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Modelling and simulation of electric power steering system using permanent magnet synchronous motor

Rahul R Hiremath[1], T B Isha[2]

[1]Department of Electronics and Communication Engineering,
[2]Department of Electrical and Electronics Engineering, Amrita School of Engineering, Coimbatore, Amrita Vishwa Vidyapeetham, India.

E-mail : rahul.1492rh@gmail.com, tb_isha@cb.amrita.edu

Abstract. This paper presents a control technique for Electric Power Steering System (EPS) using Permanent Magnet Synchronous motor (PMSM) for steering application. The EPS model is developed using the mathematical equations; mechanical subsystem of steering unit is modelled using the dynamic equations of steering unit. The objective of EPS system is to provide the assist torque to the steering wheel to drive the vehicle, here PMSM provides the additional assist torque along with the driver input to steer the vehicle. The control logic implemented here considers the input torque from steering wheel and vehicle speed. Depending upon these two inputs, the q-axis current component required for the PMSM motor to provide the additional assist torque is computed. The complete EPS system is modelled in Matlab/Simulink and simulated for different driving inputs.

1. Introduction

In the recent years there has been advancement in the automotive industry with more of mechanical systems being replaced by modern electronic systems. Considering the steering system, in the recent years there was an advancement from mechanical steering system to hydraulic system, which reduced the driver effort to certain extent but had major concerns associated with it like the use of pressure pumps and oils that are dependent on external environmental factors. Also, the pressure pumps are driven by the vehicle engine which affects the overall engine efficiency. The newest technology is Steer-by-wire system where the physical connection between steering wheel and the wheels are eliminated[1]. In an EPS system, the electric motor powered from the vehicle battery, assists the driver to steer the vehicle, by directly assisting the rack and pinion arrangement. The various types of motors in use can be broadly categorised into two types, ones with the trapezoidal back emf and others with the sinusoidal back emf[2]. Permanent magnet synchronous motor provides the sinusoidal back-emf and hence is suitable for good torque control[3]. These motors are smaller in size, lighter in weight and have lower rotary inertia, makes them a good choice for EPS system.

Different types of control techniques are available for the PMSM control. Field oriented control (FOC) gained popularity as it provides smooth speed and torque control. The FOC control strategy was studied in paper[4]. It provides the sensorless estimation of speed based on back emf. In paper[5], the speed estimation of motor has been studied based on the back emf generation. In paper[6] the control of PMSM has been done through the Space Vector Pulse width modulation (SVPWM). SVPWM provides less harmonic content, less switching loss and has the higher utilization efficiency of power supply voltage. Also output current of three-phase inverter with SVPWM technology is significantly closer to sine wave, which is responsible in generating the rotating magnetic field that is close to a circular form[6].

In this paper the focus lies on to replicate the complete EPS system, by modelling it using Matlab/Simulink and test for various driving scenarios with different vehicle speed. The PMSM model available in Simulink library is used for the study. The EPS model is developed with the dynamic equations of mechanical steering unit[2] and the control unit which consists of the torque control of motor based on the driver input and assist logic. Here the friction between the road and wheels is neglected and only the vehicle speed is considered to provide the assist torque. This reduces the driver effort to steer the vehicle.

The complete details of Electric power steering system is given in section 2. The EPS dynamic model is described in section 2.1, the PMSM motor assist in section 2.2 and Electronic control unit (ECU) in section 2.3, EPS model with PMSM in section 2.4, section 3 discusses the simulation results followed by conclusions.

2. Electric Power Steering System

2.1. EPS dynamic model

In the Electric power steering system described in this work, the structure consists of a column type steering with steering wheel, steering column and the rack and pinion arrangement for wheels. The torque sensor has been mounted on the steering wheel which determines the driver torque. This work uses a permanent magnet synchronous motor with gear arrangement for the steering shaft to provide the torque assistance. The torque signal from the torque sensor is sent to Electronic control unit (ECU). Depending on the driving conditions, different amounts of assist torque is produced by the motor, which acts on the wheels through rack and pinion arrangement. The assist logic and specific control for driving condition is implemented in ECU. The basic EPS system structure is shown in figure 1.

