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Analysis And Simulation of Hybrid Electric Energy Storage (HEES) Systems for High Power Applications

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Abstract

At recent years, using hybrid energy storage systems has become a global solution to supply continuous, reliable and clean energy to power electronic devices. By using these technologies, many advantages of energy storage systems can be combined properly and an adequate energy supply for specific applications is achievable. In today's world, there is a continuous global need for more energy which, at the same time, has to be cleaner than the energy produced from the traditional generation technologies. This need has facilitated the increasing penetration of distributed generation technologies and primarily of renewable energy sources.
In addition, by maturating renewable energy sources and technologies around it, providing a significant part of the total energy generation, requiring fewer costs with cleaner characteristics for environment, has become possible. The extensive use of such energy sources in today's electricity networks can indisputably minimize the threat of global warming and climate change. There are many advantages in using renewable energy sources alongside with the energy generated by fossil fuels which is discussed in this article. This work also discusses different types of energy storage devices and studies the advantages and disadvantages of these devices. Then different types of renewable energy sources and their role in in hybrid energy systems will be analyzed and noted. Some energy storage systems are modeled and simulated. Required power electronic circuits in hybrid storage systems will be introduced. At the end, some practical examples of hybrid energy systems (such as Battery-Supercapacitor) are presented, modeled and simulated.

Introduction

Continuous and reliable electric power supply is important for power systems. Sometimes, unwilling outages or using an energy source with low reliability can be harmful for electrical systems. Due to incremental fuel cost, shortage of reliability in power sources, increasing demand, and inappropriate effects of fossil fuels on environment, demands for using renewable energy sources have been increasing [1], [2]. Power generated by wind turbines and photovoltaic cells is a function of different parameters such as radiation intensity, temperature and wind speed [3]. Compounding renewable energy sources such as wind power with fossil fuels can improve this variety nature to gain controllability of power supply [2].
Hybrid power supply is a system in which different types of energy generation have been connected to energy storage systems supplying the load at any time [1], [4]. In a hybrid power supply system, output power is constant while its input power is generated by different sources. In recent years, using Hybrid Electric Energy Storage (HEES) systems have become more important and different models have been proposed.

This work studies the difference sections of an HEES system and then tries to show how to analyze, model, and simulate the true behavior of hybrid energy storage systems. Different electrical storage systems are compared in Tables 1 and 2 after investigation of energy storage systems. In section 5, some mathematical equations of different storage systems that indicate their behavior are presented and modeled. In section 6, the behavior of HEES systems is investigated by simulation using MATLAB/Simulink. More complicated HEES systems such as battery/flywheel/supercapacitor hybrid system will be our future work.

Purpose of Hybrid Electric Energy Storage Systems

The main purpose of a hybrid system is to achieve a controlled output power while its energy sources happen to be accidental. Sometimes to increase the availability of hybrid energy sources, using auxiliary power sources such as diesel generator and fuel cell would be possible. In Fig. 1, a hybrid system is shown in which a renewable energy along with an auxiliary power source has been used. A DC/DC converter controls the output power [2]. This kind of converters is designed in order to operate in maximum power ranges. This method decreases the costs of the system.

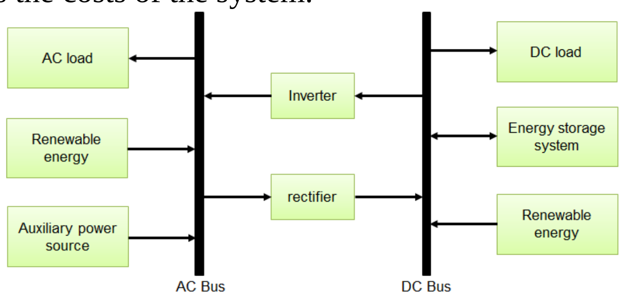

Figure 1. An example of hybrid electric energy system

A. Economic Aspect of Hybrid Electric Energy Systems

Using a hybrid electric energy system can lower the costs of consumed energy; also increase the reliability and control of the system. A wind/photovoltaic hybrid energy system can be the best option for isolated places [4]. Sometimes due to high costs of required equipment or administrative costs, supplying the power from main network is more economic [5].

