State of charge control based improved hybrid energy storage system for DC microgrid

Rital R. Gajjar[1], Nimay Chandra Giri[2], Unnati Patel[3], Rakeshkumar C. Gajjar[4], Dhavalkumar Dave[3], Abouelmaaty M. Aly[5]
[1]Department of Electrical Engineering, Faculty of Engineering and Technology, Parul University, Gujarat, India
[2]Department of Electronics and Communication Engineering, Centurion University of Technology and Management, Odisha, India
[3]Department of Business Management, International Business Management, Middlesex University, London, United Kingdom
[4]Department of Electrical Engineering, Sardar Vallabhbhai Patel Institute of Technology, Vadodara, Gujarat, India
[5]Department of Power Electronics and Energy Conversion, Electronics Research Institute, Cairo, Egypt

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ABSTRACT

This paper proposes a non-communication power management plan for a renewable solar-photovoltaic (PV) hybrid direct current (DC) microgrid consisting of batteries and supercapacitors (SCs). An effective control strategy for bidirectional converters has been proposed for power supply and load generation at different operating modes and state of charge (SOC) limits of the hybrid energy storage system (HESS). The battery and SC combination provides power to the load during normal or peak operating hours. The proposed hybrid power management system was tested under uneven load and generation using MATLAB. The proposed control enhanced the operation of microgrids by utilizing HESS with a novel control strategy based on the SOC. Seamless mode switches among different operating modes are also presented in this paper. This approach ensures stable current control, minimizes charging-discharging mode changes, mitigates the risk of overcharging and over-discharging batteries, extends battery service life, and balances the SOC across different energy storage units. Consequently, this strategy enhances the operational stability and economic efficiency of the DC microgrid. The proposed methodology provided better power allocation and improved the life of the battery.

Corresponding Author:

Abouelmaaty M. Aly
Department of Power Electronics and Energy Conversion, Electronics Research Institute
Cairo, 12577, Egypt
Email: abou@eri.sci.eg

1. INTRODUCTION

The renewable energy-based solar-photovoltaic (PV) energy has become an attractive option for the application in distributed generation due to its high efficiency, reliability, low cost, and less maintenance [1]. The intermittent nature of the solar-PV source makes it necessary to deploy energy storage devices [2], [3] as the power variation will lead to a significant deviation in bus voltage and reduce the stability of the microgrid system. As the solar-PV source generates direct current (DC) power, appropriate converters must provide power to the conventional alternate current (AC) loads. In grid-connected mode the role of the energy storage system is not significant; because it plays the role of reducing energy changes or enabling the system to operate in stand-alone mode when the grid is not available [4]. Proper and effective energy management is crucial for the seamless operation of an integrated standalone DC microgrid. Therefore, an in-depth investigation into coordinated energy control is necessary. In the absence of frequency and phase in the integrated standalone DC microgrid, the bus voltage becomes a vital reference indicator for assessing the microgrid's stability.

Droop control is a widely employed method for regulating DC bus voltage. It exhibits robust scalability compared to alternative methods and facilitates power distribution even without communication. The trade-off between bus voltage regulation deviation and power distribution accuracy arises due to line impedance. Several approaches based on droop control have been proposed to address this challenge.

Chen *et al*. [5] introduced a nonlinear droop control that effectively alleviates the aforementioned contradiction in constant power load situations. However, its performance diminishes in non-constant power load scenarios. The research in Jafari *et al*. [6] developed a frequency injection adaptive droop control by introducing a low-amplitude AC signal into the DC bus. This approach fundamentally eliminates the dependence of secondary control on communication.

Maintaining the stable operation of the integrated standalone DC microgrid requires a focus on energy management, which stands as a crucial research component. It is significant to provide a well-designed coordination control strategy among the integrated energy units in the islanded DC microgrid. Zhang and Wei designed [7] an energy management strategy based on the charging and discharging power of the energy storage unit to maximize the use of PV energy. A different energy management system has also been proposed for the coordinated control of standalone microgrids [8], [9]. A dynamic power control scheme is presented in [10] with two configurations of microgrid. In the proposed work in [11], reported the performance analysis of a hybrid AC/DC microgrid under the influence of battery energy storage location and proved that compared to the AC grid with a battery energy storage system, the DC grid with a battery energy storage system of the high inertia enclosure achieved an average of 40% better performance [12]. It offers a reliable transition for the operation of multiple solar PVs and batteries situated at different locations.

