Implementation of Hybrid Energy Storage Systems to Compensate Microgrid Instability in the Presence of Constant Power Loads

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Abstract Microgrid systems have been adopted globally to implement the renewable energy-based electrification, but constant power load (CPL) has caused instability issues. To improve the stability of the microgrid system, a virtual impedance-based load side compensation technique is used. In this paper, to implement this storage-based compensation technique, the hybrid energy storage system (HESS), with a battery unit as well as ultracapacitor unit, is introduced to reduce the deficiency in the case of using either battery-only or ultracapacitor-only storage system and offer the combined features with higher energy and higher power density. Here, the storage will provide high power density with quick charging/discharging time and the ultracapacitor will compensate the transient demand for a short period of time; therefore compensating the required power by the combined features of its constituents. Besides HESS is operated by a simple implementable algorithm, it improves overall efficiency, cost effectiveness, life span; reduce the energy storage size and stress on the battery. This proposed system adds up to the existing and ongoing research work in this field by providing a new way to counter the problems faced because of constant power loads in microgird systems. Along with introducing a combination of load side compensation, HESS and ultra capacitor this work would go a long way in reducing battery size, stress on battery and increase efficiency by improving battery reponse time and percent overshoot in volatge. To verify the performance of the proposed system, necessary results performed at Matlab/Simulink platform are presented in this paper.

Keywords Hybrid Energy Storage System, Constant Power Load, Energy Management Algorithm, Microgrid. Load Side Compensation.

1. Introduction

With advent of the microgrid system, though it has a number of advantages over conventional grid system, stability issues have grown into a major concern to researchers around the world. Since the microgrid system basically deals with the constant power load (CPL) and CPL exhibits negative incremental characteristics, it hampers the microgrid system stability considerably. At present, as the continual increase of the modern inverter-based loads, the problem is being intensified. To improve the stability of the system, engineers, professionals, and researchers have conducted a number of research works around the world [1-6]. In [7], Kwasinski and Onwuchekwa outlined the typical strategies for mitigating the problems of CPL in DC microgrids. In this discussion, the effect of adding filters and capacitors was studied. But, this is an expensive system with the additional problem of capacitor failure which increases with rated voltage. Load shedding of CPLs can restore stability, but this is of little practical value since it only temporarily restores the system without increasing long-term capacity. Linear and non-linear controllers can also be used but the former cannot guarantee global stability of the desired equilibrium point and the latter is very challenging in its design and changes with each system's parameters. Stabilizing power can be generated and sent to the load power reference for slightly modifying the CPL behavior of the load. Using such a constrained optimization technique, a method to design the stabilizing system is proposed in [8]. Coupling two systems together can allow the oscillating characteristics of the two systems to dampen each other out [9]. The systems may have slightly different characteristics, usually because of different inductances, or they may be identical but coupled with a small delay factor. Mathematical analysis for two systems has been done to find the region of stability. It is cumbersome to identify the system's stability characteristics for the large complicated system. For that particular case in DC microgrids, instead of over- linearizing, sliding mode control technique- with nonlinear modeling of the system- has been adopted by the researchers. By using a sliding mode controller, a sliding surface has been established to stabilize the voltage of the entire system [10].

To have appreciable operational performance, Bo Wen et al introduced a four-wire-grid architecture to implement renewable energy resources in islanded mode operation. Apart from that, a three phase AC system has been discussed in [11]. Instead of the conventional frame analysis, here, researchers have presented dq frame analysis for small signal stability. Next, Zeng Liu et al, at [12], have researched on the distributed power system. In that occasion, using infinite norms input/output matrix, they have identified a stability criterion for DPS. It is evident that, due to the negative incremental load characteristics, the instability problem is intensified with the increasing proportion of the constant power load. Nadeem Jelani has worked to find out the nature of this relationship and has investigated the previous works on this issue. To solve the instability problem, he introduced a STATCOM compensation technique at [13]. At [14], Dena Karimipour et al worked on Popov's Stability criterion, one of the advanced nonlinear techniques, to handle CPL instability issues. Using this technique for AC systems, they have accomplished stability analysis of the microgrid system. Yanjun Dong et al worked with pulse width modulation rectifier to mitigate the constant power load instability. In their research, they introduced a simulation model for AC microgrid systems loaded with CPL at [15]. By adopting a boost rectifier as a CPL load, Zeng Liu et al investigated the stability issues of the system. In that occasion, they used infinite norm impedance matrix for their analysis. Researchers have noticed that all available techniques for CPLs compensation can be classified into several groups of common criteria based on the location of providing compensation. The classifications are mentioned below.

- Feeder side compensation to make the system robust against CPL instability.
- Compensation by adding intermediate circuitry or elements between the feeder side and load to enhance system stability.
- Load side compensation so that the system doesn't experience the effect of Constant Power Loads.

In this paper, because of having a number of advantages over the other compensation generalized techniques, virtual impedance based load-side compensation technique has been adopted to improve microgrid stability [16-17]. The compensation is done in the load side.

Energy storage has been promoted as a very significant tool in the integration of renewable energy-based microgrid systems. It is adopsed by the system engineers and operators due to several important features such as energy time frame shifting, ancillary features, capacity firming, intermittency handling, transmission congestion relief, and power quality improvements. Besides that, from recent researches regarding microgrid stability, the energy storage system can be considered as an important tool to retain microgrid stability. In practice, an energy storage unit assures the required power when it is needed to compensate. In this course, battery storage is the most basic of its kind among the distributed network energy storage systems. It provides easy implementation as well as geographical independence; hence it is comparatively popular to other storage technologies. But, batteries, though easy to implement, are not preferable for compensation technique due to their low power density [18]. Hence, the storage system only comprised of the battery units doesn't experience a sound functionality in microgrid arrangement in case of highly variable distributed energy systems like renewable energy sources [19-23]. From figure 1, it can be interpreted that the ultracapacitors range in between the conventional batteries and the conventional capacitors in terms of energy density and power density, and therefore, usually installed for the applications where batteries have a shortfall when they require a transient high power. Moreover, to handle the situation of transient high power requirement, conventional capacitors cannot be used because they lack expected energy. On the other hand, ultracapacitors offer a high power density along with adequate energy density for the most transient high power applications [24]. From the view of purpose and application, ultracapacitors are compared with compared with conventional batteries such as lead acid battery, hydrogen fuel cells etc. considering the necessary storage parameters in table 1 below.

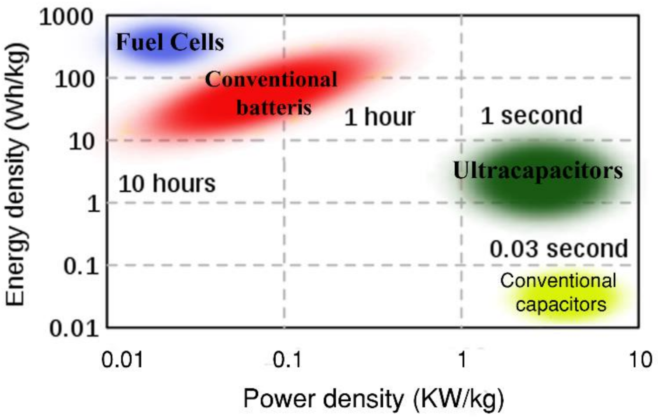

Figure 1: Comparison of various electrochemical storage devices in Energy Density, Power Density and charging time [25].

Table 1: Battery vs Ultracapacitor Parameters [26].

