Modelling and Simulation of Battery Electric Vehicle with consideration of Propulsion Load and Auxiliary Load

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Abstract. As electric vehicle becomes a favorable alternative for sustainable and cleaner energy emission in transportation, modeling and simulation of electric vehicle has attracted increasing attentions to the researchers. The preliminary study of electric vehicle is preferably done using simulation software to avoid expensive on the road test and reducing manufacturing time. Therefore, it is important to ensure a comprehensive simulation model of the battery electric vehicle (BEV) considering both propulsion and auxiliary load in order to obtain accurate data analysis. This new and improved BEV simulation model was developed based on mathematical equation using white-box modelling in Matlab-Simulink environment. The model consists of BEV powertrain; HV and LV battery, DC-DC converter, DC-AC inverter/rectifier, transmission gearing, tire, vehicle dynamic, controller (driver), electrical motor (PMAC) as propulsion load and two groups of auxiliary loads. The simulation test in three driving cycles has verified its robustness and effectiveness in achieving the performance objectives.

Keywords: modelling, battery electric vehicle, propulsion load, auxiliary load, Matlab-Simulink.

Introduction

The issues of energy conservation and environment protection have raised an increasing awareness on the importance of heading towards a sustainable alternative transportation. In regard to this, automakers and researchers have essentially spent their time and effort to gradually improve the vehicle drivetrain efficiency and fuel economy; shifting from conventional internal combustion-based high emission vehicle (ICEV) to low or zero emission vehicles. As a result, these days, many sustainable candidates are already made available on the road, for instance; hybrids (HEV), plug-in hybrids (PHEV), fuel cells (FCEV), and battery electric vehicles (BEV). Among all the alternatives, battery electric vehicle (BEV) is the most prominent in term of performance, energy efficiency, noiseless, less maintenance, produces zero tail pipe emission and can be regulated by the power grid regulator as illustrated in Figure 1 [1-8].

However, the major drawback of BEV from being widely adopted is the range limitation due to the constraint of energy storage capacity in batteries which is also the most expensive part of the vehicle [2, 9]. Prospect consumers are aware of BEV advantages, but many are reluctant or unable to pay 20% to 50% more than comparable ICEVs value [9]. Nevertheless, the battery price is continually decreasing due to the research and development in battery technology. Consequently, BEVs and ICEVs parity price is projected to be realized in 2020 [11]. Therefore, in these remaining years, BEVs deserve an enormous attention by the researchers to prepare them for the next upcoming technologies.

At present state, modeling and simulation has becoming an essential step to facilitate system design while reducing the costs and time of actual product development [12]. Since BEV is equipped with various electrical and mechanical components which are expensive and complex to be tested, modeling and simulation can help automakers in minimizing the energy consumption, correctly sizing the components and choosing the best control strategy. Developing a good and accurate simulation model is imperative in order to avoid incorrect conclusions. The model has to be comprehensive and multidisciplinary accounts for different physic domains; mechanical, electrical, power electronic, control and thermal [13].

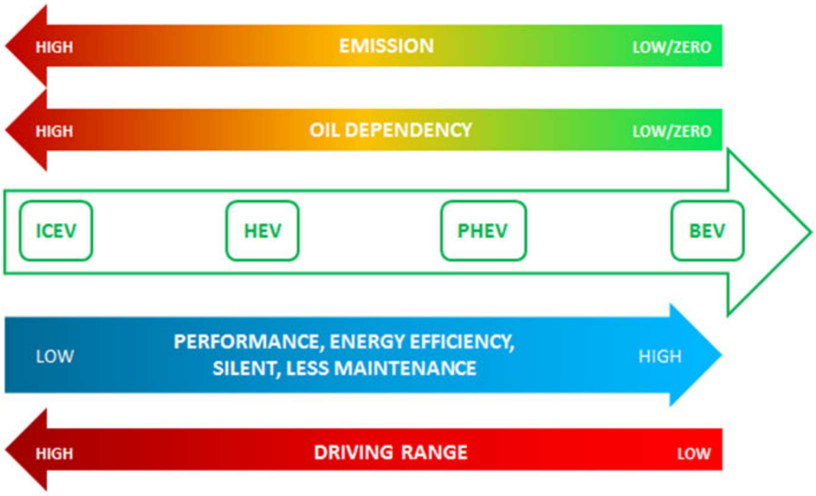

Figure 1. Development in electric vehicle technology.

