Abstract—In this paper, a new control strategy is proposed for PV based DC grid system with battery and supercapacitor as a hybrid energy storage system (HESS). To complement the supply demand mismatches in a PV energy based system a hybrid energy storage system consisting of battery and supercapacitor (SC) is generally used. The traditional control approach for HESS uses the high/low pass filter (HPF/LPF) method for system net power decomposition and HESS power dispatch. But due to the slow dynamics of the battery this can create a voltage imbalance problem in the system. We refine a conventional control strategy and propose a new control strategy with the utilization of uncompensated power from the batteries to increase the performance of overall HESS system. Thus, we reduce the stress in the batteries during larger power fluctuations which increase life of the battery. The effectiveness of proposed scheme is shown by simulation studies in MATLAB/SIMULINK.

Keywords— Battery, DC micro grid, Energy storage system, Hybrid energy storage system, Supercapacitors

I. INTRODUCTION

With the rapid penetration of the renewable energy sources and increased concern about energy saving, the design of an electrical power system focuses on increasing utilization of green technologies [1]. PV and wind turbines are the two commonly known green energy technologies. PV is the best choice in terms of sustainability and reliability, but its generation and stability is easily affected by varying operation conditions like change in irradiance, temperature, humidity, and partial shadings effects [2]-[3]. Due to the variable nature, a battery energy storage system is used to solve the problem related to load demand and generation mismatch in real life scenarios [4].

Hybrid energy storage system is implemented to minimize the system power mismatch as well as to have effective and optimal utilization of different energy storages. Batteries with high energy densities are used to compensate the slow transients because of their capabilities to smoothen the temporary slow transients. However, it is unable to deal with sudden high power fluctuations and this affect the life of batteries [3]-[5]. To deal with the larger power fluctuations and to reduce the stress in battery, supercapacitors can be used in combination with batteries to form a HESS. This combination can effectively solve the varying power and energy fluctuations and is generally used to stabilize the output grid voltage in a standalone PV systems with less stress in battery storage system.

In order to control the power sharing between batteries and supercapacitors different control strategies have been reported in literature [3], [6]-[10]. These strategies include fuzzy logic control, neural network, and model predictive control. Hassan et. al [8] has presented a non-linear controller technique for tight DC voltage regulation and effective SC current tracking for electrical vehicles with fuel cell and SC. In [3], multi-mode fuzzy logic based HESS controller for PV system was designed and demonstrated the increased battery life. In [10], shows that battery lifetime can be enhanced upto four times when it is operated in combination with SC. However, the above mentioned control strategies have drawbacks that they require larger computational time and resources. The basic idea behind the above mentioned controller is that the batteries support the temporary slow power fluctuation while the supercapacitors support the high frequency power fluctuations. The proposed control strategy is simple to implement, effective and does not requires large computational time and resources.

This paper is organized as follows. The overall system architecture and modelling of the PV panel, battery and supercapacitor are discussed in Section II. The proposed control strategy is explained in Section III. The system modelled in MATLAB/SIMULINK and simulation results are presented in Section IV. The discussion on analysis, results and future works is presented in Section V this is followed by a conclusion in Section VI.

II. SYSTEM ARCHITECTURE

The overall architecture of the HESS system proposed in this paper is shown in Fig. 1. It consists of a PV array which acts as a primary energy source. The combination of the batteries and supercapacitors are formed to make a hybrid energy storage system which deals with the mismatch
between the PV generation and load demand. The PV power is fed to the DC link using a DC/DC boost converter which works on maximum power point tracking (MPPT) mode. From this, we can achieve the maximum utilization of renewable energy sources. The battery and supercapacitor is connected to the DC bus using a bidirectional DC/DC converter. The bidirectional DC/DC converter works in two mode: 1) charging mode during surplus energy when generation is higher than load demand, and 2) discharging mode when the generation is lower than the load demand. The combination presented is effective in supplying long duration average load demand and short duration peak power surges.

A. Modelling of PV Panel

The non-linear voltage current characteristic equation of the PV module is given by Eq. (1) as in [11].

$$I_{pv} = N_p I_{ph} - N_s I_{rs}(e^{\frac{q(V_{pv}+N_s R_s)}{N_p A K T}} - 1) - \frac{N_p V_{pv}}{N_p R_s} + I_{pv} R_s$$  

where,

- $N_p$ = total number of cells connected in parallel
- $I_{ph}$ = light generated current or photocurrent (A)
- $N_s$ = total number of cells connected in series
- $I_{rs}$ = cells reverse saturation current (A)
- $V_{pv}$ = terminal voltage (V)
- $I_{pv}$ = terminal current (A)
- $R_s$ = series resistance (Ω)
- $R_{sh}$ = shunt resistance (Ω)
- $A$ = ideal factor
- $K$ = Boltzmann’s constant (1.38 * 10^{-23} J/K)
- $T$ = cells working temperature (K)

The remaining parameters mentioned in Eq. (1) can be determined from specification given in [11].