Parameters	**Ultracapacitors**	**Batteries**

Energy Storage	W-s of Energy	W-Hr of Energies
Charge Methods	Voltage across terminals i.e. from a battery	Current and Voltage
Power Delivered	Rapid discharge linear or exponential voltage decay	Constant voltage over long time period
Charge/Discharge Time	ms to s	1 to 10 Hrs
Form Factor	Small	Large
Weight	1-2g	1g to > 10kg
Energy Density	1 to 5 Wh/kg	8 to 600 Wh/kg
Power Density	High, > 4000W/kg	Low, 100 to 3000W/kg
Operating Voltage	2.3V to 2.75V/Cell	1.2V to 4.2V/Cell
Lifetime	>100k cycles	150 to 1500 cycles
Operating Temperature	-40 to +85 °C	-20 to +65 °C

In this paper, the hybrid energy storage system (HESS), with a battery unit as well as ultracapacitor unit, has been introduced to reduce the deficiency in the case of using either battery-only or ultracapacitor-only storage system and offer the combined features with higher energy and higher power density. By function, the charging/discharging time and the ultracapacitor is to compensate the transient demand for a short period of time; therefore compensates the required power by the combined features of its constituents [27-33].

The contribution of this paper is that, here, an HESS has been designed which is a portable device consisting of both ultracapacitor and battery. As microgrid is a distributed power system, load side compensation technique can be used by implementing this portable CPL compensator. Here, an ultracapacitor contributes also in transient power demand where a battery handles the nominal power requirements. Performance comparisons and analysis for various storage systems with designed hybrid storage system have been performed and relevant graphical analogies have been represented in this paper.

2. Conventional Energy Storage Systems for Microgrid Applications

Since CPLs have negatively incremental load characteristics, CPL-loaded microgrids experience transient spikes or sudden peaks in bus voltage response. In practice, though CVL power range is of KW or MW and CPL power is of 533 W, the transient peaks created by CPL load are significantly higher than that of the previous one (as observed from figure 2). For instance, microgrid bus voltage is illustrated at figure 2 without any compensation (in the presence of CPL). To handle this issue, energy storage systems are used in microgrid application. Here, in this paper, two kinds of conventional energy storage systems are delineated in the case of microgrid application. At first, the battery-only compensator is presented here with the regarding simulation platform and performance graphs in several cases. Similarly, the ultracapacitor-only compensator is described here with necessary detail for microgrid application. Furthermore, the advantages and limitations of each storage system will be described.

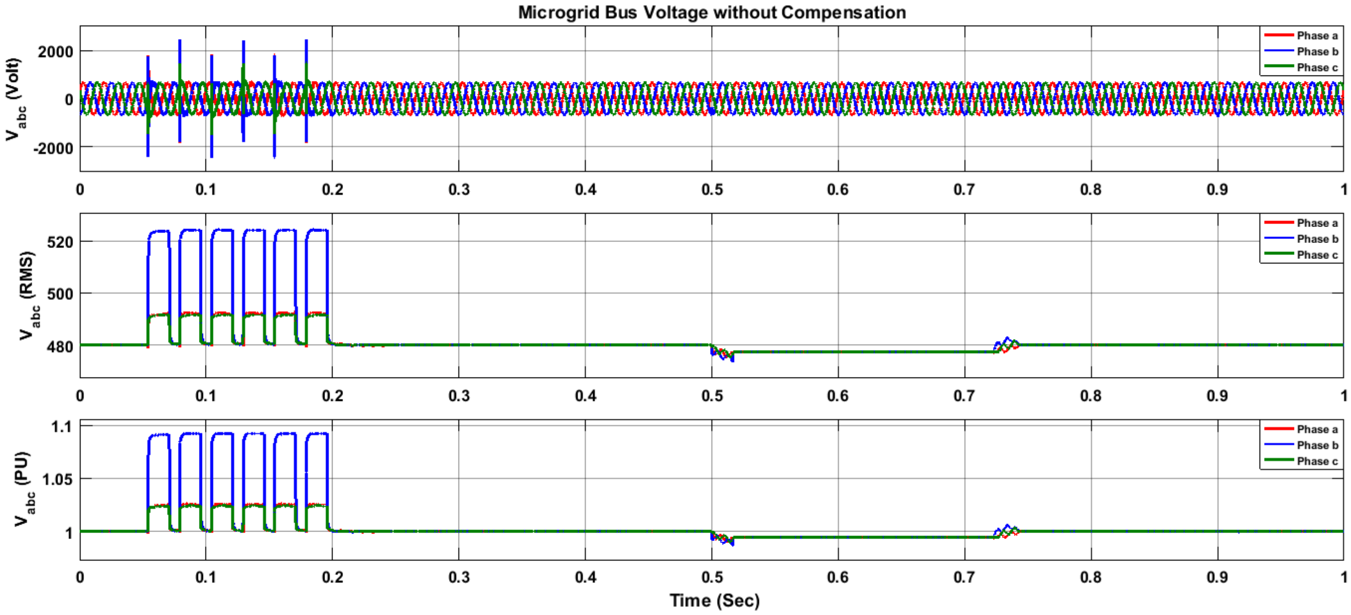

Figure 2: Top: Microgrid bus voltage without any compensator (in presence of CPL). Middle: Microgrid bus voltage (RMS) without any compensator (in presence of CPL). Bottom: Microgrid bus voltage (pu) without any compensator (in presence of CPL).

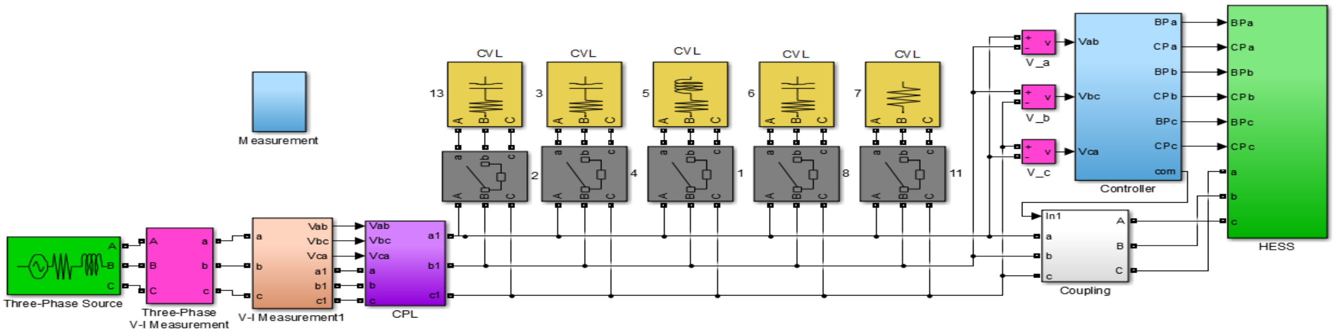

Figure 3: Simulation platform for entire microgrid system using compensator unit in Matlab/Simulink.

A. Battery-Only Compensator:

When microgrid voltage tends to fluctuate from the stable voltage range, battery delivers the required compensation to stabilize the microgrid voltage. In figure 3, simulation platform is presented for the entire microgrid system using compensator unit (here, battery as compensator unit) in Matlab/Simulink.

In figure 6(a), the representation of the battery power support and the power demand for a certain period of time is illustrated to comprehend the practical scenario. In next the figure, at 6(b), the power demand and the respective power support by the battery-only compensator in transient cases are illustrated. To illustrate the characteristic of battery-only compensator, the instances of battery terminal voltage, current, SOC, and power are presented at figure 4 (in presence of CPL). In figure 17 in the comparative analysis, the terminal voltage response is presented in the case of the battery only compensator. The SOC in figure 4 indicates that the battery releases charges during this time to make the CPL load stable by using a proper stability algorithm for discharging. It works by increasing the slope of SOC in cases of high amount of current discharge. In the voltage graph, it is clear that the voltage remains fairly stable.

