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Integrated Energy Management Strategy for Grid-Connected DC Microgrid

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Abstract- According to the unpredictable behavior of renewable energy sources and load demand, energy management in DC microgrids is difficult and complex. Balancing power converter regulation processes, peak demand and lack power are some of the main issues. For the DC microgrid to operate reliably and effectively, great care must be taken in how the photovoltaic (PV) system and battery energy storage system (BESS) are used. For the purpose of resolving the preceding issues, this paper proposes employing the DC microgrids centralized energy management approach. Coordinating between the DC microgrids intellectual layer and several electrical surface parts is the CEMS. To control energy during peak and off-peak load demand, optimize PV-BESS consumption and carry out load dropping operations, it makes use of multi-optimization. In order to prevent overusing AC grid power, a suitable approach to the PV-BESS problem is also developed and addressed via linear programming. In cases of PV power deficiency, the best way to implement load splitting is to solve a mixed-integer linear programming problem in order to maintain power balance and DC bus voltage management. The PV systems efficient functioning in maximum power point tracking, OFF-MPPT mode (i.e., voltage regulation), and BESS charging and discharging are all shown by the proposed CEMS. It is demonstrated that the DC microgrid operations performance, efficiency and availability are enhanced by the hierarchical control structure of CEMS. Therefore, a 48V and 1.2-kW PV-BESS-based DC microgrid system is built in MATLAB/Simulink to demonstrate the effectiveness of the proposed method under various conditions.

Keywords- PV system, DC microgrid, load shedding, battery energy storage system (BESS) and centralized energy management scheme (CEMS).

I. INTRODUCTION

The combination of renewable energy sources (RES) offers a new framework for future grids that are sustainable. Since they provide an effective infrastructure for integrating several RES and loads over AC grids, DC microgrids are growing in popularity [1], [2]. DC microgrid collections enhance the economy, efficiency, resilience and quality of the system [3], [4], and [5]. Additionally, synchronization and harmonics have no effect on the DC microgrid, in contrast to the AC grid. Power converters enable the integration of several renewable energy sources (RES) such as fuel cells, photovoltaic (PV) systems and wind energy with the

DC microgrid to create low, medium and high voltage grids [6], [7]. The PV system is one of the most feasible renewable energy sources (RES) due to the abundant availability of solar energy. PV system deployment in the electrical grid is being aided by the technologies decreasing installation costs. Nevertheless, the power output of the PV system is susceptible to external variables like temperature and solar radiation, resulting in power output fluctuations. Battery energy storage systems (BESS) are deployed alongside PV systems to maintain a consistent output power in order to overcome this problem.

In a DC microgrid, the availability of RES and customer demand have made an efficient energy management system vital [8]. Stochasticity in PV production and battery usage for DC microgrid energy management through resource optimization are among the difficulties addressed in [9], [10], and [11]. The hierarchical coordinating operation is recommended by the literature [12], [13] and [14] to carry out the power interchange and economic dispatch in a DC microgrid. In [15] and [16], an energy management method is examined for the hybrid AC-DC microgrids best operating cost and scheduling. For the DC microgrid to operate effectively and dependably, a number of power management techniques are presented [17], [18] and [19]. Greater focus is placed on the controller than on energy management and finding the best way to use RES. A three-layered simplified form of a DC microgrid power management technique is described in [20]. The DC signal method is employed to provide power flow and synchronised control. Nevertheless, there is not much study done on the microgrids ideal energy management. The best operating planning for a hybrid AC-DC microgrid is proposed in [21], [22] and [23] using decentralized control and power sharing techniques.

