ANN-Based Reactive Power Control in V2G Hybrid Microgrids

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ABSTRACT:

With the increasing integration electric vehicles (EVs), reactive power management is crucial for preserving voltage stability and guaranteeing effective distribution of energy in hybrid AC/DC microgrids. These microgrids integrate DC and AC systems, providing greater flexibility and reliability for decentralized energy management. This study introduces an Artificial Neural Network (ANN)-based approach for reactive power management and converter sizing, aiming to enhance voltage regulation and overall system stability. The proposed ANN method is compared with traditional Proportional-Integral (PI) controllers, demonstrating notable improvements in reducing Total Harmonic Distortion (THD) & improving power quality. By optimizing reactive power compensation and selecting the optimal converter size, this approach offers a more efficient and resilient solution for managing hybrid microgrids, particularly those incorporating EVs, ensuring better energy management and improved system performance.

Keywords: Interlinking converter, hybrid microgrid, electric vehicle, reactive power, droop control, ANN Controller.

I. INTRODUCTION

A microgrid is a localized energy system capable of operating independently or in conjunction with the main power grid. Microgrids provide enhanced energy reliability, flexibility, and efficiency by supporting critical loads during grid disturbances or failures. This paper presents a fully distributed energy management framework hybrid AC/DC microgrids, integrating ADMM with a modified Crow Search Algorithm to enable decentralized optimization. The approach enhances cost efficiency and handles nonlinearity and mixed-integer constraints, but its reliance on metaheuristic tuning parameters and the lack of validation under communication delays or cyber-attack scenarios limit its scalability and practical deployment [1]. Additionally, the seamless switching control strategy AC/DC hybrid microgrids addresses transient over-current & voltage during mode switching but still faces large fluctuations and implementation complexities that affect long-term stability [2]. Introduction of the cascaded PI-FOPID controller that is optimized by the Gorilla Troops Optimizer (GTO) in enhancing frequency response in two area hybrid microgrids is an effective way of reducing frequency variants and tie line power variations [3].

An optimized fuzzy PIDF load frequency controller using the Marine Predator Algorithm (MPA) enhances system response under varying disturbances but introduces increased complexity and dependence on MPA performance, which may not always guarantee optimal results [4]. A novel "Virtual Shaft-to-Shaft Machine" (VSSM) mechanism ensures self-synchronization in AC-DC interlinking converters (ILCs), simplifying control without current or AC voltage sampling. However, its performance under varying system parameters and in large-scale applications remains unexplored, limiting practical implementation [5]. The improved reactive power control (IMRP) scheme for cascaded photovoltaic (PV) converters minimizes reactive power requirements, improving adaptability to power imbalances. However, the complexity of control loops and precise power calculations increases system complexity and scalability issues [6], [7].

The study introduces a data-driven reactive power disaggregation algorithm to estimate inverter settings from AMI data, eliminating the need for distribution models. While accurate, the approach was limited by availability of detailed AMI data, & its performance can be compromised in regions with low voltage volatility [8]. A grid-connected inverter system for Battery Energy Storage Systems (BESS) in microgrids uses active & reactive power control to stabilize voltage fluctuations, though the design of the low-pass filter (LPF) with a genetic algorithm (GA) requires careful tuning for optimal performance [9]. The adaptive long short-term memory (A-LSTM) algorithm for predicting voltage fluctuations during electric vehicle (EV)

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charging offers timely early warnings for charging anomalies. However, its reliance on historical charging data limits robustness, especially in real-world scenarios lacking fault data [10].

An Electric Continuously Variable Transmission (ECVT) for EVs improves transmission efficiency in urban conditions but is limited by a lack of extreme condition analysis and the cost implications of mass production [12]. The hybrid SAR-ANFIS approach for optimizing charging costs for plug-in EVs enhances grid management but faces delays in optimal solution search and centralization issues that reduce flexibility and resilience [13], [14], [15].

