Close Loop Speed Controller for Brushless DC Motor for Hybrid Electric Vehicles

Avanish Kumar and P. R. Thakura

Abstract Vehicle emissions are the great concern of the modern world and hybrid electric vehicles is one of the feasible solutions because it mitigates pollution and increases fuel efficiency. Power electronics plays an imperative role in Hybrid Electric Vehicle because it consists of converters for high-performance electric traction motor drives. It is important that the traction motor must fulfill the demands of the various driving cycles. In this chapter, a detailed performance analysis of controlling the speed of Brushless DC (BLDC) motor with or without disturbances (or load) is addressed. The chapter also involves the design and implementation of a controller which minimizes the initial overshoots. This work was conducted with the purpose of developing a three-phase inverter for BLDC motor drive system. The two different controllers are designed and simulated for closed-loop speed control of BLDC motor at different loading conditions. The simulation work is performed in MATLAB Simulink platform and results match with the theoretical one.

Keywords BLDC motor · Hybrid electric vehicles · MATLAB Simulink
PID controller · Speed control · Traction motor drive

1 Introduction

Hybrid Electric vehicles (HEVs) uprising has been feasible only after the beginning of the state-of-the-art power electronics devices and converters. The development high-performance and high power density motors also contribute significantly in the development of HEVs [1, 2]. The two major companies Toyota and Honda started the production of HEVs in the year 1997. After that continuous efforts are taken

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towards the realization of high-performance, environmentally suitable HEVs around the globe. In countries like India, the HEVs are still far from the realm of automobile sector. But nowadays many efforts are being taken to bring commercially sustainable HEVs.

HEVs have two energy sources which feed the two prime movers, i.e. an electrical motor drive and the Internal Combustion Engine (ICE). The fuel feeds the ICE and the battery or fuel cell feeds the electrical motor drive. The prime movers may be connected together in series or in parallel using various possible architectures, i.e. series, parallel and series—parallel. The control strategy for each is different but the entire focus is to capitalize on the fuel economy, while meeting the demand torque and speed along the entire driving cycle [3, 4].

This chapter consists of 7 sections. Section 2 reviews different hybrid electric vehicle architecture. Section 3 introduces the types of synchronous motor, and elaborates BLDC motor. Section 4 presents power converter which is used to feed the BLDC motor also some technical background to 3-phase inverter and the gate driver circuit is discussed. Section 5 addresses the motor model and three-phase inverter model. Section 6 discusses the simulation models and results which are used to simulate the three-phase inverter with a PMBLDC motor in MATLAB Simulink and Sect. 7 presents the conclusion and future work.

2 Hybrid Electric Vehicles

In HEVs there are various power trains architectures, the most important architectures are the series, parallel and series–parallel ones.

2.1 Series Architecture

A Series Hybrid Electric Vehicles (SHEVs) as shown in Fig. 1, has power sources connected in electromechanical series. The propulsion power to the drive wheels is

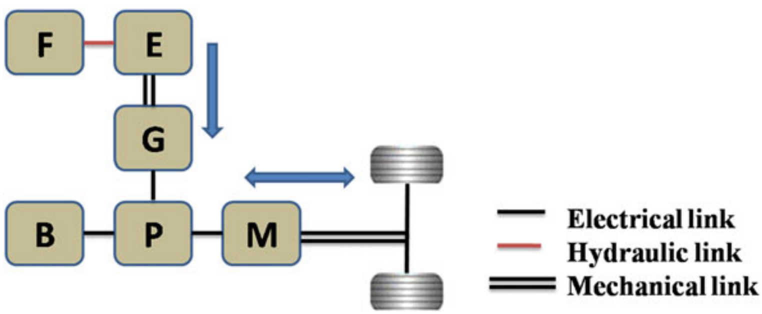

Fig. 1 SHEVs powertrain architecture. B: battery, E: ICE, F: fuel tank, G: generator, M: motor, P: power converter

provided by electrical powertrain only and an engine—generator (Genset) unit recharges the energy storage system (B) that provides energy to the electrical powertrain.

