Simulation of a Hybrid Compressed Air/Li-Ion Battery Energy Storage System for Electric Vehicles

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Abstract

Recently, the importance of using hybrid energy storage system in electric vehicle applications has been increasing because the batteries commonly used as an energy source in these applications have some significant problems such as low lifetime, and high charging time. In this study, a hybrid energy storage system which combines a li-ion battery with a compressed air storage (CAES) system is proposed for electric vehicle applications. The effectiveness of the proposed system is tested on a system whose CAES unit is modeled in Matlab/SIMULINK environment and adapted to the model of li-ion battery through Advanced Vehicle Simulator (ADVISOR). The simulation results show that the proposed hybrid energy storage system provides a remarkable improvement in the State of Charge (SOC) value of battery and, as a result, this can eliminate the problems occurring in electric vehicle applications with only battery.

Key words: Energy storage systems, Compressed air energy, Li-ion battery, Electric vehicles, Advisor model

1. Introduction

Fossil fuels such as natural gas, gasoline, and diesel have been widely used to provide energy to vehicles for many years. However, the running out of fossil resources as well as to the environmental problems related to their wide usage has revealed the need for new energy resources to power vehicles. So far, as an alternative to vehicles powered by fossil fuels, many studies have been conducted on electric vehicles powered by stored energy resources [1 – 4]. In these studies, either a battery or a hybrid storage unit which includes one of ultra-capacitor, flywheel, and compressed air energy storage (CAES) units together with a battery, was used as storage system.

Generally, batteries have the most common usage to store energy in electric vehicle applications [1, 2]. Batteries are storage units with high energy density, and they are used as the main energy source in electric vehicles [5, 6]. However, they bring some disadvantages with themselves such as high charging time, causing serious damage to the environment if disposed and have short lifetime [3, 6]. Another unit used for energy storage in electric vehicles is CAES systems. In recent years, the use of CAES systems in electric vehicles applications has been increasing because they are clean energy sources that can be easily obtained from the atmosphere and does

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not have any environmental damage [7–10]. Today, CAES systems in various applications consist of a carbon- fiber high pressure air tank in which the air can be stored at high pressure.

In this study, a hybrid energy storage system containing a li-ion battery and a CAES system is proposed for the electric vehicle applications. The model of proposed system is obtained by combining the CAES system modeled in Matlab/SIMULINK environment with the li-ion battery model in ADVISOR. The organization of paper is designed as follow: in Section 2, the li-ion battery and compressed air energy sources are described, ADVISOR models are given in Section 3, simulation results are described in Section 4, and finally, the outcomes obtained from the proposed model are revealed in Section 5.

2. Energy Sources

2.1. Li-ion Battery

As mentioned in section 1, batteries are widely used as energy storage devices in electric vehicle applications. In various applications, we face with different types of these devices which convert chemical energy to electrical energy [2, 3, 7]. In this study, a li-ion battery model defined with ESS_LI7_temp in ADVISOR is used as a main energy source in the hybrid energy storage system.

2.2. Compressed Air Energy Storage System

The block diagram of CAES system, which is modeled on Matlab/SIMULINK environment and adapted to ADVISOR, is shown in Fig. 1. The CAES system mainly consists of a high pressure air tank to store air mass, a pneumatic motor working with compressed air to generate rotational mechanical energy and a DC generator to generate electric energy. The stored energy in the high pressure air tank is obtained by increasing the enthalpy of air mass. When running the block of compressed air storage system, the pneumatic motor demands an air mass flow from the air tank by depending the power requirement of electric vehicle. In each step of the simulation, the amount of air mass consumed by pneumatic motor is subtracted from the total air mass in the tank. Therefore, the amount of total air mass assigned as a constant for the tank at the beginning will reduce continuously depending on the amount of air mass demanded by pneumatic motor during the simulation. In this system, the pneumatic motor is coupled to the DC generator. DC generator produces an electric energy as long as it is driven by the pneumatic motor and transfers this energy to the “Power Bus” block.

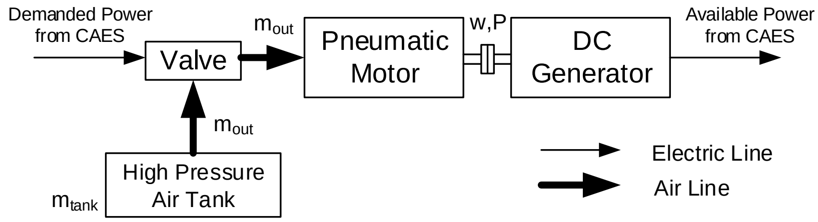

Figure 1. Block diagram of the CAES system.

