



PONTIFICIA UNIVERSIDAD CATÓLICA DE CHILE
ESCUELA DE INGENIERÍA

CONSENSUS-BASED DISTRIBUTED CONTROL FOR INTER-CLUSTER BALANCE IN MODULAR MULTILEVEL CONVERTERS

IGNACIO EN-LAI BRAVO KONG

Thesis submitted to the Office of Research and Graduate Studies
in partial fulfillment of the requirements for the degree of
Master of Science in Engineering

Advisor:
JAVIER PEREDA

Santiago de Chile, October 2024

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*Profound thanks to my parents and
siblings for all their support*

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ABSTRACT

The Modular Multilevel Converter (MMC) stands out as a crucial topology for a variety of medium and high voltage applications in power converters, thanks to its structural and operational characteristics. Its structure, consisting of interconnected low-power submodules, allows for flexible adjustment of its operating voltage, which highlights its important modularity and scalability properties. However, the implementation of these converters typically involves a centralized control scheme, which restricts the advantages of their modularity and scalability in operation.

To address this problem, this thesis proposes a consensus-based distributed control scheme for a three-phase MMC. The control objectives are achieved by employing Local Controllers (LCs) in each cluster of the converter, which operate in conjunction with a single Central Controller (CC). A consensus algorithm is implemented to accomplish the inter-cluster energy balance of the MMC by controlling the circulating currents of the converter. This strategy utilizes consensus variables shared by the LCs through a designated communication channel to equalize the capacitor voltages of the submodules. This reduces the computational load of the CC compared to the centralized control scenario.

This thesis analyzes the proposed control strategies and the design of the necessary control tasks for the correct execution of the consensus-based distributed control scheme. The operation of the MMC utilizing this control scheme is validated through simulations and experimental results, verifying that the voltage balance of the capacitors is achieved under different operating conditions.

Keywords: Modular Multilevel Converter (MMC), Consensus-Based Distributed Control, Capacitor Voltage Balancing Control, Inter-Cluster Voltage Balancing Control.

RESUMEN

Las características estructurales y de operación del Convertidor Modular Multinivel (MMC) lo establecen como una topología crucial para una variedad de aplicaciones de media y alta tensión en el contexto de convertidores de potencia. Su estructura, compuesta por la interconexión de submódulos de baja potencia, permite un ajuste flexible de su voltaje de operación, lo que resalta sus importantes propiedades de modularidad y escalabilidad. Sin embargo, este tipo de convertidores normalmente se implementan utilizando un esquema de control centralizado, lo que restringe los beneficios de la modularidad y escalabilidad en su operación.

Para abordar este problema, esta tesis propone un esquema de control distribuido basado en consenso para un MMC trifásico. Los objetivos de control se logran empleando Controladores Locales (LCs) en cada clúster del convertidor, los que operan en conjunto con un único Controlador Central (CC). Un algoritmo de consenso es implementado para lograr el balance de energía entre los clústeres del MMC por medio del control de las corrientes circulantes del conversor. Esta estrategia utiliza variables de consenso compartidas por los LCs a través de un canal de comunicación designado, para así balancear los voltajes de los capacitores de los submódulos. Esto reduce la carga computacional del CC en comparación con el escenario centralizado de control.

Esta tesis analiza las estrategias de control propuestas y el diseño de las tareas de control necesarias para la correcta ejecución del esquema de control distribuido basado en consenso. El funcionamiento del MMC utilizando este esquema de control se valida mediante simulaciones y resultados experimentales, verificando que el balance de voltaje de los capacitores se logra bajo diferentes condiciones de operación.

Palabras Claves: Conversor Modular Multinivel (MMC), Control Distribuido Basado en Consenso, Control para Balance de Voltaje, Control para Balance Inter-Clúster de Voltaje.

1. INTRODUCTION

In recent years, significant progress has been made in the area of electrical power conversion and transmission, in terms of technological development and academic research. These advancements are largely due to the increasing global energy demand, which drives the exploration of new conversion methods and topologies capable of handling larger energy quantities with greater efficiency.

In this context, power converters are an essential tool that are widely utilized in modern power systems. They enable the control and transformation of electrical energy from one form to another, adapting its use for different electrical loads or for its efficient transmission. Diverse types of power converters can be found in numerous applications, including AC drives for control of industrial processes, traction technology for transportation, power processing in electrical networks and power quality improvement, among other uses (Gonzalez, Verne, & Valla, 2013). In this work, the main focus is on a specific type of converters known as Voltage Source Converters (VSCs).

VSCs are characterized for utilizing a DC capacitor as an energy storage element in their DC-link. VSCs exhibited higher market penetration and more development in industrial applications compared to other types of converters, such as Current Source Converters (CSCs) and matrix converters (Du et al., 2018). Fig. 1.1 shows a possible classification for VSCs, where different subcategories of power converters can be recognized depending on the utilized topology.

Employing the basic two-level inverter for medium and high voltage applications presents drawbacks, including high operating switching frequency, large switching losses, large switch stress and nonavailability of high-power devices, among others (Dwivedi, Jain, Gupta, & Chaturvedi, 2018). Furthermore, in high-voltage applications, the converter transistors must be capable of blocking the increased voltage during their operation,

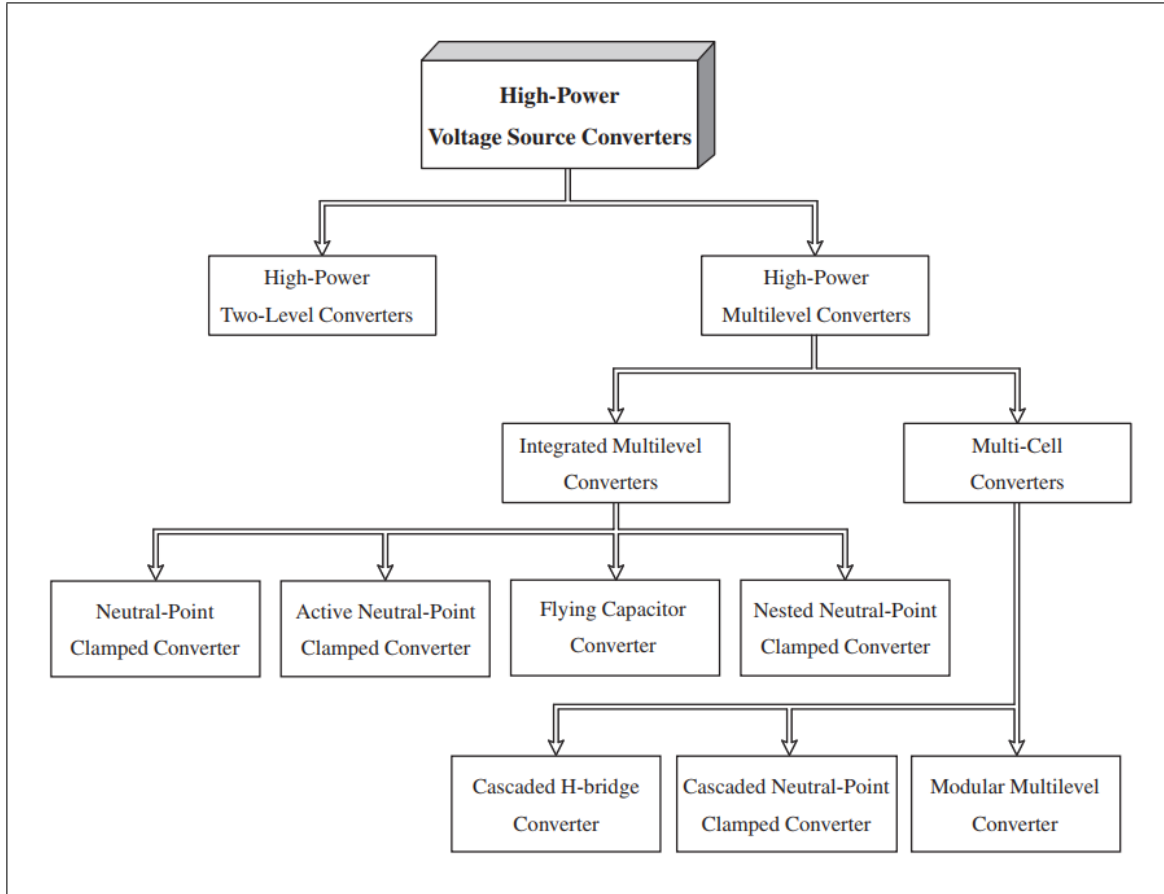


Figure 1.1. Classification of voltage source converters (Du et al., 2018).

which is typically addressed by connecting multiple devices in series. However, this approach also has drawbacks, such as increased power losses and uneven voltage blocking of the transistors (Du et al., 2018).

Due to the above problems, multilevel converters are preferred for medium and high voltage applications. This type of converters are characterized for generating a voltage waveform composed of different steps with a controllable amplitude, frequency and phase. Compared to the two-level converter, multilevel converters have advantages such as good power quality, low switching losses, high voltage capability and low dv/dt (Abu-Rub, Holtz, Rodriguez, & Baoming, 2010). The most recognized topologies in the category of integrated multilevel converters are the Neutral Point Clamped (NPC) and the Flying Capacitor (FC).

As the power requirements for an application increases, integrated multilevel converters require significant modifications to increment their operating and output voltage levels. Furthermore, these converters must be shut down in the event of internal or external faults, leading to production losses in industrial processes (Soomro, Akhter, Hussain, Ansari, & Munir, 2022). As a result of these issues, the denominated cascaded or multi-cell converters have been researched and developed. This type of converters are characterised by being composed of multiple low-power submodules or cells in a cascaded connection, which allows higher operating voltage levels through the coordinated operation of the submodules.

In the literature, two of the most researched cascaded converters are the Cascaded H-Bridge (CHB) and the Modular Multilevel Converter (MMC). The MMC in particular, stands out as one of the most used converters in diverse applications due to its advantages compared to other topologies, which are discussed in the following section.

1.1. Modular multilevel converter (MMC)

The Modular Multilevel Converter (MMC) is one of the most attractive converters for medium and high voltage applications due to its features, such as output voltage waveforms with low harmonic content, very high efficiencies and a high blocking voltage capability, which reduces the stress on the switching devices of the submodules (Santos & da Silva, 2014). These characteristics make it suitable for various applications such as HVDC transmission systems, medium voltage motor drives, Static Synchronous Compensators (STATCOMs), among others. This converter is also the subject of extensive research in the academic area, aimed at exploring and developing new applications for this topology.

Fig. 1.2 shows the general structure of the three-phase MMC studied in this work, also referred to in the literature as Double Star Chopper-Cell (DSCC) or Double Star Bridge-Cell (DSBC). The MMC is composed of various cells or submodules, which are

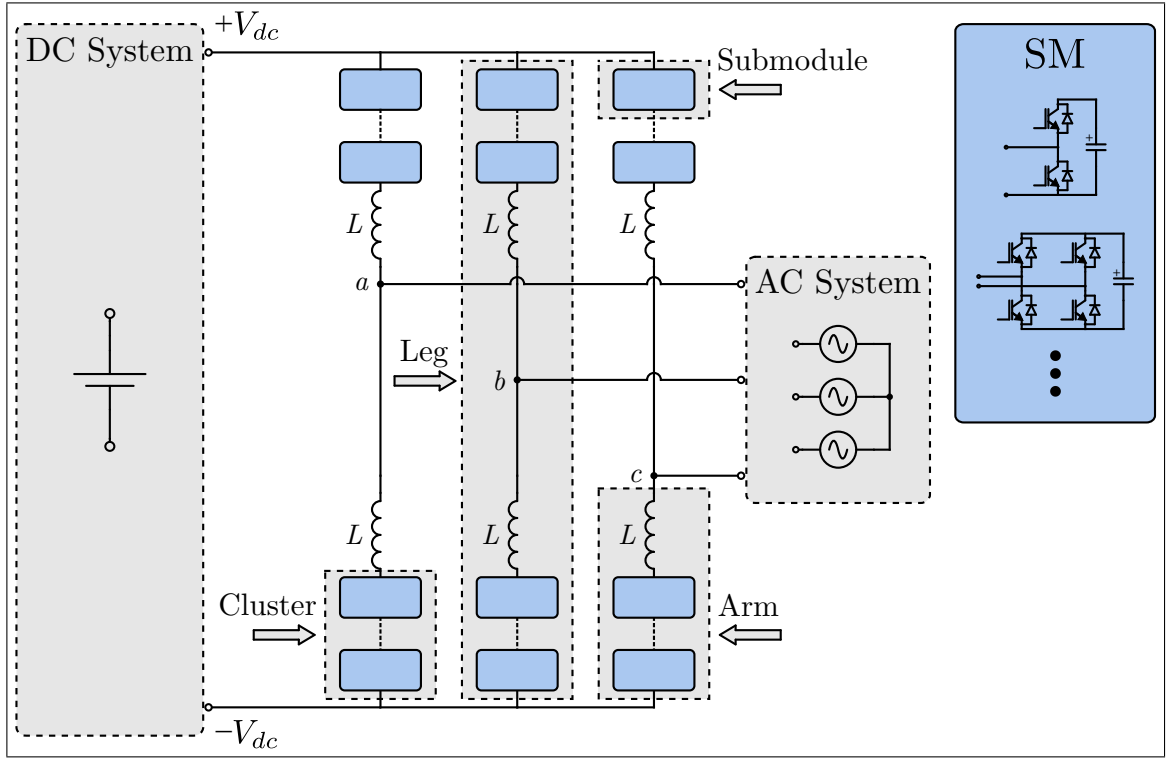


Figure 1.2. General structure of a three-phase MMC topology.

considered the main building block of this configuration. Normally, the submodules are identical to each other and may have different topologies depending on the converter application, such as Full-Bridge (FB) or Half-Bridge (HB), among others. The submodules are arranged in a cascaded manner to form clusters or arms, which must operate coordinately to control the power flow between the AC and DC ports.

Scalability and modularity are recognized advantages that make the MMC preferable over other multilevel topologies. Since the MMC is constructed through the connection of various identical submodules, designing converters for higher voltage applications involves adding new submodules to the system, which allows the generation of a greater number of voltage levels. For this reason, the number of submodules used in an MMC is largely dependant on the operating voltage of the specific application and the maximum voltage rating of the transistors used in the cells. For example, in medium voltage motor drives, the required number of submodules per arm ranges from 5 to 20 depending on the

operating voltage, while in HVDC transmission, the necessary number is approximately 200 to 400 submodules per arm (Raju, Sreedevi, P Mandi, & Meera, 2019).

Considering the above, and despite the discussed advantages that the MMC offers, ensuring the safe and stable operation of the converter requires addressing various control challenges. Submodule capacitor voltage control, capacitor ripple control and circulating current control are some of the difficulties in the operation of the MMC, resulting in a control scheme with a higher complexity compared to other multilevel converters.

1.2. Capacitor voltage balance in the MMC

During the operation of the MMC, it is necessary to control the voltage of the floating capacitors in the submodules, ensuring they remain close to their designated reference value. This is essential to achieve a high performance current control, to improve output power quality, and to provide a stable operation (Du et al., 2018). In the literature, several methods exist to achieve the energy balance of the MMC, with the sorting method being the most commonly implemented (Debnath, Qin, Bahrani, Saeedifard, & Barbosa, 2015). For this work, the control strategy utilized in (Hagiwara, Maeda, & Akagi, 2011) is described, which can be applied in the context of distributed control. This approach seeks to generate references for both the DC and fundamental AC components of the circulating currents. The strategy for energy balance of the MMC can be divided into three different controllers, which are described in the following manner:

- 1) **Averaging control:** Also known in the literature as leg voltage control or horizontal balance, the averaging control aims to adjust the average voltage of the capacitors within one leg of the converter to a specified reference value. Typically, the control approach to achieve this balance is through the regulation of the DC component of the circulating currents. This control can also be classified as a part of the inter-cluster energy balance, which aims to equalize the energy between the clusters of the MMC.

- 2) **Balancing control:** The objective of this approach is to maintain the voltage of the capacitors within the same cluster close to a reference value, which generally corresponds to the average voltage of the entire cluster. This control is also known in the literature as intra-cluster balance.
- 3) **Arm balancing control:** In (Hagiwara et al., 2011), an additional controller is introduced, which aims to minimize the average voltage difference between the upper and lower cluster within the same leg, defined as arm balancing control. This type of control is also known in the literature as vertical energy balance, which can also be categorized as a type of inter-cluster balancing control. This controller is implemented due to potential instability of the system at certain operating points. The general strategy to achieve this energy balance is through the regulation of the fundamental AC component of the circulating currents.

Fig. 1.3 illustrates the power flows within the MMC that must be generated during the operation of the converter to accomplish the energy balance. The total energy stored in the converter is controlled by the power exchange between the AC and DC ports, while the internal energy balance is achieved by the horizontal, vertical and intra-cluster balances.

1.3. Control schemes for MMCs

To achieve secure and stable operation of the MMC, adequate regulation of its internal and external variables is required. Due to this, various control schemes have been developed in the literature that aim to address the operational challenges of this converter, such as the capacitor voltage balance previously mentioned. Although, since the control schemes for the MMC are more complex than other converters, the selected control strategies can impact the scalability and modularity attributes of the MMC. Therefore, designing a converter with better modularity and scalability also requires considering these attributes while defining the control scheme of the system.

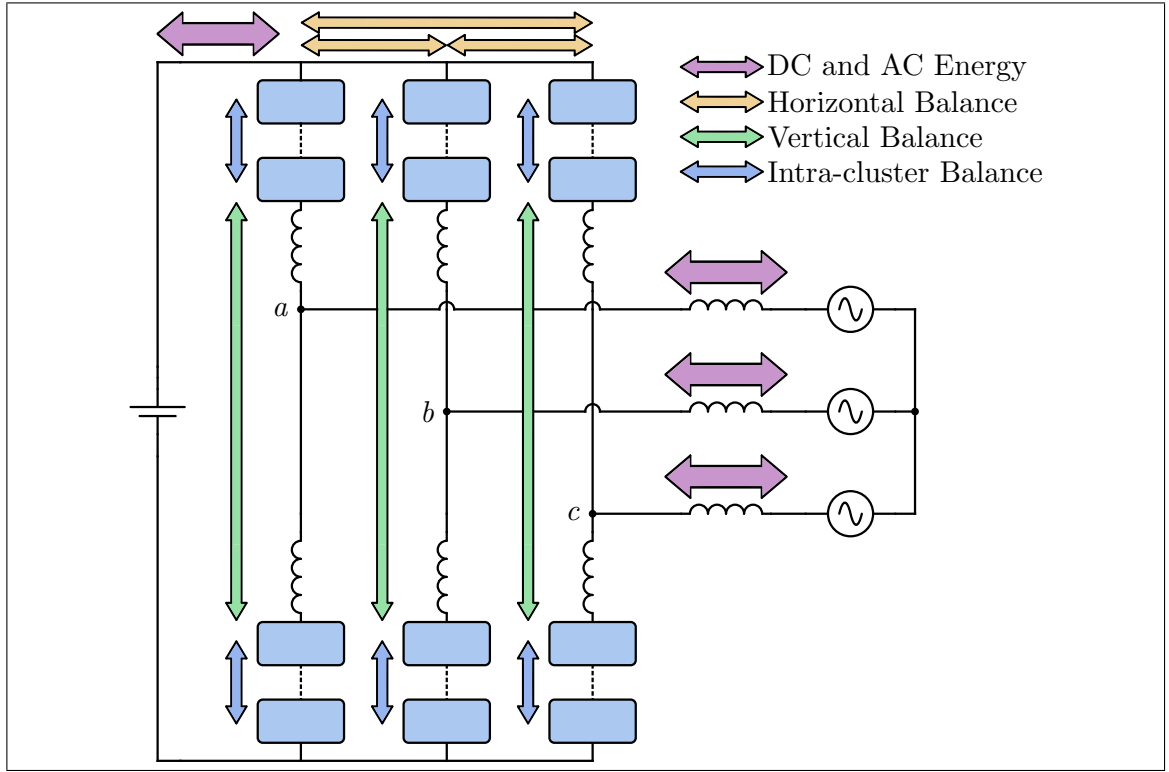


Figure 1.3. Representation of the energy balance in the MMC.

A common categorization utilized for control schemes in the context of MMCs, which has a great impact on the modularity and scalability of these converters, consists of centralized and distributed schemes.