In the Genset unit, the Fuel tank (F) feeds the ICE which provides mechanical power input to the Generator (G). G converts mechanical power into electrical power and supplies to the motor (M) or to B. Merits and demerits of the series architecture may be as follows.

Merits:

(a) G and ICE are suitably designed for the average propulsion power or even less.
(b) Genset and electrical drive train are mechanically separated allowing the ICE efficiency to maximize with a significant reduction of emissions.

Demerits:

(a) It requires two electrical machines (G and M).
(b) In order to supply the peak propulsion power, M must be sized accordingly.
(c) At least two energy conversions are required, i.e. from mechanical energy to electrical energy to chemical energy inside B, and vice versa, so as to transfer generated power from ICE to wheels of the vehicles which, in turn, reduces the efficiency of the system.

2.2 Parallel Architecture

In a parallel HEVs (PHEVs) architecture, shown in Fig. 2, the conventional powertrain arrangement is connected to an electrical powertrain arrangement through a clutch that enables the vehicles to be driven by M or ICE independently or collectively. PHEVs comprise of two independent drive trains, one is electrical drivetrain and the other one is mechanical drive train, their powers are added together by using a three-way mechanical device.

Section 2.2 provides the power demanded by M to drive the vehicle. Merits and demerits of the PHEVs architecture are as follows:

Merits:

(a) In PHEVs, only one electrical machine is required;

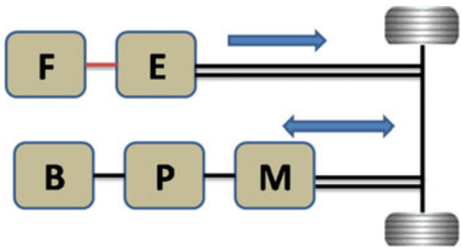

Fig. 2 PHEVs architecture

(b) M requires lower peak power in this architecture than that in SHEVs because in this architecture both ICE and M provide the propulsion power.
(c) PHEVs are more efficient than SHEVs because the generated power is transferred to wheels directly.

Demerits:

(a) A three-way mechanical device is necessary to combine ICE, M and wheels together which increases the cost.
(b) Such coupling affects the operation of ICE and imposes an unnecessary constraint on the power flow possibly turning this architecture into inferior one.

2.3 Series–Parallel Architecture

Series–parallel HEVs (SPHEVs) architecture is shown in Fig. 3. In a series–parallel configuration M, G, ICE, and the wheels of the vehicle are coupled through one or multiple planetary gear sets.

3 BLDC Motor

Permanent Magnet Brushless DC (PMBLDC)/PMBLAC motor is similar to synchronous AC machine having a permanent magnet on the rotor and winding on the stator. Motors using permanent magnets (PM) can be broadly classified as follows.

(a) Conventional DC permanent magnets motors whose armature, commutator and the brushes are the same as that of a normal DC motor except that the permanent magnets replace the field winding in the stator [5, 6].
(b) PMBLDC and Permanent Magnet synchronous motors (PMSM), the construction is similar to a synchronous motor with armature windings in the stator, but whose field winding (in the rotor) is replaced by permanent magnets and the commutation of currents in the stator phases is carried out electronically in synchronous with the rotor movement.