BEV has become a subject of interest among researchers due to its great potential as sustainable vehicle. Modeling of BEV has been performed by the automakers in various commercial simulation tools such as CarSim, SIMPLEV, MARVEL, V-Elph and ADVISOR [7]. However, most of them possessed their own limitation; focused more on propulsion load, less focus given to auxiliary load, limited option for customization based on local parameter, and concerned more on data reporting instead of modelling. Thus, the modelling of BEV has been proposed which comprises of propulsion and auxiliary loads, adapting Malaysian environment and social requirements.

The BEV simulation model is proposed in order to fill in the following gaps in current situation; the lack of exploration towards BEV due to driving range anxiety, insufficient level of accuracy in simulation model among components may lead to incorrect conclusion, and the need for simple, flexible and comprehensive design (include both propulsion and auxiliary loads). This paper presents the modeling of BEV model where the propulsion load is entirely powered by the high voltage battery, and auxiliary load takes on the low voltage battery. The simulation model is simply configured with separately boost and buck converters between the supply and loads.

Materials and Methods

Model configuration. The performance of BEV model was set according to commercial BEVs performance as shown in Table 1. The listed parameter will become the performance references for BEV model development.

Table 1. Model performance comparison among commercial BEVs.

BEV	Performance parameter			
	Top cruising speed, v_{max}	Acceleration time, t_a (0-100 km/h)	NEDC range (100% DOD)	NEDC range (80% DOD)
1. Nissan Leaf 2010-2013	144 km/h	11.9 s	175 km	140 km
2. Mitsubishi i-MiEV 2010	130 km/h	9.5 s	150 km	120 km
3. Ford Focus Electric 2013	135 km/h	11.4 s	162 km	130 km
4. LG-Proton IRIZ BEV	150 km/h	9.0 s	300 km	240 km
5. BEV model	**150 km/h**	**10.5 s**	**250 km**	**200 km**

* NEDC is New European urban and extra urban driving cycle, DOD is battery depth of discharge.

The modelling of BEV-001 has been performed in the Matlab-Simulink environment using white-box modelling. The vehicle is configured according to Figure 2 and consists of; high voltage (HV) battery pack, low voltage (LV) battery, power electronic converter and inverter, propulsion load (electric motor), mechanical transmission, HV auxiliary load and LV auxiliary load.

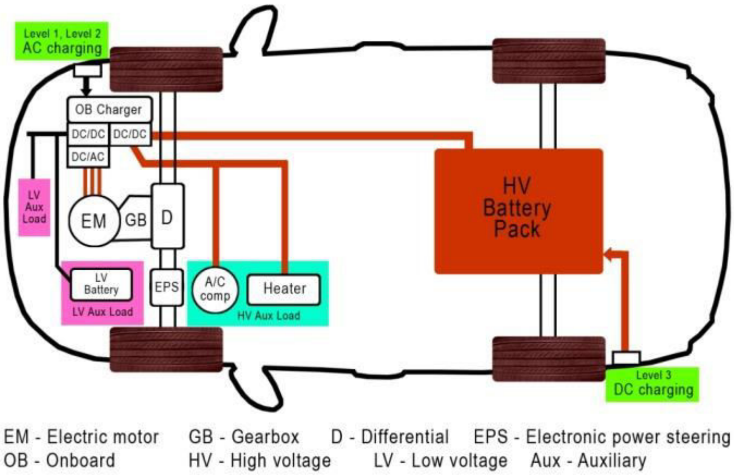

Figure 2. Component configuration of BEV.

Modelling of supply-load topology. Regardless any drivetrain layouts, BEV basically consists of three major subsystems; energy source (supply), propulsion load, and auxiliary load [14, 15]. The supply-load topology for our model is as presented in Figure 3.

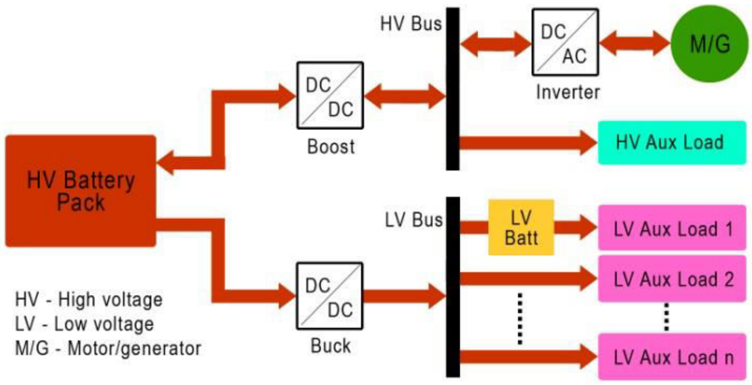

Figure 3. Supply-load topology of BEV.

