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Control Design Approach for Improved Voltage Stability in Microgrid Energy Storage System

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Abstract Nowadays, microgrid energy storage system is in great demand in order to compensate the demand-generation mismatch. In this study a new control design strategy is presented to improve voltage stability in energy storage system of DC microgrid. Motivated by various control design approaches available in the literature, a simple low pass filter control design strategy is proposed for battery and ultra-capacitor discharge in fluctuating load conditions. A low-pass filter control design is proposed in this study to establish an ultra-capacitor reference current to keep the DC bus voltage under stable operations. In order to show the efficacy of the proposed control strategy different cases have been considered when battery alone is connected in energy storage system, secondly when battery along with ultra-capacitor and low pass filter are connected. It is observed that the proposed controller exhibits comparatively better performance with the benefit of simple implementation and it increases battery life by making the battery current rise and fall quite smoothly.

1 Introduction

With the demand for power growing every day, clean and uninterrupted energy is more important to focus on. The conventional production processes involve many environmental concerns, including fossil-fuel greenhouse gas emissions, import dependency, etc. In this respect, the focus is on sustainable development (Smallwood, 2002), namely, the production and storage of renewable energy. One good solution could be a microgrid. The disadvantages include low power, power fluctuations, etc. (Cobben, Kling, & Myrzik, 2005).

Microgrids are autonomous systems that can operate in isolation disconnection or in connection with the main grid. Microgrid has various energy sources (solar, wind, etc.), storing devices such as battery, ultra-capacitor, fuel cells,etc., and different AC/DC loads. DC microgrids rely on energy storage systems (ESS) to store energy when supply outpaces demand and supply is insufficient (Ni, Guo, & Li, 2020). While many storage equipment may be used in a microgrid, we need to make the right choices, according to the characteristics.

The stability analysis for hybrid energy storage systems is suggested in order to maintain demand generation inequality and DC bus voltage regulations (Singh & Lather, 2021). On the other hand, a coordinated control method for central and local battery energy storage systems to control voltage of a middle-voltage 6.6 KV photovoltaic-supplied microgrid is suggested in ref. (Dinh & Hayashi, 2013).a decoupled controller for both Battery Energy Storage Systems (BESS) and Super capacitor Storage Systems(SCSS) are designed based on k-type compensator and Lagrange Interpolation (LI) based controllers are designed for BESS and SCSS controllers (Khan & Khalid, 2019). Furthermore, another decoupled control strategy for batteries and supercapacitors based on k - Type compensators and a non-linear PI controller (NPIC) is suggested respectively (Khan & Khalid, 2021).

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Fuel cells do not work and are also expensive in harsh environmental conditions. The problem with conventional condensers is that the energy density is lower. As battery has high energy density and ultra-capacitor are high power density device, thus these are choosen for the storage system (Kakigano, Miura, & Ise, 2010).

Batteries having high energy density are therefore preferred for the storage (Hammerstrom, 2007). Nickel Cadmium , nickel- metal hydride, lithium ion, etc could be chosen for the purpose. Because of the lower costs, lead acid batteries are mostly used (Akar, Tavlasoglu, & Vural, 2017)-(Cao & Emadi, 2012). But we have a problem that the DC Bus stability and its life are affected adversely if the battery tries to compete with the dynamic change in energy demand. The life of a battery depends in large part on its discharge depth, cycling time, rate of charge-discharge, temperature during operation, etc (Ma, Serrano, & Mohammed, 2014). The battery current rise and fall frequently due to volatile behaviour of the load, which further reduces the life of the battery (Zhou, Bhattacharya, Tran, Siew, & Khambadkone, 2011).

This creates the need for a temporary control component or something to cope with such sudden changes. A good way to solve this could be the addition of ultracapacitor (UC) in ESS. The battery will be released from high-frequency components and battery life will get a boost. Ultra-capacitors are electro-chemical condensers with dual layer, also called supercapacitors. The UC is interfaced using a bi-directional DC-DC converter. The literature contains various designs of the PID controllers(Verma, Patel, Nair, & Sikander, 2016)-(Prajapati, Rayudu, Sikander, & Prasad, 2020).

