Interlink Power Converter based on Series-Parallel Cells for Hybrid Microgrid Systems

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***Abstract*—Hybrid microgrids are systems that enable the interconnection of AC and DC networks within a unified framework, optimizing the integration of energy storage systems and DC-based renewable energy sources with the protection schemes and AC loads, predominantly induction motors. In this context, the integration of an Interlink Power Converter that facilitates AC-DC interconnection is strategically advantageous from an operational standpoint. Furthermore, adopting a multicell-based Interlink Power Converter offers additional benefits, such as the generation of multilevel voltage waveforms, which enhances the integration of filters in AC systems. Additionally, multicell-based topologies ensure scalability and fault-tolerant operation. This paper introduces an Interlink Power Converter topology based on multicell systems, which enhances system scalability. The cells comprising the system are configured in a series-parallel arrangement, enabling effective and straightforward internal balancing, while also allowing the seamless integration of energy storage systems within the converter itself. This feature enhances the system's flexibility and controllability, providing a robust solution for hybrid microgrid applications.**

***Index Terms*—Interlink Power Converter, Series Parallel Converter, Battery Energy Storage Systems**

I. Introduction

A hybrid microgrid is an integrated system that combines both AC and DC microgrids interconnected within the same distribution network. The advantages of implementing a hybrid microgrid are directly linked to leveraging the individual benefits of both AC and DC systems, thereby creating a complementary architecture with high flexibility for integrating various energy generation and storage sources. Additionally, hybrid microgrids facilitate the coherent interconnection of different types of loads and interconnected power systems [1].

However, the flexibility and scalability offered by hybrid microgrids introduce significant challenges in designing a power topology and control system capable of maintaining internal power balance, ensuring synchronization, and integrating protection schemes that must operate in a coordinated manner across both AC and DC subsystems.

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For this reason, the Interlink converter configuration plays a crucial role in the reliable operation of hybrid microgrids. Interlink converters must possess robust control and synchronization capabilities, as well as scalability and redundancy features to ensure a resilient and reliable system operation [2].

Modular Multilevel Converters (MMCs) have emerged as a highly effective solution for Interlink Power Converter for Hybrid microgrid systems Compared to conventional two-level voltage source converters (2L-VSC), MMCs offer several advantages, including lower total harmonic distortion (THD), reduced common-mode voltage, enhanced fault tolerance, seamless integration of energy storage systems, as well as inherent modularity and scalability [3]. However, achieving reliable and safe operation requires addressing critical control objectives, such as maintaining voltage balance within cells and between converter arms, regulating the DC-link current, controlling AC-side currents, and mitigating circulating currents [4].

Nevertheless, the classical MMC architecture is inherently constrained to an AC load and a DC system. To overcome this limitation and enable the integration of such multicell configurations as Interlink converters, it is proposed to extend the configuration of the three-phase nine-switch converter topology [5], replacing each of the semiconductor devices that compose the three-phase nine-switch converter structure with N series-connected cells. This modification facilitates the development of a multicell Interlink converter capable of operating within hybrid microgrid systems, where at its most fundamental level, it can interconnect two decoupled AC systems along with a DC network.

To ensure an efficient and reliable operation of the Hybrid microgrid, it is strategically critical to integrate interconnected cells within the converter that can accommodate battery-based energy storage systems (BESS). This capability allows the converter to store surplus energy when an excess arises from the energy exchange between the AC and DC systems and subsequently deliver energy to these networks in a decoupled manner during periods of energy deficit. This functionality enhances the microgrid's energy balance and overall system stability [6], [7].

One of the most significant challenges associated with implementing hybrid microgrids utilizing a multicell topology