1.3.1. Centralized and distributed control schemes

Centralized control strategies consider that all calculations and variable measurements of the converter are performed and accessible within a single processor unit or controller. In this manner, this controller is responsible for generating and transmitting the switching signals to the corresponding power transistors of each submodule in the converter. This type of strategies are preferred in the literature due to their simplicity from the control point of view and efficient decision making (Burgos-Mellado et al., 2023). Fig. 1.4a shows a standard structural diagram of the centralized control scheme, where the central

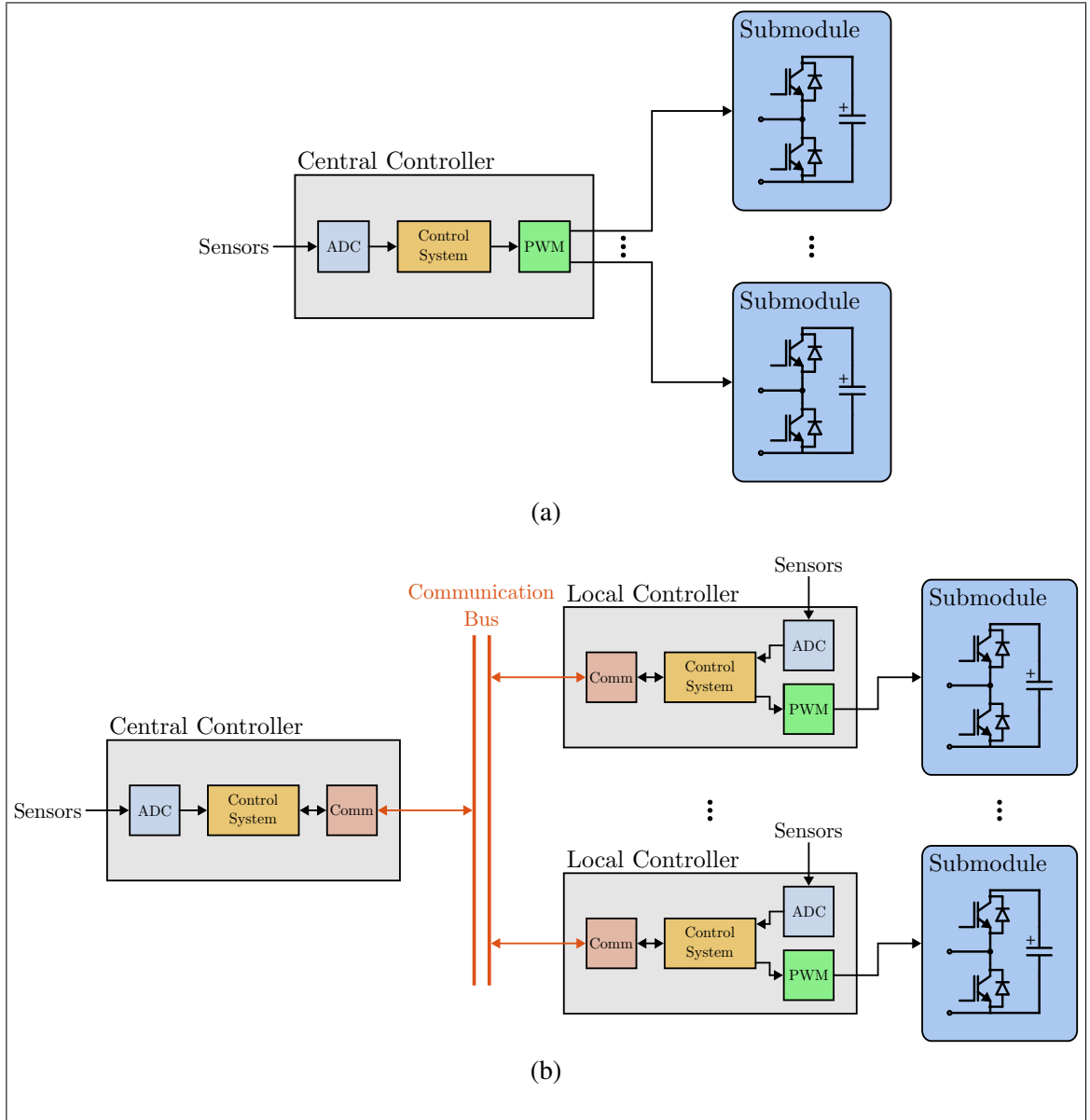


Figure 1.4. Example diagrams of control structures. (a) Centralized scheme. (b) Distributed scheme.

controller receives the system measurements and transmits the switching signals directly to the submodules.

Despite the above advantages, there are scenarios where the implementation of a centralized strategy can be challenging, especially in high voltage applications where the total

number of submodules in the converter increases. The additional number of submodules leads to an increased computational burden on the central controller, and a very high requirement for peripherals and cables, which limits the modularity and expandability of the overall system (Yang, Liu, Huang, Su, & Wang, 2020). The use of a single central controller also creates a single point of failure within the system, so malfunctions of this controller could affect the integrity of the entire converter.

Due to the above reasons, new strategies based on distributed control have been proposed and developed. These strategies reassign the necessary control tasks between a single Central Controller (CC) and multiple Local Controllers (LCs) installed at submodule, group of submodules or cluster level of the converter, among other possibilities. In this approach, low level tasks such as PWM generation are assigned to the LCs, while high level tasks are performed in the CC, such as active and reactive power control. This reduces the computational load of the CC and improves the system modularity (Yang, Tang, & Wang, 2018). Fig. 1.4b shows an example diagram of a distributed control scheme, where the LCs are located at submodule level. Each LC transmits the switching signals to the corresponding power modules and interacts with the CC and other LCs through a communication network or bus, sharing local measurements or other calculated signals.

While the use of a distributed control scheme could be beneficial in some applications over the centralized approach, its implementation must address further challenges to ensure the successful operation of the converter, such as achieving global optimum, synchronization between controllers, incorporation of communication protocols, among others.

1.3.2. Consensus based distributed control

A type of distributed control strategy that has been investigated in recent years in the context of MMCs corresponds to consensus-based controllers. Within consensus theory, the studied system is represented as a multi-agent system where one or several variables of interest must converge on a mutually agreed-upon value based on communication between

the agents. The communication network can also be represented as a directed or undirected graph with the agents acting as nodes, where graph theory can be utilized for the system stability analysis. Consensus theory has been widely used in the field of computer science in applications such as distributed sensor networks, flocking and congestion control in communication networks, among others (Olfati-Saber & Murray, 2004).

In this manner, the use of consensus-based distributed control strategies can pose as an alternative for developing more modular and scalable power converters. However, while these strategies have been successfully utilized and tested for microgrid applications, their use in the context of MMCs has not been extensively explored (Burgos-Mellado et al., 2020). The implementations of consensus-based strategies in MMCs generally involve performing low level control tasks of the converter, which are achieved by coordinating the actions and communicating the variables of interest between the LCs.

In the literature, the control tasks most frequently associated with consensus-based distributed controllers are related to the energy balance of the converter. These tasks include the submodule capacitor voltage balancing, specifically the intra-cluster energy balance of the converter, and State of Charge (SoC) balancing, as for example in (Donoso, 2022). While there are more implementations of this type of controllers in the context of MMCs, such as for regulating power sharing among submodules (Xu et al., 2021) for example, the use of consensus-based controllers applied to inter-cluster balance of the MMC has not been explored.

1.4. Thesis contribution

The main contribution of this thesis is the design and implementation of a consensus-based distributed control scheme for the inter-cluster energy balance of an MMC. The proposed distributed control strategy performs the inter-cluster balancing algorithm utilizing LCs at cluster level of the converter instead of submodule level. This means that each LC generates the switching signals for all the submodules within its respective cluster. The

energy balance is achieved by controlling the circulating currents of the converter through the interchange of control variables between the LCs. The operation of the converter and the performance of the control system are tested and validated through simulations and experiments in an MMC laboratory prototype.

1.4.1. Hypothesis

The main hypothesis of this work is:

H A consensus-based distributed control scheme can effectively achieve the inter-cluster energy balance in a three-phase Modular Multilevel Converter (MMC) by utilizing a control topology that integrates Local Controllers (LCs) at the cluster level of the converter.

1.4.2. Objectives

1.4.2.1. General objective

The general objective of this thesis is:

O To design and implement a distributed control scheme with LCs at cluster level of the converter that ensures the secure and stable operation of a grid-connected three-phase MMC. The proposed control strategy considers that the inter-cluster energy balance of the converter is achieved by a consensus controller.

1.4.2.2. Specific objectives

The specific objectives of this thesis are:

*O*₁ To review and classify the currently implemented distributed control schemes in the context of MMCs, and design the topology characteristics of the proposed consensus-based control strategy.

- O_2 To assign the controllers tasks for the execution of the proposed distributed control scheme, designing the communication structure and synchronization algorithms.
- O_3 To analyze the effect of different communication schemes between the LCs on the performance of the consensus algorithm and variables of the MMC.
- O_4 To implement the proposed distributed control scheme in a MMC laboratory prototype and verify the effectiveness of the control strategy through the operation of the converter.

1.4.3. Novelty

The main novelty of this thesis is the implementation of a consensus algorithm to perform the inter-cluster energy balance of a three-phase MMC. Previous works in the literature have successfully implemented distributed control schemes in MMCs, but the number of implementations of consensus controllers is limited. In addition, these strategies perform other control tasks of the converter, such as SoC balance or intra-cluster energy balance, so the inter-cluster energy balance using a consensus algorithm with a distributed topology of LCs at cluster level has not been implemented in the literature.

1.4.4. Thesis structure

Chapter 2 reviews the state of the art of distributed control schemes applied to power converters, classifying the existing control strategies found in the literature and discussing the main aspects of their implementation.

Chapter 3 describes the mathematical model of the MMC, introduces the fundamental principles of consensus theory utilized in the proposed control scheme, and demonstrates how these principles are applied in the implementation of the proposed control strategies.

Chapter 4 analyzes the design of the necessary strategies, tasks and synchronization approaches for the implementation of the physical hardware of the controllers.

Chapter 5 analyzes the results of the conducted simulations and experiments to validate the performance of the proposed distributed control scheme.

Chapter 6 presents the main conclusions of this thesis.

2. DISTRIBUTED CONTROL OF POWER CONVERTERS

As explained in section 1.3, the use of a distributed control topology for the operation of a power converter can serve as an alternative for applications where the use of a single central controller can be impractical in terms of modularity or scalability. In order to develop the proposed distributed control, it is essential to present a proper state of the art review of the existing distributed control schemes and consensus-based strategies utilized in the operation of power converters. Furthermore, it is necessary to introduce a common classification for the distributed control topologies present in the literature.

2.1. Control objectives on MMCs

Before designing the distributed control scheme, it is important to define the control objectives of the system. This is necessary to determine the specific control tasks each controller must perform to ensure the safe and stable operation of the converter, since there is typically one CC and multiple LCs. These objectives are illustrated in Fig. 2.1, alongside the control structure commonly employed in the operation of an MMC. The main control objectives can be described in the following manner.

2.1.1. Control of Input and Output Ports

One of the primary objectives in the operation of an MMC is the control of the power transfer between its AC and DC ports, which is achieved by regulating the output and input currents of the converter. The implemented strategy for the control of these variables depends on the type of application in which the converter is utilized, such as active and reactive power control for AC systems, torque and speed control for electrical drives, control of the AC or DC port voltage, among others.

Control of the input current also allows the regulation of the total energy stored in the converter, typically in the capacitors or batteries of the submodules, depending on the

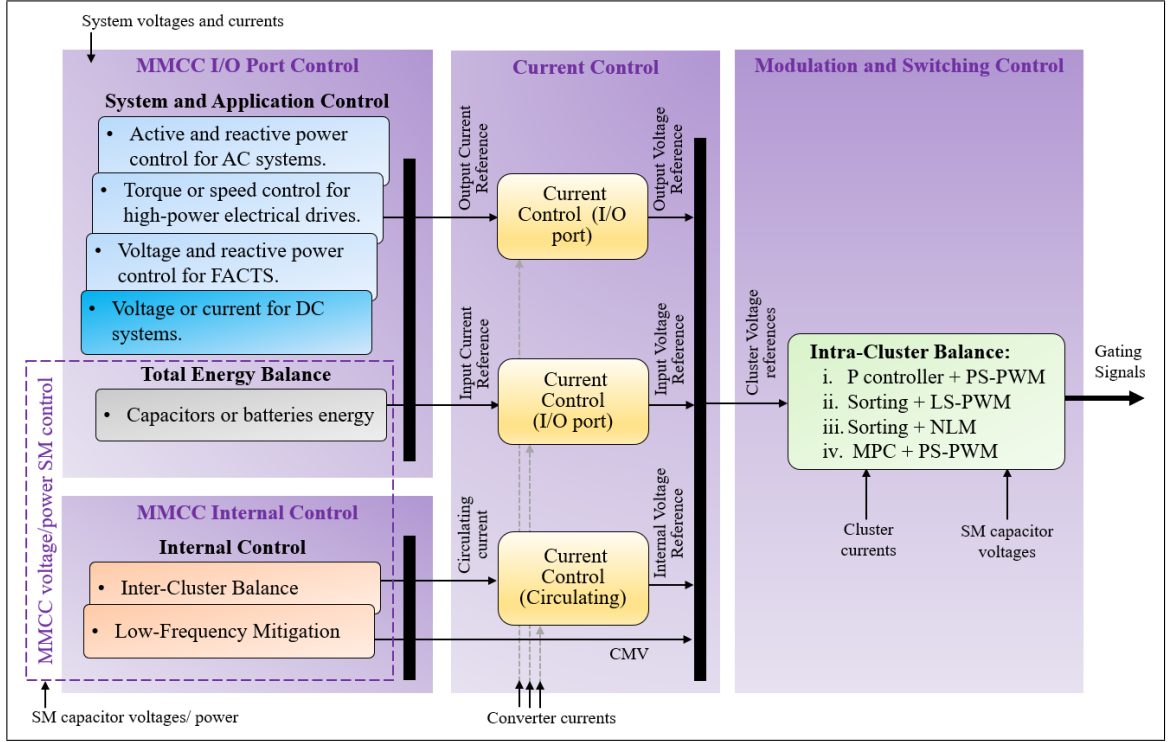


Figure 2.1. General control structure and control objectives for MMC operation.

utilized topology. This control is referred to as the total energy balance of the converter, aiming to maintain the average voltage of all the MMC submodules at a specific level.

2.1.2. Control of Internal Variables

In addition to controlling the external variables of the converter, such as the currents and voltages at the AC and DC ports, it is necessary to regulate its internal variables for correct operation. One important characteristics of the MMC is the presence of circulating currents, which can be controlled independently from its external variables. The proper control of these currents allows the following control objectives to be addressed, which are closely related to the voltage and energy balance of the submodules.

- **Submodules Capacitor Voltage Control and Balancing:** As explained in section 1.2, for the correct operation of the MMC, the capacitor voltages of the

submodules must be maintained at their reference value and with a low ripple. This is achieved by generating intra-cluster and inter-cluster power flows, with the objective of balancing the energy stored in the batteries or capacitors. The inter-cluster power flows are produced by regulating the circulating currents of the converter, equally distributing the total energy in the MMC between all clusters. This means that the respective controller needs to calculate references for both the DC and fundamental AC components of these currents depending on whether the capacitors of the corresponding clusters require charging or discharging.

Regarding the intra-cluster power flows, these aim to equally distribute the energy within a cluster among the respective submodules. The most common methods to achieve this energy balance typically involve sorting, where the capacitors are sorted and connected based on their charge level, coupled with different modulation techniques such as Level-Shift PWM (LS-PWM) or Nearest Level Modulation (NLM). Other methods are referred to as closed loop control methods, where reference values for the circulating currents are computed based on the magnitude of the capacitor voltages (Debnath et al., 2015). A classic example of this approach is the use of proportional controllers coupled with modulation strategies such as Phase-Shifted PWM (PS-PWM).

- ***Circulating Current Control:*** Circulating currents occur due to the operation of the MMC and if left uncontrolled, consist of two primary components: a DC component that affects the active power exchange through the DC port, and a second-order harmonic component (Kadandani, Dahidah, & Ethni, 2021). Circulating current control mainly refers to the suppression of this double-line frequency component to reduce the amplitude of the cluster currents. This reduces the overall power losses on the converter and the ripple in the voltage of the capacitors (Yinghong, Peng, Zimeng, & Qing, 2022). This type of control is also denoted as Circulating Current Suppression. Additionally, circulating current control can also refer to the regulation of the DC and AC components of

these currents for the energy balance of the converter. In this case, the control is associated with the injection of currents of different harmonics to achieve the inter-cluster energy balance of the MMC, and can be referred to as cluster voltage control.

To fulfill the control objectives described above, controllers must be assigned with the respective control tasks. A common classification for these tasks, which is useful in the context of distributed control, is to define higher-level and lower-level tasks. In general, high-level control aims to regulate output variables of the converter such as DC link voltage or the output power of the converter, while low-level tasks manage internal variables such as circulating currents, capacitor voltage balancing, and modulation (Isik, Burugula, Alharbi, Azidehak, & Bhattacharya, 2022). Typically, for the implementation of a distributed control scheme, LCs are assigned with lower-level tasks, while the CC is responsible for higher-level tasks.

2.2. Classification of distributed control topologies

In recent years, diverse distributed control strategies have been proposed and implemented in power converters depending on the specific application and utilized converter topology. This has resulted in rapid advancements of distributed control development, which has caused the indiscriminate use of key concepts such as distributed and decentralized (Burgos-Mellado et al., 2023). Therefore, a common categorization of distributed control strategies for Modular Multilevel Cascaded Converters (MMCCs) and its concepts should be adopted.

In this research, the classification of distributed control schemes proposed in (Burgos-Mellado et al., 2023) is utilized, which identifies three types of distributed control methodologies depending on the interactions between the controllers: decentralized, cooperative and non-cooperative schemes. Given that there are no reports of non-cooperative schemes

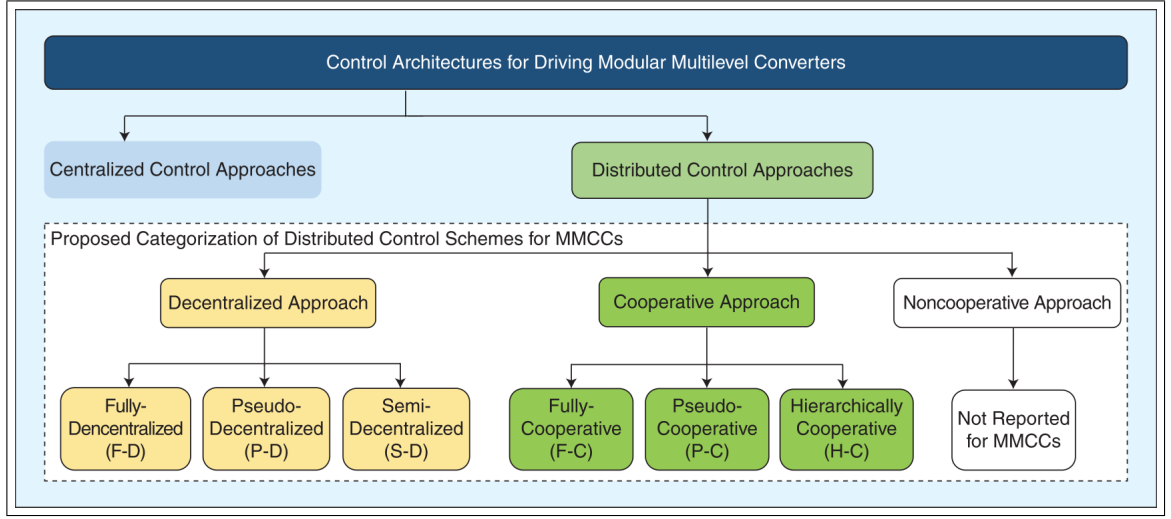


Figure 2.2. Classification of distributed control schemes for MMCCs (Burgos-Mellado et al., 2023).

implementations for the operation of MMCCs, this work focuses on the first two types of strategies. The classification is shown in Fig. 2.2 and described in the following sections.

2.2.1. Decentralized schemes

The main characteristic of the decentralized control schemes is that the LCs operate without exchanging information between them. For the calculation of control signals, the LCs utilize local measurements of converter variables, exchange of information with the CC or both. Within this group, three subcategories are recognized based on the control topology. The general diagrams of these decentralized control schemes are shown in Fig. 2.3 and are described below:

- 1) **Fully-Decentralized:** Each submodule of the converter has an LC responsible for performing the low-level tasks of the control system. Furthermore, each LC communicates and exchanges information solely with the CC, so the communication network does not consider direct interactions between the LCs.

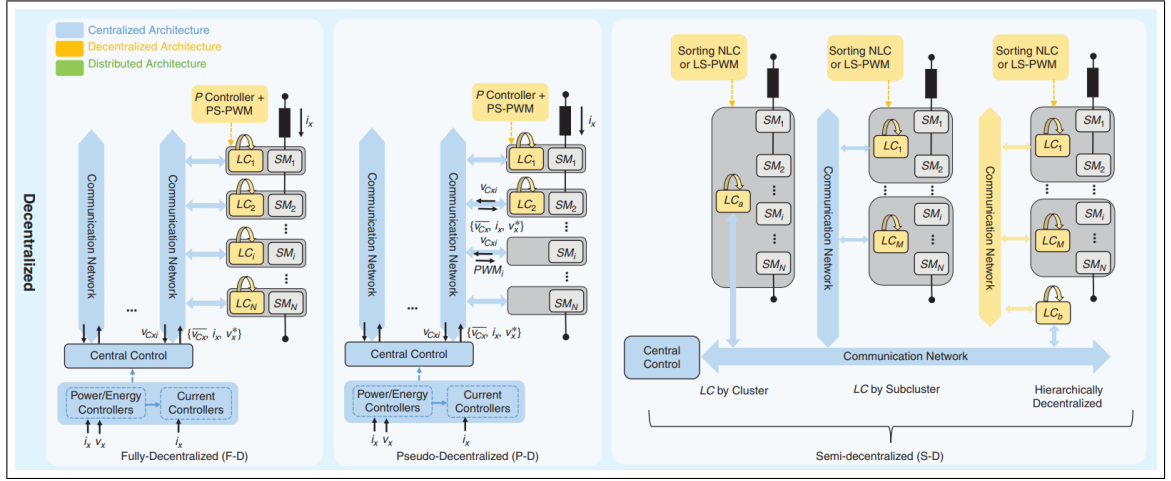


Figure 2.3. Classification of decentralized control schemes (Burgos-Mellado et al., 2023).

- 2) **Pseudo-Decentralized:** In this case, only some submodules have an LC, while others are controlled directly by the CC. This means that the control scheme incorporates elements of both centralized and decentralized approaches.
- 3) **Semi-Decentralized:** The LCs control a cluster or subgroup of submodules instead of individual ones. Communication continues to be direct with the CC, but in this case a second layer of LCs can serve as intermediaries for the communication with the CC. These intermediary LCs can also be tasked with low-level control functions.

