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IDLE SPEED CONTROL FOR AUTOMOTIVE ENGINES WITH AN INTEGRATED STARTER ALTERNATOR

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Abstract: This paper describes a model-based control design methodology for engine idle speed control in a mild hybrid-electric vehicle based on an integrated starter-alternator architecture. The paper describes physically based models of the engine and integrated starter-alternator, describes the simulation environment, outlines the control design and presents simulations results. The results presented in the paper are in a form suitable for rapid control prototyping and vehicle implementation. *Copyright © 2002 IFAC*

Keywords: hybrid-electric vehicles, engine modelling, ISC, ISA, neural network, PID tuning.

1. INTRODUCTION

Idle Speed Control (ISC) of automotive engines is a fundamental problem that has been studied for many years along with the continuing development of electronic engine management technology for automotive engines. Good ISC is a fundamental characteristic of any production engine management strategy. Simply stated, the basic goal of any ISC strategy is to achieve a stable and smooth regulation of engine idle speed in the presence of both driver-induced and random load disturbances.

In recent years, hybrid-electric (HE) drivetrains have been proposed as a possible alternative to conventional internal combustion engines. HE drivetrains permit engine downsizing for a given automobile class, resulting in fuel economy and possibly exhaust gas emissions benefits. One possible HE drivetrain configuration, also called a "mild hybrid" is a parallel hybrid that uses an Integrated Starter Alternator (ISA) in the form of an electric machine designed be placed where a flywheel is conventionally placed in a combustion engine. The ISA can assist engine start and launch, provide regenerative braking capabilities, supports larger electrical loads, and can provide torque assist during transient manoeuvres. An additional function that can be performed by an ISA is to smooth load torque fluctuations to permit better idle speed control.

Engine speed excursions due to load disturbances can be reduced if the engine has an external torque source with faster torque production response, such as an ISA. With help of the ISA, an ISC control designer has the benefit of an extra degree of freedom for control design, which is relatively independent of engine states even though the torque producer couples directly with the crankshaft. Being an electric machine, an ISA has a fast torque production response that can be beneficial to load disturbance rejection.

As expected, many different approaches have been tried for the solution of the ISC problem for SI engines. See (Li, Simpson and Yurkovich) for a review of different methods. Some researchers (Sun *et al.* 2000) treat the engine as linear system during idle speed condition and have used linear feedback control techniques, such as PID, state feedback and optimal control, to design the controller. Some use nonlinear control techniques, such as adaptive control (Feng *et al.* 2000), robust control (Orzel *et al.* 1996) and sliding mode control (Yurkovich *et al*, 2001) to achieve same goal. Other approaches, such as Fuzzy logic (Boverie *et al.* 1994) control and neurocontrol (Li and Yurkovich, 2000; Gorinevsky *et al.* 1996; Livshz *et al.* 1994), have also been tried to solve ISC problem. Most of the above approaches use the throttle and spark advancing as control inputs. Because of inherent delay between intake stroke and combustion stroke, feedback control is not enough to get desired response. Therefore, feedforward or anticipatory control using spark advancing is also used to get better response for disturbance rejection. However, anticipatory controls improve performance only for ECU scheduled disturbances whose magnitude and/or instance of occurrence are known, such as air conditioning, headlights, fans and etc. For random disturbance input, anticipatory control is not viable for implementation. Besides, using spark feedforward does not result in uniform response during disturbance kick in and kick out. The reason is that spark advancing is bounded, which results from the conditions of knocking and misfiring at the two extremes of dynamic range of this actuation mechanism.

Since the most commonly found instances of ISAs are AC induction motors, they will be chosen for this current study. AC induction motors are not simple power plants to handle. There are many issues related to motor modelling and control.

For instance, torque response of electric motors with torque controller is not just simply a first order system; rotor resistance greatly affects the motor performance; several states are difficult to measure physically (Celso, 1998; Riccardo et al., 2000). If one also considers magnetic saturation and overall efficiency, it becomes clear that this is not a small problem. The paper is organized as follows: in the next section we describe the modelling issues and approaches that were considered and the software tools that were used. In Section 3, the control development is described, and simulation results are presented in Section 4. Section 5 draws conclusions as to the benefits of ISC using an ISA.

