed. The NSGA (Non-dominated Sorting Genetic Algorithm) reduces the computational complexity based on a certain number of decision variables and a given population of solutions. The efficiency of the proposed multi-objective genetic optimization control scheme is checked through simulation experiments.

Keywords: Spark Ignited Engines, Downsizing, Turbocharger, VGT, VVT, NSGA.

I. INTRODUCTION

The automobiles play an important role in our society over the last century. Today majority of the cars and trucks are run by internal combustion engines. The combustion engine plays an important role over the electric vehicles owing to the higher energy density. However the hydrocarbons and nitrogen oxide emissions largely coming from the automobiles push the technological development to restrict the emission levels. Since the oil reserves are day by day exhausting, there is great importance in reducing the fuel consumption and the carbon dioxide gases. Over the last decade downsizing is a popular way of reducing the fuel consumption. This engine with smaller displacement volume in downsizing reduces the pumping as well as the friction losses in addition to the fuel consumption. Work done in moving the air in and out of the engine results in the pumping losses whereas the moving parts of the engine accounts for the friction losses [5].

The turbocharged engines cannot match the natural larger engine in the torque with respect to time response even though it matches with the power output and fuel consumption. In the starting part the engine rapidly reaches at 190 Nm of the torque. After that the torque with respect to time response is limited by the turbocharger system. The response time of the turbocharger system limits the time required to reach the maximum boost level, and this phenomenon is known as the turbo lag. In order to reduce this lag various systems such as twin or triple turbo systems, hybrid systems in which the turbocharger is combined with a mechanical compressor, electrically assisted systems in which an electric motor gives extra power to the turbines during transients or using variable geometry turbocharger are proposed [6]. The main problem discussed in this paper is to control this VVT and VGT so that fast torque with respect to time response can be attained. The second aim is to find a good control method that achieves good torque response. In the process the output pressure is modelled and controlled using a variable geometry turbocharger and VVT. Here valve timing and VGT are taken as the controlled variables [2].

Since the VGTs are highly sensitive to the high exhaust gas temperatures their use has been previously prevented in the Spark Ignition (SI) Engines [9]. The hardware improvements facilitated their use in SI engines. In the reference [10], a feed-forward control method for VGT in an SI engine is explained. The VGT is closed for slow speeds and pressures, where as it is opened for rapid speeds and pressures. VGT is closed all the time for optimal transient scheme whereas the VGT is opened for optimal fuel scheme [7], [11].

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In this paper a model based control scheme designed to control both the torque as well as the speed to a reference value. The optimization is done for a specific load and speed [10]. In the design of the feedback controller it can be seen that the ratio controller between the intake and exhaust pressure gives the rapid torque response. The intake pressure is taken as the reference for the output pressure [3].

In the existing methods the optimization function is taken as the minimum value of the sum of the torque integral square error and the speed integral square error. The minimum value of this objective function is taken as the optimized value. In the proposed work these conflicting objectives are considered individually. The multi objective optimization such as Non-dominated Sorting Genetic Algorithm (NSGA) is used. The optimized value is taken as the minimum value of the controller gain that gives the minimum value for both the torque integral square error and the speed integral square error [8].

II. METHODOLOGY

The simulation experiment is done on a four stroke spark ignition engine with VVT and VGT.