Demand balancing and perfect power sharing are two examples of energy management concerns that are covered in [24], [25], [26], [27] and [28]. A linear and quadratic method for managing the energy use of smart homes in grid-connected mode is proposed in [29] and is based on model predictive control. This post may be expanded to cover battery storage operations that take into account the best load shedding strategies and PV use during peak and off-peak load demand. In addition, [30] develops the master energy coordinator algorithm for energy management, which is used for allocating distributed energy resources in the grid, such as BESS. Nonetheless, further research is required to take into account the erratic nature of PV power, load demand, BESS and balancing solutions. In order to control electricity and manage energy, improved measuring infrastructure-based energy management systems (EMS) for islanded AC-DC microgrids are becoming common [31]. It is explored how the DC microgrids interact and coordinate with one another to manage energy in a linked DC microgrid [32]. It should be emphasized that load shedding and optimum power flow are not taken into consideration. Additionally, a plan for intelligent agent-based energy management was put out to improve the microgrids efficiency and dependability [33]. This paper does not take load priority into account while load transfer is in effect. To reduce operating costs and increase the use of RES power, the multi-objective particle swarm optimization-based EMS was developed [34], [35]. Nevertheless, optimum load shedding based on importance level is ignored in [34] and [35]. A multi-microgrid systems emergency control is suggested in [36], although real-time source and load uncertainties are disregarded. A decentralized grid is replacing a centralized one in the DC microgrid. As a result, [37] provides energy management using a collaborative approach that uses the fuzzy and optimization-based method to lower client energy consumption costs. It needs historical demand and source data.

The intentions of the DC microgrid as represented by numerical models are becoming more and more relevant. In order to address targets like generation reduction and load shedding, evolutionary optimization techniques are therefore presented for energy management systems [38], [39]. Furthermore, only a small number of research have examined energy management in microgrids for stability and balance operation by taking load shedding techniques into account [40], [41]. As load management in a microgrid, the under-frequency load sharing technique is presented in [42]. It is important to consider how load shedding operations and load prioritization should be developed in the event that further renewable energy sources are unavailable. The design and development of an integrated energy management system for the DC microgrid that simultaneously satisfies microgrid operating requirements is deduced from the preceding literature as the primary research gap issues. Less emphasis has been paid to the optimization system in conjunction with power electronics converter control for efficient energy management.

While the secondary and tertiary controllers use an optimization layer to provide efficient energy management, these issues with peak power, off-peak power mode, dependable BESS operation and load transfer are addressed. For the DC microgrid system, a centralized energy management scheme (CEMS) is suggested in this article in order to maximize the usage of renewable energy sources (PV power), BESS power and efficient load transfer performance. For efficient energy management, proposed CEMS collaborates with microgrid users.

This papers primary accomplishments are stated up as below.

- CEMS is suggested as an efficient energy management system for the DC microgrid in order to attain optimal PV-BESS usage and load shedding operation.
- The best load shedding strategy is based on load priority and the mathematical formulas for refinement are designed to guarantee the highest possible usage of PV-BESS electricity. Linear programming (LP) and mixed integer linear programming (MILP) solvers, two reliable traditional solvers, are used to tackle the issues.
- The established CEMS algorithms enable the DC microgrids comprehensive control and efficiently synchronize the several physically located components (such as PV, BESS, loads, and power converters with optimization platform). The centralized framework for energy management for both autonomous and grid-connected DC microgrids is provided in this paper, taking into account operating situations like peak and off-peak load demand.

II. COMPONENTS AND STRUCTURE OF A MICROGRID

Fig. 1 depicts a grid-connected DC microgrid system design with the proposed CEMS. The BESS, PV system, AC grid, and DC loads contribute to the DC microgrid. In order to gain the largest amount of power from the PV system, a unidirectional boost converter with maximum power point tracking (MPPT) is used to link the PV system to the DC bus. Despite the use of a bidirectional DC–DC converter, the BESS interfaced with the DC bus to offer flexible power transfer capabilities, allowing it to charge and discharge in accordance with control orders received from CEMS.

