MODELING AND CONTROL SOLUTIONS FOR ELECTRIC VEHICLES

Farhan A. Salem, PhD

Mechatronics Sec., Dept. of Mechanical Engineering, Faculty of Engineering,

Taif University, Taif, Saudi Arabia

Abstract

This paper extends previous work and proposes modeling and control solutions for electric vehicles, detailed and accurate mathematical models and corresponding simulink models, of both electric vehicle's electric machine and platform sub-systems was derived, coupled with the wheel rotational velocity via characteristics of the electric machine and surface conditions. Different control schemes including one and two loops control, was designed and tested to result in smooth driving for comfortable riding, to cope with different requests including reference signal variation and disturbances in the form of changes in the total mass and road surface conditions. The proposed models was created and verified using MATLAB/simulink software.

Keywords: Electric vehicle, Electric Motor, Modeling, Control

Introduction

The electric vehicle (EV) system consists of two subsystems (see Figure 1), an electric machine as drive system and the vehicle platform; the main components include electrical energy sources, control systems as a central control, and power converter as a device that converts electrical energy source with variable needs of the electric vehicle by switching devices (Bambang Sri Kaloko et al, 2011).To drive EV system, one electric motor can be used or two electric motor each for each wheel, in this paper, the case of one front drive electric motor is to be considered. Meanwhile electric vehicles generally use a battery as its main energy source (Bambang Sri Kaloko et al, 2011)(Dhameja, S., 2003)(Husain, I, 2003) , But the batteries on electric vehicles have a weakness that has the capacity and service life is limited so that necessary arrangements for charging batteries do not work hard (Bambang Sri Kaloko et al, 2011). Different researches on EV's design, modeling and control can be found e.g. (Farhan A. Salem, 2013), detailed and accurate mathematical models of both subsystems were derived and represented in simulink, both subsystems were couple with the wheel rotational velocity via characteristics of the electric motor and surface including the traction force, the torque disturbance etc, also for controlling the performance of EV, in particular, smooth driving for comfortable riding, a proper control system consisting of two loops, outer speed control and inner current control was designed, tested and verified using MATLAB/Simulink software. (Brahim Gasbaoui et al, 2011) proposed an independent machine control structure applied to a propulsion system ensuring by the electronic differential. (P. Bauer et al, 2012) two types of models are set up for a series hybrid solar vehicle, taking into account available control design strategies and control goals. (Bambang Sri Kaloko et al, 2011) Proposed a model that can be used to estimate how long the battery can be used in electric vehicles, also can be used to determine the performance of electric vehicle such as the starting process or running with constant speed. (Erik Schaltz ,2011) modeled and designed the battery electric vehicle. (Dragos Maciuca) Proposed design modification, modeling and control of the automatic steering and braking systems of an urban electric vehicle. (Qi Huang et al, 2012) discussed in detail, the modeling of electric vehicle. Then, the control of electric vehicle driven by different motors is discussed, the implementation of the controller with DSP and some test results with this platform are presented. This paper extends previous work given in (Farhan A. Salem, 2013), and proposes different mathematical and simulink models and control solutions for electric vehicle , with reference to the testing a maximum speed of 23 m/s, (that is 82.8 km/h) in maximum of 8 seconds, if an electric vehicle with total mass m=1000 kg , friction coefficient of 0.19, the air density of 1.25 kg/m^3 and aerodynamic factors of 0.75 the surface area of vehicles 1.5m^2, width of 1 m , height of 0.5, the gear ratio G, *n* at wheel radius of 0.3 m, and maximum power efficiency of 0.77

EV System modeling

The EV system consists of two subsystems, the electric motor and the vehicle platform system; both to be modeled, considering all acting forces and parameters, EV platform to be coupled with the wheel rotational velocity via characteristics of the electric motor and surface, as well as, to derive the expressions for the acting forces, to calculate required torque and power expressions, that can be used to build the simulink model, finally, suggest, design couple and test control systems.

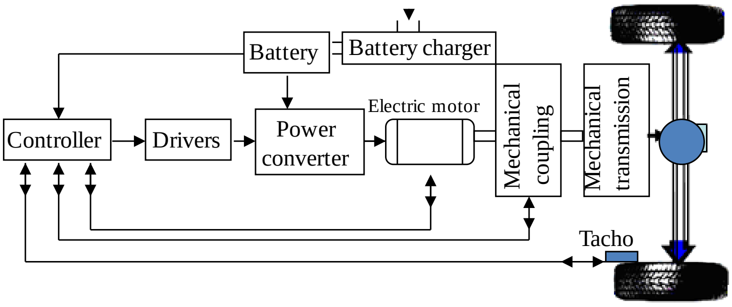

Figure 1 Architecture, Major components of electric vehicle (Farhan A. Salem, 2013)

Electric motor modeling

The sole motive force provider is electric machine (motor), therefore, EV motion control is simplified to an electric machine motion control. In order to guarantee the speed-up time, the electric motor is required to have large torque output under low speed and high over-load capability, and in order to operate at high speed, the driving motor is required to have certain power output at high-speed operation (Qi Huang et al, 2012). A detailed derivation of basic electric motor mathematical models are presented in different resources including (Farhan A. Salem)(P. Bauer et al, 2012)(Bambang Sri et al, 2011). The fundamental system of electromagnetic equations for any electric motor is given by Eq.(1) (M.P.Kazmierkowski et al, 1994) (R.D. Doncker et al, 2011)

$$\left.\begin{aligned} u_s &= R_s i_s + \frac{d\psi_s}{dt} + j\,\omega^k \psi_s \\ u_s &= R_R i_R + \frac{d\psi_R}{dt} + j\,(\omega^k - P_b\omega_m)\psi_R \\ \psi_s &= L_s i_s + L_\mu i_R \\ \psi_R &= L_R i_R + L_\mu i_S \end{aligned}\right\} \qquad (1)$$

Where : ω^k the angular speed of rotating coordinate system (reference frame). Depending on motor construction (AC or DC), the method of the supply and the coordinate system (stationary or rotating with the rotor or stator flux) the above mentioned model becomes transformed to the desirable form (Grzegorz Sieklucki , 2012), and the complement equations given by (1) is equations describing mechanical part of eclectic motor. Because of the ease with which DC machines can be controlled, systems of DC machines have been frequently used in many applications requiring a wide range of motor speeds and a precise output motor control (Farhan A. Salem, 2013). The selection of motor for a specific electric vehicle is dependent on many factors, such as the intention of the EV, correspondingly allowable variation in speed and torque and ease of control, etc. based on this, and for simplicity, assuming the motor to be an armature controlled DC motor, the DC motor open loop transfer function without any load attached relating the input voltage, $V_{in}(s)$, to the angular velocity, $\omega(s)$, given by Eq.(2):

$$G_{speed}(s)=\frac{\omega(s)}{V_{in}(s)}=\frac{K_t}{\left\{\left[(L_a s+R_a)(J_m s+b_m)+K_t K_b\right]\right\}}=\frac{K_t}{\left[(L_a J_m)s^2+(R_a J_m+b_m L_a)s+(R_a b_m+K_t K_b)\right]} \quad (2)$$

The geometry of the mechanical part determines the moment of inertia, the EV platform can be considered to be of the cuboid or cubic shape, with the inertia calculated as shown below, where the total equivalent inertia, J_{equiv} and total equivalent damping, b_{equiv} at the armature of the motor with gears attaches, are given by Eq.(3), also the total inertia can be calculated from the energy conservation principle, as given by Eqs.(4) (5):

$$b_{equiv}=b_m+b_{Load}\left(\frac{N_1}{N_2}\right)^2, \quad J_{equiv}=J_m+J_{Load}\left(\frac{N_1}{N_2}\right)^2, \quad J_{load}=\frac{bh^3}{12} \quad (3)$$

$$0.5*m_{total}*\upsilon^2=0.5*J_{load}*\omega^2 \Rightarrow J_{load}=\frac{m_{total}*\upsilon^2}{\omega^2} \quad (4)$$

Considering that linear velocity of EV, depends on motor's angular speed, wheels radius, r, and gear ratio, n, substituting, gives:

$$\omega=\omega_{shaft}*n=\frac{\upsilon n}{r} \Rightarrow \upsilon=\frac{\omega r}{n}, \quad \rightarrow J_{load}=\frac{m_{total}*r^2*\omega^2}{n^2*\omega^2}=\frac{m_{total}*r^2}{n^2} \quad (5)$$

