Determination of Power Consumption of Electric Vehicle for Assorted Pavement Gradient Using MATLAB/SIMULINK

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Abstract

Due to less pollution, silence and high efficiency electric vehicles are fascinating to the citizens widely. There are number of physical and electrical aspects are to be considered during vehicle modeling. When electric vehicle runs on the concrete surface rolling resistance resist the vehicle tire to move fast. On the other hand when the vertical angle of vehicle drive is increased or decreased by somewhat degrees the forward force is also increased or decreased respectively. In this paper, a typical electric vehicle dynamic is modeled to mechanical parameter after conversion its mechanical torques, the electrical power is obtained by required mechanical torque and angular velocity of propel as well as wheel. The permanent magnet DC motor is used to simulate the vehicle speed and torque. MATLAB created surface or road gradients are used to investigate torque in different ups and downs at different angle. After analyzing battery error the proportional integral controller gain is derived for achieving desired output from the vehicle.

Keywords: speed, gradient, torque, motor, controller, MATLAB, force

1. Introduction

The oil reserves are not inexhaustible, it is therefore necessary to find additional energy sources. This change has also become necessary due to the fact that the burning of oil gives a negative environmental impact [1]. Nowadays most cars are using internal combustion engines but manufacturers are considering using diferent kinds of energy soruce that reduce the pollution [2]. The energy carrier which seems be the most usable is the electrical energy [3]. The electric vehicle designing is complex process including energy distribution, vehicle transmission, road characteristics and so on [4]. In this paper, s series of speed and slope of angle are formed in MATLAB workplace then the car specifications are assumed to find the required torque in each up and down [5]. There are several terms are concerned with the mechanics which are used in MATLAB to state the variables during the designing electric vehicle. After that wheel torque is converted to motor torque. In this article the Permanent Magnet DC (PMDC) motor is used to simulate the torque-speed characteristics of the motor. The PMDC motor has inverse characteristics between the torque and speed. In this point of view when the vehicle is driven up in two or three degree with horizontal axis it requires large torque where less speed is conducted [6]. Subsequently motor electrical power requirements are fulfilled by adding DC battery stored in vehicle [7]. During the large ups and downs of vehicle movement there are different requirement of current to meet the demand of power needed to achieve torque to reach the peak of the valley. In this case the PI controller is used to monitor voltage and current level with the demand [8].

2. Electric Vehicle Drive Train Operation

In a typical gasoline powered vehicle the gas tank is not a part of the design model [9]. There is no way to put the gasoline to the tank when vehicle only consumes the gasoline from

the tank [10]. A standard shift from internal combustion engines to electric vehicles is that in an electric vehicle the battery is part of the drive train as shown below in Figure 1.
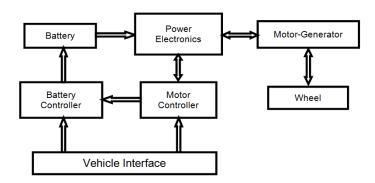

Figure 1. Electric Vehicle Drive Train with vehicle interface

The drive train consumes energy from the battery during motoring action. The drive train can also fed charge back to the battery when the motor is operated as a generator during regenerator action [11]. This can be occurred during braking or during the vehicle is being powered by an Internal Combustion Engine (ICE). In the diagram, the batteries are generally constructed of Lithium Ion cells and supplies 300 volts (+ve) and have high current capacity to the power electronics. A battery controller monitors key battery parameters and controls the battery pack. The power electronics unit inverts the DC battery voltage into three-phase AC voltage at the appropriate frequency and voltage for the motor to meet the required speed and torque [12]. The AC motor is typically a high efficiency AC Induction Motor (IM) or Permanent Magnet Synchronous Motor (PMSM). These motors supply either acceleration torque or braking torque for both directions of rotation. When the vehicle's brakes are applied the motor operates in regeneration mode thus reversing both the current direction and torque direction. The reversed torque direction offers vehicle braking torque while helping to recharge the battery. The Vehicle Interface corresponds with the Battery Controller and Motor Controller, and provides an interface with the vehicle-level controls and sensors [13].

