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Original Research Article

Cooperative Battery Bank-Based Energy Management System for DC Microgrids with Demand-Responsive Energy Sharing

Muhammad Zakir[1]*, Abdullah Said[2], Wannas Karam[3]

[1]MIRAD Department, Hazara Electric Supply Company Limited (HAZECO), 426-A, PMA-Link Road, Jinnahabad, Abbottabad, Khyber Pakhtunkhwa, Pakistan
[2]Department of Electrical Engineering, University of Engineering and Technology, Peshawar, University Post Office Box No. 814, Jamrud Road, Peshawar, Khyber Pakhtunkhwa, Pakistan
[3]Department of Computer Science, University of Swat, Main Campus, Charbagh, Swat, Khyber Pakhtunkhwa, Pakistan

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***Corresponding author:** Muhammad Zakir
MIRAD Department, Hazara Electric Supply Company Limited (HAZECO), 426-A, PMA-Link Road, Jinnahabad, Abbottabad, Khyber Pakhtunkhwa, Pakistan

Abstract

The challenges associated with the evolving energy systems call for an intelligent DC energy management system (EMS) crucial for enhanced efficiency, improved reliability, and cooperative energy sharing. This paper presents a strategy of EMS for a DC microgrid with energy-sharing capability through a cooperative battery bank model by employing a SIMULINK/MATLAB simulation. Each nanogrid of the microgrid cluster utilizes an energy flow switching circuit to connect its PV array, DC load, and individual battery unit. The proposed microgrid comprises four nanogrids having individual battery units linked together via switches and a communication link, forming a cooperative bank model. By taking into account the instantaneous PV-load imbalance, the EMS regulates the energy flow at each nanogrid, while allows for energy sharing between nanogrids determined by the state-of-charge (SOC) of the battery bank. The simulated results validate the exactness of the presented method. Furthermore, the approach is simple in terms of both the system's framework and its management, and also extendable to any number of nanogirds' cluster using an array of switches for the interconnection among them and their batteries.

Keywords: DC microgrid, Energy management system, Cooperative battery bank, Photovoltaic systems, Battery storage, DC-DC bidirectional converter, Energy sharing, Load demand response.

1. INTRODUCTION

About half the world's population, especially the rural areas, still lacks access to a centralized energy system. Smart grids are drastically replacing the existing centralized AC energy systems (Saeed *et al.,* 2021). Because of their all-encompassing scope, they have the advantages of improved reliability, efficiency, and cost-effectiveness in addition to several other benefits. These potential merits of smart grids are the outcomes of microgrids, which are their fundamental stepping stones. Due to issues of connecting the rural areas and distant consumers or loads with the main grid, the microgrids stand out as better suitable options for their energy demands. A microgrid is an array of nanogrids clustered together. A combination of a power generating unit e.g., solar photovoltaic (PV) array or wind turbines, etc., power converters, a storage element, and loads constitute a nanogrid. This could be a building, a home, or an institute. Microgrids have the flexibility to extend to a broader area and can integrate other renewable energy sources, providing a pathway to both rural and urban applications (Xu *et al.,* 2020; Alam *et al.,* 2024).

Microgrids with adequate energy management systems (EMS) offer considerable reduction in energy losses, cost, and intermittency of the loads. In order to utilize the various energy resources, several number of researchers have explored and carried out efficient energy management methods (Zhao *et al.,* 2016; Gholinejad *et al.,* 2021). For example, optimization-based methods have been studied and presented for optimal solutions to the EMS (Fathima & Palanisamy, 2015; Meng *et al.,* 2016). By configuring microgrids in multiple ways, authors have tried to minimize the cost and increase revenues of the microgrids (Derakhshandeh *et al.,* 2013; Ashique *et al.,* 2017). Furthermore, efforts have been made to connect microgrids with the main AC grid by the use of inverters for overall cost reduction (Vayá & Andersson, 2013; Gottwalt *et al.,* 2013; Tushar *et al.,* 2014).

Because of their reduction in dependency on external sources and immunity towards the disturbances and risks coming from foreign systems, they operate independently in power blackouts and energy outages (Bokopane *et al.,* 2024). This ensures energy security and enhances reliability. Moreover, they eliminate the need for fossil fuel requirements that a traditional AC system uses during power production, thus contributing to the mitigation of global warming issues and environmental adversities (Dong *et al.,* 2024; Bacha *et al.,* 2024). Additionally, the production and consumption of energy locally lead to more efficient use of energy in comparison to the centralized grid. Moreover, they are flexible as they can be upgraded or scaled down according to load demands and plans, thus making them scalable solutions for society (Boonraksa *et al.,* 2023).

Standalone operation of the microgrids inherently needs DC or renewable energy sources, such as PVs and wind turbines, which naturally produce DC power. This in turn requires the utilization of modern power electronic devices and converters (Ullah *et al.,* 2020). Moreover, the efficiency and compatibility of such systems are further enhanced by the use of DC storage batteries for both rural and urban applications (Alluraiah & Vijayapriya, 2023; Jin *et al.,* 2023). In earlier times, before the implementation of AC, the primary source of electric energy generation, transmission, and distribution was DC. Nevertheless, the sharp technological advancement and increase in DC-operated equipment and devices have reawakened DC electrification (Sepehrzad *et al.,* 2021). Furthermore, the power losses associated with AC systems such as corona, reactive power, harmonics, and power factor losses are significantly reduced or eliminated with the adoption of DC systems (Bidram *et al.,* 2024).

