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Design and Development of Microcontroller Based Electronic Speed Governor for Genset/Automotive Engine

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Abstract: *The engine speed controller of a conventional diesel engine is called a Governor. In order to control engine speed, the governor controls the amount of fuel using fuel rack. The fuel rack is connected to throttle actuator lever and driven from microcontroller. The actuator motion is controlled to achieve set-point rpm so required pulse width modulation duty cycle to drive actuator is calculated from digital PID algorithm. PIC 16F877A microcontroller based hardware is developed for the implementation of the controller. The system broadly involves interfacing hardware and the software for PID algorithm. A continuous PID controller is governed by an equation which describes the dynamic time varying behavior of the input or the error signal. This is digitized using numerical approximations and is programmed in the microcontroller. This system is a closed loop control system with feedback signal generated by a digital magnetic pickup, which gives a pulse output which is TTL compatible. The PID algorithm along with the hardware achieves the speed control of the diesel engine. The hardware and software are validated in real time by considering different speed settings.*

***Keywords*:** Electronic Speed Governor, PID, Throttle Actuator, PIC16F877A, Pulse width modulation.

I. Introduction

The basic task of electronic speed governor system is to prevent the engine from exceeding the maximum revving speed specified by the engine manufacturer. Since the diesel engine always operates with excess air because the intake flow is not restricted, it would overrun if there were no means of limiting its maximum speed. Depending upon the type of governor control system, its functions may also include holding the engine speed at specific constant levels such as idling or other speeds within a specific band or the entire range between idling and maximum speed.

A diesel engine is the most common solution for the distributed power generating systems due to its superior fuel efficiency compared to the other types of internal combustion engines. In conventional diesel engine systems, a fly-wheel type governor which is mechanically synchronized with the engine crankshaft has been widely used to control engine speed. However, the electronic governor gradually extends its use in the various applications because of its superior control performance, simple structure, and maintenance free characteristics. In industries, electronic governor with Proportional, Integral, and Derivative (PID) speed controller is generally used for such applications.

Electronic speed governor has good speed control performance and is relatively inexpensive. With a diesel engine, there exists no single control-rack position which would permit the diesel engine to maintain its speed accurately within the operating speed range without a governor. At idle, for example, without a governor the engine speed would either drop until the engine stalls, or it would continue to increase until the engine races, culminating in self-destruction. The basic job of every governor is to limit the engine's maximum speed. To achieve stable response of engine the PID (Proportional Integral Derivative) algorithm is implemented. Engine rpm is taken as controlled parameter and throttle angle is taken as controlled variable. The throttle angle is adjusted through throttle actuator via pulse width modulation signal. The pulse width modulation signal is calculated in PID loop. Every time the engine's rpm error is processed in PID loop and required pulse width modulation control signal is calculated. The closed loop system is achieved through feedback from engine rpm. The total set-up of electronic speed governor is shown in Figure 1.

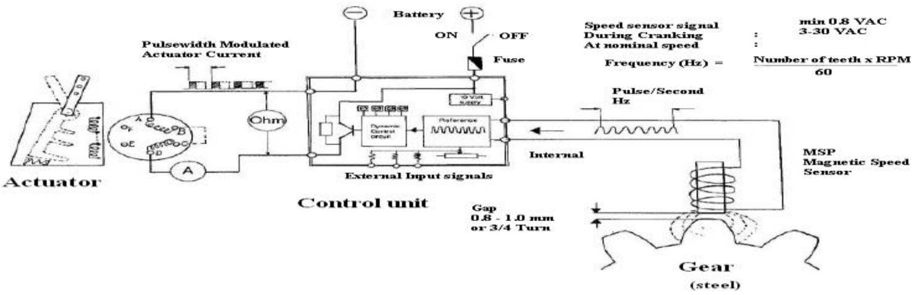


Figure 1: Electronic Speed Governor Setup.

II. Objective

The project is an endeavor towards an effective design and development of microcontroller based electronic speed governor for genset/automotive engine.

