JSER

Journal of Solar Energy Research (JSER)

Journal homepage: www.jser.ut.ac.ir

Design, Analysis, and Electrification of a Solar-Powered Electric Vehicle

F. Mohammadi[a]

[a] *Electrical and Computer Engineering Department, University of Windsor, ON N9B 1K3, Canada* **Email:* Fazel@uwindsor.ca,

ARTICLE INFO

Received: 10 Sept 2018
Received in revised form: 02 Dec 2018
Accepted: 05 Dec 2018
Available online: 15 Dec 2018

Keywords:

Battery;
Electric Vehicle;
Inverter;
Solar-Powered Electric Vehicle (SPEV);

ABSTRACT

Nowadays, the automobile industry is moving towards hybridized and fully electric vehicles. The industry has been slowly moving towards this future from decades. Firstly, hybrid and semi-hybrid cars became famous, and now due to the advancements in battery technology, fully electric cars are becoming increasingly popular. Due to the car manufacturers designations, the electric cars have reached the stage of mass production. Many countries such as the U.S., Germany, and France have pledged to reduce the usage of gasoline and diesel cars, and increase the use of electric vehicles due to the diminishing non-renewable resources. In this paper, electrification of an electric vehicle has been performed, in which the solar energy has been used along with the traditional plug-in energy to power the vehicle. The solar energy absorbed from the sun by the solar panel is converted into chemical energy, and stored in batteries. Therefore, the solar-powered electric car can work with an electric motor instead of an Internal Combustion Engine (ICE) to drive the car. Also, the motor can run on AC current which is converted by the inverter from DC current stored in batteries. To drive the car in electric mode, a 360 V Li-polymer battery pack with 100 kWh energy capacity has been proposed to install in the car. Thus, the approach of transforming solar energy into chemical energy, and converting chemical energy to mechanical energy have been applied in this solar-powered electric car. Moreover, the functionality of off-road driving, as well as on-road has been considered. In order to increase/decrease the ground clearance of the car, equipping the car with air suspension system has been investigated.

1. Introduction

The current global transportation technologies are mainly focused on Internal Combustion Engine Powered vehicle that causes to the significant threat to green gas emission. Even though, there are several great movements of the global transportation technology to hybrid fuels and battery electric vehicle. Due to the cost, reliability, and compatibility of the electric vehicles still, customers have not being attracted to the new transportation technologies [1-3]. The main energy resource of Solar-Powered Electric Vehicle (SPEV) is from the sun. The SPEVs can achieve zero pollution. The main advantages of SPEVs are due to using clean energy from the sun, utilizing regenerative braking system to recycle the energy, higher energy efficiency because of less mechanical losses, lower noise in the mechanical system and engine while running, zero-emission and easy implantation, control and fault diagnosis [4]. The SPEV should be equipped with any types of energy storage system. The energy required to run the electric motors is typically stored in rechargeable batteries. Energy storage system such as batteries, fuel cells, and super-capacitors has been identified as an activating technology for transportation electrification and smart grid applications, and battery systems can further have a significant effect on electric vehicles (EVs) and the electric grid. In high-power applications such as EVs and plug-in hybrid EVs (PHEVs), the energy storage system is usually formed by modules/cells connected in series to increase the voltage and connected in parallel to increase the capacitance [5].

There have been many research works performed to generate the whole power needed to drive an electric vehicle by the solar panels or hybridize the electric vehicles to generate a significant portion of the required power by the sun lights. The authors in reference [6] have introduced a custom, light-weighted electric vehicle prototype for partial solar powered and demonstrated the custom energy-efficient electric vehicle prototype and the possibility of a partially solar-powered electric vehicle. Reference [7] dealt with a cost-effective and user-friendly design to investigate the possibility of energy recovery from the solar energy by using the solar panel to power the car. Reference [1] mainly focused on the design of the inbuilt solar system to charge an electric vehicle with considering several features, such as security system, drive guidance system, route detection, android app support, Wi-Fi, battery update etc. The hardware development of the hybrid electric vehicle by using the solar and regenerative braking systems have been discussed in reference [8]. Reference [9] presented a new system architecture which made efficient use of the powered produced by the solar panels used for charging the batteries of the solar-powered electric vehicles. in this design, several electric vehicles may be charged with their own solar panels and the hub, which in turn are charged by a large capacity photovoltaic panels or by the electric grid in case the power provided by the panel is insufficient. Once all the batteries connected to the system reach their certain maximum charge limit, excess energy from the vehicles and the hub is pumped into the grid, thus utilizing the energy that would have otherwise been wasted. In reference [10], the authors have provided details about experimental electric vehicle prototype, which the goal was to build an all-electric power-train prototype with multi-power sources input, and an open computer-based setup to test new power management architecture. Reference [11] has investigated the design considerations related to the plug-in solar electric vehicle to increase the driving range. The authors in reference [12] have analyzed an electrical system for the powertrain of the hybrid electric vehicle which is powered by the fuel cell, battery, and solar panels. Reference [13] presented a method to optimize the on-board energy system of the electric vehicle in the aspect of electro-load characteristics. The proposed power battery system and low voltage energy system have been charged with the on-board charger. The low voltage battery charging was optimized by solar panels to save energy. The objective of this paper is to propose the engineering structure of the low-cost SPEV that would meet the requirements of the global customers. This paper investigates the precise analysis and calculations to electrify of an electric vehicle, in which the solar energy can be used along with the traditional plug-in energy to power the vehicle.

