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Implementation of Electronic Throttle-by-Wire for a Hybrid Electric Vehicle using *National Instruments' CompactRIO* and *LabVIEW Real-Time*

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***Abstract*— A vehicle propulsion system based on internal combustion engine (ICE) includes a throttle body whose function is to regulate the amount of air-fuel intake into the engine to vary the engine's power and thus vehicle acceleration. A mechanical throttle valve body attached to the ICE's air intake manifold is linked to the driver's accelerator pedal via mechanical cable. An alternative system is based on an electronic throttle: an electro-mechanical device controlled electronically by power transistors. Coupled with an accelerator pedal and a built-in position sensor, the system is referred to as an electronic throttle-by-wire (TBW). This paper describes implementation of an electronic TBW in a conversion hybrid electric vehicle. It explains components and sub-systems of the TBW and application of a closed-loop throttle position control. The controller used is an embedded *CompactRIO* controller from *National Instruments*, programmed with *LabVIEW Real-Time*. Bench testing of the TBW and throttle position control system is presented.**

Keywords— electronic throttle, throttle-by-wire, hybrid electric vehicle, CompactRIO, LabVIEW, PID control.

I. Introduction

Interest and awareness of society to preserve depleting fossil-fuel resources have led to the development of the hybrid electric vehicle (HEV) as alternative to conventional combustion-engine vehicles. For retrofit-conversion of a conventional vehicle into a parallel hybrid electric vehicle, some mechanical and electrical modifications are required [1]. Apart from installation of electric motors onto the vehicle, the existing internal combustion engine (ICE) propulsion system needs to be enhanced, which includes the engine's throttle. Fig. 1 shows block diagrams of mechanical throttle and electronic throttle system.

The vehicle's existing cable-driven mechanical throttle valve has to be replaced by an electronic throttle, for two objectives. The first objective is to disengage the direct mechanical link from the driver's accelerator pedal to the engine's throttle, because in a vehicle, the driver's power request is given by the accelerator pedal. In a hybrid electric vehicle, this power request should not go directly to the engine; instead, the power request is processed by an energy management system (EMS) - separate from the vehicle's engine control unit (ECU).

The EMS controls the power split between the two propulsion sources, namely the combustion engine and electric motor. The EMS achieves this by controlling two sub-systems: the engine's throttle to vary engine power, and the motor drive to vary motor power [1]. Fig. 2 illustrates the power and signal flow from the accelerator pedal to the propulsion sources in a parallel hybrid electric vehicle. The second objective of incorporating an electronic TBW is to enable electronic control of the engine's throttling system, so that signal from the EMS can control the throttle blade's deflection.

To operate the electronic throttle system, the accelerator pedal requires a position sensor (APS) whose signal is read by the EMS. The throttle body also has a throttle position sensor (TPS) for the system to know actual deflection of the throttle. The APS command signal and TPS feedback signal form a closed-loop throttle position control system, which can be implemented separately by an independent controller – an electronic throttle controller. Fig. 3 shows block diagram of an electronic throttle-by-wire (TBW) closed-loop control system.

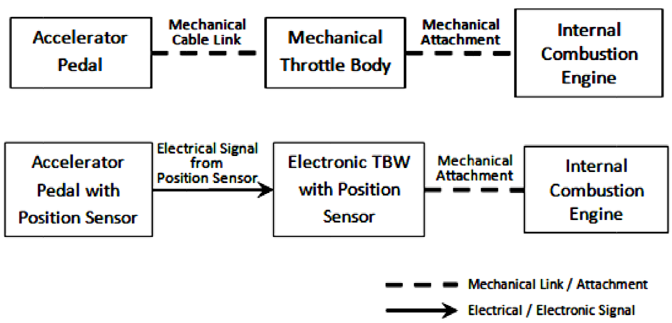

Fig. 1. Vehicle's throttle system: mechanical throttle (top) and electronic throttle (bottom)

