

Modelling of an advanced charging system for electric vehicles

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Abstract - Climate Change is recognized as one of the greatest environmental problem facing the World today and it has long been appreciated by governments that reducing the impact of the internal combustion (IC) engine powered motor vehicle has an important part to play in addressing this threat. In Malaysia, IC engine powered motor vehicle accounts almost 90% of the national greenhouse gas (GHG) emissions. The need to reduce the emission is paramount, as Malaysia has pledged to reduce 40% of CO₂ intensity by 2020 from 2005 level by 25% of improvement in average fuel consumption. . The introduction of electric vehicles (EVs) is one of the initiatives. However in terms of percentage, the electric vehicles have not been commonly used by people nowadays and one of the reasons is lack in charging infrastructure especially when cars are on the road. The aim of this study is to simulate and model an advanced charging system for the charging infrastructure of EVs /HEVs all over the nation with slow charging mode with charging current 25 A, medium charging mode with charging current 50 A and fast charging mode with charging current 100 A. The slow charging mode is proposed for residence, medium charging mode for office parking lots, and fast charging mode is called fast charging track for charging station on road. With three modes charger topology, consumers could choose a suitable mode for their car based on their need. The simulation and experiment of advanced charging system has been conducted on a scale down battery pack of nominal voltage of 3.75 V and capacity of 1020 mAh. Result shows that the battery could be charging less than 1 hour with fast charging mode. However, due to limitation of Tenaga Nasional Berhad (TNB) power grid, the maximum 50 A current is considered to be the optimized passive mode for the EV's battery charging system. The developed advanced charger prototype performance has been compared with the simulation result and conventional charger performance, the maximum variation has been found 15%, this closed agreement between the advanced charger prototype, simulation model and conventional charger validate the prototype model. Furthermore, based on the result presented in this report, the battery to be charged up to 85% of its rated capacity by constant current mode only rather than continue with constant voltage, which could shorten the battery charging time by 16% and prolong the battery life by 10%.

1. INTRODUCTION

Environmental issues and increasing prices of non-renewable fossil fuels had triggered researchers to find an alternative for internal combustion vehicles. Although exhaust from the vehicles have received increasing attention as a source of air pollution around the globe since 1970, more than 90% of vehicles on the road nowadays still using gasoline and diesel fuels as their source of energy [1]. With improvement in the battery of electric vehicles in terms of size, price, internal resistance, and energy



density, it give a hope that the electric vehicles will be widely used by the people. Electric vehicles have advantages over conventional internal combustion vehicles in terms of operating cost, less emission, and energy efficiency. According to Nissan [2], their popular car Nissan Leaf 30 kWh have a travel range up to 155 miles per full charge based on the New European Driving Cycle (NEDC). According to the US Department of Transportation, about 78% of the population drives average 40 miles or less per day [3]. Thus, with a single charging, most of the consumers could get to and from the workplace easily without extra charging needed.

Nissan leaf [2] and i-MiEV [4] electric cars are equipped with 3.3 kW or 6.6 kW on-board charger which will take about 4 to 7 hours for fully charging the batteries at 240 V voltage supply. According to SAE hybrid committee [5], the charging power for Level 2 on-board charger with 240 V supply is allowed up to 19.2 kW. The higher the charging power means the shorter the charging time. The main goal of this study is to simulate and model an advanced charger for electric vehicles whereby the consumers could choose charging power level according to their needs. The general system design of the proposed charging system is presented in figure 1. Through a user interface panel, consumers are able to set the desired charging current accordingly. The integrated management system, which is a computer based control unit, will then set a reference current to the on-board charger. The on-board charger consists of a dc-to-dc converter circuit will be able to control the voltage and current output depends on the pulse width modulation (PWM) input signal. Due to the error, i.e. the different between the reference and the actual current level, the pulse width modulator will generate and feed a proper switching signal value to the dc-to-dc converter to provide a proper output current. At the same time, the management system also monitor the condition of the battery in terms of their voltage, current, and temperature in order to control the charging power rate. Besides, there is a switching mechanism to swap between the battery charging mode and the discharging mode.

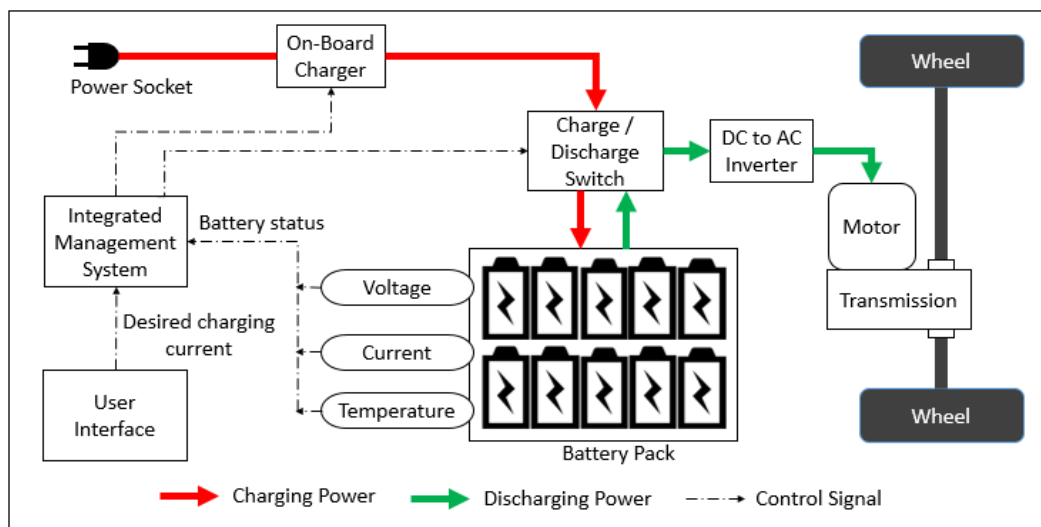


Figure 1. The proposed charging system design

2. METHODOLOGY

The propulsion power of an electric car has been estimated based on the vehicle weight, size, road gradient, and speed. An electric car weight of 9.81 kN, wheel base of 2.2 m, CGx location from front wheel of 1.2 m and rear wheel of 1.0 m, CG height of 0.55 m, projected frontal area of 2.86 m² is considered to estimate the vehicle propulsion power for the different road gradients and speed. The estimated propulsion power was used to select the traction motor and the battery pack. Vehicle traction torque and propulsion power are estimated by using the equation by Wong [6] and Rahman et al. [7] with taking account the vehicle weight, wheelbase, wheel radius, CG location, rolling motion resistance, aerodynamic resistance, slope angle, air density, drag coefficient and travelling speed.

2.1 Propulsion power requirement and battery pack design

An electric car of weight 9.81 kN is used to estimate the vehicle power requirement to maintain the vehicle motion in different road conditions. The traction torque required by a vehicle to propel forward at a desired velocity can be described as follows:

$$T_t = F_t \times r_{wheel} \quad (1)$$

where T_t is traction torque in Nm, F_t is traction force in N and r_{wheel} is radius of the drive wheel in m. The traction force, F_t can be calculated as follows:

2.1.1 Traction force for initial condition (during stand still to start moving).

$$F_{t(initial)} = m_a g \left(\mu \frac{l_{fr} + f_r h / L_{wb}}{1 + \mu h / L_{wb}} + \sin \theta_g \right) \quad (2)$$

where m_a is the mass of the vehicle in kg, g is the gravitational acceleration constant equal to 9.81 m/s², μ the adhesion coefficient of the road, l_{fr} distance from the front wheel to CG in m, f_r the coefficient of rolling motion resistance, h is the height of CG in m, L_{wb} the wheel base in m, θ_g the slope angle with respect to the horizon in degree.