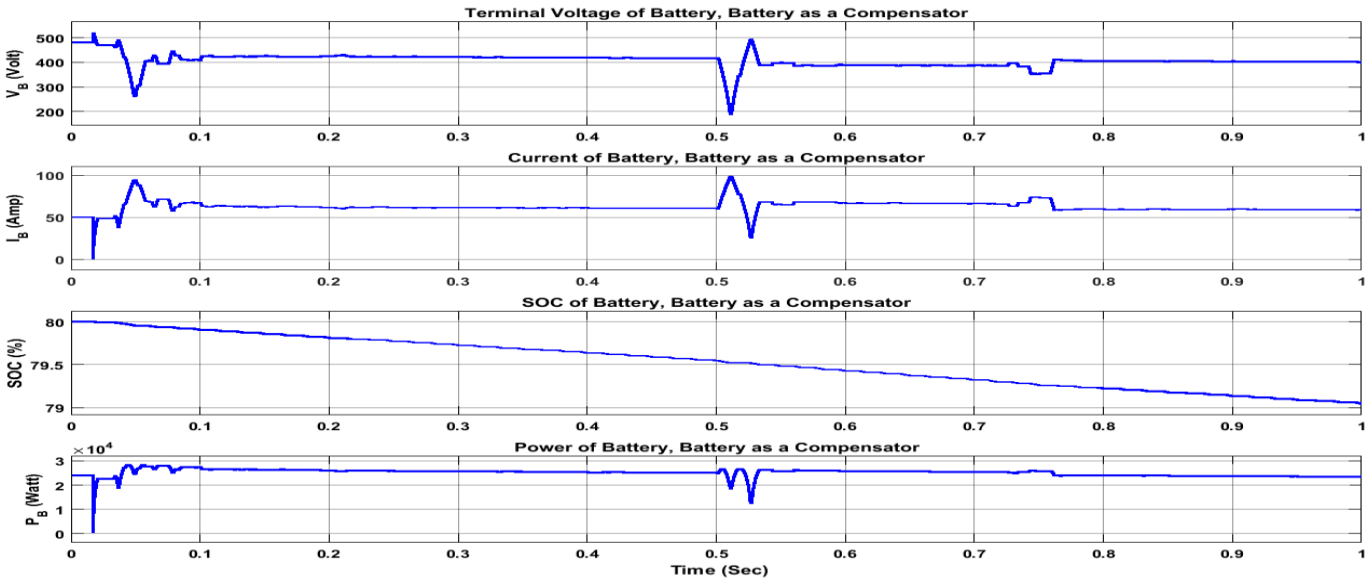

Figure 4: The characteristics of the battery terminal voltage, current, SOC, and power (in presence of CPL) when battery-only is used as compensator. First one: Terminal voltage of battery.
Second one: Current of battery. Third one: SOC of battery. Last one: Power of battery.

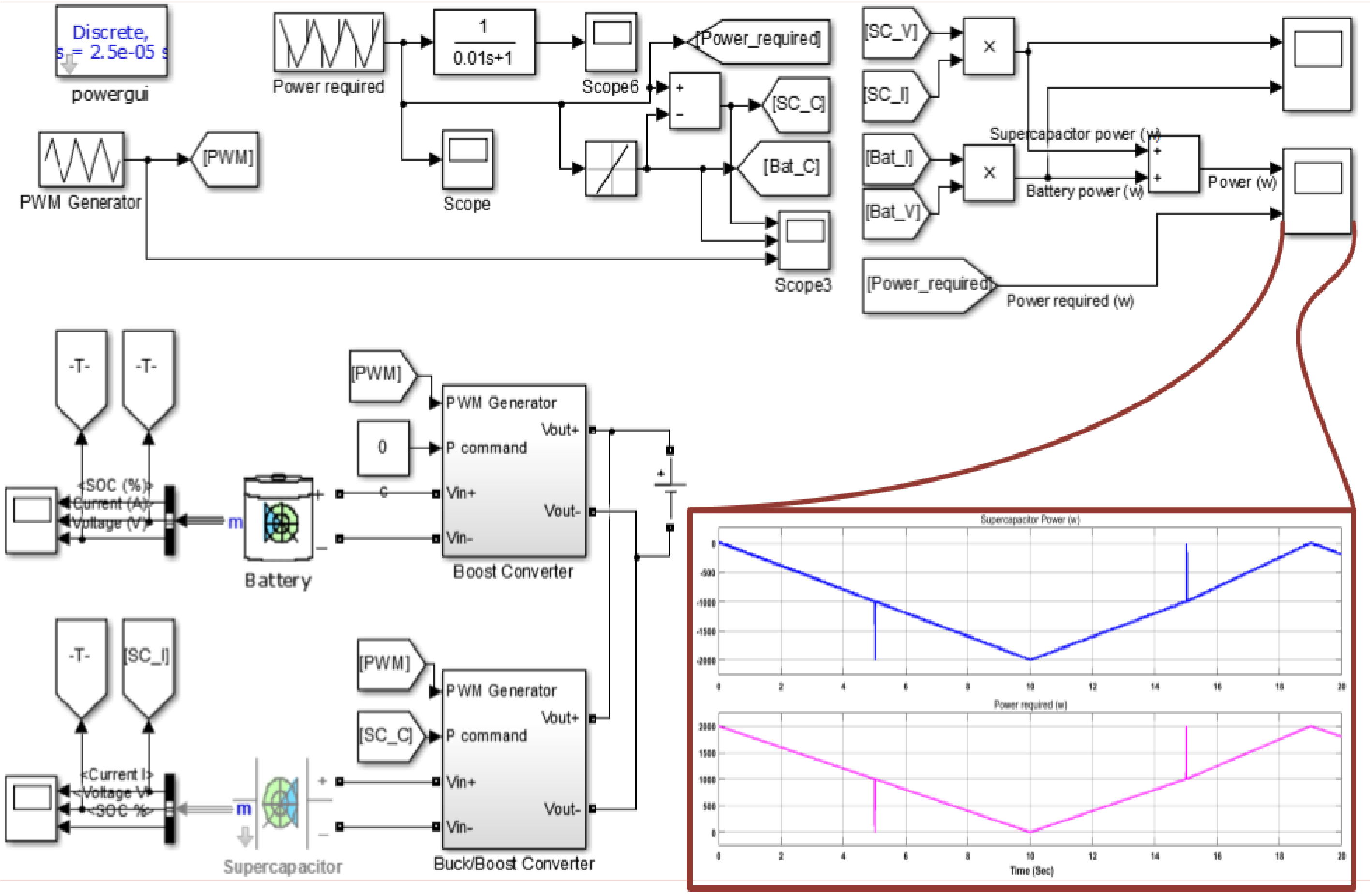

Figure 5: The simulation platform for performance comparison between battery only compensator and ultracapacitor-only compensator. Data shown in the graph: Supercapacitor power (top), Power required (bottom).