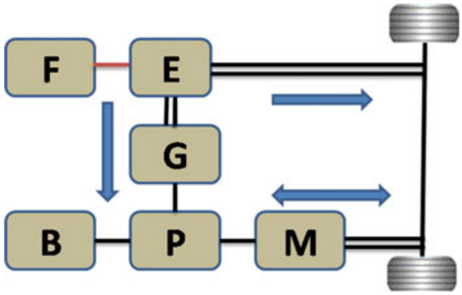

Fig. 3 SPHEVs powertrain architecture

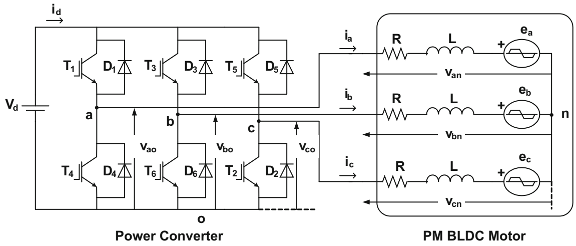

Fig. 4 Equivalent circuit of three-phase PMBLDC motor drive

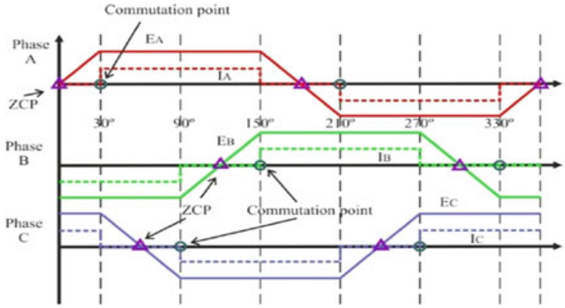

Fig. 5 Ideal back EMF voltages and three-phase currents of the PMBLDC motor

The PMBLDC motor is similar to an AC synchronous motor shown in Fig. 4 with permanent magnets on the rotor and three-phase concentrated winding on the stator. It is characterized by having a trapezoidal back EMF which is shown in Fig. 5 and driven by square-shaped currents. On the other hand, PMSM has distributed winding on the stator, having a sinusoidal back EMF and is driven with sinusoidal phase currents. The BLDC motor is usually designed in three configurations, i.e. single-phase, two-phase and three-phase BLDC motor, among these three-phase configurations are the most common. The number of power electronic switches increases with the number of phases. The stator is made up of stacked steel laminations and construction is similar to induction motor. The rotor is made up of PM pairs having north and south pole in consecutive order. Since it is a synchronous motor, the stator and rotor rotate at the same frequency. This means that there is no slip between the stator and the rotor in BLDC motor.

PMBLDC motor is best suited for drive application in HEVs because of the following reasons:

(a) PM BLDC motor has high efficiency with respect to conventional DC motor because the rotor which consists of permanent magnet does not require any power for producing excitation and also since there is no mechanical commutator is present in PMBLDC motor the frictional losses as well as heat produced by the commutator during arcing is completely eliminated.
(b) The permanent magnets are made up of very high flux density magnetic materials, which can produce very high torque for the same stator current.

(c) The characteristics of PM BLDC motor and separately excited DC motor are very similar which makes the control strategy easier as we have less number of variables to control.
(d) In the PM BLDC motor, the carbon brushes were absent so there is no wear and tear and also the operation is maintenance free. Due to inside out construction of PMBLDC motor, the stator winding produces heat on the outer periphery, the air gap and bearing of rotor do not get heated up so as like DC motor.
(e) The induced EMF in PM BLDC motor is of trapezoidal shape. The magnitude of induced EMF is constant for 120° in both half of the cycle, i.e. positive and negative half, the output power can be uniform when we excite the phases of rotor by 120° wide current. The power density of PM BLDC motor is 15% more than PMSM

4 Power Converter

The power converter device which converts DC power into AC power at desired output voltage and frequency is known as inverter. Some industrial applications of inverters include variable-speed AC drives, induction heating, UPS for computers, etc., there are mainly two types of inverters;

(a) Voltage Source Inverter (VSI): In this inverter, the DC source has negligible impedance, i.e. it has high voltage at its input terminals which shown in Fig. 6a. as the load varies output voltage remains unchanged or constant.
(b) Current Source Inverter (CSI): the CSI is fed with variable current and very high impedance DC source, for this inductor is used in series with stiff DC source which is shown in Fig. 6b. In CSI, output current remains constant even if the load changes.