2.1.2 Traction force for moving condition (dynamic component)

The major external forces acting on a vehicle are shown in figure 2 which include the aerodynamic resistance R_a , rolling resistance R_{roll} , grade resistance R_g ($W \sin \theta_g$), and tractive effort F_t . So that the traction force at moving condition could be found as:

$$F_{t(dynamic)} = \frac{Wa}{g} + R_{roll} + R_g + R_a \quad (3)$$

$$= \frac{Wa}{g} + f_r m_a g + m_a g \sin \theta_g + \frac{1}{2} \rho_{air} C_D A_f v^2 \quad (4)$$

where ρ_{air} is the air density in kg/m³, C_D is the coefficient of aerodynamic resistance, A_f is the frontal area of the vehicle in m² and v is the travelling speed of the vehicle relative to the wind in m/s.

Vehicle traction on the maximum grade is due to rolling resistance and grade resistance. The aerodynamic resistance, R_a is considered zero as the vehicle moves on the maximum grades very slow ($v \cong 0$). Besides, the acceleration, a is also considered zero as the $v \cong 0$. So that the traction force at the maximum grade is

$$F_t = R_{roll} + R_a \quad (5)$$

$$= f_r W + m g \sin \theta_g \quad (6)$$

The maximum tractive force that the tire-ground contact can support is described by the product of the normal load and coefficient of road adhesion, μ . Any small amount over this maximum tractive force will cause the tire to spin on the ground.

$$F_{t,max} = \mu W \quad (7)$$

The propulsion power required to propel the vehicle at maximum speed, $P_{prop,max}$ in Watt or W is the product of the traction force and the maximum travelling speed which could be found from Equation 4, and based on maximum travelling speed (v_{max}):

$$P_{prop} = F_{t(dynamic)} \times V_{x,max} \quad (8)$$

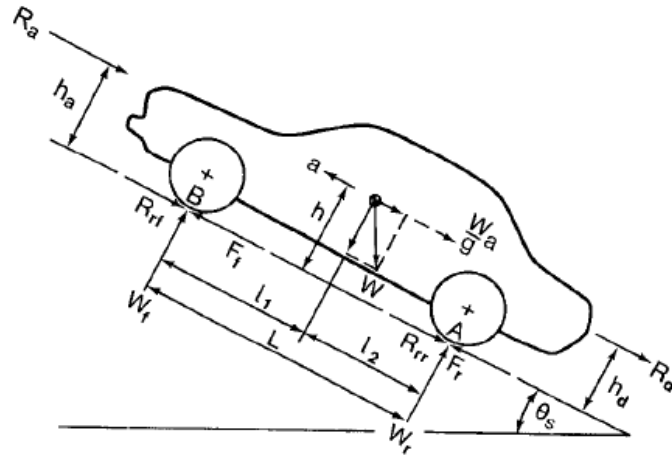


Figure 2. Forces acted on a car

By considering the car traction at the starting of 0.5 km/h, urban speed of 40 km/h, and maximum speed of 90 km/h (25 m/s), the traction force and propulsion power requirement are calculated and summarized in Table 1. Besides, it were considered that the adhesion coefficient value μ is 0.4, coefficient of rolling motion resistance, f_r is 0.02, Drag coefficient, C_D is 0.24, Frontal area, A_f of 2.86 m², and air density ρ_{air} equals to 1.2 kg/m³.

The propulsion power for the vehicle can be estimated as following equation, where, P_{req} is the vehicle required propulsion power in kW, F_t is the traction force in N and V is the vehicle speed in m/s. Power required for the vehicle can be predicted as,

(i) Initial start-ups mode

$$P_{req(initial)} = F_{t(initial)} * \frac{V}{1000} \quad (9)$$

By using, $F_{t(initial)}$ is 2.29 kN and V is 2.78 m/s (10 km/h), the vehicle required propulsion power $P_{req(initial)}$ for the vehicle initial start-ups can be computed as 6.37 kW.

(ii) Dynamics mode

$$P_{req(dynamics)} = F_{t(dynamics)} * \frac{V_{crusing}}{1000} \quad (10)$$

By using, $F_{t(dynamics)}$ is 0.136 kN and V is 11.11 m/s (40 km/h), the vehicle required propulsion power, $P_{req(dynamics)}$ for the vehicle dynamics mode can be computed as 1.5 kW.

Based on table 1, a traction motor with rated power more than the calculated maximum power would be suitable to propel the car. Electrical motor with terminal voltage V_m of 100V and peak power of 18kW are considered in the design of the power supply. The battery size is estimated as 18 kWh to

travel 160 km with speed of 100 km/h. It is noted that if the car is equipped with 20 kWh battery, it would get the traction power at initial start-ups, propel on 10% grade, and cruising speed (overdrive).

Table 1. Battery size required for 160 km travelling.

Traction Mode	Speed	Ft (kN)	Pprop (kW)	Ib (A)	Battery size (kWh)	Consideration
Initial start-ups (Reduction)	10 km/h	6.37	17.7	177	15	
Urban mode @ 10% gradient	40 km/h	1.5	13.5	135	12	Motor rating voltage, V=100 volts
Crusing speed (Overdrive)	90 km/h	0.85	21.25	213	18	

Discharge current drawn from the battery I_b by the motor to meet the power demands of the car in different road conditions has been estimated as follows,

$$I_b = \frac{P_{prop}}{V_m} \quad (11)$$

In order to design the battery pack for the vehicle traction, battery cells with nominal voltage of 3.75V and rated capacity of 43Ah were considered. By connecting 6 cells in a 2-series, 3-parallel (2S3P) formation, 7.5V battery modules with 129Ah capacity are formed. The battery pack that have terminal voltage of 100V and 12.9kWh capacity are made by connecting 13 modules in series. The battery pack capacity is enough to supply the maximum power that required by the vehicle. The series/parallel configuration enables design flexibility to achieve the desired voltage and current ratings with a standard cell size. If higher currents are needed, it could be achieve by connecting two or more cells in parallel. On the other hand, if higher voltages needed two or more cells can be connected in series.

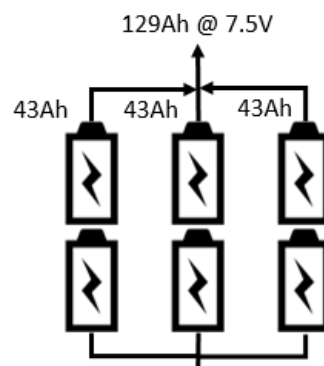


Figure 3. Battery module (2S3P) with 7.5V terminal voltage and 129Ah capacity

2.2 Charging system simulation design

The on-board charging system utilize a dc-to-dc step down or buck converter to supply a suitable power level to the battery as shown in figure 4. The current sensor captured the actual current of the buck converter output and fed them back to the controller. The controller work by using the difference, or error, between the actual and reference current in order to feed appropriate signal value to the pulse width modulator (PWM). The PWM signal then control the switching process of the buck converter in order to supply the desired current to the battery. The parameters value of the PID gains are obtain manually by try and error tuning method as discussed in [8, p. 483].

