TEST Engineering & Management

January - February 2020
ISSN: 0193 - 4120 Page No. 15154 - 15167

Modelling and Validation of Electric Vehicle Drive Line Architectureusing Bond Graph

Ataur Rahman*, MD Nurul Hasan, Mohd Zaki
Department of Mechanical Engineering,
Kulliyyah of Engineering, International Islamic University Malaysia
P.O. Box 10, 50728 KL, Malaysia
Corresponding author:arat@iium.edu.my

Article Info
Volume 82
Page Number: 15154 - 15167
Publication Issue:
January-February 2020

Article History
***Article Received**: 18 May 2019*
***Revised**: 14 July 2019*
***Accepted**: 22 December 2019*
***Publication**: 28 February 2020*

Abstract:
An electric vehicle control technique (EV) can be systematically determined using Bond Graph. It is useful to determine the performance of the electric motor, inverter and battery when charging / discharging an electric vehicle separately. A simulated bond graph model shows how energy is transferred from one component to another of EV drive line. The bond graph simulation model is useful for optimizing the design of the EV powertrain and control in terms of charging / discharging, analyzing the behavior of the vehicle in both traction and cruising modes.Thus, the bond graph model helps to optimize the overall architecture of an electric vehicle driveline that could be crossed in all driving conditions. The purpose of this article is to present the behavior and characteristics of the bond graph on the simulation and optimization of an EV driveline. A bond graph simulation model is also used to analyze the EV drive cycle in terms of speed, traction, engine power, energy consumption, engine torque, voltage and battery charge / discharge current..The connectivity graph simulates the depth of discharge (DOD) of an EV battery and compares the simulated result with the laboratory and road test results. The simulated DOD was found to drop to 8% for EV when drive testing is considered for UDDS and 8.5% for HWFET. While, it was 7.6% for the car in the laboratory and road tests.Thus, the bond graph Matlab-Simulink model can be validated and considered as an advanced tool for optimizing EV driveline architecture.

Keywords:Bond Graph; Electric vehicle power train; Battery; Drive Cycle.

1. INTRODUCTION

Electric Vehicles (EVs) has been developed/developing to face the problems of fossil fuel depletion and to reduce the green house (GHG) emissions [Moriarty and Honnery, 2008]. However, the lack of power transmission, imbalance battery cells' charging/discharging, battery cooling system and excessive weight has caused the drawback on the introduction of EV in the road.Simulation is a highlight in the development of electric vehicles to optimize powertrain, battery size, charge / discharge cells and maintain battery health.A structural description organizes the model based on the topology of the system (Rahman et al., 2018). Bond graph is energy transfer between subsystems enabled by mechanical and electrical networks.. Mechanical networking has been considered as the power transfer from electrical motor to the tire-road interfaces. While, the electrical network has been considered battery modules to the inverter and electrical motor. The electrical network also used to connect the thermisters (temperature sensors) to the fuzzy controller of the battery cooling system and cells balancing system [Rahman et al., 2018a]. There are many techniques have been published on the cells balancing which allow the cell of the battery pack to maintain the individual cell charge balance with varying maximum 1.5% [Mizanur et al., 2016, 2015], battery cooling system which able to maintain the battery pack temperature less than 40^0C and prevent the battrey from overheating and even fire [Rahman et al., 2014, 2017, 2016].

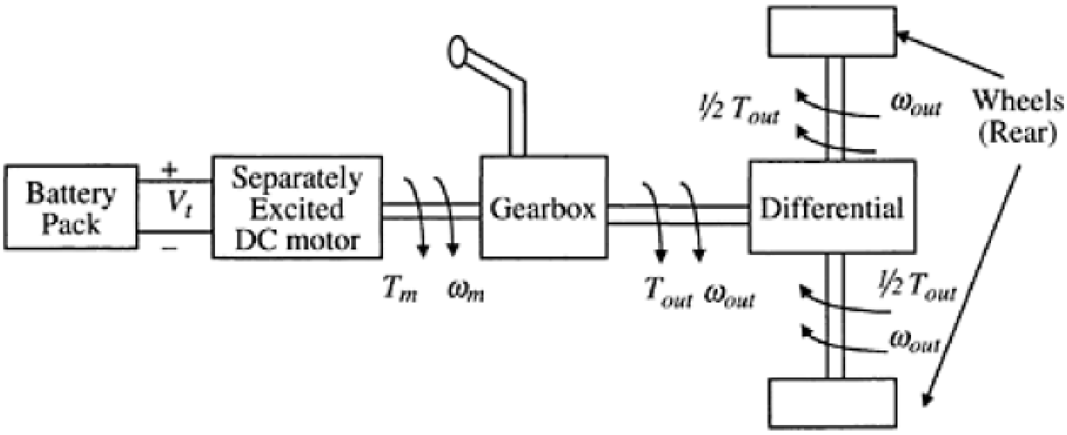

Fig. 1: Structure of mechanical linkage of EV power train.

A bond graph is a graphical description suitable for scaling the physical elements of a system [Borutzky, 2010, Larminie and Lowry, 2003, Silva et al., 2012]. This is very useful for modeling a system, such as the electrical, mechanical, and thermal structure of an electric vehicle (EV). The functions of the system components are more intended for design management. Software, such as Matlab-Simulink, is used to design and analyze simulation-based control. The mechanical coupling of a transmission component is referred to as a vehicle transmission. The change in power between the electric motor and the wheels is called a transmission (mechanical network). EV drive consists of a DC motor, gearbox (transmission), driveshaft, differential connected to the drive wheels. The energy supplied to the electric motor starts at zero speed and increases efficiency due to the spontaneous change of electrical energy to mechanical energy [Moriarty and Honnery, 2008].

There are two main components to the bond graph: effort (e) and flow (f). The change in energy in an element has three types: inertia (I), capacitance (C), and resistance (R). Function I is to store energy, while R is to decapitate energy. The battery is calculated as V_{bat} voltage as a function of the battery charge level (SOC). SOC is intentional based on the current i_{ch} chopper. The chopper function is an electronic controller for changing the direction of rotation of the motor. From a helicopter, it is used without any loss. U_{ch} and i_a are the output voltage of the armature of the chopper and the DC motor through the circuit, respectively. The motor constant η_m gives the connection between electrical and mechanical. Torque T_m displayed the armature current i_a, connecting the angular velocity ω_m with the counter electromotive force e_a.

2.0 Mathematical Models

The basic mathematical model for EV architecture design are presented based on the kinetics of EV on road by modified equation of Rahman et al. (2012):

The torque at the differential:

$$\frac{T_{drive\_sha\_l}}{2} + \frac{T_{drive\_sha\_r}}{2} = T_{dif} \tag{1}$$

$$\frac{\omega_{wheel\_l}}{2} + \frac{\omega_{wheel\_r}}{2} = \omega_{dif} \tag{2}$$

$$J_{diff}\frac{d}{dt}(\omega_{diff}) = T_{aux,2} - f_{dif}\,\omega_{diff} - T_{diff} \tag{3}$$

The torque at the motor:

$$J_{mot}\frac{d}{dt}(\omega_{gear}) = T_{mot} - f_m\,\omega_{gear} - T_{aux,1} \tag{4}$$

