Development of rapid charging system for EV battery

Ataur Rahman, Abdul Hassan Jaafar

Abstract--- ***The adaption of electric vehicle in worldwide is increasing in acceleration fashion while in Malaysia has been a slow hike, especially with the lack of infrastructure development. There are few conventional charging stations of EV are set up in shopping malls and hotels are not enough to initiate the EVs in the country. However, the charging awaiting time is quite longer could be about 5 to 6 hours which makes Malaysia is slowly falling out from EV trend. The development of quick charging system from this study might be considered as the development of electric mobility solutions. A prototype on-board charging system with three different charging modes: the slow charging mode is normally considered for residence, medium charging mode for office parking lots, and fast charging mode for charging station on road. The quick charging mode has been developed to charge the battery in 1.5 - 2.0 hours with maximum charging current 50 A with auto activated quick evaporative battery thermal management system. The performance of the quick charging system has shown that the battery to be charge up to 85% of its rated capacity by constant current mode rather than constant voltage, which has shorten the battery charging time by 16%. However, it might shorten the battery life about 5% due to the fast redox reaction of the electrochemistry of battery.***

Keywords: Electric vehicle; Charging; infrastructure; Quick charging.

1. INTRODUCTION

Nowadays, more than 90% of the road vehicles still using crude oil based fuels as their source of energy although since 1970 the product of these fuels was recognized as a cause of air pollution globally [1,2]. Environmental problem and rising costs of non-renewable crude oil had driven scientists to look for a substitute for gas combustion engine. The chance for the electric vehicles (EVs) to be commonly used is high due to enhancement in energy density, internal resistance, size and price of the battery. Besides, EVs is better than the conventional internal combustion engine (ICE) vehicles in their operational cost, environmental pollution, and energy efficiency. One of most popular EVs, Nissan Leaf, with full charge of 30 kWh battery capacity could travel about 250 km based on the NEDC [3] [3]. NEDC is a driving cycle designed to measure the emission levels and fuel economy of a passenger car. This range capacity could benefit most of the consumers to get to and from the workplace where around 78% of the people drive average 64 km or less in a day as according to the US Department of Transportation [4]. Refilling the battery take about 4 to 7 hours based on Nissan leaf [3] and i-MiEV [5] EVs which came with 3.3kW or 6.6kW on-board charger at 240VAC power supply. For single phase 240VAC supply (known as Level 2 charging scheme) the permitted power for the on-board charger is up to 19.2 kW as according to SAE hybrid committee [6]. The speed of the charging time is directly proportional to the charging power where high power takes less time [7]. The main purpose of this project is to develop an advanced on-board charger for EVs whereby the users could select the charging current according to their requirement. Based on the charging level set by the users, the computer based integrated management system (IMS) shall allow the required current to flow into the battery. The on-board charger regulate the power flow by means of switching mode power supply (SMPS) where the output voltage and current are controlled by the pulse width modulation (PWM) input signal. Meanwhile, the IMS continuously get the feedback data about the battery voltage, input current and temperature to estimate a proper charging power for safety of the battery and vehicle.

2. METHODOLOGY

The battery pack of 18 kWh power density has been developed from combination of few battery cells. Lithium ion battery cells with 3.75 VDC nominal voltage and 43 Ah rated capacity are connected in series and parallel connection to meet the vehicle traction power. The series-parallel cells formation enables flexibility in designing the desired battery pack with a standard cell size. The vehicle maximum traction power for the acceleration (0-10 km/h) can be estimated by using the equation of Rahman et al. [8]:

$$P_{max(0-10km/h)} = \mu mg \left(\frac{L_{fr} + {f_r h}/{L_{wb}}}{1 + {\mu h}/{L_{wb}}} \right)(v) \qquad (1)$$

where m_a is the mass of the vehicle in kg, μ is the road friction coefficient, l_{fr} distance from the front wheel to central gravity of the car 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 road grade or slope and v is the speed of EVs in m/s. The required battery size for EV as presented in Table 1.

The battery chargers usually classified by their charging speed (rate of charging current). Slow charging mode is the most commonly use charger with C/10 charging rate. It also known as overnight charger where it takes about 14 to 16 hours to charge the battery from empty. In between slow and fast modes, there is medium mode where it takes about three to six hours to recharge the battery. Fast charger (quick) use

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shorter time to recharge the battery which is around one to one and half hours. The disadvantage for this fast charging is caused spike temperature about 60^0C and above which might damage battery and even start the fire. Therefore, an integrated system that continuously monitor the battery has been developed to prevent the batteries temperature from unwanted spiking and over charging.