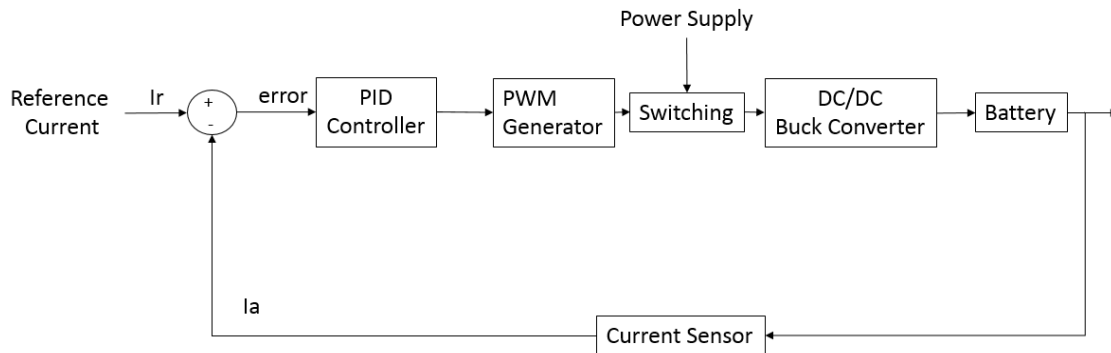


Figure 4. Buck converter (dc-to-dc) with closed-loop control system block diagram

Buck converter also known as step-down dc-to-dc converter consists of dc input voltage source V_s , controlled switch S , diode D , filter inductor L , filter capacitor C , and load resistance R as shown in Figure 5. Mathematical calculation on how to find suitable values for inductor and capacitor are shown here based on [9], [10] and [11].

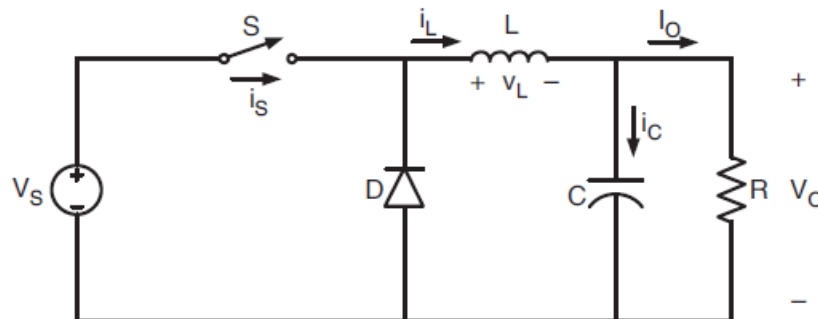


Figure 5. Basic diagram of a buck converter circuit

The duty cycle denotes the conducting time, t_1 of the switch as a proportion of the cycle period of T , where $T = 1/f$ and f is switching frequency. The duty cycle, D is calculated as:

$$D = \frac{t_1}{T} \quad (12)$$

In a buck converter, the output current is the average value of inductor current I_L , and if the losses are neglected then the output current is estimated as below where it is depend on the duty cycle value [12]

$$I_{OUT} = \frac{I_{IN}}{D} \quad (13)$$

The minimum value for inductor L and capacitor C are found by the following equation:

$$L = \frac{V_{OUT} \times (V_{IN} - V_{OUT})}{\Delta I_L \times f_s \times V_{IN}} \quad (14)$$

$$C = \frac{\Delta I_L}{8 \cdot f_s \cdot \Delta V_{OUT}} \quad (15)$$

Where ΔI_L is the inductor current ripple, f_s is the switching frequency and ΔV_{out} is the output voltage ripple. The value for duty cycle, inductor and capacitor are calculated and summarized in table 2.

Table 2. Estimated values of converter parameters

Parameters	Calculated parameters for real size charger ^a	Calculated parameters for scale down charger ^b
Duty cycle, D (equation 12)	0.022	0.440
Inductor, L (μH) (equation 14)	685	94
Capacitor, C (μF) (equation 15)	30	120

^a Consideration: $V_i = 240$ V, $V_o = 5$ V, $f = 25$ kHz, $\Delta I_L = 30\%$, $\Delta V_{out} = 10$ mV

^b Consideration: $V_i = 240$ V, $V_o = 100$ V, $f = 25$ kHz, $\Delta I_L = 30\%$, $\Delta V_{out} = 10$ mV

3. RESULT AND DISCUSSION

Simulation result of a real electric vehicles charging process is presented in this section. In order to validate these result, a small size battery with 1020 mAh rated capacity has been used for both the simulation and experimental of the charging process.

3.1 Simulation of charging process for Electric Vehicles

The battery charging process was then simulated by MATLAB Simulink tool. The charging currents are varies in order to observe the charging time for the 12.9 kWh battery of the vehicle accordingly. To standardize the charging process, the state of charge (SOC) of the battery is considered to be zero percent at the beginning of chaging process.

Table 3. Proposed EV battery charging parameters for simulation

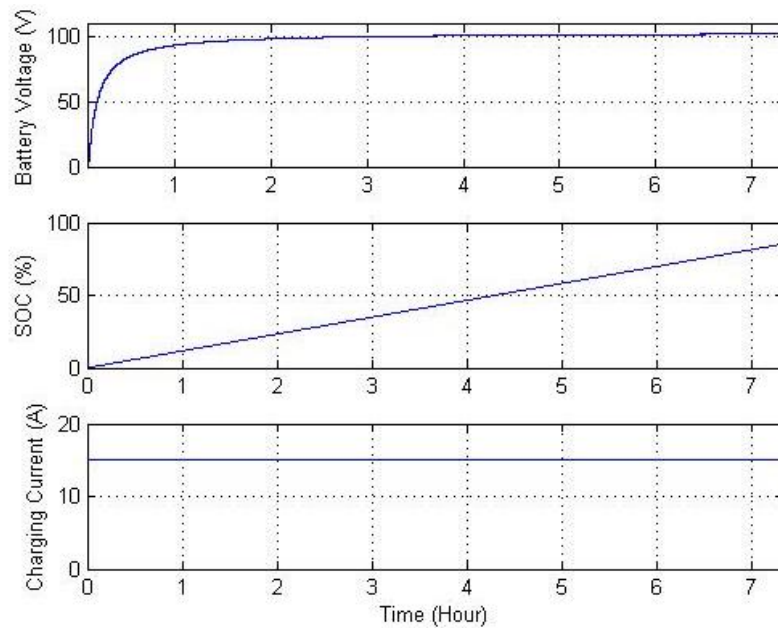
Terminal voltage (V)	Battery capacity (Ah)	Initial state of charge (%)	Charging current / C-rate		
			Slow mode	Medium mode	Fast mode
100	129	0	0.1C – 0.2C	0.3C – 0.6C	0.7C – 1.0C

It is proposed that the C-rate for slow mode is from 0.1C to 0.2C, for medium mode is from 0.3C to 0.6C, and for fast mode is from 0.7C to 1.0C. The battery parameters that are considered for the charging system simulation in MATLAB Simulink are summarized in table 3. In the simulation, the constant current (CC) mode without constant voltage (CV) mode is considered for the battery charging process until the state-of-charge (SOC) reaches at 85%. There are two reasons for considering CC mode without CV during the charging process; extend the battery life span and shorten the charging time. Besides, the time taken to charge the battery to 100% of SOC is compared between simulated and calculated time. For calculated charging time, the following equation is considered:

