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A STANDALONE DC MICROGRID ENERGY MANAGEMENT STRATEGY USING THE BATTERY STATE OF CHARGE

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Abstract. *This article introduces an enhanced energy management strategy that employs the state of charge (SoC) of batteries in standalone DC microgrids with photovoltaic (PV) modules. Efficient energy management is crucial to ensure uninterrupted power supply to the load units in microgrids. To address the challenges posed by external factors such as temperature fluctuations and variations in solar irradiance, energy storage systems are deployed to compensate for the negative effects of the external factors on the output power of PV modules. The proposed approach takes into account various parameters of the microgrid elements, including the available power from the sources, demand power, and the SoC of batteries, in order to develop an efficient energy control mechanism with load-shedding capability. By considering these parameters, the strategy aims to optimize the utilization of available resources while ensuring a reliable power supply to the connected loads. The SoC of the batteries plays a critical role in determining optimal charging and discharging profiles, enabling effective energy management within the microgrid. To evaluate the effectiveness of the proposed approach, an algorithm is designed and simulations are conducted. The proposed algorithm utilizes a hybrid approach by combining power and SoC-based methods for efficient control. Through analysis of the simulation results, it is found that the presented approach is capable of delivering the intended load power while increasing the life cycle of the batteries with the pre-defined SoC levels.*

Keywords: DC microgrid, energy management strategy, battery state of charge, photovoltaic systems

STRATEGIA ZARZĄDZANIA ENERGIĄ SAMODZIELNEJ MIKROSIECI DC Z WYKORZYSTANIEM STANU NAŁADOWANIA BATERII

Streszczenie. *Niniejszy artykuł wprowadza ulepszoną strategię zarządzania energią, która wykorzystuje stan naładowania akumulatorów (SoC) w autonomicznych mikrosieciach prądu stałego z modułami fotowoltaicznymi (PV). Efektywne zarządzanie energią ma kluczowe znaczenie dla zapewnienia nieprzerwanego zasilania jednostek odbiorczych w mikrosieciach. Aby sprostać wyzwaniom związanym z czynnikami zewnętrznymi, takimi jak wahania temperatury i zmiany natężenia promieniowania słonecznego, systemy magazynowania energii są wdrażane w celu skompensowania negatywnego wpływu czynników zewnętrznych na moc wyjściową modułów fotowoltaicznych. Proponowane podejście uwzględnia różne parametry elementów mikrosieci, w tym dostępną moc ze źródeł, moc zapotrzebowania i SoC akumulatorów, w celu opracowania wydajnego mechanizmu kontroli energii z możliwością zrzucania obciążenia. Biorąc pod uwagę te parametry, strategia ma na celu optymalizację wykorzystania dostępnych zasobów przy jednoczesnym zapewnieniu niezawodnego zasilania podłączonych obciążeń. SoC akumulatorów odgrywa kluczową rolę w określaniu optymalnych profili ładowania i rozładowywania, umożliwiając efektywne zarządzanie energią w mikrosieci. Aby ocenić skuteczność proponowanego podejścia, zaprojektowano algorytm i przeprowadzono symulacje. Proponowany algorytm wykorzystuje podejście hybrydowe, łącząc metody oparte na mocy i SoC w celu zapewnienia wydajnej kontroli. Poprzez analizę wyników symulacji stwierdzono, że prezentowane podejście jest w stanie dostarczyć zamierzoną moc obciążenia, jednocześnie zwiększając cykl życia akumulatorów przy wstępnie zdefiniowanych poziomach SoC.*

Słowa kluczowe: mikrosieć prądu stałego, strategia zarządzania energią, stan baterii akumulatorów, systemy fotowoltaiczne

Introduction

Autonomous DC microgrids have emerged as a promising solution for decentralized and off-grid power systems, operating independently from the central grid [1, 10]. Energy storage systems, particularly batteries, play a crucial role in these microgrids by ensuring reliable power supply, managing renewable energy intermittency, and enhancing system stability. Effective control strategies for battery charging and discharging are essential to optimize energy management within autonomous DC microgrids, enabling efficient resource utilization and uninterrupted power delivery to connected loads [4, 5, 11, 20]. Precise control of battery operations is fundamental to maintaining system performance, prolonging battery life, and meeting load demand requirements.

