Enhanced energy storage system efficiency for remote area-based DC microgrid

Maior eficiência do sistema de armazenamento de energia para microrredê DC baseada em área remota

Mejora de la eficiencia de los sistemas de almacenamiento de energía para microrredes de corriente continua en zonas remotas

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Mohammed Abdulelah Albasheri
PhD Student in Electrical Engineering
Institution: LREA Laboratory, Department Electrical Engineering, University of Medea
Address: Medea, Algeria
E-mail: albasheri.mohamed@univ-medea.dz

Ouahid Bouchhida
PhD in Electrical Engineering
Institution: LREA Laboratory, Department Electrical Engineering, University of Medea
Address: Medea, Algeria
E-mail: bouahid2000@yahoo.fr

Youcef Soufi
PhD in Electrical Engineering
Institution: Department of Electrical Engineering, University Echahid Larbi Tebessi
Address: Tebessa, Algeria
E-mail: youcef.soufi@univ-tebessa.dz

Abdelhafidh Cherifi
PhD in Electrical Engineering
Institution: IUT de Mantes-en-Yvelines, Laboratoire END-ICAP-UMR 1179, Université Paris Saclay-Versailles
Address: Versailles, France
E-mail: abderrezzak.cherifi@uvsq.fr

ABSTRACT
This article suggests a hybrid storage system-based DC microgrid to supply the needs of remote areas with variable loads demands. This would help solve problems like limited energy storage systems, complicated consumption, and unstable power production from renewable sources. Energy storage is an attractive option for isolated zones; however, a single storage unit may not be sufficient owing to constraints in capacity, power, energy density, and life cycle. Consequently, this study is concerned with hybrid energy storage systems.
battery/supercapacitor, which combine the most advantageous characteristics of various energy storage technologies to attain relevant performance. Furthermore, the supervision energy management technique based decoupling frequency is designed with low pass filter to separate the current to tow elements, low frequency current absorbed by the battery and high frequency current that absorbed by the supercapacitor. Furthermore, PI controllers are employed to control the DC link voltage, and the current of battery and supercapacitor. Energy management control plays an important role to improve the system performance, ensure power allocation among source, storage devices, and load consumption, and to maintain the battery and supercapacitor at their limitation states of charge (SOC), the system must be able to match the load requirements during a shortage and absorb any surplus power provided by wind energy. To confirm the achievement of the objectives of this study, the comparative simulation between battery storage alone and hybrid storage system combined of battery and Supercapacitor. The simulation results show that the hybrid storage battery and supercapacitor allow to increases the stability of DC link voltage with an overshoot less than 1.5% compared to 7.5% when battery alone and fast dynamic response. in addition, reduces the battery stress and increases its lifetime in the case of hybrid storage.


**RESUMO**

Este artigo sugere uma microrrede DC baseada em sistema de armazenamento híbrido para suprir as necessidades de áreas remotas com demandas de cargas variáveis. Isso ajudaria a resolver problemas como sistemas limitados de armazenamento de energia, consumo complicado e produção de energia instável a partir de fontes renováveis. O armazenamento de energia é uma opção atraente para zonas isoladas; No entanto, uma única unidade de armazenamento pode não ser suficiente devido a restrições de capacidade, potência, densidade de energia e ciclo de vida. Consequentemente, este estudo está preocupado com sistemas híbridos de armazenamento de energia bateria/supercapacitor, que combinam as características mais vantajosas de várias tecnologias de armazenamento de energia para atingir desempenho relevante. Além disso, a técnica de gerenciamento de energia de supervisão baseada em frequência de desacoplamento é projetada com filtro passa-baixa para separar a corrente para elementos de reboque, corrente de baixa frequência absorvida pela bateria e corrente de alta frequência que absorvida pelo supercapacitor. Além disso, controladores PI são empregados para controlar a tensão do link DC, e a corrente da bateria e do supercapacitor. O controle de gerenciamento de energia desempenha um papel importante para melhorar o desempenho do sistema, garantir a alocação de energia entre a fonte, os dispositivos de armazenamento e o consumo de carga, e para manter a bateria e o supercapacitor em seus estados limitados de carga (SOC), o sistema deve ser capaz de atender aos requisitos de carga durante uma escassez e absorver qualquer energia excedente fornecida pela energia eólica. Para confirmar o alcance dos objetivos deste estudo, foi realizada a simulação comparativa entre armazenamento de baterias isoladamente e sistema híbrido de armazenamento combinado de bateria e Supercapacitor. Os resultados da simulação mostram que a bateria de armazenamento híbrido e o supercapacitor permitem aumentar a estabilidade da
tensão de ligação DC com uma sobrecarga inferior a 1,5% em comparação com 7,5% quando a bateria sozinha e resposta dinâmica rápida. Além disso, reduz o estresse da bateria e aumenta sua vida útil no caso do armazenamento híbrido.