A. HV Battery Model. The HV battery pack is a lithium-ion battery based on Winston Battery model WB-LYP40AHA [16] as shown in Figure 4. The battery pack comprises of eight modules, where a module consists of two-parallel and 12-serial (2P, 12S) cells connections. These connections will increase the pack Ah capacity from 55 Ah to 110 Ah and nominal voltage from 45 V to 360 V.

The mathematical equations for HV battery state of charge (SOC) is given as follows;

$$SOC(t) = SOC(t_0) - \int_0^t \frac{i_{bat(t)}}{3600 \cdot C_n} \quad (1)$$

where $SOC(t_0)$ is the initial SOC level, $i_{bat(t)}$ is the battery current and C_n is battery rated capacity.

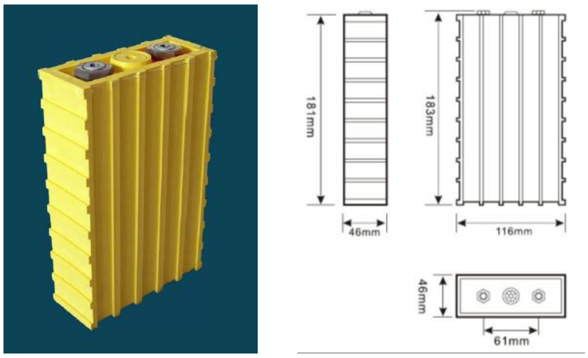

Figure 4. High voltage traction battery WB-LYP40AHA [16].

B. DC-DC Converter. The DC-DC converter is to increase or decrease the voltage from the HV traction battery to suit the voltage requirement of the loads. Two types of DC-DC converters are used; boost converter, and buck converter. Both are assumed operating in continuous mode. The voltage ratio and current ratio of boost converter are based on the following equations;

$$\frac{V_o}{V_i} = \frac{1}{1-D} \tag{2}$$

$$\frac{I_o}{I_i} = (1 - D) \cdot \eta_{DCDC} \tag{3}$$

where V_o is the output voltage (bus voltage), V_i is the input voltage (battery voltage), I_o is the output current, I_i is the battery current, and D is duty cycle.

C. Propulsion Load. Propulsion load, typically an electrical motor is the most important load to EV as it serves for vehicle traction and usually the most energy consuming load. One advantage of using electric motor is its capability to recuperate energy during regenerative braking which helps to increase the traction battery energy level during driving. Propulsion load could be any type of AC or DC motor, however the most popular candidates for EV are induction motor (IM), brushless dc (BLDC), brushless ac (BLAC or PMAC), and switch reluctance motor (SRM). The BEV model are PMAC motor based on YASA-400 from YASA Motors [17]. This motor possesses a high torque and power density capability that suitable for EV applications.

Figure 5. YASA-400 electric motor from YASA Motors [17].

The electromagnetic torque for permanent magnet AC motor (PMAC) is given by the following equation;

$$T_{em} = k_e \left[f(\theta_e) i_a + f\left(\theta_e - \frac{2\pi}{3}\right) i_b + f\left(\theta_e - \frac{4\pi}{3}\right) i_c \right] \tag{4}$$

where k_e is motor torque constant, θ_e is rotor angle and i_a, i_b, i_c is phase currents from inverter.

D. Vehicle Dynamic Model. It is necessary to identify each of the acting forces in a vehicle direction to determine its movement behaviour. The dynamic model for BEV is based on [14] as illustrated in Figure 8 and represented by the equations (5) – (8).