2. MODEL DEVELOPMENT

The IC Engine-ISA system chosen for this paper consists of a gasoline engine and a generic pancake AC induction motor that is coupled directly to the engine crankshaft between engine block and transmission, as shown in Fig. 1. Fig. 2. depicts a block diagram representation of the system dynamics based on physical principles. From Fig. 2, we can see that the dynamics of relevance to this problem are:

1. Engine Intake manifold pressure dynamics.
2. Engine torque production dynamics (delay).
3. Composite system Inertia dynamics.
4. ISA torque production dynamics.

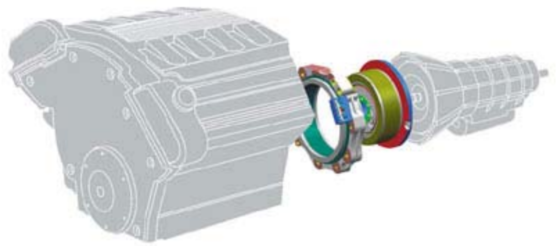


Fig. 1. System configuration of SI engine with ISA.

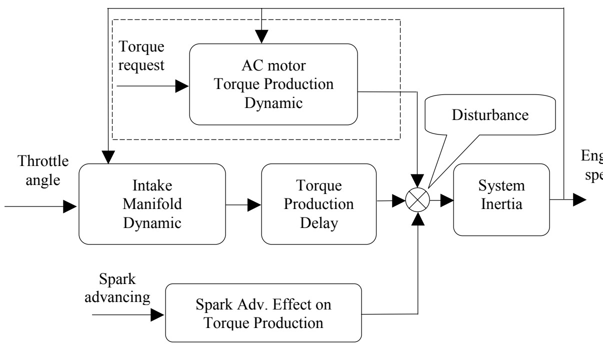


Fig. 2. System block diagram.

2.1 Internal combustion engine modelling.

Application of elementary physical principles to the IC engine (Rizzoni, 2000) results in the following continuous time differential equations:

$$\frac{d}{dt}p_m + K_2\omega p_m = K_1\alpha,\ K_1\alpha = \dot{m}_{TH}\frac{RT_m}{V_m},\ K_2 = \frac{\eta_v V_d}{4\pi V_m}$$

$$J_T\frac{d}{dt}\omega + b_T\omega = \tau_{eng} + \tau_{sp} - \tau_d$$

$$\tau_{eng} = K_\tau p_m\left(t - t_d\right)$$

$$\tau_{sp} = K_{sp}\delta$$

The linearized engine model in crank angle domain at idle speed ω_0 is:

$$\frac{dp_m}{d\theta} = -K_2 p_m + \frac{K_1}{\omega_0}\alpha - \frac{K_1\alpha_0}{\omega_0^2}\omega,\ K_1\alpha = \dot{m}_{TH}\frac{RT_m}{V_m},\ K_2 = \frac{\eta_v V_d}{4\pi V_m}$$

$$\frac{d\omega}{d\theta} = \frac{1}{J\omega_0}\tau - \frac{\tau_0}{J\omega_0^2}\omega$$

$$\tau = \tau_{eng} + \tau_{sp} - \tau_d$$

$$\tau_{eng} = K_\tau p_m\left(\theta - \theta_d\right)$$

$$\tau_{sp} = K_{sp}\sigma$$

Here, p_m, α, ω, τ and σ are *perturbations* around operating point of ω_0.

2.2 AC induction machine modelling.

Fig. 3 shows the block diagram representation of AC induction machine dynamics.