**RESUMEN**

Este artículo sugiere una microrred de CC basada en un sistema de almacenamiento híbrido para abastecer las necesidades de zonas remotas con demandas de cargas variables. Esto ayudaría a resolver problemas como los sistemas limitados de almacenamiento de energía, el consumo complicado y la producción inestable de energía a partir de fuentes renovables. El almacenamiento de energía es una opción atractiva para las zonas aisladas; sin embargo, una sola unidad de almacenamiento puede no ser suficiente debido a las limitaciones de capacidad, potencia, densidad energética y ciclo de vida. En consecuencia, este estudio se ocupa de los sistemas híbridos de almacenamiento de energía batería/supercondensador, que combinan las características más ventajosas de varias tecnologías de almacenamiento de energía para alcanzar un rendimiento relevante. Además, la técnica de gestión de la energía de supervisión basada en el desacoplamiento de frecuencias se diseña con un filtro de paso bajo para separar la corriente de los elementos de remolque, la corriente de baja frecuencia absorbida por la batería y la corriente de alta frecuencia que absorbe el supercondensador. Además, se emplean controladores PI para controlar la tensión de enlace de CC y la corriente de la batería y el supercondensador. El control de la gestión de la energía desempeña un papel importante para mejorar el rendimiento del sistema, garantizar la distribución de la energía entre la fuente, los dispositivos de almacenamiento y el consumo de la carga, y mantener la batería y el supercondensador en sus estados de carga (SOC) de limitación, el sistema debe ser capaz de adaptarse a las necesidades de la carga durante una escasez y absorber cualquier excedente de energía proporcionado por la energía eólica. Para confirmar la consecución de los objetivos de este estudio, se realiza una simulación comparativa entre el almacenamiento en batería solo y el sistema de almacenamiento híbrido combinado de batería y supercondensador. Los resultados de la simulación muestran que el almacenamiento híbrido de batería y supercondensador permite aumentar la estabilidad de la tensión de continua con un sobreimpulso inferior al 1,5% frente al 7,5% de la batería sola y una respuesta dinámica rápida. Además, reduce el estrés de la batería y aumenta su vida útil en el caso del almacenamiento híbrido.

1 INTRODUCTION

The power production has made the greatest progress in raising the proportion of renewable energy in its power supply; renewable energy was increased to reach almost 30% of the world's electricity generation in 2022. In the last ten years, the percentage of power generated from renewable sources has climbed by over 9% (Secretariat, 2019). Among the more potential renewable power-generating techniques is the wind energy (Watil et al., 2022). The power conversion technologies used permanent magnet synchronous generators (PMSGs) offer several advantages over conventional variable-speed aero generators among various wind conversion concepts (Lajouad et al., 2019). Benefits self-excitation, flexible control, no gearbox, and great dependability are only a few of the advantages of this kind of machine over conventional ones (Watil et al., 2020)-(Barra et al., 2021).