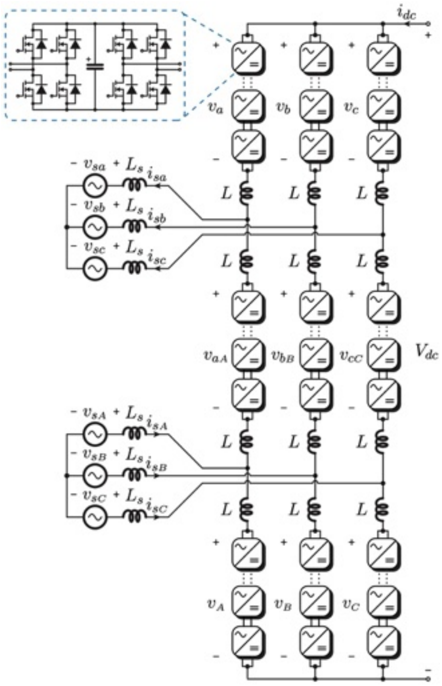


Fig. 1: Proposed Interlink Power Converter

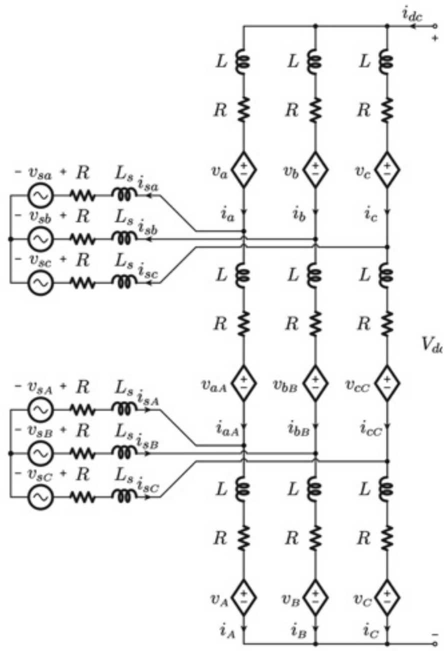


Fig. 2: Model of proposed Interlink Power Converter

as the Interlink converter lies in achieving accurate voltage balancing across the interconnected cells. Failure to maintain this voltage balance leads to increased converter losses, deterioration in the quality of the generated voltage and current waveforms, and, in critical scenarios, converter instability that could ultimately result in system disconnection. To address this issue, various cell topologies have been proposed, each aiming to optimize the internal voltage balancing mechanisms while simultaneously providing fault-tolerant capabilities against both AC and DC short circuits, as well as ensuring compatibility with heterogeneous balancing strategies, among other performance-enhancing features [8], [9].

Among the emerging power converter architectures, the Modular Multilevel Series/Parallel Converter (MMSPC) presents significant advantages over conventional power module configurations. The distinctive feature of the MMSPC lies in its capability to achieve both series and parallel interconnections between its cells. This added flexibility in the switching states enables the attainment of multiple control objectives, including the internal voltage balance, without requiring additional sensors or complex control strategies.

In addition, the ability to reconfigure the interconnections between cells contributes to a more efficient energy transfer process. By reducing the number and influence of parasitic elements, such as inductances and resistances within the power paths, the converter achieves lower conduction losses and improved dynamic performance. This structural characteristic not only enhances the overall efficiency of the system but also supports a more stable operation [10]–[12].

In this work, an Interlink Power Converter based on MMSPC Cells for Hybrid Microgrid Systems is proposed. The proposed system facilitates the interconnection and decoupled control of two AC systems and one DC system. Additionally, through the integration of MMSPC-based cells, it enables the utilization of heterogeneous energy storage systems comprising battery- and capacitor-based technologies, thereby achieving a system with high energy and power density. Moreover, this paper presents a comprehensive model of the proposed system, along with a detailed description of the control and modulation strategies developed for this novel configuration, and its subsequent validation through simulation results.

II. Topology description

A. Power Topology

The proposed system configuration is illustrated in Fig.1. The converter is based on nine arms, which each one is composed by N cells connected in series.

In this proposal, the system consists of two three-phase AC systems, each comprising AC voltage sources (v_{sx} with $x \in \{a, b, c\}$ and v_{sX} with $x \in \{A, B, C\}$) along with series resistances and inductances that emulate the AC-line (R_s, R_S y L_s, L_S respectively). These AC systems are interconnected through the proposed Interlink Converter, which connects at an intermediate point forming by two arms. At the terminals of the converter, a DC network is connected, consisting of a capacitor linked to a voltage regulated by the proposed topology, independent of the connected DC-load.

The topology defining the type of cell to be implemented depends on the operational objectives of the Interlink Converter. Given that this paper focuses on an Interlink Converter for hybrid microgrids, the use of MMSPC is proposed. This approach leverages the additional degree of freedom provided by parallel connection capability, facilitating intrinsic balancing among the N cells comprising the converter. Each MMSPC unit consists of eight IGBT-based semiconductor switches and integrates an energy storage system (Fig.1), which can be implemented using either capacitors or batteries.

Due to the inherent flexibility of MMSPC cells, within a single converter arm, some cells may integrate batteries while others incorporate capacitors, forming a heterogeneous energy storage system. This configuration enhances operational flexibility and contributes to improved balancing within the Hybrid microgrid.