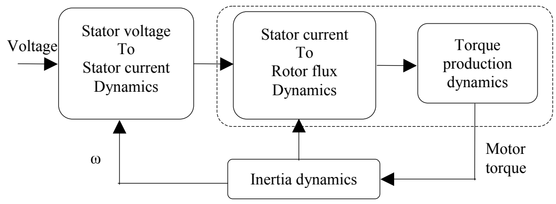


Fig. 3. Block diagram of AC induction machine.

Looking at Fig. 3, we can see that there are essentially two parts representing the Voltage-to-Torque production dynamics for an AC Induction machine. The first part is the voltage to current production dynamics and the second part is the current to torque production dynamics. Detailed models of the voltage to current dynamics have been described in Celso (1998). For the sake of brevity, the nonlinear continuous time equations for a particular AC induction motor in the rotor reference frame are reproduced below.

$$\frac{di_d}{dt} = \left(-\frac{R_S}{\sigma} - \alpha L_m\right)i_d + \omega_e i_q + \left(\alpha\beta\right)\psi_d + \beta\omega_r\psi_q + \frac{1}{\sigma}u_d$$

$$\frac{di_q}{dt} = \left(-\frac{R_S}{\sigma} - \alpha L_m\right)i_q - \omega_e i_q + \left(\alpha\beta\right)\psi_q - \beta\omega_r\psi_d + \frac{1}{\sigma}u_q$$

$$\frac{d\psi_d}{dt} = -\alpha\psi_d + \left(\omega_e - \omega_r\right)\psi_q + \alpha L_m i_d \quad ,$$

$$\frac{d\psi_q}{dt} = -\alpha\psi_q - \left(\omega_e - \omega_r\right)\psi_d + \alpha L_m i_q$$

$$\frac{d\omega_r}{dt} = \frac{P}{2J}\left(k_t\left(\psi_d i_q - \psi_q i_d\right) - T_l\right)$$

i_d, i_q, u_d and u_q are stator current and voltages in the rotating reference frame; ψ_d, ψ_q are rotor *d-q* fluxes in the rotating reference frame; ω_e is the rotating reference frame speed; ω_r is the electrical rotor speed; T_l is the load torque and

$$\alpha=\frac{R_r}{L_r},\ \beta=\frac{L_m}{L_r\sigma},\ \sigma=\frac{L_sL_r-L^2_m}{L_r},\ k_T=\frac{3}{2}\frac{P}{2}\frac{L_m}{L_r}.$$

Assuming a current-fed inverter instead of a voltage converter, the motor model is reduced to a third order system as follows:

$$\frac{d\psi_d}{dt} = -\alpha\psi_d + \left(\omega_e-\omega_r\right)\psi_q + \alpha L_m i_d$$

$$\frac{d\psi_q}{dt}=-\alpha\psi_q-\left(\omega_e-\omega_r\right)\psi_d+\alpha L_m i_q$$

$$\frac{d\omega_r}{dt} = \frac{P}{2J}\left(k_t\left(\psi_d i_q-\psi_q i_d\right)-T_l\right)$$

If we set $\psi_q=0$, the reduced order motor model becomes:

$$\frac{d\psi_d}{dt} = -\alpha\psi_d + \alpha L_m i_d$$

$$0=-\left(\omega_e-\omega_r\right)\psi_d+\alpha L_m i_q$$

$$\frac{d\omega_r}{dt} = \frac{P}{2J}\left(k_t\psi_d i_q-T_l\right)$$

If ψ_d can be kept constant, and not allowed to saturate, the torque produced by motor is only determined by i_q. The current to torque production dynamics corresponding to the above equations is almost instantaneous in response to current.