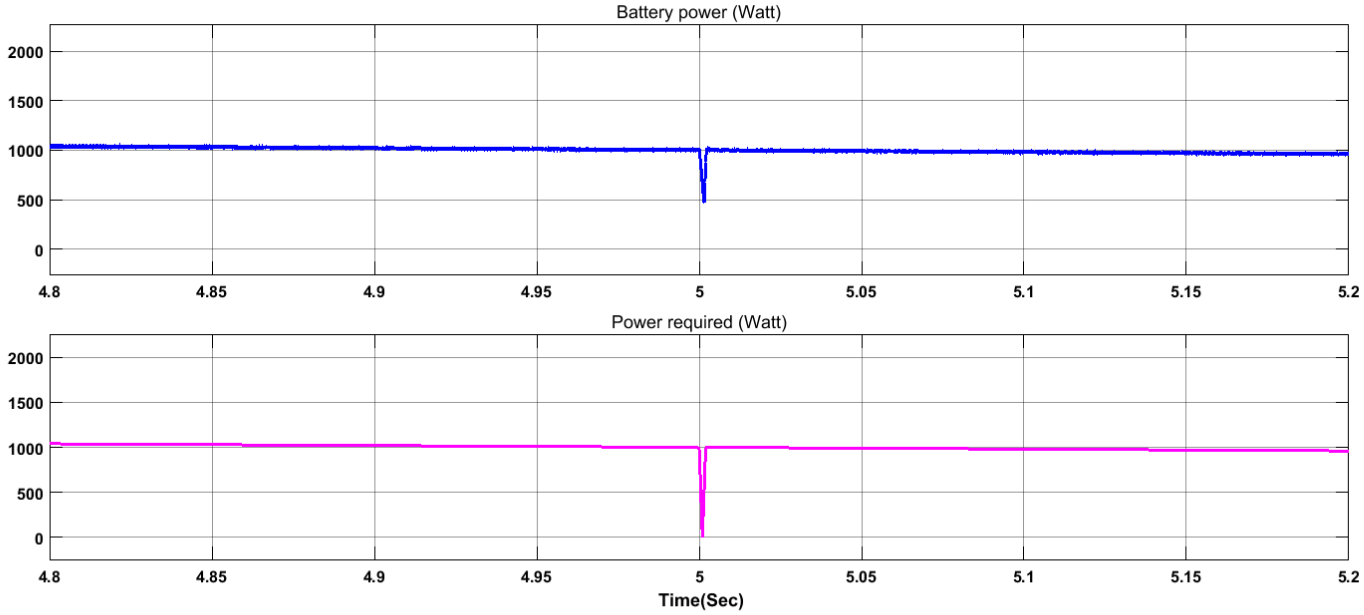

Figure 6(a): Representation of the battery power support and the power demand.

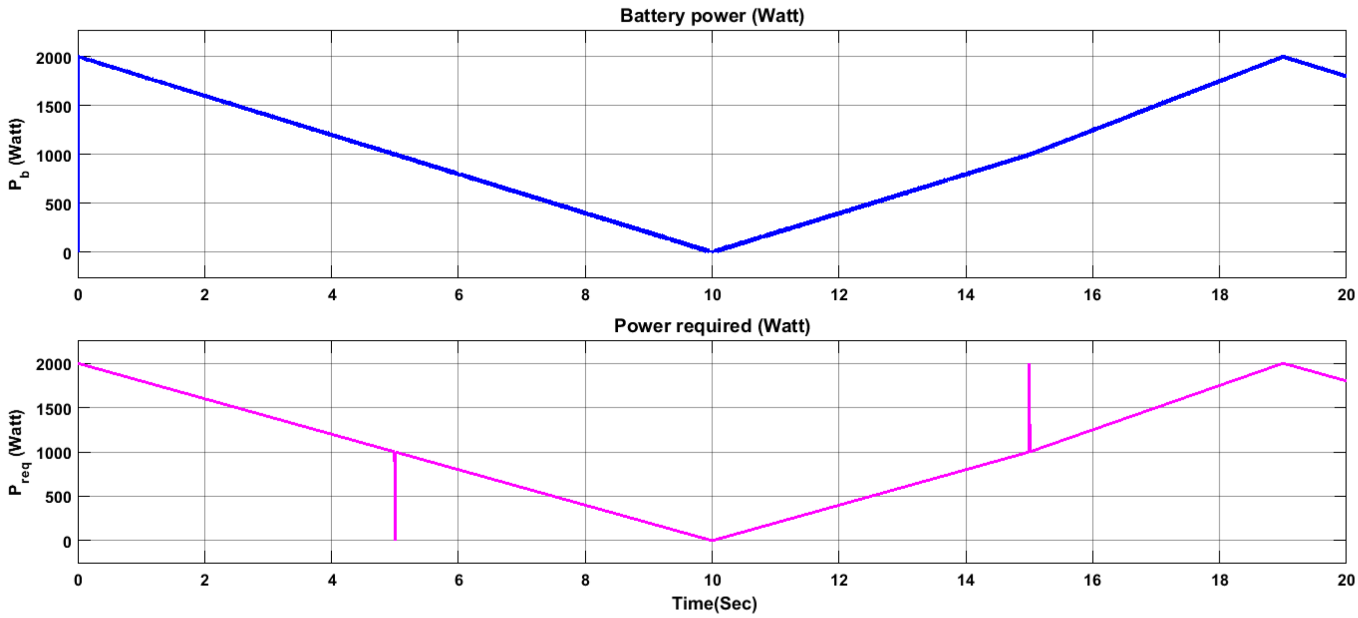

Figure 6(b): Representation of the transient power demand and respective battery support.

Battery only compensator and ultracapacitor-only compensator performances are compared using the simulation platform shown in figure 5. As is evident from the above graphical representations, the battery-only compensator can supply the nominal power efficiently for a longer period without charging-discharging backward and forward, but, in another occasion, it's ineffective while it comes to feeding transient demand. Due to the large response time and low power density, the battery needs longer time to retain stability. As can be seen from the figure 6, to retain microgrid stability, the transient spikes must be handled effectively. Hence, ultracapacitor-only compensator is used as compensator unit to mitigate microgrid instability. The load profile of the microgrid system is presented at figure 7 in presence of CPL loads. This profile is used to conduct the experiment in the test bed.

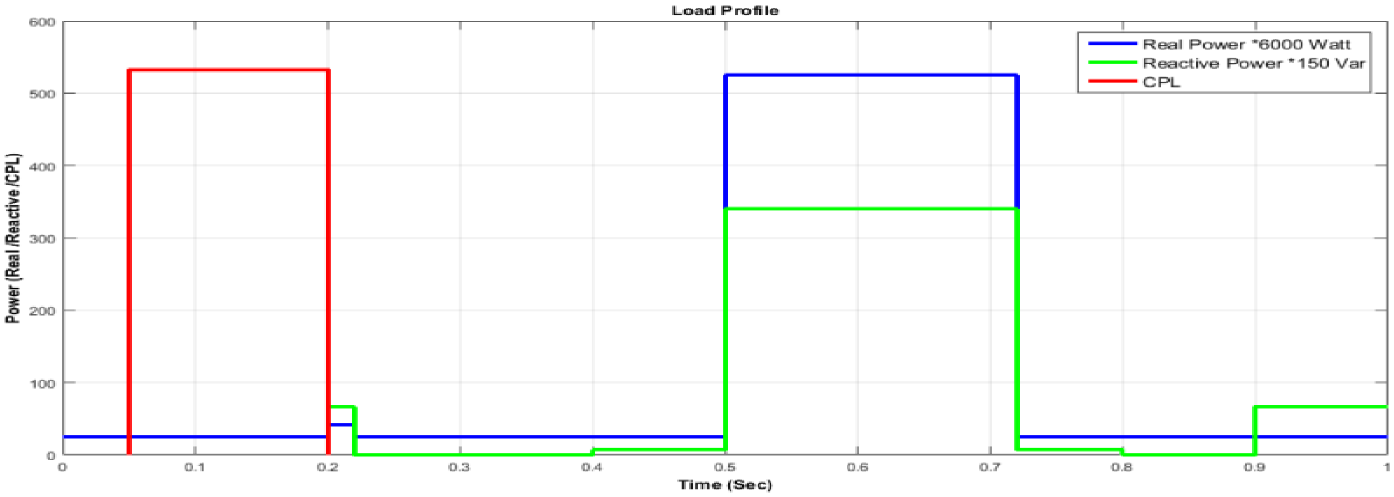

Figure 7: Load profile of CPL loaded microgrid system.

A. Ultracapacitor-Only Compensator:

When microgrid voltage tends to fluctuate from the stable voltage range, an ultracapacitor delivers the required compensation to stabilize the microgrid voltage. In figure 3, simulation platform is presented for the entire microgrid system using compensator unit (here, ultracapacitor as compensator unit) in Matlab/Simulink.