For the hardware as well as MATLAB simulation Metal–Oxide Semiconductor Field Effect Transistor (MOSFET) is used as a power switch for three-phase VSI.

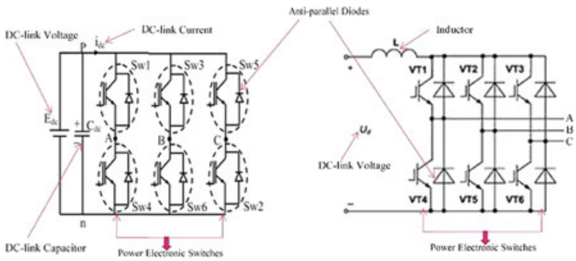

Fig. 6 Three-phase inverter **a** VSI **b** CSI

5 BLDC Motor Model

The mathematical model of PMBLDC motor is a fundamental requirement for the corresponding performance analysis and control system design. The mathematical model which was used in order to simulate the BLDC motor consisted of an electrical and a mechanical part [7, 8] (Fig. 7)

$$V_{\mathrm{AN}} = Ri_{\mathrm{A}} + L\frac{\mathrm{d}i_{\mathrm{A}}}{\mathrm{d}t} + e_{\mathrm{A}} \tag{1}$$

$$V_{\mathrm{BN}} = Ri_{\mathrm{B}} + L\frac{\mathrm{d}i_{\mathrm{B}}}{\mathrm{d}t} + e_{\mathrm{B}} \tag{2}$$

$$V_{\mathrm{CN}} = Ri_{\mathrm{C}} + L\frac{\mathrm{d}i_{\mathrm{C}}}{\mathrm{d}t} + e_{\mathrm{C}} \tag{3}$$

where V_{AN}, V_{BN}, V_{CN} denotes the phase voltage, i_{A}, i_{B}, i_{C} are the stator current, L is the stator inductance/phase, R is the stator resistance/phase and e_{A}, e_{B}, e_{C} represents the induced back EMF in each phase.

The back EMF of a three-phase BLDC motor is the function of rotor position with each phase is 120° electrical degree apart from each other and given by

$$e_{\mathrm{A}} = K_{\mathrm{e}}\omega_{\mathrm{m}}F(\theta_{\mathrm{e}}) \tag{4}$$

$$e_{\mathrm{B}} = K_{\mathrm{e}}\omega_{\mathrm{m}}F\left(\theta_{\mathrm{e}} + \frac{2\pi}{3}\right) \tag{5}$$

$$e_{\mathrm{C}} = K_{\mathrm{e}}\omega_{\mathrm{m}}F\left(\theta_{\mathrm{e}} + \frac{4\pi}{3}\right) \tag{6}$$

where K_{e} motor back EMF constant, θ_{e} is electrical rotor angle ω_{m} rotor speed and F is a trapezoidal back EMF reference function with respect to the position of rotor, with boundaries between +1 and −1.

Simulating an inverter of a BLDC motor in Simulink uses phase currents, back EMF, rotor position and DC-source voltage as inputs. For each of the different position intervals shown in Table 1, we get different voltages to the motor.

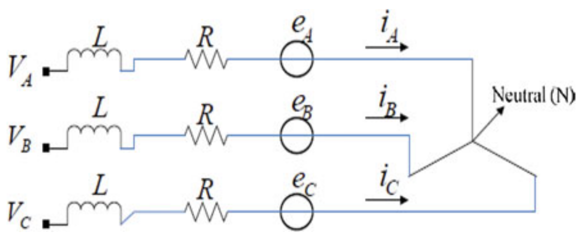

Fig. 7 Equivalent circuit of the star-connected BLDC motor

Table 1 Switching sequences

Sequence	Rotor position (Θe)	Switching (ON)	Phase current		
			A	B	C
1	0°–60°	Sw6, Sw1	Edc+	Edc−	OFF
2	60°–120°	Sw1, Sw2	Edc+	OFF	Edc−
3	120°–180°	Sw2, Sw3	OFF	Edc+	Edc−
4	180°–240°	Sw3, Sw4	Edc−	Edc+	OFF
5	240°–300°	Sw4, Sw5	Edc−	OFF	Edc+
6	300°–360°	Sw5, Sw6	OFF	Edc−	Edc+