By substituting values, the equivalent EV open loop system transfer function will be given by Eq.(6), the EV open loop system, relating the armature input terminal voltage, $V_{in}(s)$ to the output terminal voltage of the tachometer $V_{tach}(s)$, with most corresponding load torques applied considered are given by Eq.(7), where T is all disturbance torques, including coulomb friction, and given by ($T=T_{load}+T_f$). To measure the output speed and feed it back to control system, tachometer is used, tachometer is a sensor used to measure the actual output angular speed, ω_L .. Dynamics of tachometer, and corresponding transfer function can be represented by Eq.(8), for desired output maximum linear speed of EV of 23 m/s, (that is *82.8* km/h), the tachometer constant is $K_{tach}=0.4696$:

$$G_{speed}(s)=\frac{\omega_{robot}(s)}{V_{in}(s)}=\frac{K_t/n}{\left[(L_a J_{equiv})s^2+(R_a J_{equiv}+b_{equiv}L_a)s+(R_a b_{equiv}+K_t K_b)\right]} \quad (6)$$

$$G_{open}(s)\frac{V_{in}(s)}{V_{tach}(s)}=\frac{K_{tach}*K_t}{(L_a s+R_a)(J_m s+b_m)+(L_a s+R_a)(T)+K_b K_t} \quad (7)$$

$$V_{out}(t)=K_{tac}*d\theta(t)/dt \Rightarrow V_{out}(t)=K_{tac}*\omega \Rightarrow K_{tac}=V_{out}(s)/\omega(s) \quad (8)$$

Modeling electric vehicle, EV, dynamics

The speed of EV depends upon the balance between the motive forces developed by the electric motor and running resistive forces (Norman S. Nise, 2011) therefore, when deriving an accurate mathematical model for EV dynamics, it is important to study and analyze dynamics between the road, wheel and EV considering all the forces applied upon the EV system, dynamics modeling involves the balance among the several acting on a running EV forces. The disturbance torque to EV is the total resultant torque generated by the acting resistive forces, given by Eq.(9):

$$F_{Total} = \mathrm{F_{aerod}} + \mathrm{F_{rolling}} + \mathrm{F_{climb}} + \mathrm{F_{Linear\_acc}} + F_{\mathrm{angular\_acc}} \qquad (9)$$

Where, the forces are given by:

$$\mathrm{F_{rolling}} = F_{normal\_force} * \mathrm{C_r} = M * g * \mathrm{C_r}$$

$$\mathrm{F_{aerod}} = 0.5*\rho*\mathrm{A}*\mathrm{C_d}*\left(\upsilon_{vehicl} + \upsilon_{wind}\right)^2 * sign\left(\upsilon_{vehicl} + \upsilon_{wind}\right) \Rightarrow \mathrm{F_{aerod}} = 0.5*\rho*\mathrm{A}*\mathrm{C_d}*\upsilon_{vehic}^2$$

$$\mathrm{F_{climb}} = M * g * \sin(\alpha)$$

$$\mathrm{F_{wind}} = 0.5*\rho*\mathrm{A}*\mathrm{C_d}*\left(\upsilon_{vehicle} + \upsilon_{wind}\right)^2$$

$$\mathrm{F_{norm}} = F_{\mathrm{climb}} - F_{lift} = \left(M * g * \sin(\alpha)\right) - \left(0.5*\rho*C_L * B * \upsilon^2\right)$$

$$\mathrm{F_{acc\_angle}} = IaG^2 / r_{wheel}^2$$

Where: C_r The rolling resistance coefficients, C_d : Aerodynamic drag coefficient characterizing the shape of the EV, C_L: The coefficient of lift, (C_L to be 0.10 or 0.16), M : The mass of the SMEV and cargo (*Kg*). *g:* The gravity acceleration (m/s^2), α :Road or the hill climbing angle, *road slope* (*Rad*.). To determine the electric battery capacity, we need to estimate energy required of EV platform, the requested power in *kW* that EV platform must develop at stabilized speed can be determined by multiplying the total force with the velocity of the *EV*, and given by:

$$P_{Total} = (\sum F) * \upsilon = F_{Total} * \upsilon \qquad (10)$$

Electrical power (in watts) in a DC circuit can be calculated by equation *P= I x V* ,where: *I* is current in Amps and *V* is voltage. Based on fundamental principle of dynamics the acceleration of the vehicle isgiven by:

$$\alpha = \frac{P_m - P_{total}}{M * \upsilon}$$

Where: P_m :The power available in the wheels of the vehicle. *M, v*: vehicle mass and speed. An accurate mathematical model for EV dynamics are presented in detailed form in (Farhan A. Salem, 2014), The total running resistance is given by Eq.(11)

$$F_{Total} = \left[M * g * \sin(\alpha)\right] + \left[\mathrm{M} * \mathrm{g} * \left(\mathrm{C_{r0}} - \mathrm{C_{r1}} * \upsilon\right) * sign(\upsilon)\right] + \left[0.5*\rho*\mathrm{A}*\mathrm{C_d}*\left(\upsilon_{vehicl} + \upsilon_{wind}\right)^2 * sign\left(\upsilon_{vehicl} + \upsilon_{wind}\right)\right] + \mathrm{F_{Linear\_acc}} + \left[\left(M + \frac{J_{wheel}}{r^2}\right)\frac{d\upsilon}{dt}\right] \qquad (11)$$

Depending on desired accuracy, and main research purpose, different resources, introduce different forms of he total running resistance (The forces which the electric machine of the vehicle must overcome) and vehicle dynamics, including or simplifying different factors , including; (Brahim Gasbaoui, 2011) introduced Eq.(12), (Bashir M. Y. Nouri, 2005) introduced Eq.(12), (Norman S. Nise, 2011) introduced Eq.(14) , (Hedaya Alasooly, 2011) introduced Eq.(15). Based on Eq(11) , for disturbance torque, two simulink models function block models, shown in Figure 2(a)(b), are proposed.

$$F_d(t) = R_\omega mg\sin(\alpha) + mgC_r r + 0.5\rho A C_d r\upsilon^2 \qquad (12)$$

$$T_d = 0.5r^2 m\frac{d\omega}{dt} + 0.5m*r*g*\sin(\alpha) + C_r\omega \qquad (13)$$

$$F_d(t) = m\dot{\upsilon}(t) + 0.5\rho\upsilon^2(t)*A*C_d + m*g*C_r \qquad (14)$$

$$F_d(t) = \mathrm{C_r}*m*g*\cos(\alpha) + m*g*\sin(\alpha)*0.5C_d*A*(\upsilon-\upsilon_{wind})^2 + K_m*m*a \qquad (15)$$

Based on all derived equations, and for simplicity, the open loop transfer function, relating the armature input terminal voltage, $V_{in}(s)$ to the output terminal voltage of the tachometer $V_{tach}(s)$, with main corresponding load torques considered, is given by Eq.(16) , the basic open loop simulink model where EV the dynamics is coupled with the wheel rotational velocity via characteristics of the electric motor and surface, with disturbance torque is shown in if Figure 3(a):

$$G_{open}(s) = \frac{2K_{tach}*K_t}{2b_{equiv}L_a s^2 + r^2ML_a s + 2b_{equiv}R_a s + r^2MR_a s + C_r L_a s + 2J_{equiv}L_a s + 2K_b K_t + C_r R_a + 2J_{equiv}R_a} \qquad (16)$$

State space modeling

The basic equations characterize the relationships between the state, input, and output variables for the EV forward path of the Figure 3, can be given as follows:

$$R_a*I_a + L_a*I_a = V_{in} - V_{EMF} = V_{in} - K_b\omega$$

$$J_{equiv}*\frac{d\omega}{dt} = T_m - T_{fric} - T_{load}\,,$$

$$where: \quad J_{equiv} = J_m + J_{vehicl} + J_\omega \;,\quad T_M = K_t*I_a \quad, T_{fric} = k_f\,\omega$$

Taking the state equations to be the motor armature current, $I_a(t)$, and angular speed, ω *(t)*, we rewrite the above equations to have the following form:

$$\frac{d\omega}{dt} = \frac{K_t*I_a(t)}{J_{equiv}} - \frac{b_m*\omega(t)}{J_{equiv}} - \frac{T_{Load}}{J_{equiv}}$$

$$\frac{di_a}{dt} = -\frac{R_a*I_a(t)}{L_a} - \frac{K_b*\omega(t)}{L_a} - \frac{V_{in}(t)}{L_a}$$

The resulting state-space equations with two inputs and two outputs are, given by:

$$\begin{bmatrix} I_a \\ \dot{\omega} \end{bmatrix} = \begin{bmatrix} -\frac{R_a}{L_a} & -\frac{K_b}{L_a} \\ \frac{K_t}{J_{equi}} & -\frac{K_f}{J_{equi}} \end{bmatrix} \begin{bmatrix} I_a \\ \dot{\omega} \end{bmatrix} + \begin{bmatrix} \frac{1}{L_a} & 0 \\ 0 & -\frac{1}{J_{equi}} \end{bmatrix} \begin{bmatrix} V_{in} \\ T_{load} \end{bmatrix}$$

$$\begin{bmatrix} I_a \\ \omega \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} I_a \\ \omega \end{bmatrix}$$

Bases on this state space representation, the simulink model of open loop EV system, is built and shown in Figure 3(b), in this model, both representations of load torque are combined in one function block, with internal manual switch. Any of models given in Figure 3(a)(b), can be used to simulate the system dynamics and to design and test control system, as well as, the overall system performance.

Testing open loop model

Test input signal

The reference input for testing the proposed overall design of EV, including control system design, EV mechanical design and dynamics model, are to be both step input signal with 36 input, and motion profile (also called reference tracking or driving cycle) consisting of an acceleration, then constant speed, and breaking decceleration until zero velocity is reached, the simulink representation of the reference profile tracking and corresponding output profile is shown in Figure 3(c).