B. Topology Model

The equivalent arm voltage generated by the series-connected cells is categorized into sectors within the converter. The voltages of the upper arms are denoted as V_a, V_b and V_c. The voltages of the intermediate arms are defined as V_{aA}, V_{bB} y V_{cC}. Finally, the voltages of the lower arms are designated as V_A, V_B y V_C. Thus, each of the nine arms of the converter can be modeled as a series controlled voltage source with an inductance and resistance L and R, representing the coupling inductances and the arm losses respectively, like is presented in Fig.2.

Using the model proposed in [13] and making an extension of the results presented in this document, the following equations governing the AC current systems can be derived:

$$(2L_s + L)\frac{d}{dt}i_{sx} + (2R_s + R)i_{sx} = -v_{sx} \\ -\mathbf{Q}(V_x - (V_{xX} + V_X)) \qquad (1)$$

$$(2L_S + L)\frac{d}{dt}i_{sX} + (2R_S + R)i_{sX} = -v_{sX} \\ -\mathbf{Q}((V_x + V_{xX}) - V_X) \qquad (2)$$

Using the same structure, it is possible to obtain the model of the DC current system:

$$(L_{dc} + \frac{2}{3}L)\frac{d}{dt}i_{dc} + (2R_{dc} + R)i_{dc} = v_{dc} \\ -\mathbf{P}(V_x + V_{xX} + V_X) \qquad (3)$$

Where:

$$\mathbf{P} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{bmatrix}; \mathbf{Q} = \frac{1}{3}\begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \qquad (4)$$

In this particular case, since the MMSPC cell is strategically modulated as presented in the following section to ensure intrinsic voltage balancing among the N cells within the same arm, the circulating current does not need to be controlled for internal converter balancing.

III. Control and Modulation Strategy

Considering that the MMSPC modules operate correctly, as will be described later in this document, it can be assumed that all voltages of the interconnected cells are balanced at the same nominal voltage (v_{dccell}). Consequently, the arm voltages of the proposed system can be rewritten as:

$$V_x = Nv_{dccell}(m_{dc} + m_{sac}) \qquad (5)$$

$$V_{xX} = Nv_{dccell}(m_{dc} + (m_{Sac} - m_{sac}) \qquad (6)$$

$$V_X = Nv_{dccell}(m_{dc} - m_{Sac}) \qquad (7)$$

With: $(x \in \{a, b, c\})$, $(xX \in \{aA, bB, cC\})$ and $(X \in \{A, B, C\})$.

By defining the relationship between the modulation indices and the respective arm voltages, it is possible to independently control both AC systems and the DC system. To control the upper three-phase AC system, it is sufficient to regulate the alternating modulation indices defined by m_{sac}. The lower three-phase system can be controlled through the three-phase modulation index defined by m_{Sac}. Finally, the modulation index m_{dc} allows controlling the DC voltage imposed by each arm.

In this way, replacing equations (5), (6) and (7) in (1), (2) and (3) it is possible to obtain each current model in order to design the control scheme:

$$\frac{i_{sx}}{m_{sac}} = \frac{-Nv_{dccell}}{(2L_s + L)\mathbf{s} + (2R_s + R)} \qquad (8)$$

$$\frac{i_{Sx}}{m_{Sac}} = \frac{-Nv_{dccell}}{(2L_S + L)\mathbf{s} + (2R_S + R)} \qquad (9)$$

$$\frac{i_{dc}}{m_{dc}} = \frac{-Nv_{dccell}}{(L_{dc} + \frac{2}{3}L)\mathbf{s} + (2R_{dc} + R))} \qquad (10)$$

The proposed control scheme is presented in Fig.6. It is possible to control each current in an decoupled manner, in order to fully control all the internal dynamics of the proposed system. The PIs controls for the AC currents and DC current component are tuned using the expression shown in (8), (9) and (10).

A. Modulation Scheme

The proposed modulation strategy is based on the Phase-Shifted PWM (PS-PWM) method for MMSPC, previously introduced in [14]. Its primary objective is to maximize the instances where the cells operate in parallel, but only for short durations. This approach enables internal charge balancing among storage units by adjusting the triangular carrier frequency. The strategy determines the switching states that configure the battery and capacitor within each cell in series, parallel, or bypass mode, ensuring a sensorless and efficient voltage balancing mechanism. The selection of switching states depends on whether the modulation controls internal or external interconnections.