II. SYSTEM DESCRIPTION

In order to optimize energy distribution and increase system flexibility, an AC/DC hybrid microgrid combines both AC and DC systems. By linking different energy sources and loads, this hybrid structure enables effective power management, particularly in decentralized energy systems.

The AC/DC hybrid microgrid design is shown in Figure 1, whereby the DC microgrid is made up of DC loads and a DC supply. In contrast, an AC source, AC loads, with a link to the utility grid make up the AC microgrid. The Interlinking Converter (IC) facilitates exchange of power b/w the AC & DC microgrids, allowing them to operate independently or in coordination. This connection ensures optimal energy distribution and stability, enabling the system to balance power supply and demand efficiently. The hybrid microgrid setup provides increased reliability and supports voltage regulation across the entire system. In this proposed method, two distinct cases are considered for effective power management within the AC/DC hybrid microgrid system.

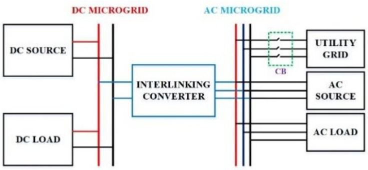

Fig 1. AC/DC hybrid microgrid scheme

A. Case 1: Power Management with Full Capacity of the IC

In this scenario, the Interlinking Converter operates at its full capacity, allowing for efficient and seamless power exchange b/w the AC & DC microgrids. This ensures that both systems are optimally balanced, maintaining voltage stability and efficient energy distribution across the grid.

B. Case 2: Power Management with Low Capacity of the IC

In this case, the Interlinking Converter operates at a reduced capacity, limiting power transfer b/w the AC & DC microgrids. Energy management system adapts to these constraints by efficiently managing power distribution within each grid. Despite the reduced converter capacity, the system continues to operate stably, demonstrating its ability to handle reduced power transfer and still maintain functional energy management.

1) Minimum Participation of EVs

In this sub-case, electric vehicles participate minimally in the energy management system. EVs contribute less to the total energy flow, and the emphasis is still on balancing power between the AC and DC microgrids. This situation demonstrates how the system functions when EVs play a little role in power exchange.

2) Maximum Participation of EVs

In this sub-case, electric vehicles are heavily integrated into the energy management system, playing a significant role in power distribution. The EVs can either supply power back to the grid or absorb excess energy, improving the overall system's flexibility and efficiency. This scenario demonstrates the advantages of EV participation in managing hybrid microgrids and enhancing energy stability.

III. CONTROL TOPOLOGY

The AC/DC hybrid microgrid's smooth operation and stability depend heavily on the deployment of an efficient control architecture, especially when dynamic components like EVs are present. Power is effectively transmitted across the AC and DC grids while preserving voltage regulation & stability across a range of load scenarios thanks to a well-designed control system. Effective power flow management is crucial to preserving grid stability and maximizing energy use since the addition of EVs into the grid adds new challenges, such as fluctuating cycles for charging and discharging. In this proposed system, the control topology includes three distinct strategies to handle the different operational requirements of the hybrid microgrid. These strategies are:

1) IC Control Strategy with SRF-PLL

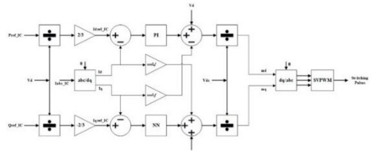

Fig 2. Inter Linking Converter Control Strategy

Figure 2 presents the IC Control Strategy with SRF-PLL (Synchronous Reference Frame Phase-Locked Loop), which is a key component in managing power exchange b/w AC & DC microgrids. Under this control topology, reference power values for active (Pref_IC) and reactive (Qref_IC) power are input into the system. These references are processed by a gain block and passed through a PI (Proportional-Integral) controller, which helps maintain the balance of power between the two microgrids by adjusting output of Interlinking Converter (IC).

