Sādhanā Vol. 33, Part 5, October 2008, pp. 581–590. © Printed in India

DSP-based electric power assisted steering using BLDC motor

R MURUGAN, S NANDAKUMAR and M S MOHIYADEEN

Bharat Electronics Limited, Nandambakkam, Chennai 600 089
e-mail: muruganr@bel.co.in; nandakumars@bel.co.in; mohiyadeenms@bel.co.in

Abstract. This paper introduces a design and implementation of electrically assisted power steering (EAS) using BLDC motor for a vehicle. The control architecture consists of two layers of control, namely the vehicle speed associated control and the torque assist control. In the higher level of control architecture, the vehicle speed controller works as an assistance level controller for the steering effort. In the lower level, the torque controller gives the effort level control. This has been realized by torque sensor and vehicle sensor interfaced in the DSP. For implementing in the system, a DSP-based BLDC motor controller with three-phase inverter module is specially designed using Hall-effect sensor feedback and a single dc-link current sensor. This work is implemented in a Light Commercial Vehicle having a recirculating ball type gear. This is for the first time (EAS) being implemented for this type of vehicle any where in the world. Generally, EAS having clutch to disconnect the motor in high speed or abnormal conditions from the gear box. In this implementation the motor is directly coupled to gearbox without clutch and all abnormalities are handled by the processor. This is implemented without modifying the vehicle supply system like changing the existing alternator or rating of the battery and using the existing sensors. The design is such a way that the feel of the driver assistance can be varied easily at any time. The performance of the control system is experimentally verified and it is tested in one of the Light Commercial Vehicle (LCV).

Keywords. BLDC motor; EAS; steering.

1. Introduction

Power steering is a system for reducing the steering effort on vehicles by using external source to assist in turning the wheels. Most new generation vehicles now have power steering, owing to the trends toward greater vehicle mass and wider tires, all increase the steering effort needed. Modern vehicles would be difficult to maneuver at low speeds (e.g. when parking) without assistance. Most power steering systems work by using a belt-driven pump to provide hydraulic pressure to the system. This hydraulic pressure is generated by a pump which is driven by the vehicle's engine. While the power steering is not used, i.e. driving in a straight line, twin hydraulic lines provide equal pressure to both sides of the steering wheel gear.

When torque is applied to the steering wheel, the hydraulic lines provide unequal pressures and hence assist in turning the wheels in the intended direction.

Electric Power Steering systems use electric components with no hydraulic systems at all. Sensors detect the motion and torque of the steering column and a computer module applies assistive power via an electric motor coupled directly to either the steering gear or steering column. This allows varying amounts of assistance to be applied depending on driving conditions. In the event of component failure, a mechanical linkage such as a rack and pinion serves as a back-up in a manner similar to that of hydraulic systems. Electric systems have an advantage in fuel efficiency because there is no hydraulic pump constantly running. Their other big advantage is the elimination of a belt-driven engine accessory, and several high-pressure hydraulic hoses between the hydraulic pump, mounted on the engine, and the steering gear, mounted on the chassis. This greatly simplifies manufacturing.

The demand of electrically assisted power steering (EAS) has rapidly increased in past few years because of energy savings compared to Hydraulic Power Steering (HPS). Alternating current (ac) motors are designed to be highly efficient and easily controlled with modern power circuitry. Because of the developments in switching techniques, it is quite feasible to use ac motors with a battery supply as source. The traditional worm gear driven dc motor system is constrained by the limitations of the dc motor brushes and size of the motor for the same torque of BLDC. In this case BLDC motor has been used as an actuator in the application for electric power steering. The BLDC motor provides high torque and easy control (Chan & Fang 2002; Chu *et al* 2001; Desai & Emadi 2005; Jun-Uk Chu *et al* 2004; Kevin Brown *et al* 1990; NamhunKim *et al* 2007). The basic mechanical properties of the vehicle are essentially invariant among all of the available brands. The electrically assisted power steering system consists of BLDC motor mounted to the frame of the steering column and coupled to the wheels through a worm speed reducer. Electrically assisted power steering is shown in figure 1.

