

Generator voltage stabilisation for series-hybrid electric vehicles

P. Stewart*, D. Gladwin, J. Stewart, R. Cowley

Department of Electronic and Electrical Engineering, University of Sheffield, Mappin St. Sheffield, UK

Abstract

This paper presents a controller for use in speed control of an internal combustion engine for series-hybrid electric vehicle applications. Particular reference is made to the stability of the rectified DC link voltage under load disturbance. In the system under consideration, the primary power source is a four-cylinder normally aspirated gasoline internal combustion engine, which is mechanically coupled to a three-phase permanent magnet AC generator. The generated AC voltage is subsequently rectified to supply a lead-acid battery, and permanent magnet traction motors via three-phase full bridge power electronic inverters. Two complementary performance objectives exist. Firstly to maintain the internal combustion engine at its optimal operating point, and secondly to supply a stable 42 V supply to the traction drive inverters. Achievement of these goals minimises the transient energy storage requirements at the DC link, with a consequent reduction in both weight and cost. These objectives imply constant velocity operation of the internal combustion engine under external load disturbances and changes in both operating conditions and vehicle speed set-points. An electronically operated throttle allows closed loop engine velocity control. System time delays and nonlinearities render closed loop control design extremely problematic. A model-based controller is designed and shown to be effective in controlling the DC link voltage, resulting in the well-conditioned operation of the hybrid vehicle.

Keywords: Automotive; Model-reference control; Time delay; Hybrid vehicles

1. Introduction

The series-hybrid electric vehicle drivetrain [1] consists of [2] petrol internal combustion (IC) engine, AC generator, DC rectification, battery energy storage, three-phase inverter and traction drives (Fig. 1). The stability of the DC link between the AC/DC rectifier and the traction motor inverter drive is operationally critical whether the prime mover be a petrol or diesel IC engine [3]. Firstly a prime objective for the operation of the traction drives is to deliver smooth, ripple-free torque. Controllers for this purpose rely on a stable DC link supply. Of particular importance is its ability to reject both dynamic and static loads from the traction drives and also an ability to absorb excess energy under regenerative braking regimes. A direct advantage of maintaining the integrity of the DC link voltage is the associated maintenance of the IC engine at its optimal operating point in terms of fuel efficiency and pollutants [3]. Again, the rejection of dynamics from drive loading is instrumental in achieving this goal.

The control system for the series-hybrid electric vehicle (SEV) has both cascaded and nested structures, and consists of a velocity set-point controller for the IC engine via an electronically actuated throttle, and current control loops around the traction drive units (Fig. 2). Traditionally this control loop relies on crank velocity feedback from a low resolution encoder. In the method presented here, high bandwidth/accuracy measurements are fed back from the DC link, a method which enables a higher performance controller to be implemented. There are a variety of power control strategies applied to hybrid electric vehicle (HEV) powertrains [4,5] which generally try to achieve a number of goals in a four cost function [2],

- maximise fuel economy
- minimise emissions
- minimise system costs
- maximise driving performance.

1.1. Choice of operating point

Of particular importance in this analysis is the twin goals of maximising fuel economy and minimising emissions such as hydrocarbons (HC) and carbon monoxide (CO). The

* Corresponding author. Tel.: +44 (0) 114 2225841; fax: +44 (0) 114 2225196.

E-mail address: p.stewart@shef.ac.uk (P. Stewart).

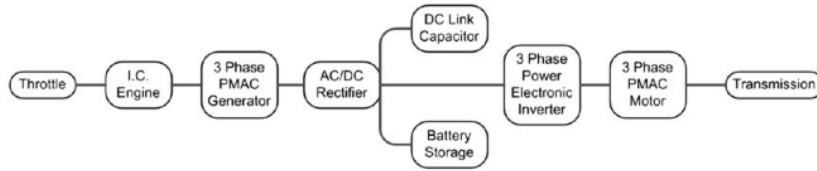


Fig. 1. Series-hybrid electric vehicle drivetrain.