The modulation follows PS-PWM scheme, where switching states are determined by the interconnection between $N = 3$ cells. This defines two interconnection types: (i) Internal

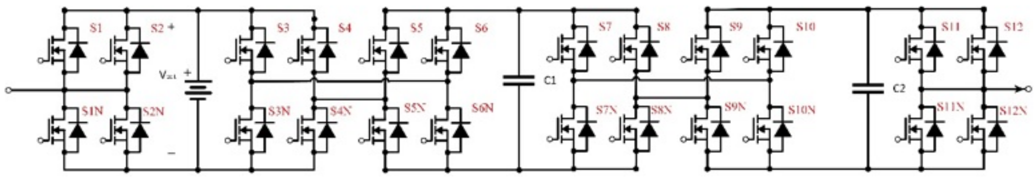
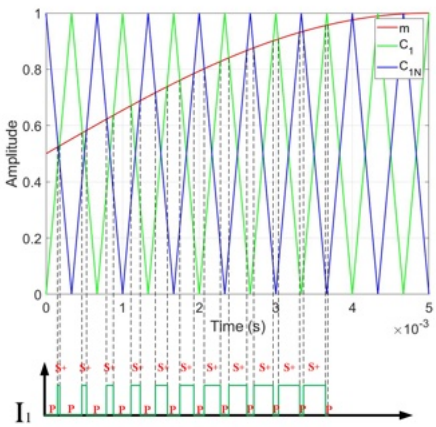
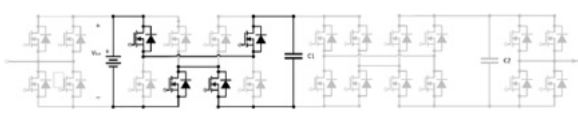


Fig. 3: One arm of the proposed Interlink Power Converter based on MMSPC cell



(a)



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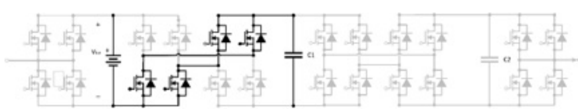

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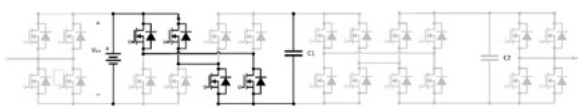
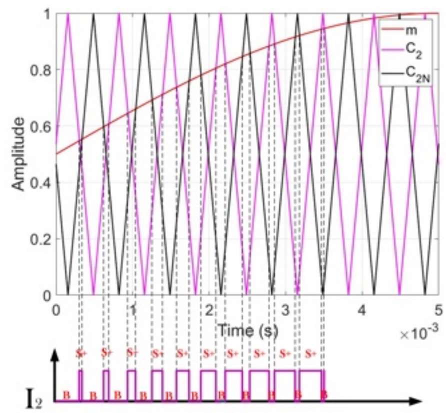
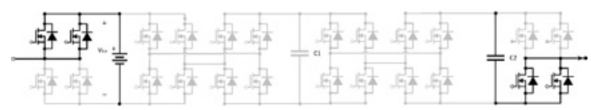


(d)

Fig. 4: Modulation strategy for internal interconnection cells. a) Triangular carrier definition and pulses generation. b) Cell parallel connection (P). c) Cell serial positive connectionn (S+). d) Cell serial negative connection



(a)



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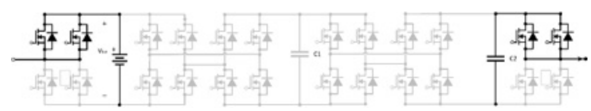
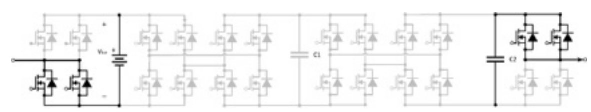


(c)



(d)

Fig. 5: Modulation strategy for external interconnection cells. a) Triangular carrier definition and pulses generation. b) Serial positive connection (S+). c) Bypass connection (B). d) Serial negative connection

Interconnections, referring to adjacent cells (Fig.3, switches S_3, S_4, S_5, S_6, S_7, S_8, S_9, and S_{10}), and (ii) External Interconnections, corresponding to switches at both converter terminals (Fig.3, switches S_1, S_2, S_{11}, and S_{12}).