Phase angle θ is used to transform the reference power into the d-q frame using an abc/dq transformation, allowing for the separation of active and reactive components of the current (Id and Iq). This decoupling enables precise control of power flow between the AC and DC systems. Additionally, an NN block is incorporated to optimize the reactive power compensation, adapting to dynamic system conditions in real-time and improving overall efficiency.

Once the signals are processed, they are used by the SVPWM (Space Vector Pulse Width Modulation) block to generate switching pulses, which are sent to the IC. This guarantees steady voltage levels and effective power transfer across the AC and DC grids. In order to ensure dependable and balanced functioning of the hybrid microgrid system, the system continually checks its final voltage (Vdc) and modifies the control settings as necessary.

2) Power Management Strategy of IC

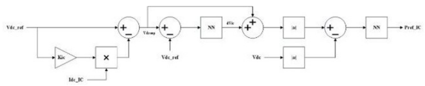

Fig 3. Power Management Strategy of Interlinking Converter

The IC's Power Management Strategy, which is intended to effectively control the electrical power interchange across the AC and DC microgrids in order to guarantee system stability and peak performance, is shown in Figure 3. The control strategy starts by comparing the reference DC voltage (Vdc_ref) with the actual DC voltage (Vdc), creating an error signal. This error is processed by a PI controller to regulate the voltage and ensure that the DC grid operates at the desired voltage level.

The output of the PI controller is used to determine the droop voltage (Vdroop), which is subtracted from the reference voltage to manage voltage fluctuations effectively. The droop control mechanism helps maintain voltage stability by adjusting the reference value in response to changing load conditions. This error signal is then fed into a NN block, which adapts to dynamic conditions and provides the necessary adjustments for power flow control. The output of the NN is used to adjust the voltage control signal (dvic), which further controls the voltage regulation process. The system continuously monitors the actual DC voltage (Vdc) and compares it with the reference value. The NN ensures that any discrepancies between the desired and actual voltage are corrected in real-time, optimizing power management process.

Finally, power reference for Interlinking Converter, Pref_IC, is calculated and provided to the converter to ensure efficient power distribution between the AC & DC microgrids. This power management strategy ensures that the IC operates within optimal parameters, maintaining voltage stability and efficient power transfer between the two systems.

3) Power Management of Each EV in the V2G Network

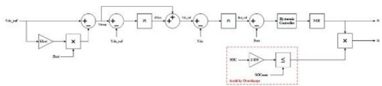

Fig 4. Power management of each EV in V2G network

Figure 4 illustrates the Power Management of Each EV in the Vehicle-to-Grid (V2G) Network, which focuses on integration of EVs into microgrid system for optimized energy exchange. The control strategy begins by comparing the reference DC voltage (Vdc_ref) with the actual DC voltage (Vdc). The resulting error is processed through a PI controller to regulate the voltage and ensure stability in the system.

The voltage error is used to generate the droop voltage (Vdroop), which adjusts for variations in load and ensures that the DC voltage remains within acceptable limits. The droop control mechanism plays a crucial role in maintaining voltage stability while responding to dynamic changes in the grid. The error is then fed into another PI controller, which further ensures that the DC voltage remains consistent, aligning the actual voltage with the reference value.

A key aspect of this power management strategy is the integration of battery current (Ibat), which is regulated to manage the charging & discharging cycles of EVs within the system. Hysteresis controller adjusts the charging behavior of the EVs based on the system's requirements. Additionally, the State of Charge (SOC) is monitored to prevent overcharging of the EV batteries. The SOC is scaled and compared to the maximum allowable charge (SOCmax) to ensure that the EV batteries do not exceed safe charge levels. This avoids potential damage to the batteries and ensures their longevity. The logic controllers (S1 and S2) are used to make decisions based on the SOC and system conditions. These controllers determine when the EVs should supply power back to the grid or absorb power from the grid, depending on the energy needs of the microgrid and the current battery status.