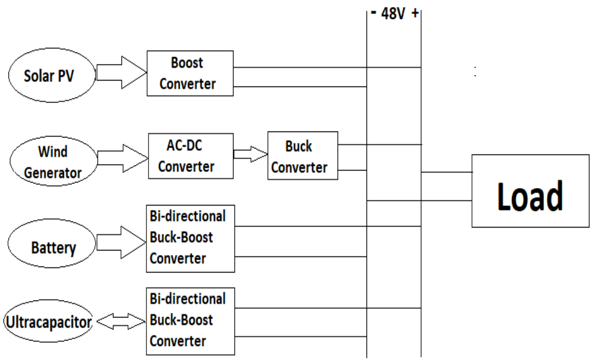

Fig. 1 Structure of a DC Microgrid

The structure of the micro-grid is illustrated in fig 1. The battery and the ultra-capacitor is connected to the DC bus through a bi-directional buck-boost converter (Robinson, 1997)(Bose, 2002). In both the modes, converters can work as per the power flow requirements, i.e. both charging and discharging occurs according to the power demand. The actual loads may be BLDC fan, an LED TV, an LED light, etc,.

The main aim of energy storage system is to supply or absorb the additional voltage that is required to keep the nominal value of the DC bus. The battery however, can't charge /discharge so quickly and these rapidly changing loads can adversely affect the battery's life. Ultracapacitor is therefore considered to solve transient problems on the bus side in order to maintain the voltage of the grid (Dheeraj & Sikander, 2021).

This paper offers a uniquely designed control with the Low Pass Filter (LPF) for determining the discharge of both the battery and the ultra-capacitor of the hybrid energy storage system in case of different loading conditions of the grid. The proposed method maintains the bus voltage at different loads and its transient stability also improves. Also, the proposed control helps in improving the battery's life and performance by eliminating the transient compensation pressure from the battery.

The novelty of the proposed work is the LPF control design for the hybrid energy storage system where voltage stability in fluctuating load conditions is achieved. This design is simple and does not use any complex methodologies or controls like fuzzy logic or FOPID as done by many other researchers in the past. This reduces the recovery time of the system and makes it faster as well.

The simulation results suggest that the proposed control for ultracapacitor discharge exhibits better performance especially in terms of bus voltage deviation and the recovery time when subjected to different loads.

2 Battery Discharge Process Control

The battery is used to supply a constant voltage. There are two cases, in first case when battery needs to be charged, the converter works as a buck converter whereas in the second case, when battery is in discharge mode, the converter is used as a DC-DC boost converter. The battery discharge process is depicted in Fig 2, where an interior current loop and an external voltage loop is shown.

Now, when the microgrid is separated from the central grid, the battery must be discharged. The battery is thus a long-term energy source and act as a voltage source. The DC bus connects the power supply to DC loads. We will use a ultracapacitor to fill the energy gap in the battery as mentioned above, since the large current can negatively affect the battery. When the load changes suddenly, the ultra-capacitor offers high-density power.

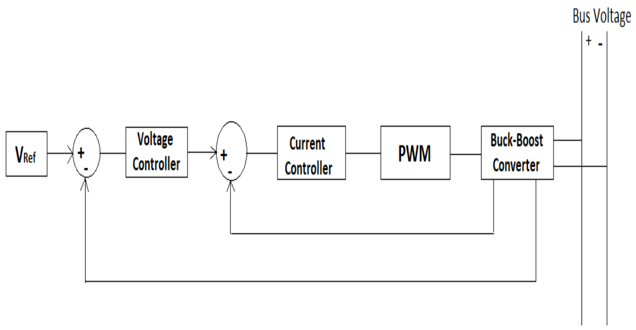

Fig. 2 Battery discharge process

As shown in Fig 2, the voltage and the current controllers are used for the outer and inner loop respectively. K-factor approach is used for designing these controllers to get proper response and required stability from the converter (Venable, 1983).

The ultra-capacitor aims to provide the transient compensation at different loading appearances, rather than the battery that provides the DC bus with the constant voltage. Microgrid power is sufficiently increased by a growing load, and DC bus voltage drops to damaging levels. Likewise, if a particular load is disconnected by the system, the bus voltage peaks sharply. These situations therefore cause the system's stability problem and are also hazardous for the health of the system components. A control method with Low Pass Filter has been proposed which solves the problem of transient in the system and keeps the bus voltage always within the stability limits.

3 Proposed Control Methodology

Here, a low pass filter (LPF) is designed to keep the system in desired stability limits. The bus voltage is sensed and filtered to split the high and low frequency component of the voltage. This is done by passing the bus voltage through the low pass filter. The high and low frequency voltages are extracted to decide the current reference for the ultra-capacitor converter. This is as shown in Fig 3. Therefore, the battery gets only the low voltage to deal with and thus, when there is a load change, battery's current decrease or increase smoothly unlike the condition where battery alone is contributing.