Autonomous power production using independent wind energy conversion systems (WECSs) is an accomplish option for electrifying rural or remote regions where transmission lines are unavailable (Lin et al., 2021), (Kord; Zamani; Barakati, 2023). Furthermore, it is generally recognized that wind energy source is fundamentally interrupted due to the unpredictable character of the resource and its reliance on geographic and climate variables. Energy storage devices are another key area to investigate that might help mitigate this problem by holding the energy of electrical generated by the independent wind energy system, particularly during times of peak wind power generation (Abedi et al., 2020), (Barelli et al., 2020). Energy storage must be capable for supplying both power capacity and high energy to manage conditions such as high winds or rapid load fluctuations that may continue for a few seconds or more (Mendis; Perera, 2014). Energy storage systems in RAPS systems are often used to balance out power imbalances between generation and load demand, improve power quality and stability, demand levelling, controlling voltage, and providing continuous power (Argyrou et al., 2021); (Koohi-Fayegh; Rosen, 2020). The development of batteries presents a promising answer to the issue of balancing electrical supply and demand (Chong et al., 2018). Historically, batteries have been the main component for storing energy in solar systems. However, there are problems over their efficiency in
charging and discharging, as well as their relatively short lifetime. Although batteries have a high energy density, which makes them suitable for continuous low-frequency power transfer, they have a low power density (Abdulelah et al., 2023). The last point indicates that the battery exhibits low charge and discharge rates, resulting in fast power fluctuations that interrupt its charging and discharging cycles. This, in turn, reduces the battery’s lifetime (Zakzouk; Lotfi, 2020). Relying only on one type of energy storage system, such as a battery, may not be enough in properly resolving the many challenges associated with renewable energy. On the contrary, a hybrid integration of these technologies may provide a practical and effective solution (Nair; Costa-Castelló, 2020).

The most popular of HESS are supercapacitors (SC) and batteries energy storage systems (BESS). In-depth analysis of energy storage devices, including relevant case studies, comparative analyses, and the latest research findings, is presented in (Albasheri et al., 2022); (Singh; Lather, 2020a); (Kotb et al., 2022), (Jing et al., 2018). BESSs offer a large capacity of energy storage but a poor power density (Lu et al., 2023). Due to the low power density of BESSs, that may be subjected to significant stress, resulting in an increase in the inside temperature to satisfy the rapidly varying transient load necessary. Most of the time, The BES power limit’s rate of change is insufficient to handle sudden, significant load variations, particularly in microgrids. Furthermore, since tiny residential loads have a variable load factor, the frequency of discharge and charge cycles rises, reducing the battery life expectancy (Pan et al., 2023). In contrast, SCs has a significant power density and a low density of energy. Power imbalances in systems with widely changing generation and loads are often regulated using SC. (Raza et al., 2023)- (Punna et al., 2022). A single device cannot concurrently deliver high energy and power requirements due to the intrinsic constraints of battery and SC. Consequently, in order to guarantee the mixed benefits of high power and energy density (Ma; Yang; Lu, 2015); (Reigstad et al., 2021). Battery-SC mixed storage energy system is used to extend battery lifetime, decrease battery cost and size, apply less demand on the battery, enhance dc link responsiveness, and provide power balance in terms of power production, load needs (Yang et al., 2020)- (Salameh et al., 2021).
Three factors determine the power fluctuations in an independent microgrid: fluctuations in the power exchange, power fluctuations in the power resources and storage devices, and unexpected fluctuations in DC consumption. Power fluctuations and long-term energy balance can only be managed by an effective energy management methods (Gugulothu; Nagu; Pullaguram, 2023). Various energy management strategy for independent microgrid consist HESS was developed (Amry et al., 2023), (Elmorshedy et al., 2021). A hierarchical power management plan for two DC microgrids linked by dual active bridge (DAB) converters is suggested in (Thankanadar Saraswathi; Swaminathan; Periasamy, 2021). A wind energy, a solar energy source, and battery are numerically modelled in the form of hybrid differential algebraic equations of the Filippov type to build a multivariate nonlinear predictive control model based control of voltage and load monitoring approach has presented in (Dizqah et al., 2015). For the regulation of DC microgrids equipped with HESS, an energy management method utilized an artificial neural network and a hybrid bat search and (ANNHBS) is presented (Singh; Lather 2020b). the suggested control technique seeks to regulate dc bus voltage while also enhancing sharing power between supercapacitors (SC) and batteries to balance generation and needed. A renewable grid-tied system using the HESS management approach was detailed in (Fakham; Lu; Francois, 2011), with an emphasis on high battery SoC and charging capacity limitations. For battery, photovoltaics (PV), and supercapacitors, an approach to energy management is proposed. The meta-heuristic Jaya algorithm is used in the suggested control plan to maximize the battery rate of flow, discharge and charge cycles of the power system while balancing SC and PV. Using EMS as a means to combat transient energy mismatches and mitigate the negative impacts of transiently high charge/discharge current rates on BESS is necessary in order to achieve these goals. (Gugulothu et al., 2023).