The moving average filter satisfactorily divides the essential and fluctuating power components. The multiple sources and storage operate under multi-time scale droop control with supervisory control in the second configuration. Different power management and energy management strategies are discussed in [13]–[15] with different energy sources and different power converters for interfacing are discussed in [16].

Because batteries work slowly, supercapacitors (SCs) are used with the batteries to stabilize the charge. A control scheme is also provided to ensure a smooth transition between the different modes of operation [17], [18]. The authors proposed a crucial aspect of the design of a DC link voltage controller operating stably in all operating modes of a DC microgrid [19]. The authors displayed that the battery and SC storage play a significant role during island operation mode to supply the customer with unpredictable generation and load conditions [20]–[22]. It consumes the excess power from solar-PV and supplies it when the generation is less while maintaining the DC-link voltage. The authors developed a proportional-integral (PI) and a self-adaptive fuzzy-PI controller to optimize the double closed-loop control strategy [23]. Techno-economic-environment optimization analysis of different energy sources is presented in [24], [25].

Majority of the the methods presented in the literature still heavily depend on external communication and are not well-suited for applications requiring high reliability. To address the issue of high reliance on external communication for power distribution, this study focuses on the island operation of DC microgrids. It introduces a power secondary distribution method based on state of charge (SOC) without the need for communication among hybrid energy sources. Utilizing the traditional low pass filter method and droop control, the control system autonomously redistributes power based on the SOC of different energy storage units to achieve SOC balance.

By leveraging the characteristic that voltage cannot change suddenly, the control system ensures smooth current control. This approach minimizes the frequency of charging-discharging mode changes, contributing to an extended service life for the battery. The efficacy of the proposed control strategy for distributed hybrid energy storage system (HESS) is validated through both simulation and experimental studies. In summary, to prolong the life of the batteries and the SC, overcharging, and over-discharging are to be avoided. The primary focus of this research is to optimize the operation of the microgrid by introducing a power allocation method that takes into account the state SOC of the HESS and to enhance the operation of microgrids by introducing a novel control strategy based on the SOC of battery and SC. The proposed methodology aims to optimize power allocation and improve the overall efficiency of the microgrid with an expanded life of energy storage system. The primary contributions of the paper are:

- Design an improved energy storage system for the DC microgrid.
- Better control of HESS without communication for automatic switching of operating modes.
- Reduces the number of charge and discharge cycles resulting in extending the service life of a battery.

2. PROPOSED SYSTEM ARCHITECTURE

Figure 1 presents a proposed power management scheme that integrates a DC microgrid with solar modules as the primary source for a battery and SC based HESS with a DC load. All different energy sources, loads, storage, and control are connected to a common DC line. This system ensures the stable operation of the microgrid. This control system plays an important role in controlling the DC bus voltage, generating, and monitoring the current consumption of the solar-PV, battery, and SC. This paper's primary purpose is to develop a system that gives a secure, uninterrupted, and reliable power supply to the connected load. The power relationship of each part is as (1):

