
Modelling and Simulation of Two Gear Electric Vehicle in MATLAB SIMULINK

*¹Sudarshan Khond, ²Yasir Sheikh, ³Mohan Renge

^{1,2,3} Shri Ramdeobaba College of Engineering and Management, Nagpur
Email: khondsr1@rk nec.edu, sheikhmn@rk nec.edu, rengemm@rk nec.edu

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Abstract

With evolution of Electric drives design for electric vehicles, key aspects such as control, dynamic performance, efficiency and weight-torque ratio are some of the key parameters considered for optimization. Of these, torque to weight ratio is pivotal. As a typical traction load requires high starting torque and low torque during high speed, direct motor coupling may result in oversizing of motor or motor insufficient to drive desired load. Thus to optimize weight, size, cost and torque to weight ratio of an electric drive, gear system is used that provides high torque at standstill to start and accelerate the vehicle and high speed with required torque once the vehicle is set in motion. In this paper we aim to demonstrate Two-gear-Electric vehicle driven using induction motor with V/F control where it will be apparent how use of gear box optimises electric drive rating and related parameters.

Keywords

Electric Vehicle, Two Gear, Modelling, Simulation, Design, MATLAB SIMULINK

Introduction

Modelling and simulation activities have become inseparable part of electric vehicle design from last 4-5 decades. Electric vehicle design presents complexity owing to the interfacing of mechanical-electrical-electronics and to some extent chemical components compared to conventional IC engine-vehicle designs which have well defined techniques and rules with mature simulation tools.[1]

However to increase energy efficiency of the vehicle, reduce CO₂ emissions and to avoid penalties set by the governments original equipment manufacturers(OEM's) have now taken task of design and market setting of Hybrid and Electric vehicle very seriously.[4]

One of the most crucial point in Electric vehicle development program are power density (kW/Kg) and torque to weight ratio.[7] For directly driven electric vehicles, it becomes tough to produce high torque at the start as required by the load and relatively lower torque at high speeds. The problem can be overcome with the help of Two-gear system which scales high torque required to be produced by the motor down and inversely, reduce the speed by same factor.[3]

Model is designed and simulated considering various forces acting on the vehicle, drive control, motor inertia parameters and variable torque and speed scaling factor which will facilitate user to optimize the block for various environment for driving, different control topologies, use of different motor so that customized results for optimum design for particular drive cycles in local area using various topologies for

Smooth and efficient operation can be derived. [6]

Torque-speed Characteristics of Drive and Load

Figure 1(a) shows Torque (T_e)-speed characteristics of induction motor operated with V/F control method. As evident from fig., torque generated by the motor remains constant up to rated speed of motor which is achieved by keeping ratio of voltage and frequency constant if speed is increased beyond rated, voltage cannot be increased above rated to prevent damage to the winding insulation. Thus Torque of the motor drops with increase in speed thereby keeping power output (P_e) of motor constant.

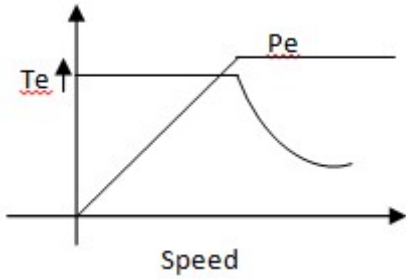


Figure 1(a): Torque, Power-speed Characteristics with V/F Control

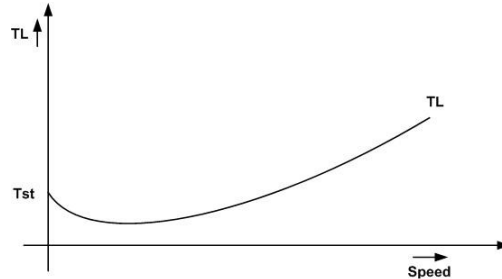


Figure 1(b): Torque-speed Characteristics of a Typical Traction Load

Figure 1(b) shows torque-speed characteristics of load. At standstill position, vehicle is required to overcome stiction. Also to ramp up to a certain value of speed, acceleration torque are also required thus motor needs to produce a high starting torque. However, as vehicle speed increases stiction and acceleration aren't required. [8]

Necessity of Gear Box.