B. Application of Hybrid Energy in Power Systems

Here are some main advantages of using hybrid electric energy sources in the power systems:

- Spinning reserve, for instant support of the generation unit, unifies load profile and avoids the system from effects caused by dynamic responses of the generation unit.
- Voltage regulation for generation units which are off-grid
- Frequency stability
- Procrastination capacity of an installing generation unit

Energy Storage Sources

Thermal energy, compressed air energy, hydro pump, chemical battery, supercapacitor, magnetic super conductor, flywheel and fuel cell are the most important technologies for storing energy. Performance indexes of an energy storage system are including main costs, cycle efficiency, life cycle, self-discharging rate, power density and energy density [10]. The role of these systems in HEES is to store the energy provided either by a renewable energy source of by any other kind of fossil fuel.

A. Chemical Battery

Chemical battery stores electrical energy in the form of chemical potential energy. Batteries have some advantages such as high energy density, low self-discharging rate, low main cost, long lifetime and some disadvantages like low power density and high dependency on temperature. An important factor affecting lifetime of batteries is how they are charged [10].

B. Flywheel

Flywheels are unique among the energy storage devices with their ability to supply very high power. In fact, the rate at which energy can be recharged into or drawn out of the flywheels is limited only by the motor-generator design and can be very high. Flywheels are one of the oldest, simplest, and most common mechanical devices [11]. The main characteristic of a flywheel is that they can store a high mass of energy is a very short period of time, an aspect which batteries lack. So if flywheel is taken into account in a HEES along with battery, system's efficiency and performance can be increased.

C. Supercapacitor

The most direct and literal way of storing electrical energy is with a capacitor. In its simplest form, a capacitor consists of two metal plates separated by a nonconducting layer called a dielectric. When one plate is charged with electricity from a direct-current source, the other plate will have induced in it a charge of the opposite sign. Capacitors can be charged substantially faster than conventional batteries and cycled tens of thousands of times with a high efficiency. Conventional capacitors have been developed for daily peak load in summer for less than one hour with small capacities. However, the main problem presented by conventional capacitors is the low energy density. If a large capacity is required, the area of the dielectric must be very large. This fact makes the use of large capacitors uneconomical and often cumbersome. This is particularly true in stationary HEES applications [12].

D. Fuel Cell

Fuel cell is an electrochemical device that converts chemical energy produced by a chemical reaction to electrical energy. Fuel cell advantages are including high power density, high energy density, high reliability, high efficiency, lack of noise pollution due to lack of mechanical parts, high range of power (mW to MW), ease of maintenance, friendly characteristics for environment and some disadvantages such as long start time and high costs [13].

E. Comparison of Different Energy Storage Technologies

Base on application and willing energy stored mass adequate technology must be used. Tab. 1 compares four energy storage devices used in hybrid energy systems [14].

Table 1. Comparison of four energy storage devices in hybrid energy systems

Charact eristics	***Battery***	***Flywhe el***	***Superca pacitor***	***Fuel cell***
Power density (w/kg)	To 400	1-200	1-10	Differen t
Energy Density (wh/kg)	To 650	100-900	1-5	Differen t
Lifetime (cycle)	To 1000	10000	100000	Differen t
Self-Dischar	Up to 30% in	Low	50% in month	Not possible

ging rate	month

Hybridization of Energy Storage Technologies

The main purpose of a hybrid energy system is to achieve a power source with both high power density and high energy density. With hybridization of different energy storage technologies, one can have all advantages of them together and increase the system's reliability and optimization. A hybrid energy system should be carried out for some special applications such as operating regenerative braking energy in electric vehicles or metros, because an energy storage source with high power density and high energy density is required. Tab. 2 compares these parameters [13].

Table 2. Qualitative comparison of energy storage devices

Device	***Specific energy***	***Specific power***
Chemical battery	high	low
Ultra-capacitor	low	high
Flywheel	low	high
Fuel cell	high	high

A. Load's States

In an electric system, loads are required to have either high power, or low power. As it is shown in Fig. 3, when load needs low power, the source with high energy density is on top of priorities. When load needs high power, both sources supply the load together. In some special applications such as absorbing regenerative braking energy in metros, regenerative braking energy first stores in the storage device with high power density and then it is delivered to storage devices with high energy density [12], [13].