$$P_{PV} + P_{HESS} = P_{Load} \tag{1}$$

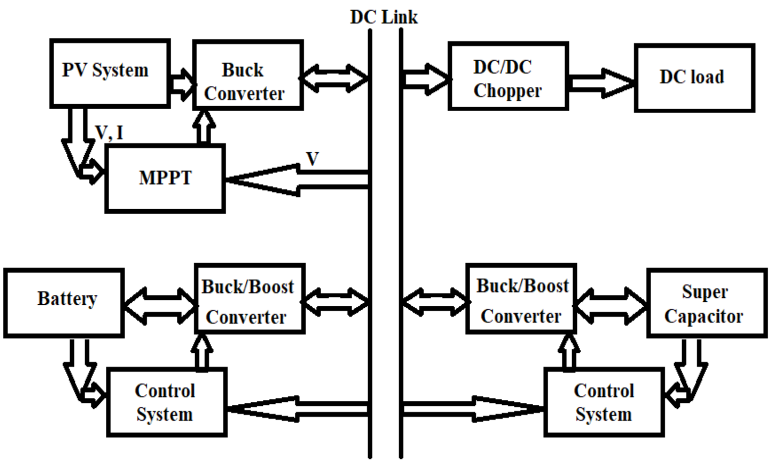

Figure 1. Proposed HESS with solar-PV

With solar-PV as a primary energy source connected with the DC link through a buck converter, the HESS comprises a battery and SC. With its high energy density, the SC acts faster than the battery to sudden fluctuations in load or generation and balance the stability of the system. In contrast, a battery with high power density can supply the load for an extended period.

2.1. Control system for hybrid DC microgrid

To optimize the independent control of each HESS, and improve system reliability and "plug and play" capability, the converter within HESS incorporates droop control to stabilize the DC bus voltage. The enhanced control structure is employed to oversee power distribution among the hybrid energy sources. Utilizing the SOC, adjustments are made to the output power of the battery and SC within the module, aiming to maintain SOC within a healthy range. Across the various hybrid energy sources, overall output is regulated through a reference bus voltage regulator based on SOC. This ensures the overall available capacity of each hybrid energy source remains relatively consistent.

The use of V-I droop control in each hybrid energy source eliminates the need for communication in coordinating their control. This approach offers high reliability, scalability, plug-and-play functionality, and facilitates convenient installation and deployment. Battery and SCs are mainly used to follow the current instructions given by the power distribution controller, as shown in Figures 2 and 3. Reference current (I_Ref), battery current (I_battery) and SC current (I_SC) respectively represent the reference current and the actual current of the battery and SC. V-I droop control can be expressed as (2):

$$V_{o^*} = V_{DC} - R_V I_o \tag{2}$$

V_{DC} is the reference value of DC bus voltage under no load, V_o* is the specified value of converter output voltage after correction, and R_V is the droop coefficient.
The value of R_V is determined by:

$$R_V = \frac{(V_{DC} - V_o min)}{I_o max} \tag{3}$$

$V_{o}{}_{min}$ is the allowable minimum steady-state value of DC bus voltage, and $I_{o}{}_{max}$ is the maximum current value that DC/DC converter can output/input.

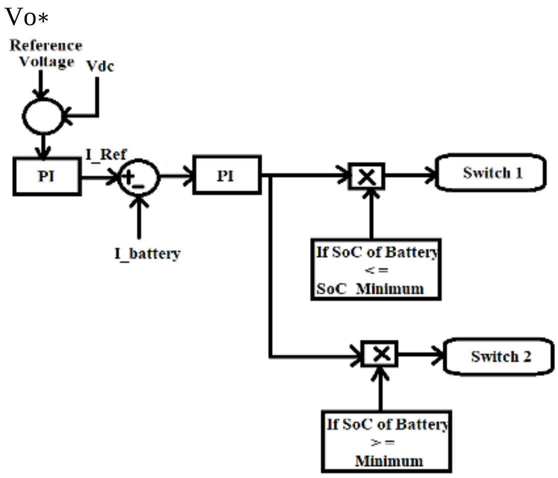

Figure 2. Battery control method

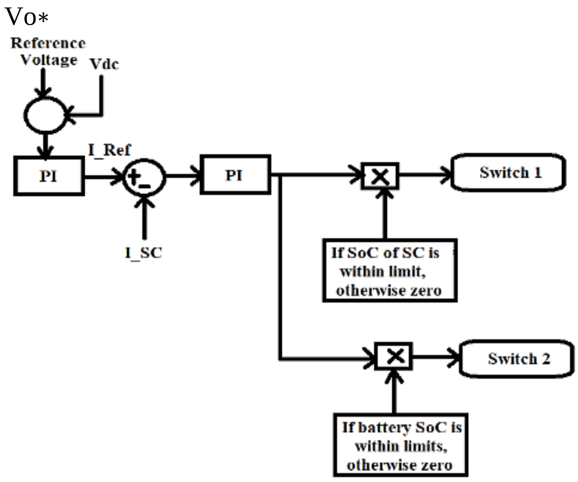

Figure 3. SC control method

2.1.1. Control for PV system

As the output from solar-PV is intermittent, maximum power point tracking (MPPT) with the incremental conductance method is used to extract the maximum available power from solar-PV. The control method operates in the following operating modes: the extraction of maximum power and maintaining the voltage. When the battery or SC is less than its maximum SOC limit, it will operate in MPPT mode. When the generation is more than the consumption, the excess power will charge the battery and SC. If both the HESS elements are at their maximum SOC, then solar-PV will work in constant voltage mode and stabilize the bus voltage at the load side. The control method for solar-PV, is shown in Figure 4. The output of these control blocks operates the respective converters to apply the proper power sharing and maintain the DC-link voltage.