Running the open loop simulink model (Figure 3) for step input of 36, will result in linear speed/time, angular speed /time, linear acceleration /time, current/time, load torque/time, motor torque/time response curves shown in Figure 3(d), these curves will be used to evaluate the accuracy of designed control system, and the performance of overall EV system.

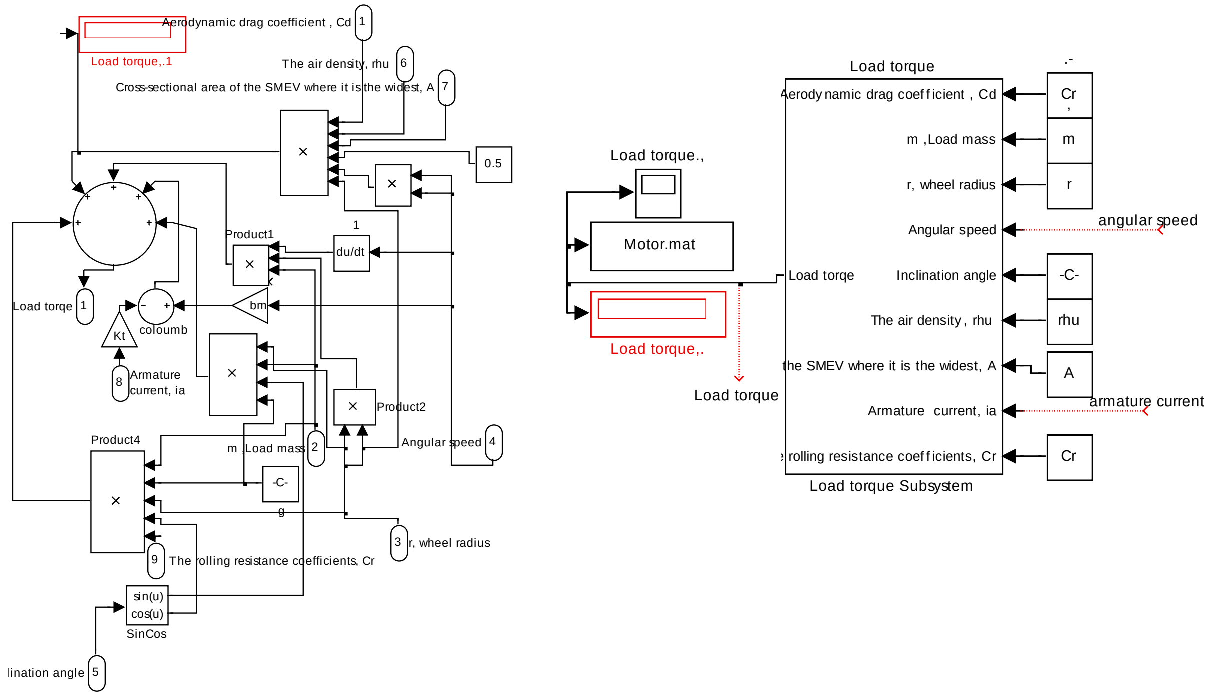

Figure 2(a) EV Disturbance torque and function model

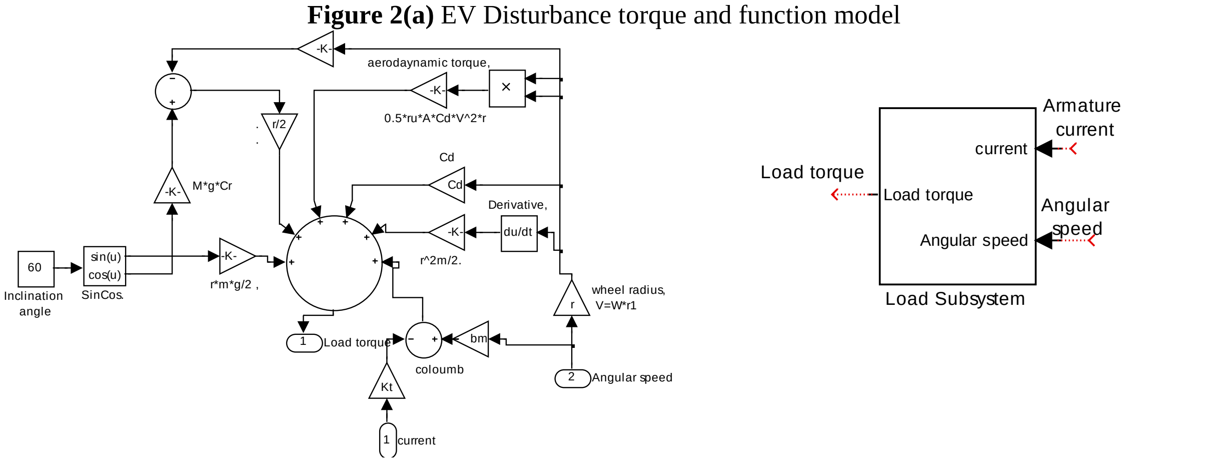

Figure 2(b) EV Disturbance torque and function model

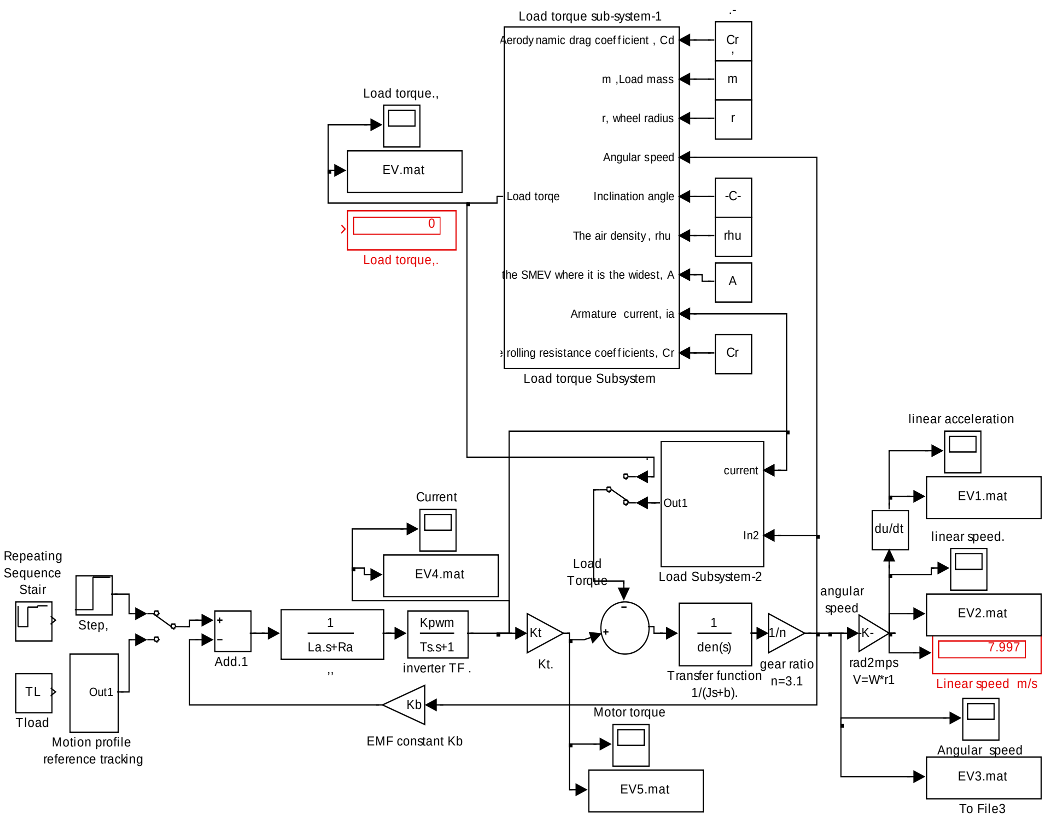

Figure 3(a) Basic EV open loop simulink model, dynamics is coupled with the wheel rotational velocity via characteristics of the electric motor and surface; two disturbance models are included with manual switch.