As shown in Figure 2(a), to load motor from its full-load value (T_2) to a value close to its maximum loading capacity (T_1), Current required (I_1) will be 6-7 times that of current required to drive motor with its rated load (I_2). Practically considering inertia of vehicle, it takes 6-15 seconds to ramp speed up from 0 to 60kmph during which time motor will either require 6-7 times full load current or we will have to use motor 6 times of its original capacity. [9]

However once vehicle ramps up to a speed, stiction no longer exists and motor is not required to produce such high amount of torque. Thus to avoid oversizing of motor along with achieving goal of providing high starting torque, gear box is essential. [5]

As shown in Figure 2(b), Torque – speed characteristics of motor is shifted upwards during low speeds to generate sufficient torque, up to T_1 (e) to overcome stiction and provide acceleration to the vehicle. Point A corresponds to maximum speed that can be generated in first gear. As gear is changed to increase speed, torque requirement reduces as stiction no longer exists and acceleration torque isn't required in substantial magnitude thus motor can now provide torque up to T_2 (e) in second gear(B). However once motor operates at point B, torque equilibrium is established and vehicle runs at its top speed for existing loading conditions. [10]

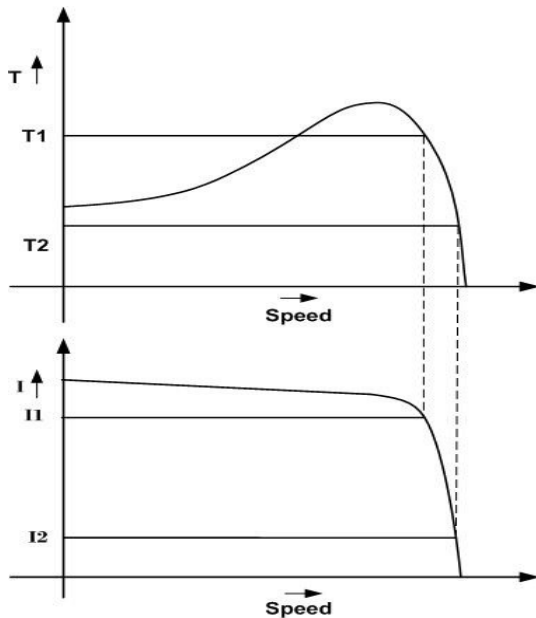


Figure 2 (a): Torque, Current-speed Characteristics of Motor

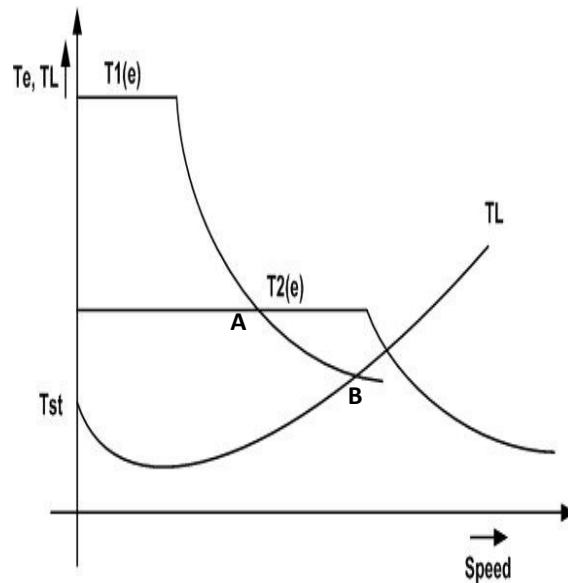


Figure 2(b): Torque-speed Characteristics for Two Gear System

Block Diagram of Simulation Model

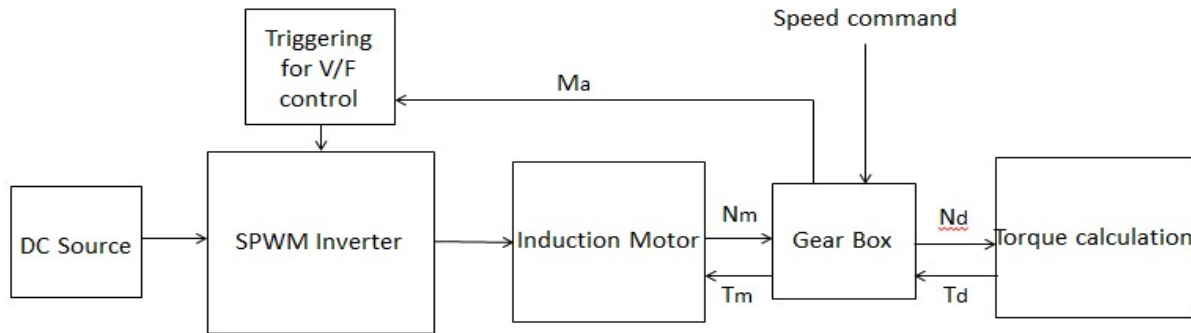


Figure 3: Block Diagram of Simulation Model

Induction motor used here is controlled with V/F control where voltage/frequency ratio is kept constant to obtain constant torque up rated voltage. Torque input given to the motor (T_m) is scaled with the help of gear box by selection of appropriate gear ratio which also scales the speed given by motor (N_m) down from the drive speed (N_d). (Figure3)

Simulation consists of variable voltage variable frequency (VVVF) control scheme for induction motor drive. A sinusoidal waveform is compared with triangular carrier waveform to obtain pulses that drive inverter bridge controlling motor input. Modulation index (M_a) controls voltage magnitude and frequency input is given to frequency of sinusoidal signal.