A vane type pneumatic motor (6AM-FRV) manufactured by Gast Company is used to drive the DC generator. The Simulink model of pneumatic motor is created by using the curves given in the catalog of the pneumatic motor [12]. The pneumatic motor is operated at a constant pressure of 5.6 bars.

The stored air mass in the tank acts as an ideal gas. Combining the law of Boyle-Mariotte and the law of Gay-Lusac, we can obtain the ideal gas equation as given in Eq. 1;

$$P.V = m.R.T \quad (1)$$

where P is the pressure in the tank with value of 300 bars, V is the volume of the tank with value of 300 liters, m is the air mass, T is the absolute temperature, and R is the gas constant value of 286.9 $N.m.kg^{-1}.N^{-1}$. In the ideal gas equation, the values of V, R and T are constant. Thus, the changing values in this equation are only P and m.

In the formulization of the air tank parameters, the tank volume has been kept constant and the heat transfer is neglected. Accordingly, the resulting air tank parameters are given as follow [13];

$$\frac{dE}{dt} = h_o \dot{m}_o \quad (2)$$

$$PV_T = mRT \quad (3)$$

where, h_o and $\dot{m}_o$ are the enthalpy and mass flow, V_T is the volume of the tank, .

3. ADVISOR Model of the System

In this section, we will describe deriving the model of an electric vehicle that is powered by using the proposed hybrid energy sources. This configuration of the hybrid energy sources consists of a li-ion battery pack and a CAES system. The aim of using the CAES system as an energy source in electric vehicles is both to maintain the SOC value of battery and to reduce the size of the battery. The specifications of the modelled electric vehicle are given in Table 1. The electric vehicle has 854 kg weight with a li-ion battery pack. If a CAES system is added to the vehicle as an energy storage source, then the total weight of the vehicle is 920 kg. In this study, weight and power of the battery are not changed. Thus, a comparison can be easily made for both mentioned conditions. The ADVISOR model of the electric vehicle with only a li-ion battery is shown in Fig. 2. The Simulink model of the same vehicle with a hybrid energy sources is shown in Fig. 3.

Table 1. m-files used in ADVISOR

Vehicle	VEH_SMCAR
Energy Storage	ESS_LI7_temp
Motor	MC_PM32evs
Transmission	TX_1SPD
Wheel/Axle	WH_SMCAR
Accessory	ACC_HYBRID
Powertrain Control	PTC_EV

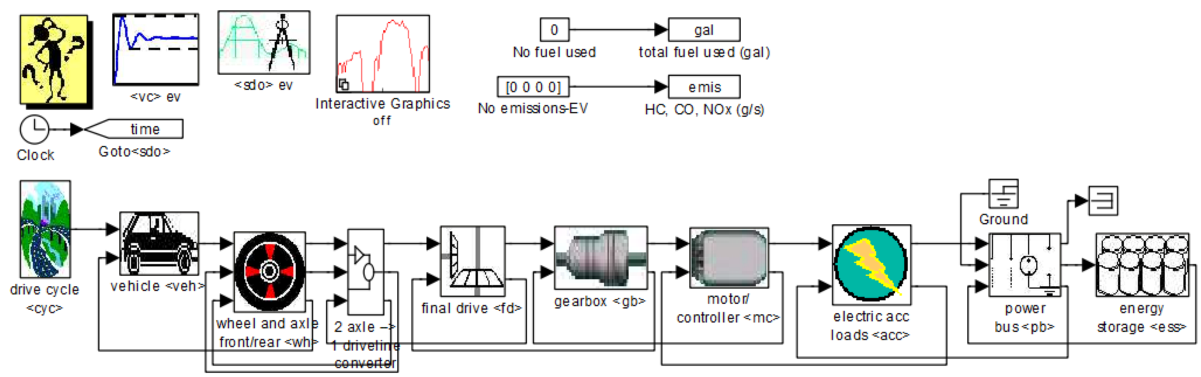

Figure 2. The model of an electric vehicle powered by a li-ion battery pack.