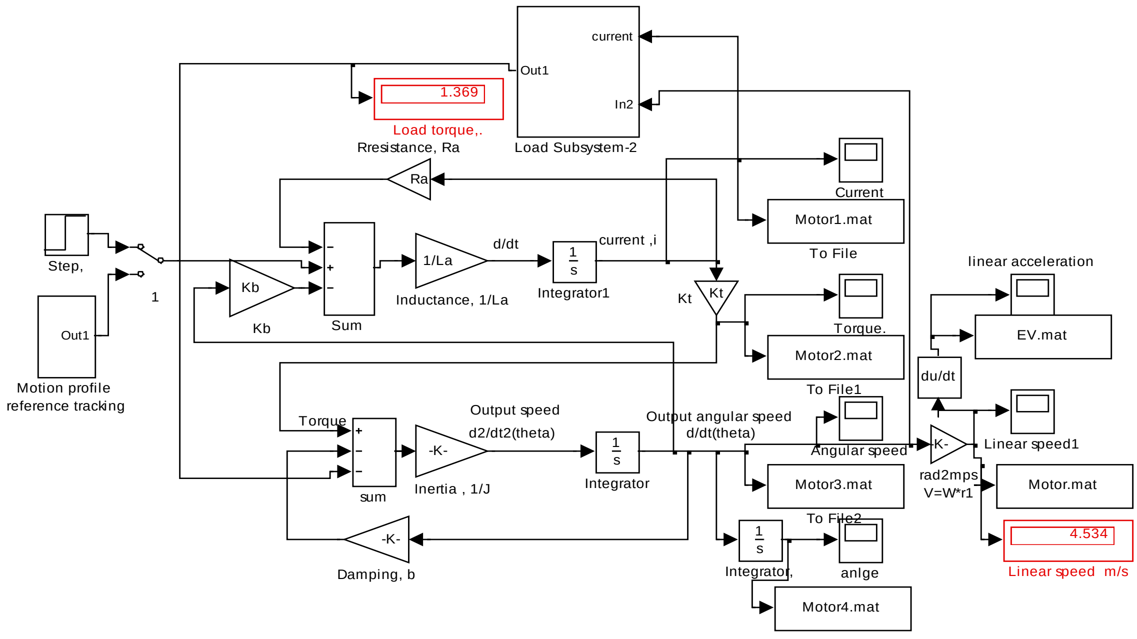

Figure 3(b) simulink model based on state space equations

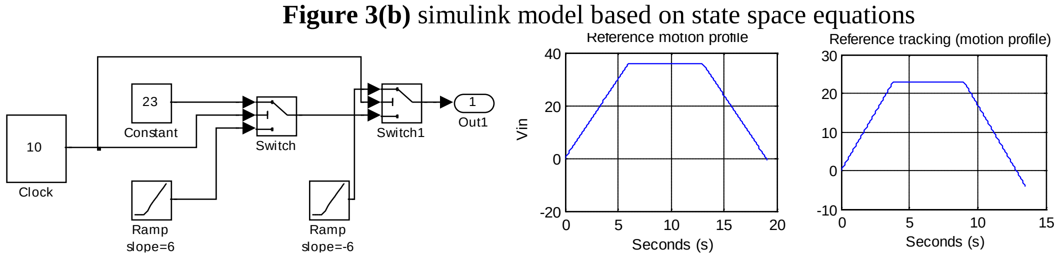

Figure 3(c) Reference tracking (motion profile), and its simulink model

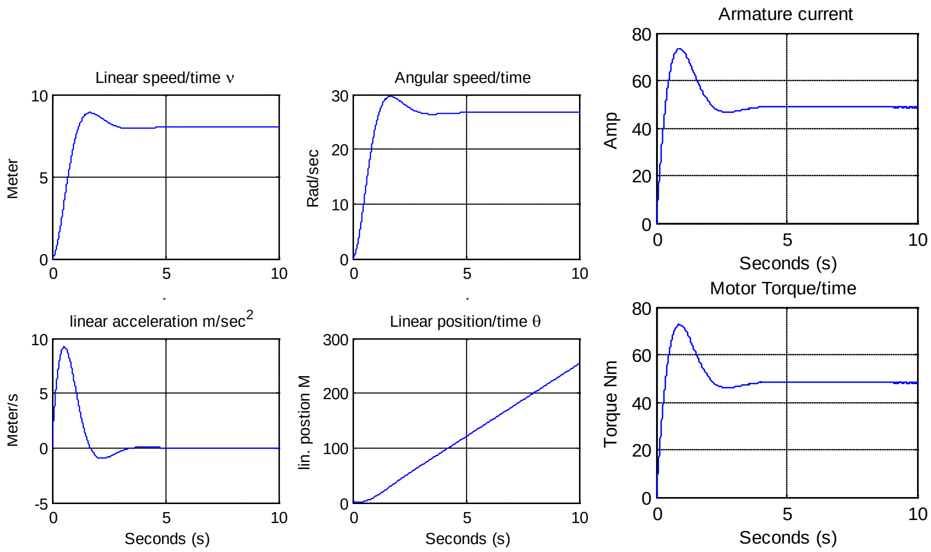

Figure 3(d) EV open loop step response curves; linear speed/, angular speed /time, linear acceleration /time, current/time, motor torque/time

Control system selection and design

Controlling the performance of EV, is not a simple task, where the design and operation parameters of EV, as well as, the road condition are always varying, therefore, the controller should be designed to make the system robust, adaptive and improving the system on both dynamic and steady state performances, resulting in smooth driving, comfortable riding, no steady state error and acceptable anti-disturbance capability at transient state.

Electric vehicle speed controller takes, the nominally fixed, voltage from the power source (battery) and outputs a variable voltage supply needed to control the motor speed. Its voltage output to the drive motors changes in response to control signals supplied by the user from foot pedal (Norman S. Nise, 2011). When the pedal is pushed, the controller delivers electrical currents from the battery to the motor; this gives the car acceleration to accelerate to the desired output speed, the sensors sense the actual output speed and fed it back to controller. the main voltage conversion is done very efficiently using PWM technique, where controller sends pulses of power to the motor thousands of times per second, where very short pulses cause the motor to go slowly and long pulses cause the motor to go fast. There are many control system strategies applied to motor control that may be more or less appropriate to a specific type of application each has its advantages and disadvantages; the designer must select the best one for specific application. both (Farhan A. Salem et al, 2013)(Hedaya Alasooly, 2011) introduced most applicable controllers are PID, PI, PI controller with deadbeat response design , and prefilter. In this paper, different control structures are to be introduced, designed, modeled and tested.

One closed loop control; Structure (1)

The proposed *one* closed loop control structure consists of one control system to control the whole EV system, it is a speed control loop shown in Figure 4, in this simulink model both load torque models given in Figure 2 are joint in one block. Suitable controllers for such structure could be PID , PI, PI with prefilter; also any suitable motor speed (*motion*) control can be applied.

Testing one closed loop control; Structure (1)

Applying motion profile input , and selecting PID controller with gains K_P= *6.66939257185701*, K_I =*9.95355387289947*, K_D = *1.09801348618173,N=528.552080842317*, finally, by running simulink model shown in Figure 4(a), will result in response curves shown in Figure 4(b)(c) , including linear speed, current, and both load and motor torques, analyzing response curves show the output track the input, resulting in desired linear speed of 23 m/s , (that is 82.8 km/h) in 3 seconds and , allmostly, without error, car acceleration would go initially to a maximum value of 35.22 m/s^2, motor draw maximum value of 250 ampere ,(which is very high, and power consuming, that would require an electric motor drive rated around 35 kW), the control signal is also, very high signal, these results can be seen studying step input response shown in Figure 4(c), such control structure can be applied to EV , and is more suitable for small EV and mobile robotic systems, including go-karts, power chairs for the disabled.