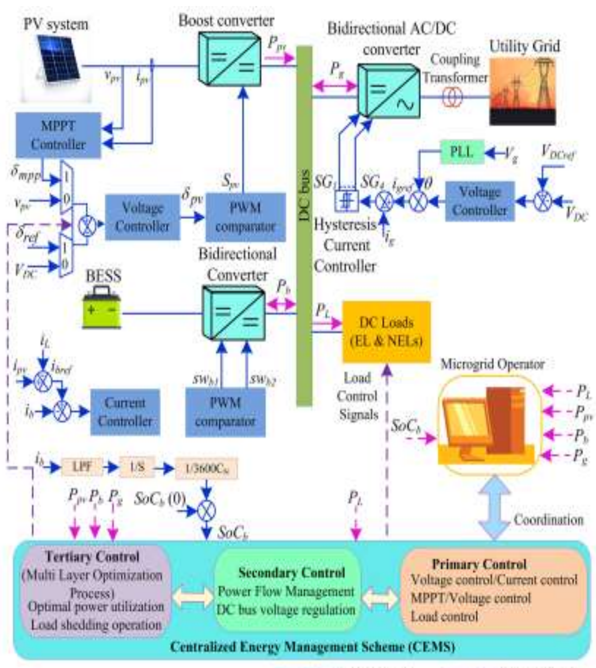

Fig 1: Structure and components of the DC microgrid

A traditional single-phase full-bridge bidirectional converter is interfaced with the AC grid and can be used in the PV system's insufficiency generation (rectifier mode) or excess generation (inverter mode). To reduce switching harmonics, an LC filter is coupled to the AC-DC converter's output side. To lessen voltage ripples, a capacitor is placed across the bidirectional and boost converters. The DC bus is where the DC loads are linked, and they are divided into nonessential (NELs) and essential (EL) loads. In the DC microgrid, the available PV power is used to meet the load demand at any given time. The PV system, BESS, AC grid, and load are all balanced and coordinated by the microgrid operator, which is depicted in Figure

The planning, maintenance, peak load management, network congestion, and voltage support are the duties of the microgrid operator [43], [44]. In order to guarantee optimal power exchange during peak and off-peak demand, the operator keeps vigilant view on the whole operation. For the DC microgrid to operate dependably, the microgrid operator and CEMS collaborate. In Fig. 1, the dotted arrow in purple and magenta indicates the power flow and control signals.

III. CONTROL SCHEME FOR MICROGRID

The DC microgrid's energy management system depends significantly on the control strategy. This article describes the development of the CEMS for the efficient and dependable operation of DC microgrids. It oversees and regulates the power flow to and from all linked loads and sources in the DC microgrid system. As seen in Fig. 1, the CEMS consists of the primary, secondary, and tertiary control. As shown in Fig. 1, the tertiary and secondary control layers supply the reference and decision signals for the main control layer after receiving the generation and load signals from sources, load demand and microgrid operator. The control signals needed to successfully run the PV system in MPPT and OFF-MPPT mode are provided by the primary control layer. The DC bus and PV system are interfaced by a bidirectional boost converter. For boost converter operation, a voltage controller is used. It generates gate pulses by comparing the PV voltage to the DC bus voltage, which turns the PV system into an OFF-MPPT state. Additionally, in MPPT mode, the PV system's voltage and current are monitored and sent into the MPPT algorithm, which uses the P&O approach to create the necessary duty cycle for the boost converter. The bidirectional buck-boost converter interfaces the BESS with the DC bus. The gate control signals for charging and discharging operations are produced by a current control loop. The charging and discharging procedure take into account the state of charge (SoCb) limit, which includes SoCminb and SoCmaxb. The charging process is halted to prevent overcharging when SoCb reaches SoCb max. Likewise, SoCb is attained below SoCminb BESS is unplugged from the DC bus to prevent excessive discharge. The link between the DC bus and the AC grid is a bidirectional AC-DC converter. Depending on the SoCb limit and PV power supply under various circumstances, the AC grid is either operated in feeding or absorbing mode. Its inner loop is intended to control current, while its controller is intended to control outer voltage. The current reference value is supplied by the voltage control loop and is calculated by multiplying the grid current (ig) by the unity template produced by the phase-locked loop. A hysteresis controller, whose bandwidth is proportionate to the intended switching frequency for the production of switching pulses to the converter, follows the erroneous signal.

IV. CENTRALIZED ENERGY MANAGEMENT SCHEME FOR DC MICROGRID

The newest current advancements in microgrid energy management and control techniques are extensively reviewed in [45] and [46]. Several control layers, including tertiary, secondary, and primary control layers, are included in the hierarchical control structure of the CEMS that is designed in this article with consideration for multi-optimization. The operation of the MPPT and OFF-MPPT modes, load control, voltage control, and current control are all handled by the principal control layer. Voltage management and power balancing operation are the goals of the secondary control layer. In case of PV power deficiency, the tertiary control layer takes over. It is the primary role for achieving optimal load shedding and maximum PV and BESS power use. In this section, the objective functions are solved according to their precedence and complexity [47], [48]. The secondary control layers regulate power flow and voltage for power management and voltage stability based on variables like PV power, load power and BESS SoCb value. MPPT, OFF-MPPT and load switching operations are carried out by the CEMS primary control layer. The DC microgrids technical components (sources, converters, and loads) receive control signals from the primary level to ensure dependable operation under a variety of conditions. In this article dependability is defined as a continuous supply to important load based on the set preference, taking into account the DC microgrids dependable functioning. The CEMS algorithms and mathematical framework are addressed presented in the section that follows.