This method is valid for both isolated and discrete loads as just the bus voltage is calculated and current sensors are not needed. In the conventional control methods where the load power is considered for controlling the bus voltage, we need current sensors. This conventional approach is okay for isolated loads but in case of discrete loads the number of current sensors need to be increased as per the requirement. Then these current sensors need to have a good communication and finally transmitted to the local controller. Therefore, we need a good communication network which might be an extra issue to deal with and also it makes the system more complex.

The LPF control is designed so that it activates the ultra-capacitor when there is a transient or high frequency component in the bus voltage. This gives battery the time to decrease or increase its current with ease and therefore it helps the battery to enhance it's life. As already discussed, the battery life majorly depends on the charge discharge rate and cycling time, therefore, proposed control method is helpful in extending the battery's life.

The system is simulated with the designed LPF, and the results are discussed in next section. We sense the bus voltage and apply a low pass filter with a cut off frequency below the frequency of oscillations in dc bus voltage. Now, we can determine that the oscillation frequency is 10 Hz. Simulation results indicate this when ultracapacitors are not participating in the hybrid energy storage system. Due to the slow operating controller of the battery this lag comes. Thus, 8 Hz (50.24 rad/s) is selected as the cutoff frequency for the LPF. The low pass filter transfer function is as follows:

$$LPF(s) = \frac{50.24}{s + 50.24} \tag{1}$$

Fig 3 shows the proposed control method for the ultra-capacitor and battery discharge in a DC microgrid. In the low-pass filter, the low- and high-frequency components of the output power are filtered based on the voltage from the DC grid. The low-frequency voltage goes to the voltage controller and then act as the current reference for the discharge of the battery's current.

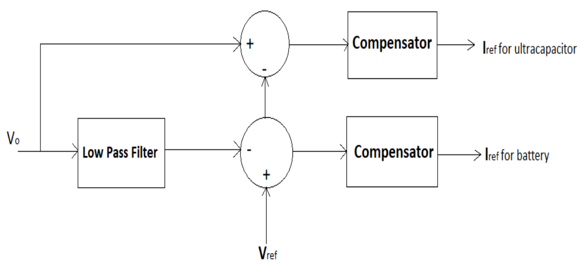

Fig. 3 Proposed Control Method

In the case of the ultra-capacitor discharge, the bus voltage is compared to the output of the LPF, and the resulting error is the component of the output voltage that is of high-frequency. Now, to get the current reference for deciding the discharge of the ultra-capacitor, this voltage interfaces the voltage controller and decides the current reference for the ultra-capacitor. The error gives the required duty cycle to the pulse width modulation (PWM) generator. Further, PWM regulates the switching of the two MOSFETs.

At steady-state, when the volatge is at the rated value, the output of the ultra-capacitor current will be near to zero. Since the voltage of the DC bus increases bluntly as the load increases, LPF gives the high voltage peaks as voltage references to the battery and the low voltage peaks are given to the UC as voltage references. This peak voltage is equal to the output of the UC, therefore, the voltage is boosted as it speeds up the recovery process.

This system operates the ultra-capacitor in two modes: the external voltage control loop and the internal current loop. In the outer loop, the proposed control is used only when the bus voltage changes drastically due to transients, but K-type controllers are used in the internal current loops (Venable, 1983).

In the current and voltage control, a type 2 compensator is used. Type 2 compensators' overall transfer function is as follows:

$$T_{ci} = \frac{A(s+w_s)}{s(s+w_p)} \tag{2}$$

Here, at w_s frequency we have one zero and the poles are at zero and at w_p frequency.

4 Design and implementation of controller

Batteries and supercapacitors both have bidirectional converters of 500 watts and a 48-volt output. The other parameters of the battery and supercapacitor, on the other hand, are shown in Table 1.