B. Modelling of Battery

The electrical circuit representation of the battery model we used is shown in Fig. 2. An electrical circuit based model is used to characterize the battery given in [12].

The voltage equations of batteries are given in Eq. (2) and Eq. (3).

$$E = E_o - k \frac{Q}{(Q - \int idt)} + Ae^{-B \int idt}$$

$$V_{batt} = E - Ri$$

where, $i$ and $V_{batt}$ are terminal current and voltage of battery respectively, and other parameters can be determined from specifications given in [12].

C. Modelling of Supercapacitor

Supercapacitors are electrical energy storage devices which offer high power density and extremely high cycling capacity. Recent development in technology has made supercapacitors an interesting option for short term energy storage in low voltage power system applications [13].

The $C1$ is the main capacitance of SC responsible for energy storage and charge handling. The $R1$ shows the self-discharge effect of SC and equivalent series resistance (ESR) accounts for the losses during charging and discharging. The $R_p$ and $C_p$ are responsible for the fast dynamic behavior of SCs. The procedure to determine the other parameters is discussed in [14].
III. PROPOSED STRATEGY FOR CONTROLLING HESS

A. Conventional Control Strategy

The basic idea of the conventional control strategy is to allocate the slow transient power demand to batteries and fast transient power demand to supercapacitors. The block diagram representation of the conventional control strategy is shown in Fig. 4. The DC grid voltage is used to sense the generation and demand mismatch. If generation is greater than load demand, the grid voltage tends to rise and vice versa. During such conditions the PI compensator generates the total reference current to be absorbed or supplied by HESS to stabilize the DC grid voltage. The required current is decomposed into two parts in such a way that the batteries support the slow transient power demand and the supercapacitors supplies the fast transient power demand. Due to the slow dynamics of the battery it takes some time to supply the required power and to reach steady state. During such conditions DC bus voltage takes longer time for stabilization.

B. Proposed Control Strategy

The block diagram representation of the proposed control strategy is shown in Fig. 5. The main purpose of the proposed control strategy is to reduce the stress on the batteries and increase the operating life of the batteries. Unlike the conventional controller we divide the power requirement to low and high frequency component.

\[ I_{batt\_ref} = LPF(I_{total\_ref}) \]  

\[ I_{sc\_ref} = I_{total\_ref} - I_{batt\_ref} \]  

Due to the slow dynamics of the battery, the actual battery current is unable to track the references current during the rapid changes in load and supply. Therefore there will be an uncompensated power by the battery which is given as

\[ P_{b\_uncomp} = (I_{batt\_ref} - I_{batt\_actual}) \times V_b \]  

The uncompensated power is compensated by the supercapacitor. So, the new reference current of the supercapacitor is given by Eq. (7).

\[ I_{sc\_ref(new)} = (I_{total\_ref} - I_{batt\_ref}) + (I_{batt\_ref} - I_{batt\_actual}) \times V_b/V_{sc} \]

With the implementation of proposed control strategy the uncompensated energy by battery is released by the supercapacitor during the sudden load change which will be helpful to recover the DC voltage as fast as possible. In addition, it supports the power until the battery comes into a steady discharge stage enhancing the battery performance as well. During the steady state condition there will be less variation in the uncompensated power and hence it does not affect much under that condition. Thus, with this control strategy, we can have a maximum utilization of the supercapacitor as well as an increase in battery life.

IV. SIMULATION RESULTS

The proposed control strategy is evaluated and compared with the conventional control strategy for four different operating conditions. The nominal system parameters used during simulation of the DC grid is listed in Table I.

<table>
<thead>
<tr>
<th>TABLE I</th>
<th>SYSTEM PARAMETERS OF DC GRID</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV array parameters @ STC</td>
<td>Values</td>
</tr>
<tr>
<td>Open circuit voltage ((V_{pv}))</td>
<td>320 V</td>
</tr>
<tr>
<td>Short circuit current ((I_{pv}))</td>
<td>11.92 A</td>
</tr>
<tr>
<td>Mpp voltage ((V_{mppt}))</td>
<td>273 V</td>
</tr>
<tr>
<td>Mpp current ((I_{mppt}))</td>
<td>11.13 A</td>
</tr>
<tr>
<td>Mpp power ((P_{mppt}))</td>
<td>3038 W</td>
</tr>
<tr>
<td>Battery specifications</td>
<td>Values</td>
</tr>
<tr>
<td>Type</td>
<td>Lead Acid</td>
</tr>
<tr>
<td>Ah capacity</td>
<td>14 Ah</td>
</tr>
<tr>
<td>Terminal voltage ((V_{batt}))</td>
<td>48 V</td>
</tr>
<tr>
<td>No of batteries in series</td>
<td>6</td>
</tr>
<tr>
<td>Supercapacitor specifications</td>
<td>Values</td>
</tr>
<tr>
<td>Terminal voltage ((V_{sc}))</td>
<td>320 V</td>
</tr>
<tr>
<td>Capacitance ((C_{sc}))</td>
<td>2.9 F</td>
</tr>
<tr>
<td>DC/DC converters parameters</td>
<td>(L_{pv} = 1.7 \text{ mH}, L_{b} = 1.63 \text{ mH}, L_{sc} = 1.32 \text{ mH})</td>
</tr>
<tr>
<td></td>
<td>(C = 440 \mu F, R = 47 \Omega)</td>
</tr>
</tbody>
</table>