In order to keep ψ_d constant, we can simply apply PID control on i_d to maintain ψ_d at constant value. Actually, there are many issues related to field-oriented flux control and estimation, but they are beyond the scope of the ISC problem. For this paper, we assume that all the states of the motor are available for control design. In the motor inertial dynamics equation, the torque produced by the electric motor is a linear function of current i_q. In fact, there still exist some dynamics in the torque production process because a current-fed inverter is not an ideal conversion device and it does have dynamic behaviour between the desired current command and actual current output. However, these dynamics occur on a much faster time scale and can be neglected for our purpose. Such an approach has been previously described in Novotny (1996), where the desired current to actual current (and therefore, torque) dynamics is assumed to be of the first order. Empirical data show that dynamic response can be modelled as first order system with time constant of 0.01 second or even less. For our purpose, we will then model AC induction motor torque production dynamics as a first order system with time constant of 0.01 second in the stator reference frame. Therefore, the simplified motor model is:

$$\tau_{const}\frac{d\tau_{isa}}{dt}=-\tau_{isa}+\tau_{isa\_ref},\tau_{const}=0.01$$

The above equation linearized at idle speed at ω_0, and converted to crank angle domain become:

$$\tau_{const}\frac{d\tau_{isa}}{d\theta}=\frac{-\tau_{isa}}{\omega_0}+\frac{\left(T_{isa\_0}-T_{isa\_ref\_0}\right)}{\omega_0^2}\omega+\frac{1}{\omega_0}T_{isa\_ref},\tau_{const}=0.01$$

τ_{isa}, ω and T_{isa_ref} are *perturbations* around the operating point at ω_0. These equations have been implemented as a block in Simulink, as shown below.

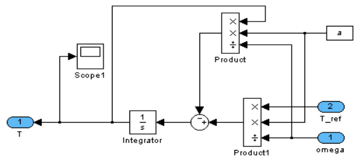


Fig. 4. Simulink implementation of ISA dynamics.

2.3 Combined system model

The linearized combined system model is listed below:

$$\frac{d}{d\theta}p_m = -K_2p_m + \frac{K_1}{\omega_0}\alpha - \frac{K_1\alpha_0}{\omega_0^2}\omega,$$

$$K_1\alpha = \dot{m}_{TH}\frac{RT_m}{V_m},K_2=\frac{\eta_v V_d}{4\pi V_m}$$

$$\frac{d\omega}{d\theta}=\frac{1}{J\omega_0}\tau-\frac{\tau_0}{J\omega_0^2}\omega$$

$$\tau=\tau_{eng}+\tau_{isa}+\tau_{sp}-\tau_d$$

$$\tau_{eng}=K_\tau p_m\left(\theta-\theta_d\right)$$

$$\tau_{sp}=K_{sp}\sigma$$

$$\tau_{const}\frac{d\tau_{isa}}{d\theta}=\frac{-\tau_{isa}}{\omega_0}+\frac{\left(T_{isa\_0}-T_{isa\_ref\_0}\right)}{\omega_0^2}\omega+\frac{1}{\omega_0}T_{isa\_ref},$$

$$\tau_{const} = 0.01$$

The control inputs to the system are α, σ and T_{isa_ref}, and the system output is the engine (and ISA) speed ω. Once again, we remind the reader that the variables are *perturbations* about their nominal values.

Physical nonparametric modelling in the form of Neural Networks was also explored. Initial results show that these can be very useful for modelling the overall system due to their capacity to capture system nonlinearities and delays. Previous approaches to the use of Neural Networks to model the system dynamics are described in Gorinevsky (1996) and Li (1996).

For this paper a Neural Network ARX model was developed using a two layers feedforward perceptron. The hidden layer has neurons with tansig (hyberbolic tangent) activation whereas the output layer has linear neurons. The regression vector was chosen to be [α(k), α(k-1), σ(k), σ(k-1), T_{isa_ref}(k), T_{isa_ref}(k-1), T_{isa_ref}(k), T_{isa_ref}(k-1), ω(k-1), ω(k-2), ω(k-3)] and the output vector is [ω(k)]. The structure of the observer is shown in Fig. 5.