Table 1 Parameters of Battery and Ultra-capacitor interfacing converters

Components	Ratings
Inductor of UC converter	650μH
Inductor of battery converter	250μH
Battery	36 V, 146Ah
Super-capacitor	165 V, 48 V
Switching frequency	30kHz

The open-loop transfer function is calculated using small signal analysis. The inductor current to duty cycle and output voltage to duty cycle of a battery interfacing converter is: (Venable, 1983).

$$\begin{aligned} \frac{i_l}{d} &= \frac{190230.41(s+129.7)}{(s^2+431.8s+1412760.4)} \\ \frac{V_o}{d} &= \frac{-0.3686(s^2-11068s-212703645)}{(s^2+431.8s+1412760.4)} \end{aligned} \tag{3}$$

Inductor current to duty cycle is described by the following equation for an ultra-capacitor open-loop small-signal transfer function:

$$\frac{i_l}{d} = \frac{73166(s+235.8)}{(s^2+259.4s+987944.3)} \tag{4}$$

For voltage and current controllers, type two comensators are used. Generally, the transfer function of these compensators are expressed as in equation below:

$$T_{s(Type2)} = \frac{A(s+w_z)}{s(s+w_p)} \tag{5}$$

w_z and w_p are the frequencies at which the system goes to zero and an undefined value (infinity). w_z is called as the zero frqeuency and w_p is the pole frequency. For a type-2 compensator we have one zero and two pole frequencies at w_z, zero and w_p respectively.

The type 2 compensator's transfer functions used in this paper are (Bhosale & Agarwal, 2017):

$$\begin{aligned} T_{ci} &= \frac{78.74(s+1180.2)}{s(s+6510.4)} \\ T_{cv} &= \frac{181(s+84)}{s(s+220.5)} \end{aligned} \tag{6}$$

5 Analysis and Simulation Results

The following table 1 shows the simulation parameters. MATLAB simulation, is used to compare the two methods discussed in this paper. ESS with battery alone is simulated first and then with the combination of battery and ultra-capacitor for a fair comparison. In the following two sections, a thorough analysis is carried out, complete with all the simulation results and their discussion.

5.1 Energy storage system with battery alone

In the case where only a battery is connected to the energy storage system, below are the simulation results. At t = 0.5 seconds, the load is changed from 100 Ω to 20 Ω. The voltage on the DC bus drops to 45.1 volts at 0.5 seconds. Additionally, the battery's current rises to a higher value abruptly at load decrement. When the load increases at 0.5 seconds, the system recovery time is 0.02 seconds. The simulation results can be seen in Fig 4, Fig 5 and Fig 6.

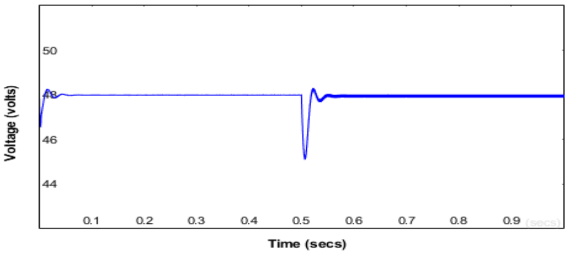

Fig. 4 Bus Voltage when load decreases

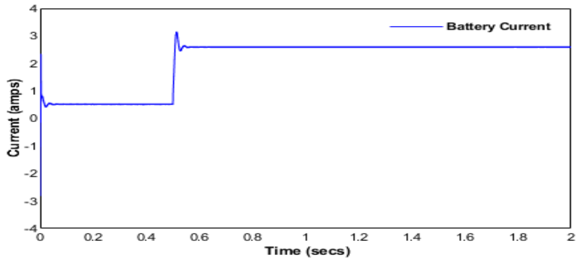

Fig. 5 Battery Current when load decreases

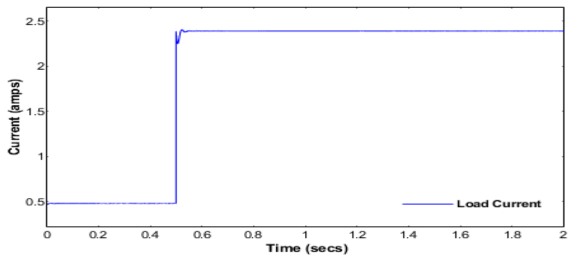

Fig. 6 Load Current when load decreases

In Fig 7, we can see the voltage deviation when the dc load changes from 20 Ω to 100 Ω at 0.5 seconds. The DC bus voltage shoots up to 51.1 volts which is quite high and may lead the system towards instability. In this case, the battery's current decreases steeply as the load power in total comes down, see Fig 8. This sudden decrease is however, not good for the health of the battery and thus we need something to eliminate this transient requirement of the system. The bus recovery time is 0.03 seconds in this case. The graph of load current can be seen in Fig 9.

