Design and Analysis of a standalone DC microgrid with battery and fuel cell energy storage penetration for different load characteristic

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***Abstract*—This paper presents a distributed control system of energy storage device connected with a standalone DC microgrid. The energy storage devices consist two Nickel-Metal-Hydride batteries and a hydrogen fuel cell. Decentralized charge controller has been presented in this paper. The main idea to use decentralized charge control to reduce the bus voltage variation in the microgrid and also to utilize the storage devices optimally. In this model, the storage devices can share the load power equally. To understand and validate the model, resistive and inductive load have been connected to the DC microgrid. The simulation has been done in Matlab/Simulink environment.**

Keywords: DC microgrid, energy storage, power sharing, charge controller.

I. Introduction

The advent of electricity generation had experienced the famous dispute between Thomas Edison, who supported direct current (DC) systems and George Westinghouse, who supported alternating current (AC). The battle is known as “War of Currents”. It is obvious that the AC system had won and has been using broadly in the power system. The main factor behind the success of AC system at that time was the invention of a transformer and the polyphase AC machine[1]. A microgrid can be defined as a local distribution system which consists energy generation, storage system and controllable, uncontrollable loads which are able to operate in grid-connected and standalone modes[2].

An analysis has been done for the energy storage requirement of a DC microgrid system in [3], [4]. In the research work, a distributed droop control system has been introduces to minimize the bus voltage variation and ensure optimal use of storage devices. It is very important to design an energy storage system to implement DC microgrid successfully. An energy management approach has been discussed for an off-grid DC microgrid with supercapacitor penetration [5]. It also shows the dynamic and static characteristic of a DC microgrid. The research works[6], [7][8] focused on the technology, distributed control system and optimization techniques of DC microgrid. A control method has been introduced for DC microgrid with hybrid energy storage penetration which is able to improve the system stability during the operation transition period[9].

A microgrid can consist of different types of loads such as resistive or inductive. The behavior of the loads is not same. A control strategy has been introduced to control a virtual DC machine connected to dc microgrid with energy storage penetration[10]. In [11], a decentralized control system has been discussed to dynamically share power among the storage devices of an autonomous microgrid. The market of energy storage based electric vehicles (EV) is growing and impacting on the grid. An optimal and fast EV charging system has been proposed, which connected to a DC microgrid[12], [13]. These papers also discussed the energy management system and current/voltage charge controller for storage systems.

An extensive research which incorporates life cycle analysis, optimization system and environmental impact such as CO2 emission, has been done on distributed energy generation system which includes different energy storage devices, micro turbines and photovoltaic system[2]. The application of flywheel connected with microgrid has been discussed in [14].

The different control strategy of battery, energy scheduling techniques in microgrid system, economic dispatch of power from the storage devices to the microgrid and optimal power sharing method have been investigated and proposed in several types of research[15]–[19].

Due to major advances in power electronics and use of distributed energy resources (DER), the DC distribution system is now the key factor to increase the overall efficiency of the power system. This paper presents an equal power-sharing strategy among the storage devices connected to a DC microgrid for resistive and motor load.

II. SYSTEM DESCRIPTION

A DC microgrid has been designed with two Nickel-Metal-Hydride batteries and a hydrogen fuel cell as an energy storage system. A current controller which has been proposed in[13] used as a distributed control system of the storage devices. The bidirectional buck-boost DC-DC converter has been used to maintain the charging and discharging current of the storage devices.

An anti-parallel connection was considered during connecting the switches of the converters. The connection can be defined as a parallel connection but with different polarities. During the simulation, circulating current has been observed between the switches of the converter. An inductor was able to suppress the circulating current.

A voltage converter has been proposed in figure 1 to maintain the voltage of the permanent magnet DC machine which has been used as an inductive load.

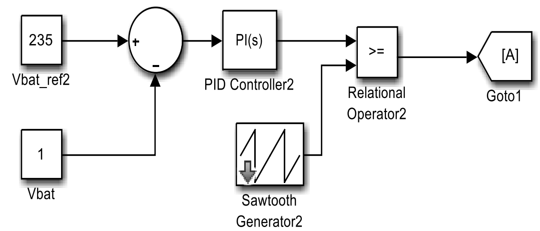

Figure 1. Proposed constant voltage based energy storage charge controller.