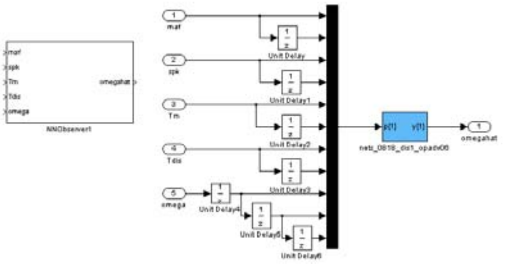


Fig. 5. NNARX model of idle speed dynamics

The resulting network was trained using the Levenberg-Marquardt back propagation training method. The system inputs and outputs for training were obtained by putting the plant under PI control and injecting a prescribed disturbance profile. The controller outputs and the disturbance profile were then used as the training inputs for the model. The plant response was taken as the target. The entire training can be done offline after all the data has been collected via an experimental run. Fig. 6. shows the various disturbance profiles chosen for the network training and testing. The topmost profile was chosen to generate training data. The remaining two were chosen to test the model performance.

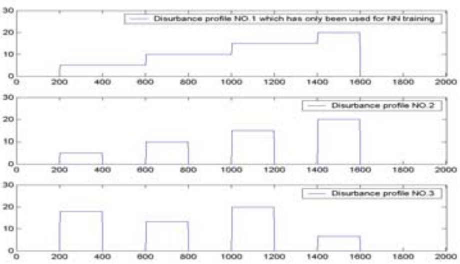


Fig. 6. Disturbance profiles for training and testing NNARX model of idle speed dynamics.

Fig. 7. shows the NN model performance for the above disturbance profiles, which is the model response to the training profile after training. Fig. 8. and Fig. 9. are for the other two disturbance profiles mentioned above. From these plots we can conclude that the model response is quite good for the region of training data used. Since the training data was generated with the plant under closed loop control, this model is accurate in regions where the plant output is close to the idle setpoint.

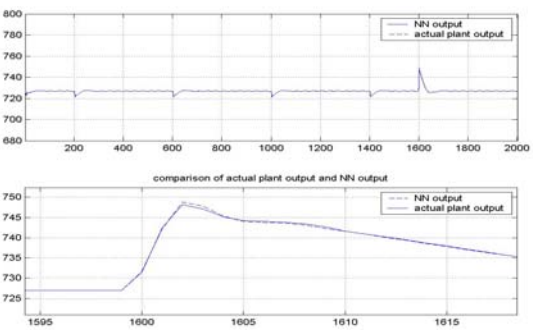


Fig. 7. NNARX model performance

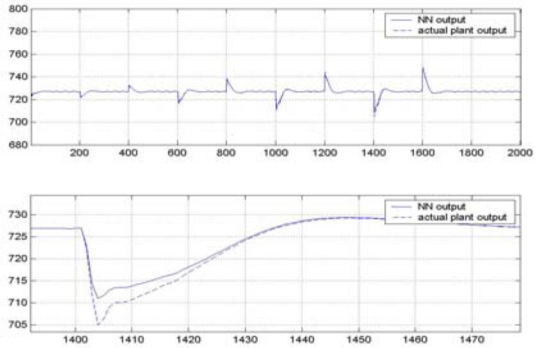


Fig. 8. NNARX model performance

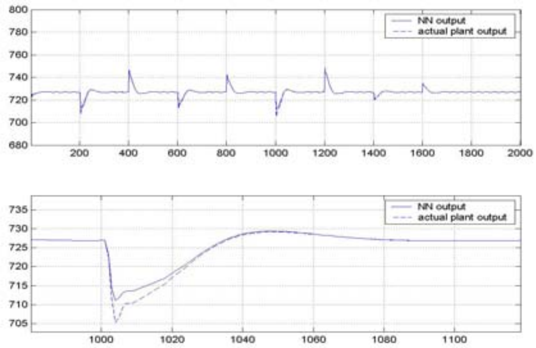
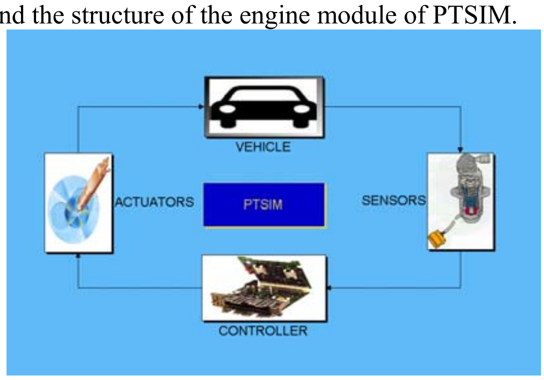