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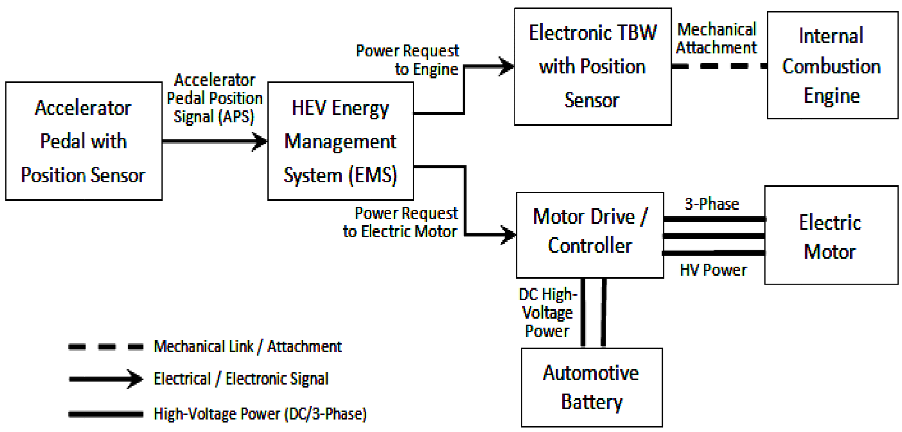

Fig. 2. Signal and power flow from accelerator pedal to propulsion power sources in a parallel hybrid electric vehicle

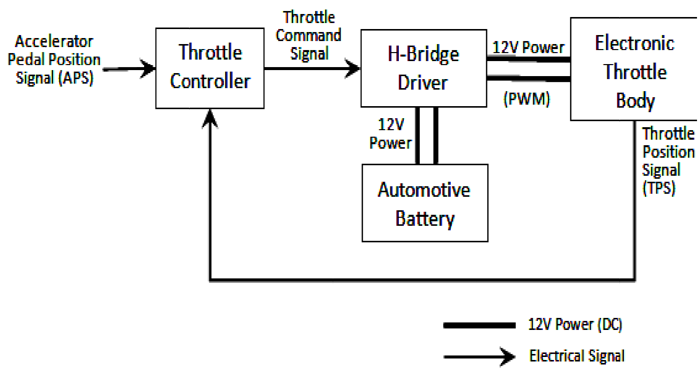

Fig. 3. Electronic throttle-by-wire (TBW) closed-loop control system

In this HEV conversion project, to reduce the additional required components, throttle position control is executed by the same controller which performs energy management - the EMS controller [1]. In this project, the controller is built on *National Instruments*' configurable FPGA-based controller – the *CompactRIO*, and programmed with *LabVIEW Real-Time*, for a real-time, deterministic control.

Various research has been reported on modeling and analysis of electronic throttle control. The intricate part of such system includes the hard nonlinearity of the pre-loaded spring, friction and unknown system parameters [2]. System identification is carried out with experimentation, data analysis and understanding of system behaviour to determine the required parameters, following which, non-linear control design is carried out using input-output feedback linearization technique [2], [3]. In [4], nonlinear control of the throttle system is also proposed, simulated and analyzed using SimMechanics and implemented with dSPACE RCP hardware, highlighting the friction compensator and joint stiction actuator, in addition to the nonlinear spring compensator, dead-zone and filtering.

A discrete PI controller with parameter scheduling, combined with feed-forward controller is simulated and tested in [5] but without friction or backlash compensation. A dual control algorithm is investigated in [6], using Xilinx-FPGA for process modeling and control implementation. For small initial throttle movement from zero, the system is regarded as linear and a large-signal control mode with PID controller is utilized. For all other instance, a small-signal control mode is employed, along with nonlinear friction, spring force compensation and air disturbance [6].