The following are the main objective

1. To design drivers for both throttle actuator and magnetic pickup sensor.
2. To design hardware for the system using PIC16F877A microcontroller.
3. To develop an experimental setup for mounting of throttle actuator and magnetic pickup sensor.
4. Implement the PID algorithm in embedded C code.
5. Application of the designed algorithm in an embedded controller to verify on actual engine operation.

III. System Description

The following Figure 2 shows block diagram of working of electronic speed governor system. The magnetic pickup sensor is mounted on engine flywheel. The engine rpm is measured in capture compare module of the PIC microcontroller. The throttle actuator's lever is directly connected to the engine fuel pump. The throttle actuator is controlled from the pulse width modulation signal so it is directly connected to the RC2 pin of the PIC microcontroller. The engine rpm is continuously measured and compared with the required set point and when the error signal is generated it is directly processed in the PID algorithm. The PIC microcontroller generates the required pulse width modulation duty cycle from the PID algorithm based on which diesel engine gets stabilized at required set point. The working pulse width modulation period is calculated from initial trails on the throttle actuator.

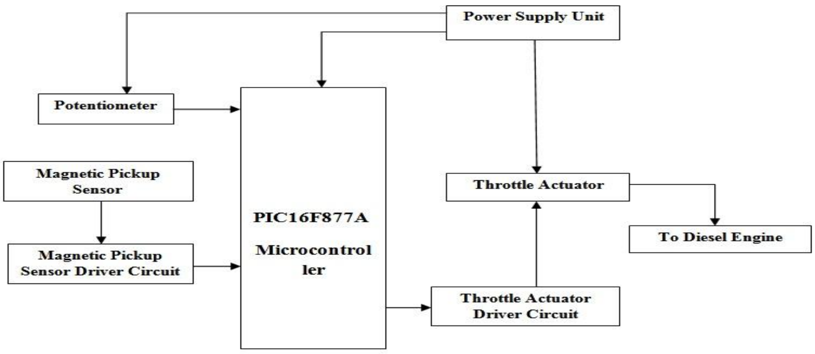


Figure 2: Block diagram of Electronic Speed Governor System.

In this project CCP1 (PWM) is used to control the position of throttle actuator. PWM stands for the Pulse Width Modulation where the width of a digital waveform is varied to control the power delivered to a load. The underlying principle in the whole process is that the average power delivered is directly proportional to the modulation duty cycle as shown in Figure 3. The pulse width modulation is required to switching the load devices through MOSFET based power stage or from any other components. The pulse width modulation has ON time and OFF time and addition of both is period. The average voltage applied to the load is varied from the pulse width modulation which directly depends upon the duty cycle. The time is inversely proportional to the frequency because of which the required period given to the load is in the form of frequency

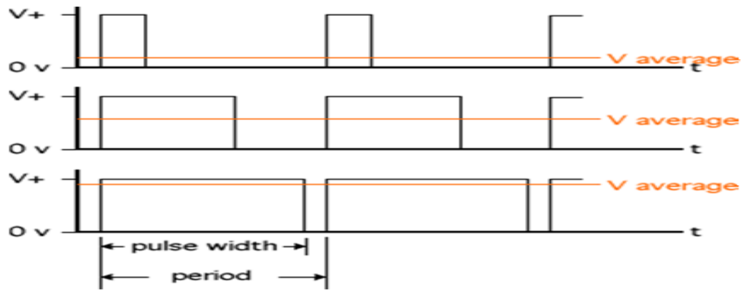


Figure 3: Pulse width modulation with different duty cycle.

IV. Design of Controller

The improved electronic speed governor system includes digital controller, drive circuit, electromagnetic throttle actuator and the engine speed sensor. The system to be controlled (plant) is the diesel engine. The electronic speed governor is a closed loop system in which feedback is taken from engine rpm. The controller output is in the form of pulse width modulation duty cycle. When the rpm error is generated the required pulse width modulation duty cycle is calculated from PID algorithm. The capture compare module in PIC16F877A is used to calculate engine rpm. The PID update time is kept in proportion with the throttle actuator response time. The key step of the electronic governor design is to choose the suitable actuator coupled suitably with fuel pump rack. The requirements to actuator of diesel engine governor system are fast response, high accuracy and reliability. Under diesel engine operating principle, the engine speed regulation is achieved by regulating the movement of the pump rack. With electronic speed controller, the movement of pump rack is mainly affected by the diesel engine speed change.

$$P=K_P e_p+K_P K_I \int_0^t e_P \, dt + K_P K_D \, de_p/dt + Pi\,(0) \qquad (1)$$

where, $P_i\,(0)$ is the nominal output.