The load current is 0.48 A at 100 Ω and the battery current is around 1.75 A that may feed the local or

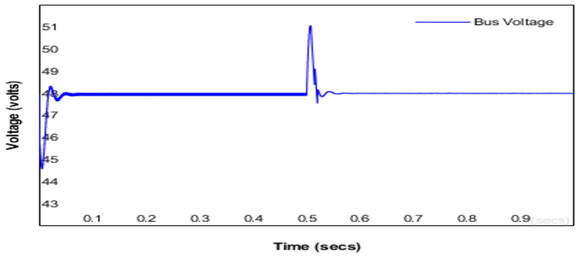

Fig. 7 Bus Voltage when load increases

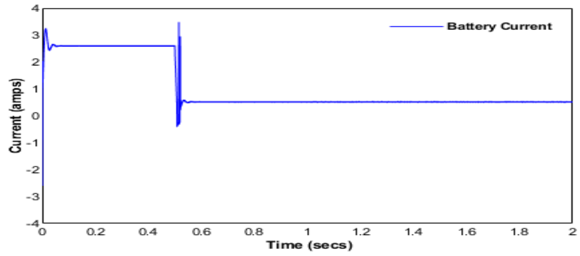

Fig. 8 Battery Current when load increases

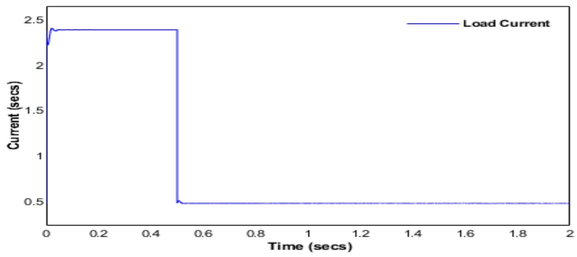

Fig. 9 Load Current when load increases

the actual loads. LED light, LED TV,etc. could be a practical load that can be connected.. When the load comes to 20 Ω, this load current changes to approx 2.35 A and consequently the battery current goes to 4.75 after a slight overshoot. This sudden change in the load demand and battery's slower interfacing converter response make the voltage to dip.

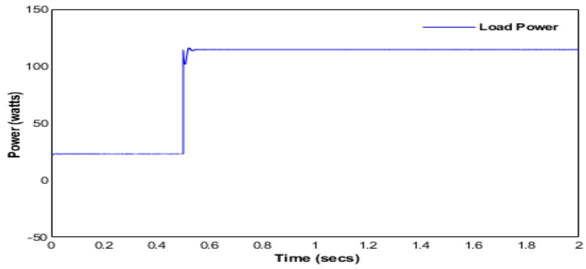

Fig. 10 Load Power when load increases

Also, the power requirement by the battery during the whole simulation time is as shown in the fig 10.

We can see that at the time of load fluctuations the the power demand increases/decreases suddenly which forces the battery current to shoot/dip in a very short duration. And as discussed earlier, this affects the battery life adversely.

5.2 When battery & UC with LPF control is present

This is the case where the energy storage system consist of both battery and the ultra-capacitor. The control of both the battery and UC is governed by the proposed LPF control. The control is so designed that until the bus voltage is set at the rated value the UC will not contribute it's current. But as soon as any load fluctuation is sensed, the UC comes into in the picture. The ultra-capacitor having high energy density is able to give the high current or absorb it as per the requirement of the system.

The simulation results for this case is shown below. The bus voltage is as usual at the rated 48 volts and the moment load is varied in the system, we can see the changes in Fig 11, Fig 12 and Fig 13. Firstly, at 0.5 seconds the load changes from 100 Ω to 20 Ω. This makes the voltage of the bus go down but due to the transient support of the ultra-capacitor, the voltage falls till 47.3 volts only. Also, we can see that the battery current which rised abruptly earlier is rising with much smoothness and slowly. The recovery time for the system is 0.04 here.