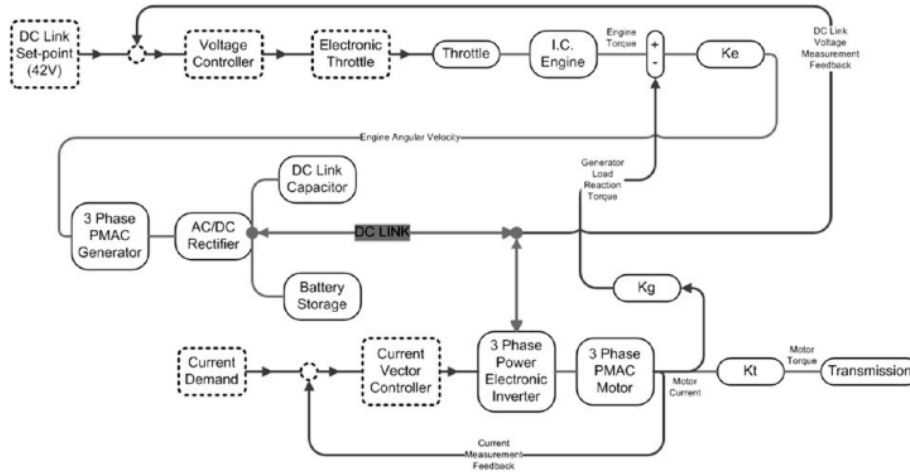


Fig. 2. Series-hybrid electric vehicle control structure.

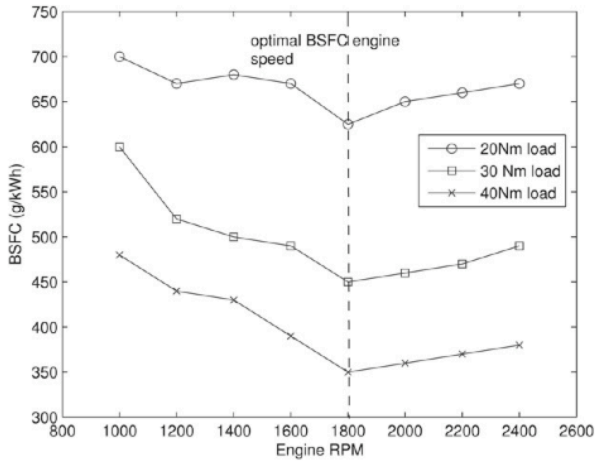


Fig. 3. Engine fuel consumption at varying loads.

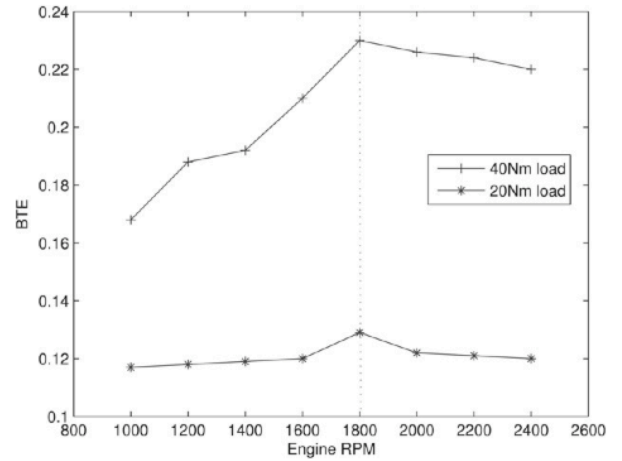


Fig. 4. Engine brake thermal efficiency at varying loads.

experimental fuel consumption and efficiency of a typical [6] four-cylinder four-stroke spark ignition engine with a nominal size of 1600cc. running on 91 octane gasoline are shown in Figs. 3 and 4.

Brake thermal efficiency (BTE) is calculated as

$$BTE = \frac{Pe}{\dot{m}_f LHV}, \quad (1)$$

where Pe is the effective power, \dot{m}_f is the fuel mass flow rate, and LHV the lower heating value of the fuel.

B the engine fuel consumption and thermal efficiency, have a corresponding optimal speed of 1800 rpm with respect to minimisation of fuel consumption and maximisation of efficiency.

With respect to emissions, CO decreases steadily through the experimental range (Fig. 5), whereas HC is relatively stable above 1600 rpm. The choice of operating point thus presents a tradeoff between objectives. HC emissions (Fig. 6) require an operating point above 1600 rpm, fuel consumption and efficiency is optimal at 1800 rpm. CO emissions are declining by approximately 0.05%/200 rpm in this region. It was thus decided to tradeoff CO emissions and fuel economy by choosing 2000 rpm as the preferred operating set-point, gaining a reduction in emissions, for a small reduction in efficiency.

