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Autonomous Power Management for Off-Grid DC Microgrid Systems

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Abstract: *In today's automated world, electricity is essential, and its scarcity will present serious problems for developing countries. Due to the unfeasibility of relying solely on fossil fuels, there has been a notable movement in favor of using renewable energy sources. DC Microgrids (DCMGs) make it easier to handle renewable energy sources, however they face efficiency issues. In remote areas, renewable-integrated DCMGs are being used more often; nevertheless, their dependability depends on battery capacity, which is impacted by the changeable nature of renewable energy sources. There are security risks associated with overcharging and discharging, and increasing storage capacity is quite expensive. Connecting nearby Microgrids enhances virtual storage and discharge capacities in both excess and deficit scenarios.*

Keywords: Autonomous DC Microgrids, Bus Signaling method, Power control and management scheme, Renewable sources, Real time simulation

I. INTRODUCTION

The global electric energy systems are required to address the increasing electricity demand while maintaining a stable supply. At present, fossil fuels are the primary source of power generation, resulting in elevated CO_2 emissions and contributing to global warming, as noted in the "World Energy Outlook 2013" published by the International Energy Agency (IEA)[1]. To tackle these challenges, there is an increasing movement towards energy systems that incorporate renewable sources such as photovoltaic systems, wind generators, biomass, and combined heat power systems. These sources are generally disseminated as components of Distributed Energy Resources (DER). Recent developments in research, technology, and regulatory frameworks are transforming power system structures, requiring innovative strategies for the planning, management, and operation of contemporary electricity networks. Microgrids have developed into a practical solution, incorporating both renewable and conventional energy sources to improve sustainability, resilience, and efficiency. Their capacity to operate autonomously from the primary grid renders them a financially viable solution, particularly in developing areas where traditional power infrastructures are inconsistent or non-existent.[2]

Microgrids can be categorized into three types: AC, DC, and hybrid AC/DC, depending on their voltage and current characteristics. DC microgrids (DCMGs) provide enhanced reliability and efficiency, owing to their integration with renewable energy sources such as photovoltaic (PV) systems, fuel cells, and batteries, in addition to their support for DC-powered loads. As the complexity of distributed generation rises alongside changing market regulations and grid liberalization, the implementation of sophisticated control strategies, automation, and communication technologies becomes crucial for the effective management of future smart grid infrastructures.[3]

The key features of FREEDM encompass a plug-and-play interface that facilitates seamless device integration, an energy router designed for effective power management and balancing, and an open-standard DGI framework that ensures efficient energy flow and fault management.[4]

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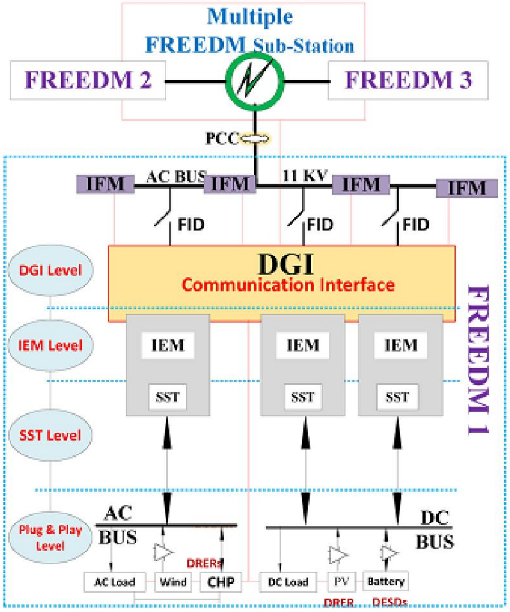


Fig 1. Future Renewable Electric Energy Delivery and Management

To tackle the core issues associated with managing extensive arrays of distributed devices and fluctuating loads, innovative control theories and algorithms based on distributed agents are essential and are presently in the development phase. The FREEDM center anticipates that a significant challenge will be the implementation of DGI applications in a distributed fashion across various execution platforms, such as IEM and IFM. Experience thus far has highlighted the importance of software and communication platforms that are based on open source and open standards. To achieve this objective, the center has outlined a standards-based execution framework for IFM and IEM applications. This framework adheres to the IEC 61850 and IEC 61499 standards. The results indicate a successful implementation of the agent-based power balancing DGI application across a network of ARM controllers.