2. Modeling Process and Key Equations

The model development process consists of 1) Determining how the model will be used, 2) Identifying the key equations including mechanical terms, parameters, and assumptions, 3) Building and refining the model, and then 4) The actual model application and evaluation. The model can be used to evaluate the energy flow of a DC motor drive train from mechanical parameters, and to determine the ability of the system to meet specific drive cycle speed and torque requirements. The major components of the model are input road torque at different road gradient condition including real time air drag resistance of environment, frontal area of vehicle, rolling resistance of vehicle even air density, demand road speed, motor model, motor controller model, battery model, and PI controller. A block diagram of the model is presented below in Figure 2. In the model the required road speed and road gradients are inputs and the major model blocks are the required forward force, wheel torque as well as motor torque, motor model, controller model, battery model, PI controller model, and feedback from the PI Controller to the main power controller. The feedback includes a one-sample delay with an initial condition to prevent an algebraic loop in the Simulink model.

3.1. Vehicle Kinetics

A simplified model of the road vehicle dynamics can be used to estimate the tractive requirement of the vehicle drive-train, from which the individual component specifications can be rated with-regard-to their peak and continuous duties. As it is seen in equation below the motor force required is directly proportional to the weight of the vehicle, frontal area of vehicle and square proportional to the linear velocity of vehicle. From the figure 2 when the sine angle is

increased the force is increased. Considering the above aspects the required force of vehicle can be written as below:

$$F_d = F_r + mg \sin\theta + F_a + m\frac{dv}{dt} \qquad (1)$$

For rolling resistance, $F_r = k_r mg \cos\theta$ $\qquad (2)$

Aerodynamic resistance or drag force, $F_a = \frac{1}{2}\rho C_d A_f v^2$ $\qquad (3)$

And the transient force required accelerating or retarding the vehicle, $m\frac{dv}{dt}$

Where: k_r = The rolling resistance coefficient which includes tire loss and is approximated to be independent of speed and proportional to the vehicle normal reaction force

   m = The vehicle and payload mass

   θ = The road gradient

   g = The gravitational constant

   ρ = The density of air

   C_d = The drag force coefficient

   A_f = The vehicle frontal area and

   v = The vehicle linear velocity

Figure 2. Forces Acting on Vehicle

3.2. Wheel and Traction Machine Torques

Determination the forces active upon the vehicle the road wheel torque can be calculated from the equation of motion merely.

$$T_w = J_w\frac{d\omega_n}{dt} + d_f r_w F_d \qquad (4)$$

Where J_w, ω_w and r_w are the wheel inertia, angular velocity and mean radius respectively and d_f is a factor proportioning torque distribution on the rear axle. By way of example for a direct rear wheel drive scenario, it is assumed that there is an equal share of the required tractive force between each wheel drive machine (i.e. $d_f = 0.5$). For an on-board drive machine option, a gear stage is included in the drive-train, thus the output torque of the traction machine is related to the road wheel torque by the total transmission gear n_t, transmission efficiency η_t and the machine rotor inertia J_m. Incorporating these into the equation of motion yields a general expression for traction machine torque:

$$T_m = J_m\frac{d\omega_m}{dt} + \frac{1}{n_t\eta_t}T_w \qquad (5)$$

Expressing the wheel and traction machine angular velocities in terms of the vehicle linear velocity yields.

Wheel angular velocity in terms of radius of wheel,

$$\omega_w = \frac{v}{r_w} \tag{6}$$

Motor angular velocity in terms of total gear differential ratio (n_t),

$$\omega_w = n_t \frac{v}{r_w} \tag{7}$$

From which the machine torque equation can be expressed in terms of the vehicle linear velocity by substituting Equation (1), (2), (6) and (7) into Equation (3).

$$T_m = \left[\left(\frac{n_1 J_m}{r_w}\right) + \left(\frac{J_w}{n_t \eta_t r_w}\right) + \left(\frac{d_f r_w m}{n_t \eta_t}\right)\right]\frac{dv}{dt} + \frac{d_f r_w}{n_t \eta_t}[(k_r \cos\theta + \sin\theta)mg + \frac{1}{2}\rho C_d A_f v^2] \tag{8}$$