2. Types of Electric Vehicles

The type of electric vehicles depends upon the purpose of the specific electric vehicle that is being designed for. Different electric vehicles serve different purposes. Some electric vehicles may be used for normal daily purposes, while may be used for commercial transportation.

2.1 Start-Stop

In this type of electric vehicles, the engine is stopped when in idle and is started again when needed. This type of implementation saves approximately 2-4% of fuel.

2.2 Mild Hybrid

In the mild hybrid implementation, the engine is stopped when there is deceleration and at all stops. There is also the mild regeneration of energy when the brakes are applied. This energy is stored on small on-board batteries. Due to the small on-board battery, the initial power assist is also small. This approach saves about 10-15% fuel.

2.3 Full Hybrid

In the full hybrid architecture, the electric motor is used to give an electric launch and pure electric drive at low speeds. Due to this, the internal combustion engine is downsized. There is also the implementation of full regenerative braking. This type of system increases fuel efficiency by 20-35%.

2.4 Plug-In Hybrid

This system is the advanced form of full hybrid electric vehicles. Most of the aspects of this architecture are the same as the full hybrid electric vehicle. In this type, the vehicle can run in both charge depletion mode and charge sustaining mode. During the charge depletion mode, the pure electric drive is used, thus reducing the fuel consumption by 40-60%. While in charge sustaining mode, the fuel consumption is reduced by 20-35%.

2.5 Plug-In Extended Range Vehicle (PERV)

In this type of electric vehicle architecture, the on-board battery is significant in size. This type of vehicle can run on full electric drive mode, even at higher speeds. During the full electric mode, there is no fuel consumption. However, the battery is suitable only for short trips.

2.6 Pure Electric Vehicle

In this type of vehicles, there is no need for an internal combustion engine. The batteries used in this type of vehicle are in large capacity. Typically, batteries ranging from 40 to 100 kWh are used to power these types of electric vehicles.

There are two different architectures that can be used to design and operate the hybrid electric vehicle. The combination of this two architectures may also be used in some cases.

a) Series Hybrid Electric Architecture

As a general definition, a specific architecture is defined as the series when only one mechanical source of power driving the propeller can be identified [14]. In the series hybrid architecture, both the electric module and the fuel module are connected in series with the electric motor. Figure 1 shows the series hybrid electric architecture.

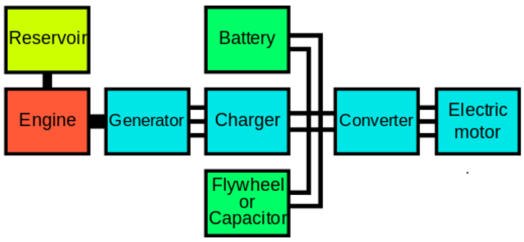

Fig. 1: The series hybrid electric architecture

b) Parallel Hybrid Electric Architecture

An architecture is defined as a parallel when multiple sources of mechanical power are present in the system [14]. In the parallel hybrid architecture, the reservoir and battery are connected in parallel, which means, with the need both energy sources can act individually or in combination to power the motors. Figure 2 shows the parallel hybrid electric architecture.

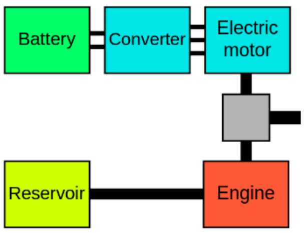

Fig. 2: The parallel hybrid electric architecture

c) Series-Parallel Hybrid Electric Architecture

An architecture is defined to be a series-parallel hybrid electric architecture if the system can choose to operate in series or parallel mode with the requirement of the situation [14]. In this architecture, the design is made to optimize both sources, as they can be used in various combinations as needed by the operational needs of the electric vehicle. Figure 3 shows the series-parallel hybrid electric architecture.