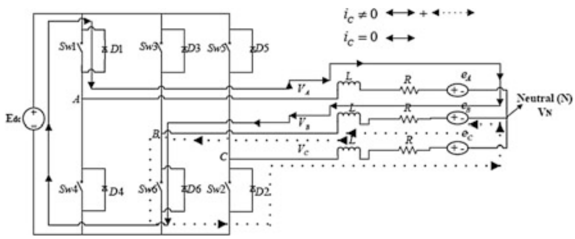

Fig. 8 Mode I (0°–60°) operation of the inverter

Rotor position (0°–60°), Sw1 and Sw6 are ON (previously Sw5 and Sw6 were ON). Figure 8 shows the current path through the three-phase inverter for the interval 0°–60°, where the path represented by bold lines with arrows represents the current through the active phase, and the dotted path represents the commutating current from the previous switching sequence.

6 MATLAB Simulation and Results

For the simulation of electrical motor drives, we have to select a proper simulation tool. In MATLAB, there is Simulink platform which is used for simulating dynamic systems. Simulink platform can also be used in the graphical environment, complex dynamic system simulations, with virtual real-time programming and a broad selection of other toolboxes (Table 2).

Figure 9 shows a block diagram of open-loop MATLAB Simulation of PMBLDC motor with three-phase Voltage Source Inverter (VSI).

The various waveform obtained in the open-loop simulation are plotted in Fig. 10a–d.

Table 2 Parameters of the motor considered for the simulation

Parameters	Value
DC voltage 'volts (V)'	310 V
Speed (rpm)	4600 rpm (481.7 rad/s)
Moment of inertia J (Kg m^2)	0.00018
Resistance R_a (Ω/phase)	1.535
Inductance L_a (mH/phase)	3.285
Torque constant K_t (N m/A)	0.49
Poles (P)	4
Frequency (Hz)	50

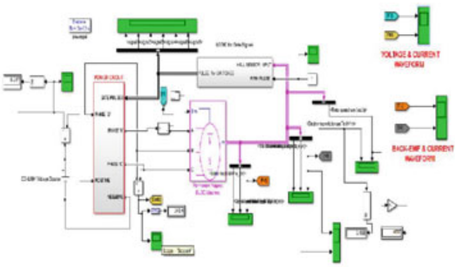

Fig. 9 MATLAB simulation of PMBLDC motor with three-phase VSI (open loop)

6.1 Controller Design

Controller is a device which monitors and alters the operating conditions of a given dynamical system. Any control method can be divided into two parts: Open-loop control and Closed-loop control. The open-loop simulation in MATLAB is already discussed. Now, we mainly focus on the closed-loop control using PID and modified PID controller and compare their Simulink results [9–11].

(a) PID Controller

Traditionally, PID control strategy has been the oldest strategy in the linear control systems. PID controllers are still used in industrial control systems due to there simplicity, reliability, robustness, and easily tuneable parameters. PID is commonly interpreted as proportional, integral and derivative controller and possesses the following properties which are given in Table 3.

The PID control structure with unity feedback is shown in Fig. 11. The role of PID controller is to calculate the error $e(t)$ by comparing the reference value and the real value, after that the variable $u(t)$ of the plant (system) is controlled tuning the proportional–integral–derivative terms.