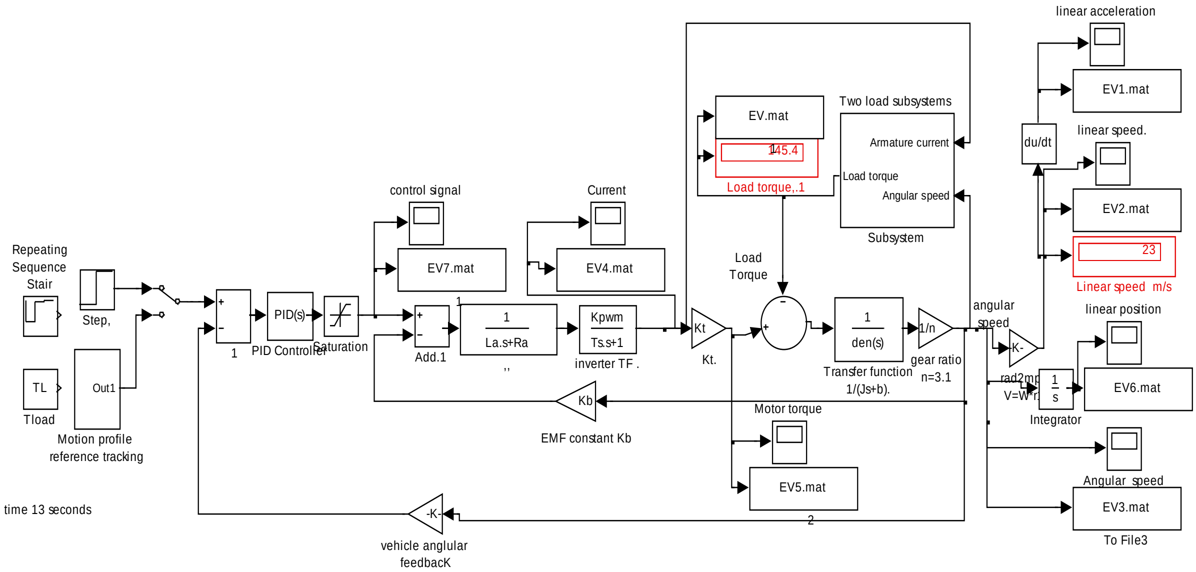

Figure 4(a) One closed loop control system for EV, applying PID controller

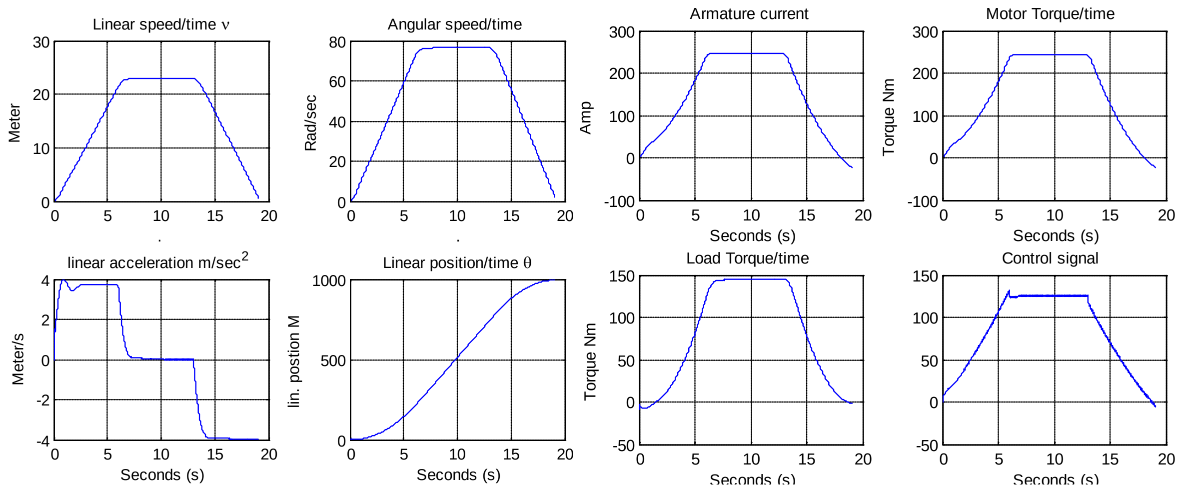

Figure 4(b) EV closed loop linear speed/time, angular speed /time, linear acceleration /time, current/time, control signal//time, motor torque/time response curves for reference motion profile input applying one control loop with PID

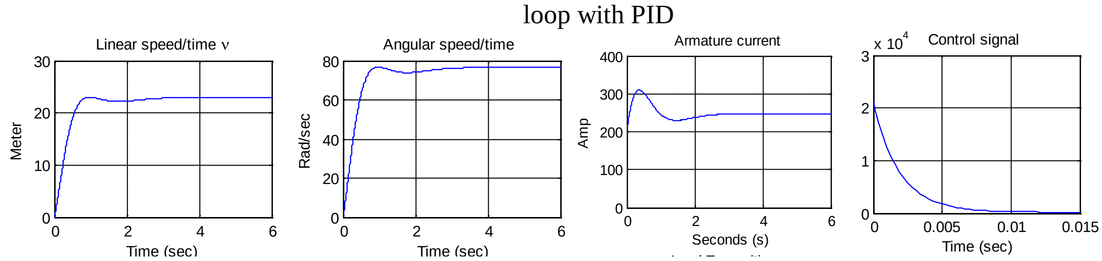

Figure 4(c) EV closed loop linear speed/time, angular speed /time, current/time, control signal//time, response curves for step input applying one control loop with PID

One **loop control; Structure (2)**

Current sensor can be applied for different application in the proposed design; first application is to relate the load torque to required current to generate motor torque to overcome the load torque. The motor torque T_m, is given by armature current i_a, times torque constant, K_t ,($T_m = K_t * i_a$). Now, dividing load torque over torque constant, converting this value in corresponding current, by current sensor, with sensor sensitivity gain K_{SC}= 0.00238, will convert all to voltage. Based on correlation between load disturbance components, given by Eqs.(11,15) and output angular speed , as well as , between output angular speed and tachometer output voltage readings, to help in calculating error fed to control system, summing both voltage signals,(load torque voltage and tachometer voltage) and feeding back both signals to control system to calculate error, will result in more fast and soft response, than direct tachometer error measuring. In the proposed model, load torque can be fed back either as equivalent voltage to control system, or can be fed to motor, also can be fed to both. Proposed model is shown in Figure 5(a) , resulted response curves are shown in Figure 5(b)

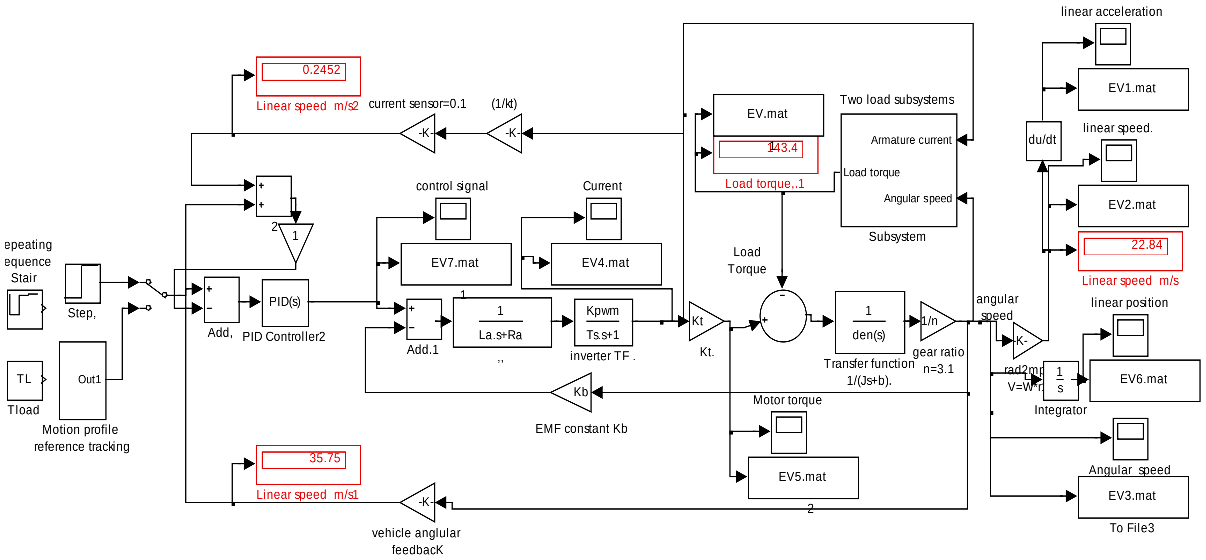

Figure 5(a) One closed loop control; Structure (2)

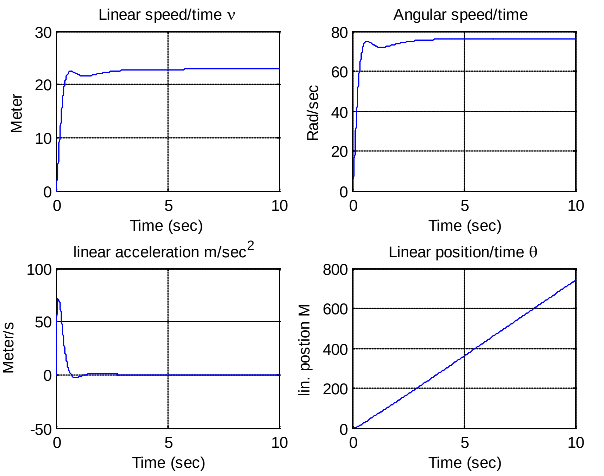

Figure 5(b) linear speed/time, angular speed time response curves, feeding back load toque to both motor as load torque and as equivalent voltage control system

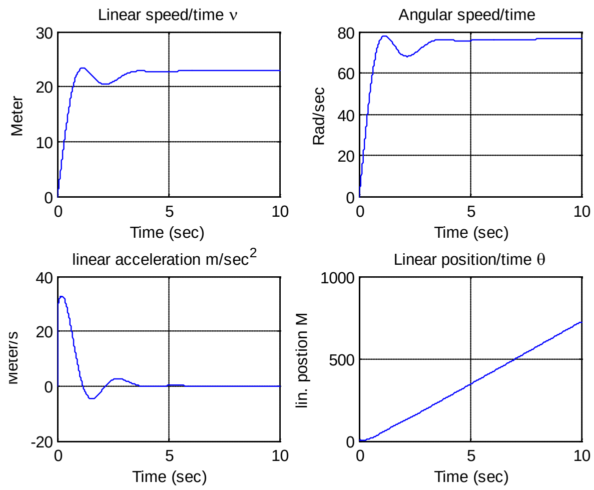

Figure 5(c) linear speed/time, angular speed time response curves, feeding back load toque as equivalent voltage *just* to control system

Two loops control system design; structure (1)

To solve the high current drawn in previously proposed two models, and to result in more smooth response and saving in power consumption, two loops control can be proposed; inner and outer; inner current regulation loop that accomplishes current regulation control to meet the current needs in accordance with the needs of electric vehicle, and the second outer loop speed regulation loop that adjusts the speed of the motor (see Figure 6). The two controllers, the current controller and the speed controller, are designed separately, since two different subsystems are to be controlled with different characteristics.