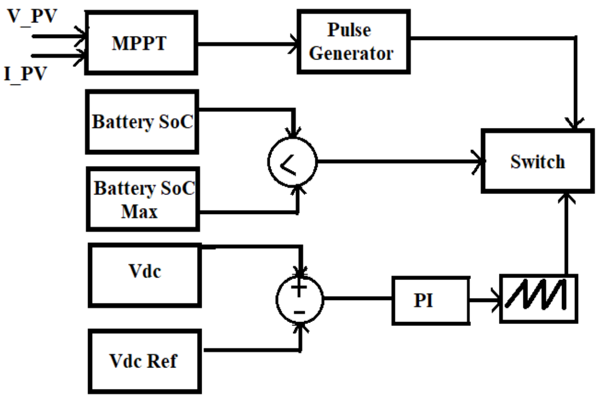

Figure 4. Solar-PV control method

2.1.2. Control for battery

The battery bank is used in conjunction with solar-PV which acts as an energy buffer for balancing the power. The battery is mainly used to follow the current instructions given by the power distribution controller. A 24 V, 83.33 Ah battery has been used with a minimum SOC limit of 20% and a maximum of 80%. The DC-link voltage to be maintained is 48 V. The battery control method is shown in Figure 2. The control structure for the SC is depicted in Figure 3.

This output is converted into a complementary pulse which is given to switches 1 and 2 of the DC-to-DC converters. The buck and boost of the battery operation depends on the ON/OFF of the switches. When the battery feds the load, switch 1 is ON, and voltage is boosted from 24 V to 48 V (<=80), and when the battery consumes the generated power, it is buck mode, i.e., 48 V to 24 V (>=20). The battery gets charged during buck operation and discharged while boosting operation.

2.1.3. Control for SC

The SC is also used in the HESS along with the battery to handle the transient load condition. The energy stored by SC is given by (4):

$$E_{se} = \frac{1}{2} V_{Sc}^{2} \quad (4)$$

In the proposed scheme, the SC is connected with the DC-link via a DC-DC bi-directional converter driven by two switches S3 and S4, of the converter control. Figure 3 shows the SC controller model, which is similar to the battery controller. It has two loops: a voltage control loop that regulates the reference input to the converter and an inner current loop that scrutinizes I_SC and compares it with the I_Ref produced by the PI controller, as shown in Figure 3. This current is limited by the SC limiter block to its maximum and minimum limit. The output is converted into a logical form that compares with the SOC limits of the battery and SC and controls switches 1 and 2 of the converters.

2.2. Operational modes

The DC link's total power depends on the generation from solar-PV, the sum/difference of power supplied or absorbed by the energy storage system, and the difference of power consumed by the load. The DC link's total power given by (5):

$$P_{py} \pm Pb \pm P_{sc} - PL = P_{dc} \quad (5)$$

The operating mode of the system varies according to the PV power produced, the load consumption, the SOC of the battery and the SC, and the DC link voltage. The following are the three modes of operation considering the situations:

- Condition I: generation greater than load ($P_{pv}>P_L$)
- Condition II: generation less than load ($P_{pv}<P_L$)
- Condition III: equal generation and load ($P_{pv}=P_L$)

Mode 1: $P_{pv}>P_{load}$ and $BAT_{socmin}<BAT_{soc}<BAT_{socmax}$: when PV power is more significant than the load requirement, the battery and SC are charged with the excess power. The fuel cell will be in an OFF state due to zero reference current.