2. Generator voltage control

Stable generator output voltage requires control authority over engine speed. A number of methodologies for idle speed

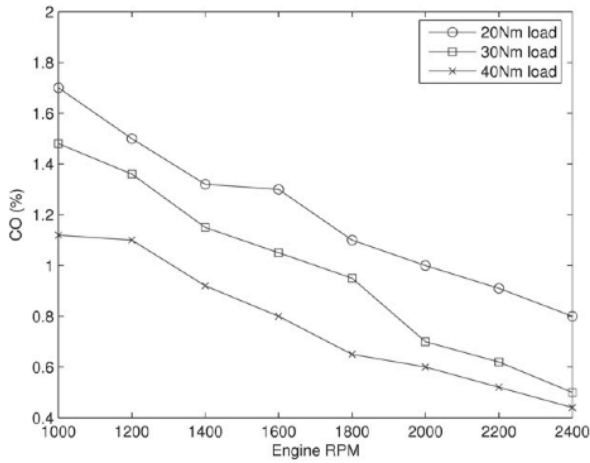


Fig. 5. Exhaust CO percentage at varying loads.

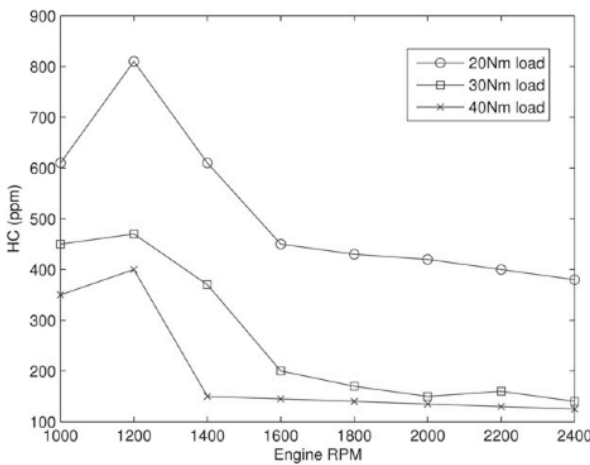


Fig. 6. Exhaust HC (ppm) at varying loads.

control (ISC) have been presented in the literature [10]. The primary motivation for ISC is to maintain a selected idle speed while rejecting torque disturbances such as power steering, alternator and automatic transmission loads.

In most production vehicles, the amount of air is controlled by a throttle bypass valve, sometimes augmented by additional valves actuated by an accessory load signal [11]. Alternatively, it is possible to directly control the throttle by direct electronic means rather than by mechanical linkages [12,13]. Compensation for the electronic throttle unit delay can be compensated to some extent by the introduction of an inner throttle control loop. However in this case, the controller is designed for the system “as is”, in order to investigate the potential for IC control with significant time delays, and also that the system would require a significant upgrade to improve the time delay even slightly. Air control provides large authority over the engine, however it is subject to intake manifold dynamics and intake-to-torque time delays. Direct control of the spark ignition timing provides a high bandwidth–low delay approach. However spark control has rather limited authority since excessive retardation of the ignition can cause combustion instabilities.

In the hybrid electric vehicle under consideration here, it is desired to produce a low-cost implementation of the control structure, and hence direct control of the throttle by electronic means is identified as the preferred technology if the inherent system delays can be overcome to produce a reliable speed controller. This is reinforced by the fact that a typical production ISC controller includes a PID loop for air control, a proportional loop for the spark control, feedforward loop for accessory loads, and other ad hoc loops for a variety of environmental compensation schemes.

The main characteristics of spark ignition engines is that they are highly nonlinear with significant time delay between throttle and torque production. The main objective of this research is to produce low-cost stable engine angular velocity control with good disturbance rejection characteristics. Torque-based control methods [14,15], generally rely on high precision feedback data such as cylinder pressure sensors, however cycle-to-cycle fluctuations coupled with low resolution crank angle measurements can pose problems for the stability of any closed loop control scheme. This often leads to the complicated implementation of further inner compensation schemes.