Current controller: The current regulation loop is the inner loop connected to the stator circuit, the current control loop guarantees limited variations of the current trough the inductor during important load variations, and this is shown in Figure 6. In this paper we are to suggest to design current regulator as PID or PI controller, in order to have small overshoot and good tracking performance current regulation can be designed as type-I system. The design of current controller as PI is discussed and introduced in details by (Farhan A. Salem, 2013) and given by:

$$G_{PI\_current}(s) = K_{P\_current} * \left(1 + \frac{1}{T_I s}\right) \tag{17}$$

Where: $K_{P\_current}$: the proportional gain (to be 1.51); $K_{I\_current}$: integral gain; T_I: time constant of current regulator (to be 0.08). It must be considered that the current regulation is faster than speed regulation. Mainly the PI zero, Z_o=- K_I/ K_P, will inversely affect the response and it could be cancelled by prefilter, the required prefilter transfer function to cancel the zero is given by:

$$G_{Prefilter}(s) = \frac{Z_o}{(s + Z_o)} = \frac{1/T_I}{(s + 1/T_I)} \tag{18}$$

Speed regulator controller: The Speed regulation loop is the outer loop, this is shown in Figure, in order to have smooth driving for comfortable riding, no steady state error and acceptable anti-disturbance capability at transient state, we are to suggest designing speed controller as PID or PI controller. In case speed controller is designed as PI regulator, a PI transfer function given by:

$$G_{PI\_speed}(s) = \frac{(K_{P\_\omega} s + K_I)}{s} = \frac{K_{P\_\omega}\left(s + \frac{K_{I\_\omega}}{K_{P\_\omega}}\right)}{s} = K_{P\_\omega} * \frac{(T_\omega s + 1)}{T_\omega s} = K_{P\_\omega} * \left(1 + \frac{1}{T_\omega s}\right) \tag{19}$$

Where, K_{P_ω}: the proportional coefficient of speed regulator; K_{I_ω}: the integral coefficient of speed regulator; T_ω: time constant of motor speed. Depending upon generic open loop transfer function, the parameters of speed controller loop can be found to be:

$$K_{P\_\omega} = \frac{J}{2T_c} \Rightarrow K_{I\_\omega} = \frac{K_P}{4T_c}$$

Where: T_c is the sum time delay due to speed loop, the same approach, with PI prefilter to cancel the zero, can be applied to speed loop PI controller.

The inverter: The input voltage V_{in} to inverter is considered as constant (36V), the main voltage conversion is done very efficiently using PWM techniques, the output voltage is adjustable via the duty cycle α ,of the PWM signal. The transfer function of the inverter can be given as by (Qi Huang et al, 2012) and given by Eq.(20). The PI current controller is affecting the inverter switching frequency to reduce the ripples in the torque and current

$$G_{converter}(s) = \frac{K_{PWM}}{T_s s + 1} \quad (20)$$

Where: K_{pwm}: gain of inverter (to be 5); T_s: time constant of PWM controller, (to be 0.25 ms)

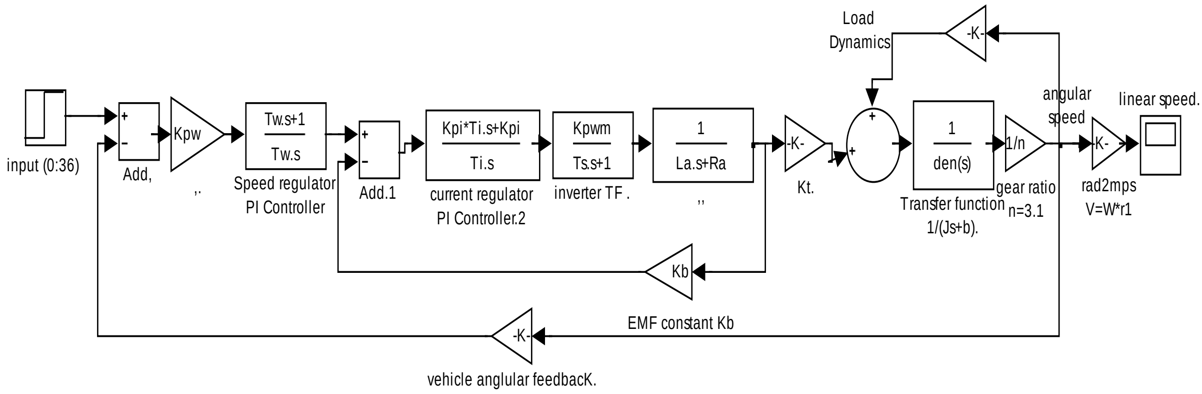

Figure SMEV model inner current and outer speed loops.

Simulation and results; two loops structure (1)

Applying two PID controller (see Figure 7(a)) , for both outer speed and inner with inverter current control, applying motion profile input and running the model, will result in response curves shown in Figure 7(b) , applying proposed design relating load torque, tachometer and corresponding voltages, will result in response curves shown in Figure 7(c), comparing curves of both designs, we see that, both system reach desired output speed, system with voltages design draw more than twice less current, (100 amp, and 240amps). Replacing Two PID controllers with PI controllers with corresponding time constants, will result in response curves shown in Figure 7(d)

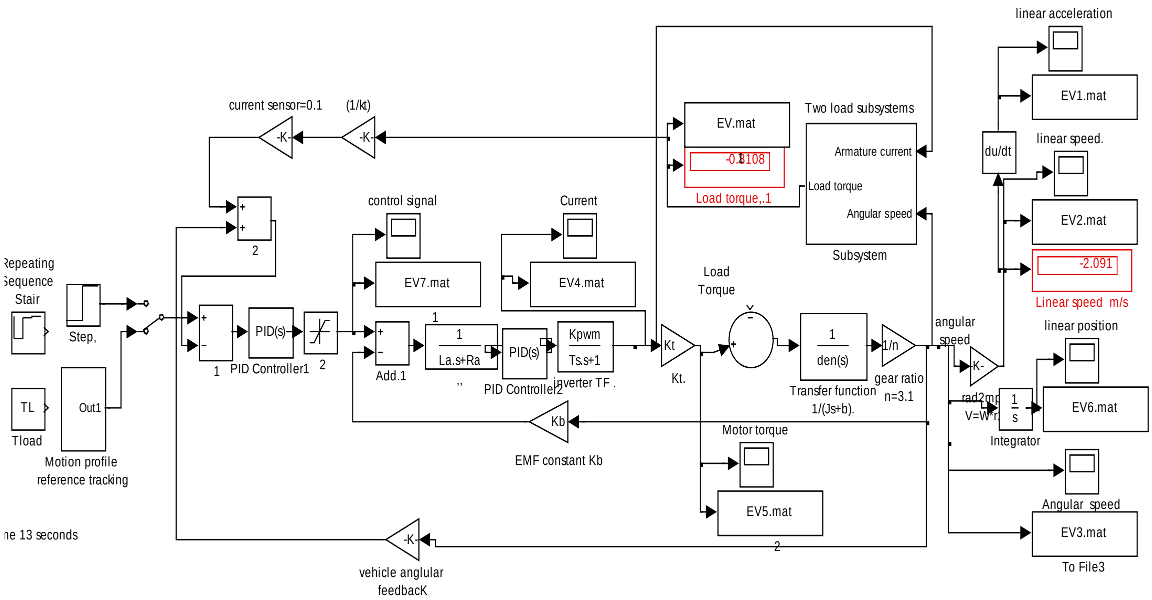

Figure 7(a) block diagram applying two controllers inner and outer,(PI, or PID)

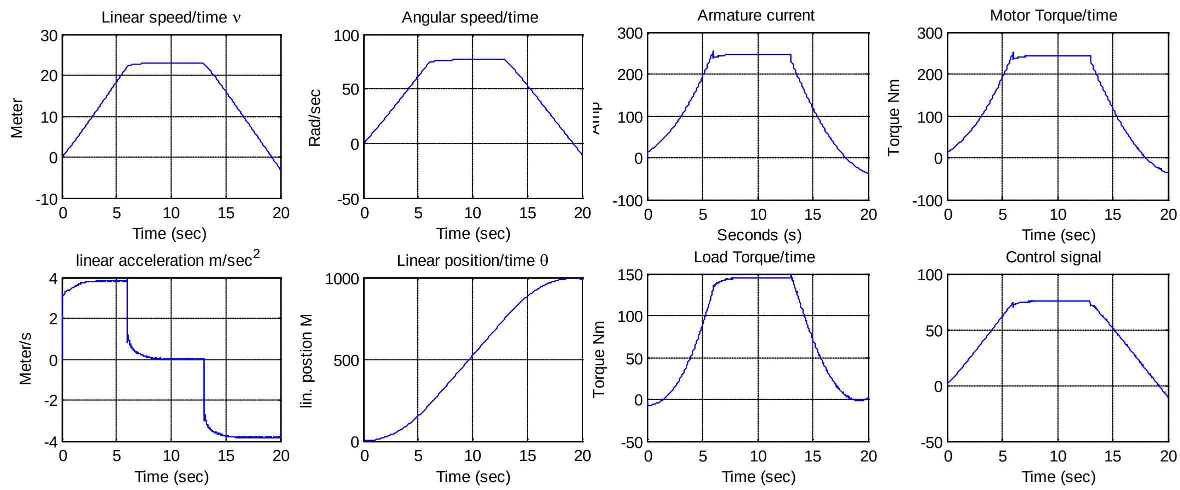

Figure 7(b) EV closed loop linear speed/time, angular speed /time, linear acceleration /time, current/time, control signal//time, motor torque/time response curves for reference motion profile input applying two PID controller for both loops .