Mechanical power is torque multiplied by mechanical speed:

$$P_m = T_m \omega_m \tag{9}$$

As noted earlier, Battery Electric Vehicles (BEV) and Hybrid Electric Vehicles (HEV) frequently use special, high efficiency Permanent Magnet Synchronous Motors (PMSM). This type of motor may be referred to as a brushless DC motor because it runs from DC voltage but does not have brushes. PMSM motors actually use AC voltage that is supplied by the Motor Controller. The motor controller inverts the DC voltage to produce an AC voltage at the proper voltage and frequency. The motor voltage is frequently a 10-20KHz Pulse Width Modulated AC voltage where the voltage and frequency are adjusted to provide the proper motor speed and magnetic field values. A DC permanent magnet motor was used in the simulation model presented below for investigating the characteristics of vehicle drive system. This type of motor is not appropriate for BEV or HEV in applications practically having weight and efficiency considerations. The motor model includes some terms and parameters for power loss and time lag while other terms were omitted from the model. The model accounts for power loss in the winding resistance and time lag due to the energy storage in the magnetic field of the winding inductance. There is no field power loss because it is a permanent magnet field.
The developed torque (T_d) is proportional to the armature current (I_A),

$$T_d(N-m) = K_m I_A \tag{10}$$

Where K_m motor physical constant is depends on physical parameter of motor construction.
On the other hand the developed voltage (V_D) is proportional to the armature speed (W_D) during the generator action.

$$V_D(Volt) = W_D(rad/sec)/K_m \tag{11}$$

Motor armature input or terminal voltage is equal to the sum of developed voltage plus resistance and inductance voltage drops. The general equation of voltage at high side of the motor controller can be written as:

$$V_H(Volt) = I_H(Amp)R_A(Ohm) + L_H(Henry)\frac{di(t)}{dt}(A/s) + V_D(Volt) \tag{12}$$

3.3. Motor Controller
The motor controller is assumed to be an ideal controller with no power loss and no time lag. The controller simply raises the battery voltage to meet the higher voltage needs of the motor. The dimensionless constant gain or K ratio of the input and output voltages is determined in order to meet the motor's needs. The same K ratio is used to adjust the current so that input and output power values are equal.
High side voltage (V_H) is equal to K times the low side voltage(V_L),

$$V_H = K V_L \tag{13}$$

High side current (I_H) is equal to 1/K times the low side voltage (V_L),

$$I_H = (^1/_K)V_L \tag{14}$$

3.4. Battery

The battery is modeled as a voltage source with an internal resistance. The model accounts for internal power loss in the resistance of the battery. There is no time lag component in the model. The battery is assumed to have a constant internal voltage, E_B. The battery terminal voltage, V_B, is equal to the sum of the internal voltage and resistance voltage drop. The battery voltage and battery current are equal to the controller low side voltage and current.

$$V_B(\text{Volt}) = I_A(\text{Amp})R_m(\text{Ohm}) + E_B(\text{Volt}) \tag{15}$$

Assuming $V_B = V_L$ and $I_A = I_L$ thus the Equation (15) can be written as:

$$V_L(\text{Volt}) = I_L(\text{Amp})R_m(\text{Ohm}) + E_B(\text{Volt}) \tag{16}$$

The battery model uses the current and voltage information from the Motor Controller to calculate the required battery's internal voltage. This voltage is compared with the actual E_B value to create a battery voltage error, B_{EER}, and that error is used by the PI controller model to adjust the loop gain.

$$B_{ERR} = E_B(\text{actual}) - E_B(\text{calculated}) \tag{17}$$

3.5. Proportional Integral (PI) Controller

The PI controller accepts the B_{ERR} signal from the battery model and uses proportional (K_p) and integral (K_i) to calculate the gain K value that is used by the motor controller.

$$K = (K_p + sK_i)B_{ERR} \tag{18}$$

4. Simulation Model Blocks
4.1. Forward Force Model

The simulation block for the forward forces include Equation (1)–(3) for the wheel torque. The block is shown below in Figure 3.
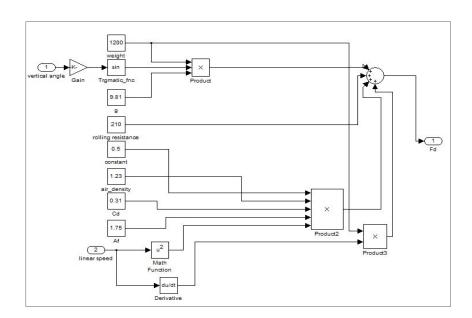