2.1. Smith Predictor

The general limitation of tuning rules for PID controllers is that they are derived for delay-free systems. For the system under consideration, the compound time delay (including throttle actuator dynamics and engine torque production etc.) between control actuator signal and torque production initiation at 2000 rpm was found experimentally to be 980 ms with a variability of ± 50 ms. Under such circumstances, a PID controller is extremely difficult to tune by standard tuning rules. A stable controller was eventually identified by trial and error with hardware in the loop. The performance of the controller is shown in Fig. 7. The experimental setup is discussed more fully in later sections of this paper. The regulator was attempting to stabilise the generated DC voltage at 42 V, the performance was as follows:

- Mean voltage 39.4 V
- Standard deviation 3.27 V.

Of particular note is the 9 s delay initialising to a quasi-steady-state condition. The chosen controller was a PD type with gains of 0.04 and 0.01 respectively. Any larger gain combinations or addition of an integral component to the controller resulted in better mean voltage values but increasing oscillatory response due to nonlinearities in the system. In Fig. 8 the PID gains have been set at 0.04, 0.01 and 0.01 respectively. The integral component has improved the mean voltage at the expense of increased voltage ripple. The performance of this controller was:

- Mean voltage 41.83 V
- Standard deviation 4.38 V.

This motivates the design of a predictive controller such as the Smith Predictor [8,9]. The predictor generally utilises a model of the plant characterized into a linear transfer function

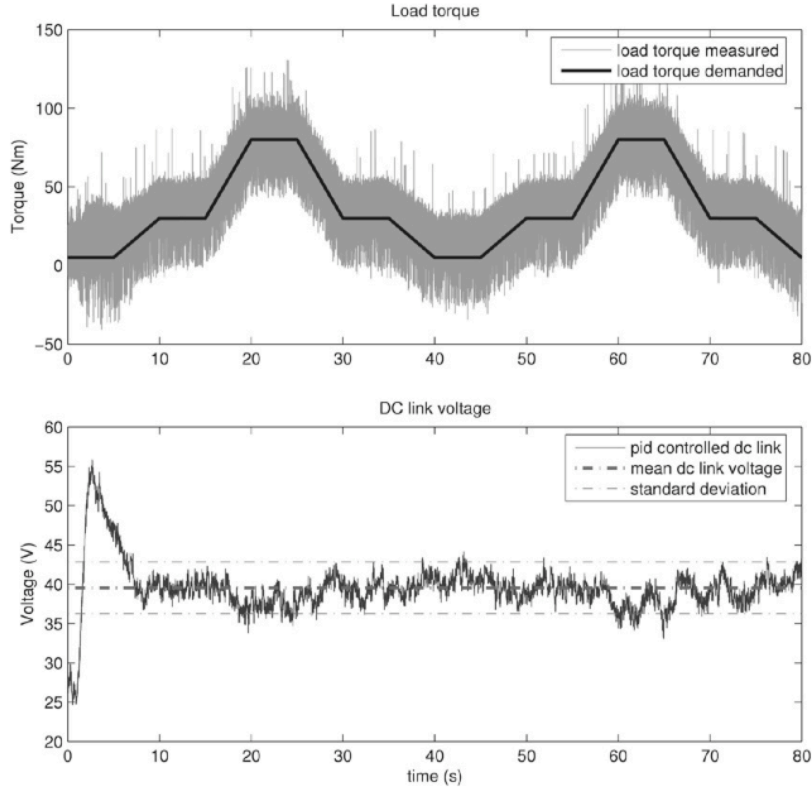


Fig. 7. Regulation of hybrid DC link voltage with PD controller.

accompanied by a time delay. A model is used to simulate the delayed and undelayed states of the plant, subsequently the real plant output is canceled by the delayed state, and the undelayed state is used as the feedback signal for the plant controller (Fig. 9). The transfer function of the plant and Smith Predictor can be written as [7]

$$\frac{Y(s)}{X(s)} = \frac{C(s)G_p(s)e^{-sT_p}}{1 + C(s)G_q(s) + C(s)[G_p(s)e^{-sT_p} - G_q(s)e^{-sT_q}]} \quad (2)$$

Hence if the model parameters exactly match the plant, Eq. (2) simplifies to

$$\frac{Y(s)}{X(s)} = \frac{C(s)G_p(s)}{1 + C(s)G_p(s)} e^{-sT_p} \quad (3)$$

The predictor removes the time delay effects from the control loop, converting the corresponding control design to a delay-free problem. The process model $G_p(s)$ contains a dead-time $T_p > 0$, with controller $C(s)$, and a loop containing a process model $G_q(s)e^{-sT_q}$.