Among the renewable energy sources, PV-based generators are preferred for their reliability and sustainability (Chauhan *et al.,* 2020). However, their power generation is highly subjected to irradiance and temperature variations. A viable solution to this problem is associating the PV-based microgrids with an energy storage system (Vieira *et al.,* 2017; Perez *et al.,* 2012). Current research evolution highlights the significant capability of cooperative battery bank (CBB) models. In this scheme, multiple batteries, of different nanogrids, work in coordination based on an EMS within a microgrid community. The potential pros of these models include optimal distribution, use, and storage of energy that facilitate power sharing, reliability advancement, and cut costs (Ni *et al.,* 2021). In case of excess surplus energy i.e., above the need of the microgrid, it can be stored or sold for future use and revenue, respectively.

Various AI and optimization techniques have been developed to improve energy management and energy flow in microgrids. Ferahtia *et al.,* (2022) proposed an optimization-based energy management strategy for a DC microgrid and evaluated its performance against a particle swarm optimization (PSO)-based EMS. Supervisory control and energy management approaches have also been investigated for microgrids (Meng *et al.,* 2016; Jin *et al.,* 2013). ANN-based techniques have likewise been applied to energy optimization and control problems (Wang & Tan, 2013; Afram *et al.,* 2017), while Cao et al. (2011) presented an optimized model for electric-vehicle charging that considers time-of-use pricing and battery state of charge. An EMS for low-level (having a few kW generating power) microgrids is presented in Marzband et al. (2017) that incorporates load demands and optimizes the storage mechanism. Nevertheless, this method carries out a series of complex procedures. Moreover, hierarchical strategies of Dragicevic et al. (2013) and Shafiee et al. (2014) have effective results in terms of efficiency improvement and better control, but these methods introduce several communication layers and sensors/transducers. This directly influences the cost of these systems. Nasir et al. (2017) proposed a scalable solar PV-based DC microgrid for rural electrification in developing regions, addressing the need for scalable renewable-energy-based microgrid configurations.

The above literature review shows that energy storage systems have significantly advanced by research on CBB models. However, these models lack developments in some crucial areas. Most still fall short of meeting the power requirements of individual nanogrids through coordinated and demand-based energy sharing, leading to losses and inefficiencies. Moreover, in the long run, performance is affected due to the absence of an integrated battery health monitoring system. Therefore, a CBB-based microgrid system is required that ensures energy sharing mechanism, resource availability, load demands incorporation, and battery health monitoring to ensure minimal losses of energy, optimize resource distribution, and prolong the battery life.

To resolve the challenges mentioned above, this paper proposes a microgrid system featuring an EMS in each nangogrid and a CBB-based energy-sharing mechanism that not only monitors the individual battery health but also incorporates load demands and resource availability in the cluster. The proposed system implements clustering multiple nanogrids through a shared battery bank, a communication link, a common bus, and individual DC-DC bidirectional converters (BiCs) at each nangogrid, while the EMS in every nanogrid uses a DC-DC boost converter (BOC), PI controller, and energy flow switching circuit (EFSC).

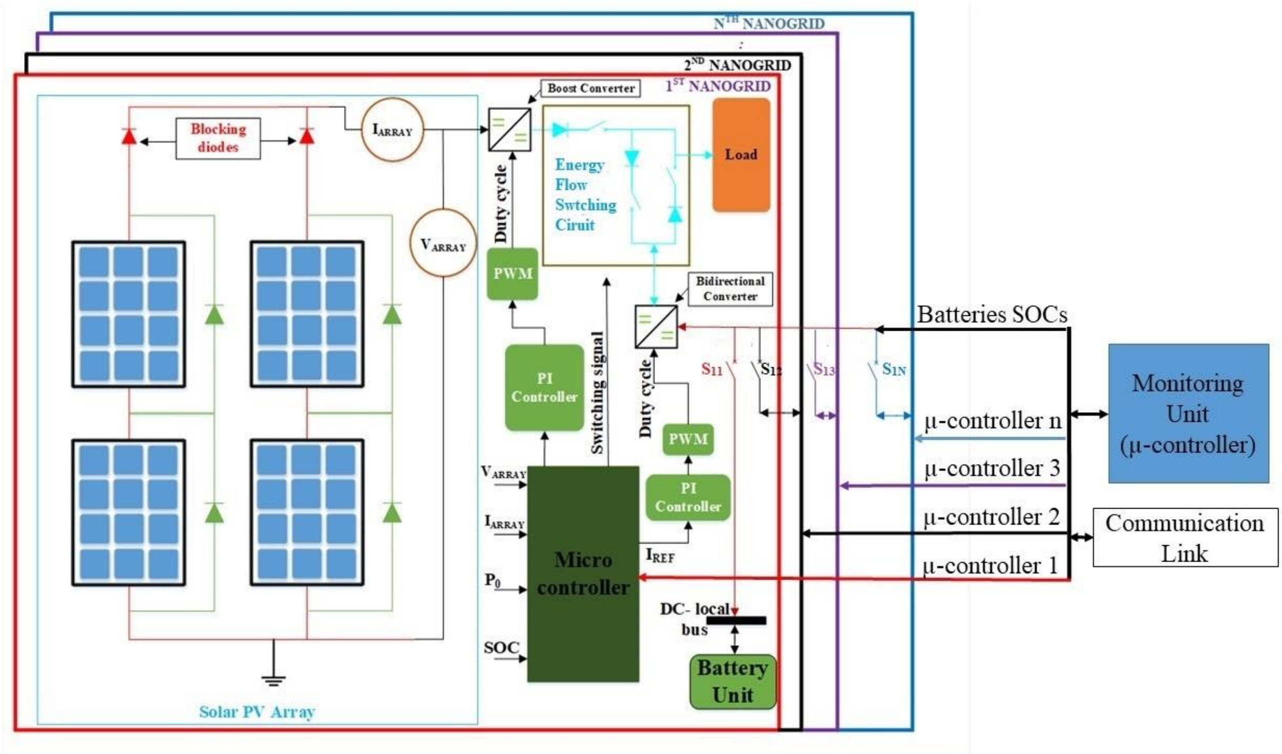

Figure 1: DC microgrid cluster block diagram comprising PV-based N nanogrids, integrating individual battery units into a cooperative battery bank configuration via switches array and a communication link