Decentralized approaches are generally the most common type of distributed control scheme in the literature, defining different control tasks for CC and LCs depending on the control scheme, converter topology and application. For example, in (Talon Louokdom et al., 2018) a per-cluster decentralized control, similar to a semi-decentralized approach, is implemented in a three-phase MMC operating as an inverter on a passive load. Fig. 2.4 illustrates the diagram of the implemented decentralized control scheme, where the CC and the LCs can be identified, along with the communication network for variable and signal transmission. For each of the six clusters or arms of the MMC, an LC is assigned to perform specific control tasks. These include measuring the capacitor voltages of the corresponding submodules, executing the voltage balancing tasks and generating

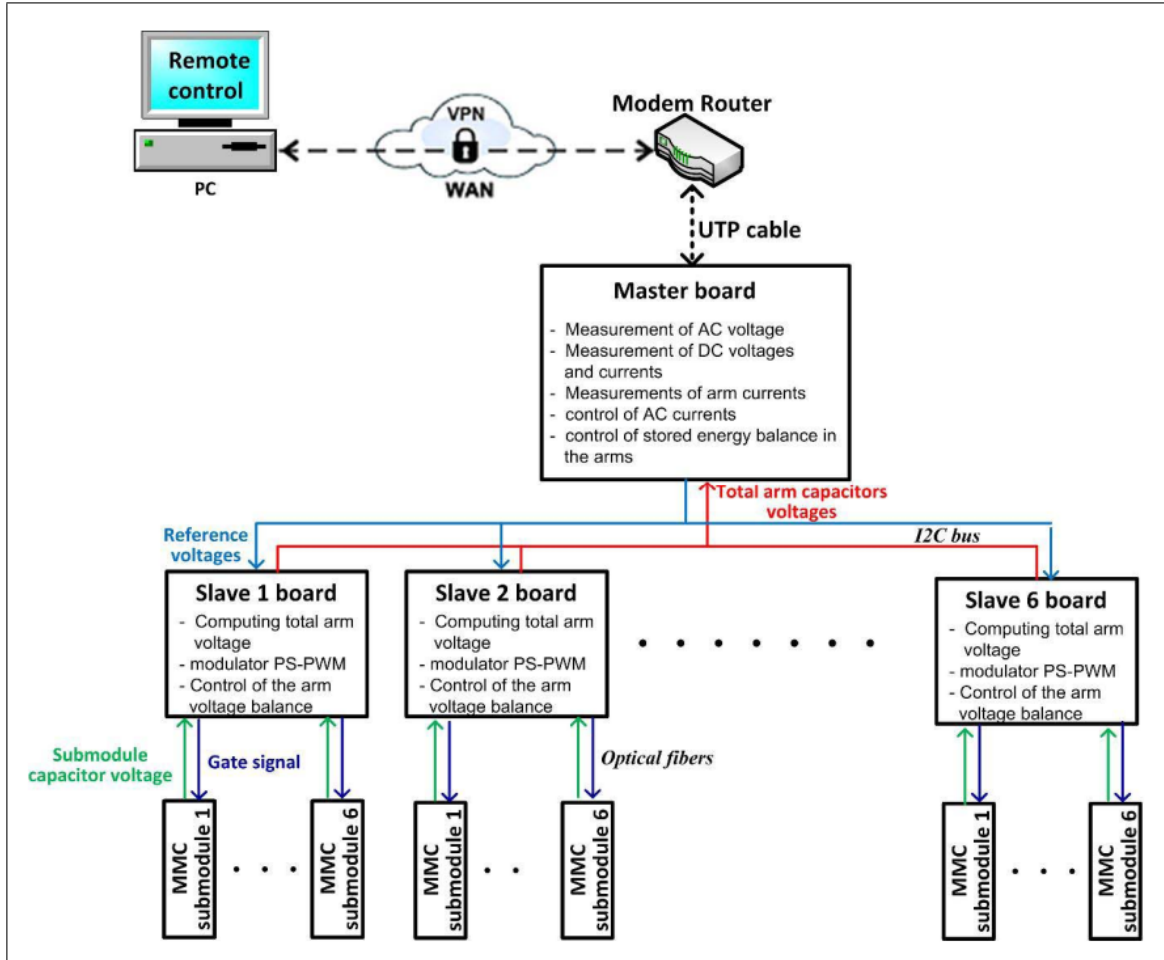


Figure 2.4. Diagram of implementation and data transmission of a decentralized control scheme (Talon Louokdom et al., 2018).

the appropriate switching signals for these submodules. The designated CC sends the cluster voltage references to the LCs through an I2C bus in each control cycle, while the LCs communicate the total arm capacitor voltages to the CC.

2.2.2. Cooperative schemes

Unlike decentralized approaches, cooperative schemes are characterized by the exchange of control information between the LCs, which can include measurements of converter variables or other types of signals. Generally, consensus theory is used as the base for the control strategy. In this group, three subcategories are also identified based on the

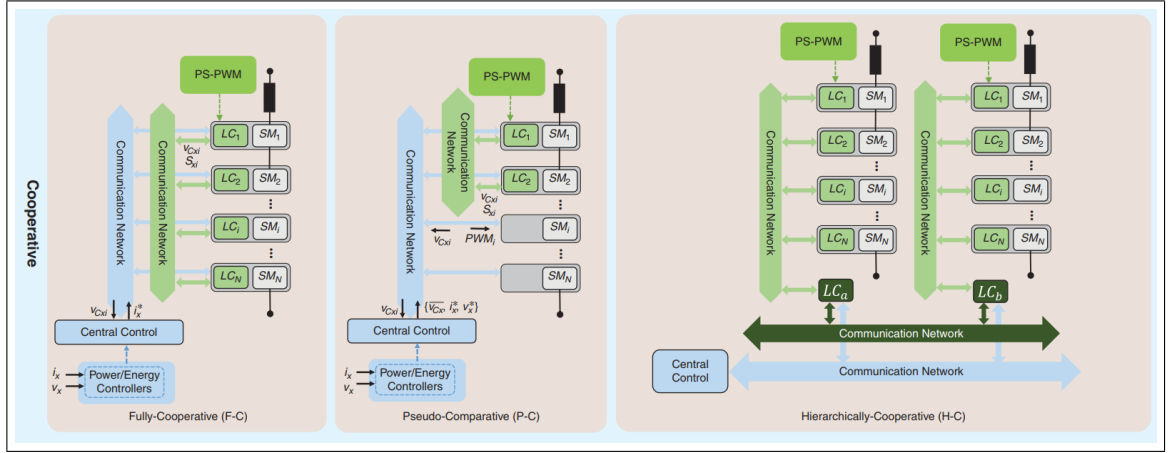


Figure 2.5. Classification of cooperative control schemes (Burgos-Mellado et al., 2023).

control structure. The diagrams of these cooperative control schemes are shown in Fig. 2.5 and their respective descriptions are as follows:

- 1) **Fully-Cooperative:** Similarly to the fully-decentralized scheme, one LC is assigned per submodule to perform the control tasks. In this case, an appropriate communication network is implemented to exchange information or variables from the submodules between the LCs.
- 2) **Pseudo-Cooperative:** Only some submodules have an assigned LC, while the others are handled centrally by the CC. In this case, information from only some of the submodules is shared between the LCs. Therefore, certain control tasks are usually assigned to a consensus-based controller, while others are executed to the CC.
- 3) **Hierarchically-Cooperative:** Each submodule within a cluster or phase of the converter has an LC, which communicates with each other to execute the corresponding control tasks, similarly to the fully-cooperative scheme. In this approach, each set of LCs interacts with another LC of higher hierarchy level, which in turn communicates with other higher-level LCs through a new communication network. This structure allows the use of consensus controllers not just at submodule level, but also for executing higher-level control tasks.

2.3. Consensus based distributed control schemes

From the previous classification of distributed control topologies, it can be noted that consensus-based control strategies belong to the category of cooperative schemes. Various implementations of cooperative schemes can be found in the literature, which vary based on the communication scheme, the variables employed for consensus, and the system level at which the LCs are located.

As described in section 1.3.2, consensus-based controllers are generally assigned with tasks related to the energy balance for the operation of power converters, being the intra-cluster capacitor voltage balance and the State of Charge (SoC) balance the most common ones in the literature.

In MMCs, the intra-cluster energy balance is performed to maintain the voltage of the capacitors within the same cluster close to their reference value. Typically, this balance is achieved through control strategies such as sorting or closed loop control methods, which are implemented in the CC in a centralized approach or in the LCs for a distributed approach. Using a consensus-based strategy, the LCs generally transmit their instantaneous capacitor voltage measurement between them through a communication channel, calculating an individual balancing component through a consensus algorithm. Additionally, other type of variables can be shared between LCs to perform capacitor voltage balance or SoC balance. For example, in (Donoso, 2022), the LCs, located at submodule level in a single-phase CHB, exchange the voltages and state of charge of the batteries in their respective submodules to achieve and maintain SoC balance. This way, the objective of this type of controllers is to reach a consensus value for the voltages or SoC of the submodules within each cluster, which typically corresponds to their nominal value.

An example of intra-cluster balance can be observed in (Song & Liu, 2019), where a closed loop algorithm for capacitor voltage balancing of an MMC is implemented with a consensus controller. In this application, the LCs are located at submodule level and

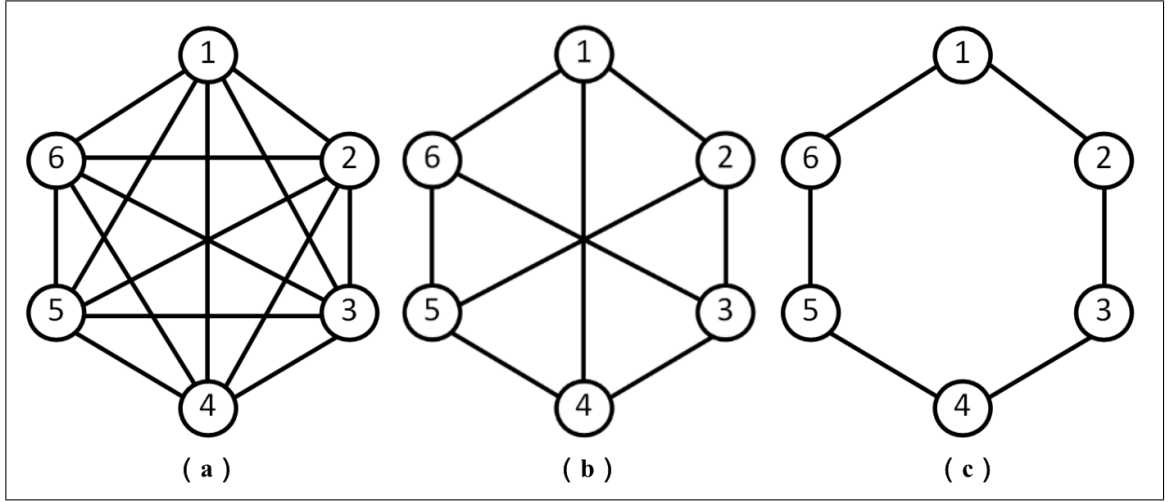


Figure 2.6. Simulation of different communication structures. (a) Full communication. (b) Partial communication. (c) Neighbour communication. (Song & Liu, 2019).

share the capacitor voltage of their respective submodules through an appropriate communication channel. Different communication structures are simulated to evaluate the effect that varied network graphs have on the convergence speed of the submodules voltages to the consensus value. Fig. 2.6 shows three different network graphs with nodes that represent the LCs from a single cluster of the MMC, and the links between them depict the connections between the submodules for the consensus algorithm. The existence of a link between one node and another implies that these LCs share the value of their consensus variables for the execution of the algorithm, so changes in the graph directly affect the calculation of the control variables. Finally, the performance of the control scheme is validated through experiments in a single-phase MMC.

Regarding SoC balance, this task refers to the balancing of the state of charge of the converter batteries, which are generally located within each submodule in the implementation of an MMCC with a Battery Energy Storage System (BESS). The balance is achieved by discharging those batteries with a higher SoC at a faster rate and those with a lower

SoC at a slower pace. This can be implemented as a consensus problem in which the controller's goal is to match the SoCs of the batteries, which generally gives individual power references for each of the batteries.

An example of SoC balancing is presented in (Neira, Poblete, Pereda, & Nuñez, 2020), where a simulation of a two-layer distributed controller is performed in a single-phase CHB BESS using Three-Port Submodules (TP-SMs). The implementation considers LCs for each of the submodules and a communication network between them for the utilization of a cooperative algorithm. The outer control layer involves a consensus controller for the SoC balance of the submodule batteries, while the inner layer consists in the control scheme for the operation of the TP-SMs using the power references from the outer control.

2.4. Communication characteristics in distributed control

In addition to how the interactions between the CC and the LCs are performed, the communication schemes employed in power converters can also be characterized by the defined physical topology and the utilized communication protocol. Different communication protocols allow various network topologies, and their selection affects transmission variables such as propagation delay of data, physical length of communication lines, communication bandwidth, among other factors. Consequently, it is necessary to present a review on the existing communication topologies and communication protocols utilized in the distributed control of power converters.

2.4.1. Communication topologies

Depending on how the physical connection is made between the controllers, different topologies are recognized. These configurations are shown in Fig. 2.7 and described as follows:

- 1) **Star:** Each LC is connected to a unique CC. As a result, the LCs only share data directly with the CC.

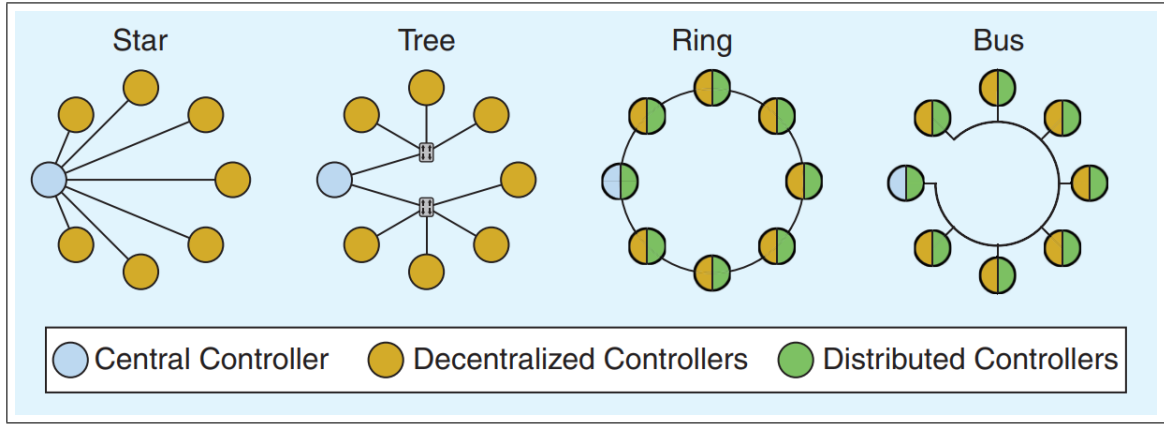


Figure 2.7. Communication topologies for distributed control (Burgos-Mellado et al., 2023).

- 2) **Tree:** In this case, the LCs are connected to a unique CC through an intermediary or another controller. Consequently, LCs are arranged in groups, forming a hierarchical structure for the data transmission.
- 3) **Ring:** The controllers are only connected to two other neighbours, producing a closed circular shape. This way, transmitted data traverses through each controller until it reaches the intended target or a full communication cycle is completed, where all controllers in the ring are updated with a single message.
- 4) **Bus:** The controllers are connected to a common channel or cable, where all the data is transmitted. Controllers must alternate in transmitting data over the bus or a transmission priority system must be implemented to prevent two controllers from trying to transmit at the same time.

In general, the communication topologies with the greatest research and potential in power converter applications correspond to tree, ring or a combination of both (Corrêa, Almeida, & Rodriguez, 2018). The main differences between these topologies are their effects on transmission delay and the number and complexity of connections between controllers. While the ring topology decreases the overall number of physical connections in the communication network, the transmission delay increases as new nodes are added to the network (Corrêa et al., 2018). The opposite occurs for the tree topology, where the

transmission delay is lower, but the complexity of the connections increases for a greater number of nodes.

While tree and ring topologies are the most addressed in the context of power converters, bus topologies implementations can also be found for some applications. However, their advantages and disadvantages compared to other topologies in the context of power converters have not been explored in the literature, particularly for applications with a large number of connected nodes.

Considering the previous communication topologies, this thesis proposes the implementation of two bus communication channels. One channel is dedicated to communication between the LCs, allowing them to share the necessary control variables through broadcast messages to perform the inter-cluster energy balance of the MMC. Additionally, the second communication bus allows the CC to transmit control variables to all the LCs simultaneously.

2.4.2. Communication protocols

Similar to communication topologies, the literature contains varied implementations of distributed controllers employing different communication protocols. Table 2.1 summarizes the characteristics of different protocols that have been utilized in the control of power converters. High bandwidth protocols such as EtherCAT and Profinet, among others, are preferred because they allow greater transmission of information for internal monitoring and control of the converter, which increases the reliability of the system (Toh & Norum, 2012).

Despite the above, in certain applications where a large number of submodules are not necessary or the size of the transmitted data is small, the use of high bandwidth protocols may be overdimensioned. An example of this can be noted in (Mathe, Burlacu, & Teodorescu, 2017), where the EtherCAT protocol is utilized in the implementation of a distributed control for a three-phase MMC with 4 SMs per cluster. In this case, it is only

Table 2.1. Attributes of communication protocols (Burgos-Mellado et al., 2023).

Protocol	Speed	Topology	Number of LCs
ModBus	115.2 Kb/s	Star, Ring, Tree, Bus	< 247
CAN Bus	1 Mb/s	Star, Ring, Bus	< 110
Profinet	100 Mb/s	Star, Ring, Bus	< 126
EtherCAT	125 Mb/s	Star, Ring, Bus	< 1000
PESnet	125 Mb/s	Ring	< 50
SyCCo Bus	1.25 Gb/s	Ring, Bus	< 50
RealSync	6.6 Gb/s	Ring, Tree, Bus	< 5000

necessary to transmit 4 bytes of data from the CC to the LCs and 2 bytes from the LCs to the CC in each control period. Therefore, other protocols with slower data transmission rates might be suitable, as indicated by the author.

For the present thesis, special emphasis is done on the Controller Area Network (CAN) protocol. While this protocol has a slower data transmission speed compared to other communication standards utilized in power converters, other advantages such as high immunity to electrical interference and low implementation complexity, position it as a viable alternative for applications where the amount of data transmitted in each control cycle is low. Undoubtedly, slow communication protocols, such as CAN, presents a challenge for distributed control.

In the case in which the CAN protocol is used for the implementation of the distributed control scheme, special care must be taken with the transmission priority of the LCs on the bus. Since the CAN protocol has a multi-master architecture, controllers with higher message priority can overwrite sent messages with lower priority, making bus access behavior not deterministic (The, Bruening, & Dieckerhoff, 2015).

2.5. Overview of the proposed distributed control structure

Considering the analysis of the current state of the art and the presented objectives of this thesis, it is necessary to define the constructive and control characteristics of the proposed distributed control scheme. The proposed structure is illustrated in Fig. 2.8, listing the main tasks assigned to the controllers and showing the implemented communication channels. This architecture utilizes LCs at cluster level of the converter. This means that six LCs are implemented, one for each cluster of the MMC, along with one CC to perform high-level control tasks. The use of LCs at cluster level has primarily been utilized in decentralized control schemes in the literature, but its implementation using a consensus-based control scheme has not been fully explored. Furthermore, this structure of LCs is convenient for analyzing the effect of the consensus controller on the inter-cluster balance of the converter. This is because the control task of intra-cluster balance can be individually assigned to the LCs, allowing the communication between LCs to be focused solely on managing the inter-cluster balance.

The proposed consensus controller is implemented in each LC and manages the inter-cluster energy balance of the converter through the control of the circulating currents. The interactions between the CC and the LCs occur via a CAN communication bus, through which the variables required for the operation of the converter are transmitted. In this implementation, the communication through this bus is unidirectional, which means that this CAN bus is only utilized by the CC to transmit the necessary control signals to the LCs. Therefore, it can be noted that while this communication channel has a bus topology at hardware level, since all the controllers are connected to the same common channel, it can be regarded as a star topology at the information exchange level.