A. System to be controlled

The system to be controlled is a diesel engine, speed-torque characteristics of which are mentioned in below Figure 4. The PID algorithm is implemented on diesel engine to achieve required set point rpm. The controlled parameter is engine rpm and controlled variable is engine throttle angle.

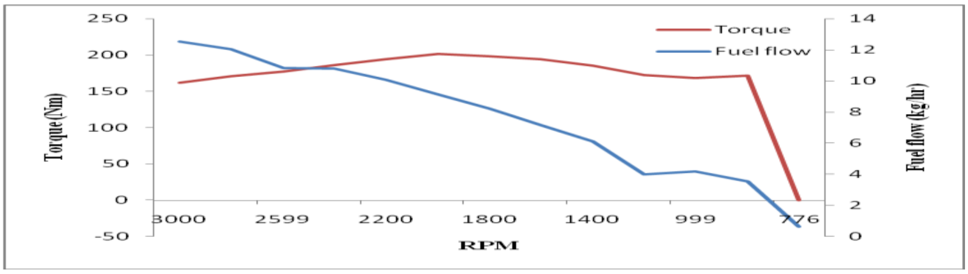
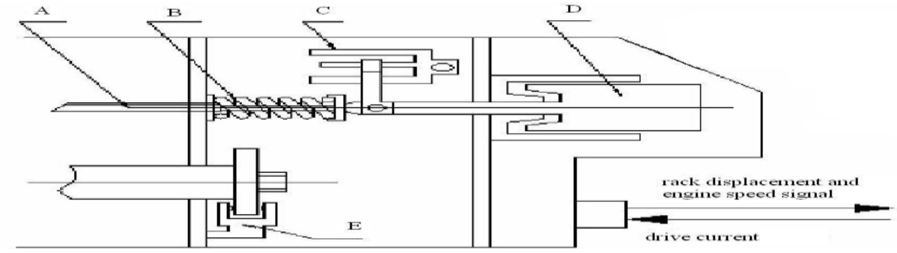


Figure 4: Base diesel engine speed torque characteristics.

The diesel engine having idle rpm is 780 with 0.58 kg/hr fuel flow. The diesel engine produces power up to 52 kW and generates 223 Nm torque at rated engine rpm. The diesel engine works on mechanical governor and having distributor type fuel pump. The above Figure 4 shows the behavior of diesel engine at various loads, the red line shows the engine Torque in Nm. The engine load is directly proportional to the fuel flow. The blue line in Figure 4 shows the fuel flow in kg/hr, which directly increases as engine torque increases.

B. Controller: Throttle Actuator

The Figure 5 shows the throttle actuator. As the actuator has two way connections it can controlled by lever from both sides, accordingly fuel pump lever can be adjusted with appropriate torque. The actuator is an electromagnetic servo device which can be integrated into a closed loop control system. An engine control system can be described as follows; an electrical signal is generated by a magnetic speed sensor which is proportional to the engine speed. The signal is sent into the electronic speed control unit which compares it to the preset engine speed setting. When the magnetic speed sensor signal and the preset engine speed setting are not equal, a change in current from the speed control unit to the actuator will change the magnetic force in the actuator. The throttle actuator is prewired for 12 volt or 24 volt. The harness included with the actuator can be used to connect the actuator to the speed control. For 12 volt operation it is preferable to connect four cables, one to each of the coil wires with maximum current is 8 Amps.



A. Pump rack B. Return spring C. Rack displacement sensor
D. Electromagnetic actuator E. Engine speed sensor

Figure 5: Throttle Actuator [1].