A. Holonic Control Principles:

Holonic principles from AI and general systems theory are applied to Smart Grids to model complex distributed systems efficiently. A holonic Multi-Agent System (MAS) architecture structures software entities within Smart Grid ICT infrastructure. The Smart Grid is seen as a holon comprising domain holons for generation, transmission, distribution, control, operation, market, and consumers. Autonomous prosumers form control holons organized in a bottom-up hierarchy. Functions include state analysis, forecasting, and scheduling. A Service-Oriented Architecture (SoA) enhances interoperability with five key services. Holonic control ensures adaptive power distribution, supporting island operation during emergencies like hurricanes or grid failures.

B. Important ICT and Automation Standards

Standardization is crucial for Smart Grids to ensure interoperability and scalability, given the evolving ICT and automation solutions. Several international organizations and projects have developed Smart Grid standards and roadmaps. The International Electrotechnical Commission (IEC) plays a key role by defining common rules for Smart Grid planning and operation. The "IEC Smart Grid Standardization Roadmap" highlights core standards like IEC TR 62357 (service-oriented integration), IEC 61970/IEC 61968 (Common Information Model – CIM), and IEC 61850 (power utility automation). Other organizations, such as NIST, DKE, and IEEE, have also developed roadmaps for intelligent grid implementation. Additionally, standards like IEC 61131-3 for programmable logic controllers and IEC 61499 for distributed automation are recommended for control logic implementation in Smart Grids.

II. LITERATURE REVIEW

The integration of intelligence in future electric energy systems has been a focus of recent research efforts. Strasser [2] provides a comprehensive review of architectures and concepts for intelligent energy systems, emphasizing advancements in automation and control. Adhikari and Wang [3] explore decentralized control strategies for DC microgrid clusters, proposing a method to enhance stability and scalability. Dragicevic [4] introduces a distributed control strategy for low-voltage DC microgrids using power-line signaling, enabling coordinated operation without additional communication infrastructure. Kumar and Shrivastava [5] present a control strategy for interconnecting islanded DC microgrids, ensuring efficient energy management and stability under varying load conditions. Ma and Zhu [6] discuss the configuration and operation of DC microgrid clusters connected via DC-DC converters, highlighting the importance of power-sharing mechanisms. In his 2016 paper, "Advancing Building Energy Management System to Enable Smart Grid Interoperation," Eun Kyu Lee addresses the integration challenges between Building Energy Management Systems (BEMS) and Smart Grids. He proposes an advanced BEMS framework designed to enhance interoperability, focusing on seamless communication and control between building energy systems and the broader smart grid infrastructure.

Papers [13]–[14] discuss the interconnection of DC microgrids. The paper [13] proposes a method for decentralized power flow control between DC microgrid clusters utilizing tie line connections, focusing on bus voltage adjustment and regulation, while avoiding the need for additional bidirectional DC-DC converters. Different configurations for interconnecting the DC microgrid clusters are analyzed in [14], and a control strategy is introduced based on hierarchical control to regulate power through the interlinking bidirectional DC-DC converter between DC microgrids.

Three methodologies (circuit switching, packet switching, and virtual packet switching) are presented in [15] for power distribution among DC microgrid clusters, drawing parallels from internet architecture.. In [16], the interconnection of ADCMGs is examined through the proposal of a centralized control strategy aimed at ensuring optimal operation of each grid utilizing a conventional non-isolated bidirectional DC-DC converter. The reliability of the system is significantly influenced by the centralized controller and the communication link. This results in a single point of failure. Furthermore, there is no provision for isolation between ADCMGs. Isolation is inherently present in [17] due to the flyback converter; however, power sharing is significantly influenced by the disparity between generation and demand, akin to the previous case, which necessitates communication among various units.

A novel DC-DC converter utilizing an LCL filter is introduced in [18], which removes transformers from the dual active bridge converter (DABC) to enhance performance in high power and high voltage transmission systems. While it demonstrates considerable advancements in minimizing weight, losses, and reactive power, it is best suited for high power and high DC voltage applications where the operating frequency is constrained. Additionally, it is deficient in galvanic isolation. Extended phase shift control is suggested for DABC in [19] to connect the low and medium voltage DC grids. The primary emphasis is on bidirectional power control, neglecting the specific conditions of the individual DC grids. The design and operation of a novel bidirectional DC-DC converter featuring a CLLC resonant tank for achieving zero voltage and zero current switching is examined in [20] for dissimilar voltage-based DC buses. However, it does not address the condition of sources linked to the individual DC buses, which affects the power flow between the DC grids. Paper [21] introduced a strategy utilizing bus states for the transfer of power between DC microgrids. The implementation of droop control for managing distributed generation within a single microgrid is limited in its ability to maximize power extraction from renewable sources and requires centralized communication for optimal functionality. A two-level tertiary control scheme is introduced in [22] to achieve optimal power sharing among DC microgrids within the cluster by regulating reference voltages in DC microgrids. However, this scheme involves limited communication and may result in suboptimal power distribution between the DC microgrids, either due to failures in upper-level communication or due to tracking inaccuracies during dynamic power fluctuations of sources and loads within the microgrids.