The adoption of the CAN bus as the chosen communication protocol is due to its aforementioned characteristics, in addition to its prevalence and integration in a variety of micro-controllers. Furthermore, this protocol is suitable for the requirements for data transmission, since it is possible to share the control variables between the controllers

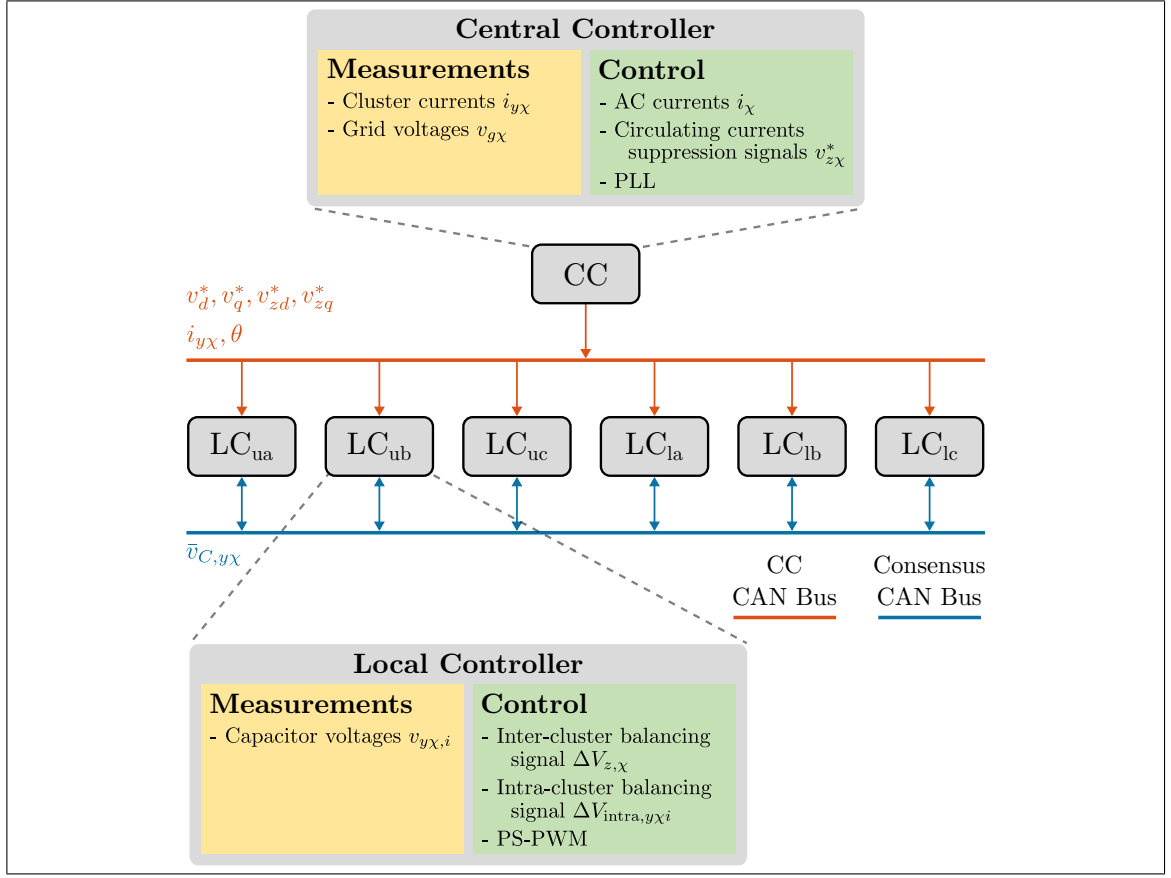


Figure 2.8. Proposed distributed topology for MMC operation.

through broadcast messages. Despite the disadvantages of the CAN protocol, such as its low data transmission speed and low amount of data per message, these are addressed when defining the structure of data transmission within the system.

An output current controller is implemented in the CC for the regulation of the power at the AC port of the MMC, which generates the phase voltage references that the converter must synthesize (v_d^* and v_q^* in the dq reference frame). Additionally, a Circulating Current Suppressing Controller (CCSC) is implemented in the CC, which generates voltage component references to eliminate the second harmonic components from the circulating currents (v_{zd}^* and v_{zq}^* in the double line-frequency, negative-sequence, rotational dq reference frame). These controllers are discussed in detail in Chapter 3. Furthermore, the CC is responsible for measuring the six cluster currents of the MMC. These currents are

not measured by the LCs because both the output current controller and the CCSC require them in each control period. Transmitting these measurements from the LCs is impractical due to the data transmission speed and data size limitations of the CAN communication bus. Performing the current measurements in the CC also prevents delays in the current measurements caused by data transmission, which could affect the stability of the output current controller, especially when using a slow communication protocol.

The previously calculated reference signals are transmitted through the CAN communication bus along with the cluster current measurements ($i_{y\chi}$ for the upper or lower cluster y of phase χ) and the phase angle for grid synchronization (θ). The CC transmits the measurements of cluster currents in a consecutive manner, which means that it only sends one current measurement to the LCs in each control step, rotating through the six measurements. This is done due to the limitations of message size and data transmission speed of the CAN communication bus. However, the correct operation of the converter is still ensured.

For the implementation of the proposed consensus controller, a second CAN bus is utilized that communicates the LCs with each other. The relevant variables for the inter-cluster balancing algorithm are transmitted through this bus by each LC, specifically the average voltages of the capacitors of their respective cluster ($\bar{v}_{C,y\chi}$). This strategy avoids the need to transmit capacitor voltage measurements to the CC, which is necessary for other balancing strategies such as sorting. These variables, together with the cluster current measurements transmitted from the CC, are utilized to calculate two balancing components that adjust the modulating signals of each submodule i within the upper or lower cluster y of phase χ : the inter-cluster balancing signal $\Delta V_{z,\chi}$ and the intra-cluster balancing signal $\Delta V_{\text{intra},y\chi i}$. In this manner, the inter-cluster energy balance is achieved by calculating the first component using the consensus controller in each LC, while the intra-cluster energy balance is accomplished through the second component. Additionally, the Phase-Shifted PWM (PS-PWM) strategy is employed to generate the switching signals of the submodules.

The system is synchronized to utilize both CAN buses simultaneously, enabling the CC and one of the LCs to transmit through their respective buses during each control period. This approach ensures that the LCs do not compete for the utilization of the CAN bus through which the consensus variables are shared.

2.6. Conclusion

This chapter presented the main control objectives that must be achieved by the control scheme to ensure the safe and stable operation of the MMC. The control tasks required to meet these objectives are classified into higher-level and lower-level tasks. In the implementation of a distributed control scheme, it is preferred to assign the higher-level tasks to the CC and the lower-level tasks to the LCs.

A classification found in the literature was presented for the distributed control topologies applied in power converters, categorizing them into two primary groups: decentralized and cooperative schemes. According to this categorization, consensus-based controllers belong to the category of cooperative schemes.

The different communication topologies and protocols utilized in the literature for the control of power converters were described. The topologies with the greatest potential for application in MMCs correspond to tree and ring configurations, while the preferred protocols are those with a higher bandwidth, such as EtherCAT and Profinet. However, implementations utilizing lower bandwidth protocols such as CAN may be preferred in applications with a smaller number of LCs or where the data transmitted in each control cycle for the operation of the converter is minimal.

Finally, an overview of the proposed distributed control scheme was provided, where the LCs are implemented at cluster level of the converter and the inter-cluster energy balance of the MMC is achieved through a consensus algorithm. Communication between the controllers is performed through the implementation of two CAN protocol buses: one for communication between the CC and the LCs, and the other for sharing the consensus

variables between the LCs. This control scheme reduces the computational load of the CC compared to the centralized case, as part of the control tasks are executed by the LCs. Furthermore, the energy balancing algorithm of the MMC is performed without transmitting the capacitor voltages from the LCs to the CC.

3. MMC MODELING AND CONTROL STRATEGY

Before defining and analyzing the strategies utilized in the proposed distributed control scheme, it is necessary to present the theoretical basis for the operation of the system. For this, first the mathematical model of the MMC is introduced, deriving the relationships between the internal and external variables of the converter. Additionally, the principles of consensus theory are presented, along with its application in the context of the inter-cluster energy balance of the MMC. Utilizing these fundamental concepts, the necessary controllers for the operation of the converter are analyzed.

3.1. MMC model

The circuit model of the studied converter topology is shown in Fig. 3.1, which corresponds to the three-phase MMC in double-star configuration. This arrangement consists of 6 clusters or arms, each containing N submodules connected in series with each other and with a cluster inductor L_s with resistance R_s . A phase or leg of the converter is formed from the connection of 2 clusters, defining an upper and lower cluster. The midpoint of a leg defines one phase of the converter's AC port, which is connected to a corresponding AC grid through an output inductance L_o with resistance R_o . The upper clusters define the positive terminal of the DC port, while the lower clusters are connected to the negative terminal of the DC port.

In order to establish the variables and parameters of the model, the subscript $\chi \in \{a, b, c\}$ represents the converter phases, while subscript $y \in \{u, l\}$ denotes the upper and lower cluster within a phase, respectively. This notation allows to define the cluster voltages $v_{y\chi}$, cluster currents $i_{y\chi}$ and output currents i_χ as shown in the circuit model of the MMC (Fig. 3.1). Additionally, V_{dc} represents the voltage at the DC port of the MMC, $v_{g\chi}$ the grid voltages and v_{cm} the common mode voltage.

The cluster voltage $v_{y\chi}$ is determined by the sum of the voltages delivered by its submodules $v_{y\chi,i}$ with $i \in \{1, \dots, N\}$. Additionally, the individual voltage output of each

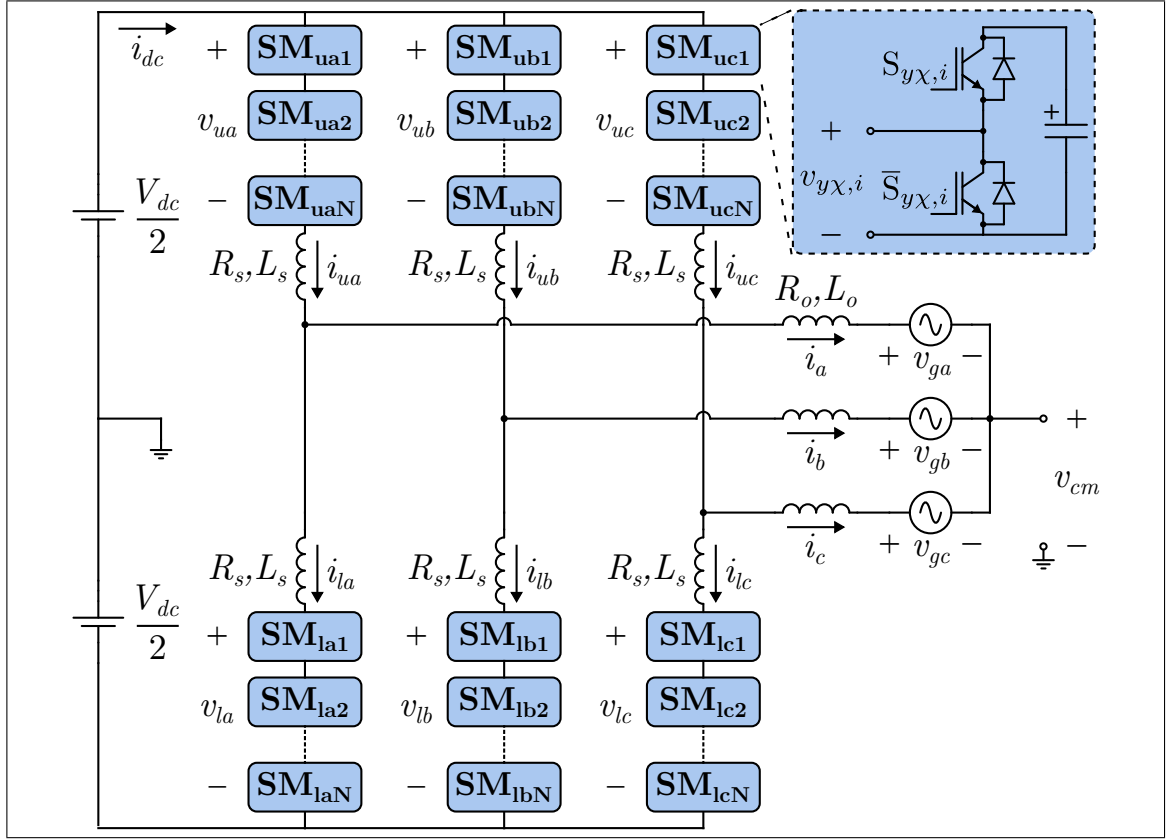


Figure 3.1. MMC model in double-star configuration.

SM depends on the employed cell topology and the switching state of its power semiconductors. In this work, it is considered that the submodules have a half-bridge topology, which means that each SM has 2 possible operating states: positive polarity connection of the DC-link capacitor to the cluster, or bypass of the capacitor. These two states can be represented by the binary variable $S_{y\chi,i} \in \{0, 1\}$ for each SM, so the cluster voltages can be represented by (3.1).

$$v_{y\chi} = \sum_{i=1}^N S_{y\chi,i} \cdot v_{y\chi,i} \quad (3.1)$$

For the analysis of the proposed distributed control topology, it is convenient to simplify the model by representing the cluster voltages $v_{y\chi}$ as ideal voltage sources, disregarding the effects of submodule switching. Fig. 3.2 shows the simplified model of the MMC.

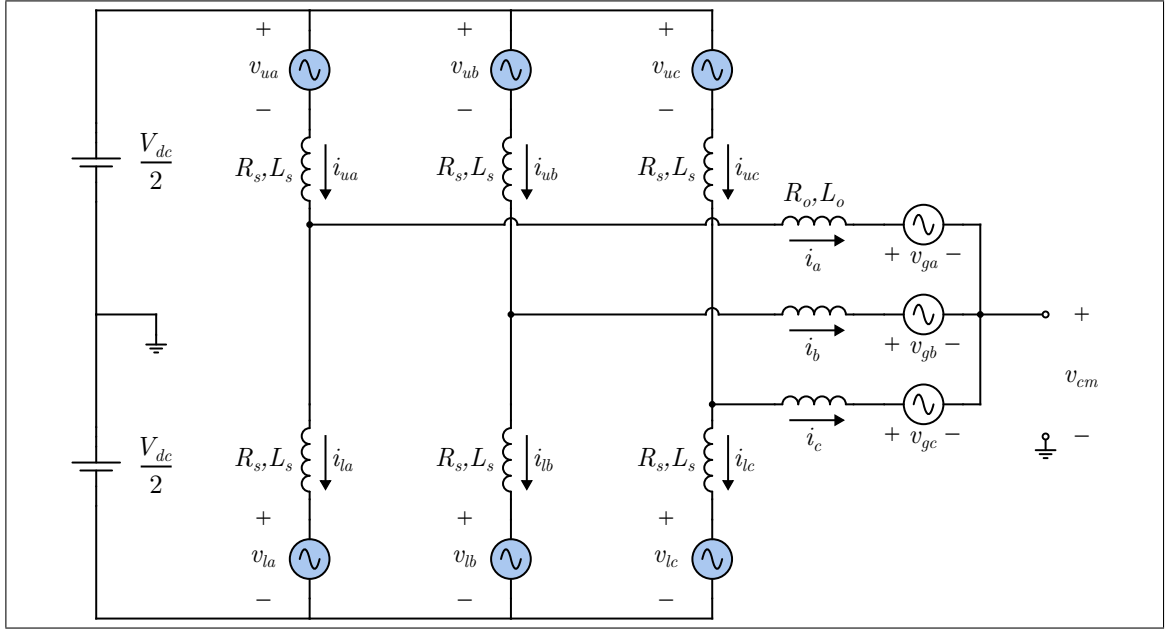


Figure 3.2. Simplified MMC model.

3.2. Fundamental equations

Applying Kirchhoff's Current Law (KCL) at the midpoint of phase χ of the MMC, the relationship between the output current and cluster currents is obtained as shown in (3.2).

$$i_{\chi} = i_{u\chi} - i_{l\chi} \quad (3.2)$$

In addition to the phase and cluster currents, the circulating current $i_{z\chi}$ corresponds to the current component that flows between the DC port and the upper and lower clusters of phase χ , which is defined as (3.3).

$$i_{z\chi} = \frac{i_{u\chi} + i_{l\chi}}{2} \quad (3.3)$$

From (3.2) and (3.3), equations (3.4) and (3.5) can be obtained, which describe the relationship between output, cluster and circulating currents of phase χ .

$$i_{u\chi} = i_{z\chi} + \frac{i_{\chi}}{2} \quad (3.4)$$

$$i_{l\chi} = i_{z\chi} - \frac{i_{\chi}}{2} \quad (3.5)$$

By applying Kirchhoff's Voltage Law (KVL) in the upper and lower clusters of each phase of the converter, the relationships (3.6) and (3.7) can be obtained which describe the mathematical model of the MMC.

$$\frac{V_{dc}}{2} = v_{u\chi} + L_s \frac{di_{u\chi}}{dt} + R_s i_{u\chi} + L_o \frac{di_{\chi}}{dt} + R_o i_{\chi} + v_{g\chi} + v_{cm} \quad (3.6)$$

$$\frac{V_{dc}}{2} = v_{l\chi} + L_s \frac{di_{l\chi}}{dt} + R_s i_{l\chi} - L_o \frac{di_{\chi}}{dt} - R_o i_{\chi} - v_{g\chi} - v_{cm} \quad (3.7)$$

By subtracting (3.7) from (3.6) and replacing the cluster currents with (3.2), expression (3.8) can be obtained which describes the dynamic model of the output currents of the converter.

$$\frac{di_{\chi}}{dt} = \frac{1}{(L_s + 2L_o)} [(v_{l\chi} - v_{u\chi}) - (R_s + 2R_o)i_{\chi} - 2v_{g\chi} - 2v_{cm}] \quad (3.8)$$

If relationships (3.6) and (3.7) are summed instead and the cluster currents are replaced with (3.3), equation (3.9) is obtained, which describes the circulating currents dynamics.

$$\frac{di_{z\chi}}{dt} = \frac{1}{2L_s} [V_{dc} - (v_{u\chi} + v_{l\chi}) - 2R_s i_{z\chi}] \quad (3.9)$$

From (3.8) and (3.9) it can be observed that the output currents and circulating currents of the converter can be controlled by the upper and lower cluster voltages. While the output currents are impacted by the difference of the upper and lower cluster voltages, the circulating currents are influenced by the sum of the cluster voltages. These equations can be rewritten using the $\Sigma\Delta$ transform as defined in (3.10), utilizing the new variables v_{χ}^{Σ}

and v_χ^Δ .

$$\begin{bmatrix} v_\chi^\Sigma \\ v_\chi^\Delta \end{bmatrix} = \frac{1}{2} \begin{bmatrix} 1 & 1 \\ -1 & 1 \end{bmatrix} \begin{bmatrix} v_{u\chi} \\ v_{l\chi} \end{bmatrix} \quad (3.10)$$

Applying the $\Sigma\Delta$ transform to (3.8) and (3.9) disregarding the effects of the common mode voltage, relationships (3.11) and (3.12) are obtained, which define decoupled equations for the output and circulating currents of the converter.

$$\frac{di_\chi}{dt} = \frac{1}{(L_s + 2L_o)} [2v_\chi^\Delta - (R_s + 2R_o)i_\chi - 2v_{g\chi}] \quad (3.11)$$

$$\frac{di_{z\chi}}{dt} = \frac{1}{2L_s} [V_{dc} - 2v_\chi^\Sigma - 2R_s i_{z\chi}] \quad (3.12)$$

3.3. Principles of consensus theory

The fundamental concepts and notation of consensus theory must be introduced in order to present the proposed control scheme. The communication structure of the multi-agent system can be modeled as an unweighted, undirected and connected graph $G = (\mathcal{V}, \mathcal{E}, \mathcal{A})$, where $\mathcal{V} = \{v_1, \dots, v_n\}$ is the set of nodes or agents, $\mathcal{E} \subseteq \mathcal{V} \times \mathcal{V}$ is the set of edges and $\mathcal{A} \in \mathbb{R}_{\geq 0}^{n \times n}$ is the adjacency matrix of G . The node index set is defined as $\mathcal{I} = \{1, 2, \dots, n\}$. The edges of the graph can be represented as the terms $e_{ij} = (i, j) \in \mathcal{E}$, which determine if there is a communication link between node i and j . This way, the elements of $\mathcal{A}$ are defined as (3.13), which in this case define a symmetric matrix.

$$a_{ij} = \begin{cases} 1, & \text{if } (i, j) \in \mathcal{E} \\ 0, & \text{otherwise} \end{cases} \quad (3.13)$$

The set of neighbors of node v_i is defined as $\mathcal{N}_i = \{v_j \in \mathcal{V} : (v_i, v_j) \in \mathcal{E}\}$. This indicates that two nodes are considered neighbors if there is a communication link between them. Each node has an associated variable of interest or consensus variable $x_i \in \mathbb{R}$. This variable can represent different physical quantities, such as position or

voltage, for example. From these definitions, the nodes in a multi-agent system have reached a consensus when the variables of interest x_i are equal to each other, that is, when $x_i = x_j \forall i, j \in \mathcal{I}, i \neq j$ (Olfati-Saber & Murray, 2004).

For the multi-agent system to reach a consensus, a consensus protocol or algorithm is utilized, which represents the control action that is calculated from the variables of interest of the agents x_i . To ensure that the system reaches a consensus, the protocol must be selected according to the dynamic of the agents. An example of a linear protocol that solves the consensus problem in the case where the agents have single-integrator dynamics $\dot{x}_i = u_i$ is shown in (3.14), where $C \in \mathbb{R}^+$ corresponds to a constant gain.

$$u_i = C \sum_{j \in \mathcal{N}_i} (x_i - x_j) \quad (3.14)$$

Considering the previous definitions, it is necessary to introduce a system that represents the energy balance of the MMC as a consensus problem. To achieve this, the system defined by the equations (3.15), (3.16) and (3.17) is proposed, which is presented in (Andreasson, Dimarogonas, Sandberg, & Johansson, 2014). These equations represent agents with double-integrator dynamics and a control input u_i given by a distributed Proportional-Integral controller. It can be demonstrated that this system has a similar structure to the proposed controller for the energy balance of the converter.

$$\dot{x}_i = v_i \quad (3.15)$$

$$\dot{v}_i = u_i - \gamma v_i + d_i \quad (3.16)$$

$$u_i = - \sum_{j \in \mathcal{N}_i} \left(\beta(x_i - x_j) + \alpha \int_0^t (x_i(\tau) - x_j(\tau)) d\tau \right) - \delta(x_i - x_i^0) \quad (3.17)$$

Where $\alpha \in \mathbb{R}^+$, $\beta \in \mathbb{R}^+$, $\gamma \in \mathbb{R}^+$ and $\delta \in \bar{\mathbb{R}}^+$ are fixed parameters, $x_i^0 = x_i(0)$ are the initial conditions, and $d_i \in \mathbb{R}$ is an unknown disturbance. With these dynamics, the agents converge to a consensus value for any constant perturbation d_i and any initial condition, provided that $\alpha < \beta\gamma$ (Andreasson et al., 2014). If $\delta = 0$, it still holds that

$\lim_{t \rightarrow \infty} |x_i(t) - x_j(t)| = 0, \forall i, j \in \mathcal{V}$ and for any constant perturbation d_i . But, in this case the states are generally unbounded, i.e., $\lim_{t \rightarrow \infty} |x_i(t)| = \infty, \forall i \in \mathcal{V}$. This system is utilized in section 3.8 to demonstrate that the energy balance of the converter can be represented as a consensus problem once the proposed control strategy is presented.