The current supply to the motor through the controlle:

$$U_{ch} - e_a = R_{eq}\,i_a + L_{eq}\frac{d}{dt}(i_a) \tag{5}$$

$$U_{bat} = f(SOC) \tag{6}$$

$$U_{ch} = v_1 - v_2 = (S_{11} - S_{12})U_{bat} \tag{7}$$

$$i_{ch} = i_1 + i_2 = (S_{11} - S_{12})i_a \tag{8}$$

When transmitting, the gearbox has a fixed ratio η_g, which is associated with the angular velocity of the shaft ω_{sha} and the engine torque T_{mot}. T_{mot} engine torque transmits energy to T_{gear}. Different angular speeds for each tire are obtained by applying the same torque to the model. The vehicle wheel has a radius R_w, and it does not include any slippage effect associated with the load on the contact area of each tire and the tangential speed with the torque differential T_{diff} and the angular velocity of the differential ω_{diff}. For the steering system, the model must determine the steering angle δ using the Ackermann geometry, including lateral movement and vehicle speed V_{veh}. The distance between the left and right wheels is regarded as T, and the distance between the front and rear wheels is considered l. The dynamic movement of speed V_{ve} is based on the summing force F_{total}. The force created by the resistance is called F_{r_total} and the equivalent mass and friction are M_{ve} and f_{fric}, respectively. The force applied due to resistance is composed by the aerodynamic force F_{aero}, the rolling force F_{roll}, and component of weight when it is in climbing hill position F_{grad} [i.e., $F_{r\_total} = m\frac{dv}{dt} + F_{roll} + F_{areo} + F_{grad}$].

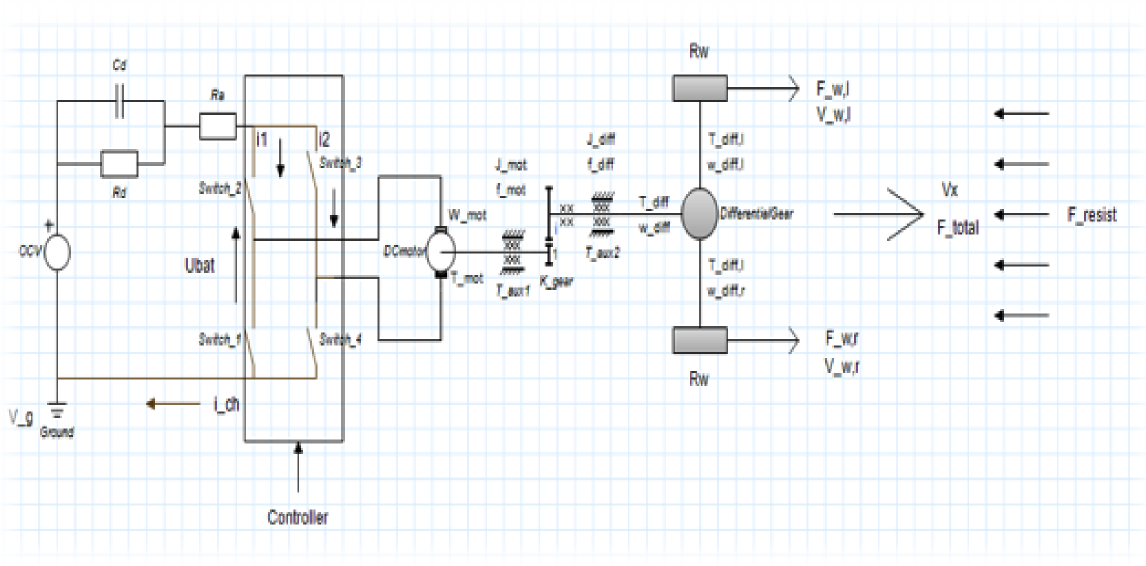

Fig.2 : The electric vehicle modeling

TEST Engineering & Management
January - February 2020
ISSN: 0193 - 4120 Page No. 15154 - 15167

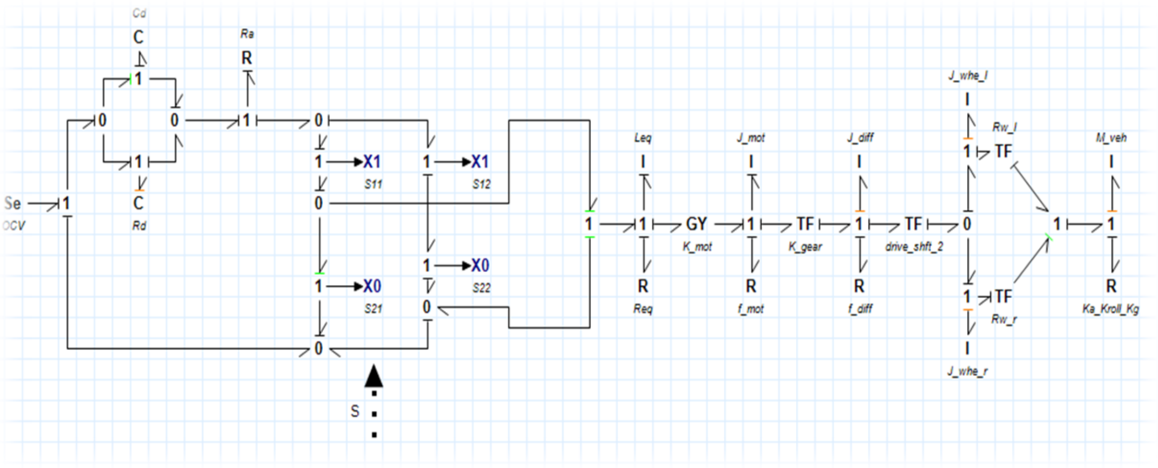

Fig.3:Bond graph structural model of electric vehicle

3.0MODELLING BOND GRAPH FOR EV

A bond graph simulation model was developed using Matlab / Simulink. The EV parameter is considered based on IIUM EV. The parameter value of the controller is considered constant. The elementary meaning was sketched using the Sim20 software. After the construction of the elements was completed, all the data was transferred using the Matlab script to simulate the EV lines of force. Based on the simulation model, EV features such as speed and time and battery size were optimized. Modeling EV using Matlab was presented in Figures 2 and 3.

3.1SIMULATION BY USING MATLAB/SIMULINK TOOL

In fig. 4, a block diagram of an electric vehicle described in the bond graph. Parameters such as electric vehicle speed, battery discharge status, engine traction current and transmission were determined using a simulation model.

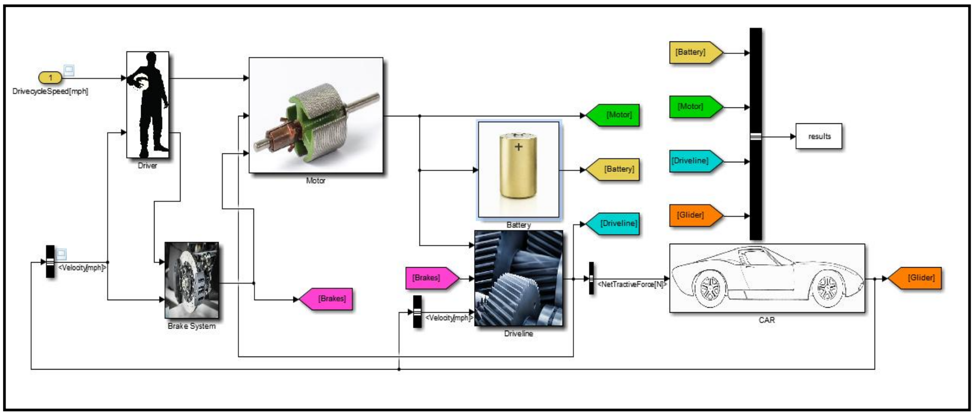

Fig.4: Complete block diagram of an electric vehicle.