An electrically assisted power steering is composed of several parts such as torque sensor, engine speed sensor, vehicle speed sensor, steering column, torsion bar and electronic control unit.

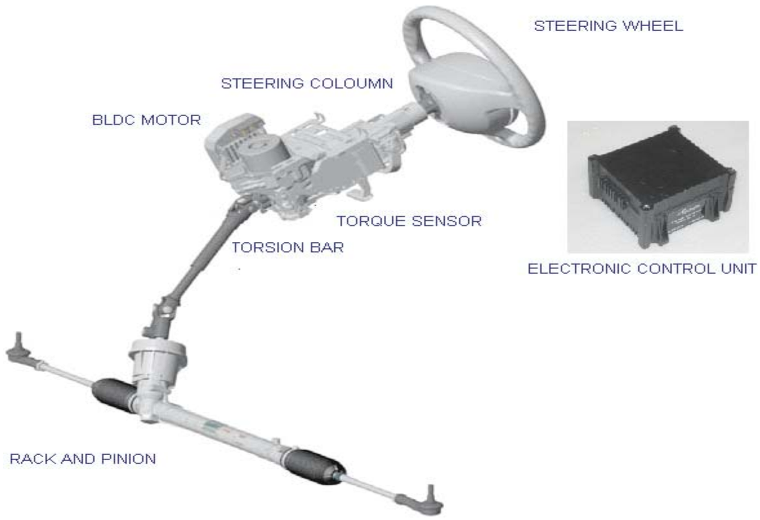

Figure 1. Electrically assisted power steering.

Torque sensor output gives the torque difference to be developed by the motor to reduce the effort required by the driver while he is steering. Engine speed signal is required to start the assistance only when the engine is ON in order to save the battery life. Vehicle speed signal is required to control the assistance developed by the motor (for the same level of torque signal) at various vehicle speed, as assistance requirement comes down as speed of the vehicle increases.

The control architecture consists of two layers of control, namely the assistance level control and the torque control. In the higher level of control architecture, vehicle speed signal works as a reference for controlling the assistance to be developed by the motor. In the inner layer torque sensor signal performs generation of torque. The torque output from motor is a function of torque sensor signal and it depends on the torque difference between the steering wheel and the wheel. The vehicle speed signal and engine speed signals are pulses with variable frequency. For system implementation, a DSP-based BLDC motor controller with three-phase inverter module is specially designed using Hall-effect sensor feedback and a single dc-link current sensor. The torque and Back EMF equations of BLDC motor are similar to that of dc motor. The current sensing is ensured by a low cost shunt resistor and used for over-current protection and current feedback.

The current control is achieved by PID controller and pulse width modulation (PWM) signals with varying duty rates. Hall-effect sensors are available to detect rotor shaft position, used for electronic commutation, motor speed and direction of rotation.

2. Hardware architecture

A block diagram of the power assisted steering is illustrated in figure 2. The electrically assisted power steering system in a vehicle consists of the following parts.

a. Digital signal processor
b. Driver and protection card
c. Three phase inverter
d. BLDC motor with Hall sensor
e. Reduction gear and sensors.

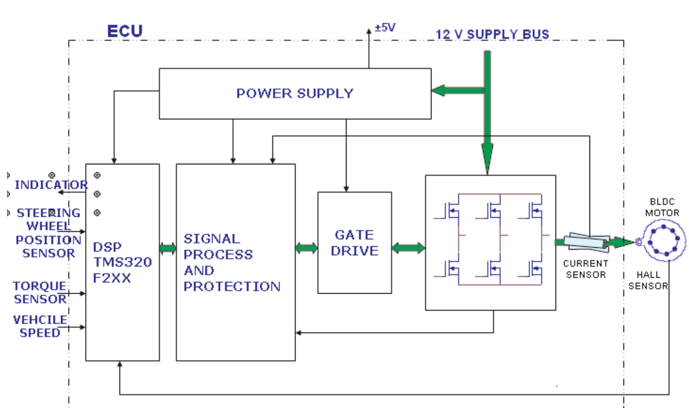

Figure 2. Block diagram of EAS.