Torque required to drive the vehicle, T_d consists of rolling friction, aerodynamic torque and component of weight out of which first two are function of speed. Rolling friction linearly depends on speed whereas aerodynamic torque depends on speed squared. Forces required to overcome by the vehicle are as follows :

Force due to rolling friction:

$$P_f \cos(\alpha) \quad (1)$$

Aerodynamic drag is calculated as:

$$F_w = 0.5 \sigma A_f C_d V^2 \quad (2)$$

Grading resistance:

$$F_g = M g \sin \alpha \quad (3)$$

Where, F_w is force due to aerodynamic drag in Nm, A_f is vehicle frontal area in sq.m., C_d is drag coefficient, σ is density of air in Kg/cubic m., M is vehicle mass in Kg, g is acceleration constant, α is angle for uphill slope.

Acceleration resistance is given as

$$F_a = (M + (J_{rot}/r_{dyn}^2)) dV/dt \quad (4)$$

Where F_a is acceleration force, M is mass in Kg, J_{rot} is inertia of rotational components in Kg*cubic mtr

And r_{dyn} is dynamic resistance of the tyre.

Total driving resistance is given as

$$F_{resistance} = F_r + F_w + F_g + F_a \quad (5)$$

Where F_r is force due to rolling resistance, F_w is force due to dynamic resistance, F_g is grading resistance and F_a is force required for acceleration.

Methodology

Gear is such designed that it gives high torque (twice of required) during first gear with the help of relay and selector switch in constant torque region of motor. Its ratio becomes 1:1 during second gear.

As rotor speeds required are different for two gears to obtain same kmph, frequency and modulating index values need to be reduced during transition from first gear to second.

Modulation index is gradually increased as frequency is increased which in turn operates motor in constant torque region. Modulation index is saturated at 0.95 to keep voltage from going above rated value thus making motor to operate in field weakening region. [2]

Hence the dynamic equation of the vehicle in motion can be given as $F_a = F_g - (F_r + F_w + F_g)$

Where F_g is force generated by the engine

Model Specifications

Motor Specifications

Type	Squirrel cage Induction motor
Rating	2 pole, 400VAC, 50Hz, 37kW
Mechanical	$J=0.37\text{Kg.m}^2$, $B=0.02791\text{N.m.s}$.