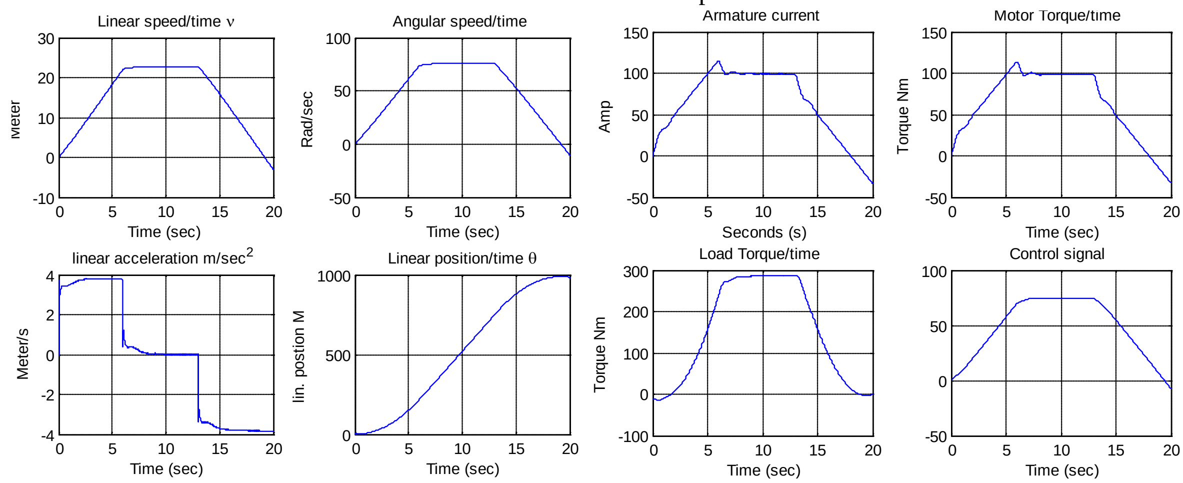

Figure 7(c) EV closed loop linear speed/time, angular speed /time, linear acceleration /time, current/time, control signal//time, motor torque/time response curves for reference motion profile input applying two PID controller for both loops applying proposed design *relating load torque , tachometer and corresponding voltages*

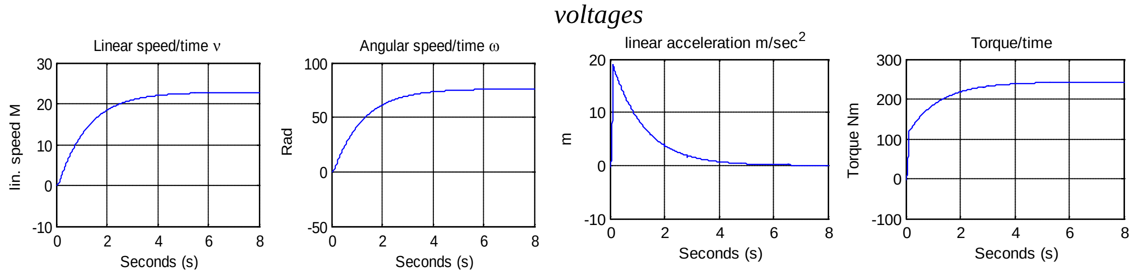

Figure 7(d) Linear speed/time, angular speed/time Linear acceleration/time, torque/time, response curves of EV for desired output linear speed of 23 m/s (that is 82.8 km/h), applying PI controller for both , inner and outer, loop

Two loops control; Structure (2)

The inner current regulation loop is connected to the stator circuit; the current control loop guarantees limited variations of the current trough the inductor during important load variations. To measure and control the inner current loop, a current sensor, with sensor gain K_{SC}, is used to measure current and feed it back to inner current controller, the simulink model of the proposed design is shown in Figure 8(a),PI, or PID can be used , to reduce the effect of PI zero, a prefilter for both inner and outer PI-controllers, can be added as shown in Figure 8(b),

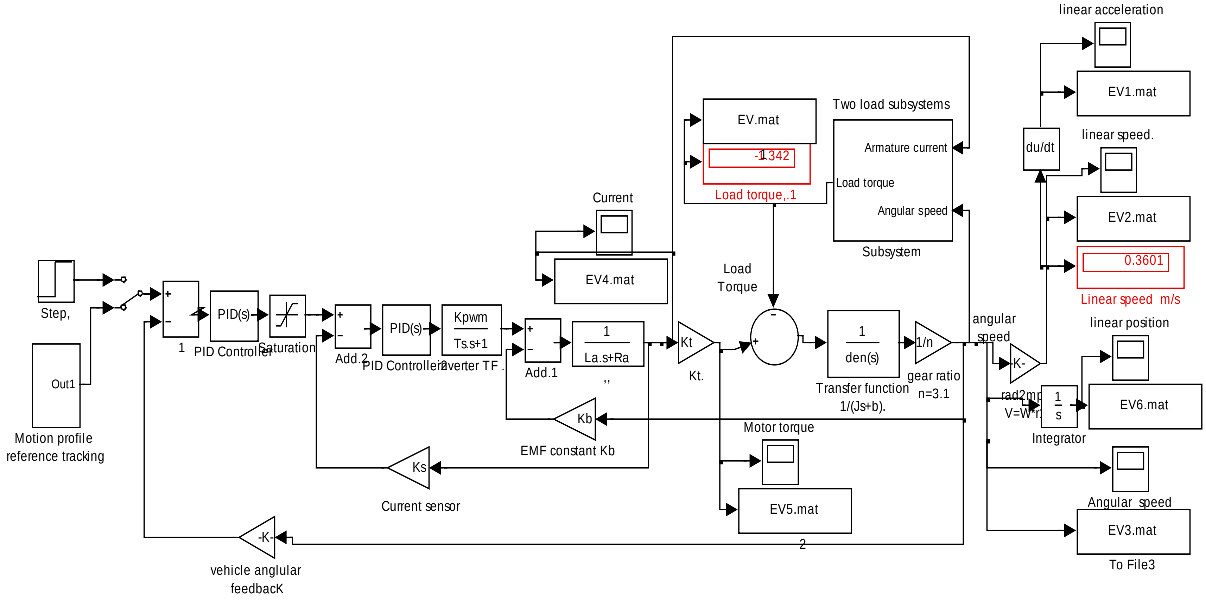

Figure 8(a) two control loops model, inner current with current sensor

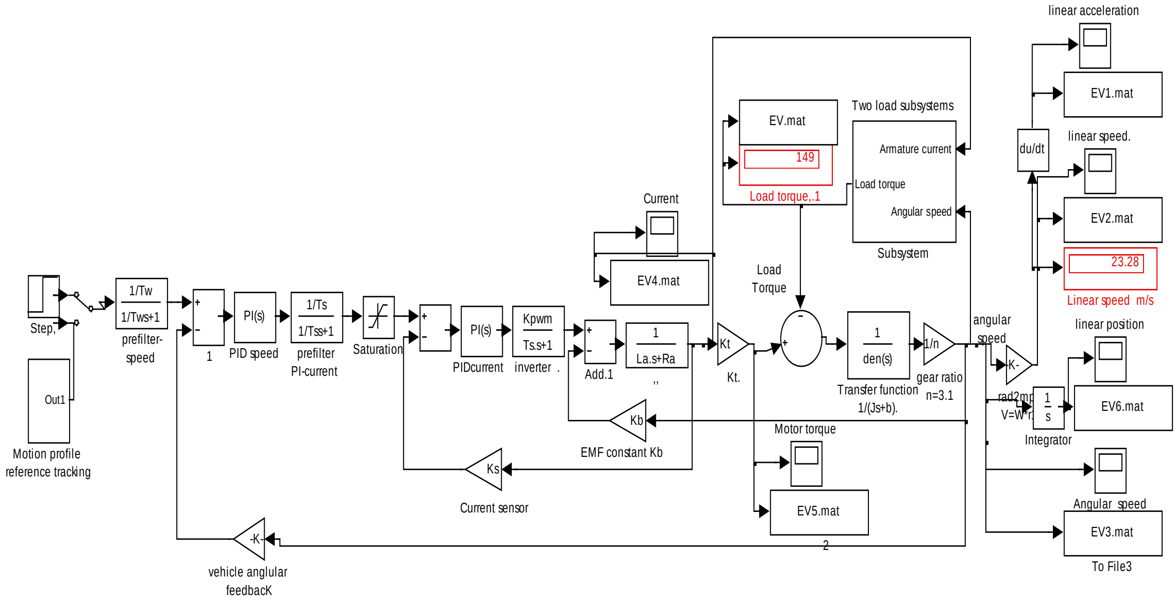

Figure 8(b) Two PI controller with two prefilter

Simulation and results; two loops structure (2)

Running simulink model given in Figure 8(a) with two PID controllers for reference profile input will result in response curves shown in Figure 8(c), the response curve show smooth response, with minimum overshoot and excellent tracking performance; this can be seen from step input response shown in Figure 8(d).