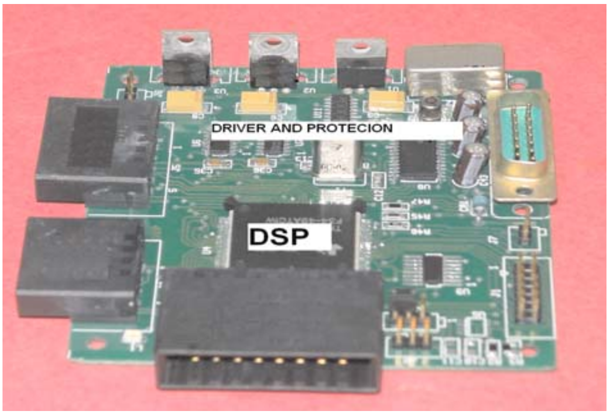

Figure 3. DSP and protection card.

2.1 *Processor*

The DSP used for control and computation is TMS320F24XX. The processor is a single chip solution based on 40 MIPS, 16 bit fixed point DSP core with several associated peripherals such as Pulse Width Modulation generator (PWM) and Analog to Digital Converter (ADC) BPRA055 1997; SPRU160C 1999; SPRU161C 1999.

2.2 *Driver and protection circuit*

The selected MOSFET Driver is from IR family. The PWM signals coming from the DSP are combined with protection logics and connected to MOSFET driver. The output of the driver is directly connected to the MOSFET switches through series gate resistor.

The current sensing is done by the low cost shunt resistor. The voltage drop is processed with analog amplifier and connected to ADC module and used for current feedback and overcurrent protection. The protection card used here is shown in the figure 3.

2.3 *Three phase inverter module*

The three phase inverter module is developed by using MOSFETs with low ON state drop and high switching frequency. The three-phase inverter card used is shown in figure 4.

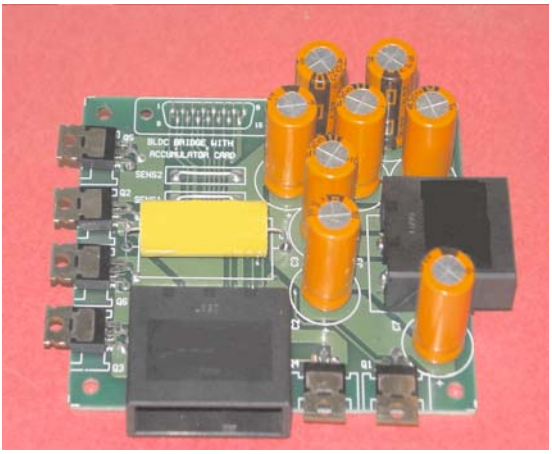

Figure 4. MOSFET card.

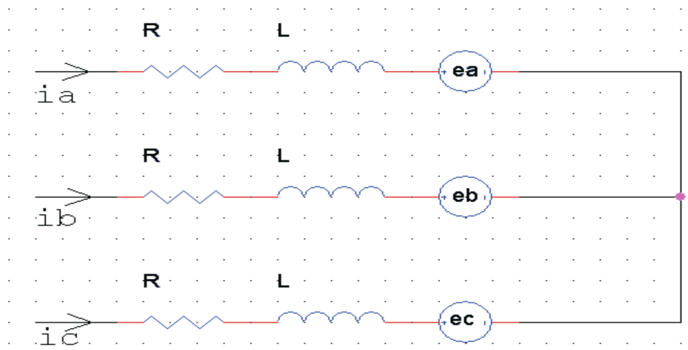

Figure 5. BLDC motor equivalent circuit.