Table 1: Battery pack requirement for 160 km travel distance

Traction Mode (Speed)	F_t (kN)	P_{prop} (kW)	I_b (A)	Battery size (kWh)
Start up speed (10 km/h)	6.37	17.7	177	18
Urban speed (40 km/h)	1.5	13.5	135	14
Cruising speed (110 km/h)	0.85	21.3	213	21

Consideration: Motor rating voltage, V_m is 100 volts

2.1 Design of quick charger

The proposed on-board fast-charging system is presented in Fig. 1. Digital switching mechanism allows the system to shift the battery mode either being recharged or discharged. Based on the users setting, the computer based integrated management system (IMS) set the charger power accordingly. The charger is built based on switching mode power supply where PWM signal control the output voltage and current. Besides, the IMS continuously get the feedback data about the battery voltage, input current and temperature to estimate a proper charging power for safety of the battery and vehicle. The control system of the on-board charger with feedback current sensor is shown in Fig. 2. The controller continuously compare the real time current value with the reference current and the error or difference become an input for the PWM generator. The generator to send a proper switching signal to SMPS converter to produce the desired current. Simulation in this study consider try and error tuning method to get the gain parameters of the PID controller as elaborated in [9].

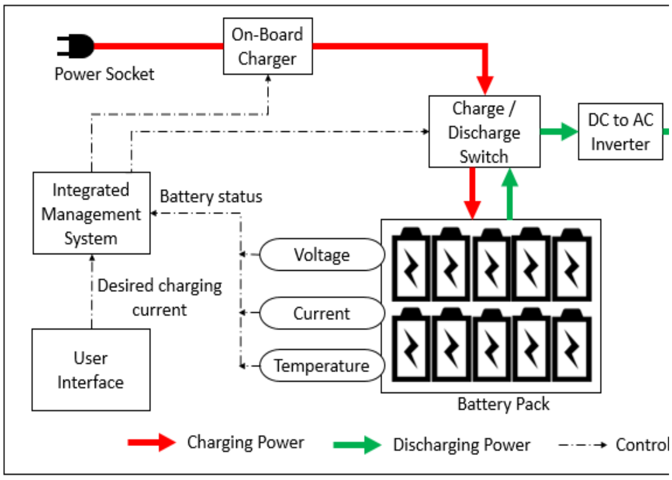

Fig. 1: The proposed charging system design

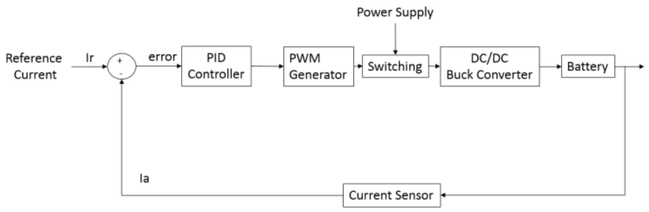

Fig. 2: Block diagram of on-board charger with feedback control system

Buck converter is one of the SMPS that basically contains power supply V_s, switching mechanism S, power diode D, energy storage elements of inductor L and capacitor, C and load resistance R as shown in Fig. 3. Theoretical approach in estimating proper sizes for inductor and capacitor has been made by using the equation of [10,11] where $L \approx V_0(1-D)/\Delta I_L f$, where ΔI_L is the inductor current ripple, f is the switching frequency and ΔV_0 is the output voltage ripple. Duty cycle represents the fraction of commutation period T during which the switch is ON and their relation is $D = t_1/T$. The relation between commutation period and switching frequency is T = 1/f. For this type of SMPS, the average value of inductor current I_L is equal to the output current. By ignoring the losses, the output current could be estimated from the inductor current and duty cycle value as $I_o = I_L/D$ [12]. In this study, the value for D, L and C are calculated as 0.21, 251μH and C≥450μF.