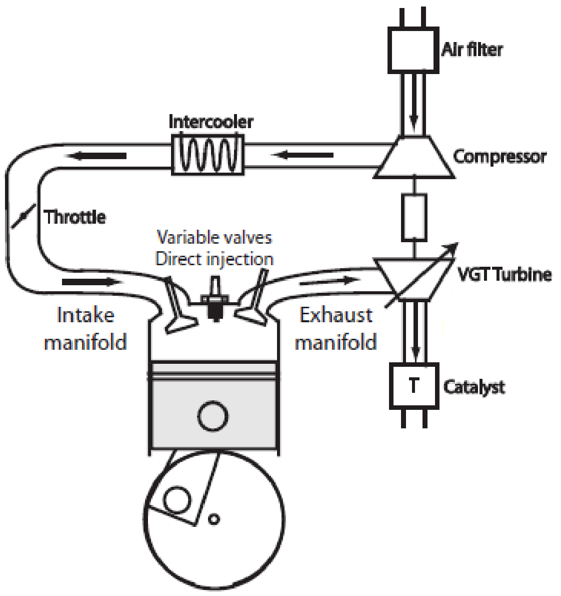

Figure A: Engine Set up

Figure A shows engine set up with sensors and actuators. The air after passing through the air is compressed and is cooled down by the intercooler. Throttle is mainly used to control the flow of air. After passing through the intake manifold the air reaches the cylinder, and the fuel is injected there. This happens in the intake stroke phase and in the compression stroke phase the air-fuel mixture is compressed and a spark plug is used in the SI engine to ignite the mixture. Afterwards combustion is initiated and the energy is transferred to the crankshaft as torque. Following this is the exhaust stroke during which the burned gases escape. Four strokes of the engine results in one engine cycle. The energy contained in the outgoing gases is utilized by the VGT to propel the compressor and the associated parts [9].

The engine model is developed in Simulink which is shown below.

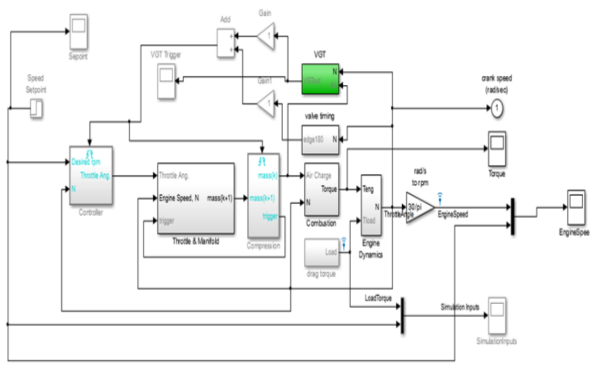

Figure B: Engine Timing Model

Figure B shows the engine timing model with the following components –Throttle, Intake Manifold, Mass flow rate, Compression stroke, Torque Generation and Acceleration and the VGT.

Along with engine model a model based controller is incorporated. The PI controller with an integral windup act as a model based controller. The main parts are Throttle, Manifold, Compression, Combustion, Vehicle Dynamics, Valve Timing and the controller.

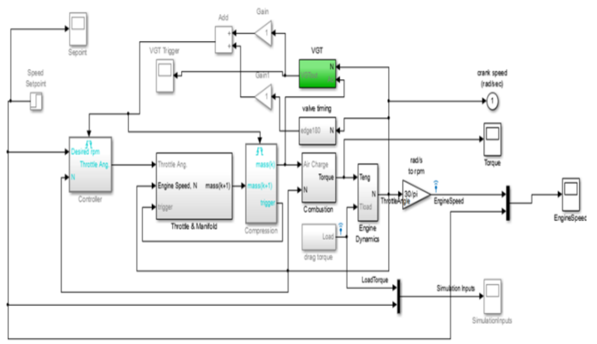

Figure C: Engine timing model with controller

In maximizing the torque with respect to time response, the formulation is developed as

$$\max_{VGT,VVT} F(VGT,VVT) \qquad (1)$$

where F is the function used to measure the torque response.

This can be modeled in a number of ways. One of them is considering the time integral. That is given as shown below.

$$F(VGT,VVT)=\int T[VGT(t),VVT(t)]dt \qquad (2)$$

where T represents the indicated work during the full engine cycle.

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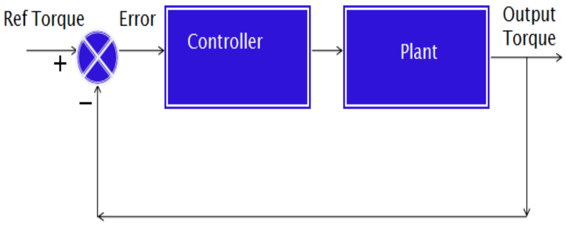

Figure D: Block Diagram

Figure D shows the block diagram of the system. It consists of a plant i.e. the engine model which has been developed in the Simulink and a controller with the optimization logic. An iterative approach is pursued for the optimization problem. The optimization is done using the matlab function fmincon. The equation (2) converges slowly. So the objective function is changed to

$$J_2(VGT,VVT)=\int[T^{ref} - T[VGT(t),VVT(t)]]^2dt \quad (3)$$

The reference value of the torque is chosen as the 25 bar IMEP 720.

The engine model is developed using the enhanced capabilities of the Simulink. The output torque is compared with a reference torque. The error is produced which is the deviation from the reference torque. Our objective according to equation (3) is to minimize the error.