Different control strategies are employed to manage the power flow in DC microgrids, each with their advantages, and challenges. These include voltage-based DC bus signalling, power-based, state of charge of battery-based and economic dispatch algorithms.

Voltage-based DC bus signalling control is a commonly used method that utilizes voltage thresholds to control battery charging or discharging [6, 12-16]. By monitoring DC bus voltage levels, this strategy ensures grid stability and allows the battery system to support peak load demand or compensate for insufficient renewable power generation. However, these approaches require a change in DC bus voltage which causes instability.

Power-based control strategies focus on adjusting battery charging and discharging rates based on power demand and availability [2, 7, 18, 21]. These techniques consider power flow within the microgrid and dynamically regulate battery operations to balance supply and demand, optimizing energy utilization and minimizing system losses. However, these methods require accurate power measurement and control devices, thus increasing system complexity. Some of them may not fully consider the battery's state of charge in power regulation.

Economic dispatch algorithms [8, 19] considering factors such as electricity prices and demand profiles, aim to minimize energy costs while meeting power requirements within the microgrid. These approaches optimize the scheduling of battery charging and discharging activities, considering the cost-effectiveness of grid power utilization versus stored energy. Economic dispatch algorithms in energy management systems have several disadvantages, which can impact their efficiency and effectiveness. Some of these disadvantages include complexity, computational time, and lack of consideration for environmental factors.

Fig.1. depicts the structure of the simple standalone DC microgrid.

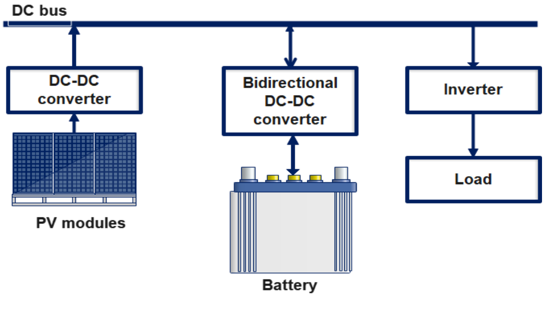

Fig. 1. Simple standalone DC microgrid structure

State-of-charge (SoC) control methods [9, 17] employ the battery's SoC as a critical parameter to determine optimal charging and discharging profiles. By monitoring and managing

SoC, these strategies ensure batteries operate within desired ranges, mitigating the risks of overcharging or over-discharging that could impair battery performance or reduce lifespan. These methods may cause instability in dynamic load and generation scenarios if the real-time power measurement of the units is not conducted. The SoC of the battery using the Coulomb counting method is as follows [3]:

$$SoC(t) = SoC(t_0) - \frac{1}{Q_{rated}} \int_{t_0}^{t_0+\tau} \eta I_b(t)\,dt \qquad (1)$$

where: $SoC(t_0)$ is the initial SoC, I_b is battery current, η_b he efficiency of the battery (between 0 and 1).

The proposed algorithm utilizes a hybrid approach by combining power and SoC-based methods for efficient control.

1. DC-DC converter modelling

DC-DC converters play an essential role in interfacing PV modules and batteries with the load units in DC microgrids. ZETA topology is selected to stabilize the voltage received by the PV modules as it can operate in boost and buck modes.

1.1. ZETA converter

The electronic circuit diagram of the ZETA converter which contains two inductors (L1, L2), capacitors (C1, C2), a diode (D), and a transistor (Q), input voltage V_{in} is depicted in Fig. 2.

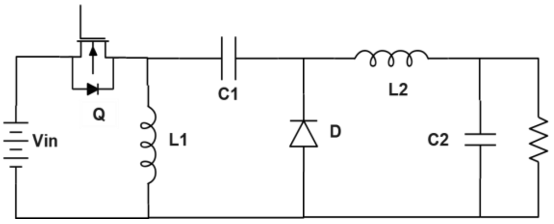

Fig. 2. ZETA circuit diagram

The converter functions in two distinct modes. During the on-mode, the MOSFET is activated, causing the diode, D, to enter its reverse-bias state, thus blocking the flow of electrical current. As a result, the voltage across inductor L1 matches the supply voltage, and there is a gradual rise in the inductor current over time. At the same time, capacitor C1 starts to charge and reaches the output voltage level. The following state-space representation describes the on state of the ZETA converter:

$$\begin{bmatrix} \frac{di_{L1}}{dt} \\ \frac{di_{L2}}{dt} \\ \frac{dv_{C1}}{dt} \\ \frac{dv_{C2}}{dt} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{1}{L_2} & -\frac{1}{L_2} \\ 0 & -\frac{1}{C_1} & 0 & 0 \\ 0 & \frac{-1}{C_2} & 0 & -\frac{1}{C_2 R} \end{bmatrix} \begin{bmatrix} i_{L1} \\ i_{L2} \\ v_{C1} \\ v_{C2} \end{bmatrix} + \begin{bmatrix} \frac{1}{L_1} \\ \frac{1}{L_2} \\ 0 \\ 0 \end{bmatrix} \begin{bmatrix} v_{in} \end{bmatrix} \qquad (2)$$

$$v_O = \begin{bmatrix} 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} i_{L1} \\ i_{L2} \\ v_{C1} \\ v_{C2} \end{bmatrix} + \begin{bmatrix} 0 \end{bmatrix} \begin{bmatrix} v_{in} \end{bmatrix} \qquad (3)$$

where i_{L1}, i_{L2} are inductor currents through L1 and L2, v_{C1}, v_{C2} are voltages across C1 and C2, respectively, v_{in}, v_o are respective the input and output voltages.

During the second mode, the MOSFET is turned off, causing a polarity change. As a result, the diode, D, switches to the forward-biasing mode, allowing electrical current to flow effortlessly through it. The current passing through the diode leads to the parallel connection of inductor L2 with the output capacitor. Additionally, capacitor C1 discharges its stored energy through inductor L1. The following state-space representation describes the off-state of the ZETA converter:

$$\begin{bmatrix} \frac{di_{L1}}{dt} \\ \frac{di_{L2}}{dt} \\ \frac{dv_{C1}}{dt} \\ \frac{dv_{C2}}{dt} \end{bmatrix} = \begin{bmatrix} 0 & 0 & -\frac{1}{L_1} & 0 \\ 0 & 0 & 0 & -\frac{1}{L_2} \\ \frac{1}{C_1} & 0 & 0 & 0 \\ 0 & \frac{1}{C_2} & 0 & -\frac{1}{C_2 R} \end{bmatrix} \begin{bmatrix} i_{L1} \\ i_{L2} \\ v_{C1} \\ v_{C2} \end{bmatrix} + \begin{bmatrix} \frac{1}{L_1} \\ \frac{1}{L_2} \\ 0 \\ 0 \end{bmatrix} \begin{bmatrix} v_{in} \end{bmatrix} \qquad (4)$$

The state-space average model is as follows:

$$\begin{bmatrix} \frac{di_{L1}}{dt} \\ \frac{di_{L2}}{dt} \\ \frac{dv_{C1}}{dt} \\ \frac{dv_{C2}}{dt} \end{bmatrix} = \begin{bmatrix} 0 & 0 & -\frac{1-d}{L_1} & 0 \\ 0 & 0 & \frac{d}{L_2} & -\frac{1}{L_2} \\ \frac{1-d}{C_1} & \frac{-d}{C_1} & 0 & 0 \\ 0 & 0 & 0 & -\frac{1}{C_2 R} \end{bmatrix} \begin{bmatrix} i_{L1} \\ i_{L2} \\ v_{C1} \\ v_{C2} \end{bmatrix} + \begin{bmatrix} \frac{d}{L_1} \\ \frac{d}{L_2} \\ 0 \\ 0 \end{bmatrix} \begin{bmatrix} v_{in} \end{bmatrix} \qquad (5)$$

1.2. Bidirectional converter

A power electronics interface is employed to establish a secure and effective link between the battery pack and the DC bus, ensuring safety and efficiency. This interface incorporates bidirectional converters, facilitating energy flow in two directions - from the battery pack to the DC bus and vice versa. In modelling DC microgrids, the bidirectional SEPIC-ZETA converter is frequently utilized due to its ability to charge or discharge the batteries without necessitating a modification in the DC bus voltage.