The primary contributions of this work are highlighted as follows:

1) This research provides an effective EMS specialized for DC microgrids, which makes optimal use of energy distribution and increases reliability and efficiency in rural and off-grid regions.
2) The proposed method performs energy flow among nanogrids by calculating the energy deficit or excess of all nanogrids, their load demands, and the state of charge of their batteries to conclude how much energy a nanogrid needs to draw from or deliver to the battery bank. This inclusive approach ensures enhanced performance and continuity of power supply in the system.
3) The presented work introduces a CBB model, where coordination is established among multiple batteries to meet the load requirements and prolong the lifespan of the battery units.
4) The proposed system offers flexibility and scalability as it can be adapted in diverse settings, from different load demands and small-sized microgrids to larger communities.
5) The effectiveness and practicality of the proposed system are validated by extensive simulations. The results depict that the reliability, efficiency, and performance of the overall system are highly improved.

2. Experimental Section

Generally, a microgrid is a localized cluster of "N" nanogrids capable of operating independently and in coordination with a main grid. In this research work, the cluster comprises four nanogrids, the configuration of which is as follows:

2.1. Composition of Individual nanogrids

A nanogrid is an integral part of a microgrid, which mainly consists of a generating unit, converters, load, and or storage equipment. A house or a building is normally considered a nanogrid. The component-wise construction of the nanogrid is explained below:

2.1.1. PV Array

The generating unit has a 2x2 order, implying that the PV array has two series and two parallel modules. Each module generates a maximum of 213 W power at standard test conditions (STC). Resultantly, the cumulative array power is 852 W. The diodes connected in parallel to every PV module are called bypassing diodes, providing an alternative pathway for current in case its associated module is under fault. Blocking diodes installed on the top of each PV string allow the current to flow out of strings while preventing its return. They also play a key role in isolating its string from the array in case of fault by becoming reverse-biased.

2.1.2. DC-DC Boost converter

Because of its advantages over other DC-DC converters, the boost converter is used in this work for two primary purposes: stepping up the PV array voltage to the required level for loads and battery, and extraction of maximum power from the PV array subject to the gate control signal from the controller.

2.1.3. Energy Flow Switching Circuit

This circuit is an essential part of the individual control systems for establishing EMS in each nanogrid. It possesses three pairs of a diode and a switch. The energy flows in one of the three modes below:

1) From PV array to load and battery, when it generates a power exceeding the load requirements, through the diode-switch pairs bridging the generating unit to load and battery, respectively.
2) From PV array to load only, when the generated power is just enough to meet the load requirements, through the pair connecting the array and load.
3) From both the PV array and the battery via the diode-switch pairs connecting these two to the load, respectively, in case of deficiency in the generated power.

2.1.4. DC-DC Bidirectional Converter

This converter acts either in buck mode, relays energy from the boost converter via the EFSC, to the battery, or operates in boost mode, feeding energy from the battery to the load via EFSC. A positive current value indicates that it's acting as a boost converter while a negative value means that it is in buck operating mode (Zakir *et al.,* 2022). It also connects its respective nanogrid (battery unit) to the whole cluster for energy-sharing purposes.

2.1.5. Load and Battery Unit

The stepped-up voltage from the boost converter is fed to the load and or battery as per the three modes explained in Section 2.1.3. The loads installed at each nanogrid are purely resistive, fixed at a constant value to keep steady power demand for the convenience of simulations. The DC storage unit either receives energy from the nanogrid when it has surplus power and simultaneously delivers energy to the cluster when its energy is higher than the self-sufficient limit, or it draws energy from the cluster when it's deficient.

2.1.6. Microcontroller

Different parameters of the system are monitored and analyzed by the microcontroller for various functions in the microgrid:

1) Tracking MPPT: Based on the inputs Varray, Iarray, and Parray, it determines the duty cycle, which is then passed through a PI controller and PWM generator, to produce a gate driving signal that enables the boost converter to draw maximum power available from the solar panels' setup.
2) EMS: The microcontroller considers the power generated, load demand, and battery condition (SOC) to activate any of the three EMS modes for the nano grid's optimal and steady operation.
3) Power Sharing: It coordinates with the shared microcontroller via a communication link, assisting in power sharing among the nanogrids. It relays real-time date, such as power generation, load demands, SOC, and voltage/current level, to the central microcontroller and executes commands received in return.

2.2. Shared Microcontroller

It performs centralized data aggregation by collecting data from all individual microcontrollers through the communication link and processes it for decision-making. Once the energy surpluses/deficits and energy transfer requirements are calculated, it determines which nanogrids should share or receive energy. Control signals are then sent to individual microcontrollers for coordinating switches and bidirectional converters, ensuring safe and efficient energy sharing. Furthermore, the centralized microcontroller oversees the energy transfer process and adjusts operations to maintain grid stability and prevent abnormalities.

2.3. Wireless Communication Link

It facilitates the real-time exchange of parameters (e.g., SOC, load, generation) between individual microcontrollers and the shared microcontroller. Additionally, it relays control signals from the central microcontroller to individual microcontrollers for energy-sharing operations, enabling efficient and reliable energy management.

2.4. Switches Sii and Sij

The switches Sii and Sij control energy flow within a nanogrid and between nanogrids by connecting bidirectional converters to batteries. These form two types of connections:

- Local Connection: Sii connects a nanogrid's converter to its battery (e.g., S11 for Nanogrid 1, and S22 for Nanogrid 2) to manage local power.
- Inter-Nanogrid Connection: Sij connects the converter of Nanogrid i to the battery of Nanogrid j for energy transfer (e.g., S12 for sharing from Nanogrid 1 to 2).