The feedback signal is given by

$$Y_{FB}(s) = G_q(s)E(s)C(s) + (G_p(s)e^{-sT_p} - G_q(s)e^{-sT_q})E(s)C(s) \quad (4)$$

Assuming perfect modeling of the plant and delay, then

$$Y_{FB} = G_q(s)E(s)C(s) \quad (5)$$

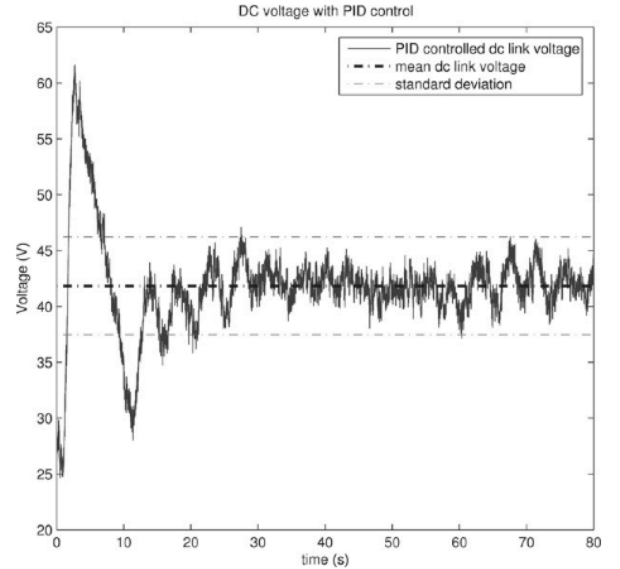


Fig. 8. Regulation of hybrid DC link voltage with PID controller.

Since

$$E(s)C(s) = \frac{1}{G_p(s)e^{-sT_p}} Y(s) \quad \text{and,} \quad (6)$$

$$G_q(s) = G_p(s)$$

then,

$$Y_{FB} = G_q(s) \frac{1}{G_p(s)e^{-sT_p}} Y(s) = e^{sT_p} Y(s) \quad (7)$$

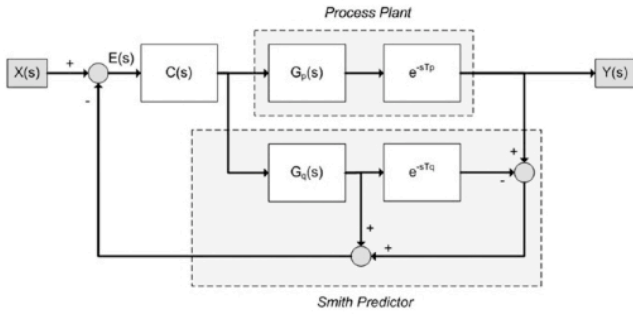


Fig. 9. Smith Predictor control structure for system with time delay.

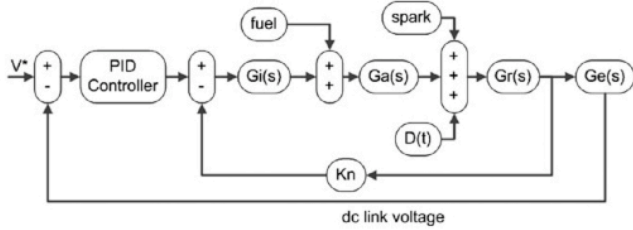


Fig. 10. Linearised engine/generator model.

Thus in the time-domain, $Y_{FB}(t) = y(t + T)$ which is the prediction of the output signal.

2.2. Engine model

The implementation of a predictive controller to overcome the significant time delays inherent in the engine requires a model which is representative of the engine dynamics and time delay [10]. In this case, for simplicity and ease of implementation, the adopted model (Fig. 10) was a set of structures linearised [16] around the operating speed of interest, which relates output torque changes to changes in fuel, spark and throttle [17].

Where V^* is the required DC link voltage, $G_i(s)$ is the inlet manifold dynamics, $G_a(s)$ is the combustion delay, $G_r(s)$ is the lumped rotational dynamics for the combined system, $G_e(s)$ is the generator electrical dynamics, Kn is the pumping dynamics, and $D(t)$ is the time-varying load from the traction motors which are reflected into the IC engine as reaction torque from the generator. Tests for obtaining the model parameter values [21], consisting of throttle, spark and load inputs result in perturbation response of the generator voltage level. This method enables direct evaluation of the model parameter values.