3.4. Submodule modulating signal

For the operation of the MMC, it is necessary to calculate the modulating signals for each submodule $v_{y\chi,i}^*$, which are utilized in the modulation stage of the control scheme to determine the switching signals of the power transistors. These signals are determined by calculating different components that are designed to fulfill the control objectives assigned to the CC and the LCs. Relationships (3.18) and (3.19), which are based on (Hagiwara et al., 2011), show the computation of the modulating signals for submodules in the upper and lower clusters of each phase respectively, where the term $\frac{V_{dc}}{2N}$ corresponds to a feedforward component.

$$v_{u\chi,i}^* = \frac{V_{dc}}{2N} - \frac{v_\chi^*}{N} + \Delta V_{z,\chi} + \Delta V_{\text{intra},y\chi i} - v_{z\chi}^* \quad (3.18)$$

$$v_{l\chi,i}^* = \frac{V_{dc}}{2N} + \frac{v_\chi^*}{N} + \Delta V_{z,\chi} + \Delta V_{\text{intra},y\chi i} - v_{z\chi}^* \quad (3.19)$$

In these relationships, v_χ^* corresponds to the phase voltage reference, $v_{z\chi}^*$ to the circulating current suppression component, $\Delta V_{z,\chi}$ to the inter-cluster voltage balancing component and $\Delta V_{\text{intra},y\chi i}$ to the intra-cluster voltage balancing component. The distributed structure of the control scheme allows the phase voltage references and the circulating current suppression components to be calculated in the CC, while the voltage balancing components are calculated in the LCs. This is done to reduce the computational load of the CC, dividing the calculation of some of these signal components between the system controllers. The strategies utilized to calculate these signals are detailed in the following sections.

In the modulation step, the Phase-Shifted PWM (PS-PWM) strategy is utilized, generating one triangular carrier wave for each submodule in the cluster with a phase shift of $\frac{2\pi}{N}$ between them and frequency f_c . The calculation of the switching signals is done by each respective LC. Furthermore, the phase shift of the carriers between the upper and lower clusters of each phase can be adjusted to minimize the harmonic content in the MMC output voltage. This phase shift should be $\frac{\pi}{N}$ when the number of submodules in each cluster N is even, and zero when N is odd. For simplicity in this implementation, the phase shift is set to zero for the conducted simulations and experiments. This approach does not limit the operation or functionality of the proposed control strategies, since it only affects the harmonic content of the output voltage. The implementation of the PS-PWM strategy is detailed in section 4.2.

3.5. Output current control

One of the main objectives during the operation of the MMC is to achieve a regulated power flow through the AC port of the converter. To accomplish this, and considering the distributed structure of the control scheme, an output current controller is implemented within the CC. This controller generates the phase voltage references v_χ^* of the converter, which are utilized by the LCs to determine the individual submodule voltage references $v_{y\chi,i}^*$ and the total cluster voltage reference $v_{y\chi}^*$. It is assumed that the CC measures all the cluster currents $i_{y\chi}$ and grid voltages $v_{g\chi}$ during each control step.

The block diagram of the output current controller is shown in Fig. 3.3. For this implementation, a dq synchronous reference frame current controller is implemented, where the output currents of the converter are calculated from the cluster currents measurements using (3.2). The required phase angle θ for grid synchronization is obtained through the use of a Synchronous Reference Frame Phase-Locked Loop (SRF-PLL) utilizing the grid voltage measurements v_{ga} , v_{gb} and v_{gc} . Finally, the phase voltage references v_d^* and v_q^* are obtained in the dq reference frame, which are then transmitted to the LCs along with the grid phase angle θ utilizing the corresponding communication bus in each control period.

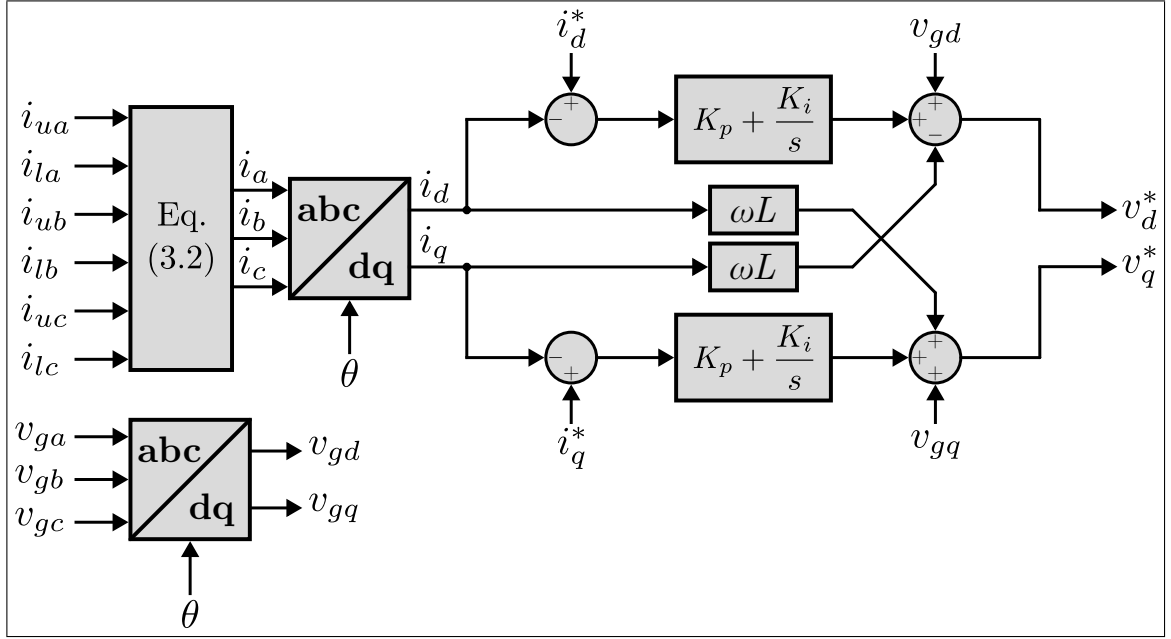


Figure 3.3. Block diagram for the output current controller.

3.6. Circulating current suppressing controller

As explained in section 2.1, without proper control of the circulating currents, the operation of the converter generates second-order harmonics in both these currents and the cluster currents. For this reason, a Circulating Current Suppressing Controller (CCSC) is implemented to eliminate these harmonic components, based on (Tu, Xu, & Xu, 2011).

The block diagram of the CCSC is shown in Fig. 3.4. For the operation of this controller, the cluster current measurements $i_{y\chi}$ are used to obtain the circulating currents $i_{z\chi}$ from (3.3). By applying the double line-frequency, negative-sequence, rotational dq frame transformation, two DC components are obtained representing the circulating currents, similar to the synchronous reference frame of the output current controller. In this case, the direct and quadrature reference signals are set to zero to minimize the second harmonic components. The outputs of the CCSC are the voltage component references v_{zd}^* and v_{zq}^* in the negative-sequence, rotational reference frame, which are transmitted to the LCs through the communication bus in each control period.

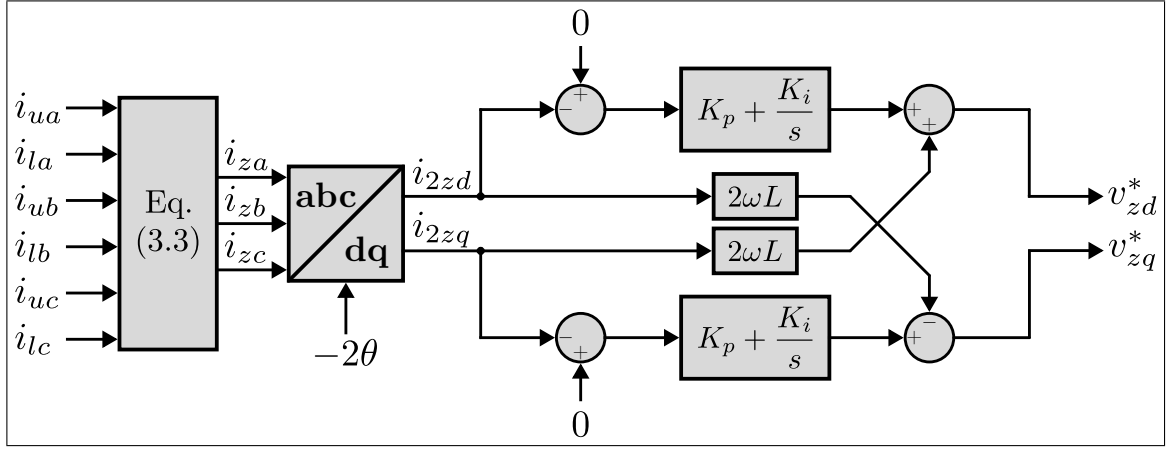


Figure 3.4. Block diagram for the Circulating Current Suppressing Controller.

3.7. Capacitor voltage balancing

The proposed strategy for capacitor voltage balancing, which is based on the controllers presented on (Thitichaiworakorn et al., 2012), consists in computing balancing signals within each LC that adjust the voltage references v_{dq}^* sent by the output current controller. Two balancing terms must be calculated for each submodule: the inter-cluster ($\Delta V_{z,\chi}$) and the intra-cluster balancing term ($\Delta V_{\text{intra},y\chi i}$). The main advantage of this approach is that these signals can be calculated directly in each LC by using local measurements and shared variables that are transmitted through the communication buses in each control step, reducing the computational burden of the CC. It is assumed that each LC measures the capacitor voltages from all the submodules within their cluster during each control step, allowing the calculation of the average capacitor voltage of the cluster.

3.7.1. Inter-cluster balancing control

The inter-cluster balancing signal seeks to equalize the capacitor average voltage of each cluster with each other. As explained in section 1.2, two types of control actions are recognized depending on the necessary power flows in the converter to achieve the voltage balance: the horizontal and vertical energy balance. A control strategy is implemented for

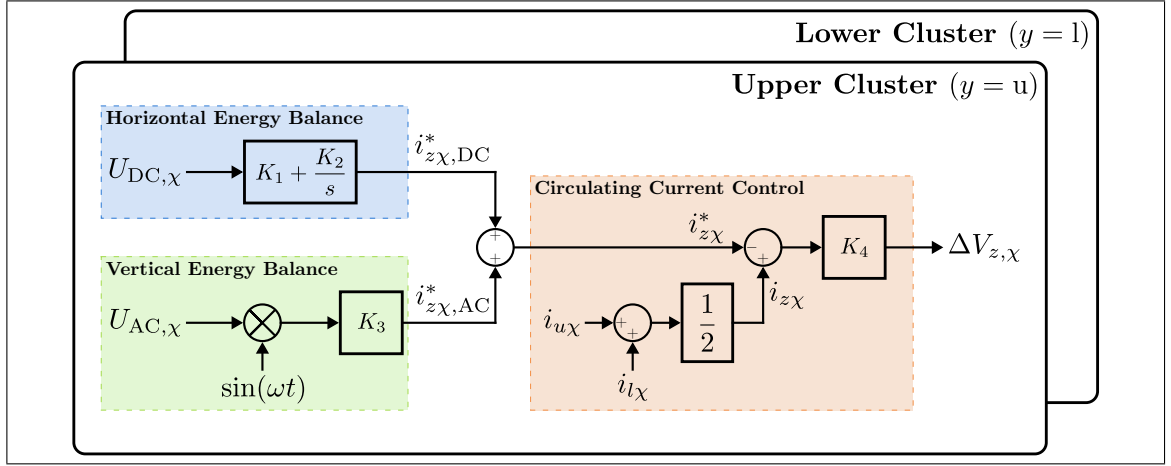


Figure 3.5. Controller block diagram for inter-cluster balancing signal calculation.

each control action, aiming to define a reference for the circulating current of each phase. The complete block diagram of the inter-cluster balancing controller is shown in Fig. 3.5, and its main components are analyzed in the following sections.

3.7.1.1. Horizontal energy balance

The horizontal energy balance is accomplished between the clusters of different phases or legs of the converter, which is achieved by comparing the phase average voltages of the capacitors. This suggests that each LC should have approximate local values of the phase average voltages $\bar{v}_{C,\chi}$. These values are calculated using the cluster average voltages $\bar{v}_{C,y\chi}$ shared on the consensus CAN bus, as shown in (3.20).

$$\bar{v}_{C,\chi} = \frac{1}{2} (\bar{v}_{C,u\chi} + \bar{v}_{C,l\chi}) \quad (3.20)$$

With these definitions, it is possible to formulate the error signal between the phase average voltages $U_{DC,\chi}$ as the consensus algorithm shown in (3.21).

$$U_{DC,\chi} = -K_{DC} \sum_{j \in \mathcal{N}_i} (\bar{v}_{C,\chi} - \bar{v}_{C,j}) \quad (3.21)$$

In this relationship, K_{DC} corresponds to the proportional gain and $\mathcal{N}_i$ represents the set of neighbors of agent i . This algorithm enables the simulation of various communication structures between LCs with different network graphs by modifying the equivalent graph of the system. Considering that the CAN communication bus physically connects all the LCs, to simulate connectivity changes between the agents, the LCs ignore the variables transmitted by other LCs if there is no communication link between them in the equivalent network graph. The error signal $U_{DC,\chi}$ is then utilized with a PI controller to obtain a reference for the DC component of the circulating current of the corresponding phase $i_{z\chi,DC}^*$. It is important to note that since the controller compares the phase average voltages, and for the calculation of the vertical energy balance, there needs to be communication between the upper and lower clusters of each phase.

3.7.1.2. Vertical energy balance

The vertical energy balance is executed between the upper and lower clusters or arms of each phase. Unlike horizontal power balance, each LC needs to compare only two cluster average voltages to obtain the corresponding error signal $U_{AC,\chi}$, specifically the upper and lower cluster average voltages from the corresponding phase. This calculation can be defined as the relationship shown in (3.22), where K_{AC} corresponds to the proportional gain of the controller.

$$U_{AC,\chi} = -K_{AC} (\bar{v}_{C,u\chi} - \bar{v}_{C,l\chi}) \quad (3.22)$$

To generate the vertical power flow, a sinusoidal component is introduced to the reference of the circulating current with the same fundamental frequency as the output current, as shown in Fig. 3.5. If this component is in phase with the phase output voltage, active power is transferred from the upper cluster to the lower cluster. If they are out of phase by 180° instead, active power is transferred in the opposite direction, from lower cluster to upper cluster (Thitichaiworakorn et al., 2012). In this manner, the error signal $U_{AC,\chi}$ is utilized to generate a reference for the AC component of the circulating current $i_{z\chi,AC}^*$.

3.7.1.3. Circulating current control

Utilizing the computed DC and AC references for the circulating current, the inter-cluster balancing component can be obtained. The controller compares the overall reference with the calculated circulating current utilizing relationship (3.3). The upper and lower cluster currents, $i_{u\chi}$ and $i_{l\chi}$ respectively, correspond to the values transmitted by the CC through the communication bus. Since only one current measurement is sent in each control period, the circulating current calculation in each LC is updated only when one of the cluster currents required for this computation is transmitted by the CC.

It should be noted that, to ensure that the inter-cluster balancing signals $\Delta V_{z,\chi}$ are equal between the upper and lower LCs of each phase, the system must ensure that it utilizes the same measurements of cluster average voltages and cluster currents for the calculations in each control period. This guarantees that the error signals $U_{DC,\chi}$, $U_{AC,\chi}$ and the locally calculated circulating currents are equal in both LCs of the same phase, which ensures that the signals $\Delta V_{z,\chi}$ are also equal.

The computed balancing component $\Delta V_{z,\chi}$ is the same for each submodule within the respective cluster, and any voltage differences between the submodules are rectified by the intra-cluster signal component.

3.7.2. Intra-cluster balancing control

The intra-cluster balancing signal, also known as individual-balancing control, aims to equalize the capacitor voltages of the submodules within the same cluster. Each LC is responsible for calculating the balancing signal for each of the submodules within its corresponding cluster. For this reason, the proposed calculation strategy is similar to the centralized controller case, since each LC has access to the voltage measurements of the submodules in each control period. The LCs do not require information from the other LCs, so it can be concluded that the implemented intra-cluster control is a type of decentralized control. Fig. 3.6 shows the block diagram of the controller, where the voltage

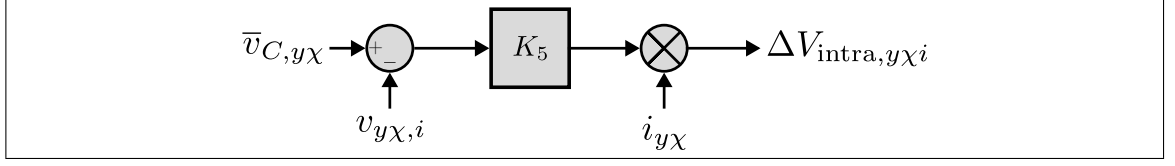


Figure 3.6. Controller block diagram for intra-cluster balancing signal calculation.

of each submodule is compared with the average voltage of the cluster $\bar{v}_{C,y\chi}$, which is calculated as (3.23).

$$\bar{v}_{C,y\chi} = \frac{1}{N} \sum_{i=1}^N v_{y\chi,i} \quad (3.23)$$

Similar to the circulating current controller, the cluster current $i_{y\chi}$ corresponds to the value sent by the CC through the communication bus. In this case, the value of the cluster current is updated each time all six measurements are transmitted in a cycle, since only one current measurement is sent in each control period.

3.8. Consensus theory and inter-cluster energy balance

The following section seeks to demonstrate that the operation of the controller for the horizontal energy balance, analyzed in section 3.7.1.1, can be represented using consensus theory. The objective of this is to validate the proposed control strategy through a theoretical derivation. Furthermore, this section illustrates how different communication structures affect the calculation of the consensus algorithm.

3.8.1. Analysis of inter-cluster balance utilizing consensus theory

For the following analysis, it is assumed that the other MMC controllers operate normally and their control objectives are achieved. This is done to only analyze the effects of the horizontal energy balance. Furthermore, as the objective is to study the effects of the controller on the phase average voltages, the effects of the vertical energy balance are

not considered in the following equations, since this balance only influences the voltage difference between the upper and lower cluster of each phase. This means that the AC component of the circulating current reference $i_{z\chi,AC}$, as shown in the block diagram of the controller in Fig. 3.5, is not considered for this analysis.

To represent the horizontal energy balance as a consensus problem, the double integrator multi-agent system presented in equations (3.15), (3.16) and (3.17) is utilized. The objective of the following analysis is to develop the equations of the MMC and the balancing controller to define similarities between both systems. In the following sections, to maintain the notation of the system variables, the notation change $i = \chi$ is made in the double-integrator system.