II. Electronic TBW System

The electronic throttle-by-wire system can be broken down into several parts and components, as described below:

A. *Electronic Throttle Body (ETB)*

The heart of the TBW system is an electro-mechanical device, called an electronic throttle body (ETB) - an electrically-actuated butterfly valve with a spring return (Fig. 4). It is essentially a brushed DC motor coupled directly to the throttle blade. Since this an automotive application, the ETB is powered by the vehicle's 12V battery, as shown in Fig. 3. The ETB used in this hybrid vehicle conversion project is manufactured by *BOSCH*, model no. *DV-E5*, with a valve diameter of 50 mm (Fig. 4).

B. *Motor Driver*

A motor driver is a power-electronics device responsible to regulate the flow of power from the 12V battery to the electronic throttle. It is essentially a 2-way DC H-bridge driver, consisting of a set of 4 power transistors that control the rotational direction and speed of the motor. When energized, only a pair of transistors will be active, which determine a clock-wise or anti-clockwise direction of rotation of the throttle blade.

By varying the duty cycle of the switching transistors (PWM modulation) - which are switching at a rate of several kHz - effective current delivered to the motor is varied, so that deflection rate and angle of the throttle blade can be controlled. The motor driver receives an analog input signal from the accelerator pedal's position sensor (APS) and sends variable pulse-width-modulated (PWM) 12V power to the ETB, to vary the position of the throttle blade.

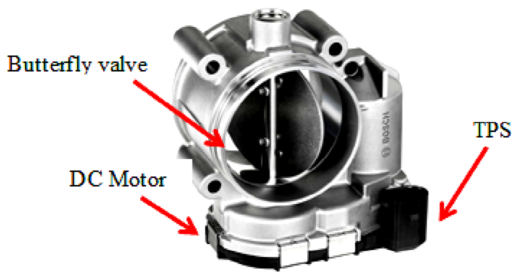

Fig. 4. Electronic throttle body (ETB) - *BOSCH DV-E5*

C. Throttle Controller

Without closed-loop control, it is impossible to achieve and maintain a certain desired opening of the throttle as any small variation in the ETB's input power or other external disturbances can immediately swing the throttle blade to the left or right. Thus, a potentiometer-type throttle position sensor (TPS), which is built into the ETB, provides feedback of instantaneous blade position to the throttle controller, which will process this signal in a closed-loop control system to determine the output duty cycle of the H-bridge driver, to achieve a certain desired setpoint of throttle position (Fig. 5).

D. Throttle Position Control System

A throttle position control system, shown in Fig. 3 and Fig. 5, ensures the TBW system closely follows the desired throttle opening as requested by the driver, represented by depression of the accelerator pedal. A PID controller makes necessary corrections to the throttle position via the throttle controller in closed-loop control, by comparing the setpoint (SP) input to the process variable (PV) signal from the TPS. The controller generates an output of PWM duty cycle control signal as the manipulated variable (MV) to the motor driver to allow the butterfly valve to be opened or closed according to the requested SP, and the TPS returns position feedback to the controller on its actual opening. This process continues until the desired SP of throttle position is achieved.

III. Hardware Implementation

A. Throttle Controller – CompactRIO

As part of an HEV retrofit-conversion kit and for fast deployment, throttle controller in this project is implemented on the same hardware platform as the HEV's energy management system (EMS): *National Instruments' (NI) CompactRIO*. The control hardware consists of an embedded controller with an FPGA backplane, for deterministic and stand-alone deployment, capable of both real-time control and continuous data logging. It is equipped with a host of modular front-end signal-conditioning possibilities (cRIO modules) for interfacing with actuators and sensors of various signal types.

B. NI cRIO Configuration

Fig. 6 shows terminal assignment of the two cRIO modules used in the TBW application – NI 9201 and NI 9401, along with the controller itself, NI cRIO-9076. The NI 9201 analog input module is used to receive 0-5V analog input from the accelerator pedal: APS and the redundant throttle position sensors: TPS 1 and TPS 2. The NI 9401 digital I/O module is used to generate digital PWM signals for the gate input of the H-bridge driver, which regulates power for the throttle motor. Only one digital channel of the NI 9401 is used for the throttle driver while other digital channels are used for energy management system (EMS) of the converted HEV.