The majority of HESS control techniques (Baset; Rezk; Hamada, 2020), (Hema Rani et al., 2019), (Mendis; Perera, 2014), (Kamel; Rezk; Abdelkareem, 2021), (Dao et al., 2021) are predicated on an assumption that battery have to fulfill mean power needs whereas SCs must serve rapid and transient electrical demands. To accomplish this, the total needed for power is separated into two parts: lower-frequency current (an average of component) and higher-frequency
current (transient component). The lower frequency current elements are provided by battery, whereas the higher frequency elements are supply by SC. Nevertheless, numerous these kinds of controller designs failed to account for the battery discharge and charge rate limitation control and decomposition pattern. In order to find a solution to these problems, a flexible charge-discharge rate limitation control that incorporates optimization methods has been established.

The following are some of the contributions that are discussed in this article:

- a review of the various constructures that are employed in the method of linking SCs and batteries to the DC bus voltage and load. This comparison is offered by a variety of structures, and it details the benefits and drawbacks of each structure;
- improve the lifespans of battery, reduces storage system size and cost;
- increases the stability of DC link voltage and the current of HESS control, under variation in load demand and power production by the wind turbine.

The objectives of this article are to optimize the energy management technique, decrease the cost of the energy storage system, and enhanced the system stability and dynamic response.

After the introduction the rest of the article is structured as follows: Section II is covered the analysis and modelling of the global structural system. The suggested energy management technique for (RAPS) is presented in Section III. Results and validation of the simulations are illustrated in Section IV. The last section is contained the conclusion remarks.

2 MODELING AND DESIGNING OF DC MICROGRID

The Remote Area Power System DC microgrid system is comprised from wind energy, storage in the form of batteries, supercapacitor SC, and DC load, as seen in Figure 1. (a) And Figure 1. (b) Show the configuration of DC microgrid with battery only. Wind energy is the primary source of power and is employed at MPP to produce as much energy as possible. three phase-rectifier and a DC-DC boost converter link it to a common dc link. HESS is connected to a shared DC link through a DC-DC bidirectional converter for each storage devices. HESS is used
to adjust the DC voltage $V_{DC}$ at the DC link while delivering electricity to compensate for generation and load imbalances.

**Figure 1.** (a): Wind energy and HESS for RAPS; (b): Wind energy and battery only

Source: Authors

### 2.1 WIND ENERGY SYSTEM

The turbine's mathematical model involving wind and tidal power is described as (Abdulelah; Ouahid; Youcef, 2021).

\[
P_m = \frac{1}{2} \rho C_p(\beta, \lambda) A v_t^3
\]

(1)

\[
T_m = \frac{P_m}{\omega_m}
\]

(2)

\[
C_p(\beta, \lambda) = 0.5 \left( \frac{116}{\lambda_t} - 0.4 \beta - 5 \right) e^{-\left(\frac{21}{\lambda_t}\right)}
\]

(3)

\[
\lambda_t^{-1} = (\lambda + 0.08\beta)^{-1} - 0.035(1 + \beta^3)^{-1}
\]

(4)

\[
\lambda = \frac{\omega_m R}{v_t}
\]

(5)

where:

- $C_p$ denotes the power coefficient, $A$ symbolizes the area of the blades, the density of wind is $\rho$,
- $\lambda$, $v$, $R$, $\omega_m$, and $\beta$ denote the tip-speed ratio, wind speed, blade diameter, rotor velocity, and pitch angle, respectively. The model mathematic of PSMG can be seen in the following (Soliman et al., 2021);
\[ v_{dq} = R_{dq}i_{dq} + L_{dq}i_{dq} + \psi_{dq}p\omega_m \]  
\[ J\dot{\omega}_m = T_m - T_e - f_f v_m \omega_m \]  
\[ T_e = \frac{2}{3} p\psi^T_{dq}i_{dq} \]

Where:

\[ \psi_{dq} = \begin{bmatrix} \psi_d \\ 0 \end{bmatrix}, \; i_{dq} = \begin{bmatrix} i_d \\ i_q \end{bmatrix}, \; \text{and} \; v_{dq} = \begin{bmatrix} V_d \\ V_q \end{bmatrix} \]
donate the flux linkages and the vector of stator current and voltage, respectively;

\[ L_{dq} = \begin{bmatrix} L_d & 0 \\ 0 & L_q \end{bmatrix}, \; R_{dq} = \begin{bmatrix} R_S & 0 \\ 0 & R_S \end{bmatrix} \]
indicate the inductances and resistors’ matrix. \( J \) is the inertial moment, the viscous friction coefficient is represented by \( f_f v \), \( T_e \) indicates electromagnetic torque.

### 2.2 BATTERY MODEL

A battery is an electrochemical cell that converts chemical energy into electrical energy. (Lakshmi; Nair, 2022). The Simulink Sim-Power Systems package was used to evaluate and improve the dynamic battery idea in this study.

The battery voltage \( V_{\text{batt}} \) may be described as follows (Comparison among various energy management strategies for reducing hydrogen consumption in a hybrid fuel cell/supercapacitor/battery system – ScienceDirect n.d.):

\[ V_{batt} = E_0 - A_b e^{-(B_it)} \frac{Q}{Q - it} I_{bat} - R_b i + A_b e^{-(B_{bat}I)} - K \frac{Q}{Q - l_{bat}} i_{bat} \]  

**Figure 2. SOC_{bat} calculation**

Source: Authors
The following is a description state of charge of the Battery $SOC_{bat}$ model developed (Benlahbib et al., 2020).

$$SOC_{bat} = 100 \left( 1 + \frac{\int I_{bat} \, dt}{Q} \right)$$  \hspace{1cm} (10)$$

The charge and discharge cycle of the battery is determined by the amount of power that is accessible, the requirement. The state-of-charge limits of the battery are used to establish the energy limitations of the battery (Alahmadi et al., 2021):

$$SOC_{bat_{MIN}} \leq SOC_{bat}(t) \leq SOC_{bat_{MAX}}$$  \hspace{1cm} (11)$$

### 2.3 SUPERCAPACITOR MODEL

An electrochemical double layer capacitor is a supercapacitor. A supercapacitor is an electrostatic energy storage device that works by polarizing an electrolytic solution. Supercapacitor is ideal for pulse power systems uses, due to their highly reversible charge/discharge behavior, which enables supercapacitors to be both charge/discharge an infinite number of times. This is possible due to the method for storing energy does not require a chemical reaction (Hemi; Ghouili; Cheriti, 2014).

The SC voltage $V_{SC}$, the capacitance $C_{SC}$ determine the Superc energy $E_{SC}$ (Yin et al., 2017):

$$E_{SC} = \frac{C_{SC} V_{SC}^2}{2}$$  \hspace{1cm} (12)$$

As a result, the stored energy will vary in accordance with changes in the capacitor voltage, and the $SOC_{SC}$ may be calculated as follows:

$$SOC_{SC} = \frac{\frac{C_{SC} V_{SC}^2}{2}}{\frac{C_{SC} V_{SCRATED}^2}{2}} \times 100\%$$  \hspace{1cm} (13)$$
3 POWER AND ENERGY CAPACITY FOR HESS

The specified minimum size of capacity by the HESS must be set to guarantee that it can correspond to the quantity of energy that must be charged or released. By merging the power profiles of the SC and battery across each dispatching period, the energy capacity needed for the SC and battery are employed. Equation (14) is employed to calculate the minimum size of capacity required for the batteries to adequately deliver by a wind turbine to the customer in one-hour intervals during the day (Roy; He, 2020).

\[ E_{\text{bat}} = \frac{E_{sj}}{DOD_{\text{max}}} \]  

(14)

where:

- \( E_{sj} \) is the total quantity of energy that the battery has discharge or charge during the simulation time and \( DOD_{\text{max}} \) is the highest depth of discharge that the battery has previously utilized.