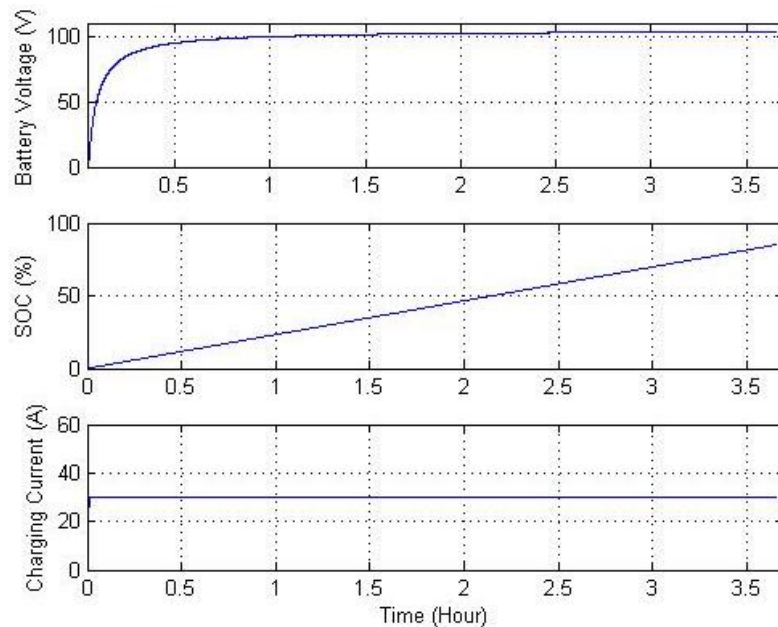
$$t_{\text{charging}} = \frac{Q}{I_{\text{charging}}} \quad (16)$$

Where Q is the battery capacity in Ah and I_{charging} is the charging current. For the simulated charging time, the data are extracted from the following simulation graphs.

In slow mode charging process, the charger sets the charging current to 0.1C and 0.2C which is equal to about 15 A and 30 A. The current level was maintains constantly as specified until the battery voltage measures 100 V and once the charger measures 85% state of charge, the charger then terminates the process. The result of the slow mode charging simulation is shown in figure 6.



(a)

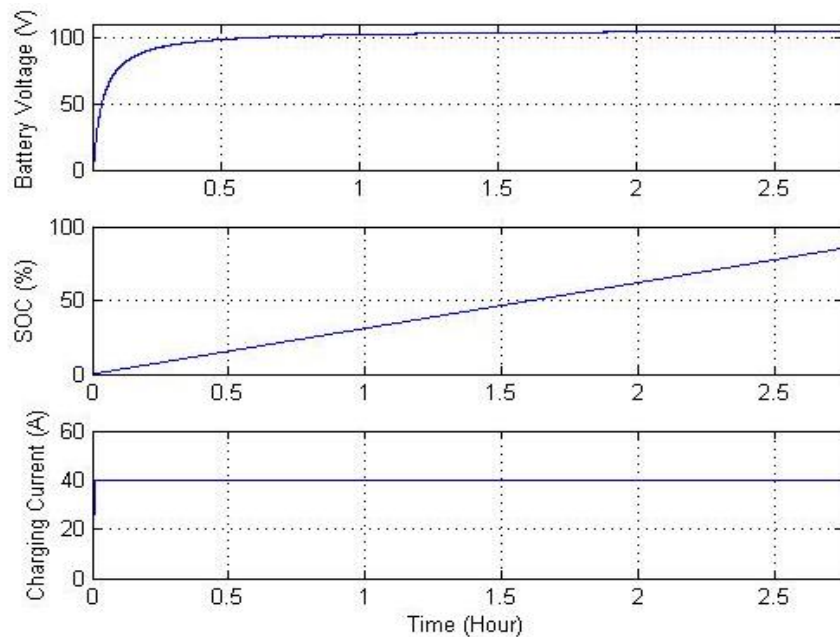


(b)

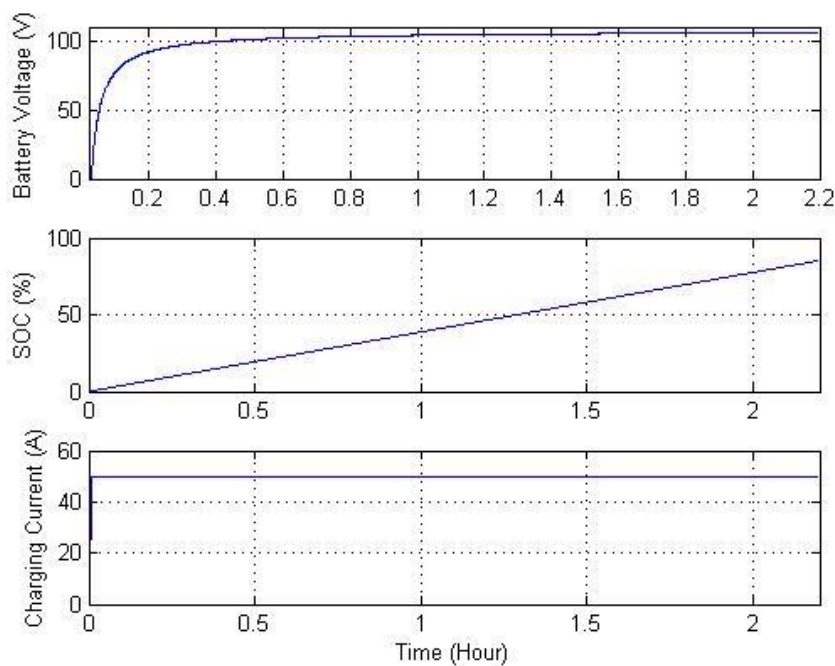
Figure 6. Simulation result for EV charging with slow mode for 85% of SOC, the charging current (a) 15 A and (b) 30A

The advantage of this mode is that it offers very less stress on the battery and this could prolong the battery life. Figure 6 show that the charging system needs about 7.31 hours for charging current of 15A and 3.65 hours for charging current of 30A to get 85% SOC of 129 Ah capacity battery.

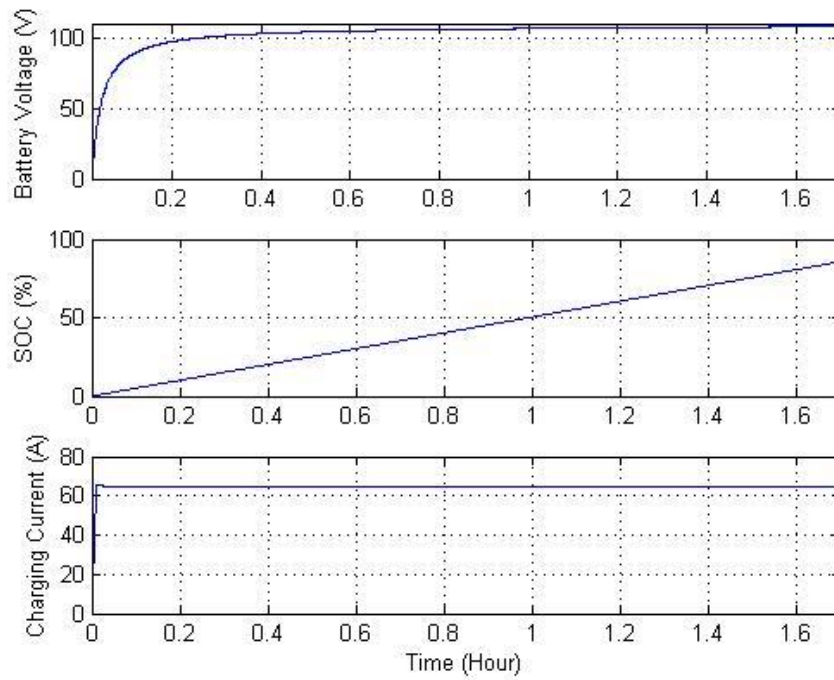
Medium mode charging was specified to have charging current from 0.3C to 0.6C and in this study they were set at 40 A, 50 A, 65 A, and 77 A. The current level was maintained constantly as specified until the charge voltage measures 100 V and the process was terminated when the state of charge reach 85%. The result of the medium mode charging simulation is shown in figure 7. The advantage of this mode is that it offers an intermediate trade-off between charge speed and stress on the battery.