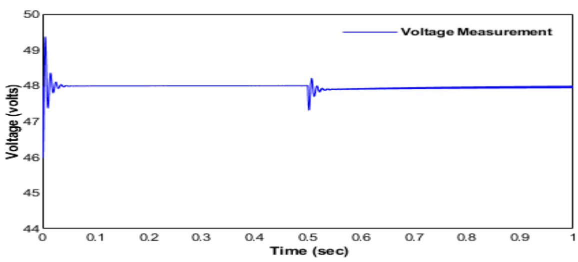

Fig. 11 Bus Voltage when load increases

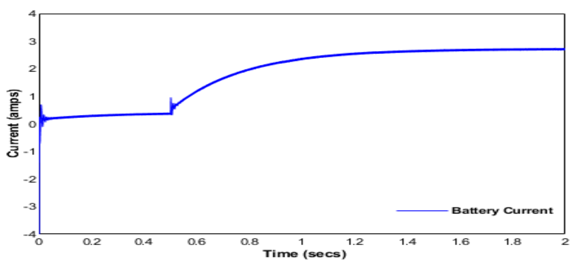

Fig. 12 Battery Current when load increases

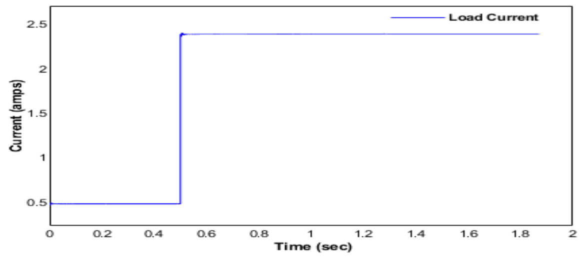

Fig. 13 Load Current when load increases

The load current is same as the previous case. The battery current goes up slowly and attains steady state without any overshoot. Initial voltage of the ultra-capacitor is taken as 40 volts. The UC current rises to 3A approximately and further comes down to as the DC bus voltage restores.

Similarly in another simulation, the load changes from 20 Ω to 100 Ω at 0.5 seconds. The bus voltage increases at this moment but unlike the earlier case it goes till 48.7 volts as can be seen in Fig 14. This is quite an improvement. Also the battery current is seen going down but slowly and there is no sudden change in the current which keeps the battery healthy. The recovery time here is again 0.04 seconds. The UC current goes down to -3A approximately and further comes up as the DC bus voltage restores. This can be seen in Fig 15 and Fig 16.

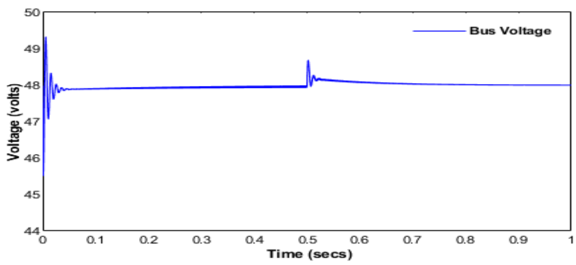

Fig. 14 Bus Voltage when load decreases

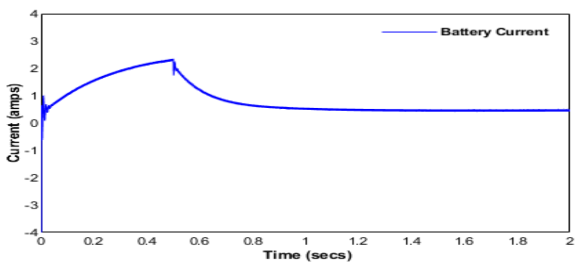

Fig. 15 Battery Current when load decreases

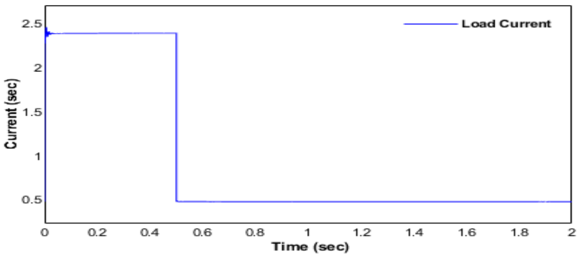

Fig. 16 Load Current when load decreases

The changes in the battery current we see here is due to the contribution of the UC. We can see in the simulation results for both the cases of increasing and decreasing loads that the ultra-capacitor is supporting the battery by providing the high pulse current in both the cases. The UC current rises (in case of load decrement) immediately and then start coming down untill the battery current is set to its nominal value as per the load power. Thereafter the UC current settles around zero.

The Fig 17 and Fig 18 shows the power requirement from the battery and UC for the DC micro-grid during the whole simulation period. We can see that at the instant where the load is varied, the power graph shows a sudden increase/decrease, giving a transient. The fig. shows the power required by battery when the proposed control is used. Here we can see that the increase and decrease of the power have got smoother.