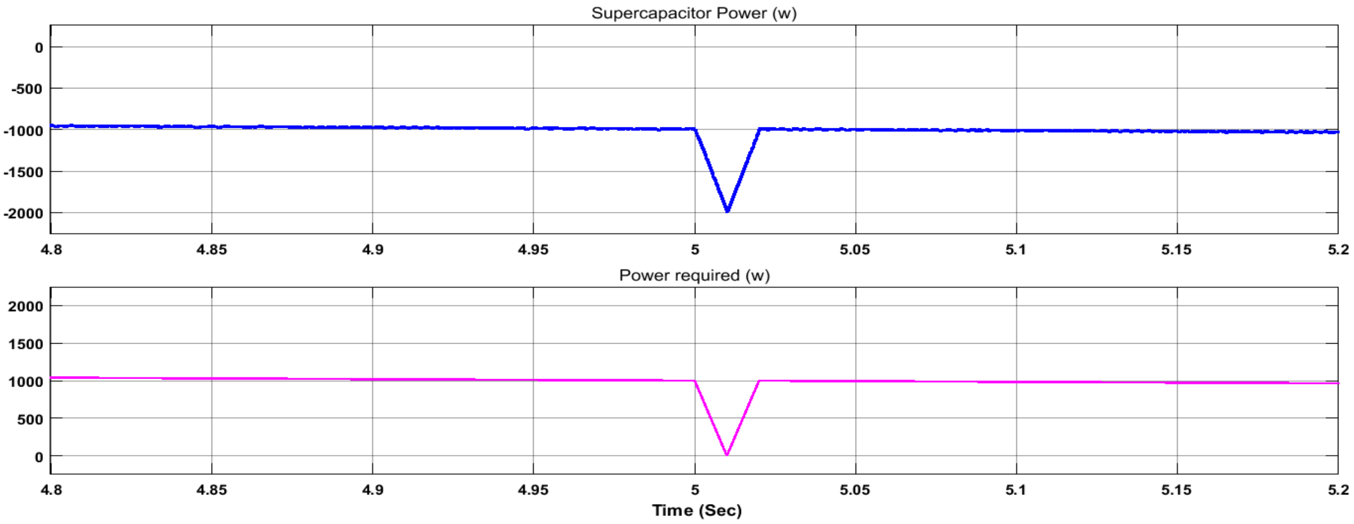

Figure 8(a): Representation of the ultracapacitor power support and power demand.

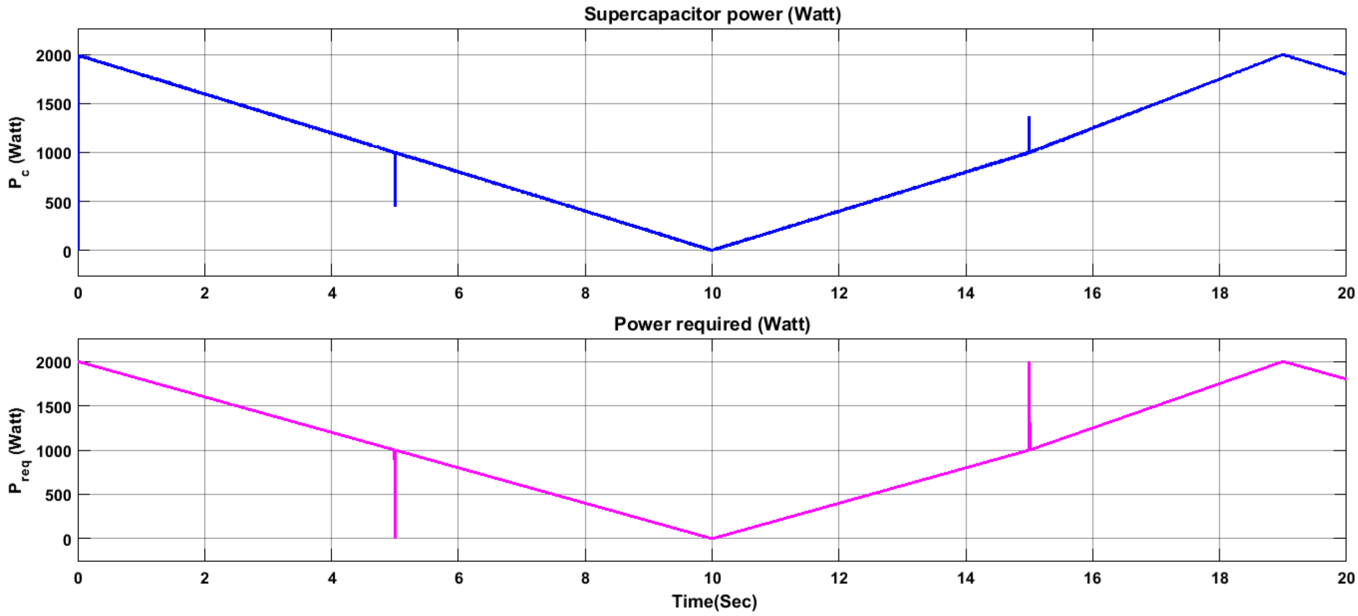

Figure 8(b): Representation of the transient power demand and respective Ultracapacitor support.

In figure 8(a), the representation of the ultracapacitor power support and the power demand for a certain period of time are illustrated to comprehend the practical scenario. In next figure, at 8(b), the power demand and the respective power support by the ultracapacitor-only compensator in transient cases are illustrated. To illustrate the characteristic of the ultracapacitor-only compensator, the instance of ultracapacitor terminal voltage, current, SOC, and power are presented in figure 9 (in the presence of CPL). In figure 17, in the comparative analysis, the terminal voltage response is presented in the case of the ultracapacitor-only compensator. Due to the higher power density and fast response time, the ultracapacitor can stabilize the switching overshoot within 0.02 sec and the grid voltage remains within stable zone of 0.95 to 1.05 per unit, which is standard stable zone for the load-side voltage of a microgrid (5% voltage regulation) and the performance is much better than that of the battery-only compensator [18]. The ultracapacitor-only compensator exhibits poor energy density but high discharging rate; therefore, this compensation technique needs to charge up frequently. On the other hand, in the case of transient load fluctuation, the ultracapacitor-only compensator represents excellent performance. After the handling the transient demand, it undergoes to charging mode again. Hence, hybrid energy storage system comprised of both the battery unit and the ultracapacitor unit is proposed as a compensator to retain the microgrid stability, to handle CPL transients effectively, and provide uninterrupted nominal support.