Only the required switches are activated to direct energy flow while preventing unwanted interactions. The switches ensure controlled and efficient energy sharing among nanogrids.

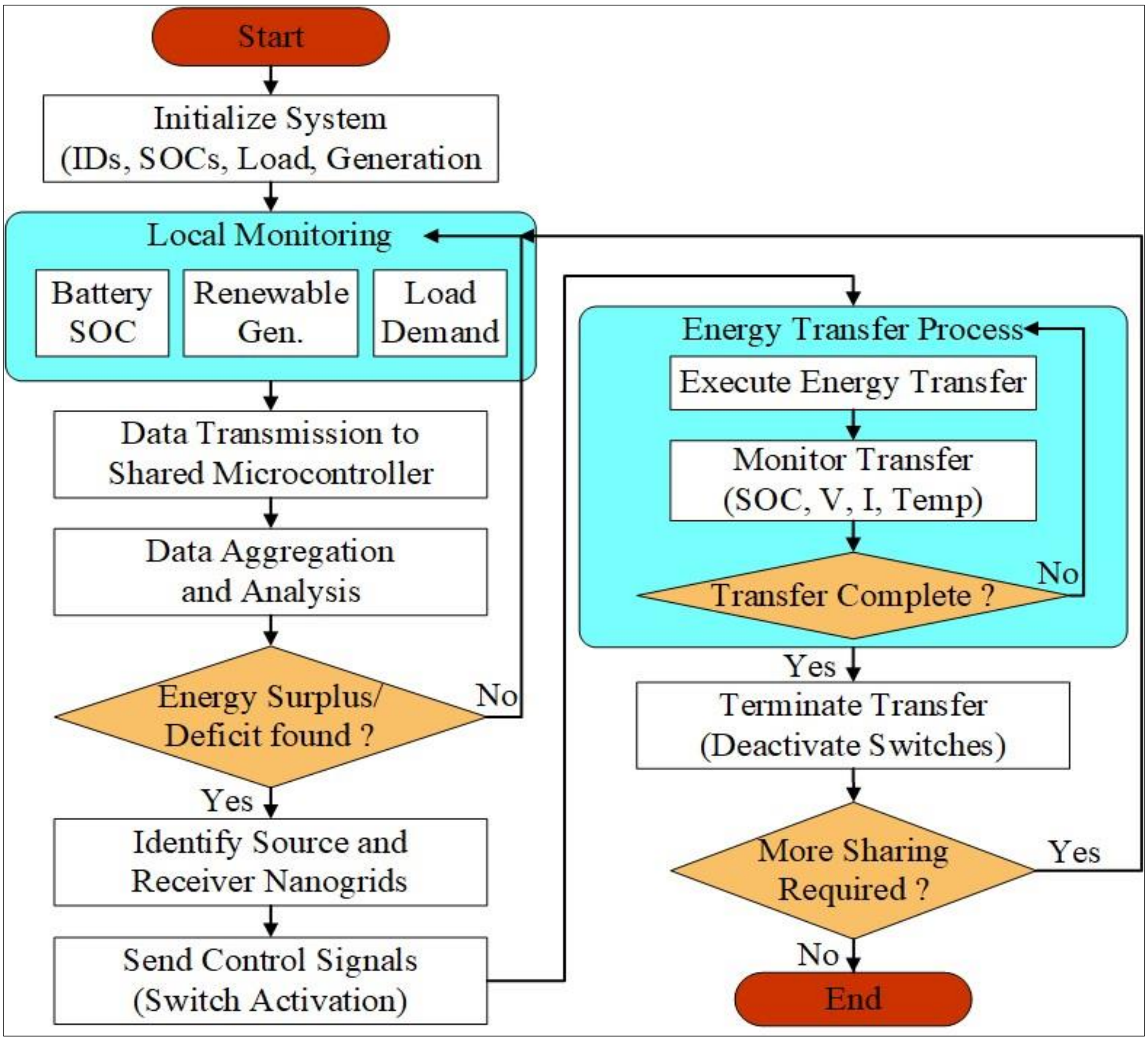

Figure 2: Flowchart of the proposed Cooperative Battery Bank-Based Energy Sharing Strategy for Microgrid

2.5. Proposed Cooperative Battery Bank Configuration

A cooperative battery bank is a configuration where multiple battery units, distributed across nanogrids, are interconnected to operate as a unified energy storage system. This cooperative setup allows efficient energy sharing, balancing, and improved reliability in a microgrid system. Each nanogrid has its battery unit, forming the building blocks of the cooperative bank. Batteries are monitored and managed locally by the respective nanogrid's microcontroller.

The flowchart of the cooperation among the nanogrids is shown in Fig. 2, and follows the following manner:

If a nanogrid is energy-deficient and unable to meet its load requirement, it primarily requests its battery unit to ensure the needed energy. Here, the SOC of the battery is evaluated; it delivers energy if it has enough SOC. In case its battery is out of charge, the other nanogrid's batteries come into play when evaluated one by one, and whichever has sufficient SOC to deliver power to both their own loads and the deficit nanogrid.

2.5.1. Energy Sharing Mechanism Among Nanogrids

Each nanogrid monitors its State of Charge (SOC), load demand, and renewable energy generation. Data is sent to the shared microcontroller. The shared microcontroller identifies: nanogrids with surplus energy, energy deficit nanogrids, and balanced (self-sufficient) nanogrids. It calculates the energy transfer required to balance the deficit nanogrids and transfers energy from surplus nanogrids to deficit ones. Switches are activated accordingly; e.g., if energy has to be transferred from nanogrid 1 to nanogrid 2, S12 is activated. For nanogrid supplying power to its own battery, Sii is activated e.g., S33 for nanogrid 3. The surplus nanogrids discharge their batteries, while the deficit ones charge their battery through the active connection. Once the deficit nanogrid SOC reaches the target level, the shared microcontroller deactivates the switches, ending the transfer. This mechanism ensures efficient energy sharing among nanogrids, optimizing energy utilization and maintaining grid stability.