Consensus algorithm and circulating current reference

From the block diagram of the controller (Fig. 3.5) considering only the horizontal energy balance, the circulating current reference $i_{z\chi,DC}^*$ can be described by the following relationship.

$$\begin{aligned} i_{z\chi,DC}^* &= \left(K_1 + \frac{K_2}{s} \right) U_{DC,\chi} \\ &= -K_{DC} \left(K_1 + \frac{K_2}{s} \right) \sum_{j \in \mathcal{N}_i} (\bar{v}_{C,\chi} - \bar{v}_{C,j}) \\ &= -K_{DC} \sum_{j \in \mathcal{N}_i} \left(K_1 (\bar{v}_{C,\chi} - \bar{v}_{C,j}) + K_2 \int_0^t (\bar{v}_{C,\chi}(\tau) - \bar{v}_{C,j}(\tau)) d\tau \right) \end{aligned} \quad (3.24)$$

From this, a comparison can be made between (3.24) and the equation representing the control action of the multi-agent system as defined in (3.17). The control action u_χ can be defined as (3.25).

$$u_\chi = \frac{N}{L_s} i_{z\chi,DC}^* \quad (3.25)$$

Utilizing (3.24) and (3.25), the following relationships are obtained by comparing both systems.

$$u_\chi = -\frac{NK_{\text{DC}}}{L_s} \sum_{j \in \mathcal{N}_i} \left(K_1 (\bar{v}_{C,\chi} - \bar{v}_{C,j}) + K_2 \int_0^t (\bar{v}_{C,\chi}(\tau) - \bar{v}_{C,j}(\tau)) d\tau \right) \quad (3.26)$$

$$\delta = 0 \quad (3.27)$$

Circulating currents dynamics

From the block diagram of the controller (Fig. 3.5) and utilizing (3.25), the inter-cluster balancing component can be expressed as (3.28).

$$\Delta V_{z,\chi} = K_4 \left(i_{z\chi} - \frac{L_s}{N} u_\chi \right) \quad (3.28)$$

From the modulating signals of the submodules defined in (3.18) and (3.19), the voltages of the upper and lower clusters shown in (3.29) and (3.30) can be obtained by considering N submodules within each cluster. These relationships consider only the phase voltage reference v_χ^* from the output current controller, the inter-cluster balancing component $\Delta V_{z,\chi}$ and the constant feedforward term. This is done because these are the predominant components and have a greater magnitude in the operation of the converter, while the effects of the inter-cluster balancing component on the phase average voltage are analyzed.

$$v_{u\chi} = \frac{V_{dc}}{2} - v_\chi^* + N \cdot \Delta V_{z,\chi} \quad (3.29)$$

$$v_{l\chi} = \frac{V_{dc}}{2} + v_\chi^* + N \cdot \Delta V_{z,\chi} \quad (3.30)$$

Utilizing the equation that describes the dynamics of the circulating current as defined in (3.9), and replacing the equations (3.28), (3.29) and (3.30), the following relationship

is obtained.

$$\begin{aligned}
\dot{i}_{z\chi} &= \frac{1}{2L_s} [V_{dc} - (v_{u\chi} + v_{l\chi}) - 2R_s i_{z\chi}] \\
&= -\frac{N \cdot \Delta V_{z,\chi}}{L_s} - \frac{R_s}{L_s} i_{z\chi} \\
&= K_4 \cdot u_\chi - \left(\frac{K_4 N + R_s}{L_s} \right) i_{z\chi}
\end{aligned} \tag{3.31}$$

To simplify the analysis, $K_4 = 1$ is chosen. By comparing (3.31) with the first integrative equation of the multi-agent system defined in (3.16) the following relationships can be defined.

$$v_\chi = i_{z\chi} \tag{3.32}$$

$$\gamma = \left(\frac{N + R_s}{L_s} \right) \tag{3.33}$$

$$d_\chi = 0 \tag{3.34}$$

Power equations and capacitor voltage

Utilizing relationships (3.29) and (3.30) for the voltages of the upper and lower clusters, along with equations (3.4) and (3.5) for the cluster currents, the power entering the upper $P_{u\chi}$ and lower $P_{l\chi}$ clusters of phase χ of the MMC can be expressed by relationships (3.35) and (3.36) respectively.

$$\begin{aligned}
P_{u\chi} &= v_{u\chi} i_{u\chi} \\
&= \left(\frac{V_{dc}}{2} - v_\chi^* + N \cdot \Delta V_{z,\chi} \right) \left(i_{z\chi} + \frac{i_\chi}{2} \right)
\end{aligned} \tag{3.35}$$

$$\begin{aligned}
P_{l\chi} &= v_{l\chi} i_{l\chi} \\
&= \left(\frac{V_{dc}}{2} + v_\chi^* + N \cdot \Delta V_{z,\chi} \right) \left(i_{z\chi} - \frac{i_\chi}{2} \right)
\end{aligned} \tag{3.36}$$

Developing these relationships, the power entering the phase P_χ is defined as (3.37).

$$\begin{aligned} P_\chi &= P_{u\chi} + P_{l\chi} \\ &= V_{dc}i_{z\chi} - v_\chi^*i_\chi + 2N \cdot \Delta V_{z,\chi}i_{z\chi} \end{aligned} \quad (3.37)$$

Based on the analysis conducted in (Cui, Kim, Jung, & Sul, 2014), the power entering phase χ , denoted as P_χ , can be defined from the output voltage reference v_χ^* and the leg internal voltage reference $v_{\chi o}^*$ as (3.38).

$$P_\chi = V_{dc}i_{z\chi} - v_\chi^*i_\chi - 2v_{\chi o}^*i_{z\chi} \quad (3.38)$$

Comparing equations (3.37) and (3.38), it can be noted that the terms in both models are similar. Therefore, the leg internal voltage reference $v_{\chi o}^*$ can be defined as (3.39) to make a comparison between both analyses.

$$v_{\chi o}^* = -N \cdot \Delta V_{z,\chi} \quad (3.39)$$

In the analysis, it is argued that the third term of equation (3.38) can be neglected in applications such as HVDC. This loses validity as the DC-link voltage V_{dc} begins to be comparable to the term $N \cdot \Delta V_{z,\chi}$. This case can occur when V_{dc} is small or if significant imbalances between the phase average voltages require a high component $\Delta V_{z,\chi}$ to balance the capacitors. By neglecting the third term of (3.38), it can be noted that the power entering the phase can be controlled utilizing the corresponding circulating current in the first term of the equation, while the second term represents the power leaving the phase through the AC port to the grid. Defining the first term as ΔP_χ , relationship (3.40) can be derived.

$$\Delta P_\chi = V_{dc}i_{z\chi} = \dot{\omega}_{c,\chi} \quad (3.40)$$

Where $\dot{\omega}_{c,\chi}$ represents the change in the energy stored in the capacitors of phase χ due to this power flow. This indicates that the capacitors of each phase can be charged or

discharged by controlling the circulating currents of the converter. Appendix B provides an alternative derivation of these results utilizing a similar procedure. The energy stored in phase χ can also be expressed as (3.41) by considering the capacitor energy equation and the phase average capacitor voltage $\bar{v}_{C,\chi}$.

$$\omega_{c,\chi} = \frac{1}{2} C_{eq} \bar{v}_{C,\chi}^2 \quad (3.41)$$

Where $C_{eq} \in \mathbb{R}^+$ represents the constant equivalent capacitance of the phase. Due to the non-linear nature of this equation with respect to the consensus variable $\bar{v}_{C,\chi}$, it is necessary to apply a first-order linearization to represent the model as the linear multi-agent system. The chosen operating point for linearization corresponds to the constant voltage reference of the consensus algorithm defined as $v_0 = \bar{v}_{C,\text{ref}} \in \mathbb{R}^+$, as shown in (3.42).

$$\omega_{c,\chi} \approx C_{eq} v_0 \bar{v}_{C,\chi} - \frac{1}{2} C_{eq} v_0^2 \quad (3.42)$$

By differentiating (3.42) and comparing with (3.40), the linear relationship between the circulating current $i_{z\chi}$ and the time derivative of the consensus variable $\dot{\bar{v}}_{c,\chi}$ is obtained, as shown in (3.43).

$$\begin{aligned} \Delta P_\chi &= V_{dc} i_{z\chi} = \dot{\omega}_{c,\chi} = C_{eq} v_0 \dot{\bar{v}}_{C,\chi} \\ \dot{\bar{v}}_{C,\chi} &= \frac{V_{dc}}{C_{eq} v_0} i_{z\chi} \end{aligned} \quad (3.43)$$

Finally, to compare the previous relationship with equation (3.15) from the multi-agent system, the change of variables defined in (3.44) is applied.

$$\bar{v}_{C,\chi} = \frac{V_{dc}}{C_{eq} v_0} x_\chi \quad (3.44)$$

Where $x_\chi \in \mathbb{R}$ corresponds to the new consensus variable, which is directly related to the phase average voltages. By substituting this new variable in (3.43), the desired

relationship is obtained.

$$\dot{x}_\chi = i_{z\chi} \quad (3.45)$$

Comparison between model and multi-agent system

By substituting the change of variables defined in (3.44) into the derived relationships that represents the control action, defined in (3.24), the final system can be represented by equations (3.46), (3.47) and (3.48).

$$\dot{x}_\chi = i_{z\chi} \quad (3.46)$$

$$\dot{i}_{z\chi} = u_\chi - \left(\frac{N + R_s}{L_s} \right) i_{z\chi} \quad (3.47)$$

$$u_\chi = -\frac{NK_{DC}V_{dc}}{L_sC_{eq}v_0} \sum_{j \in \mathcal{N}_i} \left(K_1 (x_\chi - x_j) + K_2 \int_0^t (x_\chi(\tau) - x_j(\tau)) d\tau \right) \quad (3.48)$$

It can be observed that this system has the same structure as the multi-agent system presented in section 3.3, defined with consensus variables $x_\chi \forall \chi \in \{a, b, c\}$. From this structure, the parameters of the multi-agent system are defined in (3.49), (3.50) and (3.51).

$$\alpha = \frac{NK_{DC}V_{dc}}{L_sC_{eq}v_0} K_2 \quad (3.49)$$

$$\beta = \frac{NK_{DC}V_{dc}}{L_sC_{eq}v_0} K_1 \quad (3.50)$$

$$\gamma = \left(\frac{N + R_s}{L_s} \right) \quad (3.51)$$

Considering the definition of the multi-agent system, for the system to converge to consensus, the relationship (3.52) must be met. This imposes a restriction on the proportional gain K_1 and the integral gain K_2 of the PI controller, as shown in the block diagram

in Fig. 3.5.

$$\alpha < \beta\gamma$$

$$K_2 < K_1 \left(\frac{N + R_s}{L_s} \right) \quad (3.52)$$

Based on these results, the phase average voltages converge to the voltage reference, and therefore to consensus, provided that the objectives of the other MMC controllers and the presented conditions of the multi-agent system are met. It should be noted that, due to the approximations made to the non-linear power equations, these results are valid for voltage unbalances close to the nominal operating voltage of the capacitors. In the conducted experimental tests, which are shown in section 5, it is verified that the control strategy manages to bring the phase average voltages to consensus for imbalances within a range of approximately $\pm 10\%$. However, utilizing simulations, the controller is able to balance the capacitor voltages in the presence of greater voltage imbalances for the selected system and control parameters. Since the capacitor voltages typically operate close to their nominal values during normal converter operation, it can be affirmed that the controller will maintain the phase average voltages close to the voltage reference of the controller, as demonstrated in the experimental results.

3.8.2. Effect of communication structures

To show how communication structures affect the calculation of the consensus algorithm, the communication graphs shown in Fig. 3.7 are defined. Since the horizontal energy balance is being analyzed, the communication structure is simplified. In this case, each phase corresponds to an agent of the system, in which the LCs compare their individually calculated phase average voltages to obtain the respective circulating current reference. Furthermore, an additional node or agent is incorporated into each communication structure, which represents the constant phase average voltage reference $\bar{v}_{C,\text{ref}}$, as shown in Fig. 3.7. This is done to control the value to which the capacitor voltages converge.

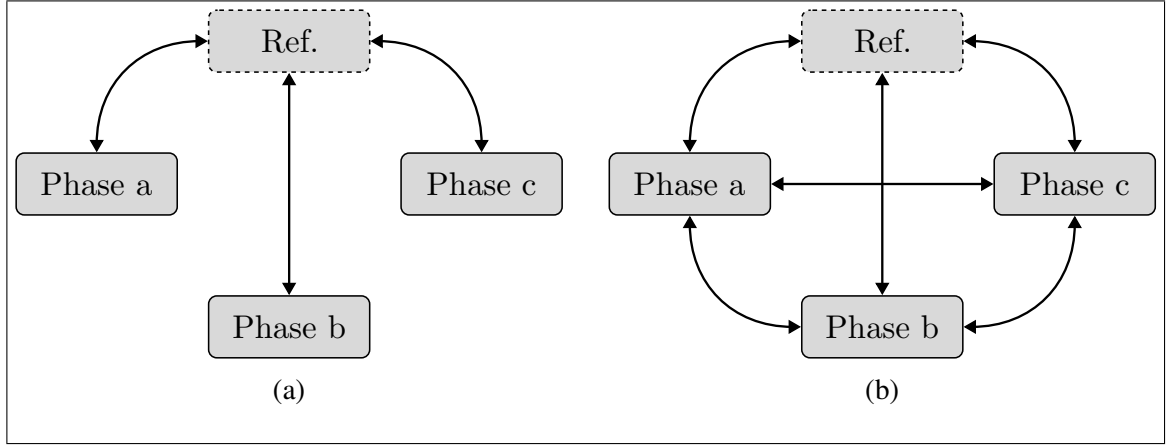


Figure 3.7. Example of communication structures. (a) Example structure 1. (b) Example structure 2.

1) Communication Structure 1

For communication structure 1, as shown in Fig. 3.7a, the LCs compare their phase average voltages only with the constant reference value $\bar{v}_{C,\text{ref}}$, without exchanging any variables with LCs from other phases. The adjacency matrix of this communication structure $\mathcal{A}_1$ is defined as (3.53), considering that $\bar{v}_{C,1} = \bar{v}_{C,a}$, $\bar{v}_{C,2} = \bar{v}_{C,b}$, $\bar{v}_{C,3} = \bar{v}_{C,c}$ and $\bar{v}_{C,4} = \bar{v}_{C,\text{ref}}$ represent the node numbering notation.

$$\mathcal{A}_1 = \begin{bmatrix} 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 \\ 1 & 1 & 1 & 0 \end{bmatrix} \quad (3.53)$$

Utilizing the consensus algorithm defined in (3.21), the error signal $U_{\text{DC},\chi}$ for structure 1 is calculated according to (3.54).

$$\begin{aligned} U_{\text{DC},\chi} &= -K_{\text{DC}} \sum_{j \in \mathcal{N}_i} (\bar{v}_{C,\chi} - \bar{v}_{C,j}) \\ &= K_{\text{DC}} (\bar{v}_{C,\text{ref}} - \bar{v}_{C,\chi}) \end{aligned} \quad (3.54)$$

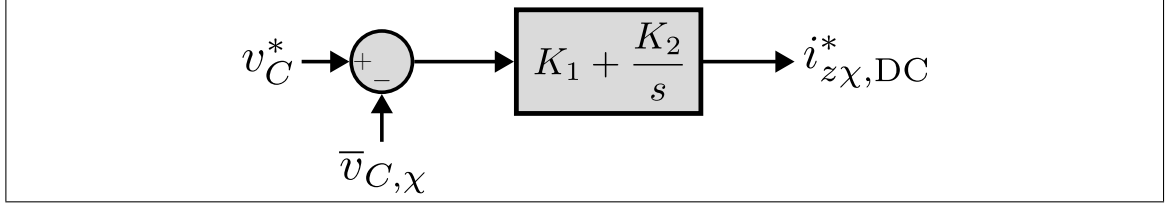


Figure 3.8. Centralized controller implementation for calculation of the circulating current DC component (Thitichaiworakorn et al., 2012).

Equation (3.54) can be compared with the error signal obtained when a centralized controller is implemented, as shown in Fig. 3.8. In this case, the error signal is obtained by comparing the average voltage of phase χ , $\bar{v}_{C,\chi}$, with a constant reference value v_C^* , in order to determine the DC reference component of the circulating current $i_{z\chi,DC}^*$. From this controller, the error signal Err_χ for phase χ in the centralized scenario is defined as (3.55).

$$\text{Err}_\chi = v_C^* - \bar{v}_{C\chi} \quad (3.55)$$

From this, it can be observed that utilizing communication structure 1 defines an error signal similar to the centralized case. In both cases, the phase average voltages are compared to a constant reference value v_C^* to balance the energy in the converter. From the communication structure, this constant value is equal to $\bar{v}_{C,ref}$, as defined in (3.56).

$$v_C^* = \bar{v}_{C,ref} \quad (3.56)$$

2) Communication Structure 2

In the case of communication structure 2, the equivalent adjacency matrix $\mathcal{A}_2$ is defined as (3.57).

$$\mathcal{A}_2 = \begin{bmatrix} 0 & 1 & 1 & 1 \\ 1 & 0 & 1 & 1 \\ 1 & 1 & 0 & 1 \\ 1 & 1 & 1 & 0 \end{bmatrix} \quad (3.57)$$

The error signal $U_{\text{DC},\chi}$ for structure 2 is calculated according to (3.58), utilizing a similar node numbering notation as structure 1.

$$\begin{aligned} U_{\text{DC},\chi} &= -K_{\text{DC}} \sum_{j \in \mathcal{N}_i} (\bar{v}_{C,\chi} - \bar{v}_{C,j}) \\ &= K_{\text{DC}} \sum_{j=1}^4 (\bar{v}_{C,j} - \bar{v}_{C,\chi}) \end{aligned} \quad (3.58)$$

By developing (3.58), expression (3.59) can be derived.

$$\begin{aligned} U_{\text{DC},\chi} &= K_{\text{DC}} \left(\sum_{j=1}^4 \bar{v}_{C,j} - 4\bar{v}_{C,\chi} \right) \\ &= 4K_{\text{DC}} \left(\frac{1}{4} \sum_{j=1}^4 \bar{v}_{C,j} - \bar{v}_{C,\chi} \right) \\ &= 4K_{\text{DC}} (v_C^* - \bar{v}_{C,\chi}) \end{aligned} \quad (3.59)$$

Based on these results, it can be observed that utilizing communication structure 2 is similar to using a variable voltage reference value v_C^* given by (3.60).

$$v_C^* = \frac{1}{4} \sum_{k=1}^4 \bar{v}_{C,k} \quad (3.60)$$

In this case, this value is equal to the average of the phase voltages from the three phases and the reference voltage $\bar{v}_{C,\text{ref}}$ defined from the communication structure. This indicates that the phase average voltages tend to equal each other by utilizing the consensus algorithm.

3.9. Conclusion

In this chapter the mathematical model and simplified model of the MMC were presented, utilizing the converter equivalent circuit and deriving its fundamental equations. The continuous-time relationships between the internal and external electrical variables of

the converter were analyzed, showing that the output currents and circulating currents of the converter can be controlled by properly regulating the cluster voltages.

The principles of consensus theory were presented, describing the necessary concepts for the analysis of the proposed voltage balancing strategy. Utilizing these concepts, a system of equations was introduced that represents a multi-agent system with double-integrator dynamics and control input given by a distributed PI controller. This system was used to represent the energy balance of the converter as a consensus problem, comparing the similarities between both models. Furthermore, the horizontal energy balance of the MMC was analyzed for different communication structures between phases, which affect the calculation of the consensus protocol within the LCs.

The proposed control strategies utilized for the consensus-based distributed control strategy were defined. These strategies generate the circulating current references to balance the capacitor voltages of the converter while regulating its AC port currents. The controllers for capacitor voltage balancing were categorized into the inter-cluster and the intra-cluster energy balance, analyzing its corresponding block diagrams. Furthermore, the proposed control strategies consider the physical and implementation characteristics of the communication between the CC and the LCs of the system, especially the limited amount of data that can be transmitted in each message utilizing the CAN communication protocol.

4. DISTRIBUTED CONTROL DESIGN

Based on the control strategies analyzed in chapter 3, it is necessary to assign and implement the tasks that must be executed by the CC and the LCs to successfully operate the converter utilizing the proposed distributed control scheme. Furthermore, since a communication scheme is implemented between the controllers, it is essential to define the necessary strategies, proper configuration and the sequence in which these tasks must be performed to ensure their correct execution and synchronization.

4.1. Assignment of controller tasks

The main tasks assigned to the CC for the operation of the converter can be summarized as:

- (i) Acting as entry point for the external power reference of the converter.
- (ii) Measuring the cluster currents $i_{y\chi}$ and grid voltages $v_{g\chi}$.
- (iii) Execute the output current controller, as shown in Fig. 3.3, transmitting the phase voltage references v_d^* and v_q^* , in the dq reference frame, to the LCs through the associated CAN bus in each control period.
- (iv) Execute the CCSC, as shown in Fig. 3.4, transmitting the voltage component references v_{zd}^* and v_{zq}^* , in the double line-frequency, negative-sequence, rotational dq frame, to the LCs through the associated CAN bus in each control period.
- (v) Computing the PLL and transmitting the grid phase angle θ and one of the measured cluster currents $i_{y\chi}$ to the LCs through the associated CAN bus in each control period.

In the same manner, the tasks assigned to the LCs are:

- (i) Measuring the capacitor voltages from the submodules of the corresponding cluster $v_{y\chi,i}$.

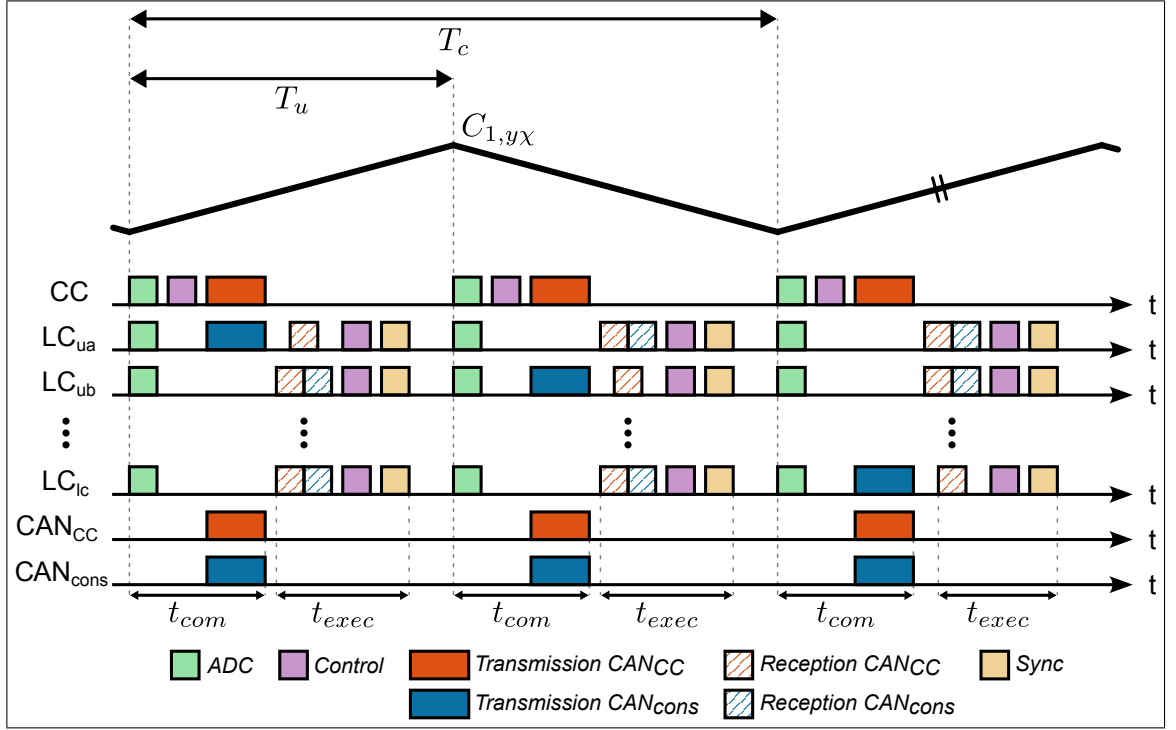


Figure 4.1. Temporal diagram of the proposed distributed control scheme.