3. Components of SPEVs

There are many critical components required to run the SPEVs. Some of the important components are shown in figure 4. The explanations of each component are given in the following subsections.

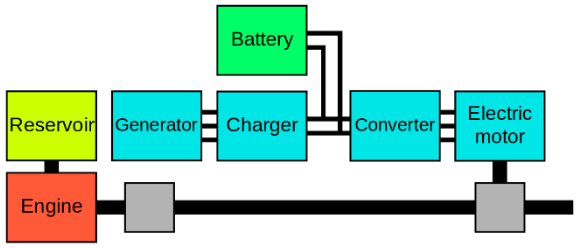

Fig. 3: The series-parallel hybrid electric architecture

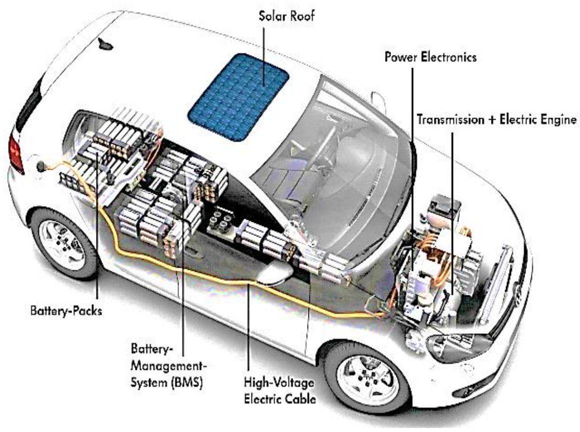

Fig. 4: Components of a SPEV (VW Golf Blue-e-motion) [15]

3.1 Battery-Packs

The batteries used to propel the SPEV are different from the SLI (Starting, Lighting, and Ignition) batteries. The SPEV batteries are designed to give more power to the electric system for a longer period. These batteries are used in charge sustaining mode or charge depletion mode. A SPEV battery-pack is basically a combination of cells connected in parallel and series. The individual cell used in the battery-packs are made from the various anode and cathode materials. The most commonly used batteries are lithium-ion batteries.

3.2 Electric Motor

An electric motor is an electromechanical device that converts electrical energy from the battery into mechanical energy to drive the wheels. The electric motor used in most of the EVs is a 3φ AC induction motor. There are two main parts of an induction motor, a stator, and rotor. The stator consists of several slots in which windings are done with conductor wire. Windings are done in such a manner to produce a 3φ rotating magnetic field when AC supply is connected to them. The rotor of the motor is a cylindrical core with slightly tilted parallel slots for conductors. When an AC supply is given to the stator, a rotating magnetic field is produced in the circuit due to which electromagnetic field (EMF) is induced in the rotor. Due to this, the rotor starts to spin in the same direction as the magnetic field [16].

3.3 Motor Controller

A motor controller is the control system which governs the electric vehicles. Its main function is to provide power to the motor at any given time. It also monitors and regulates the performance of vehicles motor, battery-packs, operator and etc. The motor controller helps achieve the desired efficiency of EV by regulating the performance aspects of the battery and motor [17].

3.4 Inverter

The inverter is a power electronics device that converts electricity from DC, stored in the battery, to AC which is then used to run the AC electric motor. It also automatically matches voltages to feed into the main control circuit.

3.5 Solar Panel

The solar panel is a combination of smaller modules known as solar cells. The solar cells can use the photovoltaic (PV) effect to produce electricity from sunlight. The energy conversion in the solar cells takes place in two steps. Firstly, when the sunlight is shed on the PV cells, light is absorbed by the semiconductor the material of cell and an electron-hole pair is generated. Electricity is generated when electron and hole are separated. The electron goes to the positive electrode and the hole goes to the negative electrode. Most of the PV cells use semiconductor material in p-n junction form [18].

3.6 On-board Charging System

This system is used to charge the battery of the vehicle. The plug-in source of electricity is connected to this system to charge the batteries quickly and efficiently.