C. H-Bridge Driver

The model of the H-bridge throttle driver is *MD30C* from *Centronics*. It receives digital PWM pulse train from the NI 9401 module to control the effective current injected into the throttle motor, to achieve certain position of the throttle blade.

Fig. 7 shows a complete wiring diagram of the entire electronic TBW system.

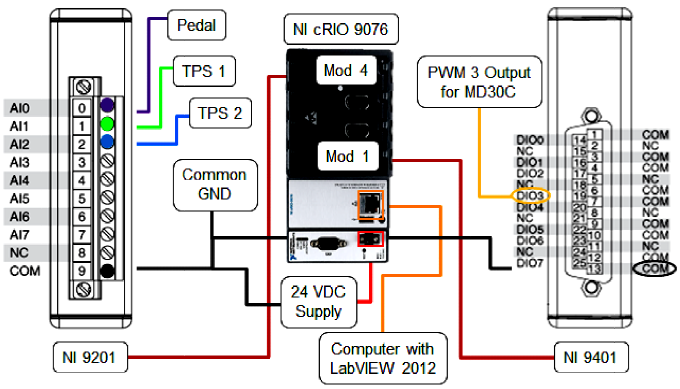

Fig. 6. *NI cRIO* terminal assignments for implementation of TBW system

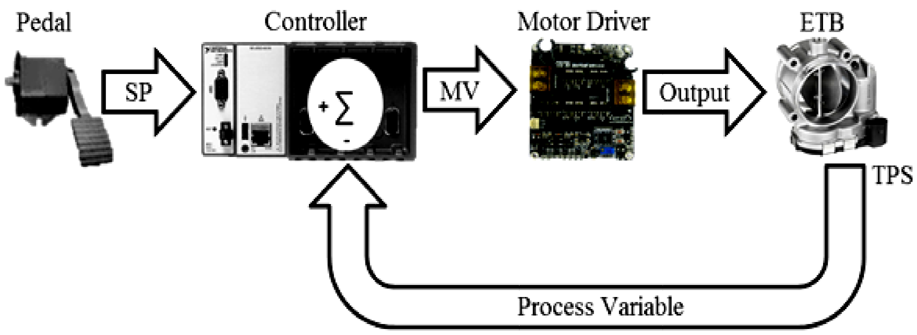

Fig. 5. Throttle position control system

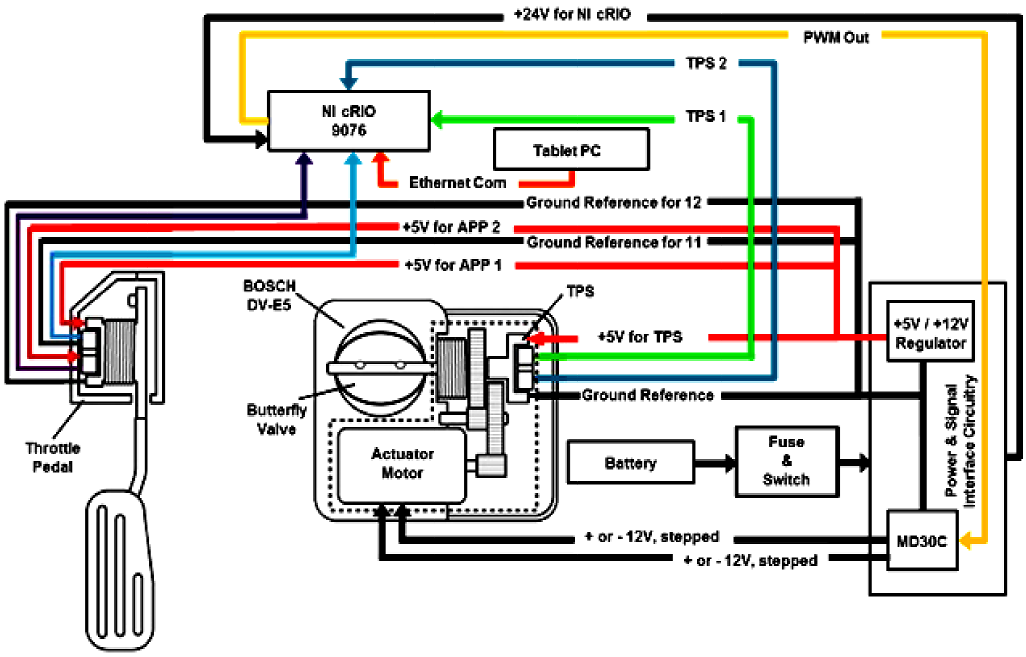

Fig. 7. Wiring diagram of electronic TBW system

D. Bench Test Configuration and Testing

Fig. 8 shows an integrated assembly of accelerator pedal, electronic throttle valve and control switches and indicators for the purpose of configuration, programming, testing and control tuning of the electronic TBW system. Bench testing of the TBW is crucial for analysis of dynamic response and fine-tuning of PID control parameters. An interface board is provided for inter-connection of various signals of the accelerator pedal, throttle, H-bridge driver and throttle controller. The *NI cRIO* controller is powered by a regulated 24 VDC supply while the throttle itself is supplied by a separate 12V power source. All sensors such as the APS and TPS which require +5V supply are provided by a regulated 5V source on the interface board using the same 12V battery supply for the ETB. In addition, a calibrated oscilloscope and function generator are used to monitor and compare the PWM pulse-train output of the NI 9401 module.

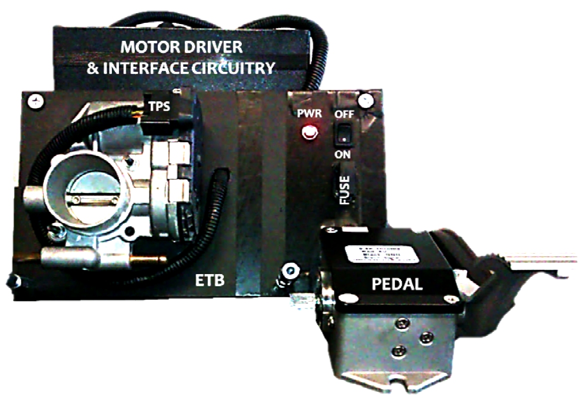