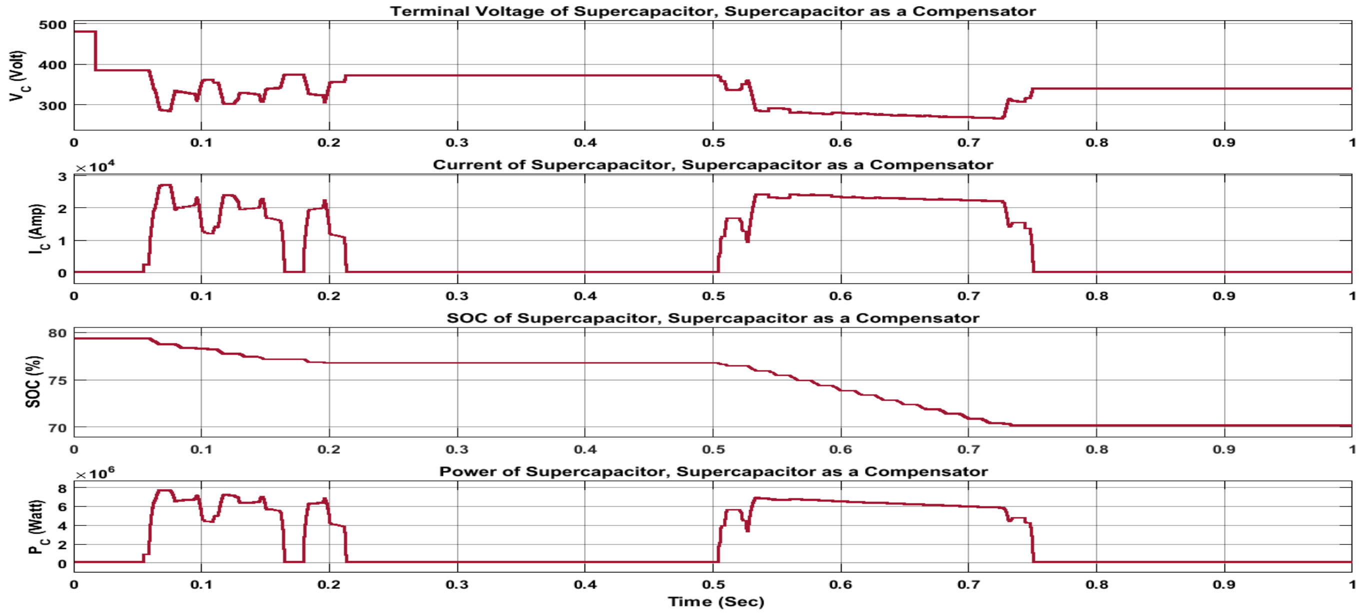

Figure 9: Characteristics of the ultracapacitor (in presence of CPL): terminal voltage (topmost), current (the second one), SOC (the third one), and power (bottom) when the only ultracapacitor is used as a compensator.

3.Proposed Hybrid Energy Storage for Microgrids

To take the advantage of highest energy density of an electrochemical battery and highest power density for an ultracapacitor (according to figure 1 and Table 1), hybrid energy storage system is proposed in this paper. Modelling of the battery was done using AC impedence method [34].

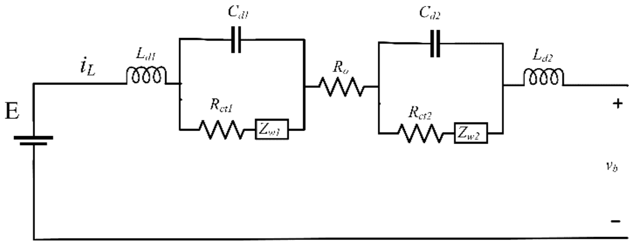

Figure 10: Modelling of the battery using AC impedence [34].

Where E is the voltage source, C_{dl} is a double-layer capacitance, Rct is charge transfer reistance, Z_W is Warburg impedence, R_o is ohmic resistance and L_d is an electrode inductance.

DC circuit test showed a relation between the internal capacitance (C_o) and the open circuit voltage (OCV). Self Discharge resistance $R_{selfdischarge}$ explains the slow gradual drop in voltage over time. Series Branch capacitance (C_{sa}) and resistance(R_{sa}) are also added in the modelling looking at the behaviour in DC test [35].

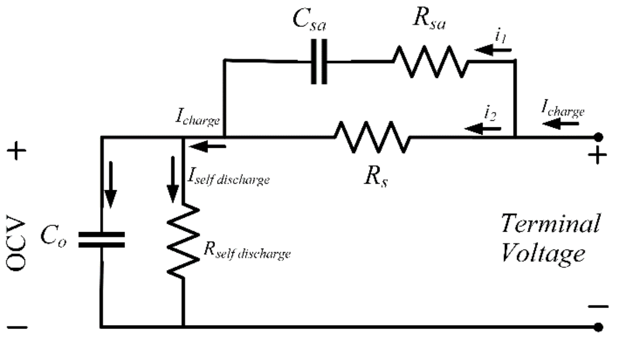

Figure 11: Electrical model of the ultracapcitor showing all the parameter [35].

A comprehensive energy management control algorithm is presented at figure 14 to retain the microgrid stability and to handle CPL transients effectively. The main advantages of a Hybrid Energy Storage System are

- Cutback of overall costs considered to a single storage system (because of decoupling the regarding energy and power, and battery, alone, should manage the nominal power support)
- Raise of entire system performance
- Raise the storage lifetime (lessen the dynamic stress as well as ensure optimized operation)

The combination of lithium-ion battery and ultracapacitor units is selected as a hybrid energy storage system unit for microgrid application (as illustrated in figure 12) with a flexible and smart energy management control algorithm. Figure 13 represents the basic structure of a Hybrid Energy Storage System for microgrids.

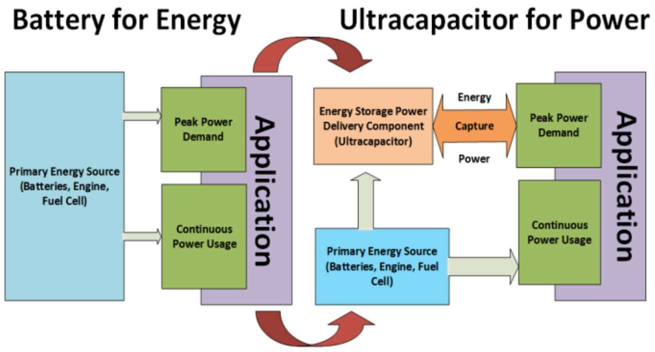

Figure 12: Hybrid Energy Storage System for Microgrid [18].

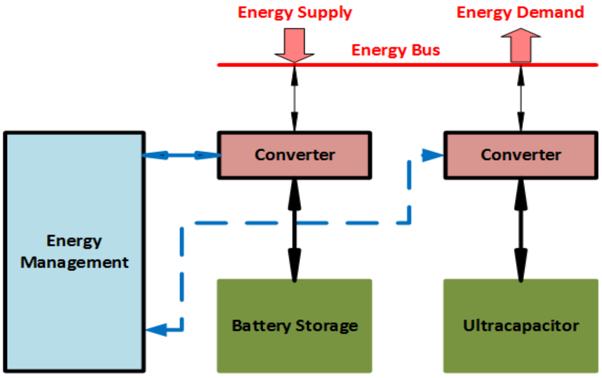

Figure 13: Basic Structure of Hybrid Energy Storage System.

The battery will initiate compensation per the algorithm when terminal voltage remains within 0.99 and 1.01 pu. If the voltage tends to fluctuate from this zone (either upper or lower), the ultracapacitor will initiate compensation. To illustrate the characteristic of HESS compensator, the instance of HESS terminal voltage, current, SOC, and power are presented in figure 19 (in the presence of CPL). Microgrid overall current, frequency and power are represented in figure 15, 16 and 17 respectively for a clear perspective.

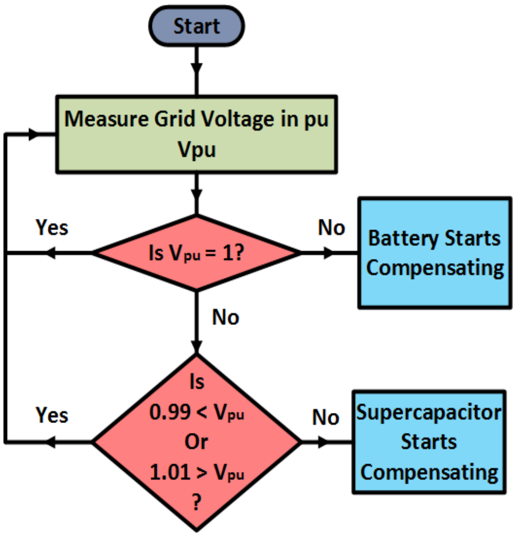

Figure 14: Energy management algorithm form hybrid energy storage system (in the presence of CPL).