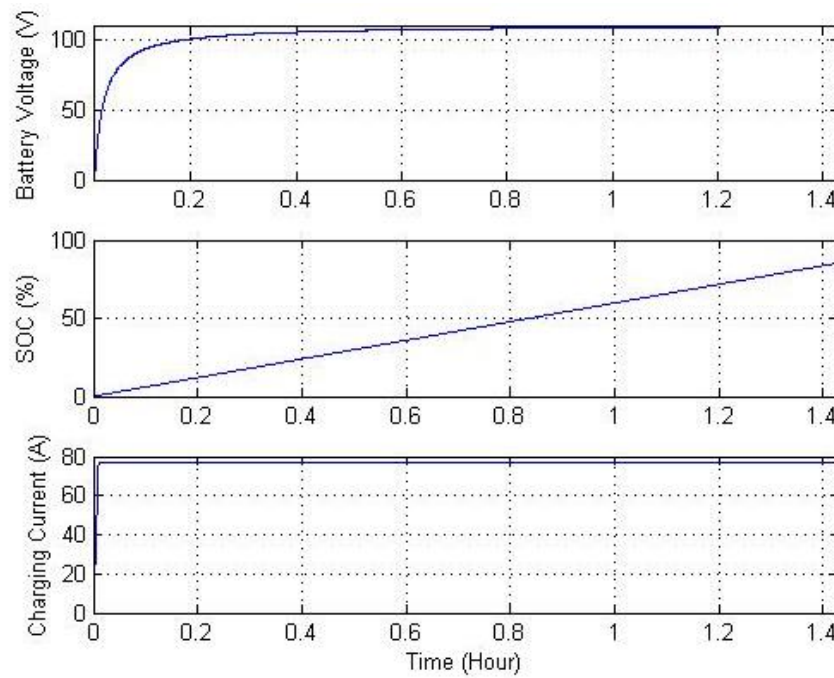
(a)



(b)



(c)

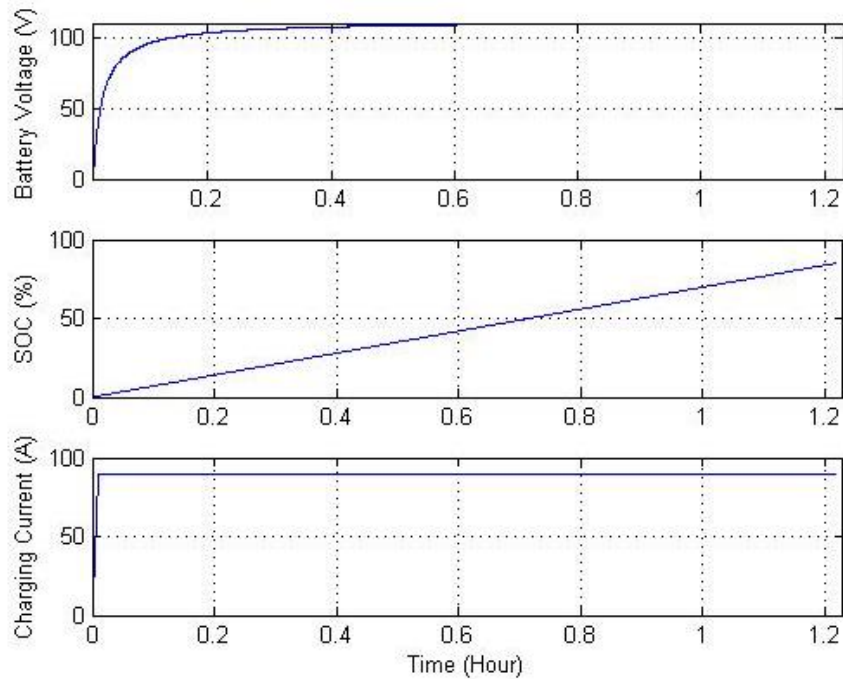


(d)

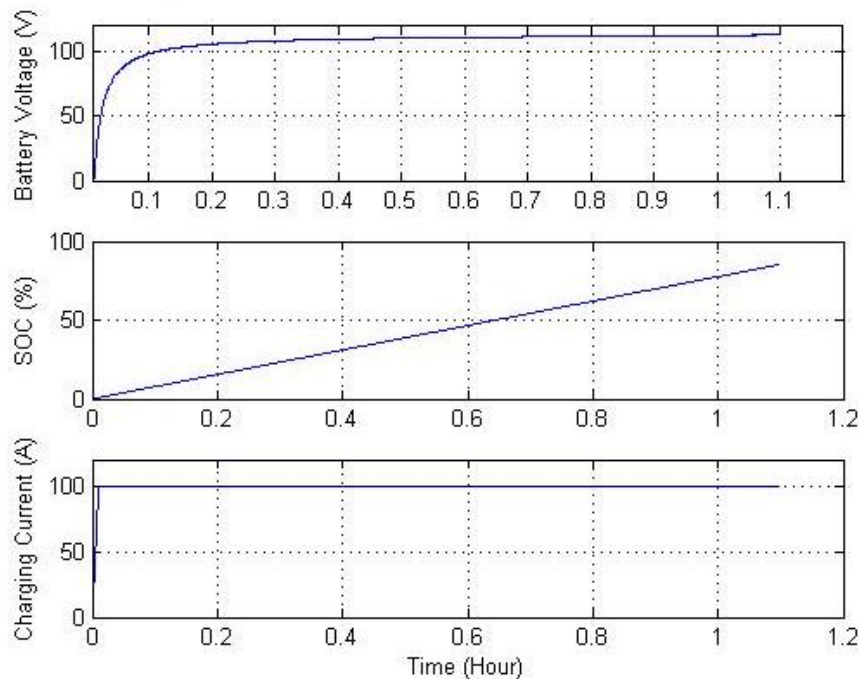
Figure 7. Simulation result for EV battery charging with medium mode for 85% of SOC, the charging current (a) 40A, (b) 50A, (c) 65A and (d) 77A

Figure 7 show that the charging system needs about 2.5 hours for charging current of 40A, 2.0 hours for charging current 50A, 1.6 hours for charging current 65A and 1.3 hours for charging current 77A.