Table 1 Throttle Actuator Specifications

Available maximum torque	2.7 Nm
Angular Travel	25 cw/ccw
Operating Voltage	12 Volt
Normal operating Current	0.9 Ampere at 12 Volt
Maximum Current	6 Ampere at 12 Volt

The Table 1 shows the throttle actuator specifications. The arrangement of the linkage for actuation of engine fuel control is an important application consideration. For proportional actuators to operate with linear control systems, it is important to obtain a linear relationship between actuator strokes and fuel delivery. The linkage configuration for diesel fuel systems is typically as illustrated in Figure 5. According to the current speed and the preset value the rotation of the actuator shaft will then adjust the fuel to the engine and cause the engine speed to be equal to the preset engine speed setting. Shaft rotation is proportional to the amount of actuator current and counterbalanced by the internal spring. Since the design has non sliding parts and is totally sealed, outstanding reliability results, a single compression spring is used to improve reliability. No maintenance is necessary.

C. Controller: PIC16F877A Microcontroller

The nominal output in Eqn. (1) is taken from the potentiometer at no load condition. The analog to digital conversion module of PIC16F877A is used to measure voltage from potentiometer. The pulse width modulation duty cycle is calculated as per the voltage from the potentiometer. The engine rpm is measured in capture compare module of PIC16F877A microcontroller. The updated values of engine rpm and the pulse width modulation duty cycle are displayed on LCD. The engine rpm is continuously compared with the set point and when error signal generates it directly processed into the PID algorithm. The pulse width modulation duty cycle is calculated from the PID algorithm and from which PIC16F877A microcontroller moves the throttle actuator lever in such a position where engine gets stable at the required set point.

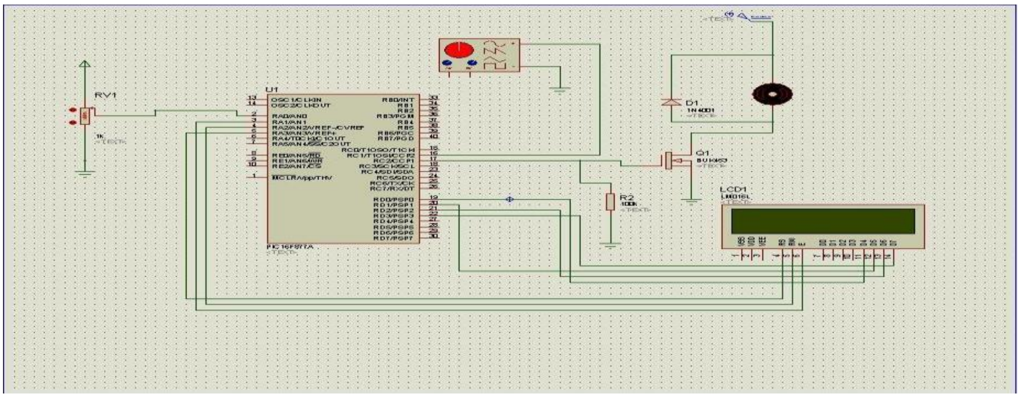


Figure 6: Schematic circuit of PIC16F877A in Proteus.

The PIC16F877A microcontroller is having both analog to digital conversion module and pulse width modulation is of 10 bit. The clock frequency of 4 MHz is used. The Proteus software is used to do the virtual simulation before going to real hardware. The Proteus implementation is shown in above Figure 6.

D. System Feedback

The closed loop control system requires feedback to take controlled action. The PID controller calculates the required pulse width modulation duty cycle from engine rpm feedback. The magnetic pickup sensor used in this project is of variable reluctance type with 750 ohm resistance. The pickup sensor is directly mounted on the flywheel of the diesel engine for feedback purpose. The magnetic pickup sensor gives output in a peak to peak voltage which is proportional to the number of teeth on flywheel and engine maximum rpm. The output voltage must be controlled such that it has to be in accordance with the controller requirements; because of which Magnetic Pickup sensor driver circuit is used. The magnetic speed sensor indicates when ring gear teeth or other ferrous projections, pass the tip of the sensor. The electrical impulse are indicated within the coil and sent to speed control unit. The signal from the magnetic speed sensor, teeth per second (Hz), is directly proportional to engine speed. The magnetic speed sensor is mounted in the ring gear case or flywheel bell housing of the engine. The threaded hole for the speed sensor should be perpendicular to the centerline of the crankshaft and centered over the ring gear teeth. When the engine is stopped, screw the speed sensor in until it touches the gear tooth, then back it out ¾ of the turn and secure it with the locknut. Any ferrous gear may be used as long as the frequency and amplitude of the resulting signal meet the speed control unit specifications. The wire lead should be twisted for the entire length from the magnetic speed sensor to the control unit. The leads may need shielding when it is longer than 3 meters.

