Design of Hybrid Battery Supercapacitor System for Dynamic Load

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***Abstract*—The Hybrid Energy Storage Systems consist of supercapacitors and batteries, which make up energy storage systems that operate with higher efficiency in the case of quickly changing loads. Because of their slower response time, batteries frequently encounter more stress due to sudden changes in loads. In this study, a new Hybrid Energy Storage System has been proposed, which has a structure based on the combination of supercapacitors for transient loads and batteries for steady state powers. The suggested Hybrid Energy Storage System has been modeled and tested in MATLAB Simulink. The simulation results have shown that the suggested Hybrid Energy Storage System has higher voltage stability on the DC bus than the Battery Energy Storage Systems. Moreover, the Hybrid Energy Storage System has been shown to have higher current sharing and lesser stress on the batteries than the Battery Energy Storage Systems.**

***Index Terms*—Hybrid Energy Storage System, Supercapacitor, Battery, Dynamic Load, DC Bus Voltage, Power Management.**

I. INTRODUCTION

As there is an increased reliance on renewable energy sources in terms of modern DC power systems, the need for loading power has been on the increase owing to turning the electricity on and off by electrical devices, the need to start high-current motors and connecting to high-power loads. The effect of loading power in the above case will result in transient voltages and currents which may lead to instability and various effects in the operation of these systems. Due to the energy density they offer and capacity for continuous power supply, batteries have gained popularity for storing energy in these systems. Batteries are known to possess a low power density and response time. This means that when there is any change in electrical load, batteries have to provide transient currents, hence resulting in losses. The increasing number of engineers and scientists has started to develop HESS (hybrid energy storage systems) using batteries and super capacitors due to the inability of these systems to meet the requirements when there are changes in load levels. Supercapacitors have a very high-power density as well as fast charge-discharge capability and hence they are capable of meeting the transient power requirement. By combining batteries with supercapacitors, the transient loading conditions and battery operation will be optimized.

In this proposal, a battery supercapacitor energy storage system will be designed to improve the efficiency of DC power systems in dynamic load conditions whereby the battery provides steady state power supply and supercapacitor supplies transient load power supply needs. The system will be analysed using the Matlab Simulink and the results obtained based on voltage stability, current distribution and dynamic load handling. The contribution made in this paper is on the analysis of coordinated power distribution between a battery and supercapacitor in order to optimize the DC bus voltage stability and improve battery efficiency under dynamic load conditions.

II. LITERATURE REVIEW

The methods used to conduct research on HESS include many varied methods aimed at improving the performance of these devices as they operate under varying dynamic loads. In addition, many different methods have been applied by different researchers on control and energy management schemes for harvesting, controlling, and management of energy production and consumption from these two devices. In one study, P. Author et al. [1] suggested modeling and control methods that would improve the transient characteristics of the systems, reducing stress on the batteries by optimizing energy management methods. Another experiment carried out by H. Chen [2] explored the application of supercapacitors and lithium-ion batteries for energy management in DC microgrids and found out that when both high and low frequencies power components were separated, there was an improvement in the performance of both batteries and supercapacitors, besides enhancing battery life in lithium-ion batteries. Finally, in another research carried out by H. Chen [3], a method for testing the control of HESS is presented, where it was shown that using this scheme, the DC bus voltage remains constant under dynamic changes of load.

A different research paper by authors A. Author et al. [4] studied fast dynamic loading along with HESS using batteries and supercapacitors, and the results proved that simulations carried out in order to analyse the transient behavior of the configurations presented resulted in better transient behavior as compared to conventional battery-powered timing.

Despite past research into hybrid battery supercapacitor systems, very few researchers have attempted to conduct any kind of dynamic load compensating scheme where the power is being shared simultaneously with stabilization of DC bus voltage.

III. SYSTEM ARCHITECTURE

A. Block Diagram

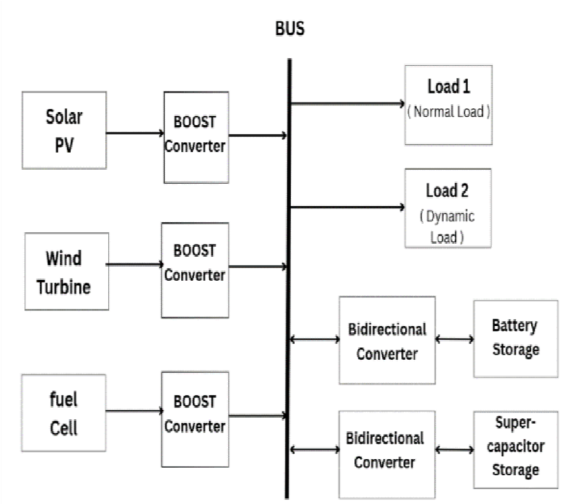

Fig. 1: Block Diagram of Hybrid Battery Supercapacitor System for Dynamic Load Application