Power Converters:

In electronics engineering, a DC-DC converter is a circuit that modifies a direct current source from one voltage level to another. These converters play an essential role in portable electronic devices such as mobile phones and laptops, which are powered by batteries. Since different internal circuits require specific voltage levels—sometimes higher, lower, or even negative compared to the battery's voltage—DC-DC converters provide a space-efficient solution.

a. Boost Converter

In this circuit, the activation of the transistor will apply voltage Vin to one terminal of the inductor. The applied voltage will result in an increase in the inductor current. When the transistor is in the OFF state, current will persist through the inductor, but it will now traverse the diode instead. We start with the assumption that the current through the inductor remains above zero, which means that the voltage at Vx will solely reflect the voltage across the conducting diode throughout the entire OFF duration. The average voltage at Vx is contingent upon the average ON time of the transistor, assuming the inductor current remains continuous.

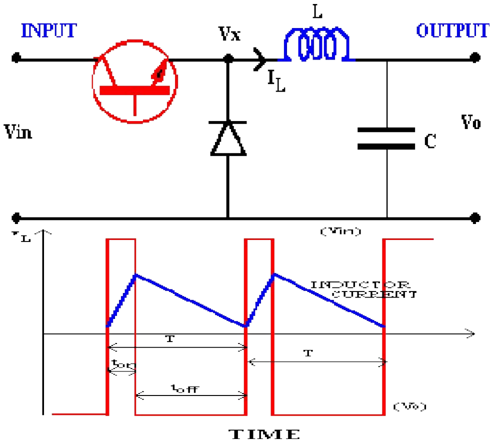
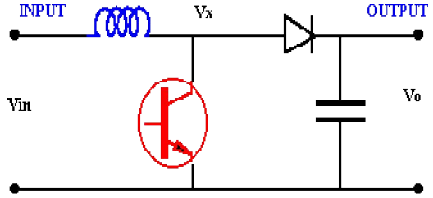


Fig 3. Circuit configuration of Boost Converter with its current waveforms

b. Buck Converter:

This circuit is used when a higher output voltage than input is required. While the transistor is ON Vx =Vin, and the OFF state the inductor current flows through the diode giving Vx =Vo. For this analysis it is assumed that the inductor current always remains flowing (continuous conduction). The voltage across the inductor and the average must be zero for the average current to remain in steady state.



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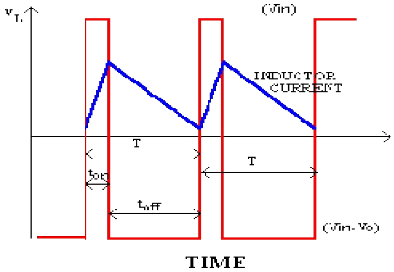

Fig 4 : Circuit configuration of Buck Converter with its current waveforms

c. CUK Converter

The buck, boost and buck-boost converters all transferred energy between inputs and output using the inductor, analysis is based of voltage balance across the inductor. The CUK converter uses capacitive energy transfer and analysis is based on current balance of the capacitor. The circuit in figure below is derived from duality principle on the buck-boost converter

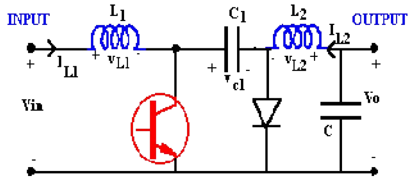

Fig 5 : Circuit configuration of CUK Converter

If we assume that the current through the inductors is essentially ripple free we can examine the charge balance for the capacitor C1. For the transistor ON the circuit becomes and the current in C1 is IL1. When the transistor is OFF, the diode conducts and the current in C1 becomes IL2.