Mode 2: $P_{pv}<P_{load}$ and $BAT_{socmin}<BAT_{soc}>BAT_{socmax}$: in this mode, when the power requirement is more significant than solar-PV generation and the battery SOC is within range, then the battery, the SC will start discharging according to the current reference generation by PI.

Mode 3: $P_{pv}=P_{load}$ and $BAT_{socmin}<BAT_{soc}<BAT_{socmax}$: when the PV generation and the load are approximately similar, PV will operate in MPPT mode. The battery and SC supply or absorb to cope with the minor difference between them.

Mode 4: $P_{pv}>P_{load}$ and $BAT_{soc}>BAT_{socmax}$: when the battery reaches its maximum limits and is unable to charge itself, the DC-link voltage will start increasing. Thus, in this situation, PV de-rating is done by switching OFF the MPPT mode and making it work in constant voltage mode.

Mode 5: $P_{pv}<=$zero and $BAT_{socmin}<=BAT_{soc}<=BAT_{socmax}$: when the SOC of the battery reaches its minimum SOC limits, the fuel cell will turn on and supply the battery in this situation. The SC will discharge and maintain the system's stability.

3. RESULTS AND DISCUSSION

The proposed hybrid system of solar PV, battery, and SC has been validated under different modes and operating conditions mentioned above. Simulink is used to simulate the system. The following are the discussions for various obtained results. Figure 5 represents a power shared by solar-PV, battery, and SC in the hybrid system with different operating modes; t=0 sec to t=1.4 sec, the system operates under mode 1, with the load maintained at 2.3 kW. The generation is 3.7 kW at t=0.5 sec, 4.1 kW at t=1 sec, and 4.5 kW at t=1.5 sec. As the load is less than the production, the remaining power is taken by the battery and SC for charging. The maximum power consumed by the battery is 1.8 kW, and the SC takes 700 W of power in mode 1 depending on their SOC at different instants. In Figure 5, from t=1.5 sec to t=1.8 sec, the load is maintained at 3.2 kW and solar-PV power is 3.6 kW. Hence, it continues to operate in mode 1. At t=2 sec, the solar-PV power decreases to 2.8 kW and triggers the system to run in mode 2. The power supplied by the battery is up to 300 W, while the SC, due to its fast dynamics, supplies 600 W power to balance the DC-link voltage. At t=2.5 sec, the solar PV power and load become equivalent, i.e., at 3.2 kW or nearby it. Hence, the system runs under mode 3. The battery and SC will operate in constant voltage mode and supply/absorb the power to balance the minor change. Figure 6 shows the variations in DC-link voltage due to fluctuations in power generation and power consumption.