1. MILP for Load Shedding Operation

The cost of power from the AC grid is significant if continuous service to all loads is needed during the PV power shortage with peak load demand. Optimal load shedding operation, supposing the flexibility of customers non-essential loads, is the most economical approach.

In order to control load, the CEMS sheds the best load according to load priority. Consequently, load priority is used to build an objective function that minimizes load shedding, and MILP is used to solve it. In this instance, the loads are divided into nonessential and essential loads. For the MILP algorithm, the power levels of the PV system, BESS, AC grid, load demand and priority (i.e., Ppv, Pb, Pg, SoCb, PL and φi) are necessary parameters.

2. CEMS Algorithm

The efficacy of the suggested CEMS is investigated using six cases, each consisting of ten distinct situations, depending on the available PV power, BESS power, SoCb limit, AC grid power and load demand. In order for the DC microgrid to operate reliably and securely, data on each source, load and microgrid operator is shared with one another. The primary goals of the CEMS are to optimize the PV systems power output, ensure a BESS operates efficiently, and reduce the load on the AC grid. For executing the various types of operation, the proposed CEMS gets input from a PV system, AC grid power, the BESS's SoCb, DC bus voltage and load demand data. Because it specifies different types of operation, BESS SoCb in CEMS plays a crucial function in energy management.

V. CASES FOR CEMS ALGORITHM VALIDATION

The efficacy of the proposed CEMS is investigated using six scenarios, each consisting of ten distinct situations, depending on the available PV power, BESS power, SoCb limit, AC grid power and load demand. In order for the DC microgrid to operate reliably and securely, data on each source, load and microgrid operator is shared with one another. The primary goals of the CEMS are to optimize PV system power, ensure a BESS operates efficiently and reduce load on the AC grid.

Input for the various modes of operation is provided by the proposed CEMS via a PV system, AC grid power, DC bus voltage, SoCb of BESS and load demand data. For computing the SoCb, the BESS current ripple is first reduced using a low pass filter. In order to ensure that the DC microgrid operates dependably, the suggested CEMS process also creates reference signals for all of the controllers and loads. Among the sources and loads, this approach guarantees optimal power management. When deciding which BESS to use for charging and discharging activities, CEMS takes SoCb restrictions into account. The functioning of a DC microgrid is shown as follows, taking into account different situations based on available power, i.e., surplus or deficit, and BESS SoCb state.

Case 1

PV power is worth higher than load demand in this case (Ppv > PL). A minimal value is thought to exist for the SoCb of BESS. After the SoCb experiences its maximum limit, it is unplugged from the DC bus and left idle, and the extra PV power is used to charge the BESS. In order to maintain DC bus voltage stability and ensure power balance, surplus photovoltaic power is simultaneously exported to the AC grid; this is shown in Cases 1 and 2. The DC bus is linked to both EL1 and every NEL.

Case 2
In order to demonstrate the efficacy of the proposed CEMS, load demands higher than PV power is taken into account. This scenario includes Cases 3–5, as in the preceding case, BESS is completely charged and its SoCb has a maximum limit or SoCmaxb. In times of high load demand and PV power shortage, the CEMS optimizes linear programming to capitalize on the maximum power of available PV power in conjunction with BESS to meet load demands, therefore mitigating the strain on the AC grid. All NELS and EL are operational in these scenarios.

Case 3
Reduced limitations of SoCb are taken into consideration and the usefulness of the proposed algorithm in load shedding operation under deficit power (Ppv < PL) situation is exhibited. In this case, as is shown in Cases 6 and 7, the CEMS uses the MILP optimization method to carry out optimal load shedding in order to guarantee DC bus voltage control.