- (ii) Calculating and transmitting the cluster average voltage $\bar{v}_{C,y\chi}$ to the other LCs through the consensus CAN bus in each control period.
- (iii) Computing the inter-cluster balancing component $\Delta V_{z,\chi}$ utilizing the proposed consensus controller, as shown in Fig. 3.5.
- (iv) Computing the intra-cluster balancing components $\Delta V_{intra,y\chi i}$ for each submodule within the cluster, as shown in Fig. 3.6.
- (v) Calculating the final modulating signals $v_{y\chi,i}^*$ for each submodule within the cluster utilizing the calculated and received control signals, as shown in relationships (3.18) and (3.19).
- (vi) Generating the switching signals for the submodules using the PS-PWM modulation strategy.

Based on the previous assignment, Fig. 4.1 shows the temporal diagram of the tasks executed by the CC and LCs in each control cycle for the proposed distributed control scheme. Each of the defined tasks can be outlined as follows:

- 1) **ADC:** This task indicates the measurement of the respective converter variables by the CC and LCs using the Analog-to-Digital Converters (ADCs) peripherals of the micro-controllers at the start of each control period.
- 2) **Control:** This corresponds to the calculation of the control references and signals using the measured variables as indicated in the proposed controllers schemes in chapter 3. It can be observed that each LC must receive the calculated control variables from the CC and other LCs before computing the corresponding final modulating signals.
- 3) **Transmission:** This task involves transmitting the relevant control variables through the two defined CAN buses. To differentiate both buses, CAN_{CC} denotes the bus that communicates the CC with each LC, while CAN_{cons} refers to the consensus bus that communicates all the LCs between them. In each control period, the CAN_{CC} bus is utilized by the CC to communicate the corresponding control variables and measurements, while the LCs alternate the use of the consensus bus to send their cluster average voltage. It can be noted that the communication is done in parallel, utilizing the two buses at the same time to reduce the total transmission time in a control period.
- 4) **Reception:** This corresponds to the acquisition of the transmitted variables from the CAN buses by the LCs. It can be noted that, if an LC transmits through the CAN_{cons} bus within a control period T_u , that LC receives data only from the CAN_{CC} bus. Conversely, if the LC does not transmit in the actual control period, the reception of data is done from both buses.
- 5) **Synchronization:** The final task in each control period is the synchronization of the carriers from the CC and LCs. This involves adjusting the phase of the carriers of every LC to account for deviations in the clocks of the micro-controllers, that would result in differences in the execution timings of the previous control tasks. The proposed synchronization algorithm is explained in detail in section 4.4.

To synchronize the previous tasks, a main triangular carrier $C_{1,y\chi}$ is established for each of the micro-controllers. The peaks and valleys of this carrier indicate when each control period should start, as shown in Fig. 4.1. For this implementation, the switching period T_c is defined as twice the control or sampling period T_u . Relationship (4.1) can

also be derived that relates the switching frequency f_c and the sampling frequency f_u of the control system.

$$\frac{1}{T_c} = f_c = \frac{1}{2}f_u = \frac{1}{2T_u} \quad (4.1)$$

This implementation has the advantage of ensuring consecutive and synchronous message transmission through the CAN buses, thereby eliminating situations where one LC competes with another for bus access.

To ensure the proper operation of the control system, the total execution time of the control and data transmission algorithms from the CC and LCs must be shorter than the control period T_u . In the simulations and experimental implementation of the system, T_u is selected to satisfy this constraint, considering the real execution times of the control algorithms and delays of the CAN transmission buses.

4.2. Phase-Shifted PWM implementation

The PS-PWM strategy is implemented in each LC by defining N triangular carriers $C_{i,y\chi}$, one for each submodule, with a phase shift of $\frac{2\pi}{N}$ between them. These carriers are utilized to generate the switching signals for the N submodules within each cluster by comparing each one with their respective calculated modulation signal. Synchronization between the controllers is achieved by designating one of these carriers as the main carrier, which serves as the reference for calculating the corresponding phase shifts of the other carriers during the synchronization algorithm. In this implementation, $C_{1,y\chi}$ is defined as the main carrier. Furthermore, the phase shift of the carriers between the upper and lower clusters of each phase is set to zero to simplify the implementation of the system. While this phase shift can be adjusted to minimize the harmonic content in the MMC output voltage, this approach does not limit the functionality of the proposed control strategies within the distributed system.

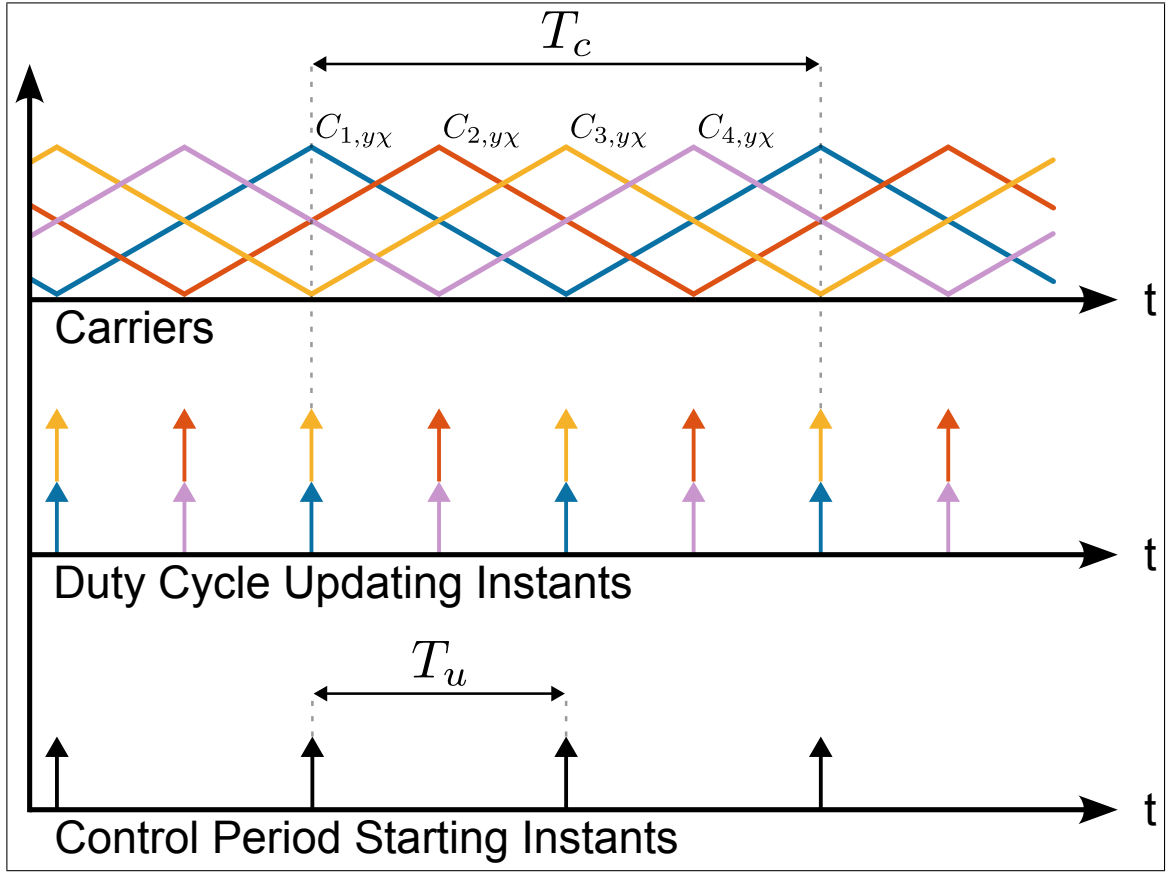


Figure 4.2. LC carrier configuration using a PS-PWM strategy for a cluster with four submodules.

Fig. 4.2 shows the PS-PWM configuration for a single LC in the case where each cluster contains four submodules ($N = 4$). The computed duty cycles are updated in each peak and valley of the corresponding carrier, while the starting instants of the control periods are determined by the peaks and valleys of the main carrier.

4.3. CAN message structure

Given the limitations on the size of the messages transmitted through the CAN buses, it is important to define a structure for the variables and data that must be sent in each control period. The CAN protocol used in the implementation of the proposed distributed control is compliant with the ISO11898-1 (CAN 2.0B) specification. Among the most

important features of this specification are a data transmission rate of up to 1 Mbps and up to 8 bytes (64 bits) of data per message.

Considering the maximum size of a CAN message, Fig. 4.3a shows the allocated size for each of the variables transmitted through the CAN_{CC} bus. Most of these variables are allocated a size of 10 bits, except the direct and quadrature components from the CCSC, which are assigned 8 bits each. Additionally, as explained in section 3.5, since the LCs require some of the measurements of the cluster currents $i_{y\chi}$ for the calculation of the balancing signals, the CC transmits one of the six currents in each control period. This means that the CC rotates which cluster current measurement is sent in each control period, and each LC updates only their required current measurements from the broadcast messages transmitted through the CAN_{CC} bus. Furthermore, one byte of each message is reserved for synchronization variables and operation commands of the system.

Similar to the messages in the CAN_{CC} bus, the variables transmitted in the CAN_{cons} bus have a size of 10 bits, which in this implementation corresponds to the calculated cluster average voltage $\bar{v}_{C,y\chi}$. In this case, one byte of each message is also reserved for operational commands and synchronization variables as shown in Fig. 4.3b.

4.4. Carrier synchronization

The carrier synchronization algorithm seeks to adjust the phase of the main carriers of the CC and LCs to compensate the deviations in the micro-controller clocks due to their normal operation. The main characteristic of the proposed algorithm is that it does not require an additional signal or channel for the synchronization. Instead, it utilizes the messages sent through the CAN buses to obtain the approximate value to which each micro-controller must set its main carrier at the end of each control period.

This implementation aims to synchronize the carriers of the LCs with the main carrier of the CC by using the messages sent by the CC in each control period. To determine the value to which the main carrier of one particular LC should be set, two execution

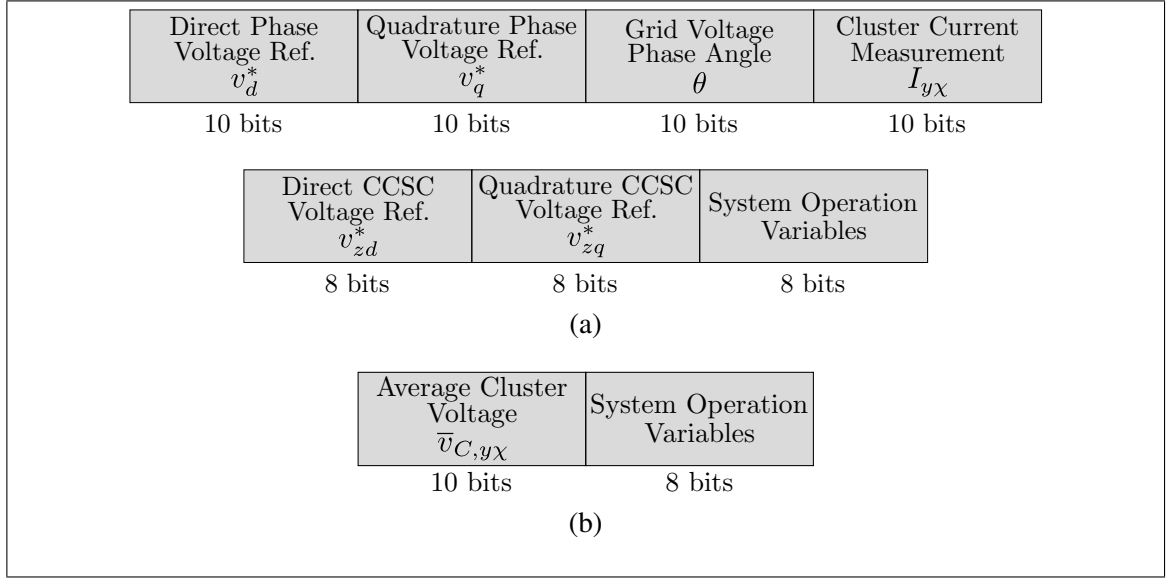


Figure 4.3. Data structure for CAN messages. (a) Structure for messages in CAN_{CC} bus. (b) Structure for messages in CAN_{cons} bus.

times must be determined: the execution time of the control algorithms and transmission delay of each message by the CC, defined as t_{com} , and the execution time of the reception, control and synchronization algorithms of the LC, defined as t_{exec} , as shown in Fig. 4.1. If the value of these times is known, it is possible to determine the elapsed time since a peak or valley of the main carrier of the CC and, therefore, the value to which the main carriers of the LCs should be set.

The time t_{com} is estimated with a constant average value, since the processing times of the CC and the message transmission through the CAN bus do not vary significantly from one period to another, given that the sending speed and the size of the messages are determined and constant values. This avoids having to measure these times and transmit them as part of the CAN bus control message to the LCs.

The time t_{exec} can vary from one period to another, primarily because the reception and control times depend on whether a particular LC needs to transmit via the consensus CAN bus. In this case, each LC is capable of precisely measuring the time between the

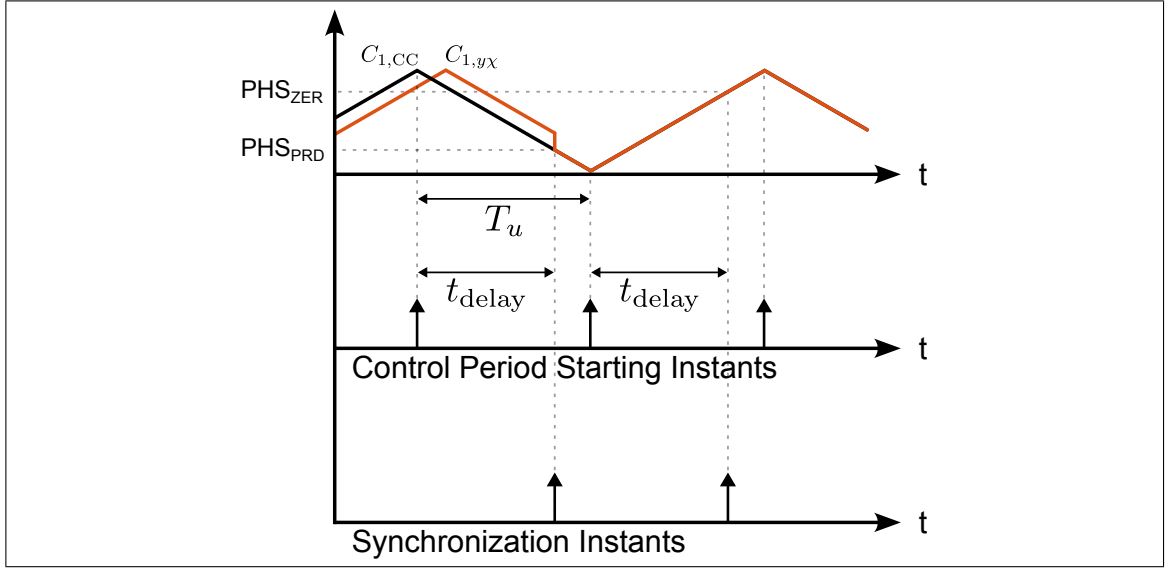


Figure 4.4. Carrier synchronization strategy.

reception of the CAN message from the CC and the instant in which it is necessary to perform the synchronization. Therefore t_{exec} can be measured directly by each LC.

Considering t_{com} and t_{exec} , the total delay from the start of the control period to the carrier synchronization instant can be determined by the sum of both times, as shown in (4.2).

$$t_{delay} = t_{com} + t_{exec} \quad (4.2)$$

Fig. 4.4 shows the operation of the synchronization algorithm. An additional consideration for the synchronization algorithm is, since the main carriers are defined as symmetrical triangular waves with an up-down count, it is necessary to know if the message sent from the CC was transmitted during a peak or a valley of the carrier. This is communicated to the LCs through the same message, using the system operation variables reserved bits shown in Fig. 4.3a. With this information, each LC sets their main carrier $C_{1,yX}$ to two possible values for the synchronization: PHS_{PRD} if the message was sent during a peak of the CC's main carrier $C_{1,CC}$, or to PHS_{ZER} if it was sent during a valley of the carrier.

4.5. Hardware implementation of CC and LC boards

After assigning the protocols and control tasks required for the operation of the converter at a functional level, it is necessary to describe the hardware utilized in the experimental setup of the proposed distributed control. The following sections analyze the main circuits implemented to utilize the peripherals of the CC and LC micro-controllers, generating the interface between the controllers and the MMC.

4.5.1. Micro-controller and controller board

The Micro-Controller Unit (MCU) utilized by the CC and the LCs corresponds to the C2000 TMS320F28379D, which is integrated as part of the LAUNCHXL-F28379D development board. The MCUs are responsible for executing the computing and communication tasks described in the previous sections, utilizing the respective peripherals included in the development board.

The integration between the MCU development board and the hardware equipment of the converter is accomplished through a dedicated interface controller board designed for this purpose. This board allows the CC and LCs to receive the respective voltage and current measurements from the MMC, which are used in the proposed control schemes. Additionally, a second circuit board is utilized to redirect the corresponding measurement signals from the voltage and current sensors of the MMC to the CC and LCs. These boards are shown in appendix C. Furthermore, each LC computes the switching signals for the submodules within its respective cluster, which are transmitted through fiber optic channels to the respective gate driver circuits. Fig. 4.5 shows the connection between the MCU development board and the interface controller board.

4.5.2. Analog-to-Digital Converter circuit

The MMC laboratory prototype employed in the experimental tests is equipped with voltage and current sensors to measure the voltage of the capacitors of each submodule,

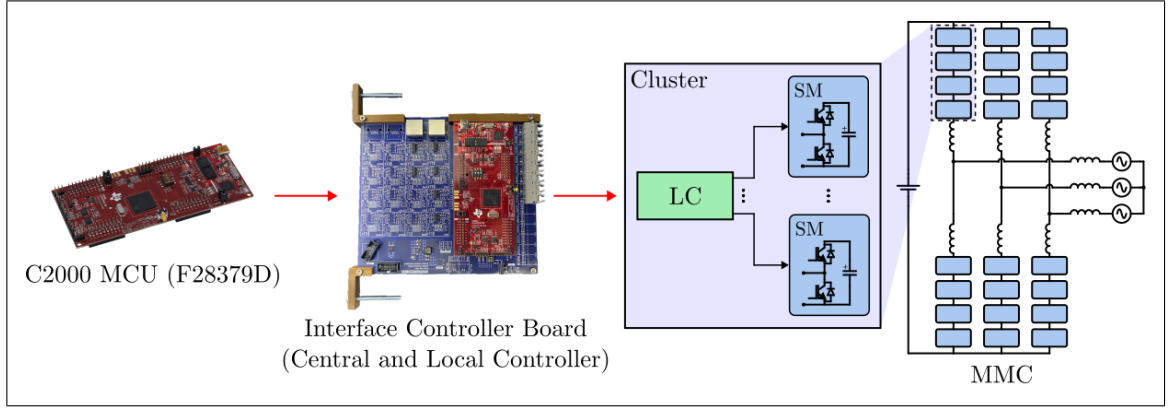


Figure 4.5. CC and LC interface controller board.

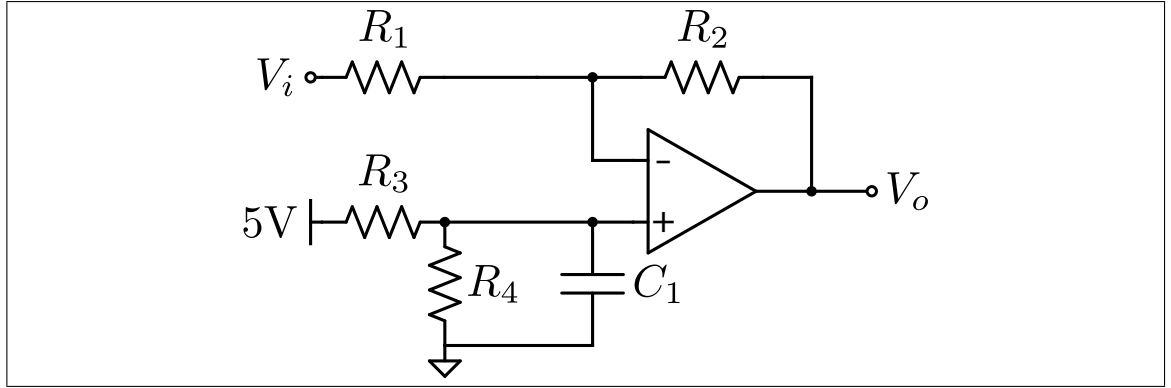


Figure 4.6. ADC circuit for signal conditioning.

and the cluster currents of the converter respectively. The signals from these sensors are transmitted to the respective CC and LCs boards. However, to enable the micro-controller to measure them accurately, it is necessary to perform the corresponding signal conditioning.

The converter uses “HV25” voltage sensors and “HAX25” current sensors, both with an output current range of $[-25\text{mA}, 25\text{mA}]$. These current measurements are converted into voltage signals with a range of $[-1.5\text{V}, 1.5\text{V}]$ by using 60Ω resistors on each of the CC and LC boards, while the voltage range allowed by the ADC peripherals of the micro-controller is $[0\text{V}, 3\text{V}]$. Therefore, “TLV9064IDR” Operational Amplifiers (OPAMPs) are utilized in a differential configuration to adjust the signals offsets, as shown in Fig. 4.6.