Fig. 9. NNARX model performance

2.4 Software tools

In this section, we describe the simulation environment used for this study. At this point we note that this study is based purely on simulation models. We feel that this is a necessary first step towards the development of model based powertrain controls. Future publications will be related to extending this work to the control of an actual prototype.

The simulation program used for this paper was the Simulink based PTSIM (Powertrain simulator) model developed at the Ohio State University (Rizzoni *et al.*, 2000). The engine model of PTSIM is based on the nonlinear dynamic equations described in the earlier section. In addition, PTSIM includes fuel dynamics, emission models and corresponding controls, and also simulates the transmission, driveline and vehicle, to provide a complete simulation environment for powertrain control studies. Fig. 10. shows the graphical user interface and the structure of the engine module of PTSIM.



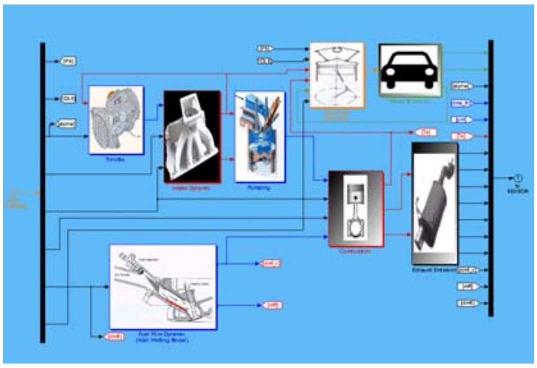


Fig. 10. Interface and engine module of PTSIM

For this paper, PTSIM was modified to include the torque production dynamics of the ISA as shown in Section 2.2.

3. CONTROL DEVELOPMENT AND RESULTS

This section describes the control methods used for this paper. Being the first step, the focus was on developing working controllers using PI control laws.

3.1 Controller Synthesis

It is known that engine speed has a steady state error in the presence of a disturbance with open loop control. In order to eliminate the steady state error, shorten the settling time and reduce the speed excursion during disturbance kick in and kick out, it is necessary to control the inputs, which, from the previous section, are assumed to be: the idle speed bypass valve, spark advance and motor torque.

For this paper, the following strategies were developed and tested:

1. Independent PI control of idle air bypass valve (IBV) and PI control of Spark only. ISA is not used. (This step is only to show the benefit of the ISA).
2. Strategy 1 plus anticipatory control of spark advance.
3. Strategy 1 plus independent proportional control of ISA torque.

PI controller tuning process

First the P control of throttle was tuned alone. Response was made faster even though steady state errors still exist. Adding I control for throttle. Once system oscillation is detected, P gain of throttle was reduced till desired response with null steady state errors and proper settling time (within 50 sampling times) was obtained. Spark P control was added and, at the same time, the P control of throttle was reduced till desired response. A little I control for spark advancing was allowed to reduce settling time and save fuel consumption by reducing airflow. ISA P control was added until it resulted in longer settling time. Finally the P control for throttle was reduced until the best response was obtained.

The explanations for above procedures are based on definition of phase margin. When the system begins to show oscillation, the system phase margin is close to critical value. In order to leave enough "space" for faster compensating components to be added on, we have to make main system "slower" to allow the added subsystems to have more "room" to improve overall system response. In one word, a system, especially a nonlinear system, with narrow phase margin (which varies with operating points) is not easily compensated through feedback control due to shifting of pole locations because oscillation poles can't always be cancelled.

3.2 Controller Testing

Fig. 11. shows the response with strategy 1. Even though the system gets zero steady state error, the speed excursion is still a lot. Table 1. shows the controller parameters used for this simulation.