Figure 3. Effects of Selecting Different Switching under Dynamic Condition

4.2. Wheel Torque

The simulation block for the wheel torque includes Equation (4)–(5) for the motor torque. The block is shown below in Figure 4.
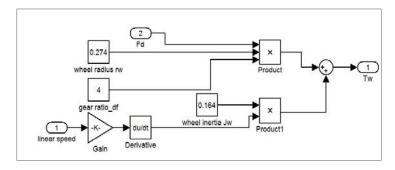

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Figure 4. Wheel Torque Model Block

4.3. PI Controller Model

The block model includes Equation 18 for the controller. The Gain (K) of the Motor Controller is determined by the output of the PI Controller model. The gain has an initial starting value of 0.1. This value was preset within the controller's integration block to minimize the possibility of a Simulink simulation error due to an algebraic loop. An algebraic loop is basically a divide by zero operation when the simulation is trying to solve the set of linear equations. The PI Controller checks to see that the output is not zero. If the output is zero then the controller outputs a small value (0.001). This is done to prevent model analysis failure due to dividing by zero when solving the linear equations. The controller also includes a gain limiting block to prevent excess feedback signals. The block is shown below in Figure 5.
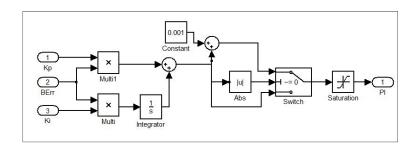

Figure 5. PI Controller Model Block

4.4. Drive System Model

The Speed and Torque values were written to the MATLAB Workspace, and the values were then read into the model speed and torque look-up tables. The Clock input to the look-up tables used the following time base values that were setup in the model parameters table: Tmin = 0, Tstep = 0.01, Tstop = 110 seconds. The displayed Scope values were also written to the MATLAB Workspace as Structures with Time. A MATLAB script was used to pre-load the speed and torque data in the Workspace, Run the Simulation, obtain the key data from the Scope Structures, and plot the data. The complete force model and motor drive model are shown below in Figure 6.
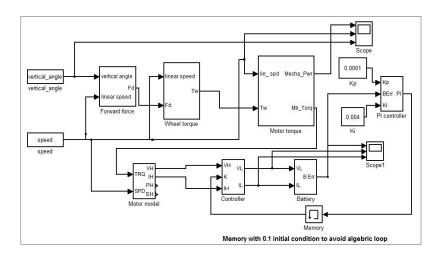
Figure 6. Forward Force Model and Motor Derive System

5. Results and Simulations

The Motor Power plot in Figure 7 shows both Motoring and Regeneration. When both current and voltage are positive values then the DC Motor is providing torque in the direction of rotation and power is being transferred to the load. This is normal motoring operation. However, when the motor current is in the opposite polarity of the voltage, then the motor is being pushed and acting as a generator with current flow back into the battery. In this case the vehicle gradient was zero in other words the speed and torque was fed by MATLAB workspace to investigate the motoring and regeneration action.
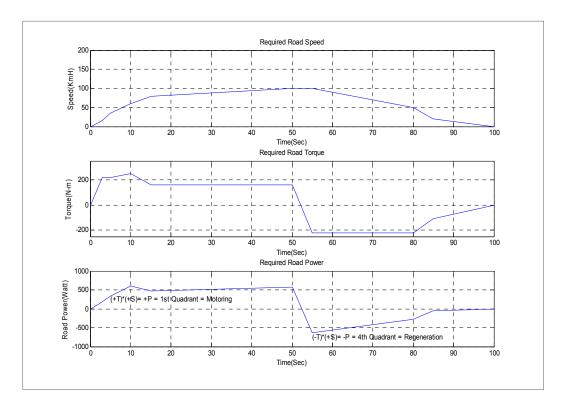