The carriers are phase-shifted by:

$$\theta = \frac{\pi}{N} \tag{11}$$

For internal interconnections, two triangular carriers and their inverted polarity signals are used (C_1, C_{1N} and C_3, C_{3N}). For simplicity, the switching states of an internal interconnection are illustrated in Fig.4 However, the same state selection logic applies to every internal interconnection within the system. When the modulation signal exceeds the triangular carriers, a positive series state is activated (Fig.4c). If the modulation signal is lower, a negative series state is selected (Fig.4d). Otherwise, a parallel connection between modules is established (Fig.4b).

For external interconnections, the modulation strategy alternates between series positive Fig.5b) series negative Fig.5d) and bypass states, as illustrated in Fig.5. The switching state selection is based on comparing the modulation signal with

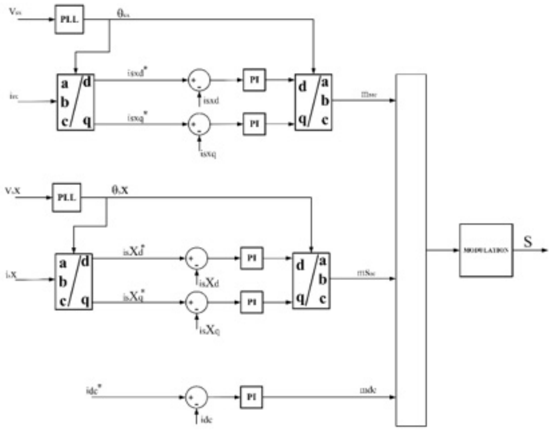


Fig. 6: Proposed Control Scheme

carriers C_2 and C_{2N}. Unlike internal interconnections, where parallel connections are possible, external interconnections replace parallel states with bypass operation, as depicted in Fig.5c).

IV. Simulation Results

The parameters of the simulation are indicated in Table I. This paper presents the implementation of a decoupled control strategy for the proposed system. The Interlink Power Converter based on Series-Parallel Cells for Hybrid Microgrid Systems consists of $N = 3$ cells per arm. In each converter arm, one of the cells integrates a battery as the energy storage system, with a nominal voltage of 100V. The remaining cells in each arm incorporate a capacitor-based energy storage system with an equivalent capacitance of C= 2000μF, like is presented in Fig.3.

For the AC system 1 (v_{sx}), a three-phase current reference of $i^*_{sx} = 8A$ is set and in $t = 0.15s$ change the reference to $i^*_{sx} = 5A$, as shown in Fig.7a). In contrast, for AC system 2 (v_{sX}), a current reference of $i^*_{sX} = 20A$ is initially established, and at $t = 0.3s$, the reference is changed to $i^*_{sX} = 10A$, as shown in Fig.7b). This decoupled current control of the AC systems is achieved by regulating the AC components of the modulation indices.

Furthermore, to validate the decoupled control of the DC current component, a reference change is applied at $t = 0.45s$, modifying the DC system current from $i^*_{dc} = 0A$ to $i^*_{dc} = -10A$. This transition implies that current starts flowing from the Interlink Power Converter toward the DC system, as illustrated in Fig.7c). The results confirm the effective operation of the proposed converter, ensuring that the control stage successfully achieves decoupled current regulation for both AC and DC systems. Moreover, no significant disturbances are observed when applying the reference changes across different systems.

Integrating a battery-based energy storage system in one cell per arm enhances the converter's capability to exchange energy among systems, increasing the flexibility of hybrid microgrids. Furthermore, the utilization of Modular Multilevel Series-Parallel Converter cells enables internal voltage balancing without additional control loops. This is inherently achieved through the appropriate implementation of the proposed modulation strategy. The correct voltage balancing among cells is demonstrated in Fig. Fig.7d), which is a critical aspect to ensure the proper operation of the converter, minimizing internal losses, and maintaining high-quality voltage waveforms.

It is important to note that one of the primary limitations of the proposed system is that the total modulation index in each arm comprises the sum of both the AC and DC components. This sum must remain within the allowable range to prevent overmodulation; otherwise, the control performance deteriorates, leading to imbalance issues and a reduction in the quality of the controlled current signals.