The heat generation into the battery due to high charging /discharging current could be roughly calculated by following equation as discussed in Rahman et al. [13]:

$$Q_{\Delta energy} = \left[\begin{array}{l} \left(\begin{array}{l} I_{b(d)} \cdot \Sigma_i \dfrac{T_{batt(i)} \Delta S_i}{n_i F} + \\ \Sigma_i I_{b(d)} \eta_i + I_{b(d)}^2 R \end{array} \right) \\ - h_m A_s \left(T_{batt(i)} - T_\infty \right) \end{array} \right]$$

with

$$T_{batt(f)} = T_{batt(i)} + \frac{1}{mc_p} \left[\begin{array}{l} \left(\begin{array}{l} I_{b(d)} \cdot \Sigma_i \dfrac{T_{batt(i)} \Delta S_i}{n_i F} + \\ \Sigma_i I_{b(d)} \eta_i + I_{b(d)}^2 R \end{array} \right) \\ - h_m A_s \left(T_{batt(i)} - T_\infty \right) \end{array} \right] \quad (2)$$

$$I_{b(d)} = \frac{\left[\begin{array}{l} m \dfrac{dv}{dt} + \left(0.005 + \frac{1}{P_{t(p)}} \left(0.01 + 0.09 \left(\frac{V}{100} \right)^2 \right) \right) \dfrac{m}{g} \\ + \dfrac{\rho_a C_D}{2} A_f V^2 + \dfrac{m}{g} \sin\theta \end{array} \right] [V]}{V_{m(vol)} \eta_m}$$

where, Q_{energy} is the heat energy develops due to charging and discharging current of battery, I_b is the battery charging/discharging current in ampere, T_b is the battery temperature in °C, Tα is the ambient temperature °C, m is the mass of the battery in kg, c_p is the heat transfer coefficient, h_m is the enthalpy, and S is the entropy.

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3. RESULT AND DISCUSSION

Lithium ion battery model and charging process was developed and simulated in MATLAB Simulink model (Fig. 3). The battery pack was considered as 18 kWh capacity and 100 V nominal voltage. The initial state of charge (SOC) was considered as 15%, the charging rate (C-rate) 0.1 C for slow charging mode, 0.6C for medium charging mode and 1.0 for quick(fast) charging mode. The charging time was estimated for the simulation as, $t_{charging} = Q/I_{charging}$ where Q is the battery capacity in Ah and $I_{charging}$ is the charging current, A.

3.1 Theoretical performance investigation

The performance of the battery charging simulation has been conducted for different charging rate is shown in Fig. 4. The simulation result shows that the SOC of the battery reaches to 85% at 7 hours, 3.5 hours, 2.5 hours, 2 hours, and 1 hours for the charging current of 15A, 30A, 40A, 50A and 100A respectively. The fast charging of battery may damage the battery due to the fast drives a non-spontaneous redox reaction through the battery electrochemistry. The quick charging operation for the battery is considered 50A, where it took 1.25 hours to reach the 60% of the battery and may allow the electric vehicle drive about 120 km. Therefore, It could be concluded that the electric vehicle can drive 287 km by allowing the battery charge on road for 1.25 hours. This time also considered as the resting time of the people of Malaysia on road after driving about 160 km. While, if the battery pack of the EV allows to charge about 2 hours with fast charging mode, the EV driving can be extended to 330 km.

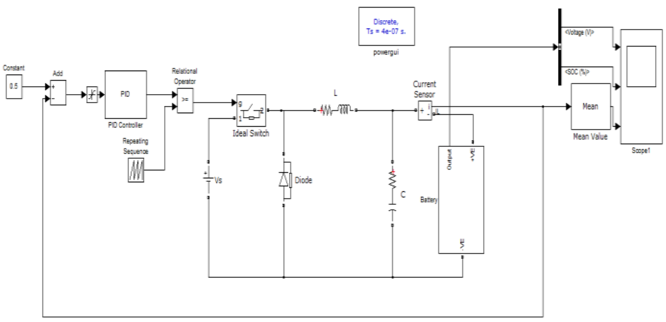
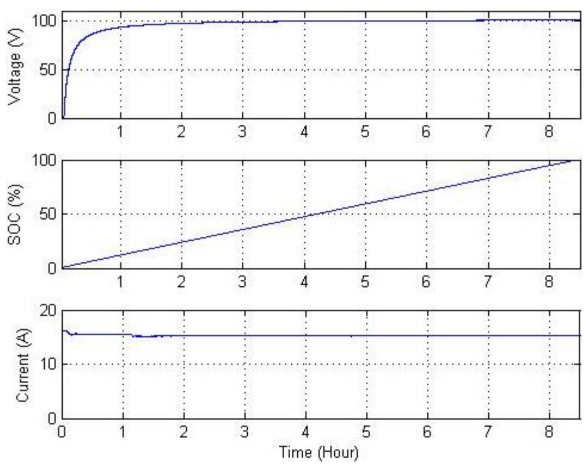
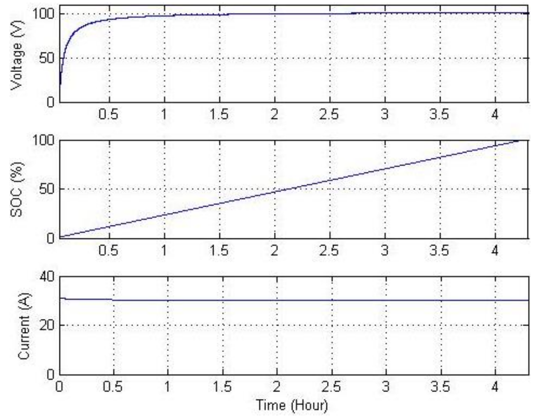