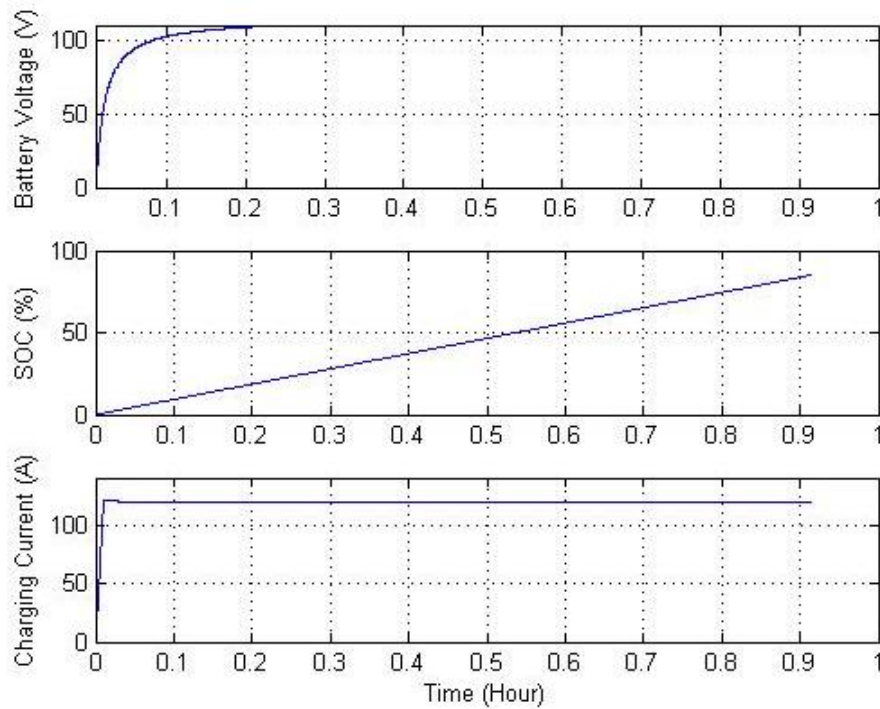
In this study, the fast mode is considered to have the charging rate of $0.7C$ to $1.0C$. The charger current was maintained constant at 90 A, 100 A, and 120 A and the charging process will be terminated when the state of charge reach 85%. The advantage of this charge mode is speed where the charging time less than one hour could be achieved and results in less stress on the battery. The following graph shows the result of the fast mode charging simulation.



(a)



(b)



(c)

Figure 8. Simulation result for EV charging with fast mode for 85% SOC with the charging current (a) 90A, (b) 100 A and (c) 120 A

For the fast charging, the charging process needs about 1.22 hours for charging current of 90 A, 1.11 hours for 100 A and 0.9 hour for 120 A.

Table 4 summarized the simulation results for the slow, medium, and fast charging mode in terms of charging current, charging rate, and charging time. It is found that by charging the battery with constant current until it reach 85% SOC, and eliminate the saturation stage with constant voltage, about 13.9% to 16% of charging time was reduced.

Table 4. Result summary for EV charging simulation

Charging Mode	Charging Current (A)	Charging Rate (C)	Simulated Charging Time (Hours)		Charging Time Difference (%) (Between 100% and 85% SOC)
			100% SOC	85% SOC	
Slow	15	1/10	8.60	7.31	15.0
	30	1/5	4.30	3.65	15.1
Medium	40	1/3	3.23	2.71	16.0
	50	2/5	2.58	2.2	14.7
	65	1/2	1.98	1.68	15.2
	77	3/5	1.68	1.43	14.9
Fast	90	7/10	1.43	1.22	14.7
	100	4/5	1.29	1.11	13.9
	120	9/10	1.08	0.92	14.8

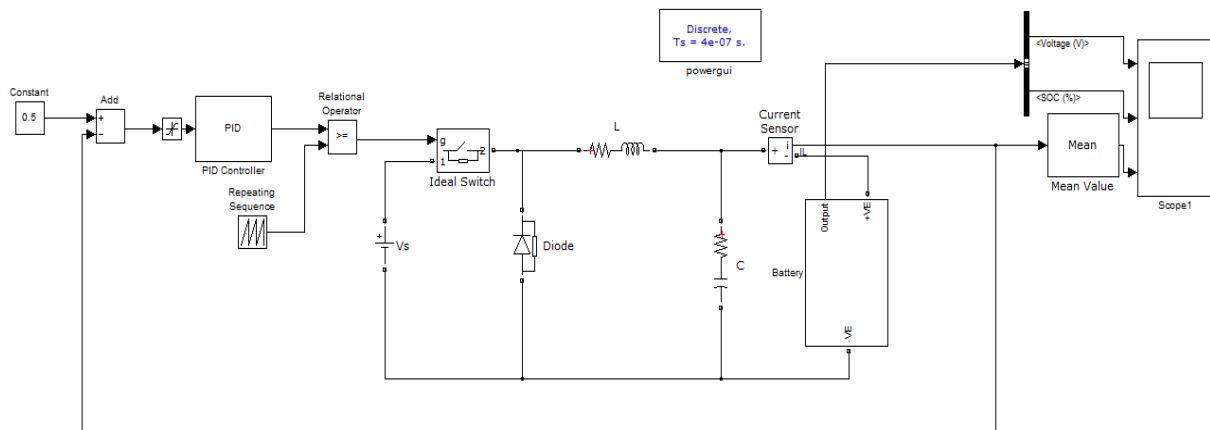
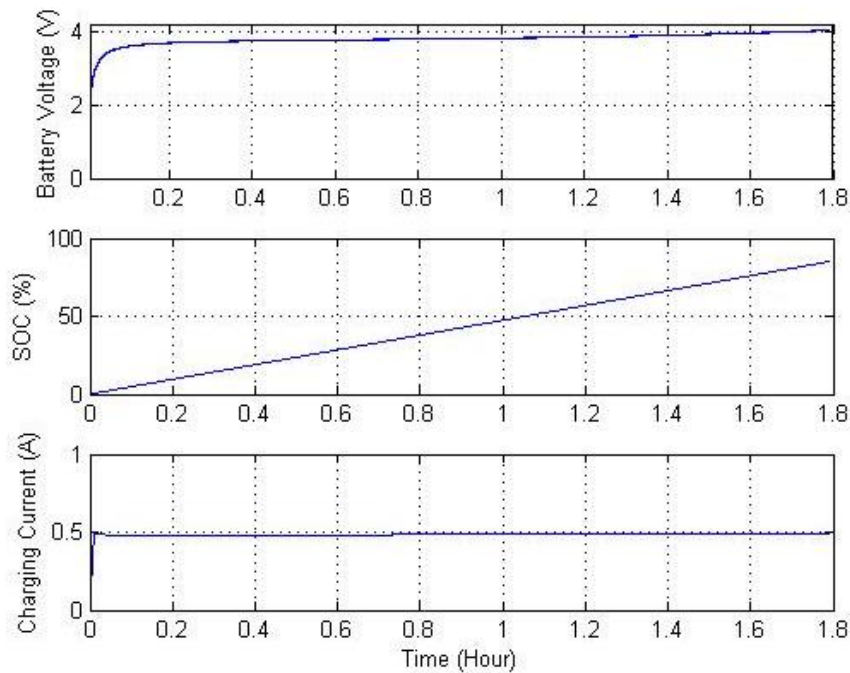