The dynamic of the EV depends on the vehicle traction effort. There are many factors significantly effect on the vehicle dynamic such as road adhesion coefficient, motion resistance due to rolling, aerodynamic, and grade as shown in Fig.5. The electric vehicle is powered by DC power. The lithium-iron phosphate ($LiFePO_4$) is considered as the source of DC power of the EV's motor power. The discharge power of the power pack depends on the dynamic behavior of the vehicle either traction or cruising. Figure 6 shows the battery state-of-discharge (SOD) when the vehicle in motion.

January - February 2020
ISSN: 0193 - 4120 Page No. 15154 - 15167

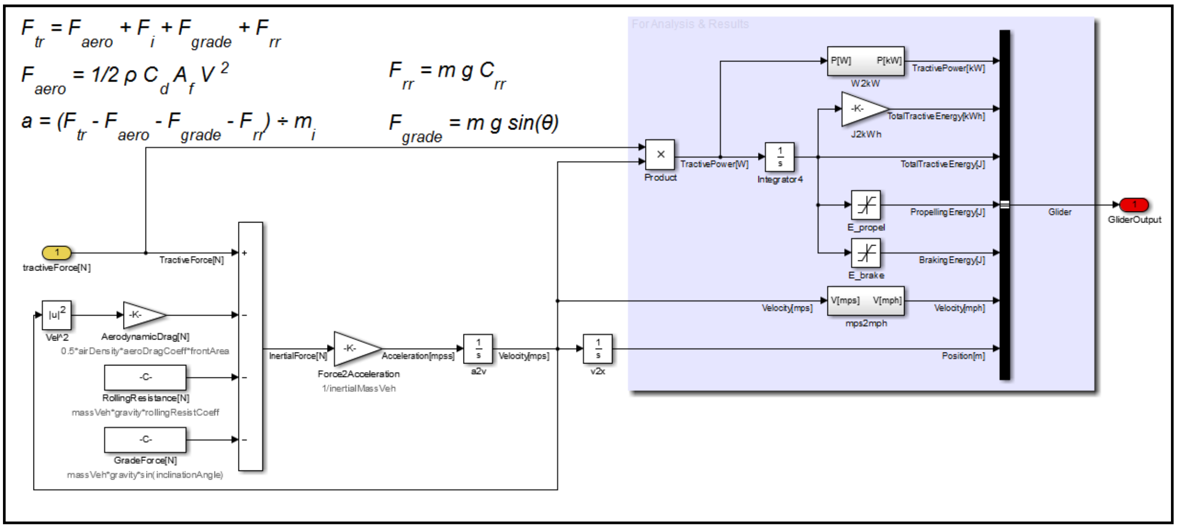

Fig. 5: Traction force developed by dynamic of the EV.

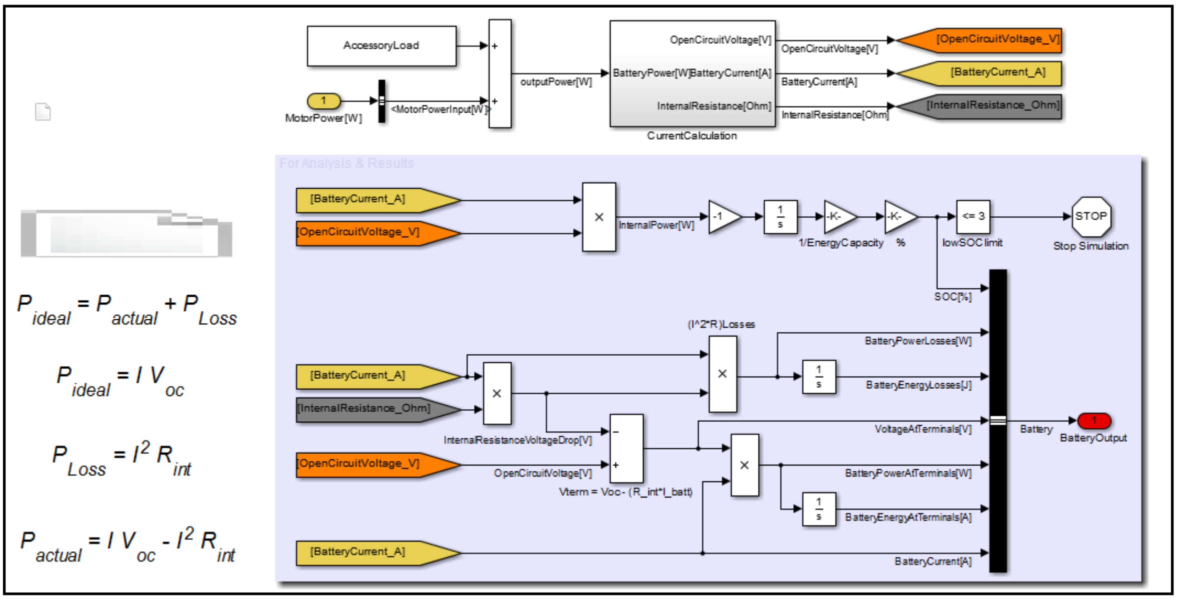

Fig. 6: Block diagram of battery discharge for the EV motion.

4.0 EV Parameter Study

The driving range of electric vehicleusing the limited battery power is a noteworthy issue.This is the critical issue in the design of electric vehicle as it causes the weight added to the EV and the EV development cost. In addition, the design of the battery also depends on the battery temperature control system and the charge balancing system. There are 2 types of testing and calculation that can be used into range of vehicle. The first one is very simplest method which the constant velocity tests. It is difficut to maintain the cosntant velocity in practice because of road physics such as drag force, rolling motion force, and aerodynamic force. However, it is assumed that the vehicle can propel with the constant velocity mode at crusing speed.

The second method is more complex, and in reality it is a simulator controlled by a vehicle through a speed change profile. The cycle or schedules were mainly developed by some countries in order to know the emissions of an electric vehicle. The Federal Urban Driving Schedule (FUDS) was developed to conduct emissions testing by the United State Environmental Agency (EUCAR, 2018). The

January - February 2020
ISSN: 0193 - 4120 Page No. 15154 - 15167

simulation was carried out on three different driving tests.

The first cycle of driving, he rides in a small town with a maximum speed of 50 km / h. Acceleration time took 4 seconds, and braking time - 3 seconds. The maximum speed reaches 150 seconds. The battery voltage was recorded as 250 volts, and the current consumption of the motor was 210A. The maximum current consumed by the engine was recorded during traction of about 250A.

In the second driving cycle, the maximum speed in one cycle is 90 km / h. Acceleration time is about 25 seconds to reach maximum. It shows the battery efficiency in a car, engine speed and car speed were reliable and logical for actual values. This simulation goes through a system block diagram in Matlab / Simulink. The maximum battery voltage was recorded as 250 V and the motor current was 240 A.

In the 3rd cycle of the ride, he shows that the top speed was 120 km / h in 350 seconds. It consists of the general characteristics that it has acceleration time, cruising time, coasting time, braking time and downtime. This plot has been described in a one-stage cycle over a long period of time in 350 time frames. He is driving on a highway whose speed is moderate. Using the battery is visible, the starting voltage is about 230 volts. The engine speed also gradually increases, followed by the speed of the car. The battery voltage increases due to the fact that the engine uses high power to increase speed to 120 km / h. The maximum battery voltage was recorded as 255V, and the motor current was 240A.