(b) Modified PID Controller

In this controller, the only integral term is connected in the feed-forward path and proportional with derivative terms is applied to the output of the plant and is fed

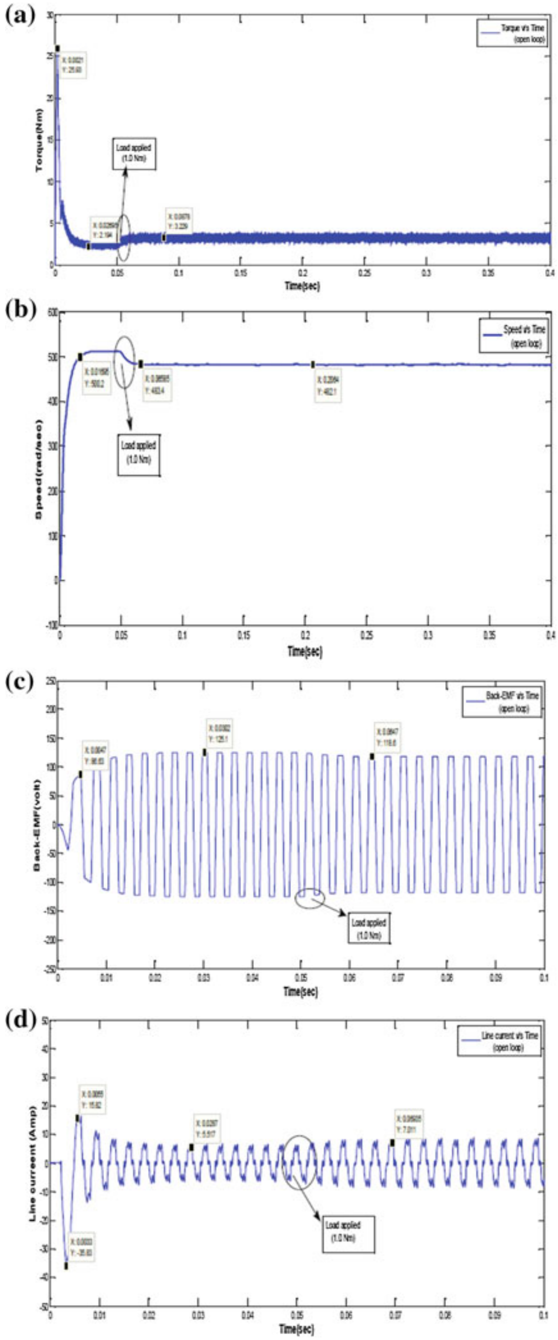

Fig. 10 **a** Torque versus time waveform for open loop (*X*-axis time; *Y*-axis toque in N m). **b** Speed versus time waveform for open loop (*X*-axis denotes time; *Y*-axis denotes 'speed (rpm)'). **c** Back EMF versus time waveform for open loop (*X*-axis time; *Y*-axis back EMF in 'volts (V)'). **d** line current versus time waveform for open loop (*X*-axis time; *Y*-axis current in 'ampere (A)')

Table 3 Properties of PID controller

Controller	Response time	Overshoot	Error
Proportional (*P*)	Small	Large	Small
Integral (*I*)	Decrease	Increase	Zero
Derivative (*D*)	Increase	Decrease	Small change

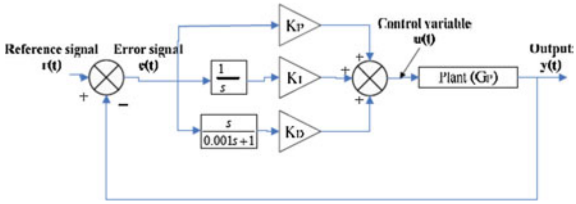

Fig. 11 Block diagram representation of a PID control system

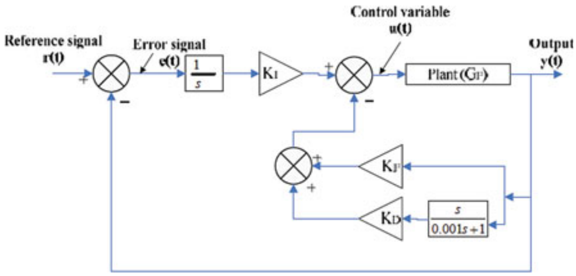

Fig. 12 Block diagram representation of modified PID control system

to the negative part of the comparator of the inner loop. This negative feedback minimizes the initial overshoot that happens in case of conventional PID.