B. System Overview

The Hybrid Energy Storage System (HESS) is comprised of two major components; Battery and Supercapacitor. The above mentioned two components are interfaced to each other through a DC bus which is further interfaced to dynamic loads. The idea behind this proposed Hybrid Energy Storage System (HESS) is to maximize the performance of HESS under dynamic loading conditions. It will be done by merging the high energy density of battery and high-power density of super capacitor. Hence this Hybrid Energy Storage System will be able to perform well under dynamic loading conditions. Furthermore, this HESS will also include the renewable energy sources such as PV, wind and Fuel Cell. The above-mentioned renewable energy sources will be interfaced to common DC bus through appropriate power electronics converter. These sources will serve the purpose of supplying energy to load as well as charging the storage systems. The major objectives for the suggested architecture for the Hybrid Energy Storage Systems include maintaining a steady-state voltage of the DC bus, as well as providing a convenient way for the power conversion from the supercapacitors and batteries to the DC bus at the same time.

C. System Components

The subsequent paragraphs discuss the main components of the proposed system:

1) Battery

In this system, the battery acts as an energy source which provides energy for steady-state load condition using the self-contained power source energy storage medium. Batteries are not designed to react to changes in the load because of their high energy density and low dynamic responses. In this whole proposed system, the battery is used for providing power for base load condition.

2) Supercapacitor

The supercapacitor acts as the secondary component of energy storage in this whole proposed system. It was added for handling transients in load conditions. The super capacitor has high power density and fast discharge rates. Therefore, the super capacitor can be able to offer peak response on dynamic loads conditions. In such cases, the super capacitor takes the load peaks and reduces battery load stress.

3) DC-DC Converter

This converter is used to link the renewable energy sources and supercapacitors to the common dc bus. The converter controls the power exchange in the system. Power changes occur very quickly, and when this happens, the performance of the whole system can be enhanced by using a DC-DC converter. In this way, energy can be moved from one source to another.

4) Common DC Bus

The Common DC Bus is the connecting link where all the sources of renewable energy and stored energy are connected to provide electricity to the load. It maintains constant voltage of approximately 200 volts DC, thereby providing stable electricity to the load. To manage power delivery to the load, the common dc bus manages energy production from renewable energy sources and delivers it to the load.

5) Dynamic Load Behaviour

In this 3-phase DC power control and delivery system, the dynamic loads have been added to test the effectiveness of the entire system. Steady-State Loads continuously feed energy into the whole system throughout the entire period of the simulation. On the other hand, at time t=1 second, a dynamic load is suddenly introduced into the system, leading to a disturbance in the entire system operation. Such dynamic load variations are typical in real operations where there is sudden change in demand.

6) Renewable Energy Sources

The system tests the use of various renewable energy sources including Solar(PV), Wind Energy and Hydrogen Powered Fuel Cells. The use of Boost Converters to link these sources of energy to the DC Bus enables them to be used to power the entire System and charge the Battery and Supercapacitor. Renewable energy sources make a Hybrid Power System Sustainable and Reliable.

D. Working Principle

The functioning of a Hybrid Power System involves the proper utilization of Power Sharing in the system. It happens between both the Battery and the Supercapacitor.

Case 1: Normal Load Condition

During Normal Operating Conditions, there will be no variation in Load demand. Under such operating conditions, the Battery would be the primary source for supplying voltage, hence the Supercapacitor would not play any role except during slight loading.

Case 2: Dynamic Load Condition

Dynamic Load Condition would mean a Sudden increase in Load at t = 1s. Since Batteries have slow dynamic response characteristics, the battery will not react promptly to the abrupt change in load demand.

Under Dynamic Load Conditions, the Supercapacitor will be responsible for the instantaneous provision of the Peak Current to the load while the Battery continues providing Base Power Supply to the load. In other words, this process ensures a smooth transition of the system to its normal state.

Case 3: Post-Transient Condition

After a Transient Condition arises and is eventually solved, the contribution of the Supercapacitor, through Peak current provision, would be reduced until finally, the Load settles down and the Battery continues its primary task of steady state power supply.