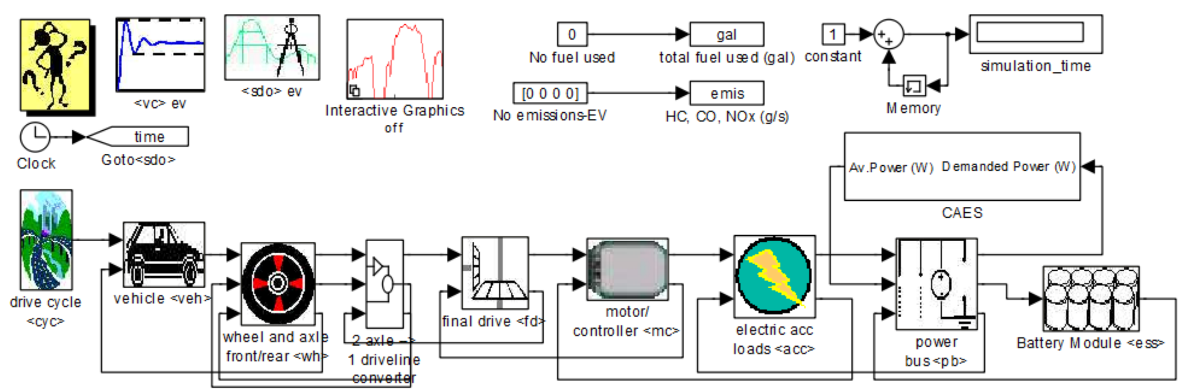

Figure 3. The model of an electric vehicle powered by hybrid energy sources

The structure and operation of ADVISOR are described with its capabilities and limitations in [11]. The arrows in ADVISOR/Simulink blocks indicate the direction of data flow. Where each modeled block forms a part of electric vehicle. First block is the drive cycle block and it contains data related to the driving route. The modeled vehicle fulfills the power demand required for the driving route by using the block operations which is until the energy blocks.

The simulink model of the power bus block is shown in Fig. 4. When an energy demand comes to the power bus block, the demanded power is primarily met from the CAES system block. CAES system block generates a power depending on the demand, and transfer the power to the power bus block. If the power generated by CAES system block meet the demanded power, then it will be transferred backward up to the drive cycle block without using the li-ion battery block. Otherwise, the power that cannot meet by CAES system block will be met by the li-ion battery block. This process is carried out by Sum1 block which uses Eq. 4.

$$P_{dem\_bat} = P_{dem\_total} - P_{av\_caes} \tag{4}$$

where P_{dem_bat} is the power demanded from the battery block, P_{dem_total} is total power demanded by the vehicle from the energy sources, and P_{av_caes} is the power generated by the CAES system block, respectively. The energy generated by each energy source is calculated by Sum2 block which uses the formulization given in Eq. 5.

$$P_{av\_total} = P_{av\_caes} + P_{av\_bat} \tag{5}$$

where P_{av_total} is the total output power of the power bus block, and P_{av_bat} is available power coming from the battery block. The power generated by two energy source is summed and, then, transferred to output of the power bus block. Therefore, the demanded total power is met by both energy sources.