2.4 *BLDC motor with Hall sensor*

The equivalent circuit of a BLDC motor is shown in figure 5. The BLDC motor used here has 8 magnetic pole pairs on the rotor and a three-phase star connected windings on stator. The voltage equation of BLDC motor can be represented as

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L & 0 & 0 \\ 0 & L & 0 \\ 0 & 0 & L \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \tag{1}$$

R = Phase resistance
L = Phase inductance
V_a, V_b, V_c = Phase voltages
I_a, i_b, i_c = Phase currents
e_a, e_b, e_c = Back EMFs.

The generated motor torque is given by

$$T = \frac{e_a i_a + e_b i_b + e_c i_c}{\omega}, \tag{2}$$

where ω is motor angular velocity.

The motor is equipped with three Hall effect sensors. The Hall sensors produce three 180° (electrical) overlapping signals as shown in the figure 6. Thus it is providing six mandatory commutation points.

The Hall sensor outputs are directly connected to processor and it generate the necessary switching sequence as per commutation.

2.5 *Gear box and sensing circuits*

The BLDC motor is connected to a reduction gear system as shown in figure 7. It drives the wheel.

The torque difference between the steering wheel and wheel is sensed by a torsion bar. The output of the torsion bar is sensed by the torque sensor. The output of the torque sensor is directly connected to ADC for processing.

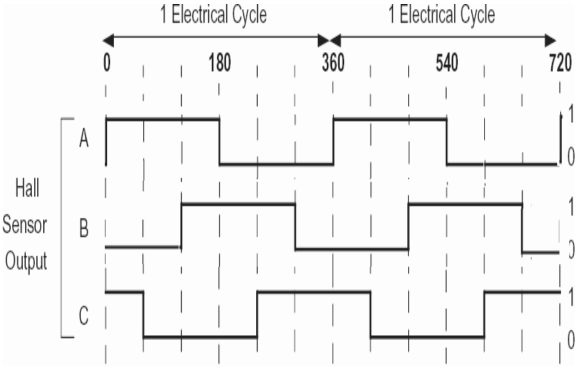

Figure 6. Hall sensor wave form.

3. Controller design

3.1 *Effort level control*

The electrically assisted power steering (EAS) incorporates a brushless electric motor located on the steering column, on the pinion that assists the driver when steering. Information like engine speed, and torque required are transmitted in real time to a DSP which determines the optimal degree of assistance the electric motor should apply. Figure 8 shows the effort required by the driver without assistance and with assistance for a vehicle at static.

Electrically assisted power steering eliminates the need for hydraulic fluids and complicated mechanical components (such as servo pumps), hydraulic lines, belts and pulleys, which add weight and volume. By eliminating the hydraulic pump, the EAS can operate without the help of the engine. Unlike a conventional hydraulic system, the EAS consumes energy only when providing assistance.

The control algorithm for the electrically assisted steering system is shown in figure 9. The effective torque and velocity control of a BLDC motor is based on relatively simple torque and Back EMF equations, which are similar to those of the DC motor.

Figure 7. Gear box with motor.

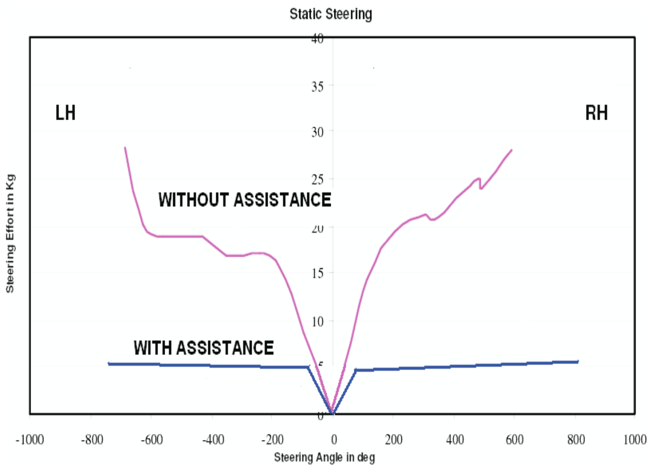

Figure 8. Effort curve.