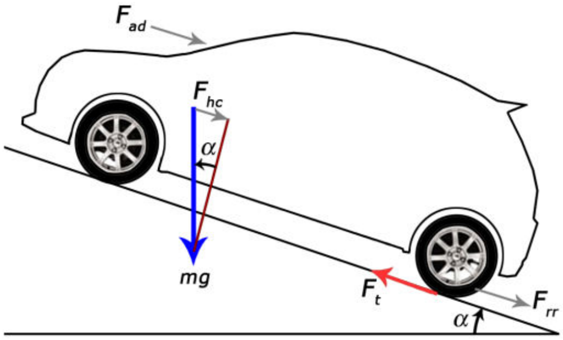

Figure 6. Forces acting on a vehicle moving uphill.

$$M\frac{dV}{dt} = F_t - (F_{rr} + F_{ad} + F_{hc}) \quad (5)$$

$$F_{rr} = MgC_r \cos\alpha \quad (6)$$

$$F_{ad} = \frac{1}{2}\rho A_f C_d V^2 \quad (7)$$

$$F_{hc} = Mg \sin\alpha \quad (8)$$

where M is vehicle curb weight, $\frac{dV}{dt}$ is vehicle linear acceleration along longitudinal direction, F_t is traction force, F_{rr} is rolling resistance force, F_{ad} is aerodynamic drag force, F_{hc} is hill climbing force, C_r is tire rolling resistance coefficient, g is gravitational acceleration, α is slope angle of the road, ρ is air density, A_f is vehicle frontal area, C_d is aerodynamic drag coefficient, and V = vehicle speed.

D. Auxiliary Loads. The auxiliary loads are loads that accomplish either necessary or desired aspects of vehicle operation [14]. These loads are clustered into four groups; initial load, comfort load, safety load and luxury load, based on their performed functions [15] as in Fig. 9. All auxiliary loads are supplied by the HV battery pack through power buses (HV and LV) except for the safety load, which is fed by the LV battery for safety purposes.

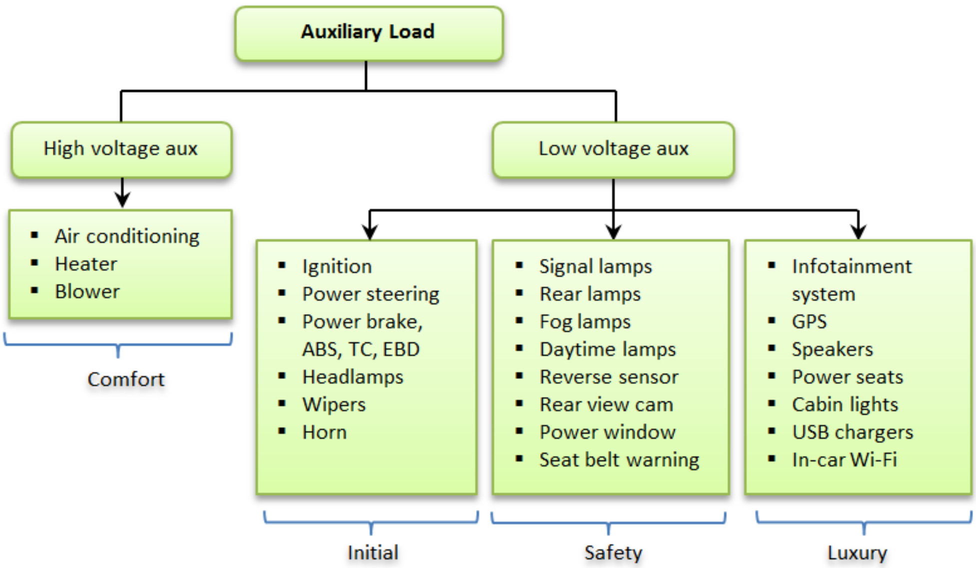

Figure 7. Auxiliary loads categorization [15].

E. Comfort Load Model. Comfort load (a.k.a. HVAC) consists of three loads; (1) air conditioner (A/C), (2) heater and (3) fan/blower. This load is the second highest energy consumption load (after electrical motor). The consumed power is proportional to the difference between outside temperature and cabin temperature. The cabin temperature is control by the user, typically set at 25^{0}C as comfort temperature (based on Malaysia weather) [18].

Air conditioner is modelled based on equation $y = ax + b$ and 3 parameters; (1) Tcomfort = 25^{0}C, (2) Tmax = 40^{0}C and (3) Pmax = 4.5kW as follows;

$$P_{AC} = aT_{out} + b \tag{9}$$

$$P_{AC} = \frac{P_{max}}{(T_{max} - T_{comf})}T_{out} - \frac{P_{max}}{(T_{max} - T_{comf})}T_{comf} \tag{10}$$

Heater is modelled in reverse to A/C by using equation $y = ax + b$ and 3 parameters; (1) Tcomfort = 25^{0}C, (2) Tmin = 5^{0}C and (3) Pmax = 5kW as follows;

$$P_{heat} = aT_{out} + b \tag{11}$$

$$P_{heat} = \frac{P_{max}}{(T_{min} - T_{comf})}T_{out} - \frac{P_{max}}{(T_{min} - T_{comf})}T_{comf} \tag{12}$$

Fan/blower is modelled based on its maximum power rating, $P_{max\_blower} = 80W$.