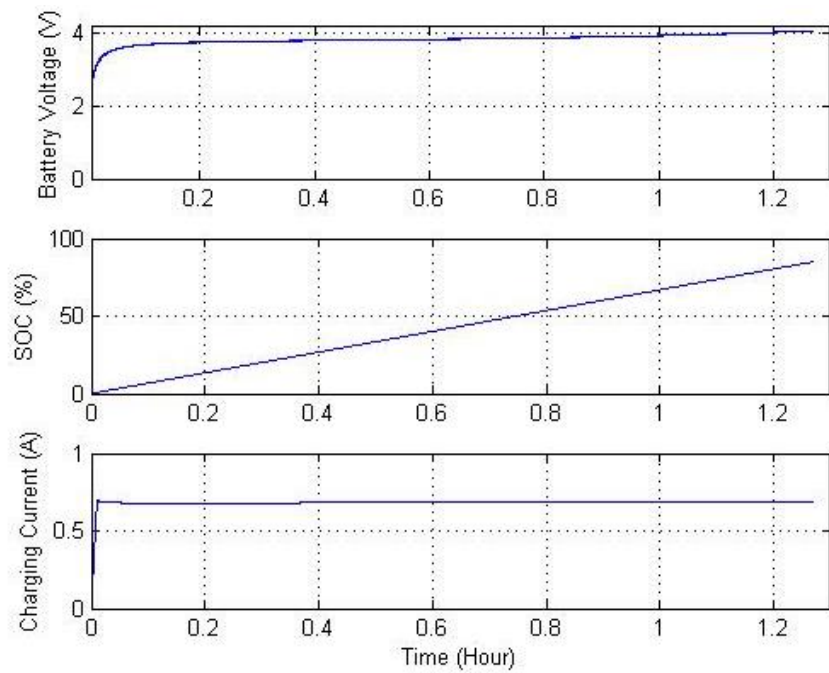
Figure 9. Diagram for charging process simulation in MATLAB Simulink tool

3.2 Simulation and experimental result of scaled-down battery charging process

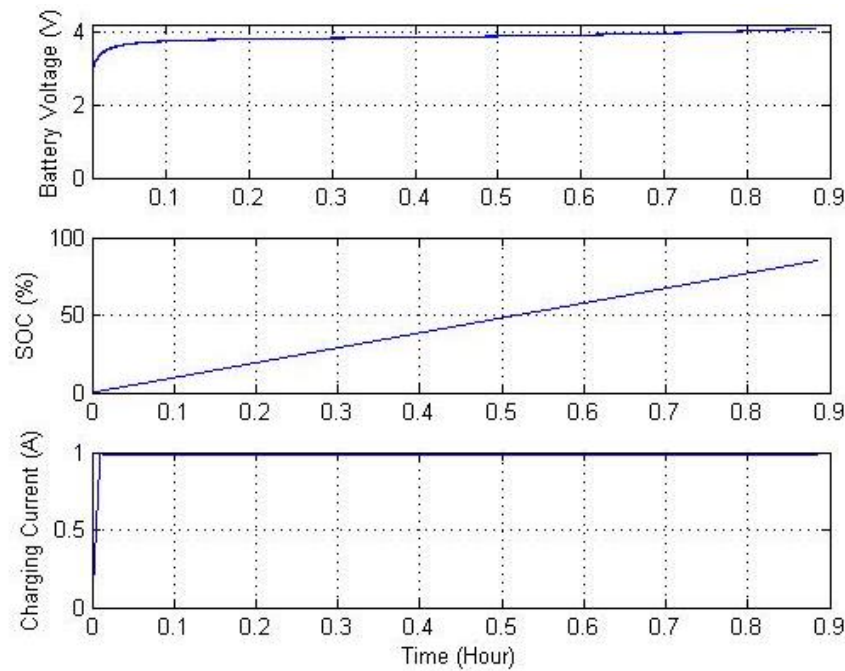
Due to the availability and accessibility to a real electric vehicles, a small size battery is considered in order to mimic as well as to validate the charging process of a real vehicles. In the simulation a battery with 1020 mAh capacity has been charged with constant current of 500 mA, 700 mA, and 1000 mA until the state of charge reach 85%. The simulation results are shown in the following graphs.



(a)



(b)



(c)

Figure 10. Simulation result for scale down battery charging with charging current (a) 500mA, (b) 700mA, (c) 1000mA

The simulation results are summarized in Table 5 in terms of charging current, charging rate, and charging time. It is found that charging time for calculated and simulation is almost the same with

maximum different of 1.6 % due to fluctuation in simulation charging current. It was found that about 12.25% to 13.73% of the charging time could be reduced by implementing the constant current mode only and charging the battery up to 85% of SOC.

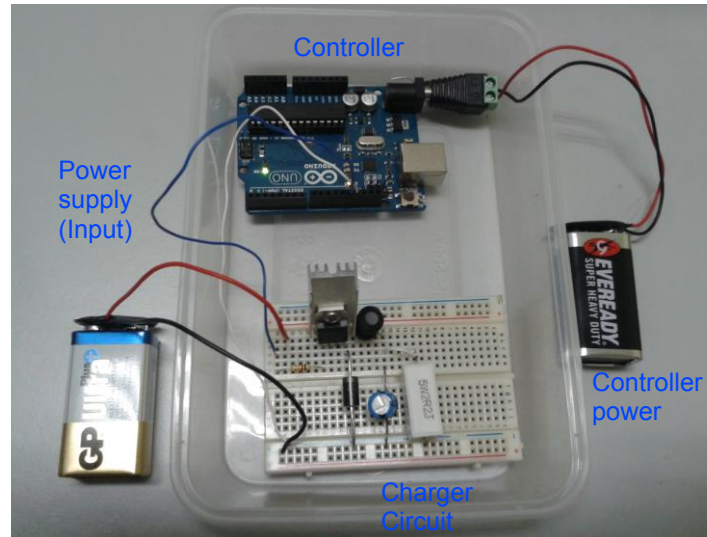
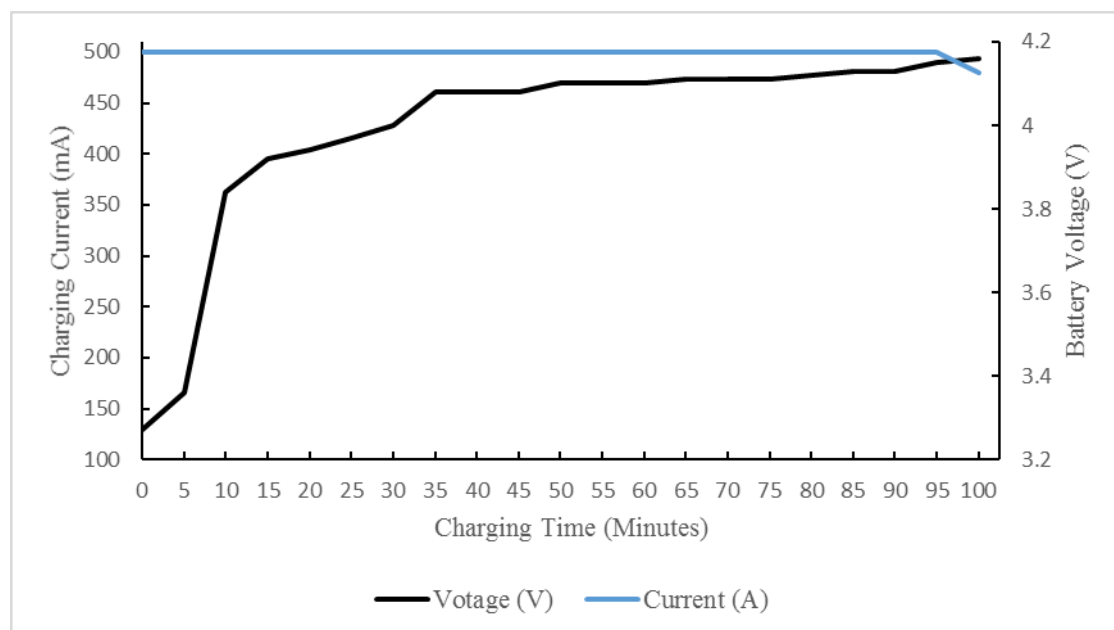
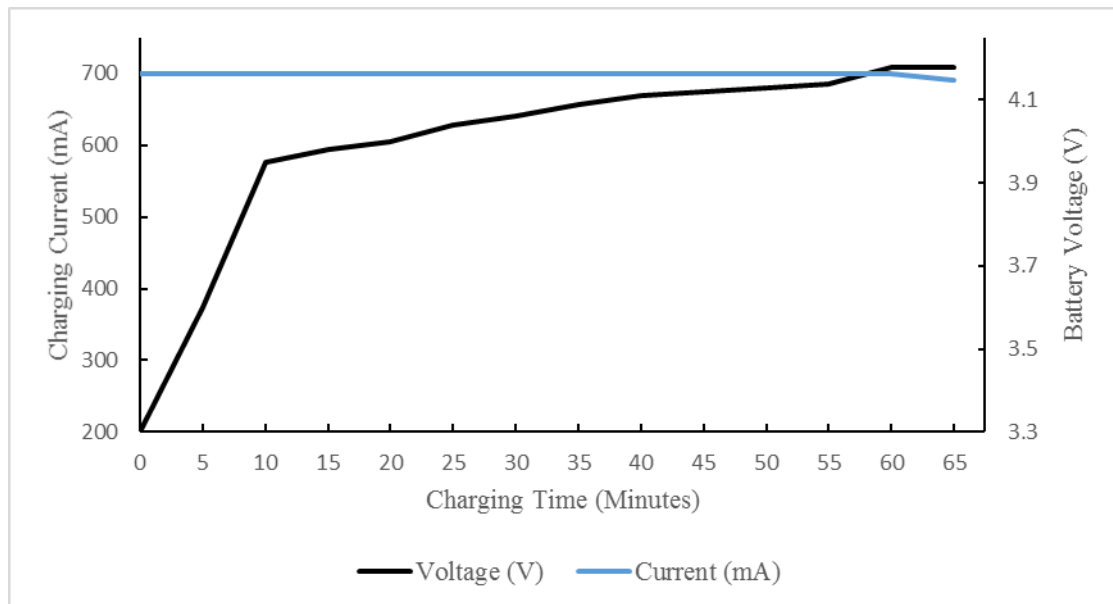