The prime objective of this paper is to get an independent control of both speed and the torque. For that in this paper a multi-objective optimization problem i.e. NSGA algorithm is proposed [4]. The algorithm is mainly used in situations when a problem cannot be solved by one objective. The steps involved in this are (1) Initialize the population (2) Calculate the objective function (3) Rank the population and selection followed by crossover and mutation(4) combine and rank the population followed by reporting the final population [1].

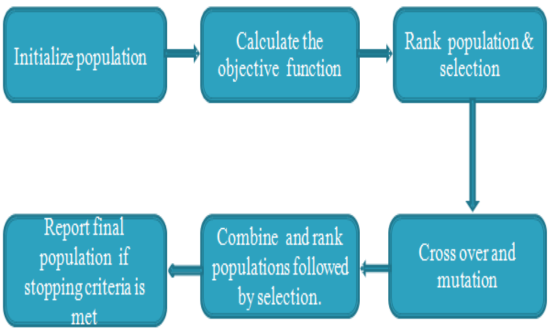

Figure E: Block diagram of NSGA Algorithm

III.RESULTS AND DISCUSSION

The Simulink scope shows the engine speed graph and the torque response. The inputs which are given to the system are shown below.

$$Throttle(degrees) = \begin{Bmatrix} 8.97, t < 5 \\ 11.93, t \geq 5 \end{Bmatrix}$$

$$Load(Nm) = \begin{Bmatrix} 25, & t \leq 2 \\ 20, 2 < t < 8 \\ 25, & t \geq 8 \end{Bmatrix}$$

The above inputs results in a speed set point which varies from 2000 to 2200 rpm. Figure F shows the simulated engine speed.

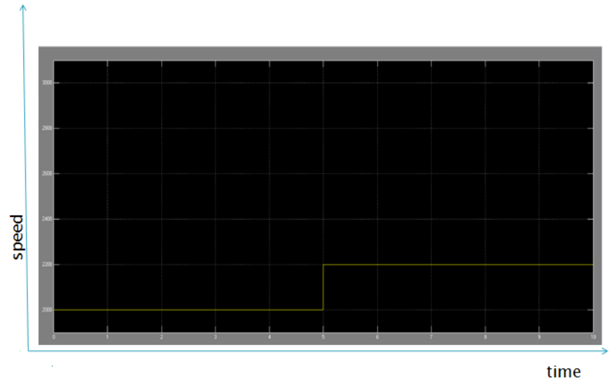

Figure F: The simulated Engine speed

The VGT trigger output for the system is shown below which consists of pulses.

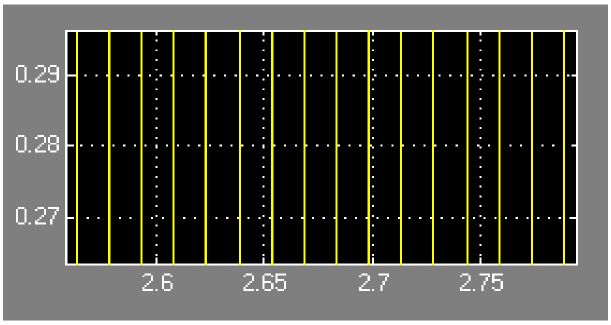

Figure G: VGT trigger

VVT trigger output also consists of pulses.

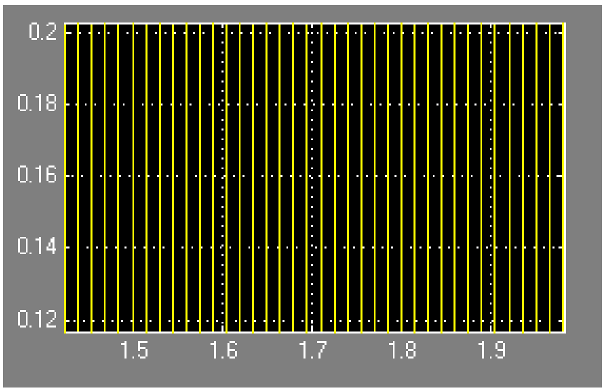

Figure H: VVT trigger

The below figure shows the speed response of the system.