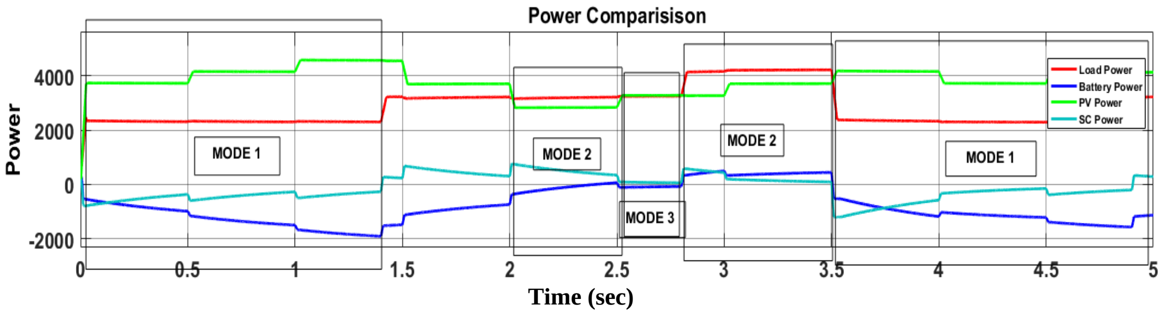

Figure 5. Power sharing by solar PV and HESS

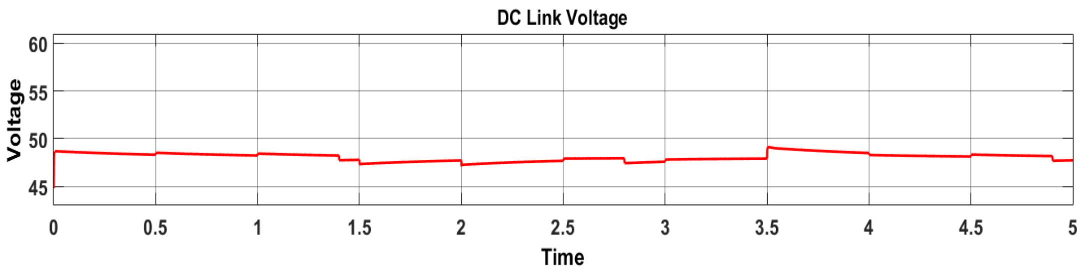

Figure 6. DC link voltage with HESS connected in the system

Figure 7 shows mode 4 operation for a HESS, where the battery hits its maximum SOC limits and cannot charge itself. So, the solar-PV will de-rate and operate in constant voltage mode, at t=1sec, solar-PV power starts de-rating to the load level. The load is constant at 1.9kW, which changes further.

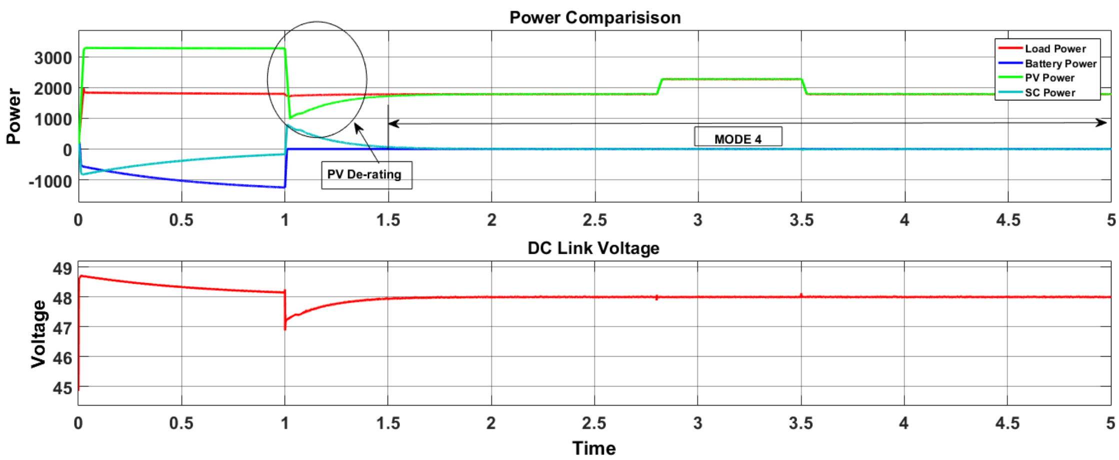

Figure 7. Power comparison for mode 4 for HESS

Figure 8 depicts mode 5 operation, i.e., solar PV power with zero generation. The DC link voltage is maintained at nearly 48 V. As shown in Figure 8, from t=3 sec to t=3.5 sec, the solar PV power becomes zero, and the battery and SC supply 2.1 kW. The power supplied by the battery is up to 2 kW, and the power supplied by the SC is from 600 W to 230 W, as shown in Figures 8 and 9. SC voltage and SOC for mode 5 are depicted in Figure 10.