Figure 11. Developed charger prototype

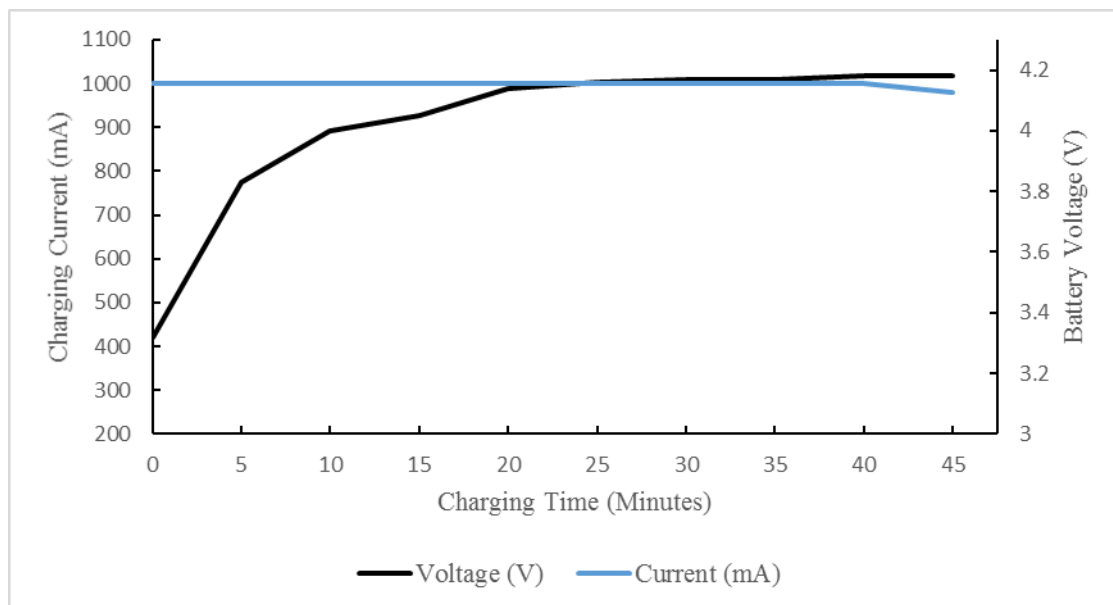
Besides, the experimental has been conducted on a scale down battery pack to identify the charging time and efficiency and to validate the simulation result, which has made based on the developed model (figure 11). The charger was set to maintain the charging current that represent the three modes charger of slow, medium, and fast. It was assumed that the slow mode was 500 mA, medium mode was 700mA, and fast mode was 1000mA. The charger voltage was set to be at the maximum rated voltage of the cell which is 4.2 V. The battery was charged with constant current until the charger voltage and battery voltage were almost saturated. At this point, the charging current started to fall towards zero. The plotted battery voltage throughout the charging process corresponding with charging current and charging time are presented in the following graphs.



(a)



(b)



(c)

Figure 12. Developed charger performance for (a) 500 mA, (b) 700 mA, and (c) 1000 mA

Time taken to reach 4.2 V are about 91 minutes for slow mode, 60 minutes for medium modes, and 43 minutes for fast mode. Table 5 shows the comparison on the charging time between simulation, conventional charger, and developed prototype charger. It was noted that for the simulation the initial battery voltage was considered at 0 V and battery SOC at 0%. While for the experiment, the initial battery was measured initially at around 3.3 V. It was found that the different charging time between the simulated and prototype charger is about 15%. The time taken to charge the battery is faster for the prototype one since the battery initially at 3.3 V and already contains the remaining charge.

Table 5. Charging time comparison table

Charging Mode	Charging time (h)		Charging time difference between simulation and prototype
	Simulation	Prototype	
Slow (500 mA)	1.79	1.52	0.27 hour (15.08%)
Medium (700mA)	1.27	1.079	0.19 hour (14.96%)
Fast (1000mA)	0.88	0.748	0.13 hour (14.77%)

4. CONCLUSION

The following conclusions have been made based on the contents of the paper:

1. The slow charging mode with charging current 15A is able to charge the battery overnight in residence or at office for 6-7 hrs, the medium charging mode with charging current 25-35 A is able to charge battery for 1.5 to 2 hrs, and the fast charging mode with charging current 100A is able to charge the battery in less than 1 hour. However, based on the power grid of Malaysia [13] the maximum 50A current can be used to charge the EV battery with the advanced charger. Therefore, the medium mode with charging current 50 A is the optimized passive mode for the EV's battery charging system.
2. Charging the battery with constant current until it reach 85% SOC, and eliminate the saturation stage which is continue with constant voltage, would reduce the charging time about 13.9% to 16%. This technique would also reduce the stress on the battery and thus prolong the battery life span.
3. The developed advanced charger prototype performance has been investigated and compared with the simulation model, the maximum variation has been found 15%, this closed agreement between the advanced charger prototype, simulation model and conventional charger validate the prototype

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