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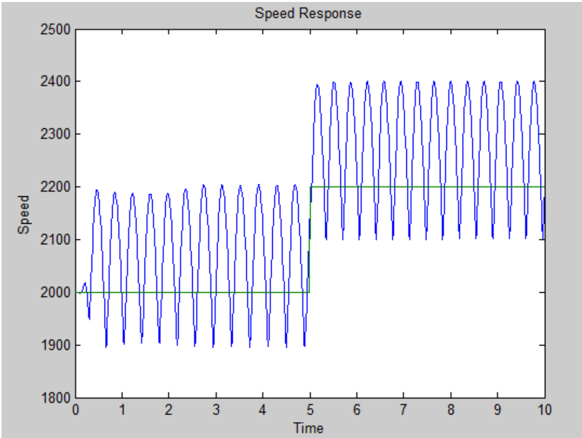

Figure I: Speed versus time

As the speed is varied from 2000 to 2200 rpm, the system exhibits a number of oscillations about the set point. The objective of this paper is to minimize this integral square error to a point.
The below figure shows the torque with respect to time of the system.

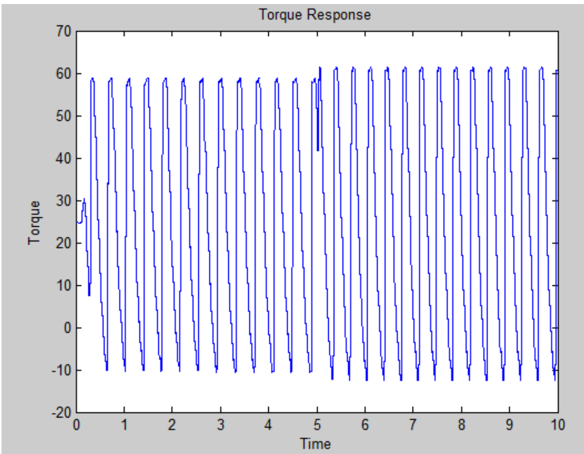

Figure J: Torque versus time

After applying the fmincon optimization the speed and torque responses are shown below.

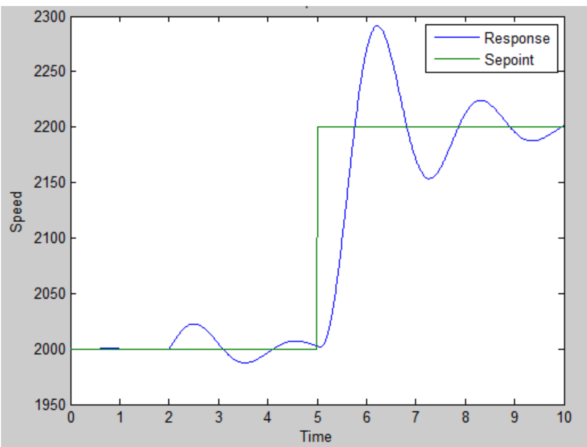

Figure K: Optimized speed response.

Here the objective function will be the sum of the integral square error for the speed and the torque.

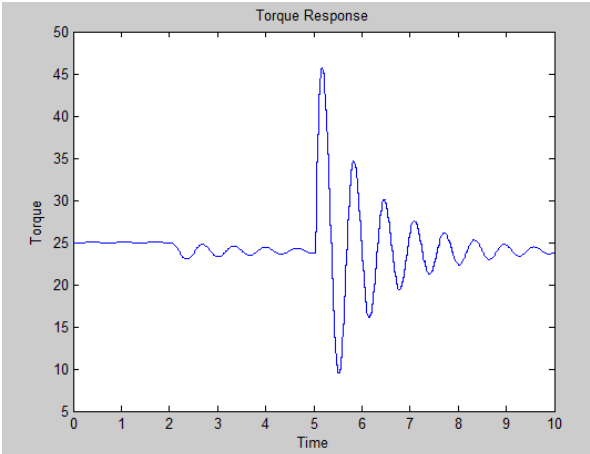

Figure L: Optimized torque response

The optimization plot after 10 iterations is shown below. From the graph, it can be inferred that the error value is minimum after 10 iterations. Also the current values proportional gain Kp and the integral gain Ki values are shown after the 10 iterations.