The integral term present in the feed-forward path helps the system to reach the steady state. This type of response can be considered as little sluggish system without steep overshoots. The typical structure of modified PID control with unity feedback is given in Fig. 12.

Simulation results for closed-loop control of PMBLDC motor drive using PID and modified PID controller are given. The torque and time, speed and time, line current and time and voltage and time waveform profile obtained in the closed-loop simulation with PID and Modified PID controller is shown in Fig. 13a–d.

From the above Simulink results, it can be observed that overshoot obtained using PID controller is more compared to that of modified PID controller in transient condition during the initial time period. Both PID and modified PID controller is able to track the desired speed during the no-load and full-load conditions

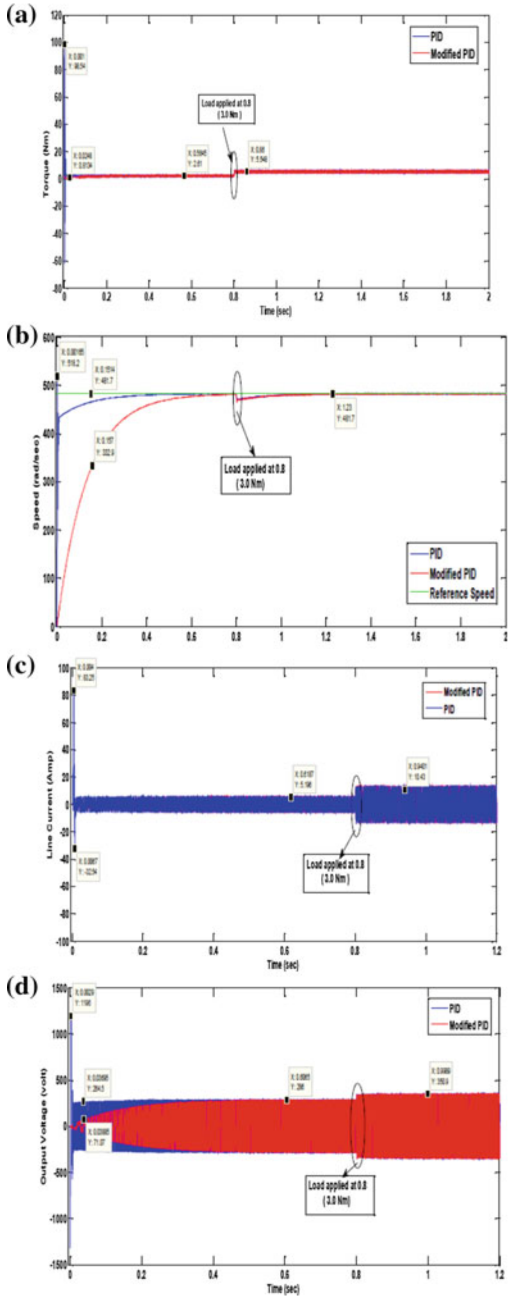

Fig. 13 **a** Torque versus time waveform for closed loop (*X*-axis time; *Y*-axis 'torque (N m)'). **b** Speed versus time waveform for closed loop (*X*-axis time; *Y*-axis 'speed (rpm)'). **C** Line current versus time waveform for closed loop (*X*-axis time; *Y*-axis 'current (A)'). **d** Output voltage versus time waveform for closed loop (*X*-axis time; *Y*-axis voltage 'volts (V)')

7 Conclusion

The control of electrical drive for the HEVs is presented in this chapter. The different vehicle architectures are being reviewed in addition to that controllers are designed and simulated for closed-loop operation of BLDC motor. The simulation result indicates that the peak overshoot gets reduced when the modified PID controller is used and gives better response in both no-load and full-load conditions compared to PID controller.

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