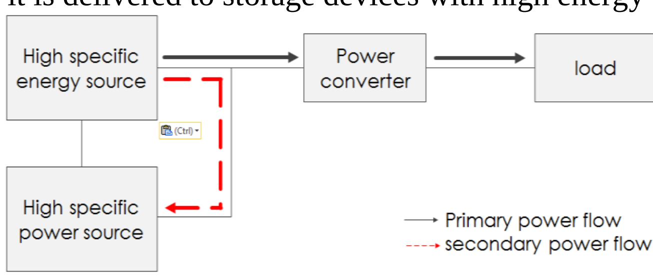

Figure 2. Configuration of a hybrid system when load requires low power

B. Battery / Supercapacitor Hybrid System

Battery has high energy density whereas supercapacitor has high power density. It is possible to have energy source with high power density and high energy density combining battery and supercapacitor. Connections of battery and supercapacitor are including non-active connection or direct connection and active connection or controlled connection. In non-active connection, battery and supercapacitor are connected in parallel without any control unit. In non-active connection, supercapacitors limit the highest value of drawn current from the battery. In this structure, when the load is connected to hybrid source, initial response to load's current is carried out by capacitors and then due to their voltage drop, load's current in supplied slowly by batteries. Using a DC/DC converter, can stop power flow between sources and causes capacitor's power to become usable completely. In active or controlled connection, according to control circuits, the control unit sets how sources supply the loads [15].

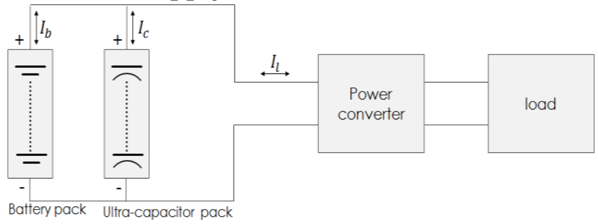

Figure 3. Non-active connection of battery / supercapacitor

C. Flywheel / Supercapacitor Hybrid System

Since flywheel's behavior is similar to batteries, one can replace them with batteries in previous structure to achieve a flywheel/supercapacitor hybrid source as shown in Fig. 4 [16]. Like previous structure, a flywheel/supercapacitor hybrid system includes two kinds of active and non-active. The main advantages of this system are high temperature compatibility and low maintenance. These characteristics are very important for military vehicles [17].

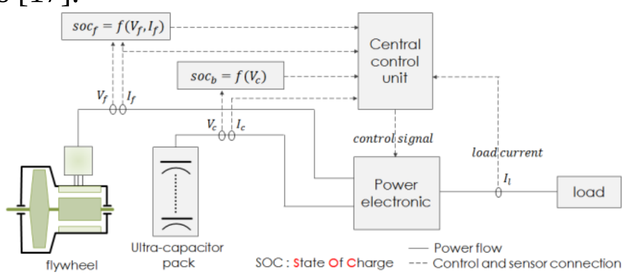

Figure 4. Active connection of flywheel / supercapacitor hybrid system

Energy Storage Systems Modelling

A. Battery Modeling

Equivalent circuit for a typical battery is shown in Fig. 5:

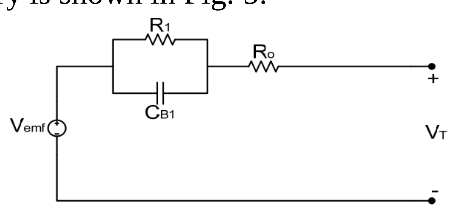

Figure 5. Equivalent circuit of battery consisting capacitor and resistance

Where parameters are calculated by:

$$SOC = SOC_{t_0} - \int_{t_0}^{t} i_t(t)dt \quad (1)$$

$$v_{emf} = v_{emf_{\min}} + k_e \times SOC \quad (2)$$

Dynamic modeling of a battery is shown in Fig. 6. According to Equations. 1 and 2. when initial charge level of capacitor reaches 30%, dynamic response of battery is found accordingly.