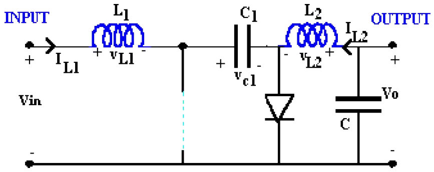

Fig 6 : CUK OFF State

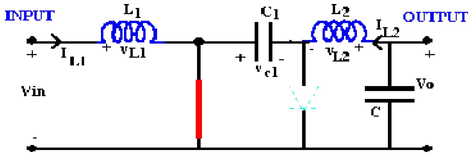

Fig 7 : CUK ON State

Typical Interconnection of two ADCMGs

The fundamental system interconnection is illustrated in figure 3. The two autonomous DC microgrids are connected through a bidirectional converter. In addition to the charging and discharging capabilities of the storage devices in ADCMGs, the emergence of power surplus or deficit within the ADCMG necessitates the implementation of an additional storage system. Raising the SS will result in higher system expenses due to extensive maintenance and initial setup costs.

III. SYSTEM ARCHITECTURE

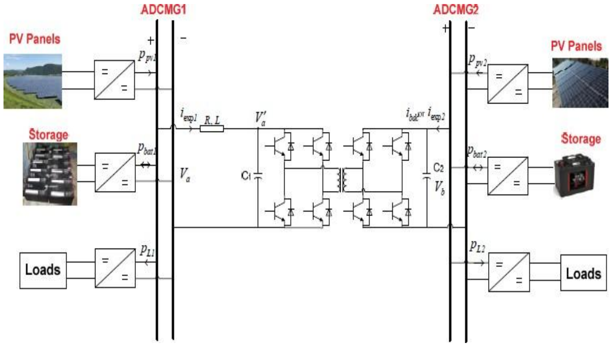

Fig 7. System Architecture for interconnection of two ADCMGs

Power Control and Management Strategy (PCMS)

Power Control and Management Strategy (PCMS) is developed based on DC bus signalling Method (DCBSM) for individual ADCMGs as well as between ADCMGs without any dedicated communication infrastructure. Source and storage units of ADCMGs are operated based on bus voltage levels in the grid by making bus voltage as information carrier between the units for proper coordination and management

Loads are managed depending on the state of charge (SoC) of battery and power condition of ADCMG which is expressed in terms of bus voltage deviation. Instantaneous SoC can be estimated by using coulomb counting method.

- Zone 1(Balanced Power Mode): As power generated by PV source ( ) is less OR equal to demand (L1 p) in the ADCMG1 which keeps battery in idle state.

$$\rho PV1 \cong \rho L1; t1 = 0; V_{aL1} < V_a < V_{aH1} \qquad (1)$$

Where VaL1is the instantaneous battery power in ADCMG1.

- Zone 2(Battery discharging mode): As the PV power is not sufficient in fulfilling the demand that yields to continuous deviation in bus voltage (Va). Once Va fall below threshold value (VaL1) then storage steps into discharging mode from idle state in order to cover the gap between supply and demand. Battery clamps the bus voltage at same threshold (VaL1) by keeping it in bus regulating mode. ADCMG1 is ready to absorb the excess power from ADCMG2 if available (i.e. operating point h.)

$$P_{PV1} + P_{Batt1} = \rho_{L1} = V_{aL1} \qquad (2)$$

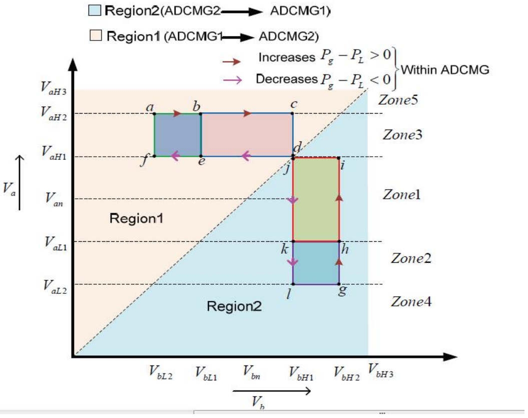

Fig 8. Proposed PCMS between two ADCMGs

- Zone 3: (Battery charging mode) : If the PV source is producing excess power than required, then this mode comes into picture where voltage Va rises continuously due to surplus power and halts at threshold limit (VaH1) by shifting the battery into charging mode. Battery is allowed to charge until its cutoff limit is met. ADCMG1 cannot feed the power to ADCMG2, but absorb the power from it when Vb is at VbH2 and battery1 in ADCMG1 is not fully charged or maximum charging rate is not met.

$$P_{PV1} > \rho_{bat} = -(\rho_{PV1} - \rho_{PL1}); V_a = V_{aH1} \qquad (3)$$

- Zone 4: (Power deficit mode): It is an extension of zone-2 and comes into active state when load rises beyond discharging rate of battery. In this mode, battery runs at maximum discharging current limit. There are two sub cases exist in this zone, in which first case deals with power import from ADCMG2 whereas in the second case, there is no power import from ADCMG2
- Zone 5: (Excess power mode) : It deals with exporting surplus power from ADCMG1 and another case is without exporting power.