TABLE I: Simulation Parameters

Parameter	Value
DC voltage system v_{dc}	350 V
DC Inductance L_{dc}	10 mH
DC line Resistance R_{dc}	0.1 Ω
Arm Inductance L	1 mH
Arm Resistance R	0.1 Ω
AC system 1 v_{sx}	0 V
Load Resistance R_s	10 Ω
Load Inductance L_s	10 mH
AC system 2 v_{sX}	110 V
AC system 2 output frequency	50 Hz
Load Resistance R_S	0.1 Ω
Load Inductance L_S	10 mH
Number of Cells per arm N	3
Battery storage system nominal voltage v_{dccell}	100 V
Battery storage system Rated capacity	5.4 Ah
Cell capacitance C	2000 μF
Carrier frequency of modulation framework	5 kHz

V. Conclusions

This paper proposed a Interlink power converter based on Series-Parallel cells (MMSPC) for hybrid microgrids systems. The use of MMSPC modules in each arm of the proposed system allows the internal voltage balance of each arm to be achieved in a simple and direct strategy, without any extra sensor or control loop to achieve a reduction in size and cost of the implementation. The proposed power topology allowing the decoupled control of AC and DC current in the Hybrid Microgrid System.

The integration of a battery module in one cell of the proposed interlink power converter allows an important flexibility of the operation of the power system, incorporating the capability of different control strategies to achieve the stability of the interconnected system, due to the capacity of storage energy in period with a surplus of energy and the injection of energy in the period with the demand is bigger than the generation.

The simulation results presented in this work validate the correct performance of the Interlink power converter, the performance of the proposed control and modulation strategy

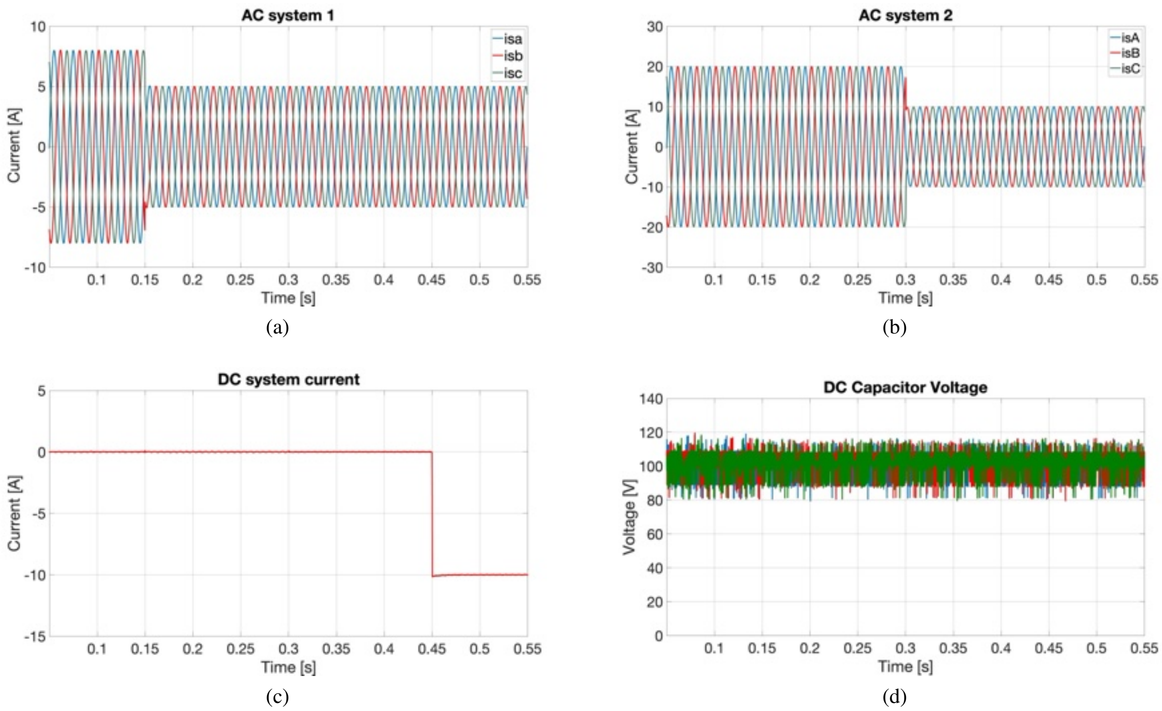


Fig. 7: Simulation Results. a) Three phase current of Ac system 1. b) Three phase current of Ac system 2. c) DC current of system. d) DC voltage capacitor voltage

and the capability of integrate different storage units in the proposed system to give to the hybrid microgrid flexibility and stability in the operation.

Potential directions for future research include experimental validation of the proposed converter using a hardware-in-the-loop (HIL) or scaled laboratory prototype and extension of the MMSPC topology for multi-port applications, enabling simultaneous interaction with multiple AC and DC grids. These future efforts aim to enhance the applicability and scalability of the proposed architecture in real-world hybrid microgrid deployments.

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