In a similar way, the SC’s minimum capacity requirement that must be met is determined. To be more specific, the formula (12) is used to calculate the necessary size of the SC.

4 OPTIMIZING COSTS FOR HESS

The reference of power for the SC and battery are provided by the LPF. LPF constant time has a direct relationship with the minimum size capacity required for the ESS, however, this relationship is inverse for the minimum size capacity required for the BES. To reduce the overall cost of the HESS ($/kWh), the LPF time constant must be set at the right value. Here, after using the curve fitting approach for determining the suitable cost formula for the ESS as a function of the LPF constant time, The PSO approach is used to determine the ideal LPF time constant. The 4th order polynomial curve fitting approach was used to generate the mathematical formula for the ESS cost as a function of the LPF constant time (Roy; He; Liao, 2020).
HESS_{Cost,LPF}(Ts) = P_1Ts^3 + P_2Ts^2 + P_3Ts + P_4 \quad (15)

where:

Ts is the LPF constant time, which is used in the HESS design to distribute power between the SC and battery, and $P_1$, $P_2$, $P_3$, and $P_4$ are the coefficients of regression.

According to Eq. (16), the global current to be provided by the HESS (batteries and supercapacitors) is equal to the voltage error between $V_{DC,ref}$ and $V_{DC}$ that is input to the PI controller.

$$I_{HESS} = I_{Wind} - I_{Load} = I_{Bat} + I_{SC} \quad (16)$$

As a result, the total value of current is composed of the high-frequency component provided by the SC and the low-frequency component provided by the batteries. LPF is used for this purpose so that only the low-frequency part of the signal is passed through, as shown in Figure 3.

![Figure 3. Low pass filter](image)

Source: Authors

This equation provides the deficit in filtered current.

$$I_{HESS} = F_{LPF}(I_{HESS}) \quad (17)$$

$$F_{LPF} = \frac{1}{Te^s + 1} \quad (18)$$
where:

\[ F_{LPF} \] indicates the low-pass filter's transfer function, Laplace operator \( s \), and \( T_c \) is the time constant.

As demonstrated in Eq. (20), SCs provide the high frequency current fluctuation element, whereas battery provides the low frequency element of current variations.

\[ I_{Bat} = F_{LPF}(I_{HESS}) \]  \hspace{1cm} (19)  
\[ I_{SC} = I_{HESS} - I_{bat} \] \hspace{1cm} (20)

### 4.1 CURRENTS AND VOLTAGE CONTROL DESIGN

The method of control for the DC link voltage a PI controller is used to acquire the current reference

\[
G_{sc}(s) = I_{sc} \frac{C_s + 2 V_d}{RL_{sc}Cs^2 + L_{sc}s + (1 - D_{sc})^2} \]  \hspace{1cm} (21)

Energy Management Method will make utilize this value in order to assess the current references \( I_{sc,red} \) and \( I_{Bat,ref} \) for the supercapacitor control loop and the battery’s control loop, respectively.

To accomplish this, the DC link voltage must be controlled using the static converters’ reference current distributions \( (I_{sc,ref} \text{ and } I_{Bat,ref}) \). the supercapacitor's control loop for its DC-DC buck-boost converter.