E. Mathematical Modelling

The system operation is controlled by fundamental electrical equations:

Power equation

$$P = V \times I \quad (1)$$

Energy stored in the supercapacitor:

$$E = (1/2)\, C\, V^2 \quad (2)$$

Power balance equation:

$$P_{battery} + P_{supercapacitor} = P_{load} \quad (3)$$

Therefore, these equations will provide information about the distribution and the dynamic behaviour of the two systems.

F. Simulation Setup

The system is simulated using MATLAB Simulink

TABLE 1: Component Parameters used in MATLAB

Sr. No	Parameters	Values
1	DC Bus Voltage	200V
2	Battery Nominal Voltage	200V
3	Supercapacitor	50 F
4	Simulation Time (t = 0 to 2)	2 sec
5	Dynamic Load Applied At	1 sec

G. MATLAB Simulation Model

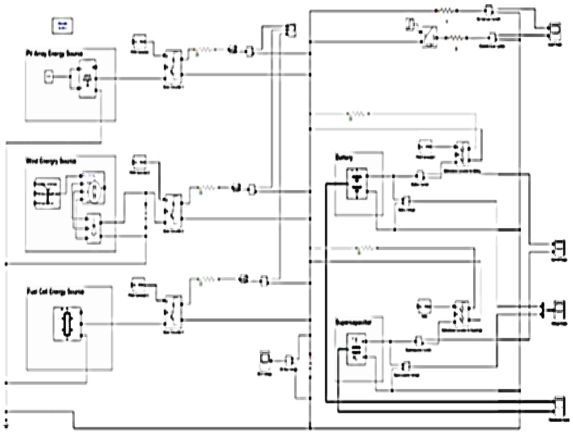

Fig. 2: MATLAB Simulation Model of Hybrid Battery-Supercapacitor System for Dynamic Load

IV. RESULT AND DISCUSSION

1. Expected system Behaviour

The expected performance of the proposed hybrid battery supercapacitor combination will be met before analysing the results from the simulation. In this case, it is the battery that will be charged with the task of supplying power in a steady state owing to its large store of energy (i.e., high energy density). On the other hand, the supercapacitor will take care of the fast-changing load transients and keep the battery in steady state.

The battery will deliver the largest part of the load in ordinary load circumstances, but, at the time of load transients, the supercapacitor will deliver the peak current, thus minimizing the stress on the battery. The coordination between the two parts will ensure stable supply of the DC bus with no variations in the voltage.

2. Battery Vs Supercapacitor Voltage Analysis

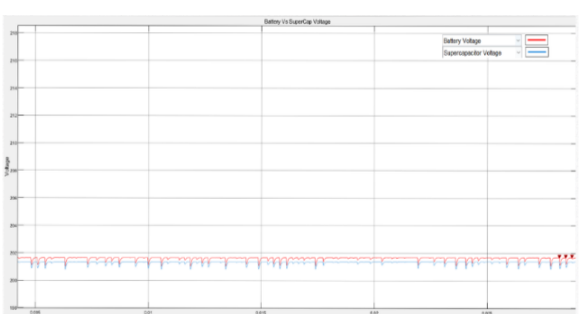

Fig. 3: Battery Vs Supercapacitor Voltage analysis

Both the voltages of the battery and supercapacitor remain steady at the same level of 200 Volts throughout the entire period of the simulation process. The operation of the battery proves to be stable and steady, and also more consistent than that of the supercapacitor. Even though there might be observed some spikes in the current values on both components whenever there are some changes in the load value, and the response of the supercapacitor to the changes will be almost instantaneous because of its ability to charge or discharge itself quickly, this does not influence the operation negatively.

3. Load Variation Analysis

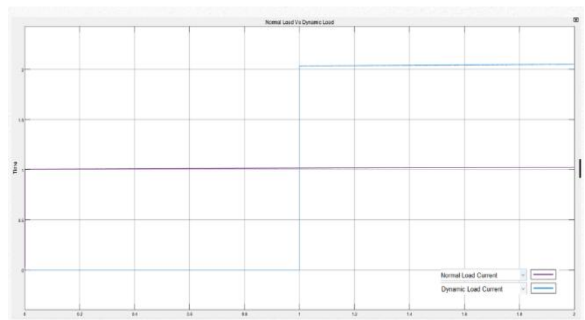

Fig. 4: Load Variation Response

The loading pattern reveals a transition from a conventional loading condition to dynamic loading condition taking around 1 second after the loading process starts at t = 1 second, when previously there were equal loading demands on the system.