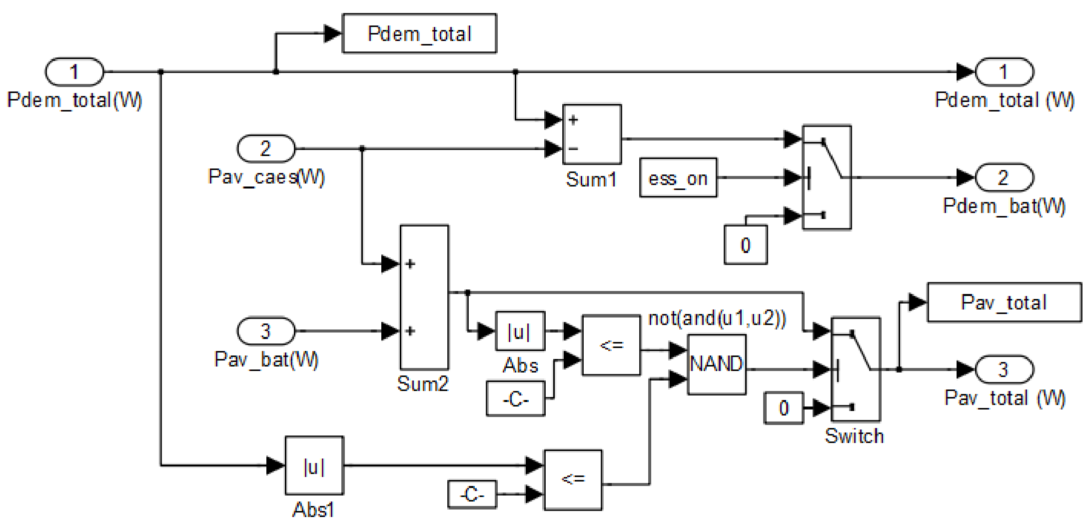

Figure 4. Simulink model of the power bus block

The CAES system generates electric energy by using compressed air as mentioned in Section 2. The Simulink model of the CAES system is shown in Fig. 5. There have been three basic components in this block: a pneumatic motor, a DC generator, and an air tank. In this structure, if a demanded power signal comes to the power bus block, Switch 1 will be active for transferring this power to the system. With activating the switch 1, the demanded power is applied to the pneumatic motor block to generate a power for driving the DC generator. Pneumatic motor performs the power generation by consuming the air mass coming to its own input. Therefore, also, the consumed air mass and the motor speed required for the DC generator block and the air tank block is calculated in this block. In order to calculate the air mass amount remaining in the tank, the consumed air mass which is obtained from the output of pneumatic motor block, is sent to the air tank block. The power and speed signals generated within the pneumatic motor block are applied to the DC generator block. The DC generator generates an electrical power according to these signals. Then, the generated electric power is transferred to the power bus block. As long as the CAES block works actively, the total air mass will reduce in the tank. The Switch 2 in the CAES system block is used to control the air mass in the tank. In the case of running out of air masses in the tank, it stops the power generation by cutting off the transmission signal among blocks.

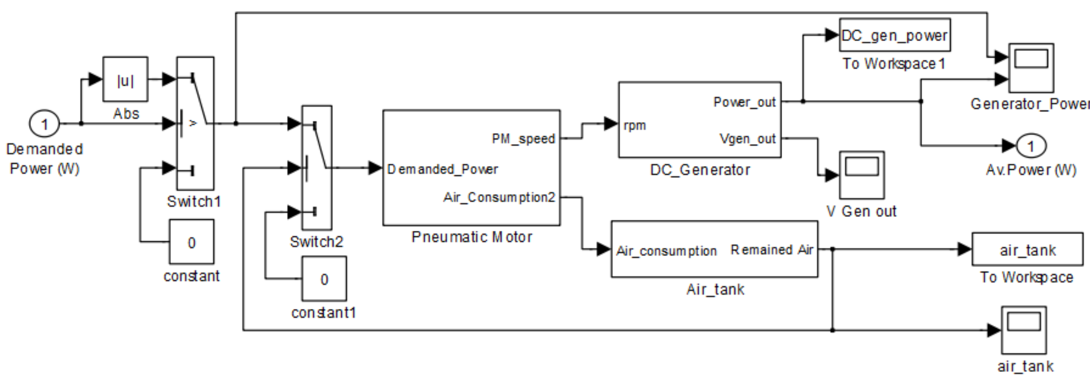

Figure 5. Simulink model of the CAES system

The Simulink model of the pneumatic motor, whose parameters are given in section 2, is shown in Fig. 6. This model consists of three basic components: an air consumption block, a speed block and a power block. The blocks are formed with the pre-lookup table blocks in Matlab/SIMULINK environment according to the catalog values of the pneumatic motor manufactured by GAST company. Firstly, the demanded power signal is applied as input to the pneumatic motor block. In order to meet the demanded power, the air consumption block calculates the amount of air mass consumption for pneumatic motor and, sends it to the switch block. Depending on the amount of demanded power, the switch block either transfers or don't transfer the amount of consumed air mass to its output. If the demanded power is greater than zero, the air mass calculated for pneumatic motor will be transferred to the output of switch block. Otherwise, it will not be transferred. The air mass consumption in the output of the switch block is sent to both the air tank block and the speed calculator block of pneumatic motor. The speed calculator block calculates the speed of pneumatic motor by using the amount of incoming air consumption and sends it to the DC generator block.