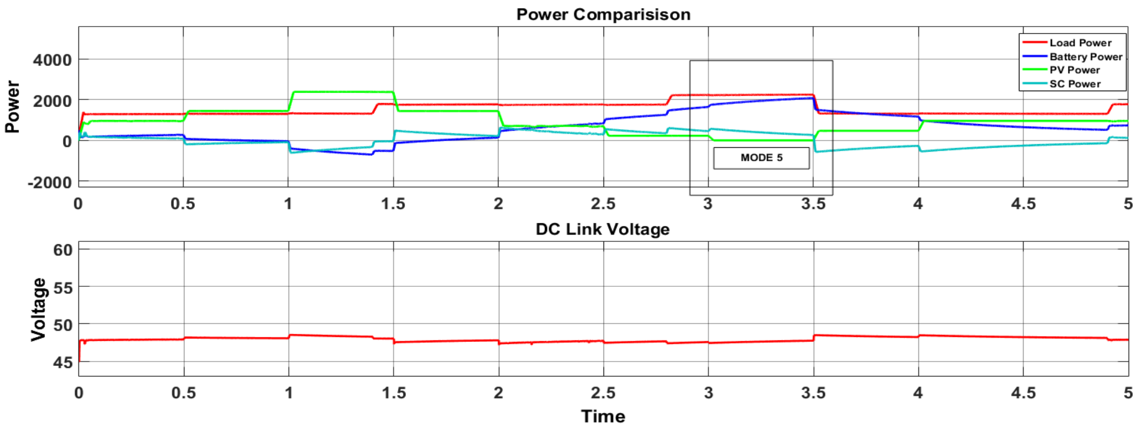

Figure 8. Power and voltage comparison for mode 5 for HESS

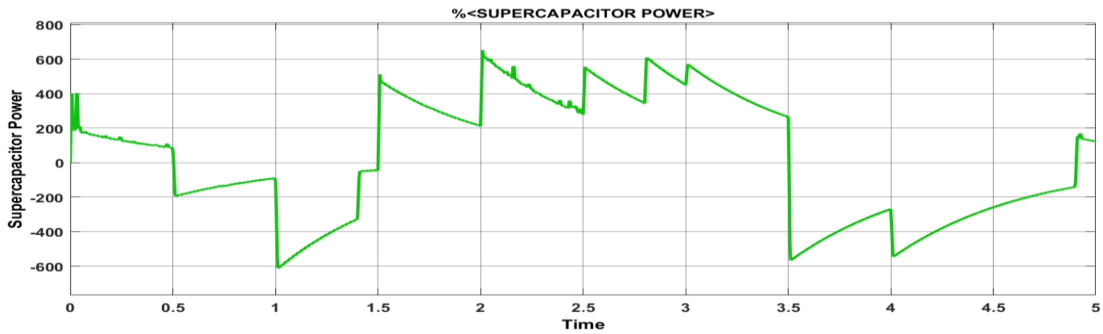

Figure 9. SC power variation for mode 5 for HESS

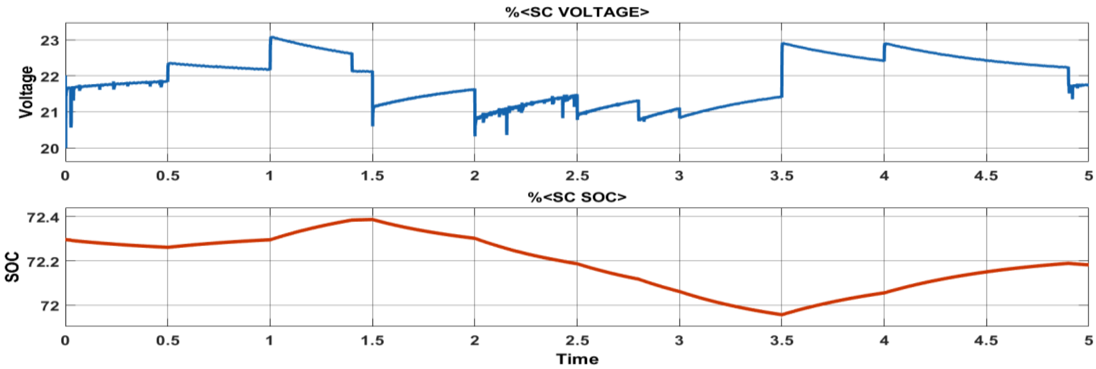

Figure 10. SC voltage and SOC variation for mode 5 for HESS

From Figures 5, 7 to 10, it is evident that following power fluctuations, the bus voltage swiftly returns to stability with minimal voltage variation. The figures illustrate that the change in battery power is relatively gradual, while the SC exhibits a rapid response to power fluctuations, aligning with the control strategy's design objectives. This observation highlights the effectiveness of the proposed control strategy with SOC balancing and does not need any communication among the hybrid energy storage compared to other methods which need communication among the different energy storage. These results prove that the best performance of the controller is fast dynamic DC link voltage recovery and less boost. When the solar-PV generation is switched, uninterrupted voltage restoration of the DC link is obtained in all operating modes. In all modes, the available power is controlled by the SC when the load changes and the battery and the solar PV supply the mean power requirement.