3. RESULTS AND DISCUSSION

The CBB-based microgrid EMS shown in Fig. 1 is simulated in Simulink/MATLAB for verification of the proposed method and exactness of the system. Table I shows the design parameters for the equipment and components of the simulated system. It is important to note the following key observations from the simulation process:

1) Operation of two nanogrids out of the 4-nanogrid-cluster is considered for the energy-sharing mechanism for simulation, as two nanogrids are sufficient to demonstrate and validate the proposed methodology, while the proposed architecture is scalable and applicable to any number of nanogrids in any configuration
2) It is necessary to define a constant/reference individual load demand to observe the different operating states: energy sufficient, deficient, or surplus, of each nanogrid. For this purpose, the loads of the nanogrids are kept constant to draw a fixed (i.e., P_{ref} = 600 *W*) as demand power
3) In order to compensate for the line and circuit losses and the effect of fluctuations in the parameters, an offset of ±10 *W* is added to the P_{ref}
4) SOC = 30 % is set as the minimum state of charge. A battery with an SOC less than this threshold value is regarded as energy-deficient and incapable of providing energy to any load. If a battery has the condition 30 % < SOC < 40 %, it is deemed as self-sufficient i.e., it can supply energy to its associated nanogrids's load. When the SOC > 40 %, the battery is considered to have surplus energy and can provide energy to other nanogrids as well
5) The overall simulation is executed in two phases. In both phases SOC 2 is set at 45%. In phase 1, SOC 1 is initialized at 20% (energy-deficient mode), while in phase 2, it is kept at 35% (energy-sufficient state)
6) The total simulation is carried out for a time (t) = 0 s to 30 s
7) The graph legends' abbreviations are compiled and detailed in the "Nomenclature" table

Table 1: Equipment and components of individual nanogrid and their design values

Parameter	Symbol	value
No. of nanogrids	N	2
DC-bus capacitance	C_{bus} (µF)	1000
Solar PV module		
STC voltage	Vmp_STC (V)	29
STC current	Imp_STC (A)	7.35
Max. voltage	V_{oc} (V)	36.3
Max. current	I_{sc} (A)	7.51
Rated power	P_m (W)	213.15
Array size (no. of modules)	$Nmodule$	4
Array power capacity	P_{max}(W)	852
DC-DC boost converter (BoC) and load		
Input capacitor	C_{inBoC} (µF)	1000
Output capacitor	C_{outBoC} (µF)	220
Inductor	L_{BoC} (mH)	2
Switching frequency	f_{swBoC} (kHz)	25
Reference/demand power of individual load	P_{ref} (W)	600
Storage unit		
Operating voltage of battery	$V_{battery}$ (V)	24
Rated battery current	I_{rated} (A)	10
Battery's capacity	$C_{battery}$ (Ah)	100
Minimum SOC	SOC_{min} (%)	30
DC-DC bidirectional converter (BiC)		
Inductance	L_{BiC} (mH)	2
Switching frequency	f_{swBiC} (kHz)	25