Based on the test drive simulation result it could be concluded that the lithium iron battery pack can be designed with terminal voltage 250V and continuous current 200A. While, the motor should have rating voltage of 250V and maximum power density 60 kWh which is the recommended motor power capacity and battery power density 62.5 kWh. The conclusion can be supported from the battery pack of Nissan Leaf, Mitsubishi EV and others.

(i) 1st Drive cycle:

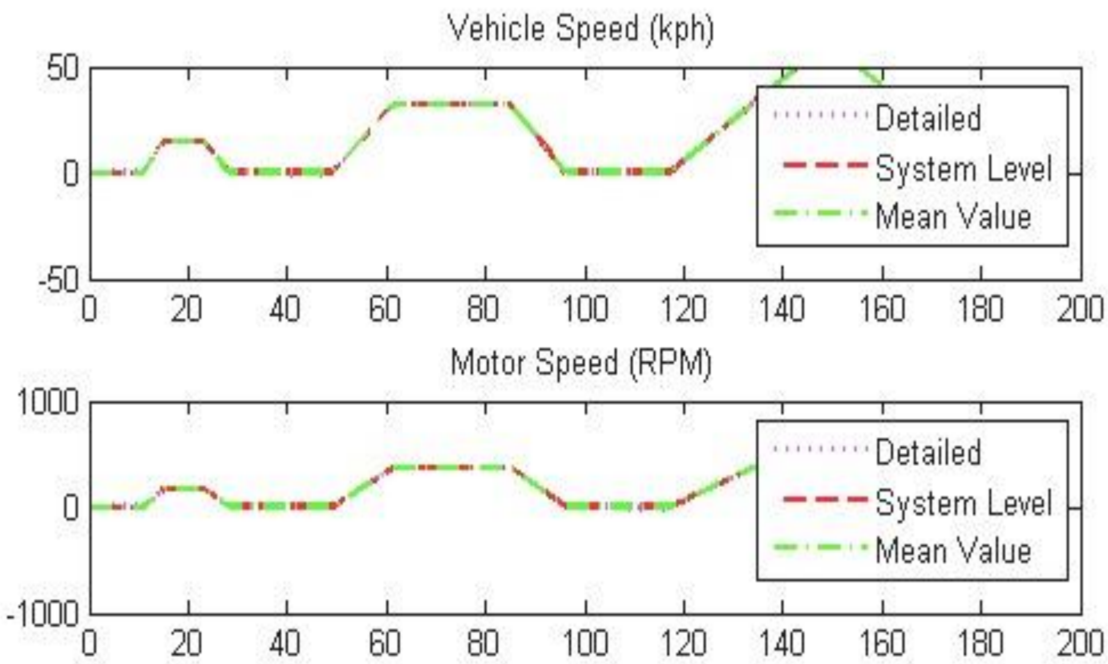

Fig. 7: Bond graph simulation on vehicle speed and motor speed versus time.

TEST Engineering & Management

January - February 2020
ISSN: 0193 - 4120 Page No. 15154 - 15167

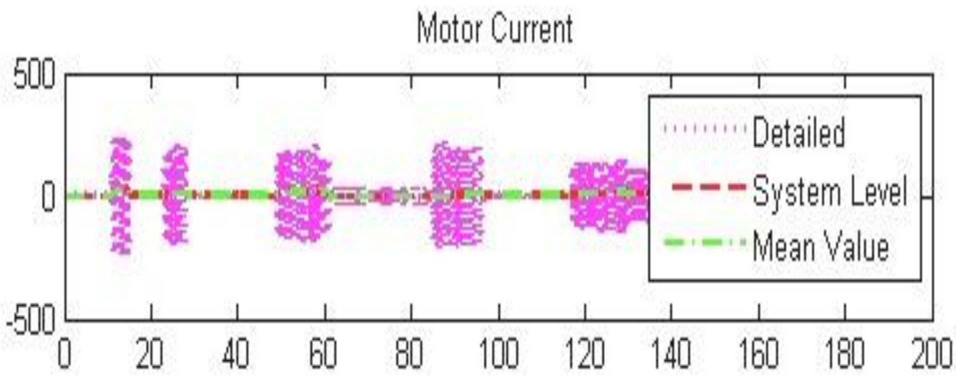

Fig. 8: Bond graph simulation result on motor current versus time.

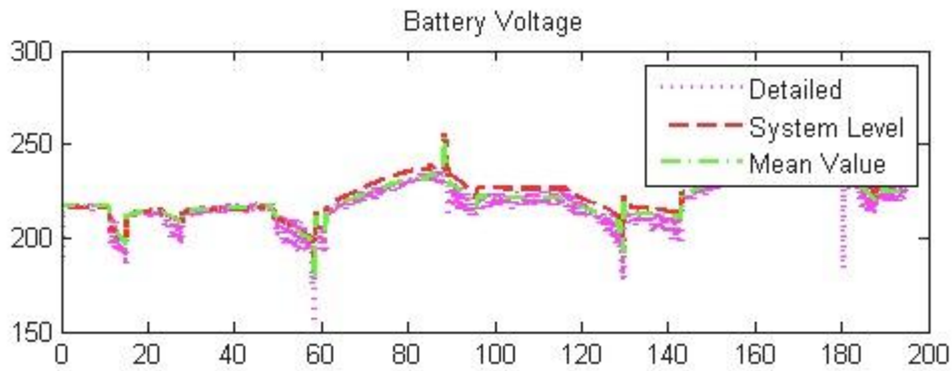

Fig.9: Bond graph simulation result on battery voltage versus time.

(ii) 2nd Drive Test:

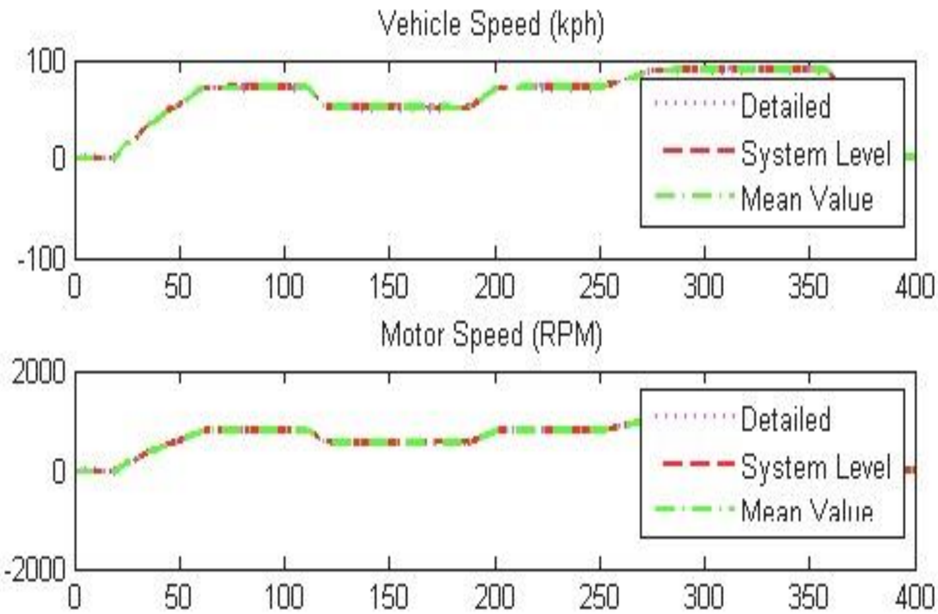

Fig. 10: Bond graph simulation on vehicle speed and motor speed versus time.