E. Software Description

The MPLAB software is from Microchip and it is an Integrated Development Environment (IDE). It is basically used for programming the ICs. In this project the coding is done in Embedded C language for that C compiler is required so HITECH C compiler is used. The PID algorithm first written in embedded C language for that initially new project is created in MPLAB IDE. After that PID code is build and compiled in MPLAB IDE from that the generated .cof file is used for debugging purpose and the .hex file is used to download it in PIC16F877A IC. It was largely used for real time debugging of PID code. The PIC16F877A is programmed through MPLAB IDE and PICKET3.

The PROTEUS is the virtual simulation software from ISIS. PROTEUS is generally used to test the behavior of the selected hardware in simulation. In PROTEUS the PID code was initially tested with different logics on virtual hardware. The magnetic pick up sensor driver circuit checked in PROTEUS by observing its output waveform on oscilloscope. The various inputs given to the magnetic pickup sensor driver circuit from function generator were observed on controller. The actuator driver circuit is also tested with different Volts and Ampere ratings in PROTEUS.

The PCB123 is the PCB design software from Sunstone Circuits. The actuator and magnetic pickup sensor driver circuit were designed in PCB123. First the schematics were drawn and from that the layout work is created. The both designs were in program through hole format so the components chosen were in same format. All the driver circuit's components were found in same specifications in PCB123. The controller board also designed in PCB123 with same program through hole format.

V. Experiment Test Rig

To perform experiments hardware has to be mounted on the engine. The throttle actuator was calibrated with respect to distributor fuel pump. The diesel engine and the dynamometer are coupled through shaft.

A. Actuator Mounting

The throttle actuator is mounted on the distributor fuel pump with actuator lever directly connected to fuel pump lever. The bracket arrangement is made to fix the throttle actuator on the engine block. As the actuator is having more weight so the bracket is designed in such a way that it can sustain actuator's weight. The fuel pump lever and the actuator lever travel are calibrated. The actuator lever's minimum position properly matches with fuel pump lever's minimum position and actuator lever's maximum position properly matches with fuel pump lever's maximum position. The actuator must be rigidly mounted as close as possible to the fuel control lever of the engine. The vibration from the engine will not affect the operation of the actuator. The preferred mounting is with the electrical connector at the top and the actuator upside down, on its back, or side way should be avoided. The linkage arrangement of throttle actuator is always important so high quality rod end bearings are used.

B. Magnetic Pickup Sensor Mounting

The magnetic pickup is mounted on the flywheel of diesel engine. The threading arrangement is given by the engine manufacturer. The initial task is to match the threads of the magnetic pickup sensors and the engine block's thread. The magnetic pickup sensor is mounted in the ring gear case or flywheel bell housing of the engine. The threaded hole for the speed sensor should be perpendicular to the centerline of the crankshaft and centered over the ring gear teeth. The spot space should be present to provide a flat surface on which to anchor the locknut. The speed sensor screw in until it touches the gear tooth, then back it out ¾ of the turn and secure it with the locknut. The ferrous gear may be used as long as the frequency and amplitude of the resulting signal meet the speed control unit specifications. The wire lead should be twisted for the entire length from the magnetic speed sensor to the control unit. The leads may need shielding in case length is more than 3 meter.

VI. Procedure of Experiment

The experiments were conducted to design and develop electronic speed governor for genset/automotive engine. Experimental setup consists of diesel engine, dynamometer, microcontroller, magnetic pickup sensor and throttle actuator. The experimental procedure is as follows.