Table 1(a): Motor Specifications

Vehicle parameters

Tyre	165/85 R15
Weight	900Kg
Tmax	500Nm@1500rpm
Pmax	50bhp@2500rpm

Table 1(b): Vehicle Parameter

Gear (Synchromesh Type)

No.	Speed range	Gear ratio
1	0-42	1:0.38
2	42-180	1:1.29

Table 1(c): Gear Specifications

Simulation Results:

For R15 tyre, diameter of the wheel is $15 \times 2.54 = 38.1\text{cm}$. Thus rpm to kmph conversion is given as $1\text{rpm} = (38.1 \times 3.14 \times 10^{-2}) \times \frac{60}{1000} \text{kmph} = 0.072\text{kmph}$ implying, $1\text{kmph} = 1/0.072 = 13.81\text{rpm}$. Gear 1 is set to operate for speeds from 0-48kmph while ramping up as shown in Figure 3(a). During this period, modulating index, M_a ramps up from 0.5 to 0.86 so that vehicle achieves desired speed by scaling the motor speed down. At $M_a=0.86$, motor speed is $1460 \times 0.86 = 1256.6\text{rpm}$ which corresponds to 96.58kmph (linear motor speed for R15 size rotor, same as wheel). Hence gear ratio of 0.49 will make vehicle run at $96.58 \times 0.49 = 48\text{kmph}$. As gear ratio changes from 1 to 2 at vehicle speed of 48kmph, speed is scaled up to achieve top speed in field weakening region of second gear as explained earlier. Thus at 48kmph, M_a is required to be reduced and increased gradually to maintain desired wheel speeds at same motor rpm. Hence there is sudden drop in M_a on inception of gear 2. After reaching a speed of 104kmph (Motor speed in kmph), M_a saturates while frequency is kept on increasing so that motor can operate in field weakening region to achieve its top speed. Point corresponding to 104kmph has rotor speed $=1440 \times 1 = 1440\text{rpm}$ ($M_a=1$) that will correspond to 2002.4rpm at wheel (1:1.45 ratio) which leads to linear speed of $2002.4/13.81 = 145\text{kmph}$ for the vehicle. Thus to operate vehicle in gear 1 till 48kmph with $M_a=0.86$ and attain 145kmph at $M_a=1$ and later in field weakening, gear ratio for gear no.1 and 2 are selected as 1:0.49 and 1:1.45 respectively with both wheel and rotor diameter for R15.