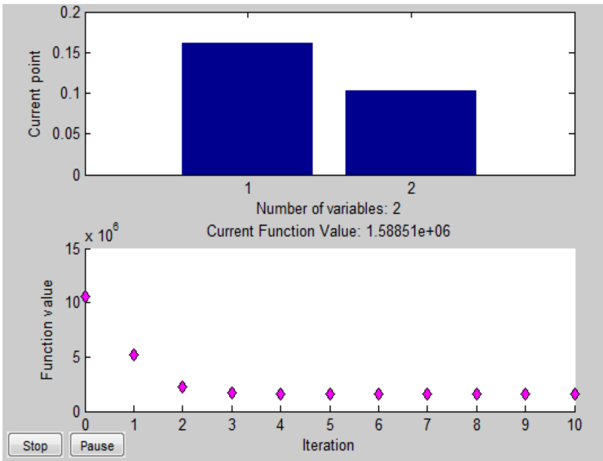

Figure M: Optimization plot

Now the NSGA algorithm is applied so as to get an independent control of both the speed and the torque ISE. Figure shown below are the optimization graph using the NSGA algorithm.

The values of Kp and Ki are selected which yields a minimum value for both the Torque ISE and speed ISE out of the 30 chosen random values of populations.

Graphs give the comparison of both the existing and those with the NSGA optimization for both the speed as well as the torque responses.

The speed and the torque responses reach the set point with minimum error. Also the system settles at a faster rate.

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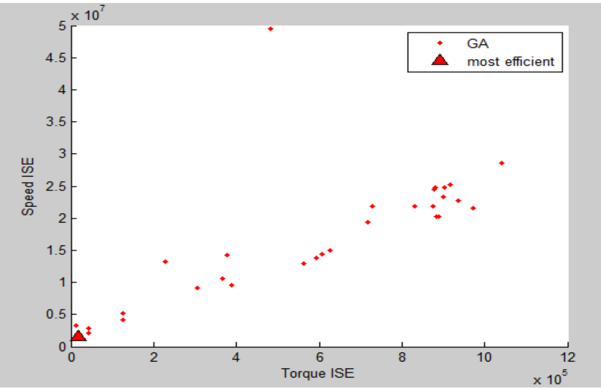

Figure N: Optimization graph using NSGA

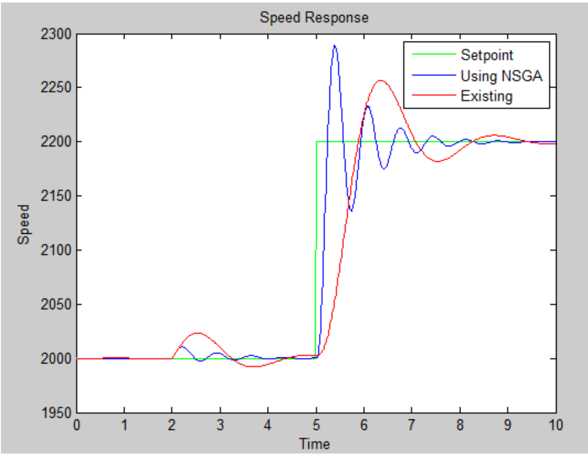

Figure O: Comparison of speed responses

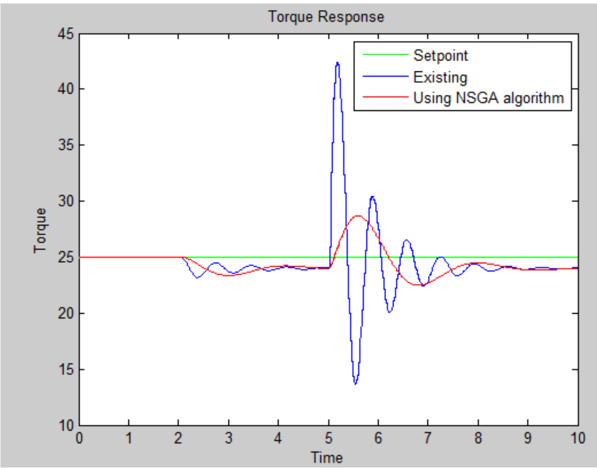

Figure P: Comparison of Torque responses

IV. CONCLUSION

The paper discusses the problem of reducing the turbo lag using the VGT and VVT. The paper deals with controlling the valve timing and variable geometry turbocharger so that torque can be increased with respect to time response. In addition to this a good control method to obtain torque response is also done. All the results show the details involves in the paper. The torque as well as the speed responses is plotted. Also the paper discusses about the NSGA optimization. The speed and the torque responses are obtained in the NSGA Algorithm yields a minimum value of both the Speed and the Torque ISE. The efficiency of the proposed algorithm is tested through simulation experiments.

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