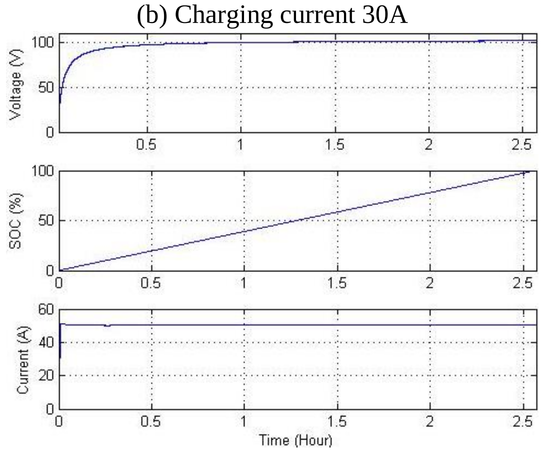
Fig. 3: MATLAB Simulink model of the charging system



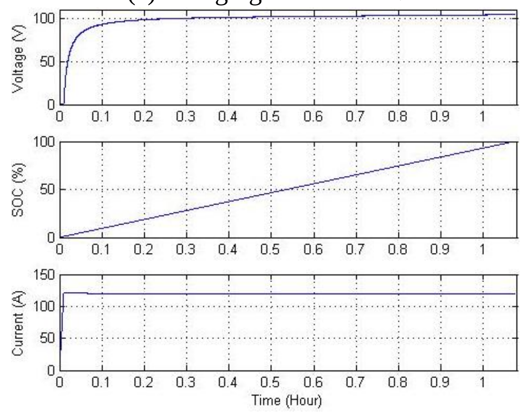
(a) Charging current 15A



(b) Charging current 30A



(c) Charging current 50A.



(d) Charging current 120A

Fig. 4 (a-d): Selected charger simulation performance for different current

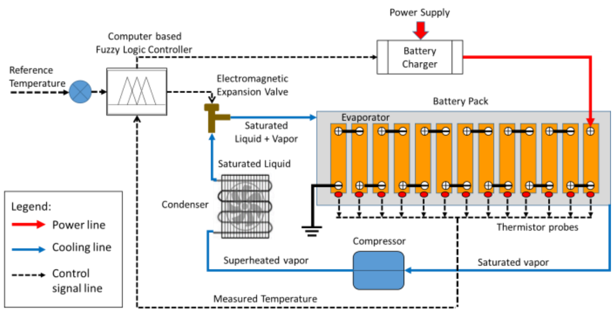


Fig. 5: Temperature control system of the battery during charging.

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However, the fast charging mode of the battery causes a temperature spike of the battery about 60^0C in shortly which not only reduce the battery life but also damage the battery electrochemistry and even fire. Therefore, it is urgent to use an auto-activated cooling system to keep the battery temperature in the range of 30-35^0C. An evaporative cooling system integrated with the charging system (Fig. 5 - 6) has been developed to maintain the battery temperature in the range of 30-35^0C. It would be able to enhance the battery life span about 15%. A digitally controlled expansion valve has been used to cool the battery in shortly by turning the saturated refrigerant R134a into saturated vapor and liquid which flash into the hollow duct of the cooling system and absorb the heat from the surface of the battery and let the battery temperature into 30-35^0C.