4. CONCLUSION

Addressing the challenge of heavy reliance on external communication in the traditional distributed HESS cooperative control method for DC microgrids, this paper introduces a communication-free dynamic cooperative control strategy based on SOC. The energy management concept presented in this paper describes the performance of the hybrid microgrid in different operating modes. The effectiveness of the control method in supplying battery power during normal operation and operation of the SC during rapid changes was also investigated. DC link voltage with a SC is more stable. SCs respond quickly to power changes. The use of a SC also reduced the load on the battery, thus extending battery life. The main features of the proposed energy management strategies are less stress on the battery, differential power distribution between the battery and SC, smooth transition, fast DC bus voltage recovery, keeping the SOC limit of energy storage in the safety zone, and reducing the reliance on communication among HESS. The results obtained prove that the presented power management strategy and management is effective in seamless mode switching between different operating modes. Nevertheless, this approach does not consider the influence of aging in energy storage elements, including factors such as SOC estimation errors and diminished maximum output power resulting from the declining life of energy storage. Future research will be directed toward addressing these aspects while minimizing communication requirements.

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BIOGRAPHIES OF AUTHORS

Rital R. Gajjar is working as an Associate Professor and Head Department of Electrical Engineering, Parul Institute of Technology, Faculty of Engineering and Technology, Parul University, Vadodara, Gujarat, India. She has done a Ph.D. in the field of advanced electrical drives for Electric Vehicles. As a team member, she has completed one industry-defined research project on Green Refrigeration Systems Using Solar Energy jointly with L&T and the University of Surrey, UK, funded by the Royal Academy of Engineering under Newton Bhabha Fund from 2017 to 2019. She can be contacted at email: rital.gajjar@paruluniversity.ac.in.

Nimay Chandra Giri received M.Tech. in Communication Systems Engineering from CUTM, Odisha, India in 2014. He is currently serving as an Assistant Professor, at the Department of ECE and Center for Renewable Energy and Environment at CUTM, Odisha, India. He has 12 years of teaching, training, and skill experience. His research and skill areas include solar PV systems, energy conversion, protected cultivation, AVS, and aquavoltaic systems. He can be contacted at email: girinimay1@gmail.com.

Unnati Patel PG Student, International Business Management, Middlesex University, UK. She can be contacted at email: patel.unnati178@gmail.com.

Rakeshkumar C. Gajjar has been working as an Assistant Professor in the Department of Electrical Engineering, Sardar Vallabhbhai Patel Institute of Technology-SVIT, Vadodara, and Gujarat, India Since 2007. He has developed one EV car called Eiravat and he is presently working on an EV bike. During his past employment, he has been working as a Power Plant Engineer in Nicholas Piramal Group "Gujarat Glass (P) Ltd. and served as Assistant Engineer-Hydel in Jyoti Ltd. Vadodara. He can be contacted at email: rakeshgajjar.elect@svitvasad.ac.in.

Dhavalkumar Dave he is an Assistant professor in the Electrical Engineering Department at Parul Institute of Technology, Faculty of Engineering and Technology, Parul University, Vadodara, Gujarat, India. He received his M.Tech. Degree in Electrical Engineering from Gujarat Technological University, Gandhinagar in 2015. His area of Interest includes the field of renewable energy sources, electrical machines, and electrical drives. He can be contacted at email: dhaval.dave@paruluniversity.ac.in.

Abouelmaaty M. Aly is an Associate Professor at Power Electronics and Energy Conversion department, Electronics Research Institute (ERI), Cairo, Egypt. He received B.Sc. in Electronic Engineering from Monoufia University, Egypt (1990) with very good honor degree. Then, he had his M.Sc. from Ain Shams University (1997), Egypt and Ph.D. from Kassel University, Germany in 2005. Since graduating, he has been with the Electronics Research Institute (ERI) in Cairo, Egypt. In 2005, he became an Assistant Professor at ERI and Associated Professor since 2016 at ERI. His research interests include renewable energy, photovoltaics, wind power, hybrid systems, energy efficiency, hydrogen and fuel cells, and electrical vehicles. He can be contacted at email: abou@eri.sci.eg.