Fig. 8. Bench-test assembly for configuration, testing and contro
l tuning

During the bench test, it was observed that I/O signals were stable (negligible noise) when the ground points of the various I/O were connected to the common ground of the two separate power supplies. Similarly for vehicle implementation, all grounding need to be connected to the vehicle chassis, which is the 12V ground of the electrical subsystem (connected to the battery's *–ve* terminal).

IV. Development of Real-Time Control Program

A. Front Panel Development on LabVIEW

One of the benefits of using *NI-LabVIEW* platform for controller development is that the graphical programming language comes with a front panel which can immediately serve as the user interface; thus, no additional programming is needed to develop the graphical user interface (GUI).

This intrinsic design of *LabVIEW* considerably shortens the development time for control prototyping and testing as the same interface used during bench testing and control tuning can also be used for end-user interface, with minor or no modification at all. By using the Tab feature of *LabVIEW*, separate features can be made available to different users, e.g. programmer, tuning engineer, and end-user or driver.

One such GUI developed during the project is shown in Fig. 9, designed for dynamic analysis and tuning of the throttle control system. This interface has switches to choose between *MANUAL* and *AUTO-PID* control for the PWM output to the H-bridge driver. The *MANUAL* option will override the calculated PWM output of the PID controller. The front panel also provides graphical indicators and waveforms to observe the response of the ETB in real time.