3.2 Performance investigation: Experimentally

A scale-down charger prototype (Fig.7) has been developed to investigate the charging time and battery temperature during quick (fast) charging mode. The charger was set to keep the charging current at 210 mA for the slow, 500 mA for medium, and 900 mA fast charging modes. For the voltage, the charger was set to cut-off when the battery cell reach the maximum rated voltage of 4.2V. Initially, the charger was set to operate constant current until the battery reaches the preset voltage. At the moment, the charger switch to constant voltage and the current that going into the battery began to decrease towards zero as the battery charge is almost full. Fig. 8 shows the voltage of the battery that being charged with correspond to the charging current and time. Besides, in this study a battery with rated capacity of 1020 mAh was used to identify the performance and efficiency of the charging process, hence validate the simulation result of the EVs charging system. In order to mimic the proposed charging system, three current level has been chosen which is 500 mA for slow, 700 mA for medium, and 1000 mA for fast modes.

Table 2: Charger performance comparison

Charging Mode	Charging Current (A)	Power Rating (kW)	Charging Time (hour)	
			Calculated	Simulated
Slow	15	1.5	8.60	8.30
	30	3.0	4.30	4.35
Medium	40	4.0	3.23	3.21
	50	5.0	2.58	2.57
	65	6.5	1.98	1.98
	77	7.7	1.68	1.67
Fast	90	9.0	1.43	1.43
	100	10	1.29	1.29
	120	12	1.08	1.08

The performance of charging process between the simulation and experiment has been presented in Table 2 for different modes. There are variation about 3.5% between calculated and simulation charging time as shown in the table. The speed of the charging time is directly proportional to the charging current where high current takes less time. However, the problems on the battery temperature spike, which causes the battery damages and even fire. Furthermore, a special cable are required to handle the high charging current. The SAE J1772 committee are going to finalize the cable and terminal connection to support charging at 200–450 V DC and 80A (36 kW) for DC Level 1 and up to 200A (90 kW) for DC Level 2 [6]. It is important also to consider the maximum power that could be supply by Tenaga Nasional Malaysia [14] for 2-wired single phase of 240V voltage supply which is 12kVA. By considering power factor of 0.98, maximum current could be supplied at 100V is about 117A. In this study, the 50A is considered as the maximum charging current for the battery in fast charging mode based on the prevention of battery temperature spike and reduces the battery life span.

Fig. 6: Evaporative cooling battery thermal management system (Rahman et al., 2017)

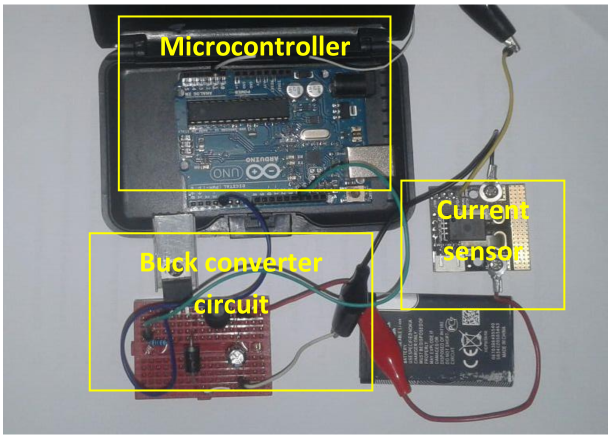
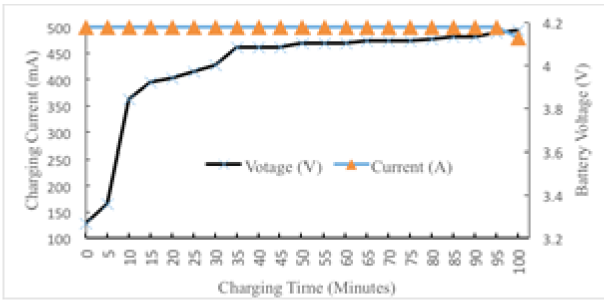