January - February 2020
ISSN: 0193 - 4120 Page No. 15154 - 15167

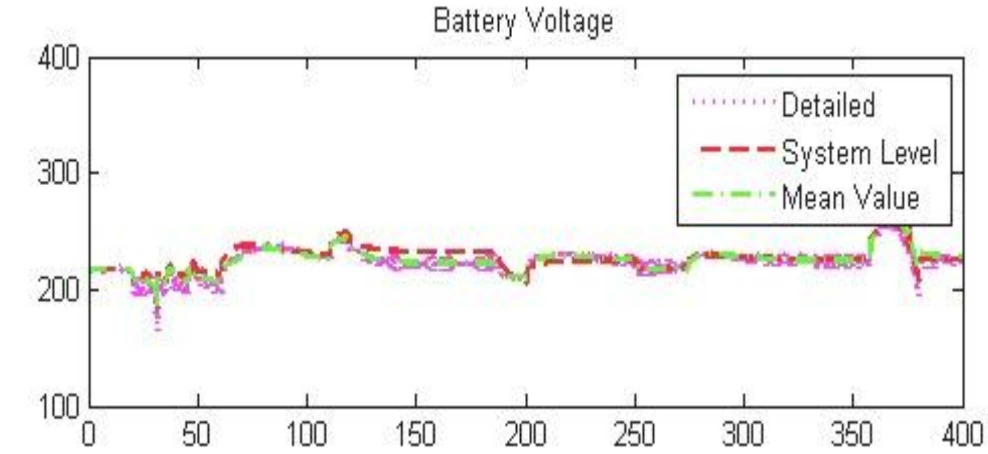

Fig.11: Bond graph simulation result on battery voltage versus time.

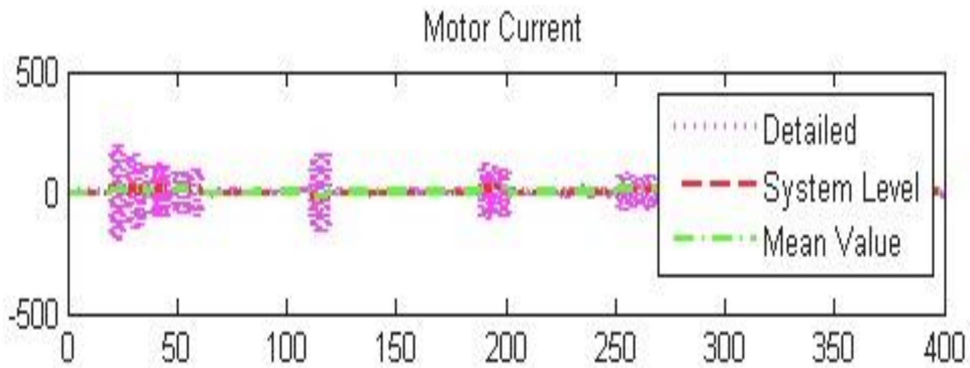

Fig.12: Bond graph simulation result on motor current versus time.

(ii) 3rd Drive cycle:

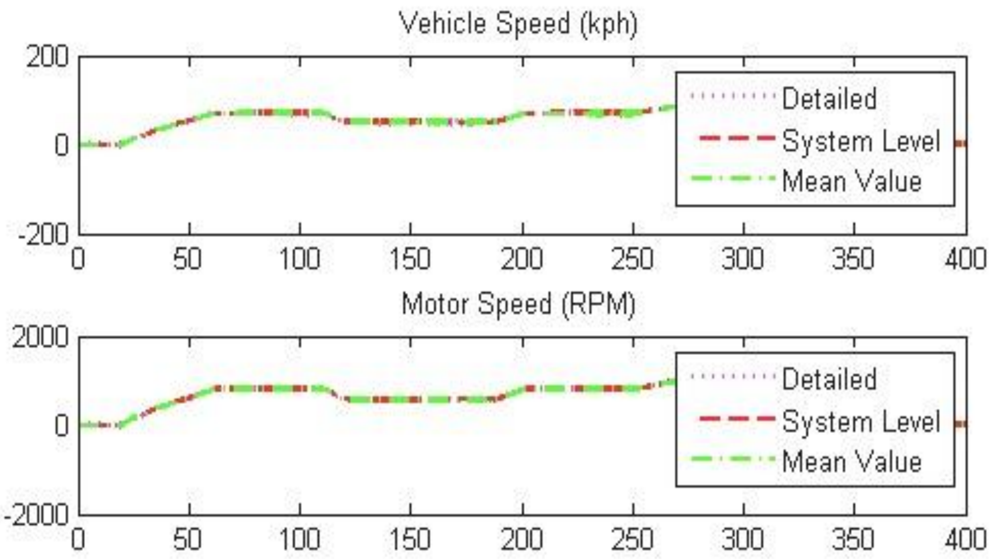

Fig. 13: Bond graph simulation on vehicle speed and motor speed versus time.

January - February 2020
ISSN: 0193 - 4120 Page No. 15154 - 15167

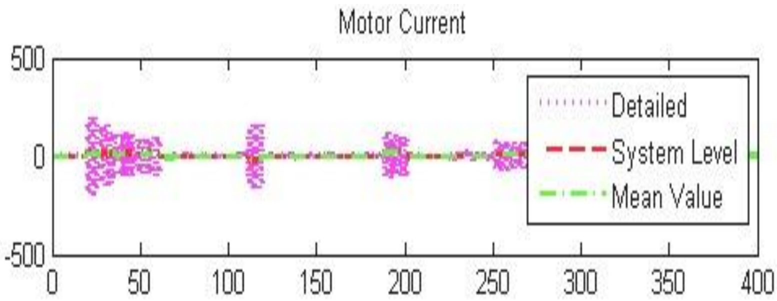

Fig. 14: Bond graph simulation result on motor current versus time.

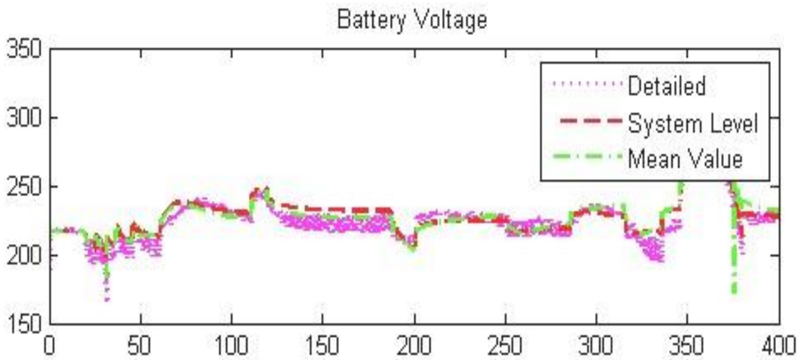

Fig. 15: Bond graph simulation result on battery voltage versus time.

5.0 MODELING OF $LiFePO_4$BATTERY

Lithium iron phosphate ($LiFePO_4$) is the efficient battery due to its high specific power, high specific energy and long cycle life [Zhou,2007]. It is believed that the current flowing from the battery to meet the load requirements EV, simulates the characteristics of the battery in terms of the state of discharge (SOD), the state of charge (SOC), depth of discharge (SOD), energy density, power density with respect to the engine speed.