- The dynamometer is set to M mode torque alpha in which load is held constant with varying rpm.
- The engine is held idle with no load.
- The rpm of the engine is increased to the required set point by varying the potentiometer VR1.
- When the engine rpm reaches the set point load is applied by dynamometer because of which rpm decreases from set point.
- The error generated by decrease in rpm is processed in PID because of which a new pulse width duration duty cycle is assigned and engine rpm reaches back to the set point at loading conditions.
- The above mentioned procedure is repeated with different set points.

A. Sample Results

Trails were conducted on electronic speed governor for different set points and loads.

Table 2 Trails conducted at set-point = 1200 rpm

Torque Nm	Engine rpm	PWM duty cycle percent	Fuel flow kg/hr	Modified engine rpm
0	780	0	0.58	780
0	780	55	0.98	1200
15	1192	61	1.22	1206
25	1187	68	1.34	1198
30	1182	76	1.42	1204

Table 3 Trails conducted at set-point = 1600 rpm

Torque Nm	Engine rpm	PWM duty cycle percent	Fuel flow kg/hr	Modified engine rpm
0	780	0	0.58	780
0	780	80	1.20	1600
15	1595	86	1.35	1598
25	1589	93	1.48	1604
30	1583	98	1.62	1598

The first trail was performed at three different loads with set point is 1200 rpm and the results are shown in Table 2. The second trail was performed at three different loads with set point is 1600 rpm and its results are shown in Table 3.

VII. Experimental Result Analysis

The electronic speed governor was tested on diesel engine at various loads. The diesel engine is initially kept at no load condition and the performance of electronic speed governor is studied. The various loads are applied on diesel engine by dynamometer and performance of electronic speed governor is studied. The pulse width modulation duty cycle was calculated by electronic speed governor in PID algorithm with respect to drop in engine rpm. Three trails were conducted for each set point. Table 4 shows average values of each trail at set point 1500 rpm and Table 5 at set point 1000 rpm.

Table 4 Results at set point = 1500 rpm

Torque Nm	Engine rpm	PWM duty cycle percent	Fuel flow kg/hr	Modified engine rpm
0	780	0	0.58	780
0	780	76	1.10	1500
15	1487	84	1.35	1505
25	1480	89	1.44	1498
30	1478	94	1.56	1495

Table 5 Results at set point = 1000 rpm

Torque Nm	Engine rpm	PWM duty cycle percent	Fuel flow kg/hr	Modified engine rpm
0	780	0	0.58	780
0	780	43	0.85	1000
15	995	46	1.13	1001
25	990	49	1.22	1000
30	987	56	1.35	1006

From the above trials on diesel engine by using electronic speed governor, it is observed that:

- As the load on the engine increases the duty cycle calculated from PID algorithm increases.
- PID update time from coding matches with the actuator response time because of which engine gets stabilize at set point without hunting.
- The engine rpm calculation method is proven very accurate as the engine rpm measured by electronic speed governor matches with the engine rpm calculated by dynamometer systems.
- The rpm calculation and PID calculation are based on interrupt logic, so there are more chances of interrupt latency but in coding these calculations solved in proper sequence which results in the stability of the engine at set point.
- The engine load, pulse width modulation duty cycle and the fuel flow from fuel pump are directly proportional to each other.

VIII. CONCLUSION

The electronic speed governor gives satisfactory results for the tested set points at 1500 rpm and 1000 rpm. The diesel engine runs very stable at different loading conditions. Overshooting and undershooting of set point was minimized because of PID algorithm. The diesel engine runs very stable at set point in both loading and unloading conditions. On the microcontroller side both the actuator and sensor calibration is quite critical and their control is very important in further development in this project.

- The electronic speed controller designed for Genset/Automotive engines is practically implemented on diesel engine to stabilize the engine for required set point at various loading conditions.
- The driver was designed such that the output peak to peak voltage of magnetic pick up sensor was reduced from 10 to 5 peak to peak voltages which are acceptable by controller.
- The driver was designed to meet the requirements of throttle actuator that is 12 Volt and 6.5 Ampere.
- The PID algorithm works very successfully and calculated pulse width modulation duty cycle as per the need of diesel engine to run at set point with no load and partial load.
- The Engine was stabilized by proper functioning of calculated gains and update time for PID.

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