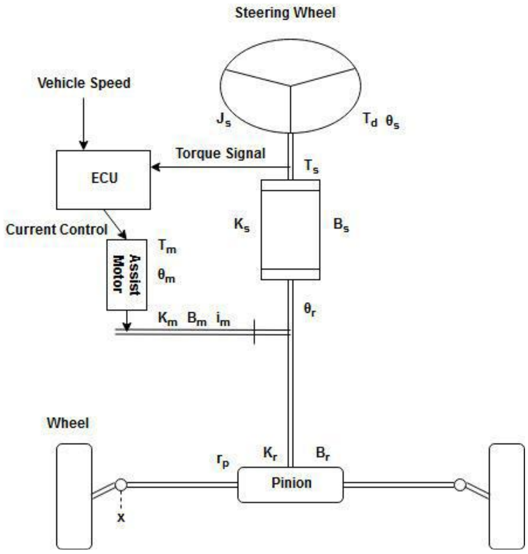

Figure 1. Basic EPS system structure.

Dynamic equations for the EPS system can be written as

Steering wheel to steering column

$$J_s\ddot{\theta}_s=T_d - K_s(\theta_s- \theta_r) - B_s\dot{\theta}_s \tag{1}$$

Assist section is governed by

$$J_m\ddot{\theta}_m=T_m- K_m(\theta_m- i_m\theta_r) - B_m\dot{\theta}_m \tag{2}$$

Rack and pinion section with x as displacement

$$m\ddot{x}=\frac{1}{r_p}[K_m(\theta_m-i_m\theta_r)i_m+K_s(\theta_s-\theta_r)]-B_r\dot{x}-K_r x \quad (3)$$

The parameters of EPS dynamic system are given in Table 1.

Table 1. Parameters of the EPS system.

Name	Symbol	Value
Inertia of steering wheel and steering column	J_s	0.0012 [kg.m2]
Steering column deboost	B_s	0.26 [Nm.rad-1s]
Rigidity of steering column	K_s	115 [Nm.rad-1]
Motor and reducer rigidity	K_m	125 [Nm.rad-1]
Reduction ratio of reducer	i_m	7.225
Deboost of rack and pinion	B_r	653.203 [N.s]
Mass of rack and pinion	m	32 [kg]
Linear rigidity	K_r	91061.4 [N/m]
Pinion radius	r_p	0.007783 [m]

The Simulink block diagram for simulation study of EPS system based on the equations (1) and (3) is shown in figure 2

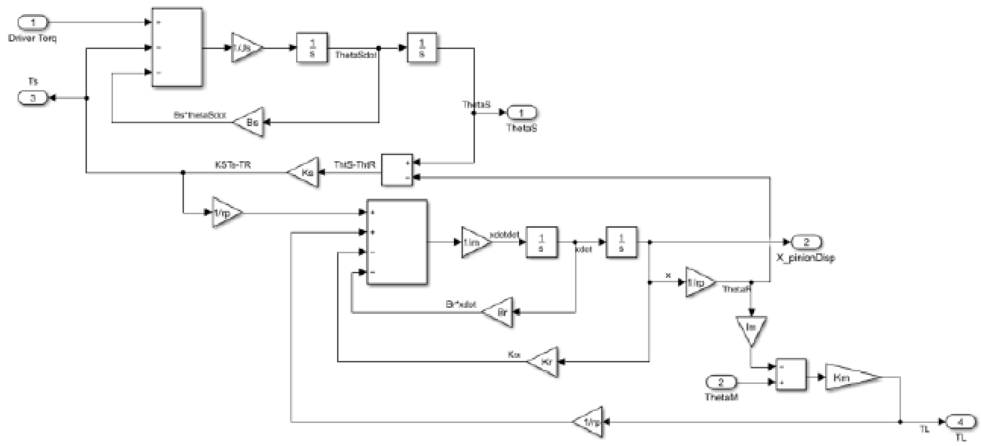

Figure 2. Dynamic block diagram of EPS system.