Case 4
In Off-peak mode and peak mode, these situations are regarded as exceptional cases in which the climate prevents the PV system from producing electricity. As mentioned in Case 6, in this instance, CEMS supplies the AC grid with control signals and imports power to supply to the ELs and NELs and charge the BESS.

Case 5
In the peak mode, if the climate prevents PV power from reaching the grid, the BESS operates in discharge mode to meet the energy level (EL) and the discharge limit is 10% ≤ SoCb ≤ 30%. MILP limits NELs, and Case 7 illustrates this circumstance.

Case 6
For demonstrate how the PV system functions well in voltage control mode while the AC grid is experiencing an outage or maintenance while the BESS is fully charged. The control signals needed to run the PV system in voltage control mode are provided by the proposed CEMS algorithm. Voltage control mode is used when the PV system is operating.

VI. SIMULATION RESULTS

Under various circumstances, MATLAB/Simulink simulates the DC microgrid operation test system. The PV systems performance under various irradiation levels, power levels and BESS charging/discharging operations are taken into consideration to highlight the unpredictability of renewable energy sources. Optimal load shedding is considered when there is a power shortfall. To maximize power extraction from the PV system, the MPPT with P&O approach is also employed. Voltage control or OFF-MPPT techniques are then integrated for the best possible energy management.

Based on PV power availability, load demand, BESS operations and load shedding, six distinct cases are examined in order to illustrate and validate the proposed method. The first case involves excess PV electricity that is used in MPPT mode to power all loads from the PV system. The extra power is also used to charge the BESS and export it to the AC grid. In the event of an AC grid outage or maintenance, PV is run in voltage control mode after the BESS reaches its maximum SoCb.

The following scenario, which deals with PV power deficiency, shows how to operate the PV and BESS optimally using LP. In this case, loads are prioritized and lowered using the MILP algorithm if the BESS impacts a lower SoCb in order to lessen the load on the AC grid. The BESS is charged and the EL is supplied by AC grid power when PV is not present (at night) and when the system is not in the Off-peak state. Only EL is supplied in peak mode by the BESS, which was charged from the AC grid during Off-peak mode.

The MILP algorithm limits all NELs. Additionally, a variety of scenarios with diverse situations based on PV systems in MPPT and OFF-MPPT mode, BESS charging and discharging, PV-BESS maximum usage, and load shedding operations are taken into consideration in order to assess the persuasiveness of the created algorithms.

The systems performance is explained under six scenarios with ten distinct test cases, and Fig. 3(a)–(i) displays the simulation results. In order to confirm the effectiveness of the proposed approach for Cases 1–6 and 7, the fluctuation in PV irradiation from morning to evening is taken into consideration. Cases 7 and 8 examine and approximate the worst-case situation of irradiation which is the nighttime. In these cases, there is no irradiation.

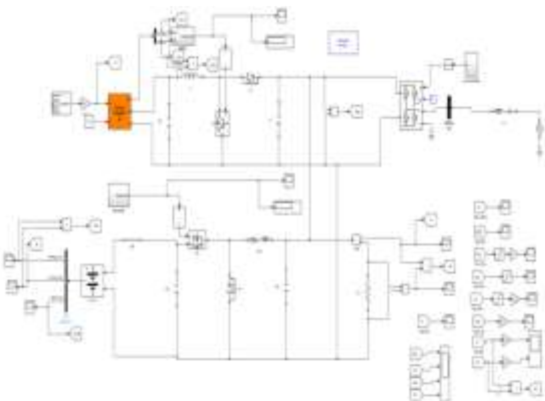

Fig 2: simulation of DC microgrid.

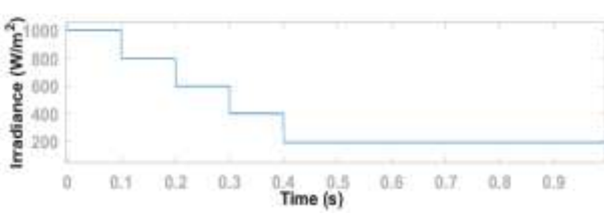

Fig.3. (a)