Here is the transfer function used to control the SC current
The following equation describes the transfer function of the PI controller for the SC current control loop:

\[ G_{\text{pi-sc}} = \frac{D_{sc}}{I_{\text{sc-ref}}} = K_{p-sc} + \frac{K_{i-sc}}{s} \quad (22) \]

The formula for the transfer function between SC current and the output voltage is given as

\[ G_{\text{scv}}(s) = \frac{V_{dc}}{I_{sc}} = \frac{R(1-D_{sc})(\frac{L_{sc}}{R(1-D_{sc})})s+1}{RCs+2} \quad (23) \]

The transfer function of the voltage control loop compensator is expressed in Eq (24).

\[ G_{\text{pi-DC}} = K_{p-DC} + \frac{K_{i-DC}}{s} \quad (24) \]

where:

- \( C \) is the DC link capacitor,
- \( R \) is the DC bus resistance,
- \( L_{sc} \) indicates for the supercapacitor's DC/DC converter's inductance,
- \( V_{sc} \) is the supercapacitor's voltage, and
- \( D_{sc} \) is the duty ratio for the super-capacitor's DC/DC converter's control.

The transfer function (TF) \( G_{\text{Bat}}(s) \) for signal disturbances in the battery converter's duty ratio \( D_{\text{bat}} \) to inductor current \( I_{\text{Bat}} \) is written as (Al Basheri et al., 2024),

\[ G_{\text{Bat}}(s) = \frac{I_{\text{Bat}}}{D_{\text{bat}}} = \frac{V_{dc}C_s + \frac{V_{dc}}{R}}{L_{\text{bat}}C_s^2 + \frac{L_{\text{bat}}}{R}s + (1-D_{\text{bat}})^2} \quad (25) \]

Here, \( L_{\text{bat}} \) denotes the battery's inductance, \( D_{\text{bat}} \) the battery's duty ratio, and \( G_{\text{Bat}}(s) \) the battery's control-to-inductor-current battery transfer function of the bidirectional converter.

The transfer function of the PI controller's close loop control is written as,
\[ G_{pi\text{-}bat} = K_{p\text{-}bat} + \frac{K_{i\text{-}bat}}{s} \quad (26) \]

4.2 ENERGY MANAGEMENT STRATEGY

The system's dynamic performance, service life of distributed generation, and system stability are all significantly impacted by the energy management approach. The DC microgrid energy management strategy's main objectives are: increasing the lifetime of energy storage devices, stable DC bus voltage, to achieve balance of power in every operating mode, to keep supercapacitor and battery state of charge within limits, to avoid the current fluctuation of HESS at the edge of SoCs, and supply transient and oscillating peak of powers exclusively from supercapacitors. Additionally, the economic performance of microgrid systems is significant control goal.

Figure 6. (a) and (b) depict in detail the SOC and power graphs for the battery and SC group. The battery group is shut down in the cases illustrated by this graph.

The flow chart method shown in Figure 7. (a) and (b) is used to choose the operational modes for the proposed dynamic energy management strategy. To identify the right mode of operation, the battery state of charge (SOC), the state of charge of SC, and the difference between power generated by wind generator and costumer power are compared.

Mode (1,2); In these modes, the power produced by wind generator is less than the required load, furthermore, the state of charge of the battery is nearly discharged. In this situation the EMS operate in Load power shedding, the load should be decried to important load.

Mode (3,4); The wind generator output power is insufficient to meet the demand for power, however, the battery's charge level is the limitation. MPPT control is worked in these scenarios.

The proposed energy management technique is shown in Figure 5, three PI controllers were used. The first employed to control the DC link voltage, and the others employed to control the current of battery and supercapacitor.
Figure 5. Energy management technique

Source: Authors

Figure 6. HESS operation mode power and SOC values: (a) battery, (b) SC.

Source: Authors

Figure 7. Flow chart of energy Management (a): for Battery/SC (b): for Battery only

Source: Authors
Mode (5,6); The wind turbine's production exceeds the need for electricity; nevertheless, the charge level of the battery is the limitation. In these cases, MPPT control is applied.