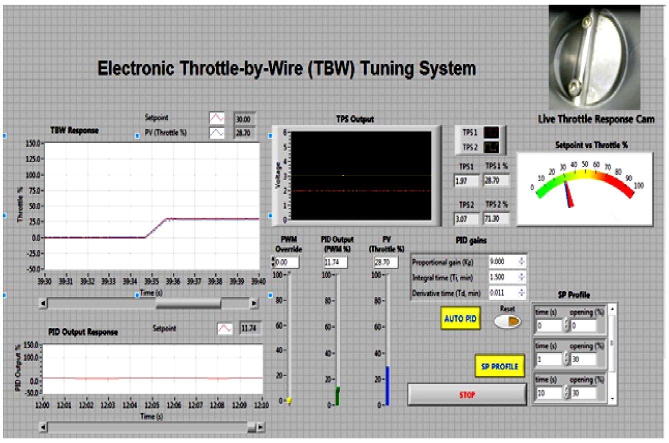

Fig. 9. *LabVIEW* GUI front panel during development and control tuning

B. Setpoint Configuration

In the program, the setpoint (SP) for throttle position is provided with a choice of pedal input (actual TBW application) or user-programmed setpoint profile (for analysis and controller tuning). Fig. 10 shows the *LabVIEW* code for throttle pedal analog input signal for control of the ETB via PID control. Manual override of the PID output is also possible to compare the response of the throttle with and without PID.

The setpoint profile control is shown in Fig. 11, for generating a timed and pre-specified setpoint value into the PID block. This feature is useful for PID control tuning: investigation of system response to variation in controller parameters of Proportional gain (K_p), Integral time (T_i) and Derivative time (T_d). This function is similar to an auto-cruise speed control application of a vehicle.

C. TPS Feedback Configuration

Throttle position feedback as shown in Fig. 12 is the process variable (PV) of the TBW system, an input for the PID block to perform PID error corrections. The actual TPS input voltage range is measured in the field and the min and max values are inserted into the '*EGU to %PID*' block to allow the PID controller to read the PV in percentage values and perform position control.

D. PWM Output Configuration

The pulse-width-modulated (PWM) pulse-train output is generated through the PID block by configuring the NI 9401 digital I/O module to 'PWM Out' mode with a signal frequency of 10 kHz (Fig. 13). The variable duty cycle pulse train is fed into the H-bridge circuit, whose *LabVIEW* code is shown in Fig. 14.

E. PID Parameter Tuning

PID tuning for the TBW control can be performed with the PID block shown in Fig. 14, by using tuning methods such as Ziegler-Nichols. Some proposed PID parameters are also used, as suggested in the simulation results of [2] and [3], which show good throttle performance. The ETB response is observed to be stable and consistent when the following PID gains are used: $K_p = 0.98$, $T_i = 0.019$ and $T_d = 0.002$. (Fig. 15). However, as can be seen from the response, further PID tuning is required to improve the performance. As shown in Table I, some qualitative observations can be made on the throttle response when the controller gains are increased. Indication of improved system performance includes smaller steady-state error, less overshoot and faster settling time.

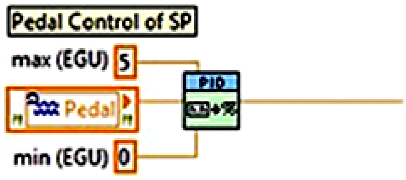

Fig. 10. Pedal control of setpoint for PID block

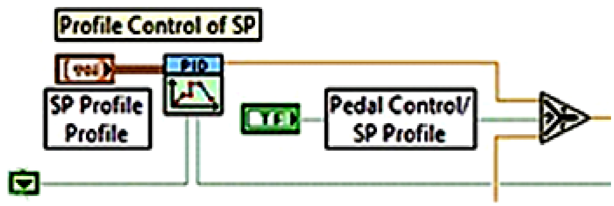

Fig. 11. Profile control of setpoint (optional)