Fig.7: Charger prototype circuit with microcontroller



(a) Battery charging at 0.5 A

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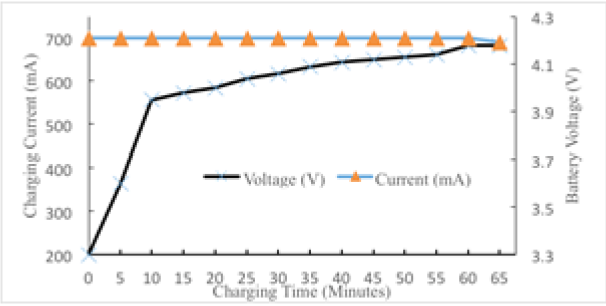
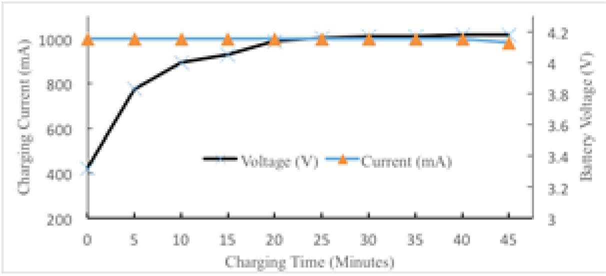


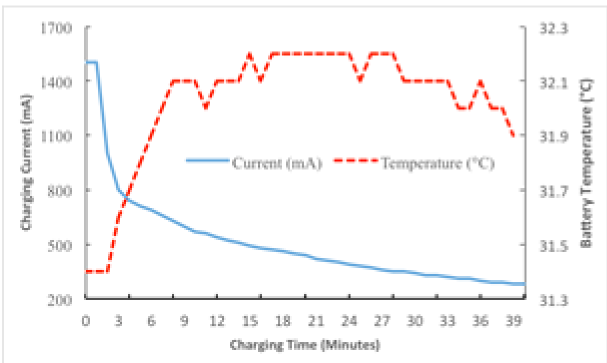
(b) Battery charging at 0.7 A



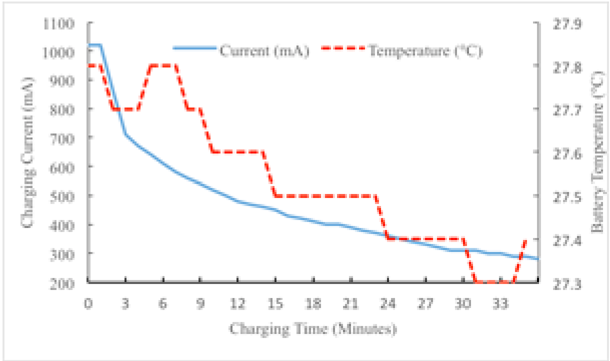
(c) Battery charging at 1.0 A

Fig. 8 (a-c): Developed charger performance

It is earlier mentioned that the battery temperature increases drastically with increasing the charging current. Therefore, it is required an effective battery thermal management system in order to prevent the battery from damaging and even fire with maintaining the battery temperature in the range of 30-35^{0}C during charging. The battery temperature has been recorder with the thermistor both in using the thermal management and without thermal management system (Fig.9). The small size battery has been damaged completely when the charging current was 2000mA and temperature was recorded about 70^{0}C even though the thermal management system has been used. However, the battery was kept below 1700 mA and found that it tends to dead although the temperature was recorded below 35^{0}C. By using the cooling system, the battery temperature was kept below 30^{0}C and it prevent the battery from damaging and useful to span the battery life. The environmental impact of damaged battery could be prevented by recycling with the advanced recycling technique to reuse the battery materials and reduce the material cost [15].



(a) Non-controlled manner



(b) Controlled manner

Fig. 9: Temperature of the battery between charging.

4. CONCLUSION

Based on the result and discussion in this paper, few points could be concluded:

1 With advanced on-board charger, consumers could able to the battery in three modes:
   a. Slow mode: fully charge the battery in 4.3 hours by using 30A current (3 kW).
   b. Medium mode: fully charge the battery in 1.68 hours by using 77A current (7.7 kW).
   c. Fast mode: fully charge the battery in 1.10 hours by 117A current (11.7 kW)

   To charge the electric vehicle faster, the higher current level could be choose and vice versa. The charging power of the proposed charging system is above the conventional Level 2 charging power which is about 6.6 kW.

2 With power supply limitations, the maximum current that the advance on-board charger could supply is about 117A with charging time of 1.10 hours.

3 To further shorthen the charging time, consumers could charge the car up to 60% of the 12.9 kWh capacity and it takes less than one hour to charge. With 60% capacity, the electric vehicle could travel about 40 miles.

4 Closed agreement between the simulated charging time and calculated charging time with maximum of 3.5% different. Fluctuation in the current during simulation give significant effect on the diffferent.

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