Mode (7,8); the wind turbine produces more power than is required, the battery is completely charged. In these situations, Load power tracking control operates. to observe the required electricity consumption

4.3 SIMULATION RESULTS

The RAPS energy-based wind energy employing HESS, battery, and SCs was simulated under varying circumstances in MATLAB/Simulink to evaluate its efficacy. The simulations assume that the battery and SCs are charged and discharged to various degrees. A comparison of the two different simulation designs is provided below. The first test of the exam involves simulating the RAPS without the SCs, and the second test involves simulating the RAPS with the SCs. These experiments were conducted with identical wind velocity and load variation patterns. It cannot utilize an actual RAPS cycle for the test, but in this simulation test, it provided most scenarios: the load was varied.

The findings of the simulation tests are shown in Figure 8. (a), illustrates the wind speed proposed [12.8,14.7,12.8,10.5,9,7] m/s. Wind power varies in reaction to variations in wind speed, as seen in Figure 8. (b), and Figure 8. (c) [600,700,600,500,400,300] watt.

In Figure 8. (b), the power waveforms of RAPS battery without SC, during the period 0 to 10s and 25s to 60s the power load needs are more than the power generated by wind turbine the battery compensates this deficit of power. And second case is the period from 15s to 20s the power production from wind are more than power needs, the battery absorbed the excess power. In interval from 10s to 15s the power generated is satisfied the power needs. As shown in Figure 8. (c), the power waveforms of RAPS battery with SC, the SC provides the rapid fluctuations in wind power and load, that reduce the stress on battery.

Figure 8. (d) depicts the batteries and SC currents, with SCs satisfying transient currents and reducing the impacts of peak currents on the batteries in
case of hybridization. However, the battery alone provides the transient term and long term together that is impacted in lifespan and effectiveness of battery.

Figure 8. (e), displays the DC bus voltage, the DC bus voltage reaches the reference at 100v in less than 0.1 seconds for the HESS. Conversely, the battery alone takes 0.55 seconds. The HESS provides faster reaction speed and 5 times less tracking time compared to other criteria like response or tracking time. During steady state, the Hybrid Energy Storage System (HESS) provides a more reliable reaction with little or insignificant deviations around the reference when compared to using just the battery. Unlike the HESS, it is noticeable that the variation of the DC bus voltage is more pronounced when using just the battery. The variance in the battery alone reaches 4V, corresponding to a relative deviation of 4%. On the other hand, the variation is less than 0.5V for HESS, representing a relative deviation of 0.5% of the DC bus voltage, making it eight times smaller. The findings indicate that the HESS effectively regulates the DC bus voltage with little departure from its reference value, outperforming the battery system alone.

In Figure 8. (f), the stator current of the PMSG is shown and the stator current’s zoom. Figure 8. (g) shown the state of charge of battery in two cases with SC and without SC. And the state of charge zoom out of long period is displayed in Figure 8. (h)
5 CONCLUSION

This paper investigated the advantages of involving SCs in the energy storage of RAPS based wind energy. SC application positively influences RAPS’s enthusiasm for reducing peak current harm to the battery, prolonging the battery’s lifespan, and reducing the DC link voltage's fluctuations. A suggested technique was provided for maintaining DC bus voltage stability in the face of fluctuations in
wind speed and load demand. The DC bus is controlled by batteries and SCs in this method. SCs are employed in all variations to increase the response dynamic of RAPS and minimize the peak current on batteries. Batteries serve their purpose for extended periods of time. Two simulation studies are provided to demonstrate the effectiveness of the suggested method and the goal underlying the utilisation of SCs. These simulation results illustrate the suggested control system's stability and efficacy. It can be seen that by incorporating SCs into the system for storing energy, the DC link voltage stability and fast response is improved. decreases battery stresses, removes the peak current impact on battery. This thereby grows longer the battery's life. Their inclusion also ameliorates the dynamic performance to meet the load demand is one of the principal objectives of this study.

Finally, this article will help researchers focus on energy management of remote eares or connected grid, this paper will allow the to improve the designing and sizing of energy storage system for microgrid or other applications related to renewable sources.

Recommendations for future work:

- using artificial intelligence algorithms for optimization and control microgrid;
- design those storage system for other application like electrical vehicles, drones etc.
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