III. ENERGY STORAGE MODEL

The nickel-metal-hydride battery in Matlab SimPower systems from Electric drives/Extra sources library has been used in this simulation. The mathematical model of the battery has been found in [20] and discussed below:

Charge condition

$$f(C, i', i, \mathrm{Exp}) = E - D * \frac{Q}{|C| + 0.1 * Q} * i' - D * C * \frac{Q}{Q-C} + Laplace^{-1}\left(\frac{Exp(s)}{S(s)} * \frac{1}{s}\right) \quad (1)$$

Discharge condition

$$f(C, i', i, \mathrm{Exp}) = E - D * \frac{Q}{Q-C} * i' - D * C * \frac{Q}{Q-C} \quad (2)$$

Hydrogen fuel cell model:

$$\text{Open circuit voltage } (E_{oc}) = K_c * E_n \quad (3)$$

$$\text{Exchange current } (i_0) = \frac{zFk(P_{H_2} + P_{O_2})}{Rh} * e^{\frac{-\Delta G}{RT}} \quad (4)$$

Where, R = 8.3145 J/ (mol K), F = 96485 A s/mol, z = Number of moving electrons, E_n = Nernst voltage, P_{H_2} = Partial pressure of hydrogen inside the stack (atm), P_{O_2} = Partial pressure of oxygen inside the stack (atm), k = Boltzmann's constant = 1.38×10^{-23} J/K, E = Constant voltage(V), Exp(s) = Exponential zone dynamics (V), S(s) = Represents the battery mode. Sel(s) = 0 during battery discharge, Sel(s) = 1 during battery charging, D = Polarization constant (Ah^{-1}) or Polarization resistance (Ohms), i' = Low frequency current dynamics (A), i = Battery current (A), C = Extracted battery capacity (Ah), Q = Maximum battery capacity (Ah), h = Planck's constant = 6.626 × 10^{-34} J s, ΔG = Size of the activation barrier which depends on the type of electrode and catalyst used, T = Temperature of operation (K), Kc = Voltage constant at nominal condition of operation.

IV. Simulation Result

The microgrid system with energy storage devices has been simulated for the verification of the model using different loads such as resistive and inductive.

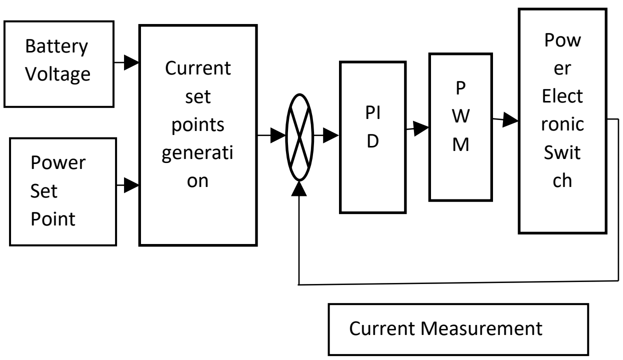

Figure 2. Block diagram of a proposed DC microgrid system

A DC microgrid has been designed with two Nickel-Metal-Hydride batteries and a hydrogen fuel cell as an energy storage system. A current controller which has been proposed in [12] used as a distributed control system of the storage devices. The bidirectional buck-boost DC-DC converter has been used to maintain the charging and discharging current of the storage devices. An anti-parallel connection was considered during connecting the switches of the converters. The connection can be defined as a parallel connection but with different polarities. During the simulation, circulating current has been observed between the switches of the converter. An inductor was able to suppress the circulating current. The microgrid system with energy storage devices (figure 2) has been simulated for the verification of the model using different loads such as resistive and inductive.

Resistive Load

The rated voltage is 310 V and the resistance is 100 Ω. Therefore, the rated current is 3.1 A. The rated power is 961W. In this simulation, a 100 **Ω** resistor has been connected with the microgrid as a resistive load.

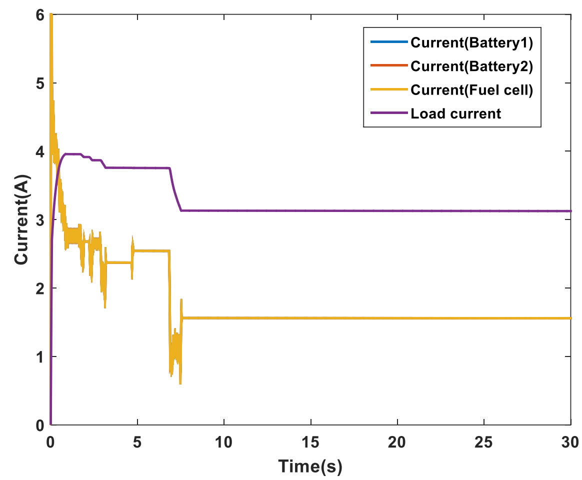

Figure 3. Energy storage currents vs load current for resistive load

Due to the equal sharing of power among the storage devices, the set points of the charge controller are same. In figure 3, it shows the current controllers are tracking the reference set points and the system is stable after few oscillations.