Results and Discussion

The complete Simulink model of BEV is presented in following Figure 8. In order to validate the model performance, performance simulation test has been employed to the model under two speed conditions; (1) constant speed input of 120 km/h (Figure 9) and (2) driving cycle speed input (Figure 10).

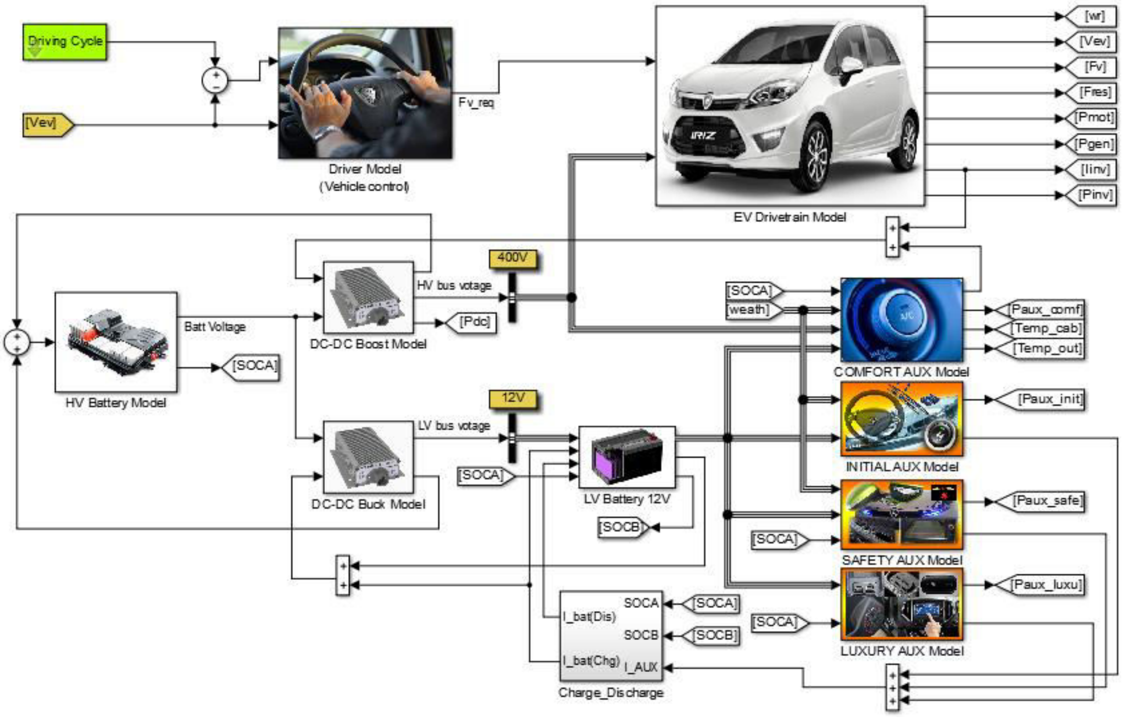

Figure 8. Simulink model of BEV.