During any 120 degree interval of phase current, I the instantaneous power (P) being converted from electrical to mechanical is

$$P = \omega Te = 2EI \tag{3}$$

Te = Electromagnetic torque

E = Induced EMF per phase.

The '2' in this equation arises from the fact that two-phase are conducting.

$$E = 2NphB_gLr\omega, \text{ per phase induced emf.} \tag{4}$$

Nph = Number of winding turns per phase

B_g = Rotor magnetic field density

L = Length of the rotor

r = Internal radius of rotor.

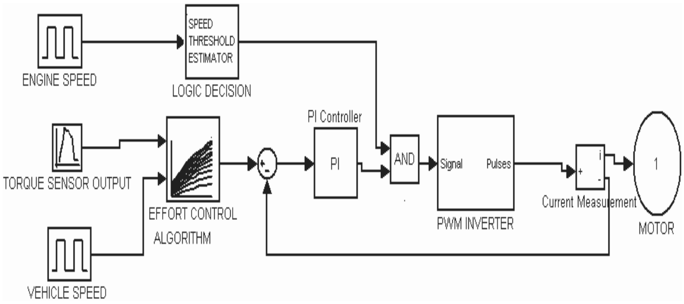

Figure 9. Control algorithms.

Using the above expression the electromagnetic torque is given by,

$$Te = 4NphBgLrI = K\phi I \tag{5}$$

K = Torque constant

ϕ = Flux per pole pair.

The system takes torque reference (I_ref) and feedback line current (Ifb) as input, produces duty-cycle reference as output. This is actually a PI controller. The following equation is implemented

$$D\_\text{cycle} = K_p(I\_\text{ref} - Ifb) + \frac{K_p}{T_i}\int (I\_\text{ref} - Ifb)dt, \tag{6}$$

Kp = Proportional constant

Ti = Time constant.

Limiters are there at final controller output. Duty cycle reference is clamped to the peak of the saw tooth carrier wave. Current control is achieved by Pulse Width Modulation (fixed frequency 20 kHz) signals with varying duty cycles. PWM width is determined by comparing the measured actual current with the desired reference current.

To sum up, the Back EMF is directly proportional to the motor velocity and the torque production is almost directly proportional to the phase current. In this control scheme, torque production follows the principle that current should flow in only two of the three phases at a time. Only one current at a time needs to be controlled so that only one current sensor is necessary. The positioning of the current sensor allows the use of a low cost resistor as a shunt.

3.2 *Assistance level control*

Figure 10 shows the effort required to be produced by the motor for various vehicle speeds. Variable steering assistance (higher at low vehicle speed and lower at high vehicle speed),

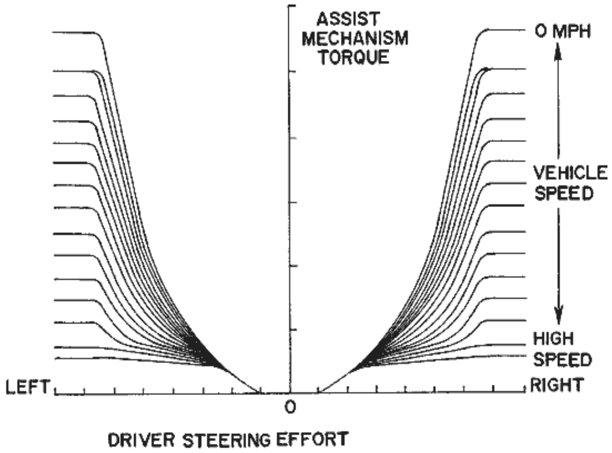

Figure 10. Boost curve for various speeds.