IV. PROPOSED METHOD

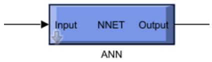

Fig 5. NN Controller

The NN Controller's structure is shown in Figure 5. The hybrid AC/DC microgrid's energy management and voltage control inputs are processed by the NN. In order to govern the Interlinking Converter's functioning, the system receives a variety of inputs, including power imbalance, voltage aberrations, and current faults. These inputs are fed into the neural network, where the NN processes them through its multiple layers and nodes, learning the complex, nonlinear relationships between the system variables.

The output generated by the NN is then used to adjust control signals that regulate power distribution, reactive power compensation, and voltage control. Unlike traditional controllers that rely on fixed parameters, the NN controller adapts to dynamic conditions in real-time, making it highly effective for managing the fluctuating nature of microgrid operations. By continuously learning from the system behavior, the NN controller ensures that the hybrid microgrid operates efficiently, maintaining stability and optimal performance even under changing conditions. This adaptive control mechanism enhances the overall system's response to disturbances, ensuring smoother transitions and improved power quality.

IV. SIMULATION RESULTS & DISCUSSION

In this, the performance of proposed method, which incorporates the NN controller for reactive power management and converter sizing, is evaluated through simulation. The suggested ANN-based control strategy is compared with conventional techniques, and the results are presented in terms for the system equilibrium, voltage regulation, and overall efficiency. The purpose of the simulation setup is to evaluate the controller's performance under different operating circumstances.

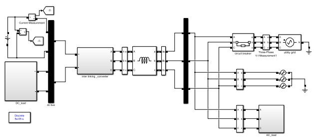

Fig 6. Simulation diagram

Figure 6 presents the simulation diagram of hybrid AC/DC microgrid system, illustrating interaction b/w AC & DC microgrids, the IC, and the control strategies implemented. The simulation results are then analyzed and discussed, providing insights into the system's performance and the advantages of using the NN controller.

Table 1. Simulation parameters

Parameters	**Values**
Rated power	20KVA
Nominal Voltage and Frequency	220V, 50Hz
Switching Frequency of Interlinking Converter	10KHz
Resistance and Inductance of IC Filter	0.1 Ω, 7.5mH
Reference Voltage and capacity of battery each EV	325V, 6.3Ah

Table 1 lists the simulation parameters used in the model, providing details about the input values, control settings, and system configuration. These parameters are critical for understanding the simulation setup and replicating the results for further analysis.

A. Proposed method Results

1) Case 1: Power Management with Full Capacity of the Interlinking Converter

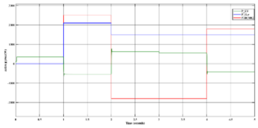

Fig 7. Power Sharing

The electrical power sharing between the three electric cars, the hybrid AC/DC microgrid system, and the Interlinking Converter over time is shown in Figure 7. Three power curves are displayed on the graph: P_EV, which displays the electric vehicle's power; P_IC, which shows the power controlled by the interlinking converter; and P_DCMG, which shows the hybrid microgrid's overall active power flow.

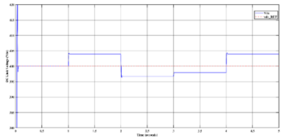

Fig 8. DC Link Voltage

The direct current link voltage (Vdc) & the reference voltage (Vdc_REF) are shown over time in Figure 8. The real DC link voltage, which varies based on power exchange and load needs inside the DC microgrid, is shown by the blue curve. The red dashed line indicates the reference voltage (Vdc_REF), which serves as the target value for the system to maintain.