Control Loops

A. PV Control Loop : The PV source operates in two modes: Maximum Power Point (MPP) mode and bus voltage regulation mode. In MPP mode, an outer loop tracks the MPP voltage ($VMPP$) using the Perturb and Observe (P&O) method, providing a reference to the inner loop.

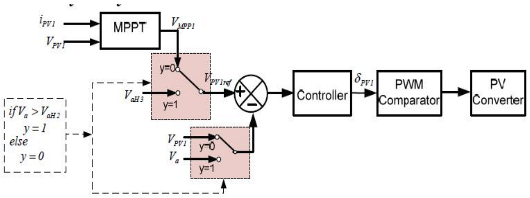

Fig 09. PV Control Loop

B. Battery Control Loop : Battery is operated either in charging or discharging modes based on their cut in thresholds. Each mode employs two loops in which inner loop is common for both the modes. In discharging mode, top outer loop gives the positive reference current ($Ibtrd1$) by regulating bus voltage (Va)at$VaL1$as load dominates, which is fed to discharging rate limiter and then checked against its cut off limit ($Vbat1L$) to ensure the optimal utilization and extended battery's life.

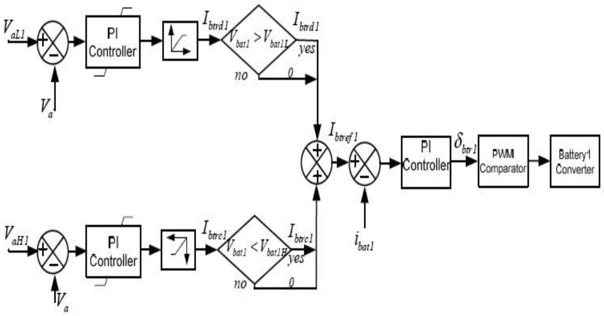

Fig 10. Control loop of battery in ADCMG1

C. Bidirectional Power Control : DABC is employed as bidirectional DC-DC converter(BDC) for transferring the power between ADCMGs. Mainly it works on conventional phase shift method .Power transfer takes place either from ADCMG1 to ADCMG2 or fromADCMG2 to ADCMG1. BDC control is shown in Fig. 5.6. It consists of two loops in which one is outer voltage loop and other is inner current loop. BDC comes to active state when one of two ADCMGs are possessing the surplus power and other grid is able to absorb. Power transfer from ADCMG2 toADCMG1 is treated as positive convention and reverse action as negative.

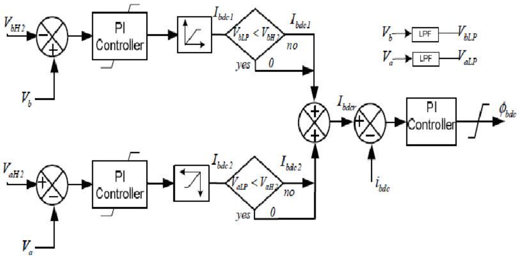

Fig 11. Control of BDC between two ADCMGs

D. Load Control : Constant power load is developed in this paper by feeding resistive load through the buck converter. Buck converter control is similar to conventional control scheme. Load shedding is performed based on DC bus voltage and battery status. If the battery voltage falls below cut-off value $VbatL2$ (equivalent to SoC=30%) then load shedding is initiated to preserve the battery to feed the essential loads effectively. Similarly, if the bus voltage decreases below the lower threshold ($VaL2$) then load shedding is activated because power deficit exceeds discharging rate of battery. Simultaneously if both occurs during worst scenario, then also it triggers the load shedding. Load can be recovered when bus voltage and battery voltage become higher than their limits.