Figure 7. Road speed, Torque and Power Curves Showing Motoring and Regeneration

5.1. Battery Voltage Error

The simulation model adjusts the controller gain (K) to meet drive torque and regeneration requirements. The simulation compared the nominal battery internal voltage, VB =200 volts or VBatt (actual), with a calculated battery voltage based on the motor voltage and current values to get VBatt (calculated). The difference, VBerr, was used as an error signal input to the Proportional Integral (PI) Controller. This VBerr signal was plotted over the range of the simulation operation. This plot is shown below in Figure 8. The maximum error of -200 occurs at the very beginning of the simulation. This large error is a natural response to starting the simulation. The simulation quickly recovers and holds an error of about +76 during the initial starting of the motor. It is normal to have a higher error here because the motor developed voltage, VD(Volt) = WD (rad/sec)/Km, is low during startup, especially when the current is increasing. The negative error occurs during regeneration. By reviewing the motor voltage drop equation, VL (Volt) = IL(Amp) *RA(Ohm) + EB(Volt), the change in current polarity will cause the reverse polarity of the IL(Amp) *RA(Ohm) term. This voltage change will impact the magnitude of the input and output of the PI controller because of the reduced difference between the calculated and actual voltage in the error equation, $B_{ERR} = E_B$ (actual) - E_B (calculated).
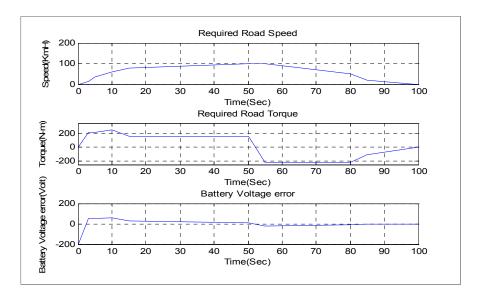

Figure 8. Battery Voltage Error (B_{Err}).

5.2. Controller Gain

The Gain (K) of the Motor Controller is determined by the output of the PI Controller model. A plot of the value of the Controller Gain (K) during the simulation is shown below in Figure 9. The controller gain increases during the time when the motor speed is increasing, and decreases when the motor speed is decreasing. The gain has an initial starting value of 0.1. This was preset within the controller in the 1/s integration block. This value is set in the simulation by opening up the 1/s block. The addition of the initial condition on the integration block helps to minimize the possibility of a Simulink simulation error due to an algebraic loop. An algebraic loop is basically a divide by zero operation when the simulation is trying to solve the set of linear equations. Figure 10 shows that vehicle gradient in different speed with variable speed. It is observed that when vehicle needs more torque to overcome the gradient motor draws more power from the battery.
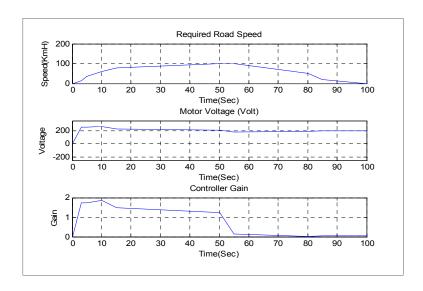
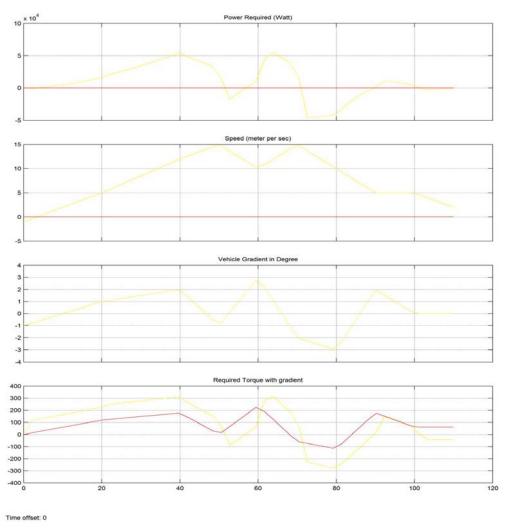Figure 9. Controller Gain K Value with Battery Voltage

Time offset: 0

Figure 9. Vehicle Linear Speed, Gradient, Torque and Power

5. Conclusion

A simulation model for a electric vehicle with vector controlled permanent magnet traction motor is developed and also verified. In this paper a battery electric vehicle have been modeled and designed. After analyzing the torque speed characteristics of motor and wheel, it is concluded that vehicle kinetic energy during running in negative slope or in zero clutch can be converted to electrical power by means of regeneration scheme of motor. On the other hand when motor requires large torque for positive slope it demands more current as well as more power to motor. Motor controller can used to monitor the condition of speed in terms of voltage and the demanded torque in terms of current to prove the instruction to be fulfilled the required value by value of gain obtained for PI controller. The battery of the electric vehicle is designed in such a way that both the power and energy requirements are fulfilled for a given driving cycle. In the simulation, linear models for the energy sources are used. The future work will incorporate more accurate models of the energy sources in the simulation.

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