where, \(L_{pv}, L_{b}, L_{sc}\) are the boost converter inductor value for PV, battery and supercapacitor. The \(C\) is output capacitor value for each converter and \(R\) is the load resistance.

The main objective of this simulation study is to observe the effectiveness of the proposed control strategy to maintain a constant DC voltage level (\(V_{ref}\)) to 380V during sudden changes in PV generation as well as during sudden changes in the load demand. The effectiveness of the proposed control strategy is also observed in terms of fast voltage restoration capability and effective power sharing between batteries and
supercapacitors. The PI parameters for the HESS voltage control loop are $K_p^V = 0.24$, $K_i^V = 289$. The PI parameters of the supercapacitor current controller loop and battery current controller loop is $K_p^{SC} = 0.063$, $K_i^{SC} = 742$, and $K_p^B = 0.025$, $K_i^B = 0.00028$ respectively.

A. Case I. Step increase in PV generation

The PV output and the DC output voltage are depicted in Fig. 6. The PV system is operated at MPPT tracking mode. The PV output is increased at 0.1s from 960W to 2725W upon an increase of the irradiance from 300W/m² to 900W/m² at 25°C. During this, load power is kept constant at 2250W. Due to a sudden increase in generation there is surplus of power generation which is needed to be taken care by the HESS system. From the results, it is observed that the output voltage is stabilized faster in case of the proposed control strategy compared to the conventional control strategy. As in the proposed method, SC supplies the high frequency component along with the error component of battery current until the battery reaches the steady state. Moreover, the output DC voltage overshoot seems to be lowered compared to the conventional one.

B. Case II. Step decrease in PV generation

The PV output and the DC output voltage are depicted in Fig. 7. The PV system is operated at MPPT mode. The PV output is decreased at 0.1s from 2725W to 960W upon a decrease of the irradiance from 900W/m² to 300W/m² at 25°C. During this, the load power is kept constant at 2250W. Due to sudden decrease in PV generation the mismatch in generation and demand is to be supplied by the HESS to maintain the DC grid voltage constant. Otherwise, the DC grid voltage will fall below the acceptable region. From the results, it is observed that the output voltage is stabilized faster with the proposed control strategy compared to that of the conventional control strategy.

C. Case III. Step increase in load demand

The output load power and the DC output voltage are depicted in Fig. 8. The PV output power is kept constant at 2725W keeping the irradiance constant at 900W/m² at 25°C. The output load demand is increased at 0.1s from 960W to 3075W. During the sudden increase in load demand the HESS supplies the excess power needed by load to stabilize the overall system performance. It can be observed that the output voltage is stabilized faster in case of the proposed control strategy compared to that of conventional control strategy. As in the proposed method, SC supplies the high frequency component along with the uncompensated power from battery until the battery reaches its steady state value. The performance seems to be improved much more compared to that of the conventional one.

D. Case IV. Step decrease in load demand

The output load power and the DC output voltage are depicted in Fig. 9. The PV output power is kept constant at 2725W keeping the irradiance constant at 900W/m² at 25°C. The output load demand is decreased at 0.1s from 3075W to 960W. During the sudden decrease in load demand the HESS absorbs the excess power due to generation and load mismatch to stabilize the overall system performance. From the results, it is observed that the output voltage is stabilized much faster in case of the proposed control strategy compared to that of the conventional control strategy.
V. DISCUSSION

The following comments are cited on the analysis, results and future works:

a) The observation we have made is that the proposed control strategy can significantly improve the performance of the controller in HESS system.

b) The improvement in performance of HESS system with analysis of the exact increase in battery life can be evaluated in future scope of work.

c) In the future works, besides the DC grid stabilization, optimal selection of battery and supercapacitor ratings can also be analyzed.

VI. CONCLUSION

The comparisons of the proposed control strategy with the conventional control strategy for various operating conditions for PV generation and load demand have been presented in this paper. We observed DC output voltage is stabilized faster with proposed control strategy than with conventional control strategy. The reason behind this improvement is due to SC supplies the high frequency component along with the error component of the battery current until the battery reaches the steady state. The proposed controller is much beneficial to enhance the life of the battery reducing stress in the battery with simple modification in the conventional controller. The proposed controller is simple to implement and its performance can be enhanced further with the optimal selection of the battery and supercapacitor ratings.

REFERENCES