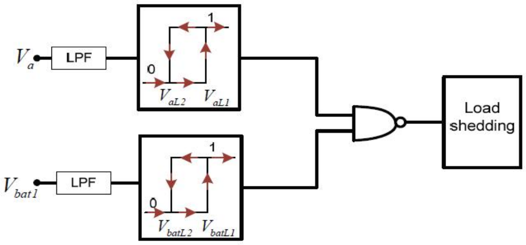

Fig 12. Load control

IV. RESULTS AND DISCUSSIONS

The operating regions of ADCMG1 are illustrated below, with battery voltage maintained above the lower cut-off limit. Voltage deviations across zones remain within ±5% of the nominal bus voltage. Initially (0 to t1), generated power matches load demand (zone-1). At t1, increased PV power (pPV1) exceeds local demand (pL1), shifting the battery to charging mode and regulating bus voltage (Va) at VaH1 (zone-3). At 2t, a sudden load decrease causes battery charging current to exceed its limit, raising Va. The PV then switches to bus regulation mode (zone-5) until t3, when irradiation decreases, returning to zone-3.

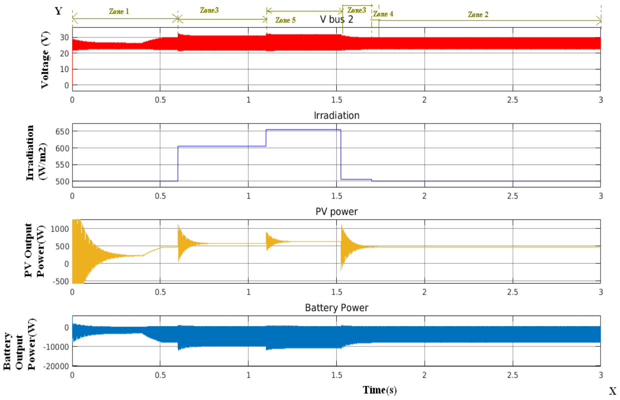

Fig 13: Parameters of ADCMG2: (a) Bus voltage, (b) Irradiation, (c) PV output power, (d) Battery output power

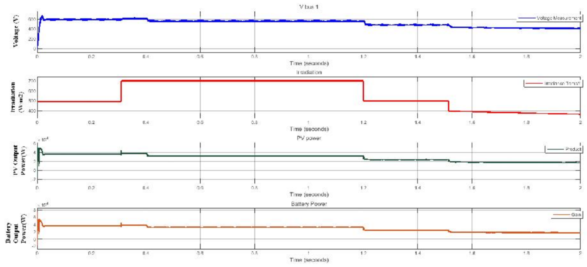

Fig 14 : Parameters of ADCMG1: (a) Bus voltage, (b) Irradiation, (c) PV output power, (d) Battery output power considering variable irradiation

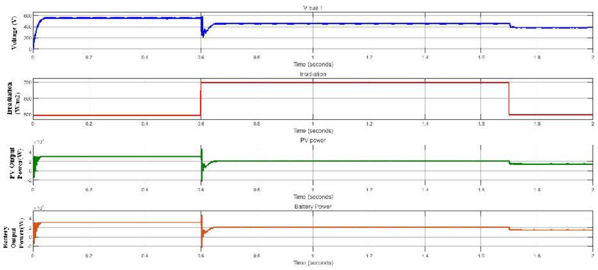

Fig 15: Parameters of ADCMG2: (a) Bus voltage, (b) Irradiation, (c) PV output power, (d) Battery output power considering variable irradiation

Table I :- Comparison of Results based on various parameters

Parameter	Case 1: Without Control	Case 2: Basic Control	Case 3: Advanced Control
Voltage Stability (V)	340 ± 20	350 ± 10	360 ± 5
Power Loss (W)	25	15	5
Load Voltage Deviation (%)	12%	5%	2%
Power Sharing Accuracy (%)	80%	90%	98%
Response Time (ms)	500	250	100
Energy Efficiency (%)	85%	92%	98%

V. CONCLUSION

A PCMS is designed utilizing bus signalling techniques for inter-DC grid power flow in the context of ADCMGs, aimed at enhancing system reliability and optimizing resource utilization. Two specific DC grid voltages (380V, 48V) are analyzed to assess the performance of the developed scheme in simulation. PCMS is analyzed under both standard and extreme conditions, including the overloading and underloading scenarios of ADCMGs, as well as the effects of overcharging and discharging of the battery. The analysis indicates that the proposed PCMS demonstrates stability, efficiency, and effectiveness in achieving communication-independent control, even amidst dynamic power variations during power exchange. This assertion is corroborated by experimental data derived from simulations conducted with a lower voltage setting of ADCMG1. The proposed system ensures isolation while simultaneously improving system reliability. The application potential of the system is suitable for low and medium voltage customers, including domestic consumers, data centers, and telecommunication systems, particularly in isolated locations where a utility connection is either absent or impractical.

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