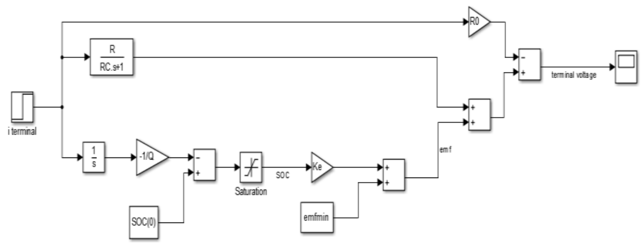

Figure 6. Dynamic model of battery in Simulink/MATLAB

Figs. 7 and 8 show the results of the simulation:

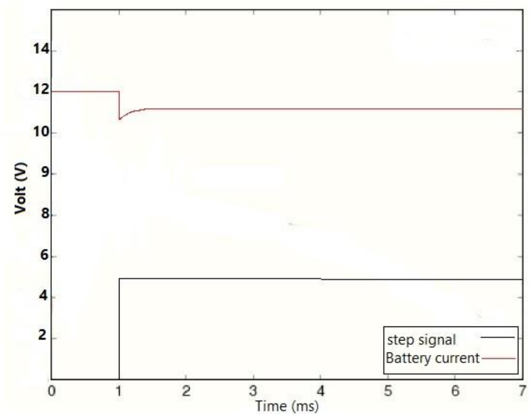

Figure 7. Battery voltage changes for a 5A step output current

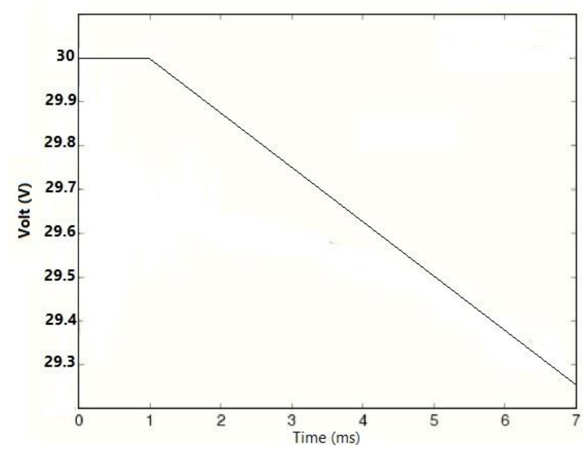

Figure 8. Battery state of charge (SOC) changes

B. Flywheel Modeling

The flywheel has to work as a fast-response energy storage device. In short-time duty operation, the flywheel can operate with 2 to 5 times of rated power. Accelerating and decelerating in a short period of time is a requirement; therefore fast torque control and minimizing axial-force stress as well as losses on mechanical bearings are the main concerns. In order that the flywheel can work with a current as small as possible in steady state hence reducing flywheel device's idling losses, permanent magnets mounted on upper and lower rotors are carefully designed by FEM. Static axial force generated by rotors' permanent magnets is nearly equal to flywheel's weight. The flywheel achieves partially-self levitation by static axial force from permanent magnets while dynamic axial variation is regulated by d-axis current. The Simulink model of a flywheel energy storage system is shown in Fig. 9.

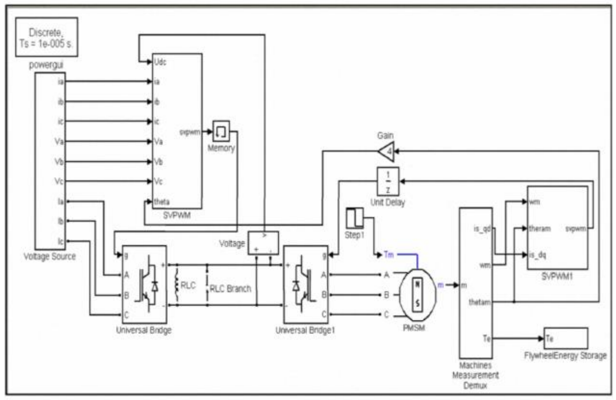

Figure 9. The flywheel model in Matlab/Simulink

The rotational energy stored in the flywheel is defined as:

$$E_{(rot)} = \frac{1}{2} I \omega^2 \quad (3)$$

Where I is the moment of inertia that is directly proportional to the mass of the rotor by means of a constant that depends on the shape factor. ω is the angular velocity. For a cylinder flywheel, the moment of inertia is dominated by [19]:

$$I = \frac{1}{2} \pi h \rho (r_0^4 - r_i^4) \quad (4)$$

Where the outer diameter and inner diameter are represented by r_0 and r_i, respectively. h is length and ρ is mass density. Thus:

$$E = \frac{1}{4} \pi h \rho \omega^2 (r_0^4 - r_i^4) \quad (5)$$

The energy scales as ω^2. The flywheel with a larger angular velocity can store much more energy. But a small and light flywheel is preferable because it can operate at high stress levels.