The maximum current required for the electric motor is 250 A when starting the car from the rest and the maximum speed during acceleration. Using the given battery specification, in the simulation model, the power density of a lithium-ion battery is considered to be 62.5 kWh at 100% charge. It is built with batteries, the capacity of each cell is 86 Ah, and the nominal voltage is 3.4 volts. The battery module consists of 2 cells in series and 3 cells in parallel (2S3P) to obtain 6.8 V and 250 A. The rated motor voltage, V_m, is 250 volts. Thus, the voltage at the battery terminals must be equal to or greater than the rated motor voltage. So that the weight of the battery pack is 121kg which is built with37 modules in series.The distance traveled of the EVwill be 250 km. However, it depends on the driving habit of the driver. If the driver brakes the vehicle very frequenly and the road has hilly track, the traveling distace of the EV will be lower as the vehicle needs high power to overcome grade resistance $F_{grade} = W \sin q$on hilly path for mobility. This is due to the fast SoD and the battery temperature spike which will also affect on the battery state-of-health (SoH).

To simulate a $LiFePO_4$ battery, an equivalent model based on electrical circuits was developed. Circuit models use a combination of circuit elements such as resistors, capacitors, and external sources to provide circuit functionality to an electrochemical cell. Simulation to test charge / discharge is performed on a single module with a constant current level. This refers to the fraction of the battery current, for example, 250Ah the current of the battery 1C, corresponding to 250A. A constant current rate of 0.125 ° C is 31.25 A, which is small compared to 1 ° C for use in charging and discharging tests in the simulation. During a discharge test, the battery is allowed to rest before it switches back to discharge to determine the voltage during rest [Zhou, 2007]. The battery voltage in the charge and discharge test is obtained by simulation and the SOC function of the battery is again displayed to determine the open circuit voltage (VOC) of the battery cell. The open circuit voltage is approximately equal to the charge and discharge at 20% of POPs. The open circuit voltage of the battery is defined as 3.26 volts.. Fig.16 shows the V_{OC} at different SoC.

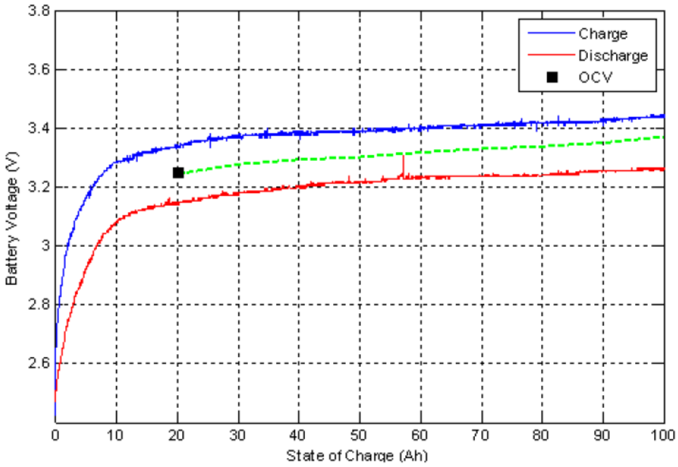

Fig. 16: Open circuit voltage approximation [Zhou, 2007].

The V_{OC} is recorded 3.45V at 100% SoC. Battery depth-of-discharge (DoD) was recorded 20% at cut-off voltage 3.25 V.

5.1 Battery simulated Performance

After considering the equivalent power density of the LiFePO4 battery received from the TS-LFP250AH battery in the MATLAB / Simulink MODEL transmission, the test is carried out on a vehicle with a UDDS driving cycle and an HWFET cycle. The results show real-time data collected to generate battery power, energy used from the battery and the SOC battery. Then the instantaneous battery voltage drop is accompanied by an increase in current. Using the data provided, the performance of the model was obtained. Variable parameters has been entered into the flowchart and set the time cycle in the EV power train model.

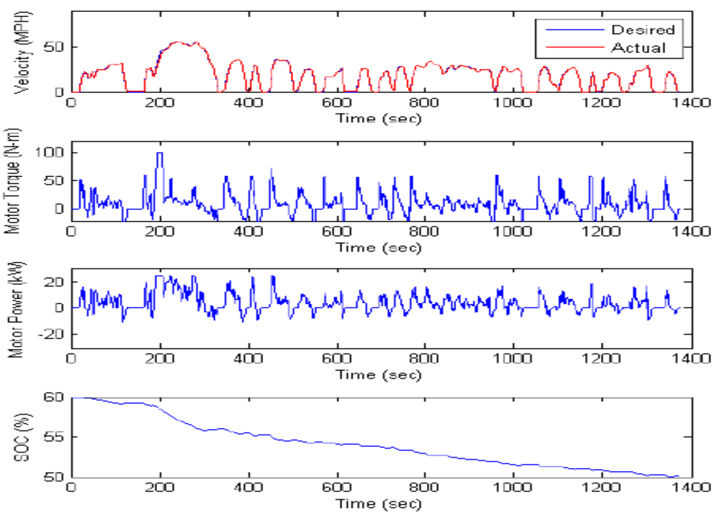

Fig. 17: UDDS drive cycle simulated result.

5.2 Urban Dynamometer Driving Simulated Result

The urban dynamometer motion cycle (UDDS) is used to simulate urban driving based on start and stop conditions. The UDDS driving cycle is 12 km per 1369 km, and the average speed is 32 km / h. During this cycle, the battery pack SOC dropped to 54% from 60% of the initial SOC (10% SOC was used). The usual conditions for starting and stopping city driving are more suitable for generating energy through regenerative braking. The simulation results (Fig. 17) show the driver's need for the vehicle load, as it is clearly seen that the desired and actual speed are almost identical.

5.3 HWFET Drive Cycle Simulation Results

The High-Fuel Test Test (HWFET) is used to simulate the movement of a vehicle on a highway. The HWFET drive cycle runs 16.5 km in 765 seconds and has an average speed of 78 km / h. During this cycle, the battery pack SOC dropped to about 43% from 60% SOC (28.5% used SOC). This shows that energy use is greater than UDDS. The simulation results (Fig. 18) show that the vehicle satisfies the higher power consumption of the HWFET driving cycle, which leads to a faster discharge of the battery.