Running simulink model given in Figure 8(b) with two PI controllers for both inner and outer loops, with two corresponding prefilters, for step input will result in response curves shown in Figure 8(e), a smooth response with excellent settling time, no overshoot is resulted.

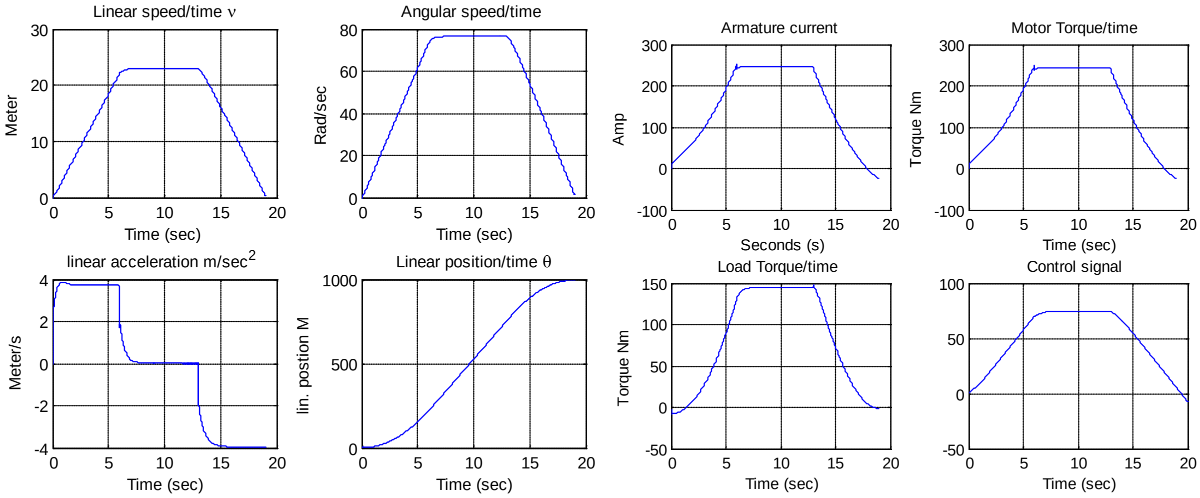

Figure 8(c) Response curves, applying motion profile input

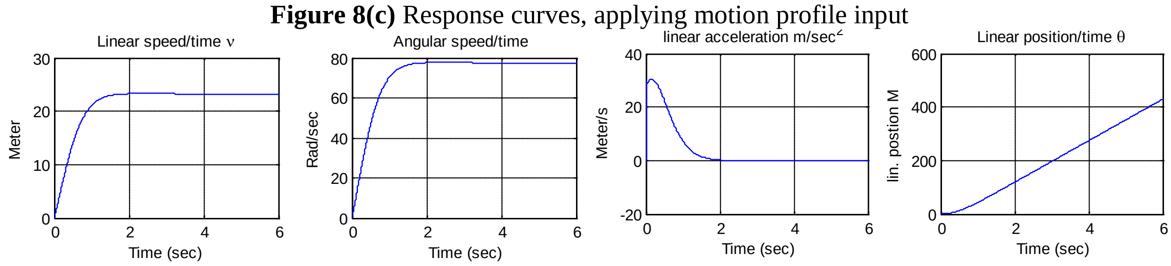

Figure 8(d) Step response curves.

Figure 8(c)(d) step response curves Linear speed/time, angular speed/time Linear acceleration/time, torque/time, response curves of EV for desired output linear speed of 23 m/s (that is 82.8 km/h), applying PID controller for both , outer and inner loops inner current loop with current sensor

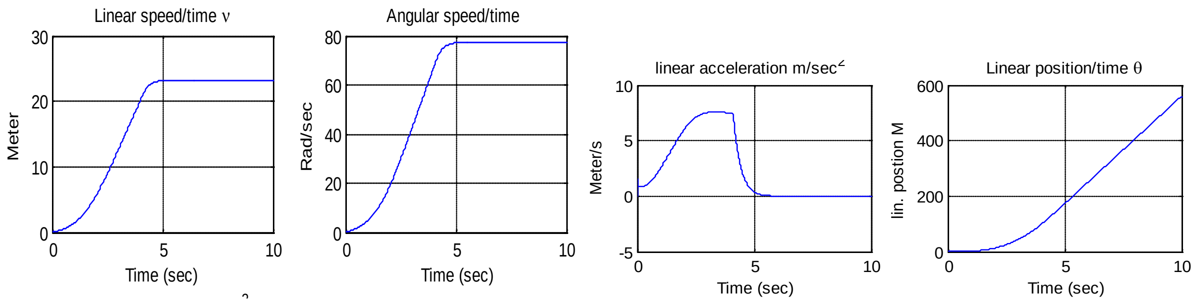

Figure 8(e) Step response curves.

Conclusion

Mathematical and simulink models and control solutions for electric vehicles, are proposed, different control schemes including one and two loops control, was designed and tested using MATLAB/simulink software, to result in robust, adaptive system and improved overall system performance on both dynamic and steady state performance.

References:

Bambang Sri Kaloko, Soebagio, Mauridhi Hery Purnomo, Design and Development of Small Electric Vehicle using MATLAB/Simulink, *international Journal of Computer Applications (0975 – 8887) Volume 24– No.6, June 2011*

Dhameja, S., Electric Vehicle Battery Systems, *Newnes, US. 2002*,

Husain, I., 2003, Electric and Hybrid Vehicles Design Fundamentals, *Pertama, CRC Press,*

Farhan A. Salem, Mechatronics design of small electric Vehicles; Research and education, *International Journal of Mechanical & Mechatronics Engineering IJMME-IJENS Vol:13 No:01,2013*

Brahim Gasbaoui, Abdelkader Chaker, Abdellah Laoufi, Boumediène Allaoua, Abdelfatah Nasri, The Efficiency of Direct Torque Control for Electric Vehicle Behavior Improvement, *Serbian jornal of electric engineering, Vol. 8, No. 2, May 2011, 127-146*

P. Bauer, Zs. Preitl,P. Gáspár,Z. Szabó, J. Bokor, control oriented modeling of a series Hybrid solar vehicle ,2012

Bambang Sri Kaloko, Soebagio, Mauridhi Hery Purnomo, Design and Development of Small Electric Vehicle using MATLAB/Simulink, *International Journal of Computer Applications (0975 – 8887) Volume 24– No.6, June 2011*

Erik Schaltz. Electrical Vehicle Design and Modeling, Electric Vehicles - Modelling and Simulations(2011), Dr. Seref Soylu (Ed.), ISBN: 978-953-307-477-1, *InTech, Available from:http://www.intechopen.com/books/electric-vehicles-modelling-and-simulations/electrical-vehicle-design-andmodeling*

Dragos Maciuca, Design, Modeling and Control of Steering and Braking for an Urban Electric Vehicle, path Report.A Research Exchange Between Partners for Advanced Transit and Highways (PATH) *University of California at Berkeley and Institut National de Recherche en Informatique et en Automatique (INRIA) Rocquencourt, France Programme Praxitèle*

Qi Huang, Jian Li and Yong Chen, Control of Electric Vehicle, *University of Electronic Science and Technology of China P.R.China. www.intechopen.com, 2012*

Ahmad A. Mahfouz Farhan A. Salem Mustafa Kamel, Modeling, simulation and analysis of electric motor, for mechatronics single joint Robot arm application, using different methods and verification by MATLAB/Simulink. I.J. Intelligent Systems and Applications, 2013, 05, 39-57

M.P.Kazmierkowski, H.Tunia "Automatic Control of Converter-Fed Drives", *Warszawa 1994*

R.D. Doncker, D.W.J. Pulle, and A. Veltman. Advanced Electri-cal Drives: Analysis, Modeling, *Control. Springer, 2011*.

Grzegorz Sieklucki ,Analysis of the Transfer-Function Models of Electric Drives with Controlled Voltage Source PRZEGL ˛ AD ELEKTROTECHNICZNY (Electrical Review), ISSN 0033-2097, R.88NR7a/2012

Norman S. Nise, control system engineering, Sixth Edition,2011, *John Wiley & Sons, Inc*

Bashir M. Y. Nouri , modeling and control of mobile robots, *Proceeding of the First International Conference on Modeling, Simulation and Applied Optimization, Sharjah, U.A.E. February 1-3, 2005*

Norman S. Nise, Control systems engineering, *Sixth Edition, John Wiley & Sons, Inc, 2011*.

http://buggies.builtforfun.co.uk/FactFiles/controller.html

Farhan A. Salem, Ahmad A. Mahfouz, Modeling and controller design for electric motor, using different control strategies and verification using MATLAB/Simulink *I.J.* Intelligent Systems and Applications, submitted and accepted to . I.J. Intelligent Systems and Applications, 2013

Hedaya Alasooly, "Control of DC motor using different control strategies" *global journal of technology and optimization 2011* .

Zsuzsa Preitl, Péter Bauer, Cascade Control Solution for Traction Motor for Hybrid Electric Vehicles, *Acta Polytechnica Hungarica, Vol. 4, No. 3, 2007*