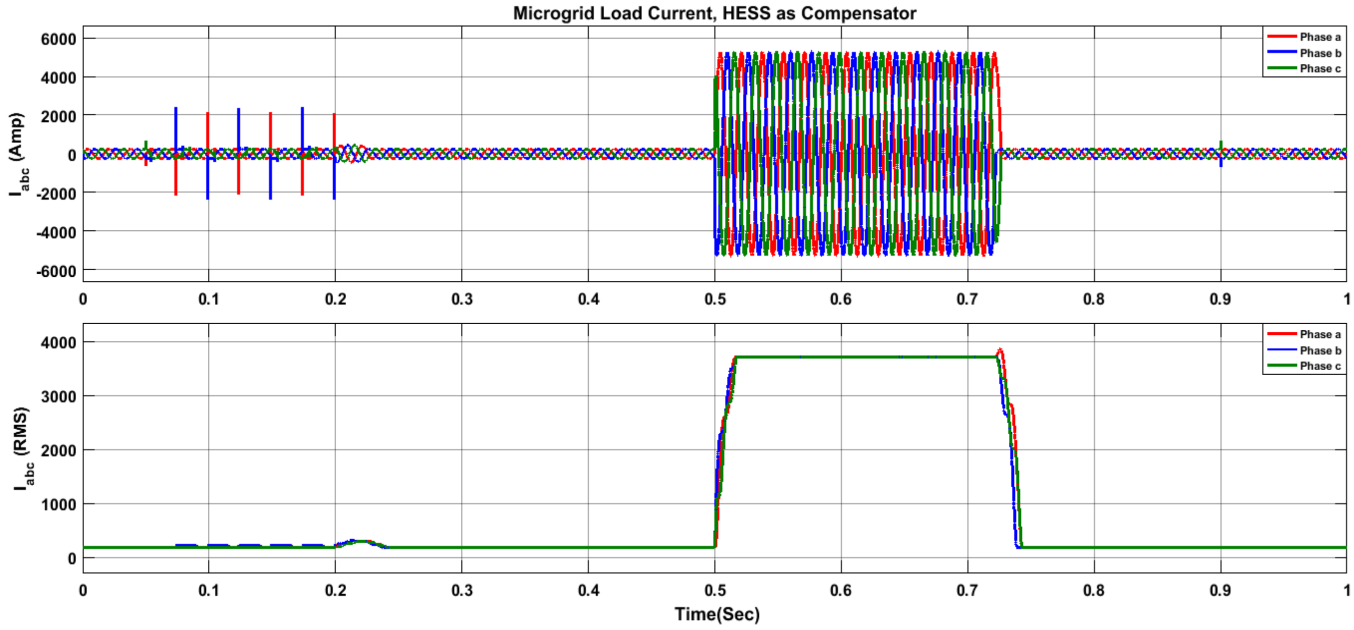

Figure 15: Microgrid current (in the presence of CPL) when hybrid energy storage system is used as compensator.

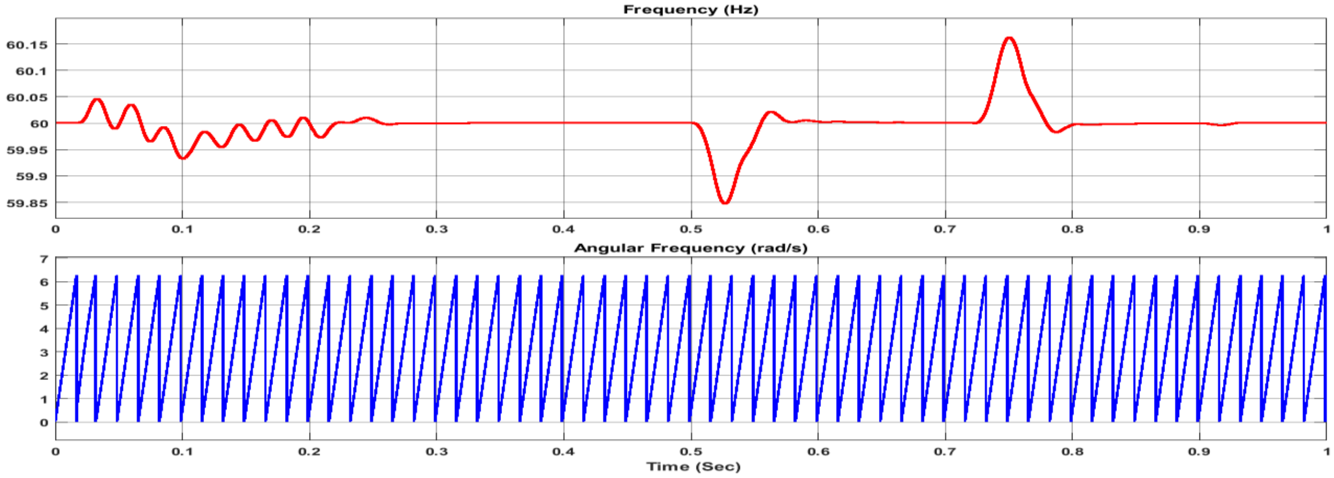

Figure 16: Microgrid frequency (in the presence of CPL) when hybrid energy storage system is used as a compensator.

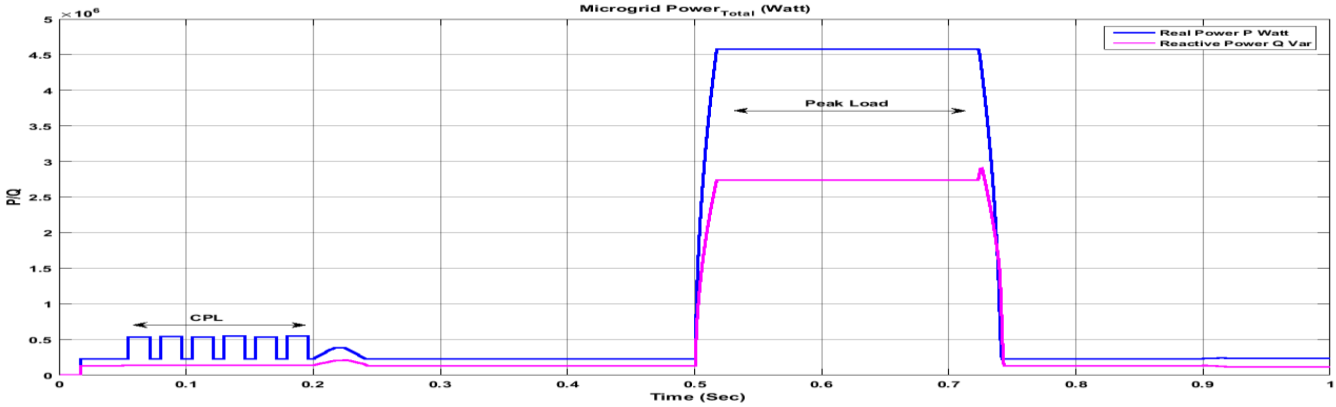

Figure 17: Microgrid power (in the presence of CPL) when hybrid energy storage system is used as compensator.