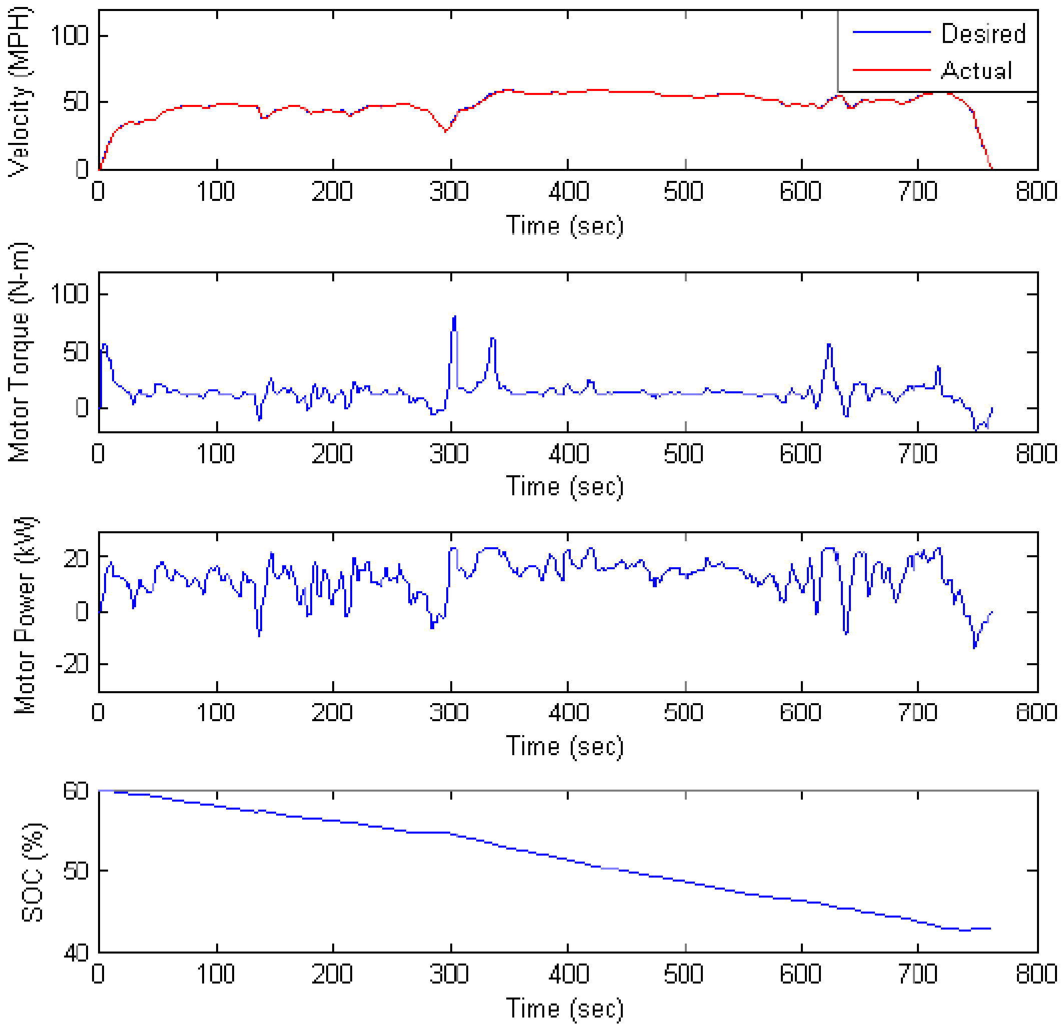

Fig.18: HWFET drive cycle simulated result.

6.0 EXPERIMENTAL RESULT

A LiFePO4 battery with a 100% charge with a rated voltage of 150 V and a capacity of 150 Ah was tested under laboratory conditions on a test bench using a dynamic load that the vehicle must have (Fig.19) when driving on the road. The applied dynamic load was controlled by the control system based on the road profile. The test bench is equipped with an AC induction motor, equipped with a CURTIS inverter. The test result has presented in Figure 19. Figure 20 shows the results of road tests after installing a 100% battery charge with a rated voltage of 100 V and a capacity of 250 Ah. The peak power consumed from the battery is clearly visible - approximately 23.5 kW, and the total energy used is 1.5 kW. At the end of the test, the SOC of the battery shows 94%. The result shows that the power of the battery supplied to the motor varies depending on the output power of the motor. Motor power indicates a zero level, which indicates that the vehicle goes down from a slope and reaches a peak for high traction and high speed.

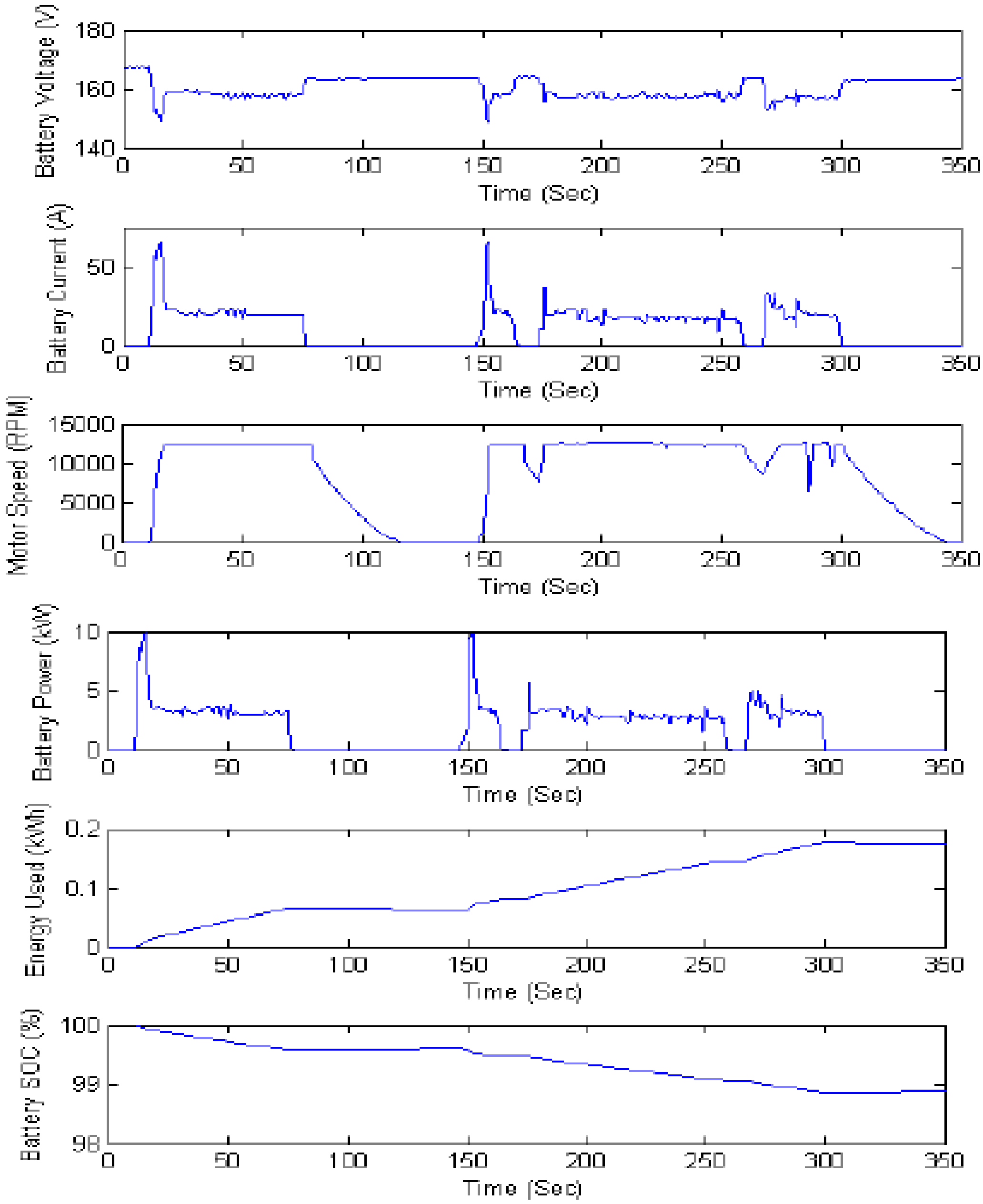

Fig.19: Laboratory Cycle Results (test bed).