Upon increasing the load instantaneously at t = 1 second, this provided us with an instance of dynamic loading in a real-world scenario. In this way, a simulated disturbance was generated in the system that would help us analyze the performance of the hybrid energy storage system. The hybrid energy storage system responded well to the increased load without making the system unstable.

4. Battery Vs Supercapacitor Current Analysis

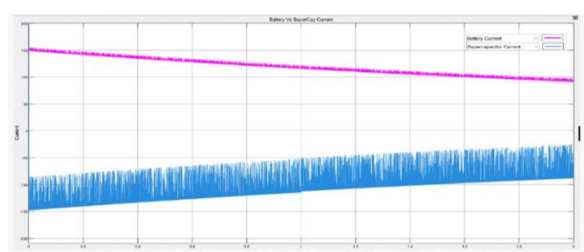

Fig. 5: Battery Vs Supercapacitor Current Response

The features described are an indicator of how power is distributed between the two devices. Since the battery is characterized by its current's smooth behavior over time, it is evident that it supplies the stable component of the load without experiencing any high current peaks and hence avoids stress on the battery, leading to increased battery life.

On the other hand, the supercapacitor is characterized by a high voltage fluctuation in the current flow over time and therefore concludes that the supercapacitor responds quickly and is capable of supplying peak current, which results from the transient demand of the load. This complementary nature of the two components leads to efficient power sharing and helps protect the battery against sudden current peaks.

5. DC Bus Voltage Stability

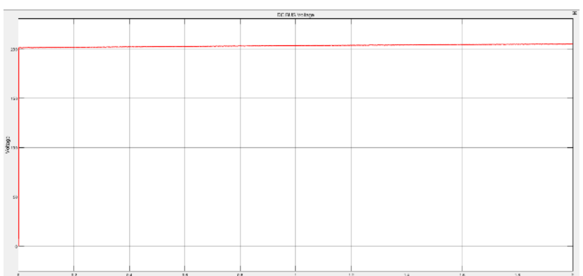

Fig. 6: DC Bus Voltage Response

The DC bus voltage has remained constant at around 200 volts throughout the whole period of the simulation. Voltage deviations have only been noted at t=1 second because there was a sudden change in load. Therefore, it is evident that the hybrid system controls the DC bus voltage, thus maintaining the stability of the system. It is evident that the supercapacitors play a very crucial role in minimizing bus voltage fluctuations.

6. Battery and Supercapacitor Parameter Analysis

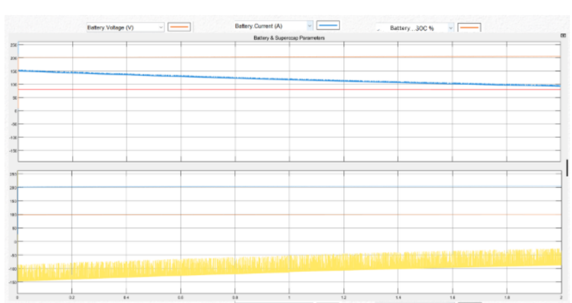

Fig. 7: Battery & Supercapacitor Parameter Response

Parameter analysis of the battery and super capacitor reveals information about energy storage and delivery by these sources. As expected, the parameter values of the battery decrease with respect to time during power delivery to a steady load. The parameters of the supercapacitor are more volatile than those of the battery, which confirms its transient performance.

7 Overall System Performance

It has been proven that the HESS operates satisfactorily in situations involving dynamic loading. In the hybrid energy storage system, the voltage of the dc bus will be steady at all times with minimal changes in voltage regardless of the variation in load. This is due to the fact that the battery provides power supply all the time and the supercapacitor takes care of transient current flow. The two energy storage devices can hence operate together to balance power between each other without overloading the battery.

V. CONCLUSION

The investigation looked at the design of a hybrid battery supercapacitor energy storage system for dynamic load operations using computer modelling. The hybrid energy storage system is capable of harnessing the high energy density of batteries and the high-power density of supercapacitors to overcome some of the drawbacks of standalone battery designs. According to the findings, supercapacitors react quickly to transient load changes while the batteries deliver a steady state of power. It means that this combination reduces stress on the batteries leading to increased longevity.

Furthermore, the DC bus voltage is kept relatively stable irrespective of any abrupt load changes. The result means that this combination not only improves the efficiency of the energy storage system but also makes it more reliable in delivering power to dynamic loads.

On the whole, the use of a hybrid battery supercapacitor energy storage system leads to an improvement in performance owing to its enhanced dynamic performance characteristics, voltage regulation, and efficiency.

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