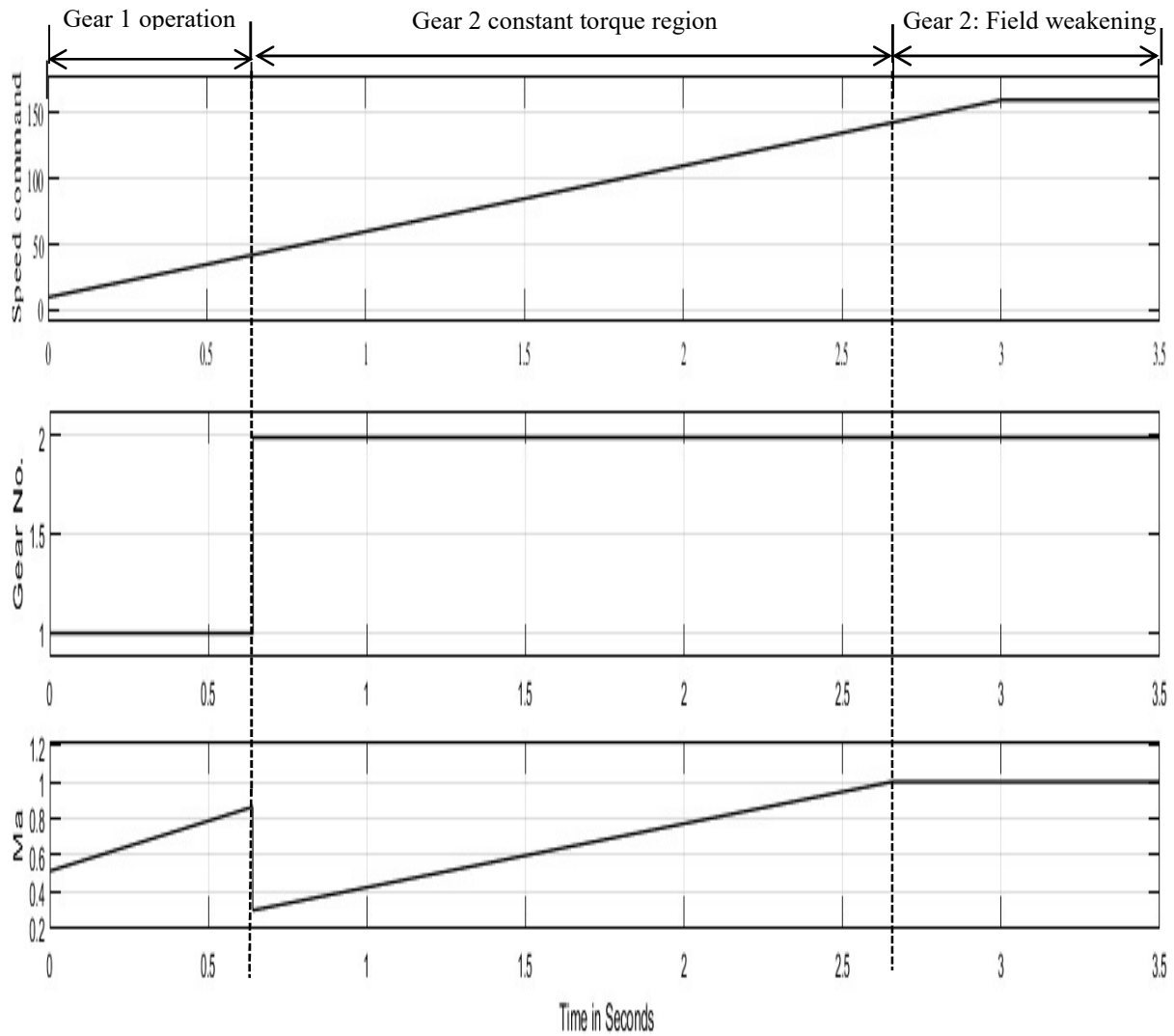


Figure 4 (a): Variation in M_a and Gear no. with respect to Speed Command

As shown in Figure 4 (b), motor torque required to drive the vehicle during first gear is low due to scaling by gear box by the factor of 0.38. At the end of first gear i.e. at speed close to 42kmph, motor torque is oscillating about 60Nm which becomes 157.8Nm at wheel due to gear. This is enough to drive and accelerate the vehicle.

At the end of second gear, motor generates torque of 425Nm which is marginally below its rated value. The difference between load and electromagnetic torque is lesser than in first gear as the load torque required by the vehicle at maximum speed is 340Nm thus reducing acceleration of vehicle as it approaches its steady state operating