C Supercapacitor Modeling

Supercapacitor behavior is something between battery and flywheel. Capacity of a typical capacitor is given by:

$$C = \varepsilon \frac{A}{d} \quad (6)$$

Fig. 10 shows a more detailed model of a supercapacitor. In this model parallel electronic resistor indicates self-discharging rate.

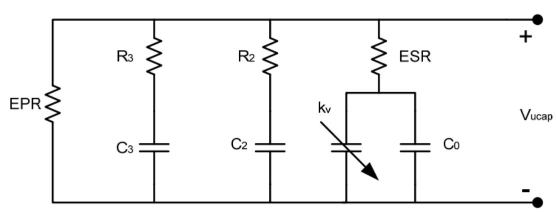

Figure 10. Detailed equal circuit of a supercapacitor

Following equations indicate parameters' values for a model with three branches:

$$ESR = \frac{\Delta v}{\Delta i} \quad (7)$$

$$C_O = \left(\frac{v_1}{i_1} - \frac{v_1 t_2 - t_1 v_2}{v_2^2 - v_1 v_2}\right) I_C \quad (8)$$

$$K_v = 2(\frac{v_1 t_2 - t_1 v_2}{v_2^2 - v_1 v_2}) I_C \quad (9)$$

$$C_2 = \frac{I_C t_c}{v_{2f}} - (C_O + \frac{k_v v_{2f}}{2}) v_{2f} \quad (10)$$

$$R_2 = \frac{\tau_{C_2}}{C_2} \quad (11)$$

$$EPR = \frac{t_4 - t_3}{\ln(\frac{v_4}{v_3}) C_{ucapr}} \quad (12)$$

Simulation of Hybrid Battery/Supercapacitor System

The behavior of HEES system is studied in this section after learning enough (by reading "help menus" and other tutorials) about how MATAB/Simulink works. Battery and supercapacitor hybrid energy storage has been simulated and results are presented. In addition, battery and flywheel hybrid system is also simulated in MATLAB that isn't presented in this paper due to lack of space. This research follows educational purposes and the results can help other students to learn more about the behavior of HEES systems and continue the future works.

Battery has high energy density whereas supercapacitor has high power density. A hybrid system consisting battery and supercapacitor is an energy storage system that includes both high power density and energy density simultaneously. This hybrid system is a proper option for storing regenerative braking energy in electric vehicles and railways [21]. Energy storage system that stores regenerative braking energy must be able to store a high amount of energy within a few seconds. Supercapacitors have this capability, but have a high rate a self-discharging. This deficit can be solved by using batteries along with supercapacitors. Thus supercapacitor charges the batteries after delivering energy from the braking operation. The main purpose of this simulation is analysis of dynamic behavior of battery and supercapacitor in an energy delivering cycle. In this system battery and supercapacitor can be arranged in different ways which are shown in Fig. 11:

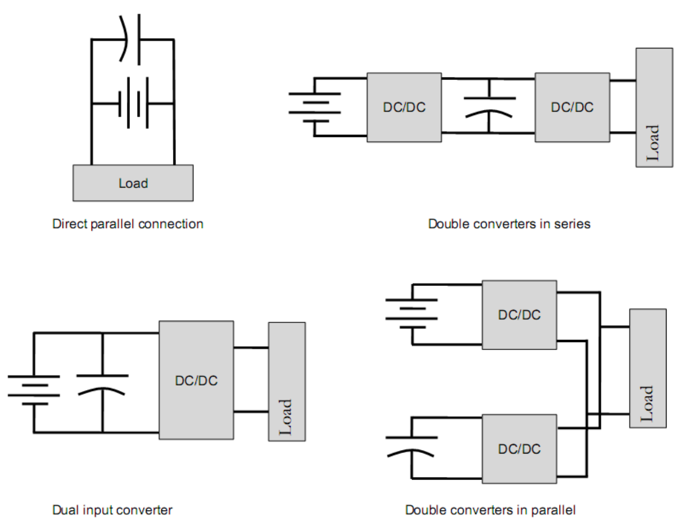

Figure 11. Different configurations of a hybrid battery/supercapacitor system

In this paper a parallel arrangement is chosen. A boost converter and three switching elements are also used.