2.2. The PMSM motor model

The Permanent magnet synchronous motor modelled in Matlab/Simulink has a three-phase wye-wound stator. It is a 6-pole interior permanent magnet motor. The mathematical model of PMSM is depicted by equations (4), (5), (6) and (7).

$$V_d=R_s i_d+L_d\frac{di_d}{dt}-N\omega i_q L_q \quad (4)$$

$$V_q=R_s i_q+L_q\frac{di_q}{dt}+N\omega(i_d L_d+\psi_m) \quad (5)$$

$$V_0 = R_s i_0 + L_0 \frac{di_0}{dt} \tag{6}$$

The below torque equation gives the rotor torque

$$T = \frac{3}{2} N(i_q(i_d L_d + \psi_m) - i_d i_q L_q) \tag{7}$$

Where V_d is d-axis voltage, V_q, is q-axis voltage and V_0 is zero- sequence voltages, ω is the rotor mechanical rotational speed, N is the number of rotor permanent magnet pole pairs and T is the rotor torque.

2.3. Electronic Control Unit (ECU) model

The Electronic control unit consists of an assist logic that is implemented using the steering torque input and vehicle speed. It selects an appropriate torque that is required for the assist motor using feedback current and the current which is needed to develop the assist motor torque using PI controller. The logic implemented in ECU is as

$$T_M = \begin{cases} 0, & 0 \leq T_d \leq T_{d0} \\ trq(v), & T_{d0} \leq T_d \leq T_{dmax} \\ T_N, & T_{dmax} \leq T_d \end{cases} \tag{8}$$

$$trq(v) = (4 - 0.0606v + 0.0003v^2)(T_d - T_{d0}) \tag{9}$$

Assist characteristics of EPS system is as shown in figure 3

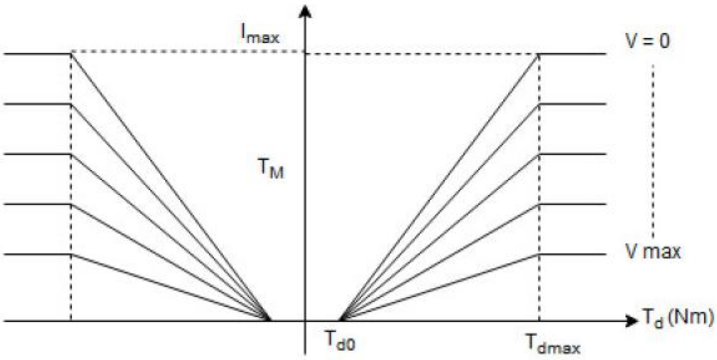

Figure 3. Assist characteristics for EPS system.

The control block diagram in simulink for PMSM with assist logic is as shown in figure 4

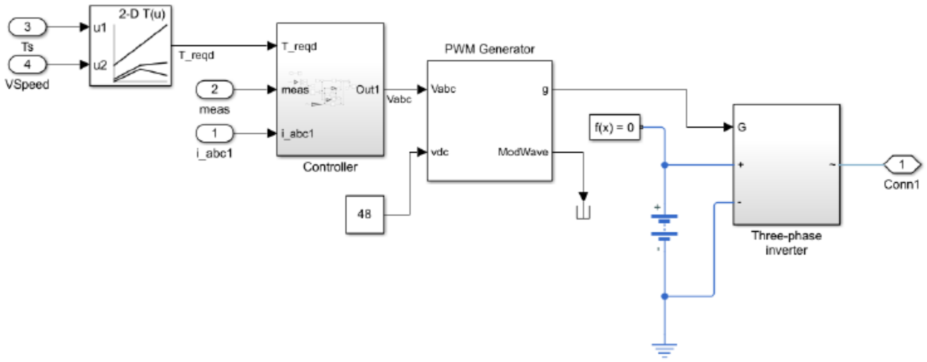

Figure 4. Simulink Control Block diagram for PMSM with assist logic.

Here T_d is the driver torque, T_{d0}, T_{dmax} is the minimum torque and maximum driver torque respectively. The logic implemented is
If the driver torque is less than T_{d0} then the motor does not provide any additional assistance as the torque required to steer the vehicle is low.
If the driver torque is between T_{d0} to T_{dmax} then the assist logic follows the equation (9) considering the speed of the vehicle.
If the driver torque is more than the T_{dmax} then the motor will provide the rated torque T_N.