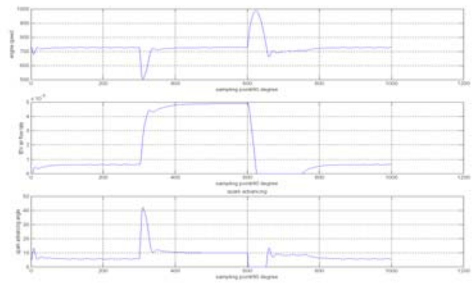


Fig. 11. Response using strategy 1.

Table 1. Controller parameters used for strategy 1.

Engine speed profile			Spark profile		
	Kick in	Kick out		Kick in	Kick out
RPM excursion	227 RPM	262 RPM	SP ADV peak	42°	0°
Controller	PID parameter		Controller	PID parameter	
	P	I		P	I
Gain	5e-5	5e-6	Gain	1.5	0.005

With PI control on spark advancing (strategy 2), speed excursion is reduced but is still more than 20% of the desired idle speed (727 RPM) as shown in Fig. 12. Table 2. shows the controller parameters used for this simulation.

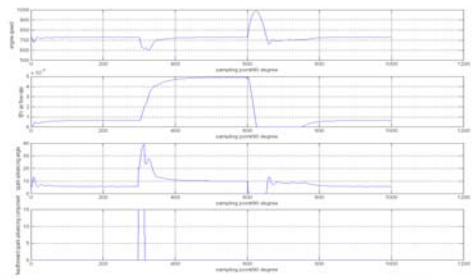


Fig. 12. System response using strategy 2.

Adding spark feedforward control on spark during the disturbance kick in, the speed excursion is smaller as shown in Fig. 12. It is clear that we can't use feed forward control on spark advancing during disturbance removal because retard spark advancing after TDC will cause misfire and higher HC emission. That means speed excursion reduction is limited if we only control throttle and spark.

Table 2 Controller parameters used for strategy 2.

Engine speed profile			Spark profile		
	Kick in	Kick out		Kick in	Kick out
RPM peak	127RPM	267 RPM	SP ADV	38.5°	0°
Controller	PID parameter		Controller	PID parameter	
	P	I		P	I
Gain	5e-5	5e-6	Gain	1.5	0.005

After including the ISA in the system, we have one more variable for control. Adding P control on motor torque with PI control on throttle and spark advancing (Strategy 3), the speed excursion falls into desired "window" which is less than ±10% of engine idle speed (Fig. 13.). The corresponding controller parameters are shown in Table 3.

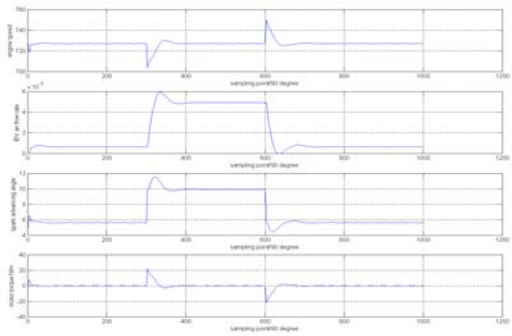


Fig. 13. System response using strategy 3.

Table 3. Controller parameters used for strategy 3.

Engine speed profile			Spark profile			Motor torque profile		
	Kick in	Kick out		Kick in	Kick out		Kick in	Kick out
RPM peak	27 rpm	27 rpm	SP ADV	11.5	4.6	Motor torque	20.5 Nm	-21 Nm
	PID parameter			PID parameter			PID parameter	
	P	I		P	I		P	I
Gain	5e-5	9e-5	Gain	1.5	0.09	Gain	9	0

4. CONCLUSIONS AND FUTURE WORK

This paper has presented a model-based methodology for the design if ISC control strategies in an ISA-based mild hybrid electric vehicle. The design has been validated on a vehicle simulator, and is in a form suitable for vehicle implementation using rapid control prototyping methods. Future work will include vehicle validation of the methods and control designs presented in the paper.

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