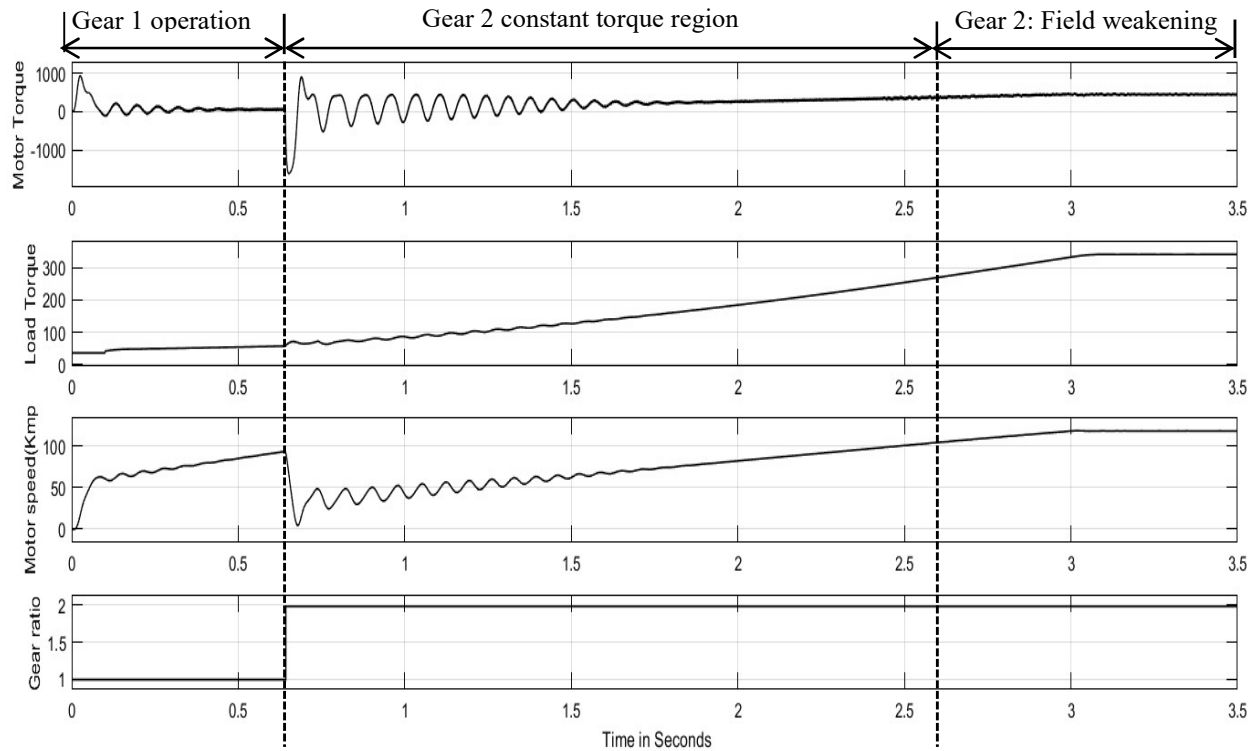


Figure 4 (b): Variation in Motor Torque, Load Torque and Gear no. with respect to Motor Speed

As shown in Figure 4(b), motor torque required to drive the vehicle during first gear is low due to scaling by gear box by the factor of 0.49. At the end of first gear i.e. at vehicle speed 48kmph (Motor speed $48/0.496 = 104\text{kmph}$), motor torque is oscillating about 60Nm which becomes $60/0.49 = 122.44\text{Nm}$ at wheel due to gear. This is enough to drive and accelerate the vehicle.

At the end of second gear, motor generates torque of 425Nm which is marginally below its rated value. The difference between load and electromagnetic torque is lesser than in first gear as the load torque required by the vehicle at maximum speed is 340Nm thus reducing acceleration of vehicle as it approaches its steady state operating point.

Conclusion

Simulation demonstrates Electric vehicle performance showing complete coordination between control, electric power, motor and mechanical components. Effectiveness of gear box in optimizing motor rating is apparent from the results explained. Simulation block can thus suffice load requirement at high speeds as in conventional IC engine driven vehicles and can further be utilized for optimization studies pertaining to various cost, performance, size and energy constrained parameters.

Oscillations in electromagnetic torque of motor causes motor power to oscillate greatly and power is fed back from the motor to the source. Further scope lies in damping the oscillation in electromagnetic torque with power control algorithms. Effect of stiction and accelerating torque required at the start isn't considered in the simulation which will also be required to be taken into the consideration for more practical design for estimation.

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