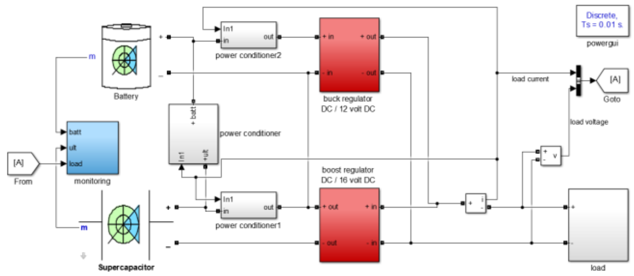

Figure 12. Hybrid battery/supercapacitor system model in Simulink/MATLAB

This system is designed to absorb regenerative braking energy and then deliver it to a constant load, so system strategy is:

- When load's current is negative (energy is flowing into system) battery is disconnected from the load and also battery and supercapacitor must be separated. In this situation only supercapacitor remains in the system to absorb regenerative braking energy.
- When load's current is zero or higher than zero, supercapacitor is disconnected from the load and its energy charges the battery.

A. Control and Energy Management System

A very important need for any HEES system would be a control system that determines which source should supply the load. Power requirements vary widely throughout a drive schedule, with peak demands during acceleration of more than three times the average power output of the whole drive cycle. A HEES system meets average propulsion demands with a high capacity energy system, and peak vehicle demands with a high power system. A control system, or energy management system (EMS) should then allocate average running demand to the energy system and peak demands to the power system.

Most approaches to design an EMS system consider inputs such as the demand current, SOC of the battery, maximum output of the battery, etc. A simple rule based system will use these inputs to allocate power with logic statements such as:

If demand current > maximum battery current, then battery power = battery maximum and capacitor power = demand - battery maximum

A rule based system is simple and easy to implement, but can result in discontinuities when inputs cross boundary values. Fuzzy logic control offers a similar, but more stable approach. A fuzzy based system sorts input values into overlapping categories with membership functions. By example, vehicle speed may lie on a range of slow to fast, but a value in between slow and fast may have a membership value of 30% fast, 70% slow. A fuzzy rule based evaluates logical statements based on the inputs in a similar fashion to a simple rule based. Output of the rule based lies on a similar sliding scale to the inputs, returning one or more results. When multiple results are returned, an amalgamation is made to deliver the final result. The method can be thought of as a way to generate a smoothly transitioned piece-wise output function of the input parameters. The output function is tolerant of error or rapid change of inputs. Fuzzy logic controllers are very well suited to EMS, but require much trial and error to implement well. Fig. 13 shows the EMS and control system of the proposed HEES system.

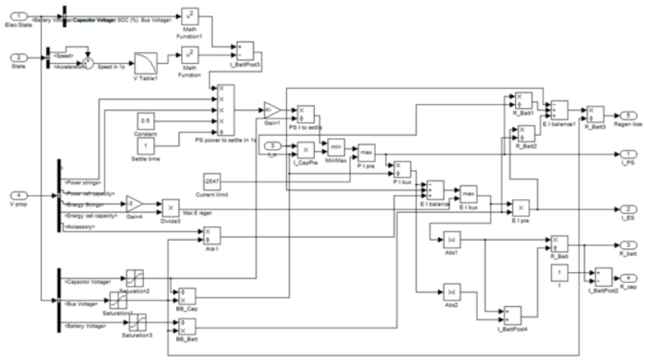

Figure 13. Control system of the proposed HEES

B. Simulation Results

The simulations results are shown in Figs. 14-16. Load's current is zero until 15 seconds and supercapacitor's energy discharges in battery. From the second of 15 to 19 (4 seconds) load's current is -15A that must be absorbed by supercapacitor. After the second of 22, a constant 3A load stands on the system.