In particular, tests were carried out to produce and tune linearised models not only at the nominal operating point of 2000 rpm, but via designed experiments between 1500 and 2000 rpm. This enabled the implementation of a parameter lookup table giving a linearised model over a range of operating conditions.

The Smith Predictor is model based, and hence highly sensitive to the accuracy of the process model [18,19]. Although the Smith Predictor provides great improvements over traditional methods, practical improvements are often limited by small changes in dead-time which can lead to

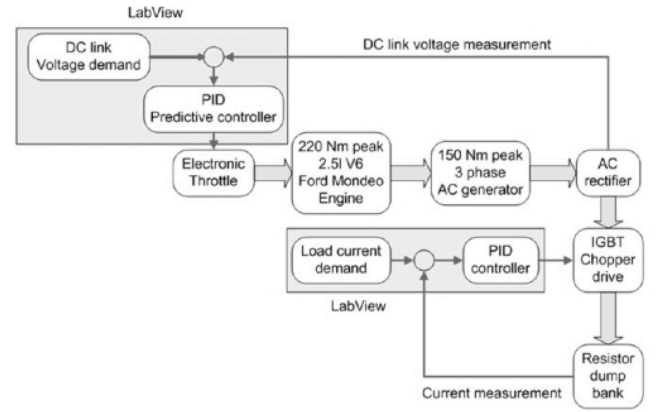


Fig. 11. Experimental rig.

instability in a highly tuned system [20]. This can be substantially overcome (as in this case), by applying the predictor to systems with well-known gains, dead-times and delays, or by being less aggressive in the controller design to allow for modeling inaccuracies. It has been shown that there will be significant improvement over PID control as long as the model parameters are within 30% of the actual plant values [19]. In the case under examination in this paper, model dead-times are accurate to a maximum error of 2%, dynamic response to a maximum error of 5% and steady-state response to a maximum error of 3%.

3. Experimental facility

The experimental setup is shown in Fig. 11. The IC engine is a 170 bhp, 2.5 l, 24 valve, V6 Ford Duratec, gasoline, normally aspirated engine. This engine was tuned to provide a peak torque of 220 N m. Directly coupled to the crankshaft, and mounted via a set of adaptor plates to the engine block is 25 kW three-phase permanent magnet generator (Fig. 12) with a back emf constant of 0.131 V/rads/s and a peak reaction torque of 120 N m. The electronic throttle is a standard Siemens unit.

Closed loop control of the rectified DC link generated was implemented in Labview, handling measurement of the DC link voltage, and implementation of the predictive controller to achieve the set-point level of 42 V. The time delay inherent in the controller was implemented as a *Pade Approximation* [22].

Load control was implemented via a second Labview unit, which controlled a 100 kW chopper drive [23], controlling the rectified DC voltage into 85 kW resistor dump circuit. Load was calculated via the 0.24 N m/A reaction torque constant of the generator. Current drawn from the DC link was controlled via a PID controller, current measurements being fed back from Hall-Effect current sensors on the DC cables. The figures presenting the results in this paper thus have measured and demanded torque which is scaled from the demanded and measured currents in the DC link. The measured current signal is extremely noisy and hence has the demand level superimposed for clarity. The authors would like to thank AT Powertrains for the use of this facility prior to decommissioning. Model parameter values have been withheld for commercial reasons.

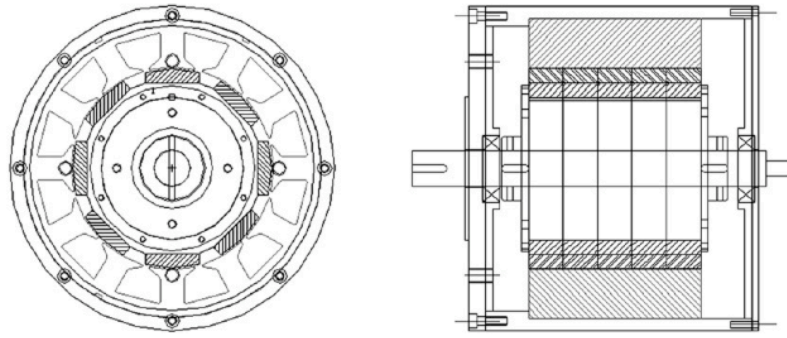


Fig. 12. Three-phase permanent magnet AC generator.