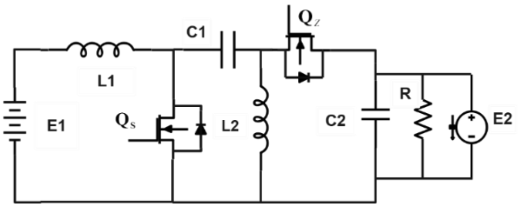

Fig. 3. The circuit diagram of the bidirectional SEPIC-ZETA converter

The bidirectional SEPIC-ZETA converter, illustrated in Fig. 3, comprises the following elements:

- The battery voltage (E1) and DC bus voltage (E2);
- Capacitors (C1 and C2);
- Inductors (L1 and L2);
- Transistors (T1 and T2);
- Load resistance (R).

2. Proposed control algorithm

The proposed algorithm functions through a series of pre-defined steps, taking into account the measured values of PV (Photovoltaic), battery, and demand power, as well as the State of Charge (SoC) of the batteries. These inputs serve as the foundation for the algorithm's decision-making process to efficiently manage the energy system.

To begin, the algorithm compares the PV power output with the load power demand. In cases where the PV power exceeds the load power, the surplus energy is utilized to meet the required load power, eliminating the need for any external source. The excess power is then harnessed to charge the batteries, ensuring optimal utilization of resources. This charging process continues until the SoC of the batteries reaches above 90%, at which point charging is automatically halted to prevent overcharging. By maintaining the SoC within the safe threshold, the algorithm enhances the batteries' life cycle, promoting their longevity and effectiveness.

On the contrary, when the PV power falls short of the load power demand, a different strategy comes into play. The algorithm then evaluates the SoC of the batteries and compares it with the lower SoC limit, which is set at 25%. If the SoC is above this limit, the batteries are brought into action to assist in delivering the required power to the load. The battery discharging process commences, ensuring that the load's power needs are met until the SoC falls below the 25% threshold. By strategically employing the batteries during such scenarios, the algorithm optimizes energy usage, making the most of available resources.

In certain situations where the total combined power from both PV and batteries is unable to meet the load power demand, load shedding becomes necessary. Load shedding is a controlled process where non-essential loads are intentionally disconnected or reduced to ensure that critical loads receive the required power. This mechanism allows the algorithm to prioritize essential loads, ensuring uninterrupted power supply to vital systems.

To perform load shedding, an objective function is proposed with minimal energy loss. The presented minimization function is:

$$\min\left|\boldsymbol{P}_{\boldsymbol{gen.}} - \boldsymbol{b}_1\boldsymbol{P}_{\boldsymbol{LD}1} - \boldsymbol{b}_2\boldsymbol{P}_{\boldsymbol{LD}2} - \boldsymbol{b}_3\boldsymbol{P}_{\boldsymbol{LD}3} - \boldsymbol{b}_{\mathbf{n}}\boldsymbol{P}_{\boldsymbol{LDn}}\right| \qquad (6)$$

when the following condition is met:

$$P_{gen} > \sum_{i=1}^{N} b_i P_{LD.i}\,(for\ b_i = 1) \qquad (7)$$

where $\boldsymbol{P}_{\boldsymbol{gen.}}$ is the power received from batteries and photovoltaic, $\boldsymbol{P}_{\boldsymbol{LD}1}$ are the required power for the controllable loads, $\boldsymbol{b}_{\mathbf{i}}$ is the parameter which has binary values. 0 and 1 demonstrate shed and active loads, respectively.

During the shedding process, the random binary numbers are assigned to the parameters until the load with minimum energy loss is shed. Each parameter representing a specific load is assigned a binary value, where "1" signifies the load is retained, and "0" denotes the load will be shed. This binary assignment allows for a systematic evaluation of all loads, ensuring a fair and unbiased decision-making process. The algorithm starts by generating these random binary numbers and associating them with each load parameter. It then proceeds to assess the impact of shedding individual loads on the overall energy loss. By selectively shedding different loads, the algorithm can analyze the resulting changes in the energy consumption pattern and determine which load's removal minimizes the energy loss to the greatest extent.