1. Operational Characteristics of SPEVs

The electric vehicle with the energy source of the battery as well as the solar cell can play a vital role when it comes to its output power and efficiency. The battery which is a storage device uses an electrochemical reaction between anode and cathode to produce energy and the energy is stored in chemical form. Whereas, solar cell produces energy from sunlight photons. The solar cells convert solar energy through the PV system into electricity. These units can be configured into parallel, series, or both, to produce more efficient capacity. The main characteristics of these cells can be sorted out as below.

4.1. Discharge Curve

Battery cells are developed for a wide range of applications. It uses a variety of technology which results in many available performing characteristics. The graph in figure 5 shows typical discharge curves of a Li-ion battery, from fully charged to fully discharged condition [19]. The temperature of the cell, the magnitude, and direction of the current are the main factors which determine the closed-circuit voltage. Thus, it can be expressed as a discharge voltage as:

$$V_d = E - R_d I_d \quad (1)$$

Also, during the charging process, the charge voltage can be expressed as:

$$V_c = E - R_c I_c \quad (2)$$

where E, V_d, and V_c are the cell voltage, discharge voltage and charge voltage, respectively. The R and I represent the internal resistant and the current in the battery, and d and c indices are used to indicate the discharge and charge processes.

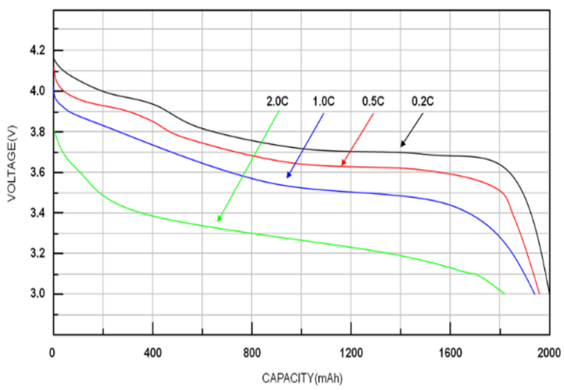

Fig. 5: The Li-ion battery performance characteristics to nominal voltage and discharge capacity

4.2 Nominal Capacity of the Battery

The quality of electricity carried out determines the cell capacity during discharge until it reaches the desired voltage of discharge as:

$$C_d = I_d T_d \quad (3)$$

Equation 3 describes the total ampere hours available for battery discharge at a discharge current or C-rate which is derived from the 100% charged state to the cut-off voltage. C_d, I_d, and T_d represent the discharging capacity, current, and duration of the discharge process, respectively.

4.3 Energy of the Battery

It is the energy capacity or the watt-hours available when the battery gets discharged at some C-rate from 100% to the cut-off voltage.

$$E_d = V_d I_d T_d \quad (4)$$

where E_d indicates the energy of the battery during the discharge process.

4.4 Power of the Battery

The power of the battery, P, is defined as energy per unit time in hours. It is expressed as:

$$P = V_d I_d \quad (5)$$

5. Engineering Design and Electrification of the SPEV

In practical projects, Lithium iron phosphate batteries, with C_6 at the anode and $LiFePO_4$ at the cathode, are being used in SPEV. The Lithium iron phosphate batteries have high energy density as compared to other alternative battery technologies such as NiMH or Lead acid batteries. The self-discharge is much lower as compared to other battery technologies. Due to this, they can sustain charges for a longer period. The weight is a considering factor when deciding the battery type to be used in an electrical vehicle. The weight to energy ratio of the Lithium iron phosphate battery is greater than any other type of battery. The electrolytes in these batteries are in Gel form rather than the liquid form. That can make the packing process simpler, and thus, reducing the overall weight of the battery pack [20].

Chemical reaction at anode during charge/discharge:

$$C_6 + Li^+ + e^- \leftrightarrow LiC_6 \quad (6)$$

Chemical reaction at cathode during charge/discharge:

$$LiFePO_4 \leftrightarrow PO_4 + Li^+ + e^- \quad (7)$$

Overall chemical reaction:

$$C_6 + LiFePO_4 \leftrightarrow LiC_6 + FePO_4 \quad (8)$$

The SPEVs charging strategy can be divided into two major ways. The *centralized charging strategy* which its main idea is to use the centralized infrastructure to gather information from all SPEVs, and centrally optimized SPEVs charging considering the grid technical constraint. Its master controller decides on the rate and duration for the individual SPEVs charge. The second strategy for charging SPEVs is the *decentralized charging strategy* that the vehicle owners are in direct control of their SPEVs charging in response to the decentralized system to schedule the electric vehicle charging to minimize the peak electric load. In this, the optimization is achieved to minimize the price charging by choosing the time when electricity is cheapest [21]. This type of electric vehicle has the capability to charge from the following sources:

- *SPEV charging stations*
- *Solar panels*

The main charging takes place from the plug-in electric vehicle charging stations. As these stations have the capacity to charge the electric vehicles in less time. The solar panel provides the secondary source of charging. The charging by solar panels is slow, due to the smaller surface area on the roof of the SPEV. Thus, it mainly functions as the range extender. The energy extracted by the SPEVs is stored in the form of chemical energy in the batteries. The energy from solar panels along with the energy form plug-in charging is then utilized by the vehicles electric motors via the motor controller. The charging of the battery is managed by the charge controller. It should be noted that the SPEV charging controller sends plug-in charging and solar panel charging to the battery. After that, the motor controller transmits the stored energy to vehicles electric motor and other essential components.

The charging controller for the SPEVs has an additional input which is the plug-in or AC power supply for charging the vehicle. During bad weather and climate, the solar panels alone can not charge the electric vehicle. Therefore, an alternative plug-in charging system is required to charge the batteries with a conventional AC power supply for increasing the overall utilization.

Furthermore, the motor controller is used to control the speed of rotation of the motor and give direction to its rotation which in turn is used for forwarding and reversing the motion of the wheels. The air suspension is added to provide extra ground clearance during the off-road trips. As per the safety concern, the air suspension is more efficient and safer than other coil spring suspension. This air suspension can work by filling the air with its diaphragm. The amount of air in the diaphragm decides the height of the air suspension which indirectly can be used for increasing and decreasing the clearance of the vehicle body.

In order to find the theoretical and practical specific energy of the battery, the overall chemical reaction is needed. With considering the overall chemical reaction (equation 8), and determine whether the chemical reaction would tend to proceed in the forward or reverse direction, ΔG° should be calculated as follow:

$$\Delta G = -nF\Delta E \quad (9)$$

where ΔG is the Gibbs free energy change, n is the number of electron exchange in the reaction, F is the Faraday's constant and E is the cell voltage. With considering 3.6V as the cell voltage, ΔG equals to -96.48 Wh/mole. In order to calculate the bill of materials for Graphite || Lithium iron phosphate cell, one-mole of the cathode and six moles of Carbon are required to obtain one-mole electron equivalent. Due to the atomic mass of each component in the chemical reaction, the weight of reactants equals to 72 g of C_6 and 158 g of $LiFePO_4$. As a result, for each cell, the total mass of active materials would be 230 g.

$$\text{Theoretical Specific Energy} = \frac{-\Delta G}{\sum M} \quad (10)$$

where M is the total mass of active materials. Therefore, the theoretical specific energy is equal to 419.5 Wh/kg. With regards to the inactive weight fraction losses (~50%) and voltage losses (5-10%) and also 85-95% efficiency due to high utilizing of active materials, the practical specific energy of the active materials would be 155-195 Wh/kg.

Due to the added off-road capability, the SPEV needs to consume about 250 Wh/km. With the desired range of 400 km, SPEV requires a 100 kWh battery-pack with 360 V. Accordingly, it needs 18650 battery cells with 3Ah capacity at 3.6V. Hence, the energy of one cell, the total number of cells, the number of cells in series and the number of cells in parallel are 10.8 Wh, 9,260 cells, 100 cells, 93 cells respectively. Thus, by determining the battery-pack configuration, the SPEV meets the expected operational requirements.

6. Conclusions

The Solar-Powered Electric Vehicle (SPEV) with off-road capabilities designed in this paper is a good example of using renewable energy resources to reduce the impact of pollution created by fossil fuels. Utilizing solar panels to generate electricity for use in the SPEV not only acts as the range extender but also reduces the carbon footprint. Solely, relying on solar energy to power the electric vehicle has many limitations such as limited range and power capabilities. Thus, the ability to charge the vehicle from plug-in AC source has been also provided. The capability to adjust the ground clearance of the vehicle with the help of air suspension provides the car with off-road capabilities.

References

[1] S. Manivannan, and E. Kaleeswaran, "Solar Powered Electric Vehicle," First International Conference on Sustainable Green Buildings and Communities (SGBC), Dec. 2016.

[2] F. Mohammadi, "Electric Vehicle Battery Market Analysis: Lead Acid," 9th Iranian Conference on Electrical and Electronics Engineering (ICEEE), Sep. 2018.

[3] F. Mohammadi, "Electric Vehicle Battery Market Analysis: Nickel Metal Hydride," 9th Iranian Conference on Electrical and Electronics Engineering (ICEEE), Sep. 2018.