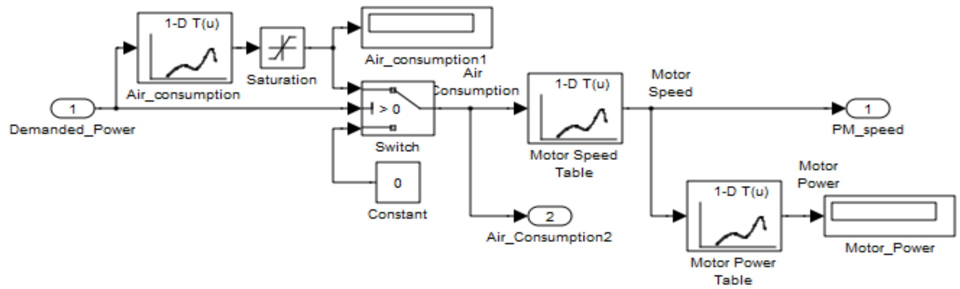

Figure 6. Simulink model of the pneumatic motor

The Simulink model of the air tank is shown in Fig. 7. The block uses the adder, subtracter and memory components to calculate the total air mass consumed from the tank and the air mass remaining in the tank. The total air mass consumption is obtained by adding the air mass consumed by pneumatic motor to the previous value of total air mass consumption, as shown in the simulink model of air tank. Where the previous value of total air mass consumption is achieved by a memory component. The amount of air mass remaining in the tank is calculated by taking the difference between the total air mass consumption and the tank air mass defined as a constant at the beginning. Then, this signal is sent to the related block through the output 1.

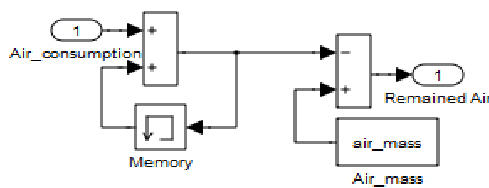

Figure 7. Simulink model of the air tank

4. Simulation Results

Simulations of the electric vehicle with the hybrid CAES / li-ion battery energy storage system are performed using UDDS driving cycle which is defined in ADVISOR. Specific characteristics of UDDS drive cycle is given in Table 2 and, the changes in speed reference for this cycle is shown in Fig. 8, respectively.

Table 2. Specific characteristics of UDDS drive cycle

Time (s)	1369
Distance (km)	11.99
Max. Speed (km/h)	91.25
Avg. Speed (km/h)	31.51
Max. acceleration (m/s^2)	1.48
Max. deceleration (m/s^2)	-1.48
Avg. acceleration (m/s^2)	0.5
Avg. deceleration (m/s^2)	-0.58
Idle Time (s)	259

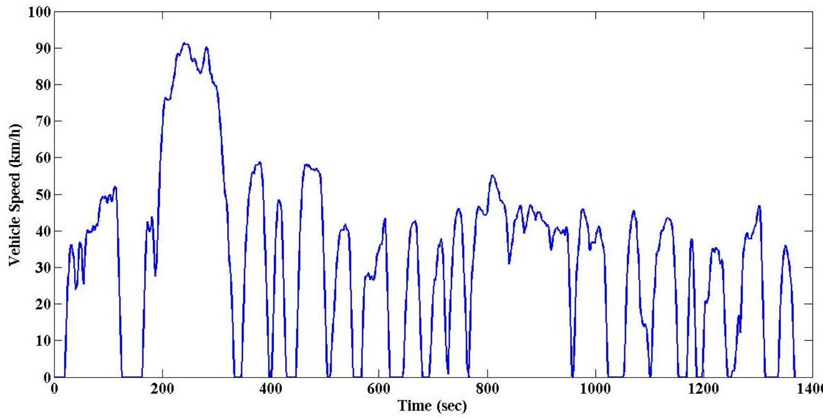

Figure 8. UDDS urban driving cycle

The simulations are individually realized for the model of electric vehicles that work with both a battery and a hybrid battery / CAES system. The model of the electric vehicles powered by both energy sources was tested in UDDS driving cycle. Some of the data obtained from simulations is used to determine the SOC value of battery.

The demanded power curve for UDDS driving cycle is shown in Fig. 9 and, the changes in battery SOC value for the same driving cycle is indicated in Fig. 10, respectively. When the vehicle runs with only li-ion battery, the SOC value of battery is obtained as 0.2582. In the case of running with the hybrid battery / CAES system of the same vehicle, the battery SOC value is achieved as 0.5533. These results show us that the battery SOC value will be maintained within the desired limits by adding the CAES system to the electric vehicle with only li-ion battery.

The changing curve of free air mass in the tank is shown in Fig. 11. The free air mass of 90000 liters in the air tank, at the beginning of the simulation, falls to 36351 liters at the end of the simulation. The discharge time of air mass in the tank changes depending on the amount of power demanded by pneumatic motor.