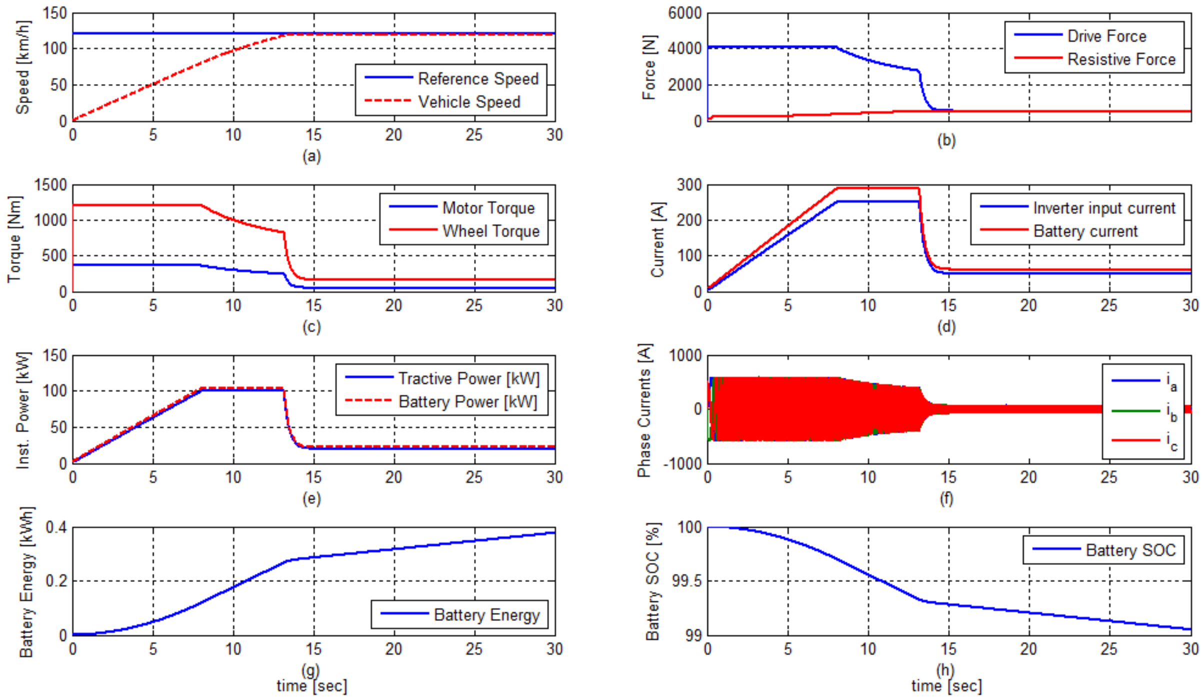

Figure 9. BEV model responses against 120 km/h speed input; (a) reference and vehicle speeds (b) drive and resistive forces (c) motor and wheel torques (d) inverter and battery currents (e) tractive and battery power (f) phase currents (g) battery energy, and (h) battery SOC.

According to Figure 9 (a), the BEV model achieved its base speed of 80 km/h in 8.1 s, reached 100 km/h in 10.5 s (acceleration time = 10.5 s) and took 13.2 s to settled. Both torque and force are maximum during beginning, however gradually reduced once the based speed is achieved and finally decreased to its minimum after the reference speed is obtained. There is some considerable resistive force in 9(b) to accumulate for net force command to the vehicle plant. In 9(c) motor torque was converted into wheel torque by the gearing ratio. In 9(d) and 9(e), the current and power shapes are similar which represent the multiple region of constant torque, constant power (flux weakening) and constant voltage. The different between tractive power and battery power is due to the power consumption of auxiliary load. Balanced and healthy condition of the drive currents is illustrated in 9(f). Finally, in 9(g), the consumption of battery energy increased slowly after achieving the targeted speed, oppositely shown by the battery SOC in 9(h).

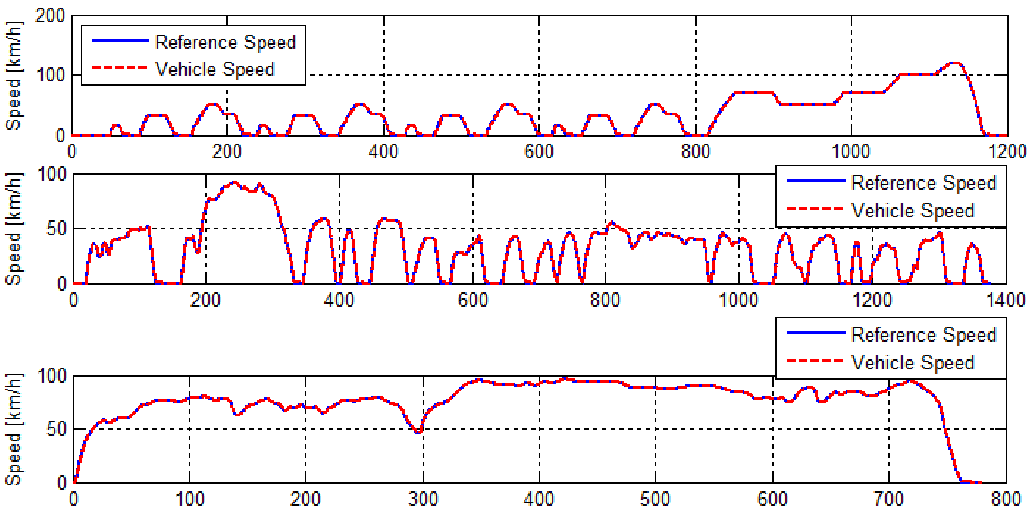

Figure 10. BEV model responses against NEDC, FTP-75 and HWFET speed input.