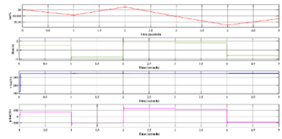

Fig 9. EV Battery outputs

Figure 9 shows the output parameters related to the Electric Vehicle (EV) battery during the simulation. The first represents the State of Charge (SOC), which varies based on charging & discharging cycles of the EV battery, indicating battery's energy storage level over time. The second graph shows the battery current (Ibat), reflecting the current flow during charging and discharging. The third graph illustrates the battery voltage (Vbat), which remains relatively stable while the battery is discharging or charging. The fourth graph represents the battery power (Pbat), showing the power output or input based on the charging/discharging state. These plots provide a comprehensive view of the EV battery's performance within the microgrid, demonstrating its dynamic behavior in response to power demands and the management of energy between the grid and the vehicle.

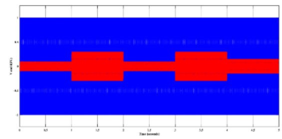

Fig 10. Three phase voltages & currents of grid

Figure 10 depicts the 3-phase voltages & currents of the grid over a period of time. The waveforms of current and voltage on the graph illustrate how the system responds to power flow between the hybrid microgrid and the AC grid. The flat areas show steady-state circumstances, in which the voltage and current of the system are constant.

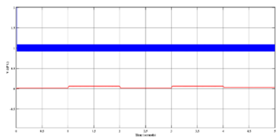

Fig 11. RMS voltage and current of grid

Figure 11 shows the Root Mean Square (RMS) voltage & current of the grid over time. RMS voltage, which remains constant at a value of 1 per unit (PU), indicating stable voltage levels in the system. RMS current, which fluctuates as the power demand changes, reflecting the grid's current flow during different periods.

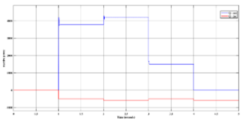

Fig 12. Reactive powers of sources and loads

Figure 12 illustrates the reactive power of both the sources and loads in the hybrid microgrid system. The reactive power supplied by the source and consumed by the load are shown over time. The graph illustrates how reactive power varies dynamically as the system adapts to different load scenarios.

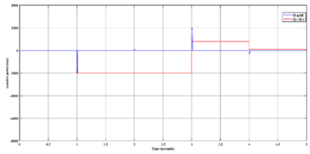

Fig 13. Reactive powers of IC and grid

Figure 13 illustrates reactive power exchange between IC & grid over time. The graph shows reactive power supplied by grid and IC during different operating periods. Initially, the grid provides reactive power, which then changes as the power demand and system conditions vary. Meanwhile, the reactive power from the IC adjusts accordingly to maintain voltage stability and ensure smooth power transfer b/w the AC & DC microgrids.

2) Case 2: Power Management with Low Capacity of the IC

a. Minimum Participation of EVs

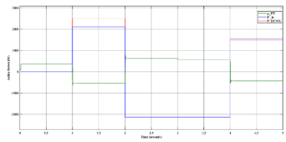

Fig 14. Power sharing

The power sharing between the hybrid DC microgrid system, the Interlinking Converter, and the electric cars is shown in Figure 14 over time. Three curves are displayed on the graph: P_EV, which indicates the power from the EV; P_IC, which shows the power controlled by the Interlinking Converter; and P_DCMG, which depicts the total active power flow in the microgrid.

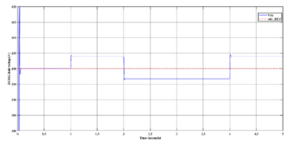

Fig 15. DC bus voltage

Figure 15 displays the DC bus voltage (Vdc) and its reference voltage (Vdc_REF) over time. The first curve represents the actual DC bus voltage, which fluctuates based on the power demands and energy exchanges within the hybrid microgrid.

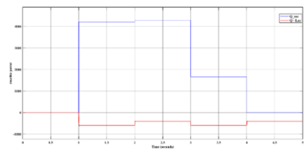

Fig 16. Reactive powers of sources and loads

Figure 16 illustrates the reactive power supplied by the source and absorbed over time by the hybrid microgrid system's load. The fluctuation is displayed on the graph in reactive power from the source and the load during different operating intervals. Initially, the source provides a significant amount of reactive power, which then adjusts based on the load conditions.