[4] J. Qian, Z. Zhong, "Simulation Analysis for Steering Mechanism of Solar-Powered Electric Vehicle," International Conference of Information Science and Management Engineering (ISME), Aug. 2010.

[5] C. Duan, C. Wang, Z. Li, J. Chen, S. Wang, A. Snyder, and C. Jiang, "A Solar Power-Assisted Battery Balancing System for Electric Vehicles," IEEE Transactions on Transportation Electrification, Vol.4, March 2018.

[6] J. Kim, D. Baek, J. Hong, and N. Chang, "Partially Solar Powered Full Electric Vehicles," IEEE 57th International Midwest Symposium on Circuits and Systems (MWSCAS), Aug. 2014.

[7] F. Ashrafee, S. Morsalin, and A. Rezwan, "Design and Fabrication of a Solar Powered Toy Car," International Conference on Electrical Engineering and Information and Communication Technology, April. 2014.

[8] A. Goel, V. Rajput, S. Bajaj, R. Mittal, A. Dube, and Ruchika, "Solar Hybrid Electric Vehicle - A Green Vehicle for Future Impulse," 3rd International Conference on Computing for Sustainable Global Development (INDIACom), March 2016.

[9] S. Sadagopan, S. Banerji, P. Vedula, M. Shabin, and C. Bharatiraja, "A Solar Power System for Electric Vehicles with Maximum Power Point Tracking for Novel Energy Sharing," Texas Instruments India Educators' Conference (TIIEC), April 2014.

[10] C. Mahmoudi, A. Flah, and L. Sbita, "Prototype Design of a Compact Plug-In Solar Electric Vehicle Application for Smart Power Management Architecture," International Conference on Green Energy Conversion Systems (GECS), March 2017.

[11] C. Kanumilli, A. Singh, A. Ganesh, and M. Srinivas, "Plug in Electric Solar Vehicle," Biennial International Conference on Power and Energy Systems: Towards Sustainable Energy (PESTSE), Jan. 2016.

[12] M. S. A. Chowdhury, K. A. Al Mamun, and A. M. Rahman, "Modelling and Simulation of Power System of Battery, Solar and Fuel Cell

Powered Hybrid Electric Vehicle,” 3rd International Conference on Electrical Engineering and Information Communication Technology (ICEEICT), Sep. 2016.
[13] H. Yu, J. Sheng, and Y. Wang, “Optimal Design of Energy System on Electric Vehicle,” IEEE Conference and Expo Transportation Electrification Asia-Pacific (ITEC Asia-Pacific), Sep. 2014
[14] “Aircraft Structures,” waybuilder.net, 2018. [Online]. Available: http://www.waybuilder.net/free-ed/Resources/15-Transportation/Aviation/AircraftStructure.asp?iNum=2, [Accessed: June 2018].
[15] “VW Golf Blue-e-motion - Ausfahrt im Elektro-Golf”, 2013, [Online], Available: https://auto-motor.at/auto-fotos/Auto/Testberichte/VW-Test/VW-Golf-Blue-e-motion-Elektro-Golf/VW-Golf-Blue-e-motion-Ausfahrt-Elektro-Golf-008.html, [Accessed: Nov. 2018].
[16] “Working Principle of Three Phase Induction Motor,” March 2015, [Online], Available: https://www.electrical4u.com/working-principle-of-three-phase-induction-motor, [Accessed: June 2018].
[17] “Important Components of Electric Cars,” August 2013, [Online], Available: https://graduatedegrees.online.njit.edu/resources/msee/msee-articles/6-important-components-of-electric-cars, [Accessed: June 2018].
[18] O. Isabella, A. H. M. Smets, and M. Zeman, “Solar Energy - Fundamentals, Technology, and Systems,” Published by UIT Cambridge Ltd., pp. 83-98, 2014.
[19] “Designing Applications with Li-ion Batteries,” [Online], Available: https://www.richtek.com/battery-management/en/designing-liion.html, [Accessed: June 2018].
[20] “Advantages of Lithium Polymer Battery Packs,” June 2016, [Online], Available: http://www.pmbl.co.uk/blog/advantages-of-lithium-polymer-battery-packs, [Accessed: July 2018].
[21] A. T. Radu, M. Eremia, L. Toma, “Promoting Battery Energy Storage Systems to Support Electric Vehicle Charging Strategies in Smart Grids”, Electric Vehicles International Conference (EV), Oct. 2017.