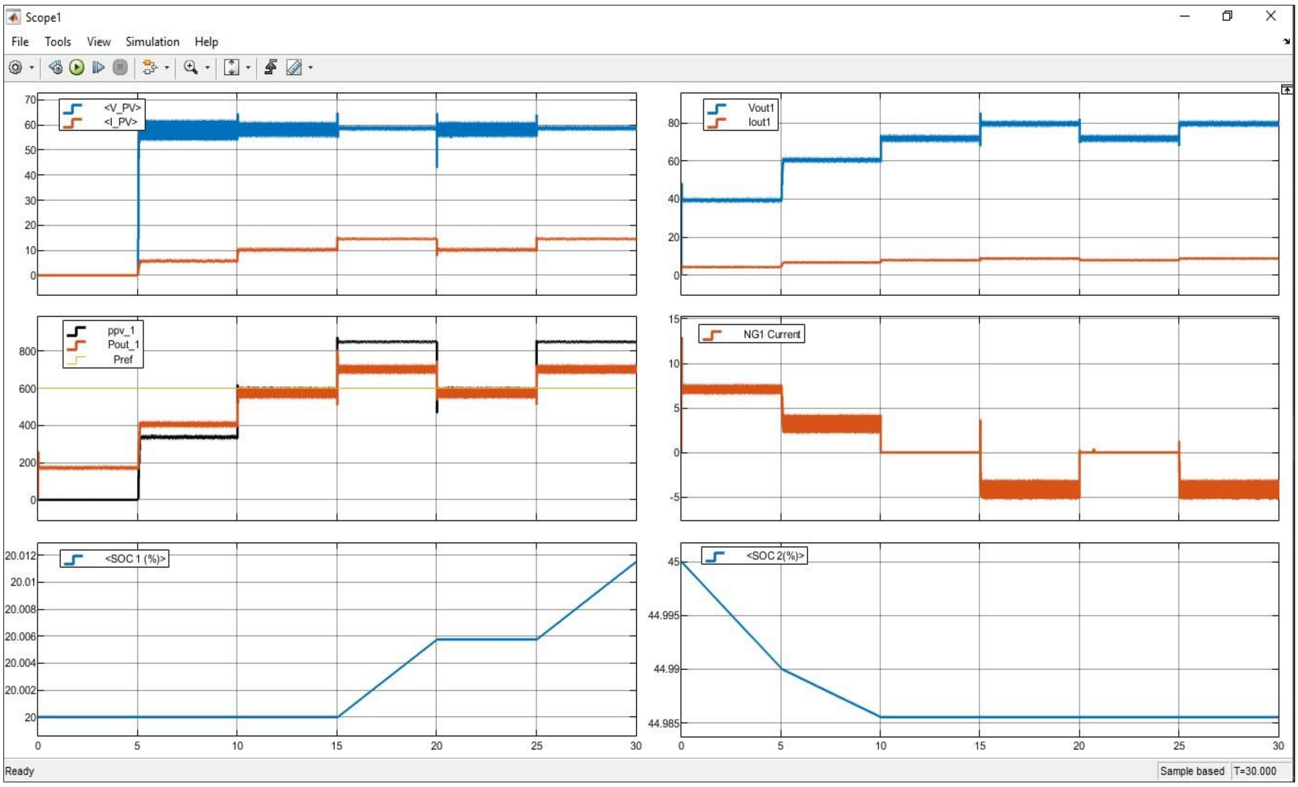

Figure 3: Phase 1 simulation: Varying operating states of nanogrid1 (examining its energy-deficient, self-sufficient, and surplus mode). PV-load power and energy balance

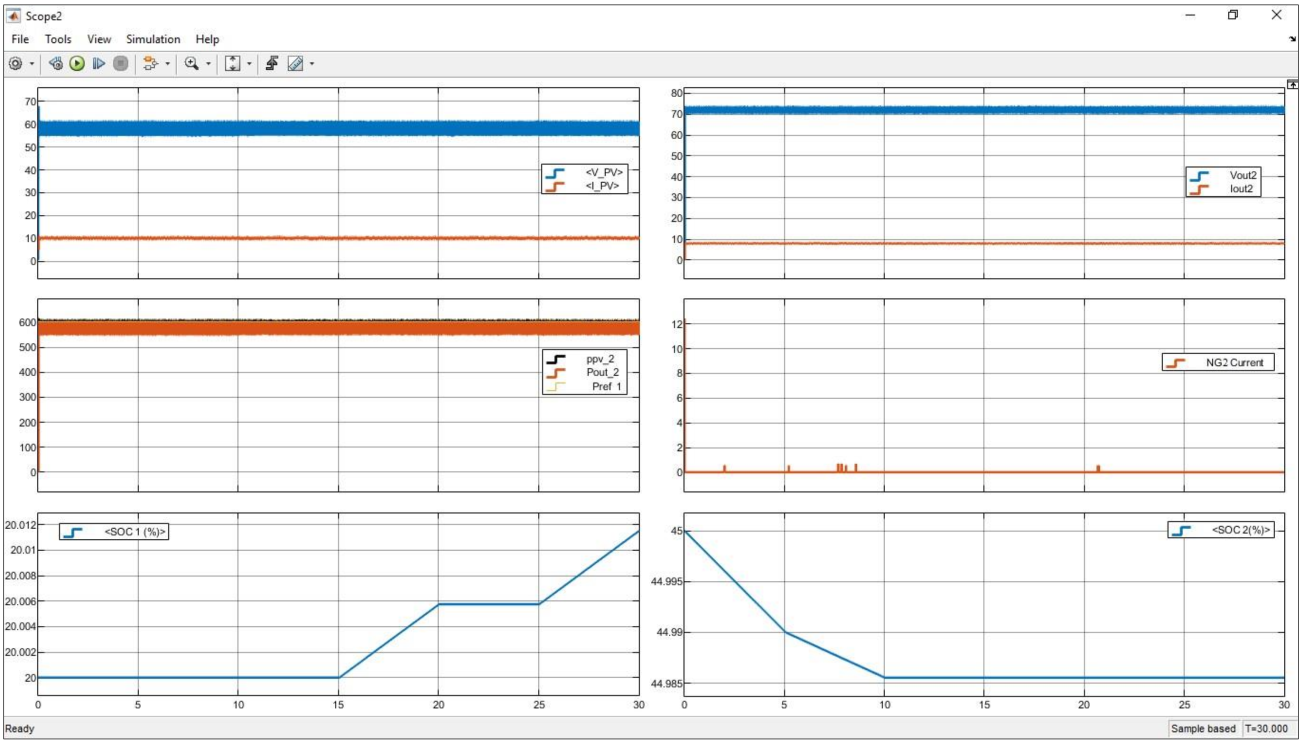

Figure 4: Phase 1 simulation: Behavior of the nanogrid2's PV/load parameters and SOCs with nanogrid1's varying operating states