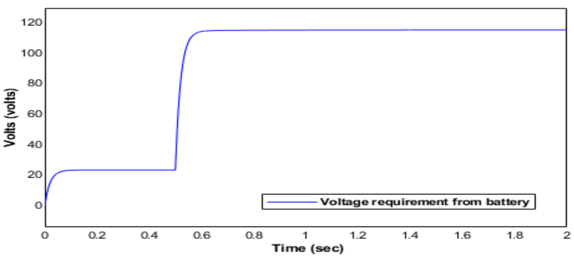

Fig. 17 Voltage Requirement from Battery

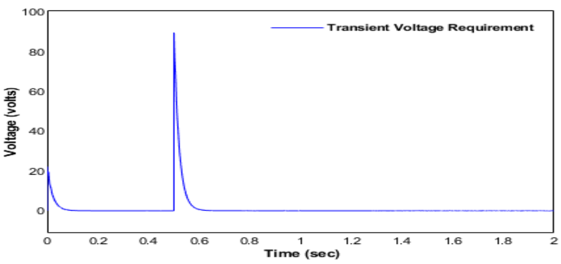

Fig. 18 Voltage Requirement from UC

Also, the transient part is fully taken care by the ultra-capacitor as suggested by the simulation results in Fig 19 and Fig 20. At both the instants of load change the ultra-capacitor gives the transient power required by the grid and gives considerable time for the battery current to rise or decrease.

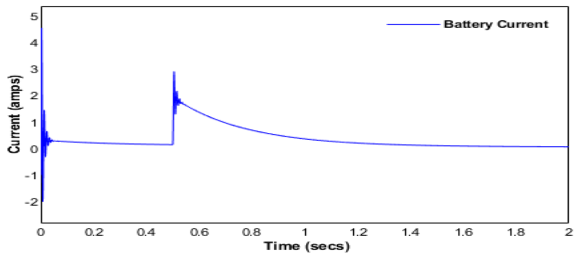

Fig. 19 UC Current when load decreases

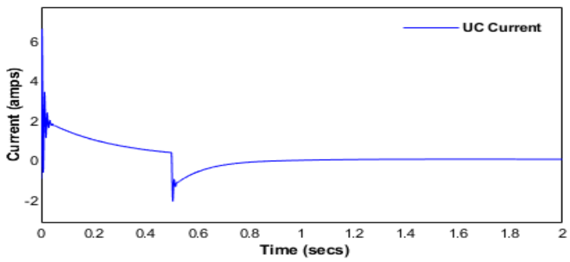

Fig. 20 UC Current when load increases

The Table 2 represents the bus voltage at different loading conditions mentioned above. The percentage deviation is better in the battery and super-capacitor energy storage system.

Table 2 Calculation of the Percentage Deviation during fluctuations in load

ESS	**Time (seconds)**	**Bus Voltage (volts)**	**Load (in Ω)**	**Deviation in Bus Voltage %**	**Recovery Time (seconds)**
Only Battery	0.5	45.1	20	6.04	0.02
	0.5	51.1	100	6.46	0.03
Battery with UC	0.5	47.3	20	1.45	0.04
(LPF Control)	0.5	48.7	100	1.45	0.04

6 Conclusion

Control strategies for battery and ultracapacitor discharge were explored in this paper. Control of ultracapacitor discharge was proposed with a low pass filter and then the results were compared to those when using the battery alone in the energy storage system. The percentage of deviation (from rated voltage) at different loads are calculated along with recovery time of the system. When ESS has only battery acting and the system undergoes a load change from 100Ω to 20Ω the voltage dips from 48 V to 45.1 V, i.e., 6.04% deviation. Similarly, when the load changes from 20Ω to 100Ω, the voltage rises to 51.1 V, i.e., 6.46% deviation from the rated bus voltage of 48V. On the other hand, when the ultracapacitor works in sync with the battery, the voltage dips to 47.3 V when the load changes from 100Ω to 20Ω and when load is changed back from 20Ω to 100Ω, the voltage rises to 48.7 V, i.e., 1.45% deviation in both the cases. These less deviations improve the battery current fall and rise that as well are discussed in the simulation results. These results indicate that the proposed controller exhibits superior performance with the benefit of simple implementation and increases battery life by making the battery current rise and fall quite smoothly. Although the cost of UC is quite high still the advantage of voltage and transient stability of the DC bus along with the enhancement of the battery life makes the overall costing lower when calculated over the years.

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