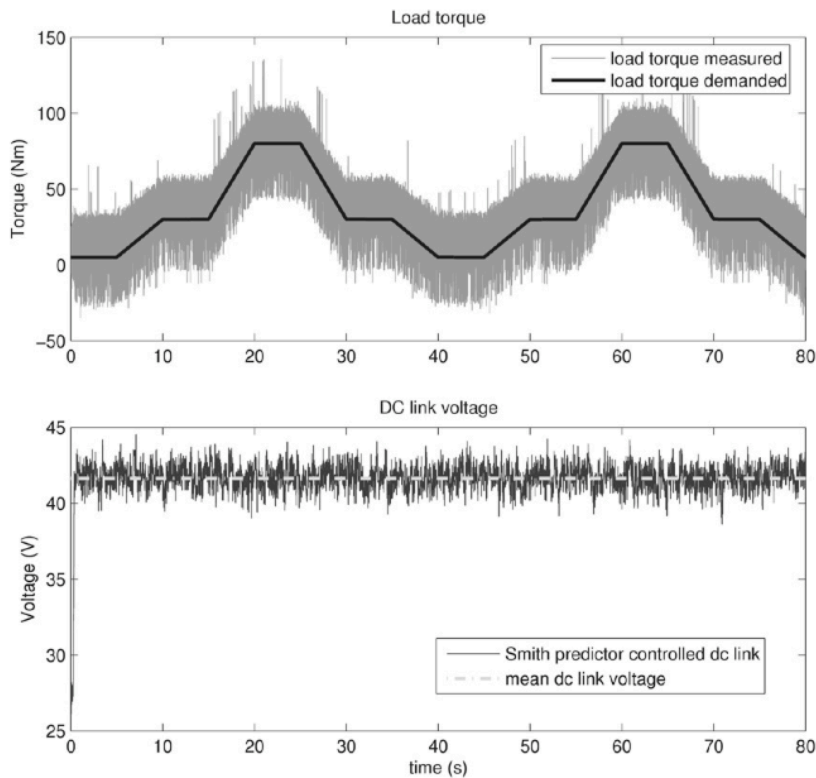


Fig. 13. Engine torque disturbance and generator output voltage.

4. Results

The experimental results presented in this paper (Figs. 7, 8 and 13) were carried out under PID or PD control (PD control in the case of the Smith Predictor), which was tracking a 42 V voltage command. In each case, the disturbance torque reflected back to the generator followed the profile presented in Figs. 7 and 13, with a peak disturbance of 80 N m. The implementation of the predictive controller improves the generator stability considerably, from a worst case of mean voltage 39.4 V and standard deviation of 4.38 V to a mean voltage of 41.64 V and standard deviation of 1.2 V for the predictor compensated system (Fig. 13).

The implementation of the Smith Predictor significantly reduced the voltage ripple generated by the hybrid powertrain.

In particular the use of a simplified linearised model has shown itself to be effective, especially considering the problems of integration and development into a real-time controller.

5. Conclusion

A control method has been presented to stabilise the generator output for the series-hybrid vehicle. Utilising feedback from the generator output, a predictive PD-type controller has been implemented, which for the first time deals effectively with the time delays inherent in an electronic throttle controlled internal combustion engine. Although it may be possible to re-design and re-engineer the system to increase the bandwidth and response of the throttle actuator, it can be expensive or difficult to do so within a design brief. Also the

time delay associated with the actuator may be related to the processing latency of the actuator control loop. The controller presented in this paper performs well even with significant process delay and dead-time, and outside the scope of this paper, has been shown to be applicable to a wide range of engines.

The authors do note however, that a reasonably accurate system model must exist before implementing a Smith Predictor, and moreover if the process model parameters vary significantly with respect to time, then some form of adaptive methodology may have to be included. Plant parameter changes due to wear, environmental, set-point, or other factors which cannot be measured directly may have to be updated in real time to match the process.

The implementation of the Predictive controller is complex in real-time computing terms, especially in terms of the limitations of processing available in typical automotive engine control units. Further work will examine the development of more compact forms of controller which are still applicable to time delayed systems.

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