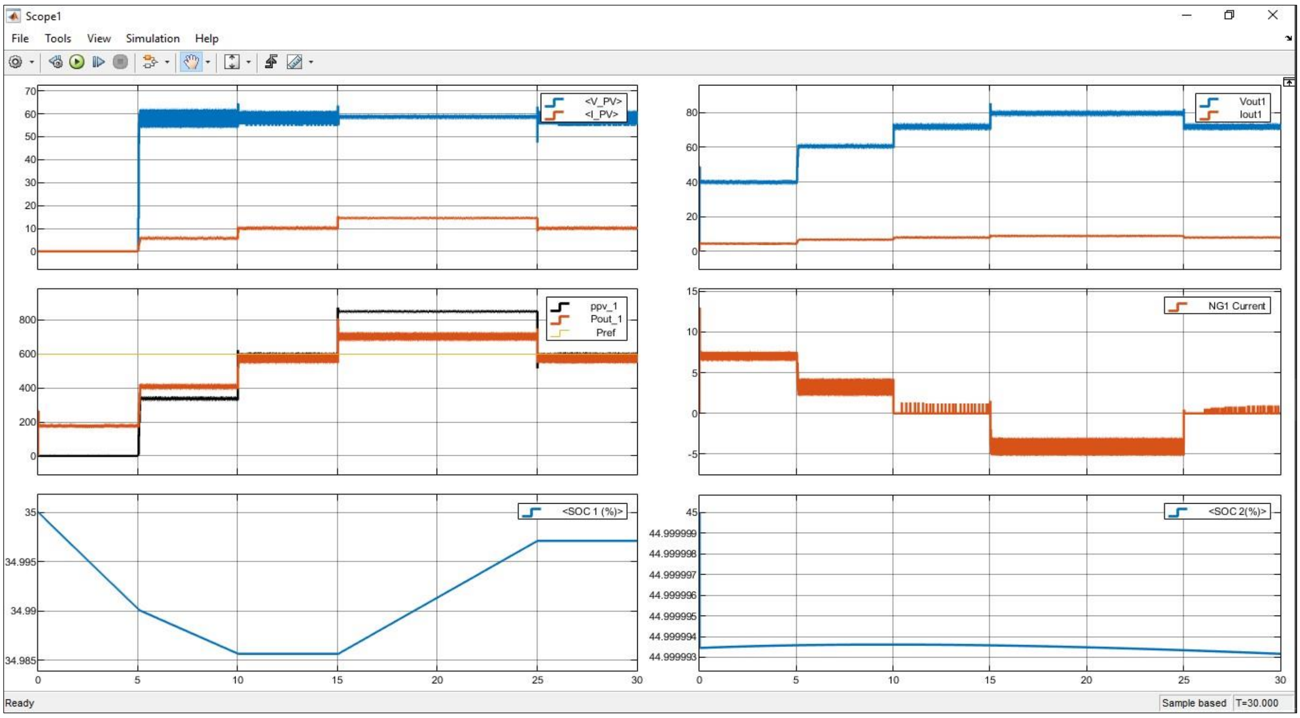

Figure 5: Phase 2 simulation: Varying operating states of nanogrid1 (examining its energy-deficient, self-sufficient, and surplus mode). Variations of key parameters over time, including PV and load current, voltage, and power; and SOCs of the batteries

3.1. Phase 1

Nanogrid1's battery is initialized at SOC = 20 %, revealing that it is less than the minimum limit, 30 %, and needs to be charged, while nanogrid2's battery is initialized at SOC = 45% that shows that it is capable of sharing energy with other nanogrids. Behavior of the SOC and power produced by each nanogrid is shown in Figures 3 and 4. Nanogrid1 is fed with a variable irradiance pattern, causing the PV array to generate variable power, as evident from Figure 3 while nanogrid2 operates in constant power producing mode as depicted in Figure 4. Since the generating power of nanogrid2 is $P_{PV2} \approx 600\ W = P_{ref}$, implying that it operates with sufficient power production for its load, it neither supplies nor demands power from its own battery unit, therefore, it stays disconnected/isolated from the battery unit through the switch S21 (that bridges nanogrid2 with its storage unit). Nanogrid1 is operated in various energy modes throughout the simulation to verify the energy sharing mechanism.

During the time duration (t = 0 s to t = 10 s), from figure 3, it is observed that nanogrid1 is deficient in power as $P_{PV1} < P_{ref}$, calling for energy that could either be drawn from its own or another nanogrid's storage system. Additionally, from Figures 3 and 4, it is seen that the SOC of nanogrid1 is less than 30 %, not in a state of energy provision, while the SOC of nanogrid2 is greater than 40 % able to supply energy to its associated as well as other nanogrids. Consequently, the switch S12 activates and nanogrid1 derives energy from nanogrid2's battery, thus showing energy-sharing between the two nanogrids.

During the time duration, (t = 10 s to t = 15 s), the nangorid1 adopts self-sufficient mode as it produces power equal to the load demand i.e., $P_{PV1} \approx 600\ W = P_{ref}$ in this region, thus it does not derive any power from any battery. Also, both SOC_1 and SOC_2 are constant in this region. The nanogrid1 starts producing extra power than the reference power at time t = 15 s, supplying power to its battery unit where SOC 1 is rising as shown in the figures. It maintains its state until t = 20 s. Again, at t = 20 s to t = 25 s, nanogrid1 is self -sufficient in this region. In the last region, the power