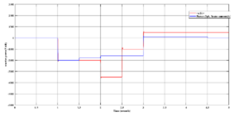

Fig 17. Reactive power sharing

Figure 17 illustrates the reactive power sharing b/w AC & DC microgrids in hybrid system. The graph shows the variation in reactive power exchanged over time, with the reactive power from the source and the power fluctuating based on system conditions.

b. Maximum Participation of EVs

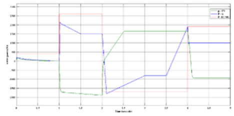

Fig 18. Power sharing

Figure 18 shows the power sharing b/w the electric vehicles, the Interlinking Converter, and the hybrid microgrid system. The graph illustrates how the active power is exchanged over time, with the EV, IC, and the overall system (DCMG) all playing roles in maintaining the power balance. The EV supplies or absorbs power based on the system needs, while the IC manages the distribution b/w the AC & DC microgrids.

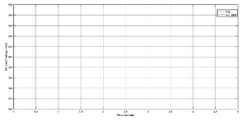

Fig 19. DC bus voltage

Figure 19 illustrates the DC bus voltage (Vdc) and its reference voltage (Vdc_REF) over time. The graph shows that the DC bus voltage remains stable and closely aligned with the reference voltage throughout the simulation period.

3) Comparison Results

The effectiveness of the NN controller and the conventional PI controller are thoroughly compared in this section, with an emphasis on how well they reduce Total Harmonic Distortion (THD). The comparison assesses both controllers' capacity to regulate reactive power and preserve voltage stability in the hybrid AC/DC microgrid. By analyzing the THD levels under various operational conditions. The results highlight the advantages of using an ANN-based approach, particularly in dynamic and fluctuating grid conditions, where the PI controller may struggle to maintain optimal performance.

a. THD Comparison table

Table 2. THD Comparison table

Condition	Time frame	PI Controller	ANN Controller
THD of grid current during power sharing	1s < t < 2s	3.19%	2.59%
	2s < t < 3s	9.06%	7.70%
	3s < t < 4s	4.23%	2.63%
	4s < t < 5s	5.41%	3.67%
THD of line currents of ACMG during power sharing	1s < t < 2s	2.14%	1.05%
	2s < t < 3s	1.57%	0.37%
	3s < t < 4s	3.61%	1.21%
	4s < t < 5s	0.17%	0.17%

Table 2 presents a comparison of Total Harmonic Distortion (THD) for the PI &s ANN controllers under different conditions and time intervals. The results show that the ANN controller consistently outperforms the PI controller in reducing THD, both for the grid current and the line currents of the AC/DC microgrid (ACMG) during power sharing. For example, in the first time frame (1s < t < 2s), the PI controller achieves a THD of 3.19%, while the ANN controller reduces it to 2.59%. This trend continues across all time intervals, with the ANN controller showing significant improvements in minimizing harmonic distortion. Specifically, in the line currents of the ACMG, the ANN controller reduces the THD to 1.05% from the PI controller's 2.14% in the 1s < t < 2s period. Overall, the table highlights the superior performance of the ANN controller in maintaining lower THD, improving power quality, and ensuring more efficient and stable operation of the hybrid microgrid system.

V. CONCLUSION

In this study, we proposed an NN-based control strategy of reactive power management & converter sizing hybrid AC/DC microgrids. The goal is enhance system stability, efficiency, and performance by optimizing power exchange b/w the AC & DC grids, particularly with the integration of EVs. By leveraging the adaptive capabilities of the ANN, the proposed method addressed the limitations of traditional PI controllers, significantly reducing THD and improving voltage regulation. The simulation results demonstrated that the NN controller outperformed the PI controller in minimizing harmonic distortions, ensuring better reactive power compensation, and providing more efficient power sharing between the EVs, the AC grid, and the DC microgrid.

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