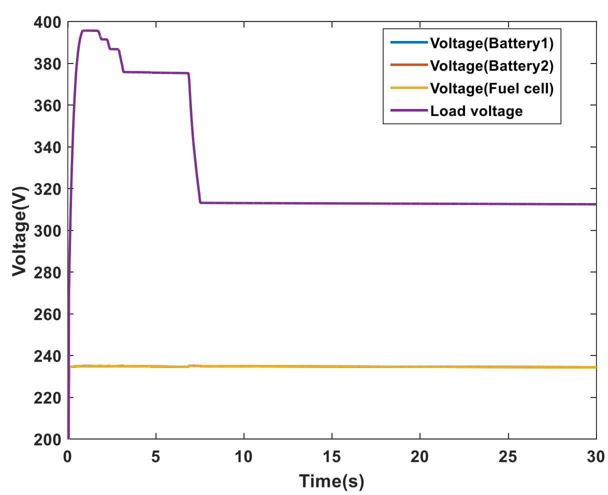

Figure 4. The voltage of the energy storage devices vs load voltage.

A comparison between load voltage and voltage of the storage devices has been shown in figure 4. The rated voltage has kept same for all the storage devices. The boost converter worked efficiently to increase the load voltage.

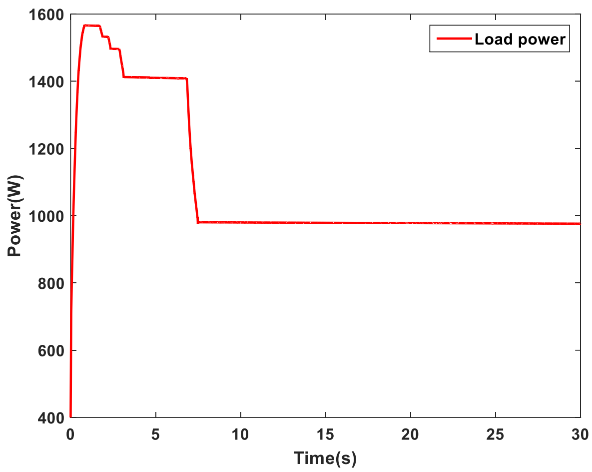

Figure 5. Power profile of the microgrid for resistive load

The figure 5 shows the simulated power is exactly same as the calculated rated power.

Inductive load

The configuration of the inductive load which has been used during the simulation has illustrated in figure 6 which is in the beginning of next page. A voltage controller has been used to put the voltage set point of the motor and a buck converter to control the applied voltage to the load.

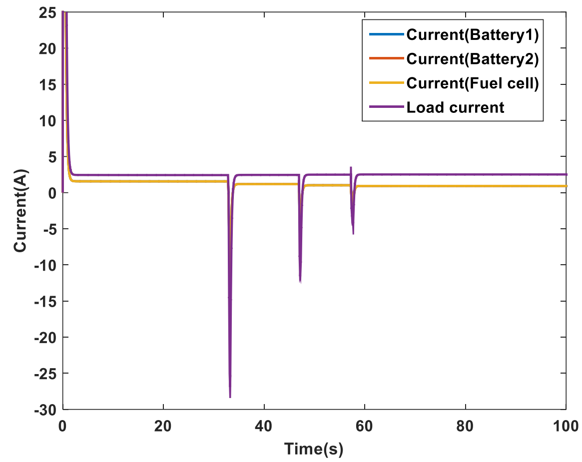

Figure 7. Energy storage currents vs load current for an inductive load.

In figure 7, it shows the current of the energy storage devices when the microgrid is connected to an inductive load (DC motor). It can be seen that the current profiles of the energy storage devices have similar kind of pattern. . This is because the power for inductive load has been assigned to share equally among the storage devices. The downward spikes are charging period of the storage devices. It is happening because when the voltage set point is decreasing the back emf of the motor is higher than the applied voltage. Therefore, the motor is injecting energy into the system