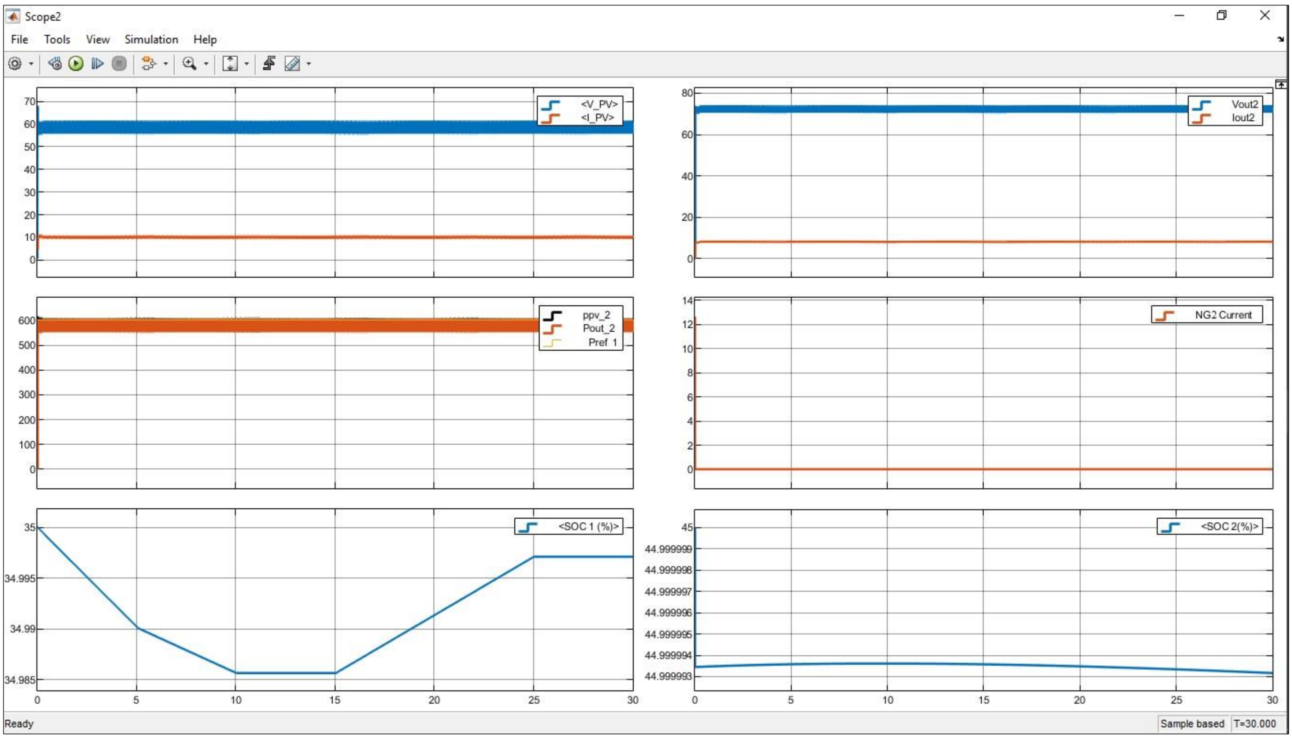

Figure 6: Phase 2 simulation: Behavior of the nanogrid2's constant parameters (PV and load current, voltage, and power) and SOCs with nanogrid1's varying operating states

from the PV-array again exceeds than that of the load demand, and the SOC 1 inclines. After t = 15 s, the SOC 2 remains constant because none of the nanogrids neither supplies nor receive energy from nanogrid2's battery.

Figures 3 and 4 also show the currents through each BiC under different modes of operation. Nanogrid2 with a constant current i.e., NG2 = 0 *A* through BiC_2 from t = 0 s to 30 s operates in self-sufficient mode and remains isolated from its battery unit. From time (t = 0 s to t = 10 s), the nanogrid1 is energy-deficient and draws energy from nanogrid2's battery as discussed earlier. This boost mode operation of the BiC for this time duration is also evident from the figures as the NG_1's has a positive value. The fact that the BiC_1's current has varying positive or negative values and corresponding rate of decrease or increase in SOC is due to the varying power generation subject to changes in irradiance (and hence the load demand) of nanogrid 1. During the time duration (t = 10 s to t = 15 s) its generating power just meets the load demand and the NG1 shows that it neither provides to nor receives any current from any battery. At time t = 15 s, there is surplus energy available and the nanogrid 1 starts supplying power to its battery unit with as the BiC_1 acts as a buck converter determined by its negative current.

3.2. Phase 2

Figures 4 and 5 show the simulation results, where the nanogrid1's battery is kept at 35 % while nanogrid2's battery is initialized at 45 % SOC while keeping the same set of variable irradiance as in Phase 1. From both the figures, it is seen that the SOC_2 remains constant (= 45 %) throughout the simulation, because nanogrid1 does not demand any energy from it as in case of energy deficiency. Nanogrid1 could call for energy from its own battery if need be as SOC_1 is above the minimum 30 % limit. Whereas, variations in the power, input and output voltage and current, SOC_1, and current through BiC_1 occur according to the modes of operation of nanogrid1 as discussed previously.

From the above discussion, the coordination between the two nanogrids is clearly observed and the energy-sharing mechanism of the proposed CBB based EMS for the microgrid is verified.

4. CONCLUSION

An efficient management system for DC microgrid allowing energy sharing among its nanogrids is proposed. For this task, we utilized two interconnected nanogrids. This technique makes use of cooperative battery bank model that interconnects the storage units of all the nanogrids and an energy flow switching circuit at each nanogrid that is connected to the PV-array, individual battery unit, and load. The energy flow switching circuit in each nanogrid supplies the load with energy based on its demand and the nanogrid's PV array and/or battery bank's ability to supply that demand. In order to observe the behavior of each nanogrid and energy-sharing mechanism, a reference value of power (600 W) required by the load is established in the controller of each nanogrid. Based on the nanogrids' shortfall and the SOCs of the battery units, energy is distributed among the nanogrids. The proposed system has been designed to ensure optimal energy flow at each nanogrid and sharing among them in response to usage patterns. The proposed architecture provides a scalable framework that can be extended to larger microgrids. However, this would require additional communication and evaluation of control considerations.

5. Future Work

The following future work can be carried out regarding the proposed EMS for DC microgrid:

1) The effect of load variation can also be incorporated into EMS in the future
2) This method can be extended to a large microgrid cluster
3) Practical implementation can be carried out for the EMS

NOMENCLATURE	
BiC_i	DC-DC bidirectional converter of the i^{th} nanogrid e.g., BiC_1 for nanogrid 1
BoC_i	DC-DC boost converter of the i^{th} nanogrid
CBB	cooperative battery bank
EFSC	energy flow switching circuit
EMS	energy management system
i	an index representing the i^{th} nanogrid, where i = 1,2,3, ... n
Iouti	individual load current of the i^{th} nanogrid
I_PV	PV array current of each nanogrid
NGi	i^{th} nanogrid's BiC current
Pout_i	individual instantaneous load power of the i^{th} nanogrid
ppv_i	PV array power of the i^{th} nanogrid
Pref	reference load demand of each nanogrid's load
PV	photovoltaic
SOC i	state of charge of the i^{th} nanogrid's battery
STC	standard test condition, where irradiance = 1000 W/m^2 and temperature = 25°C
Vouti	individual load voltage of the i^{th} nanogrid
V_PV	PV array voltage of each nanogrid

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