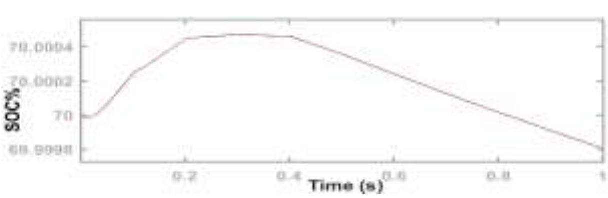

Fig.3. (b)

Fig.3. (c)

Fig.3. (d)

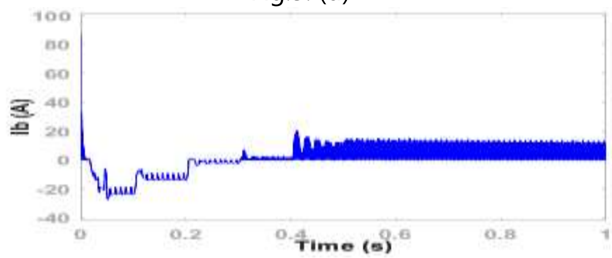

Fig.3. (e)

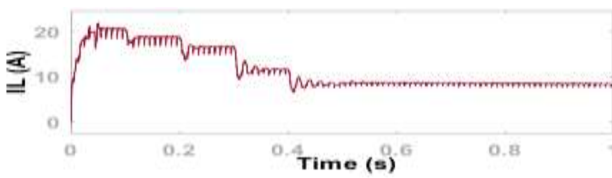

Fig.3. (f)

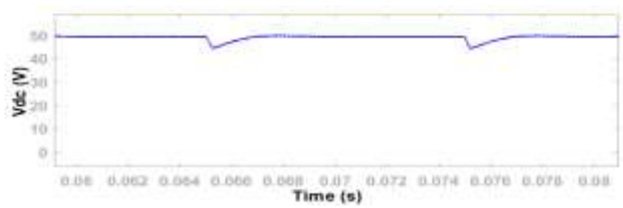

Fig.3. (g)

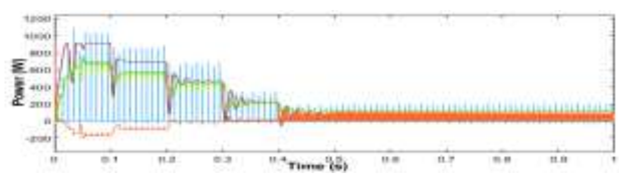

Fig.3. (h)

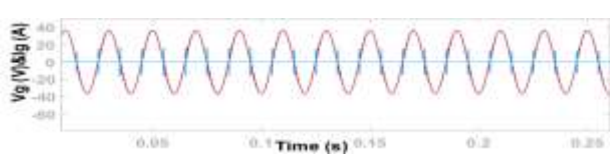

Fig.3. (i)

Fig. 3. Performance of proposed CEMS under different scenarios. (a) Irradiation (W/m2). (b) SoCb of BESS. (c) PV voltage. (V), (d) PV current (A). (e) BESS Current (A). (f) Load current (A). (g) DC bus voltage (V). (h) PV, BESS, load, and grid power (W). (i) AC grid voltage (V) and current (A).

V. CONCLUSION

This article describes how the CEMS was created for the DC microgrids dependable energy management. It consists of the main, secondary and tertiary control and has different goals. In the tertiary control loop of CEMS, the best practices for load shedding and PV-BESS use are developed and resolved using LP and MILP. Robust real-time solutions are found for the defined challenges. The proposed strategy is validated by taking into account a grid-connected DC microgrid with critical and nonessential loads that is based on PV-BESS. The success of the proposed scheme is demonstrated by an analysis of its performance across a range of settings, including peak and off-peak load scenarios and BESS charging and discharging operations. The outcomes demonstrated how to use PV-BESS to its full potential and how to operate load shedding efficiently depending on load priorities. The outcomes of the test application cases shown that the proposed CEMS can function more effectively, reliably and during peak and off-peak load demand circumstances for DC microgrids. The real-time simulator (OPAL-RT) is used to build and evaluate the created CEMS in order to show off its promising capabilities across a range of test scenarios. Analysis and real-time data confirmed that the proposed CEMS for grid-connected DC microgrid is effective. The work can be expanded by taking into account a variety of renewable energy sources in order to create energy management plans that will enable a linked AC and DC microgrid to operate optimally and dependably.

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