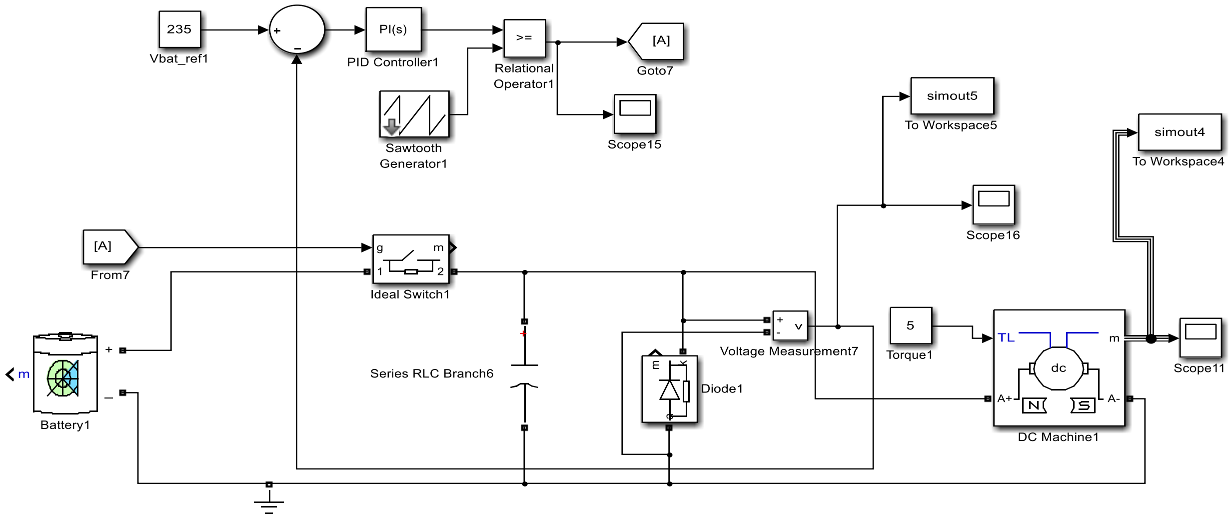

Figure 6. The configuration of DC motor load with DC microgrid system

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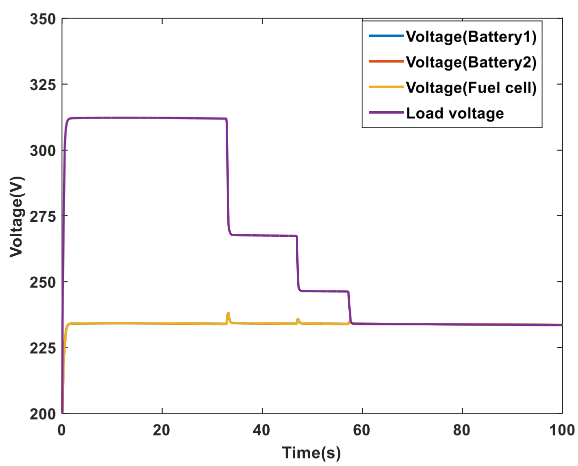

Figure 8. The voltage of the energy storage devices vs load voltage.

The rated voltage was around 310V but the voltage set points for the motor has been changed periodically to reduce the speed. The spikes in figure 8 for energy storage voltages are because of the motor back emf temporarily becomes greater than bus voltage resulting in reverse current flow due to which battery is getting re-charged.

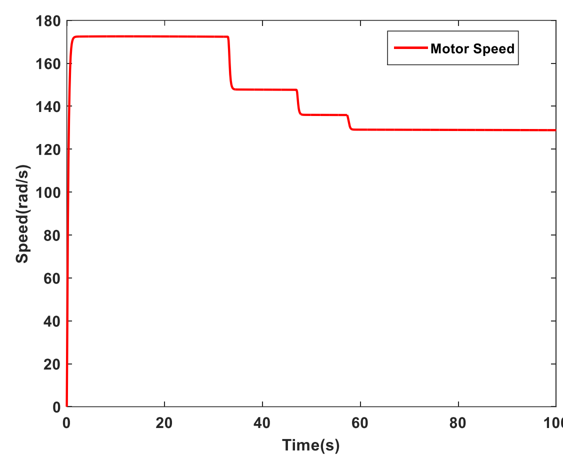

Figure 9: Speed of the Motor.

In Figure 9, it shows the speed variation of the motor due to the change of voltage set points. The initial speed of the motor was around 170 rad/s. It reached to 140 rad/s after some changes.

CONCLUSION

In this paper, a DC microgrid with different energy storage devices has been developed. The load characteristics of resistive and inductive loads have been studied and simulated by connecting with the DC microgrid. A new current and voltage controller have been introduced. The charge controller has been working perfectly and tracking the given set points. It is found that the DC microgrid can be operated with high penetration of different energy storage devices and storage devices can be controlled based on the load. During the simulation, circulating current has been observed between the switches of the converter. An inductor was able to suppress the circulating current. The implementation of the model in Matlab/Simulink has been described.

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