2.4. *EPS model with PMSM*
The Electric power steering system consist of a mechanical subsystem, Steering control unit and PMSM motor. The mechanical subsystem is mathematically modelled in Matlab/Simulink as shown in figure 2. The mechanical system has steering wheel for driver input and steering column that is connected to rack and pinion arrangement.
The PMSM used has the parameters as listed in Table 2.

Table 2. Parameters of PMSM.

Parameter	Value	Units
Stator resistance Rs	0.013	Ω
Permanent magnet flux linkage PM	0.03	Wb
d-axis inductance of stator L_d	0.0002	H
q-axis inductance of stator Lq	0.0002	H
Number of pole pairs N	6	-

The method used for PMSM control is field oriented control (vector Control) technique. In this principle the three-phase motor current is transformed to two phase current components – one is d-axis current component and other is q-axis current component, here in this technique d-axis current component is kept to zero as this contributes to flux generation which contributes to speed control of motor. The d-axis current logic is given in figure 5.

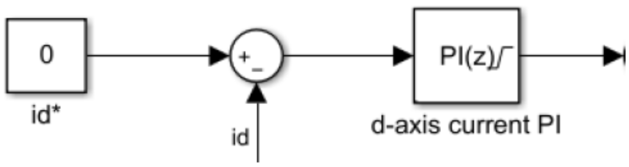

Figure 5. D-axis current control logic

Our objective is to have the torque control of the motor as per the required input from driver and according to driving conditions. The required torque is fed and the actual torque of motor is sensed, error in torque is fed to PI controller, this is the assist torque that is needed to be generated by the motor, the torque required is converted to iq current required and the actual current of motor is sensed, with this difference in q-axis current the motor generates the additional assist torque required for steering. The q-axis current control logic is given in figure 6.

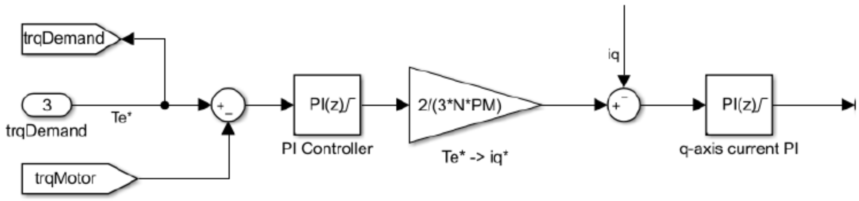

Figure 6. Torque control with q-axis current control.

Figure 7 illustrates the complete Electric Power Steering system modeled using Matlab/Simulink. The mechanical subsystem shown in figure 2, Steering ECU shown in figure 4 and PMSM model is combined to form the complete EPS simulation model as shown in figure 7.

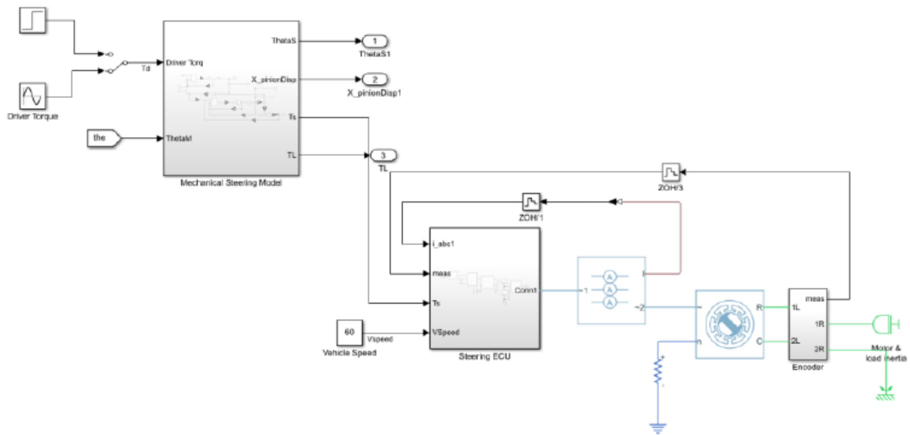

Figure 7. Complete EPS system with Steering ECU and PMSM motor.