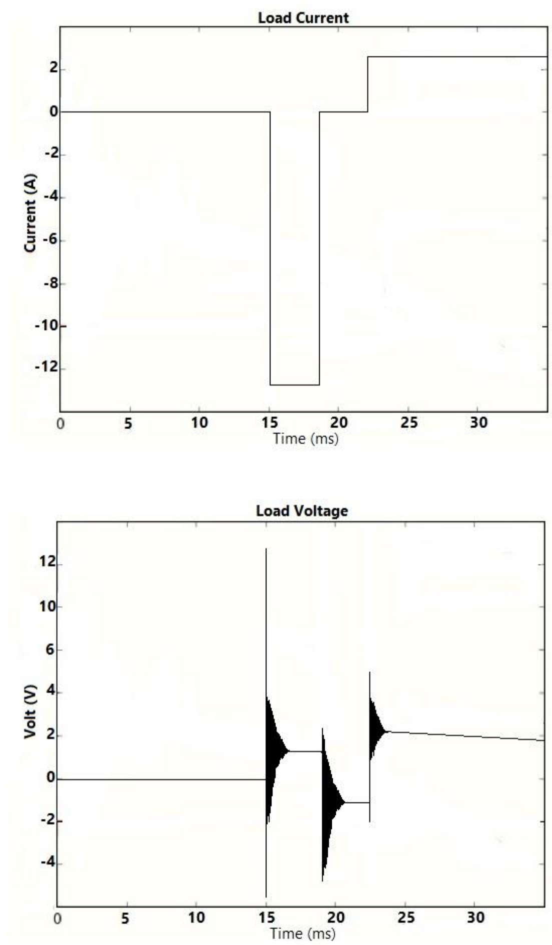

Figure 14 . Load current and voltage changes

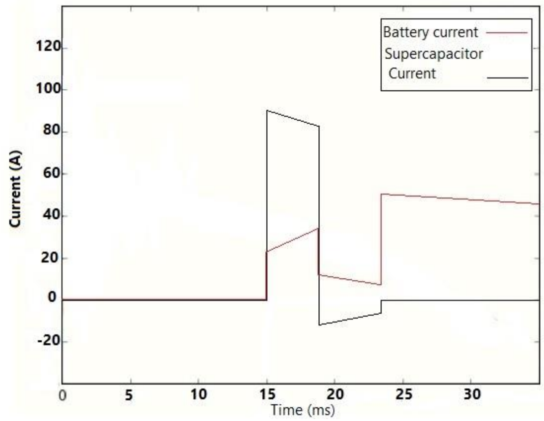

Figure 15 . battery and supercapacitor current changes

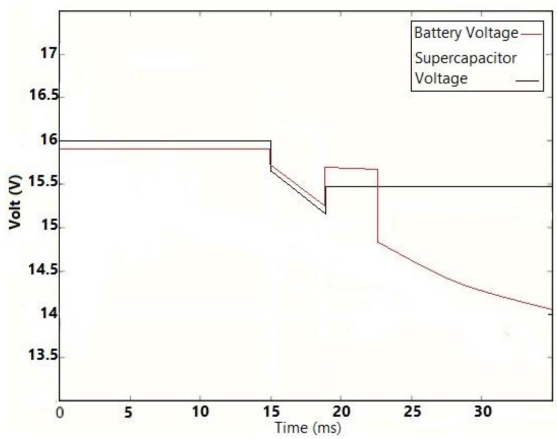

Figure 16. Battery and supercapacitor output voltage changes

Conclusion

In this paper behavior of hybrid energy storage systems was learned and investigated. This paper has educational purposes and helps for the future work to have a better understanding about Hybrid Electric Energy Storage (HEES) systems. As an example, a battery/supercapacitor hybrid storage system was simulated in MATLAB/Simulink and results were presented. Results of simulation show more reliable storage system compared to system with only one energy storage system. The future work of the author will be investigation and behavior of the more complicated hybrid storage system, like battery/supercapacitor/flywheel hybrid storage system.

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