Based on Figure 10, the model simulation tests in three driving cycles of NEDC (New European urban and extra urban driving), FTP-75 (US urban driving) and HWFET (US highway driving) have shown the performance ability of the BEV model to track the driving cycle speed input. The trip details are as shown in Table 3.

Table 3. Trip parameter comparison between BEV basic model and model with auxiliary loads during NEDC, FTP-75 and HWFET simulation testing.

Parameter	Driving Cycle					
	NEDC		FTP-75		HWFET	
	Basic	With aux	Basic	With aux	Basic	With aux
1. Time travelled (minutes)	20.00	20.00	23.00	23.00	12.75	12.75
2. Range travelled (km)	10.93	10.93	11.97	11.97	16.50	16.50
3. Residual range (km)	239.60	189.60	236.20	186.90	255.50	225.20
4. Total range (km)	250.53	200.53	248.17	198.87	272.00	241.70
5. Battery output energy (kWh)	1.7270	1.9730	1.9100	2. 0900	2.4030	2.6080
6. Traction energy (kWh)	1.6920	1.6920	1.8710	1.8710	2.3550	2.3550
7. Regenerative energy (kWh)	0.2582	0.2582	0.4010	0.4010	0.1223	0.1223
8. HVAC energy (kWh)	-	0.4244	-	0.4881	-	0.2759
9. Auxiliary loads energy (kWh)	-	0.0674	-	0.0775	-	0.0438
10. Battery SOC (%)	95.64	94.55	95.18	93.98	93.93	93.17
11. Per km consump. (kWh/km)	0.158	0.198	0.160	0.199	0.146	0.164

From Table 3, during NEDC it can be noted that the total range for BEV is 250.53 km without auxiliary load, and only 200.53 km with auxiliary load. The regenerative energy of 0.2582 kWh was recovered into the battery during braking and costing to be used during the trip. The highest regenerative energy is during urban driving (FTP-75) due to the highest frequency of braking, while the lowest is during highway driving (HWFET). The energy distribution profile during NEDC is illustrated in Figure 11.

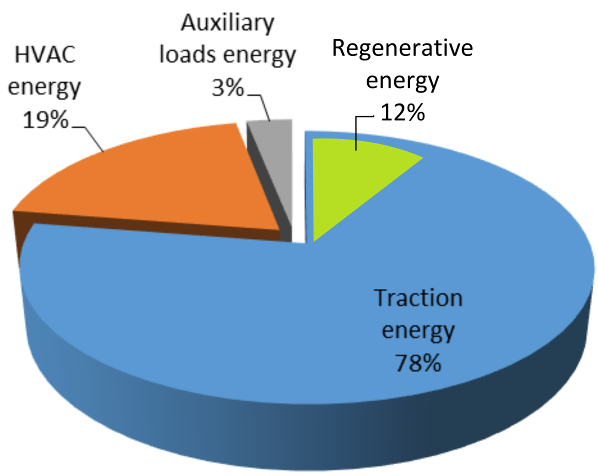

Figure 11. BEV energy distribution profile relative to battery output (kWh) during NEDC

According to Figure 11, energy distributes the highest for traction purpose in propulsion load (PMAC) as much as 78%. The second highest is HVAC (comfort load) with 19% while low voltage auxiliary load only consumed 3% of the battery energy. On the other hand, the regenerative braking feature in BEV has contributed for additional 12% to the battery energy.

Conclusion

In this study, the model of battery electric vehicle and auxiliary loads have been developed using mathematical equations via white-box modelling in Matlab-Simulink environment. The model comprises a multi-disciplinary study of control, electrical, electrochemical, mechanical, electromechanical, and power electronic systems. The model has been tested in constant speed input and three driving cycles speed input (NEDC, FTP-75 and HWFET). The results have demonstrated the model control robustness in speed tracking and achieving the targeted performances. In addition, the model also can be used to illustrate energy distribution profile between loads for the proposed driving cycle.

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