Pseudo-code for the proposed algorithm

```
If $P_{pv} > P_{load}$
Supply the load using only PV modules
Charge the batteries until their SoC>90%
else
Check the battery SoC
    If SoC>25%
If $P_{pv} + P_{bat.} > P_{load}$
        Supply the load with PV and battery power until SoC<20%
         else
         Perform load shedding
```

3. Simulation results

When the total PV power exceeds the load power, only PV modules supply the load with energy, eliminating the aid of the battery storage units. This scenario is depicted in Fig. 4, where the cumulative PV power generation amounts to 55 W, whereas the cumulative power consumption by the load is 40 W. In this situation, the battery units commence charging until their State of Charge (SoC) reaches 90% to stop overcharging. If the SoC surpasses the pre-determined threshold, the battery units cease charging. The relationship between the power source and the load is represented using binary digits, wherein "1" denotes a connection, and "0" signifies a disconnection. Concerning the battery conditions, "1" represents the charging state, "0" corresponds to the idle mode, and "-1" signifies the discharging state.

In the event that the total sum of PV power generation is less than the total sum of power consumed by the load during the same period, the PV module output power falls short of meeting the power demand, necessitating the incorporation of additional batteries. The battery's State of Charge (SoC) is checked to determine whether it exceeds 25%. If this condition holds true, the following condition is evaluated. If this condition is also met, the batteries are employed to provide the load with additional energy, and the discharging process commences (state -1) until the SoC falls under 25%. This entire process is illustrated in Fig. 5, where PV amounts to 35W, battery power is 80 W, and the battery's SoC is at 75%, while the cumulative load power is 70 W.

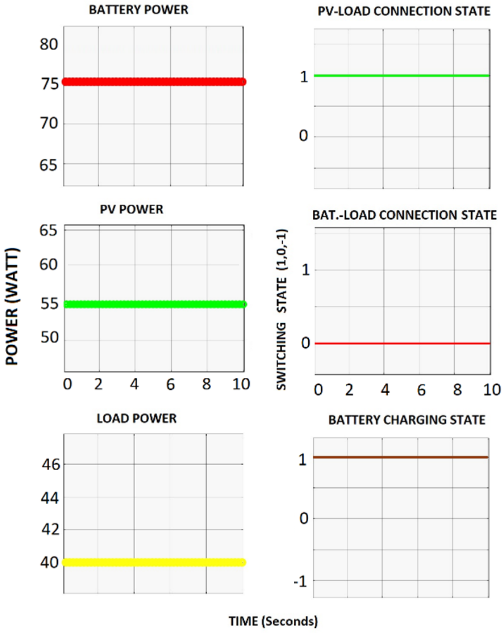

Fig. 4. Load-power source connection and battery charging-discharging states when PV power is higher than the load power

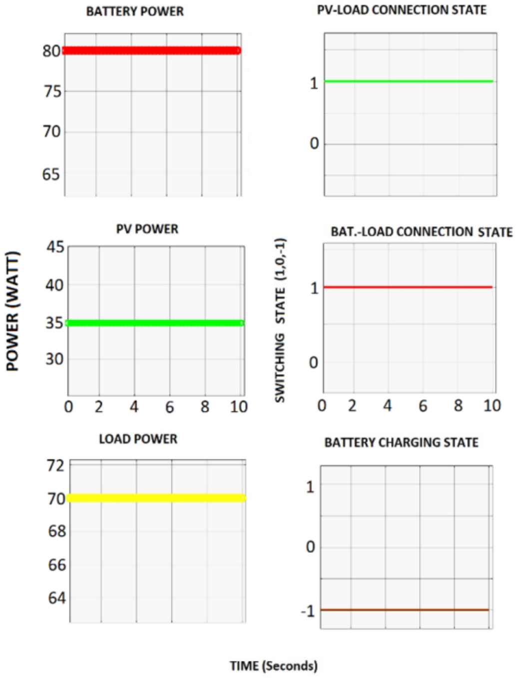

Fig. 5. Load- power source connection and battery charging-discharging states when PV power is lower than the load power

4. Conclusion

In summary, an enhanced energy management strategy for standalone DC microgrids with PV modules, using battery SoC is introduced in this research. A hybrid energy management algorithm with load shedding ability is constructed. Objective functions are built and simulations are carried out. Simulation results confirm its effectiveness, offering a promising solution for sustainable microgrid energy management.

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