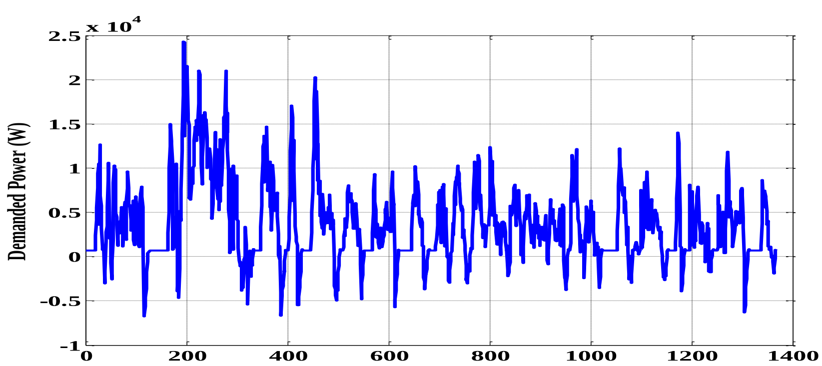

Figure 9. Demanded power for UDDS driving cycle

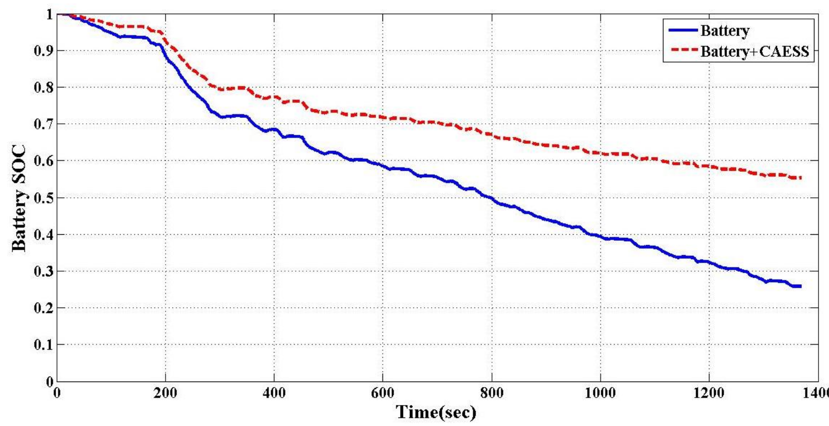

Figure 10. Changes in the battery SOC value for UDDS urban driving

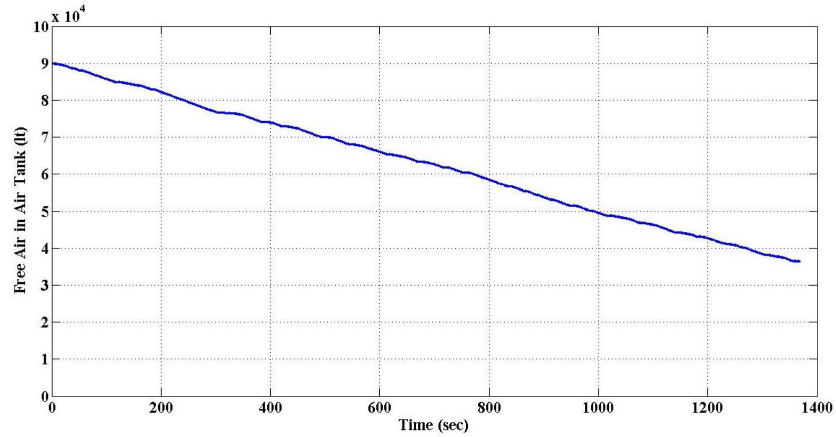

Figure 11. Changes of the free air in the air tank for UDDS drive cycle

5. Conclusion

In this study, a hybrid energy storage system including a battery and a CAES system for electric vehicle applications was modeled by using Matlab/SIMULINK and ADVISOR environments and, the simulation studies were performed on the modeled system. While the battery in this structure was used as a main energy source, the CAES system was used as an auxiliary energy source. In the simulation studies, the performance of hybrid energy storage system was evaluated comparing with an electric vehicle with only li-ion battery. The UDDS driving cycle defined in ADVISOR environment was used as a driving route for the model of both electric vehicles. The simulation results showed that the hybrid energy storage system improves the SOC value of battery from 0.2582 to 0.5533 for UDDS driving cycle. As a result, adding a CAES system to an electric vehicle with only a battery: (1) increases the distance to which the vehicle can go, (2) improves the SOC value of the battery and (3) provides to store the energy more quickly.

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