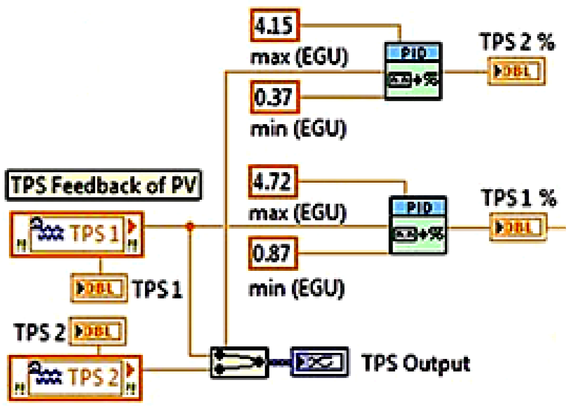

Fig. 12. TPS feedback as PV

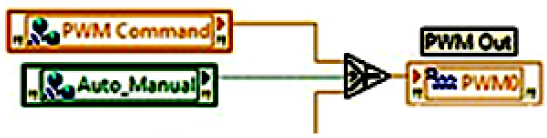

Fig. 13. PWM output block

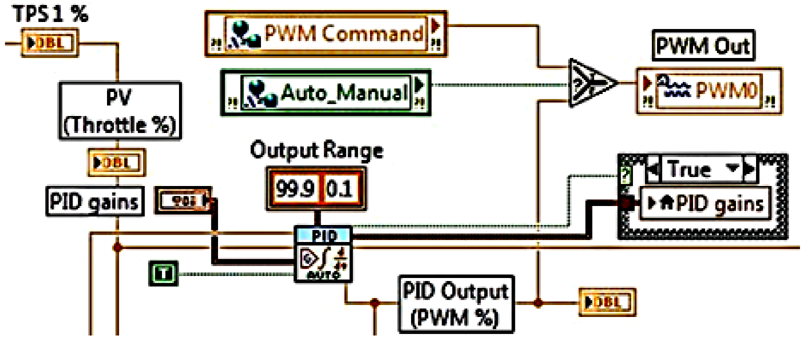

Fig. 14. PID controller block

V. Conclusion

One of the critical systems for conversion of a conventional vehicle into a hybrid electric vehicle is the electronic throttle-by-wire (TBW), required if the existing vehicle is not already equipped with an electronic throttle. A TBW system requires a finely-tuned control system to ensure a stable and reliable throttle air intake for the engine. This paper describes development and implementation of the TBW by using a *BOSCH DV-E5* throttle body, *NI CompactRIO* for throttle controller and *LabVIEW Real-Time* software for the control system and user interface. Preliminary results of throttle performance are obtained using certain values of PID gains. However, it is clear that further work is required, including modeling and dynamic simulation of the closed-loop control system, in order to fine-tune the controller and achieve an improved throttle response.

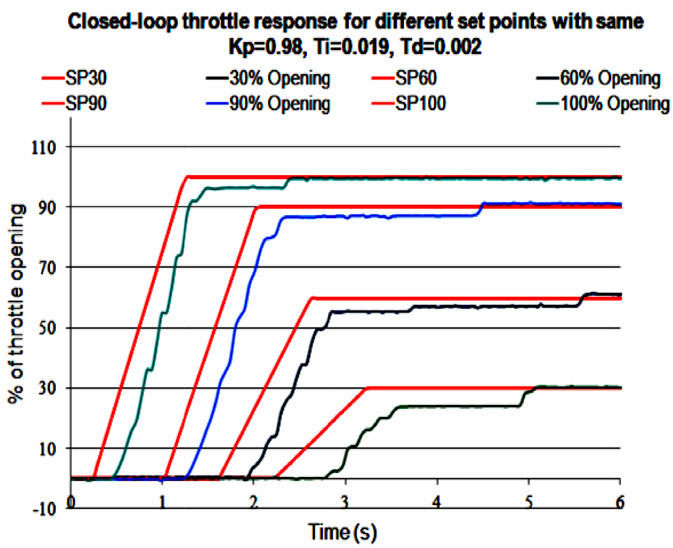

Fig. 15. Throttle response with best PID gains

TABLE I. Effect of Increasing PID Gains on Throttle Response

	Rise Time	Overshoot	Settling Time	Steady-State Error
K_p	⬇	⬆	Small Change	⬇
K_i	⬇	⬆	⬆	Eliminated
K_d	Small Change	⬇	⬇	Small Change

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