3. Simulation Results

Simulation study is done with different steering torque inputs, the steering torque was applied as a sine wave input with amplitude as 6 Nm. Here figure 8 shows the quadrature axis current component responsible for motor torque generation and figure 9 shows the driver torque and the assist torque provided by the motor. It can be seen from figure 9 that, when the torque input is between 0 to 1 Nm the motor does not provide any assist torque. If the torque exceeds the T_{dmax} value, then the motor provides the rated torque. The simulation was tested for different vehicle speed and different steering input.

The figure 8, figure 9 shows the steering torque, torque required and the assist torque provided by the motor for different vehicle speeds.

Vehicle speed set at 60 Kmph.

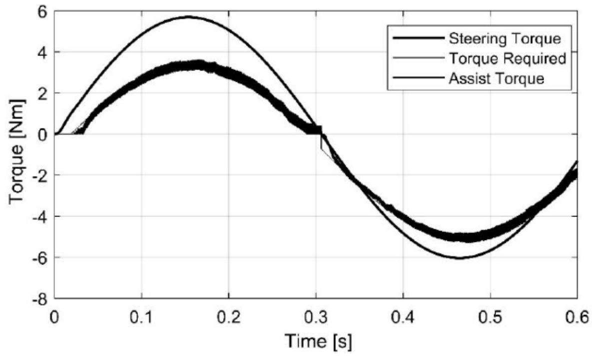

Figure 8. Steering torque and assist torque at 60Kmph.

Vehicle speed set at 8 Kmph.

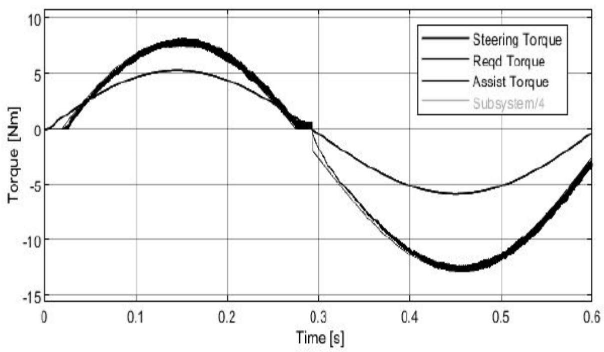

Figure 9. Steering torque and assist torque at 8Kmph.

As it can be observed in figure 9, where assist torque is greater than steering torque this implies that when vehicle is running at low speed during cornering or during vehicle parking, assist motor provides much higher torque input to wheels such that vehicle is easily steerable with less driver efforts

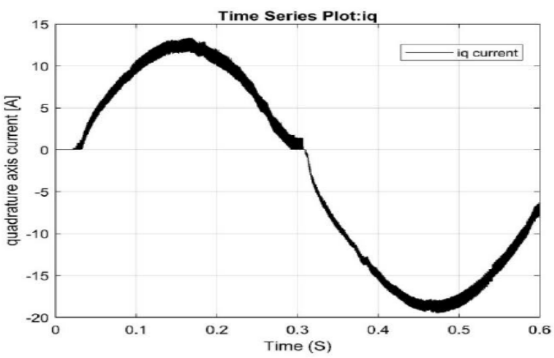

Figure 10. Quadrature axis current waveform

As it can be seen from the figure 10, the q-axis current has harmonic component, it becomes an important concern to reduce the harmonics from the feedback current. This can be done by adding a first order filter the feedback section of motor current. Thus, with the reduction of ripple content in current, the motor torque ripple can be reduced for smooth operation.

4. Conclusion

In this paper the complete EPS system using a Permanent magnet synchronous motor as assist motor, was developed using Matlab/Simulink model and simulated for different input conditions. The motor torque was controlled using feedback current. The mechanical system was built using dynamic model. The results were obtained for the different driver inputs and different driving condition. The developed simulation model can be used to test different motors in size and type. For better EPS performance, selection of the suitable motor can be done using this model.

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