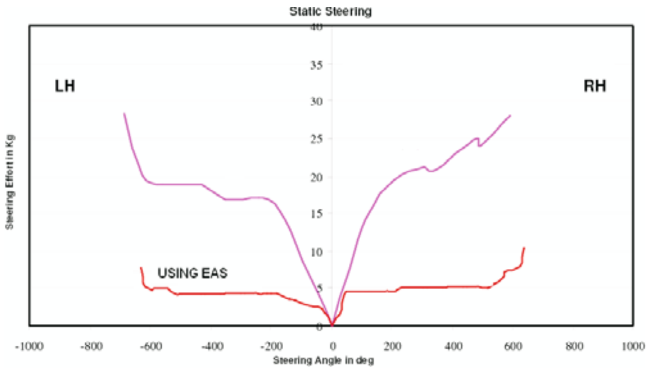

Figure 11. Driving effort output from EAS.

which improves drivability and active safety. This has been implemented by sensing the vehicle speed and accordingly modifies the effort to be produced by the electric motor by controlling reference to the controller.

4. Experimental results

In this section, the result is presented (figure 11) to ensure the validity of the proposed method at static driving. From the above figure, we can see that the effort required by the driver is almost constant entire steering wheel rotation. The effort reduction comes around 75%. The motor is selected such that the cogging torque is very less. The maximum peak cogging torque of the motor used at 10 rpm is 0·0056 Nm compared to peak torque of 2·45 Nm. The acceleration and deceleration of the motor is done in such a way that the driver does not feel the torque ripple in his hand. The torque ripple generally felt at low speed, here the system in a loop such that the system is always in acceleration/deceleration phase, so feel of torque ripple is less. Further to above, the mechanical system itself is in variable gear ratio and it has inherent torque variation more than the motor torque ripple produced by the motor. Hence the driver is not able to feel the torque ripple compared with EAS ON mode and EAS OFF mode. From this result, it is seen that the proposed EAS has performed as expected.

Maximum torque required (manual):	32 Nm
Torque required during power assistance:	8 Nm
Percentage assistance provided:	75 %
Average current consumption:	8 A

5. Conclusion

For equivalent power steering efficiency, electrically assisted power steering improves fuel consumption by 4 percent or more compared to conventional hydraulic systems. The elimination of hydraulic fluids is also more environmentally friendly for End of Life Vehicle (ELV) consideration. Electronic data management (wheel angle, vehicle speed, etc.) can be used to fine-tune the power steering parameters, enhancing the car drivability. Variable steering assistance improves drivability and active safety. Steering force feedback incorporates controlled re-centre positioning of the steering wheel and active damping of highway vibration.

References

BPRA055 March 1997 DSP Solutions for BLDC motors. Literature number: Texas Instruments Europe

Chan Lie-Tong Yan F, Shao-Yuan Fang 2002 In-Wheel permanent-magnet brushless dc motor drive for an electric bicycle. *IEEE Trans. Energy Conversion* 17(2): 229–232

Chu C L, Tsai M C, Chen H Y 2001 Torque control of brushless DC motors applied to electric vehicles. *IEEE Trans. on* 1–5

Desai, Ali Emadi 2005 A novel digital control technique for brushless DC motor drives: Current control. *IEEE Trans.* 326–331

Jun-Uk Chu, In-Hyuk Moon, Gi-Won Choi, Jei-Cheong Ryu, Mu-Seong Mun 2004 Design of BLDC motor controller for electric power wheelchair. *IEEE Trans.* 94–95

Kevin E Brown, Rafael M Inigo, Barry W Johnson 1990 Design, implementation, and testing of an adaptable optimal controller for an electric wheelchair. *IEEE Trans. on Industry Application* 26(6): 1144–1157

NamhunKim, Hamid A Toliyat, Issa M Panahi, Min-Huei Kim 2007 BLDC motor control algorithm for low-cost industrial applications. *IEEE Trans.* 1400

SPRU160C June 1999 TMS320F/C24x DSP Controllers reference guide CPU and instruction set. Literature number: Texas Instruments Europe

SPRU161C June 1999 TMS320F/C240 DSP controllers reference guide—Peripheral library and specific devices. Literature number: Texas Instruments Europe