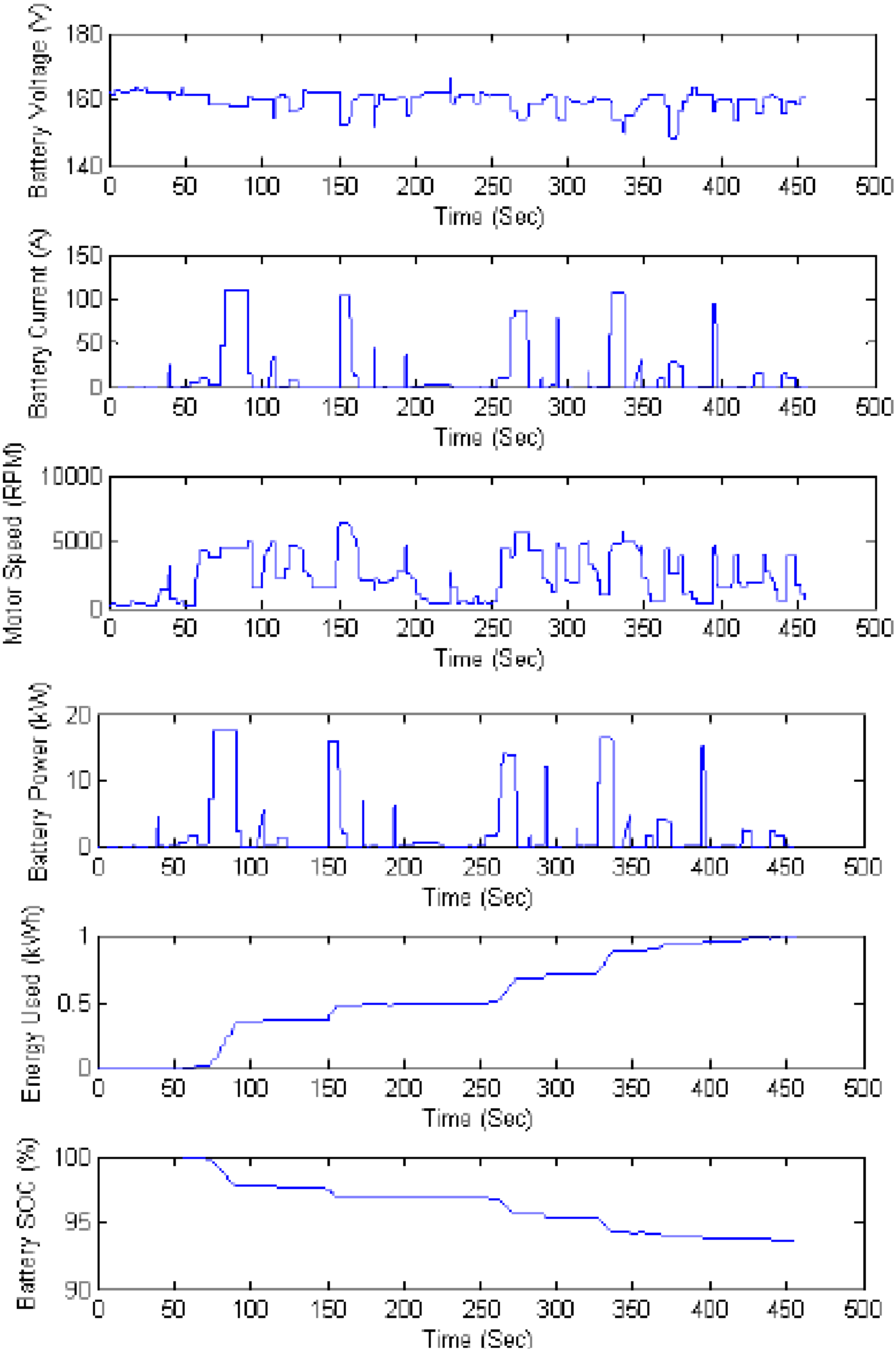

Fig. 20: Results from drive cycle on road test

January - February 2020
ISSN: 0193 - 4120 Page No. 15154 - 15167

8. CONCLUSION

A simulation model of an electric car was developed to study the characteristics of a car in various driving conditions. It was developed at Matlab-Simulink using link graphs to simulate vehicle speed, battery voltage, motor current, torque, and the SOC and SOD of the battery power source. The simulation results show that the vehicle must have a large electric motor with a large battery in order to maintain optimal speed and high acceleration during climb.

The discharge depth (DOD) of the battery is reduced to 8% used for an electric vehicle when a driving test is considered for UDDS, and 8.5% for HWFET. So far, this was 7.6% for the car in laboratory and road tests. Therefore, Matlab-Simulink, which uses link graphs, is considered a good tool for simulating the EV transmission. New technologies in the automotive industry will give more ideas, innovations and the optimal EV powertrain design. However, an extensive test is required to test the simulation model of the Matlab-Simulink Bond graph.

REFERENCE

1. W. Borutzky, "Bond Graph Based Physical Systems Modelling," Bond Graph Methodol. Dev. Anal. Multidiscip. Dyn. Syst. Model., pp. 17–88, 2010.
2. J. Larminie and
3. J. Lowry, Electric Vehicle Technology Explained. 2003.
4. P. Moriarty and D. Honnery, "The prospects for global green car mobility," J. Clean. Prod., 2008.
5. EUCAR (2009) The electrification of the vehicle and the urban transport system," Eur. Automot. Manuf., 2018, Retrieved date: 17 December 2018.
6. Y. L. Zhou, "Modeling and Simulation of Hybrid Electric Vehicles By Modeling and Simulation of Hybrid Electric Vehicles," 2007.
7. L. I. Silva, A. Bouscayrol, and C. H. De Angelo, "Modeling and control of an electric vehicle combining bond graph and Energetic Macroscopic Representation," in 2012 IEEE Vehicle Power and Propulsion Conference, VPPC 2012, 2012, pp. 973–977.
8. Rahman, Ataur., Helmi, Ahmed., and Hawlader, MNA (2017),"Two-phase evaporative cooling battery thermal management technology for electric vehicle". International Journal of Automotive Technology, Vol.18 (5), pp.875-882.
9. Rahman, Ataur., Farhan, Shuimi., Ahmed, Helmi., Hawlader, MNA. (2014). Fuzzy controlled evaporative battery cooling system for EVs/HEVs. International Journal of Electric and Hybrid Vehicle System, Inderscience, Vol.8(2), pp: 233-240.
10. C. S. Hearn, D. A. Weeks, R. C. Thompson, and D. Chen, "Electric vehicle modeling utilizing DC motor equations," in IEEE/ASME International Conference on Advanced Intelligent Mechatronics, AIM, 2010, pp. 670–675.
11. Rahman, Ataur., Azri, M., Kyaw Myo Aung.,Ahmed F. I., Mohiuddin AKM., Sany I.I (2018) Prospect and challenges of electric vehicle adaptability: An energy review Malaysia. *Energy Education Science and Technology Part A: Energy Science and Research*. 2018; 36(2): 139-152**.**
12. Rahman Ataur, Rahman Mizanur., Sany Ihsan Izan, Ahmad Faris Ismail (2018a) Power optimization of Electric Coaster. International Journal of Electric and Hybrid Vehicles, Inderscience Publisher, Vol.10(2), pp. 272-278.
13. Rahman, Ataur, Hossain, A., Zahirulalam, AHM., Mahbubur, R. 2012. Fuzzy Knowledge-Based Model for Prediction of Traction Force of an Electric Golf Car. Journal of Terramechanics, Elsevier Publisher, Vol. 49 (1), pp. 13-25.
14. Rahman, Mizanur., Rashid, M. M., Rahman, Ataur., Zahirul, Alam AHM., Ihsan, Sany (2017) Analysis of the internal temperature of the cells in a battery pack during SOC balancing. IOP Conference Series: Materials Science and Engineering, Vol. 184 (2017).
15. Rahman, Mizanur and Rashid, Muhammad Mahbubur and Rahman, Mohammed Ataur and Khan, Sheroz (2016) Resonant-boost LC converter base charge balancing system for electric vehicle. ARPN Journal of Engineering and Applied Sciences, 11 (1). pp. 362-367.