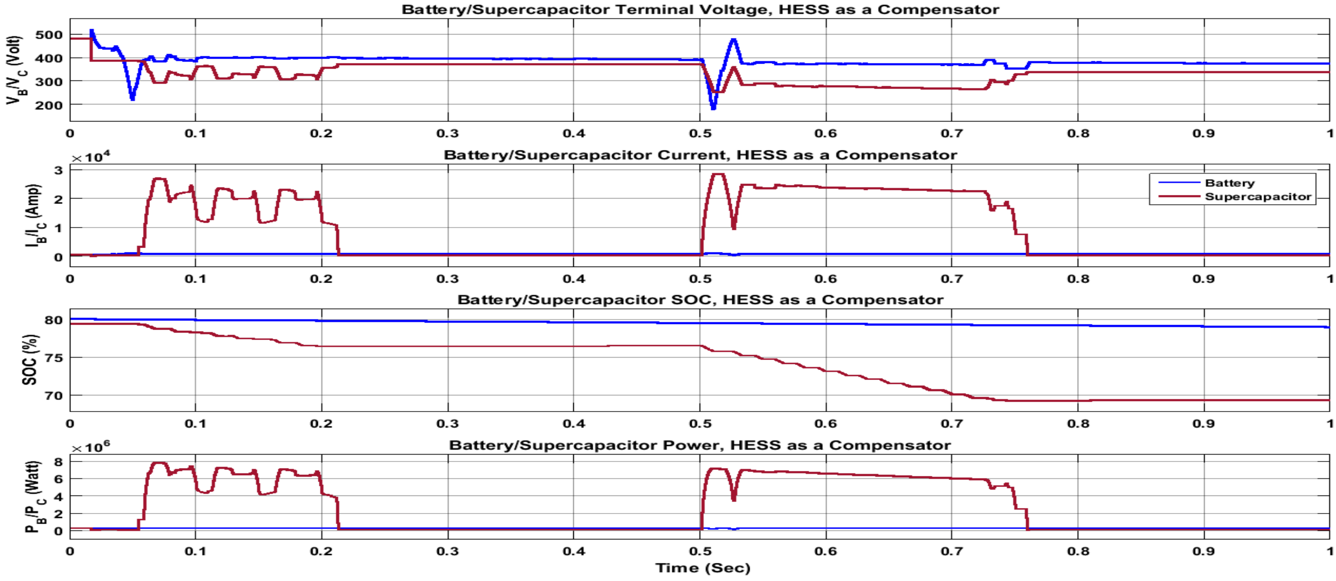

Figure 18: Characteristics of the HESS terminal voltage, current, SOC, and power (in the presence of CPL) when hybrid energy storage system is used as a compensator.

From figure 18, it can be observed that the high energy density from the battery unit and the power density from the ultracapacitor unit support both long term slow SOC demanding applications and transient fast load switching overshoot. As stated earlier here the battery compliments any change in voltage by increasing the negative slope of SOC to stabilize the voltage for CPL loads. In figure 19, the comparative analysis is presented on the performance of handling/compensating the transient spikes among the battery-only compensator, ultracapacitor-only compensator, and hybrid energy storage system as a compensator. From this, it can be seen that the transient peak occurred in the microgrid system has been compensated up to 1.023 pu in the case of battery only compensator, compensated up to 1.02 pu in the case of ultracapacitor only compensator, and compensated up to 1.017 pu in the case of hybrid energy storage system. So, it is evident that HESS can handle the transient spikes most efficiently among these three.

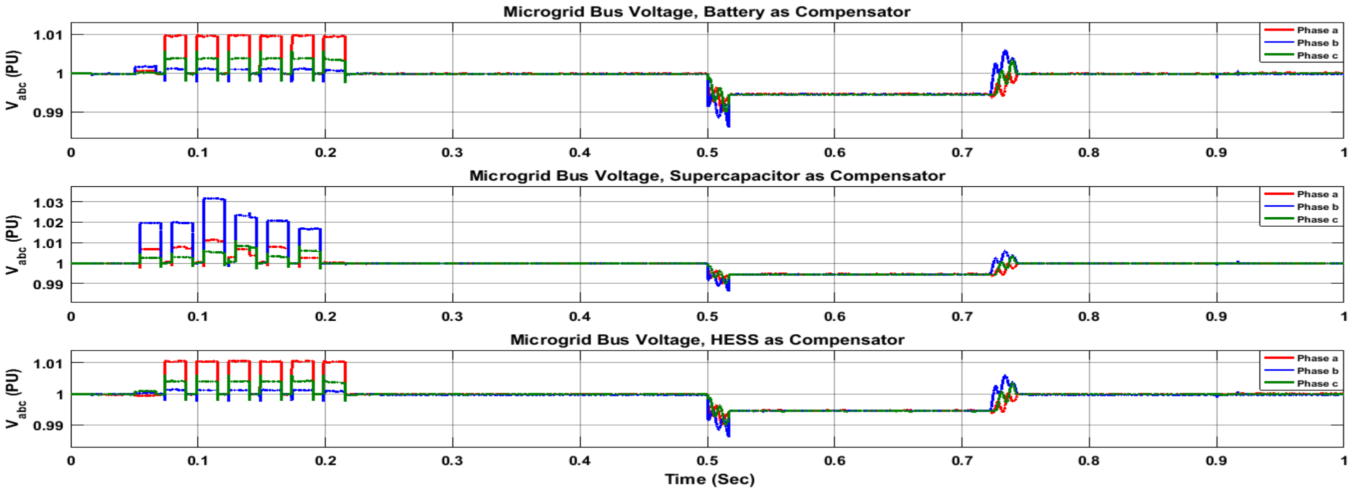

Figure 19: Performance comparison of microgrid bus voltage (in the presence of CPL) among battery-only compensator, ultracapacitor-only compensator, HESS compensator.

4. Performance Evaluation & Findings

Hybrid Energy Storage System has been developed into one of the promising tools to retain and ensure stability in the microgrid arrangement. In renewable energy based power supply policy, instability is one of the major concern for system designers. In this paper, a short overview of typical Hybrid Energy Storage System applications, energy storage coupling architectures, and basic energy management concepts have been presented to show how the stability can be managed in the transient high power requirement scenario. To identify the distinct advantages of the Hybrid Energy Storage Systems, a number of comprehensive analysis results have been presented with similar load profiles and energy management algorithms for the only battery as storage and only ultracapacitor as storage conditions. The key findings of this extended research can be outlined as

- The battery takes longer reaction time (charging/discharging) while, on the other hand, ultracapacitor reacts instantly compared to the battery. In the case of transient power demand, ultracapacitor reacts instantly and assists battery in the process.
- By using this approach, system efficiency can be increased. The microgrid voltage can be stabilized within 0.02 sec and the switching overshoot can be limited to below 1.02 per unit voltage in Hybrid Energy Storage System (HESS) as shown in figure 15. Moreover, similar characteristics have been shown for only battery and for the only ultracapacitor, but HESS has been improved significantly in this outcome.
- In renewable energy-based microgrid arrangement, the transient high power requirement is one of the major concerns for the system designers to ensure stability.
- Battery size is scaled down significantly because the transient load/peak load demand is eventually compensated by the ultracapacitor. Consequentially, the installation cost of additional battery units can be minimized; figure 6(a) implies the phenomenon.
- Generally, for long-term slow SOC demanding applications, high energy density batteries are desirable. But, the high-energy density battery unit cannot sustain at the time of load switching when transient overshoot arises. In consequence, its life cycle reduces dramatically. To solve this dilemma, an ultracapacitor with high power density can be installed to ensure longer power sustainability; figure 8 indicates that characteristic.

  Sometimes, consumers of this power supply system experience sudden black out and brown out, when the storage cannot supply the required transient peak. In this occasion, Hybrid Energy Storage System offers the most reliable operation to handle the scenario.

5.Conclusion

To implement the virtual impedance based compensation technique for retaining microgrid stability, a hybrid energy storage system (HESS) has been proposed in this paper. Here, different energy storage parameters of the battery and ultracapacitor have been compared, and it has been pointed out that battery-only compensator can supply the long-term nominal demand and the ultracapacitor-only compensator can handle the transient demand effectively. To take the advantage of these two attributes, after presenting the energy management algorithms of each conventional storage system, simulation platforms, and evaluating their performance as compensator, the hybrid energy storage system has been suggested which provides combined features of the battery and the ultracapacitor for retaining system stability in this paper. HESS, because of having high power density and quick charging/discharging time, is able to supply the nominal demand for a long period of time as well as handle the transient peaks. In this paper, first, the functional block diagram and the basic structure of the HESS have been illustrated. Then, to operate the HESS, its energy management algorithm has been depicted. After that, the necessary results to evaluate the HESS performance have been presented in this paper. From the results and the performance evaluations, it is evident that the HESS can improve the overall efficiency, cost effectiveness, and life span of the storage system. Besides that, it reduces the storage size and the overall stress on the battery.

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