To generate a signal with a voltage range of $[0V, 3V]$ from the measured signals, an offset of $1.5V$ must be generated. From the OPAMP configuration circuit, (4.3) shows the relationship between the input voltage V_i , the output voltage V_o and the voltage at the non-inverting pin V_+ .

$$V_o = \frac{R_2}{R_1} (V_+ - V_i) + V_+ \quad (4.3)$$

Setting $R_1 = R_2 = 10k\Omega$, for V_o to have the desired voltage range, a voltage of $0.75V$ needs to be generated on the non-inverting pin. This is achieved by determining R_3 and R_4 from the respective voltage divider, as shown in (4.4).

$$5 \cdot \frac{R_4}{R_3 + R_4} = 0.75 \quad (4.4)$$

For this implementation $R_3 = 68k\Omega$ and $R_4 = 12k\Omega$ are utilized, so the final relationship between the input and output voltage is specified in (4.5).

$$V_o = 1.5 - V_i \quad (4.5)$$

This signal has a voltage range of $[0V, 3V]$ and can be used directly as the input of the ADC peripheral of the micro-controller, considering the signal inversion due to the OPAMP circuit.

4.5.3. Controller Area Network circuit

The connection of the controllers to the CAN buses is implemented as the example shown in Fig. 4.7. Each CAN bus consists of two signal lines, CANH and CANL, where the data is transmitted in a differential manner. The connection between the bus and the controller is made through a “SN65HVD232” transceiver device, which adapts the differential signals transmitted on the bus to the single-ended voltages of the micro-controller, working as an interface between the two. Additionally, both buses require 120Ω termination resistors at the ends of the lines.

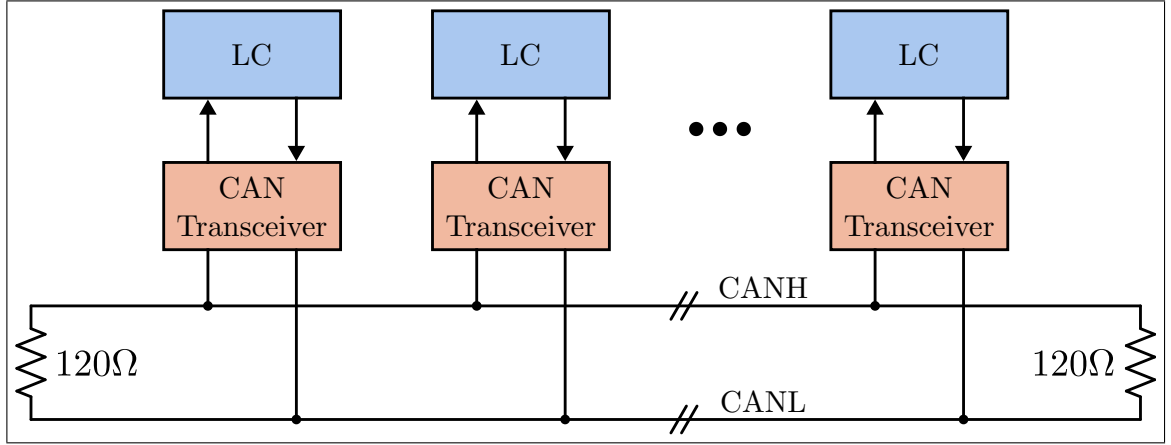


Figure 4.7. Connection of controllers to the CAN bus.

It should be noted that the CAN_{CC} bus connects the CC and the six LCs, since it is the designated communication channel between both types of controllers. Conversely, the consensus bus CAN_{cons} only connects the six LCs, as it is unnecessary for the CC to receive the consensus variables to perform the converter operation.

4.6. Conclusion

In this chapter, the assigned control tasks to the CC and LCs are presented. The temporal diagram of the system is analyzed, defining the order in which these tasks must be performed to implement the control scheme. System synchronization is achieved by assigning main carriers to the CC and the LCs, which define the start of each control period. The switching signals are obtained through a PS-PWM scheme, generating carriers for each of the submodules within the respective cluster and applying the according phase-shift relative to the main carrier.

The message structure utilized for the CAN messages is presented, defining the bit size utilized by the variables transmitted through the CAN_{CC} and the CAN_{cons} buses. Due to the limited data capacity per message in the CAN protocol utilized in this implementation, only one of the measured cluster currents is sent in each control period.

The carrier synchronization algorithm is presented, which adjusts the phase of the main carrier of each LC to align them to the main carrier of the CC. This implementation allows carriers to be synchronized utilizing the messages transmitted by the CC instead of using an additional signal. This is achieved by estimating the average duration of control calculation and transmission of the CAN messages.

Finally, the implementation details of the hardware utilized in the CC and LCs interface boards are presented. The circuits utilized to condition measurement signals for the ADCs and the connection of the CC and LC boards to the CAN buses are described, specifying the components employed for the implementation of the proposed distributed control.

5. SIMULATIONS AND EXPERIMENTAL RESULTS

In this chapter, the proposed distributed control scheme along with the consensus controller for the inter-cluster energy balance of the converter are validated through simulations and experimental tests in an MMC laboratory prototype. Initially, computational simulations are conducted to verify the operation of the system utilizing different communication structures between the LCs. The purpose of this is to evaluate the performance of the consensus controller under different communication graphs. It should be noted that the simulation of the different communication structures is conducted to demonstrate the performance of the consensus algorithm, considering that physically, the six LCs are connected to the CAN bus at all times.

The communication structures are compared based on the simulation results, and one is then selected and implemented as part of the control scheme for the MMC laboratory prototype. This implementation is utilized to validate the operation of the consensus controller in real hardware. Table 5.1 displays the system parameters utilized for the simulations, which are derived from the MMC prototype.

The sampling frequency f_u defines a control period of $T_u = \frac{1}{f_u} = 160\mu s$. This period is selected considering the total execution time of the control algorithms in the controllers and the delay in data transmission through the CAN buses, as explained in section 4.1.

Table 5.1. System parameters.

Description	Parameter	Value
DC Grid Voltage	V_{dc}	192V
AC Grid Voltage	V_g	70V _{$f-f$}
Cluster Inductance	L_s	5mH
Output Inductance	L_o	1mH
SMs per Cluster	N	4
SM Nominal Voltage	V_{SM}	48V
SM Capacitance	C_{SM}	987 μ F
Sampling Frequency	f_u	6.250kHz
Switching Frequency	f_c	3.125kHz

5.1. Simulation of communication structures

For the simulation of the system, three graphs are defined that represent different communication structures between the LCs, which are shown in Fig. 5.1. Each node within the communication graphs represents one of the six LCs located at cluster level of the converter, while the links indicate that there is an exchange of consensus variables between the corresponding LCs. This modifies the calculation of the proposed consensus algorithm utilized for the horizontal energy balancing control, as shown in equation (3.21). Furthermore, each graph includes an additional node representing the voltage reference for the cluster average voltages, which is set at the nominal voltage value of the capacitors ($V_{SM} = 48V$).

To illustrate the differences in the calculation of the consensus algorithm resulting from each of the communication graphs, equations (5.1), (5.2) and (5.3) represent the computations for the horizontal energy balancing signal U_{DC} in the upper cluster from phase a (Ua cluster) for each of the proposed structures. It can be observed that the algorithm in each case only utilizes average voltage values of clusters which are neighbours of the Ua cluster in the corresponding equivalent graph.

$$U_{DC,Ua}^{(1)} = -K_{DC} (3\bar{v}_{C,a} - \bar{v}_{C,b} - \bar{v}_{C,c} - \bar{v}_{C,ref}) \quad (5.1)$$

$$U_{DC,Ua}^{(2)} = -K_{DC} (\bar{v}_{C,a} - \bar{v}_{C,ref}) \quad (5.2)$$

$$U_{DC,Ua}^{(3)} = -K_{DC} (\bar{v}_{C,a} - \bar{v}_{C,b}) \quad (5.3)$$

To validate the operation of the inter-cluster energy control scheme, an imbalance in the average voltage of each phase is simulated. Initially, the system is set to an unbalanced start point in which the average voltage of each cluster is different from its nominal operating value. Table 5.2 shows the values at which the voltage of the capacitors of each cluster are established. Subsequently, the energy balancing control scheme is enabled to equalize the capacitor voltages towards their nominal values. This test is executed while the simulated converter is in inverter operation, delivering power to the grid through its AC port at

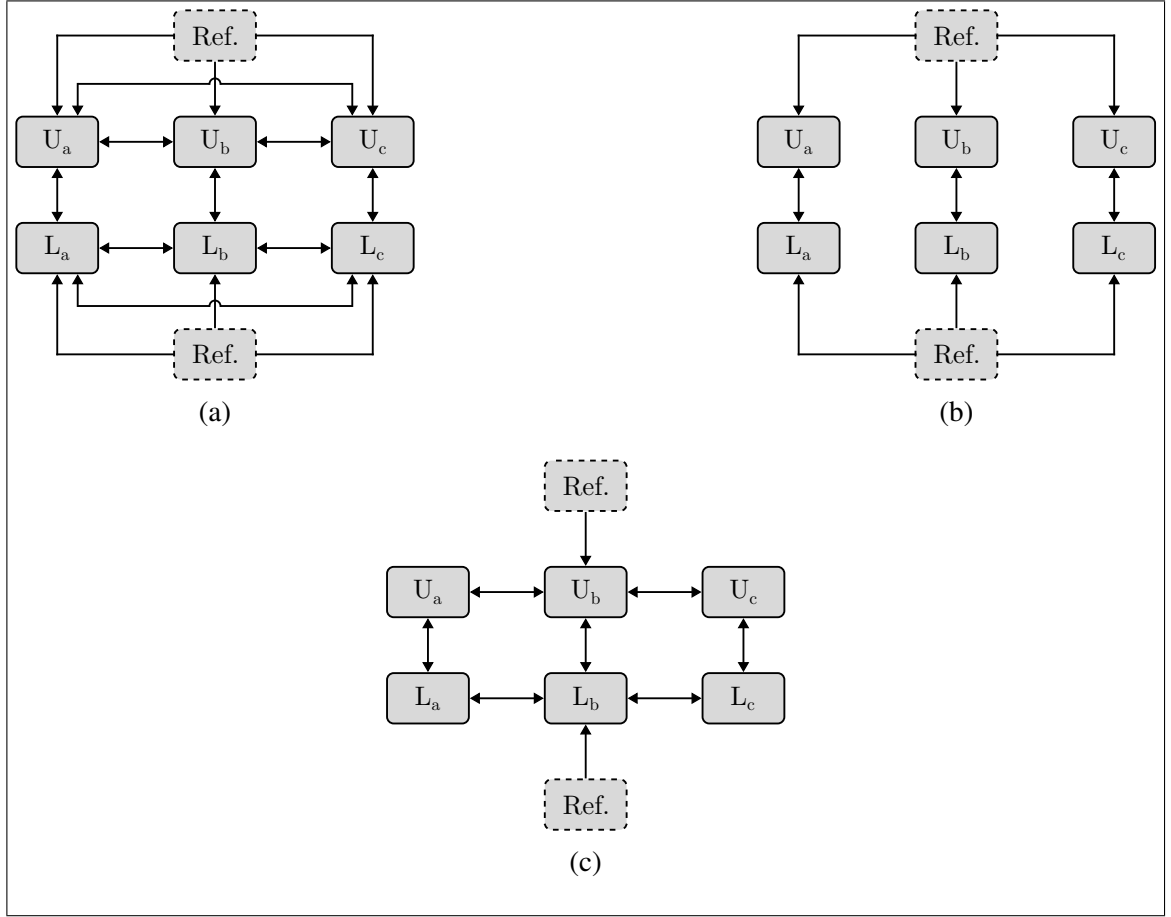
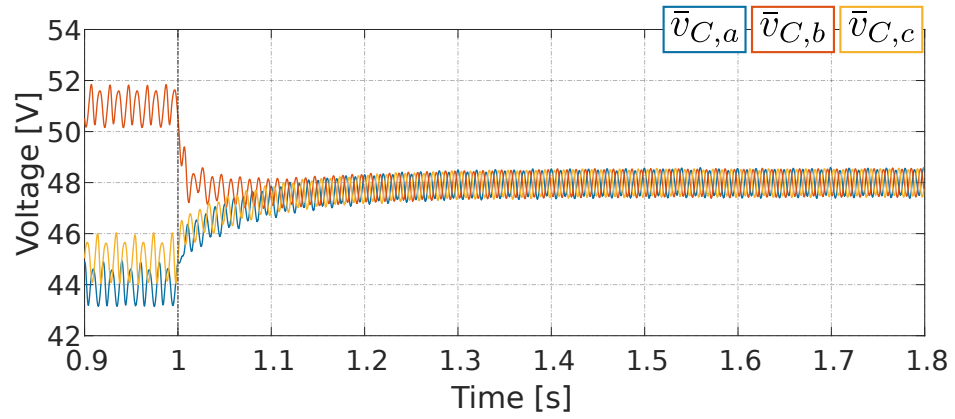


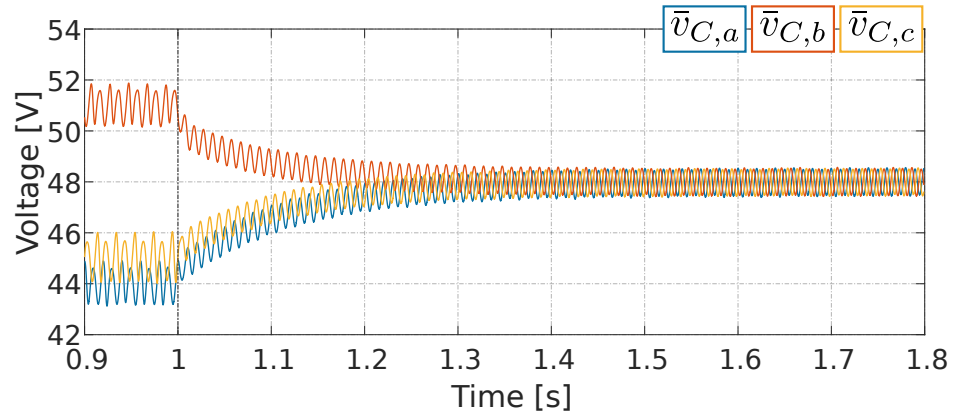
Figure 5.1. Simulated communication structures. (a) Structure 1. (b) Structure 2. (c) Structure 3.

unity power factor. It should be noted that these tests are conducted with lower controller gains than those employed in the experimental tests. This is done to more effectively illustrate the effect of the communication structures on the average voltage trajectories and their respective settling times.

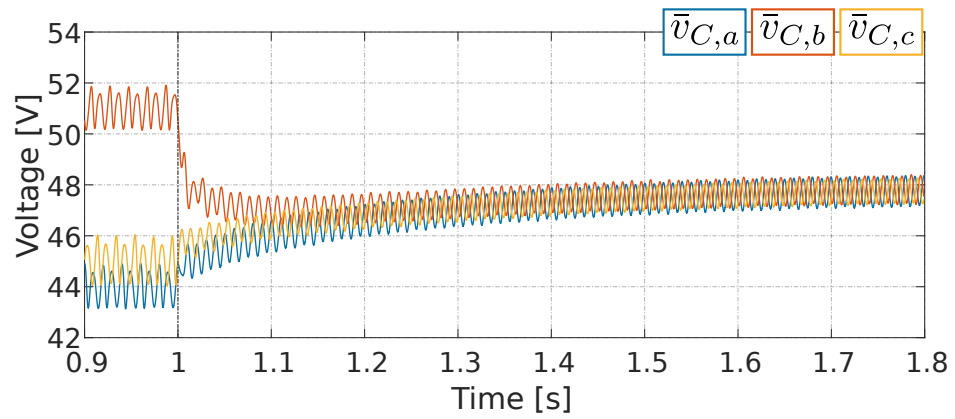
Fig. 5.2 presents the results of the simulations for the different communication structures, showing the trajectories of the phase average voltages, which are calculated from voltage measurements of the respective capacitors. It can be observed that utilizing each of the proposed communication structures, it is possible to balance the phase average voltages of the capacitors at their nominal operating values, bringing the system from the unbalanced start point to a balanced one.



(a)



(b)



(c)

Figure 5.2. Phase average voltages from simulation of communication structures. (a) Structure 1. (b) Structure 2. (c) Structure 3.

Table 5.2. Unbalanced start point for the voltages of the capacitors within each MMC cluster.

MMC Cluster	Initial Capacitor Voltage
Ua	46V
La	42V
Ub	53V
Lb	49V
Uc	47V
Lc	43V

It can also be noted that the convergence speed of the phase average voltages varies depending on the communication structure. To determine the convergence speed of each signal, the time required for the average voltages to enter a band of 2% of the nominal voltage value (48V) is identified. Table 5.3 summarizes these results, where structure 1 has the lowest convergence time and structure 3 has the highest one, when the same value for the proportional gain K_{DC} is utilized for the consensus controller. These results can also be seen graphically in the trajectories of the curves. This is due to the effect that each communication structure has on the magnitude of the horizontal energy balancing signal U_{DC} , which is calculated from the proposed consensus algorithm.

Different communication structures also affect the trajectories of the phase average voltages. For example, it can be seen how in structure 2, the voltage trajectories converge directly to the nominal voltage reference of 48V. This is due to the communication structure layout, where the respective LCs of each phase only compare their calculated phase average voltage with the defined constant reference to determine the horizontal energy balancing signal.

In the simulation results of structure 3, the voltage trajectories tend to equalize with each other at the same time that they slowly converge to the nominal value of 48V. This is also due to the arrangement of the communication structure, where only the LCs of phase b directly receive the constant voltage reference, while the LCs of phases a and c only compare their calculated phase average voltage values with those of phase b.

Table 5.3. Settling times of phase average voltages for communication structures simulations.

	Structure 1	Structure 2	Structure 3
Settling time	165ms	246ms	665ms

Based on these results, communication structure 1 is implemented in the distributed control scheme for the MMC laboratory prototype. This indicates that each LC utilizes the cluster average voltage measurements from all the other LCs for the calculation of the consensus algorithm.

5.2. Experimental results

The main objective of the experimental tests is to corroborate the performance of the proposed distributed control scheme during the operation of the MMC laboratory prototype. Furthermore, the correct operation of the converter utilizing the energy balancing control must be validated, which is achieved by evaluating its inverter and rectifier operations. The experimental hardware and the performed experiments are described in the following sections.

Note: The experiments analyzed in the following sections utilize the PS-PWM modulation as described in section 3. In this implementation, the corresponding modulating signals are normalized based on the nominal voltage of each capacitor within the submodules, which is constant and equal to each other. Appendix D presents the results of these experiments when the modulating signals are normalized according to the measured voltage of each capacitor instead. Although the conclusions of the analysis remain similar, there are differences in the harmonic content of the DC port current and output currents, which could be improved.

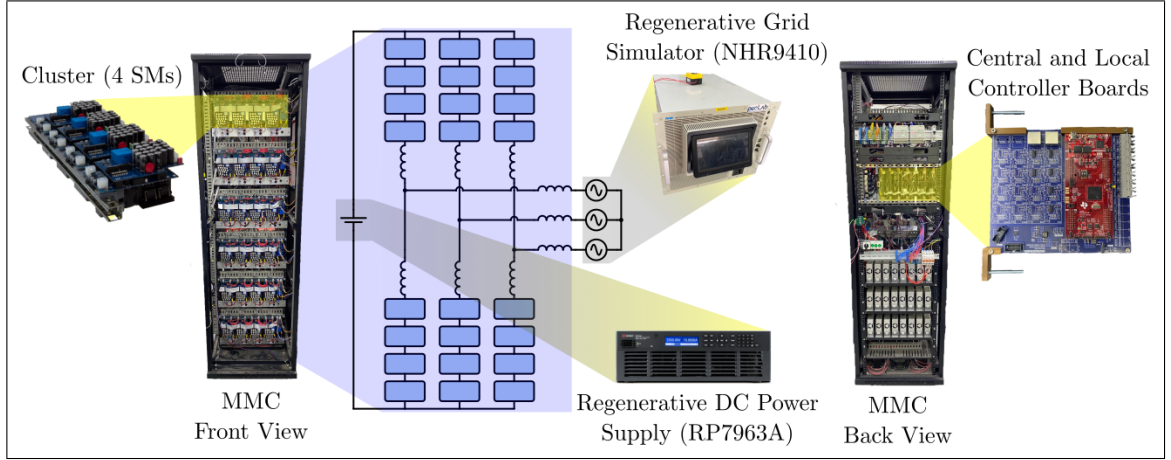


Figure 5.3. Experimental setup of the MMC laboratory prototype.

5.2.1. Experimental setup

The hardware setup employed for the experimental tests is shown in Fig. 5.3, where the equipment and main components of the MMC laboratory prototype are depicted.

5.2.2. Validation of the voltage balancing control

To validate the operation of the inter-cluster energy balance, a similar procedure to the simulations is conducted. First, the system is brought to the same unbalanced operating point utilized in the simulations, as shown in table 5.2, before enabling the energy balancing control to equalize the capacitor voltages in the MMC. This experiment is performed for two different proportional gains of the consensus controller K_{DC} , in order to test the performance of the control scheme. Furthermore, to better show the effects of the energy balancing control on the circulating currents, the use of the Circulating Current Suppressing Control (CCSC) is omitted when performing this experiment.

The results are presented in Fig. 5.4, where the trajectories of the phase average voltages are shown for the two proposed controller gain scenarios. It can be observed that in both cases, the control scheme balances the capacitor voltages to their nominal value. Furthermore, the convergence speed of the voltages to the reference value varies depending

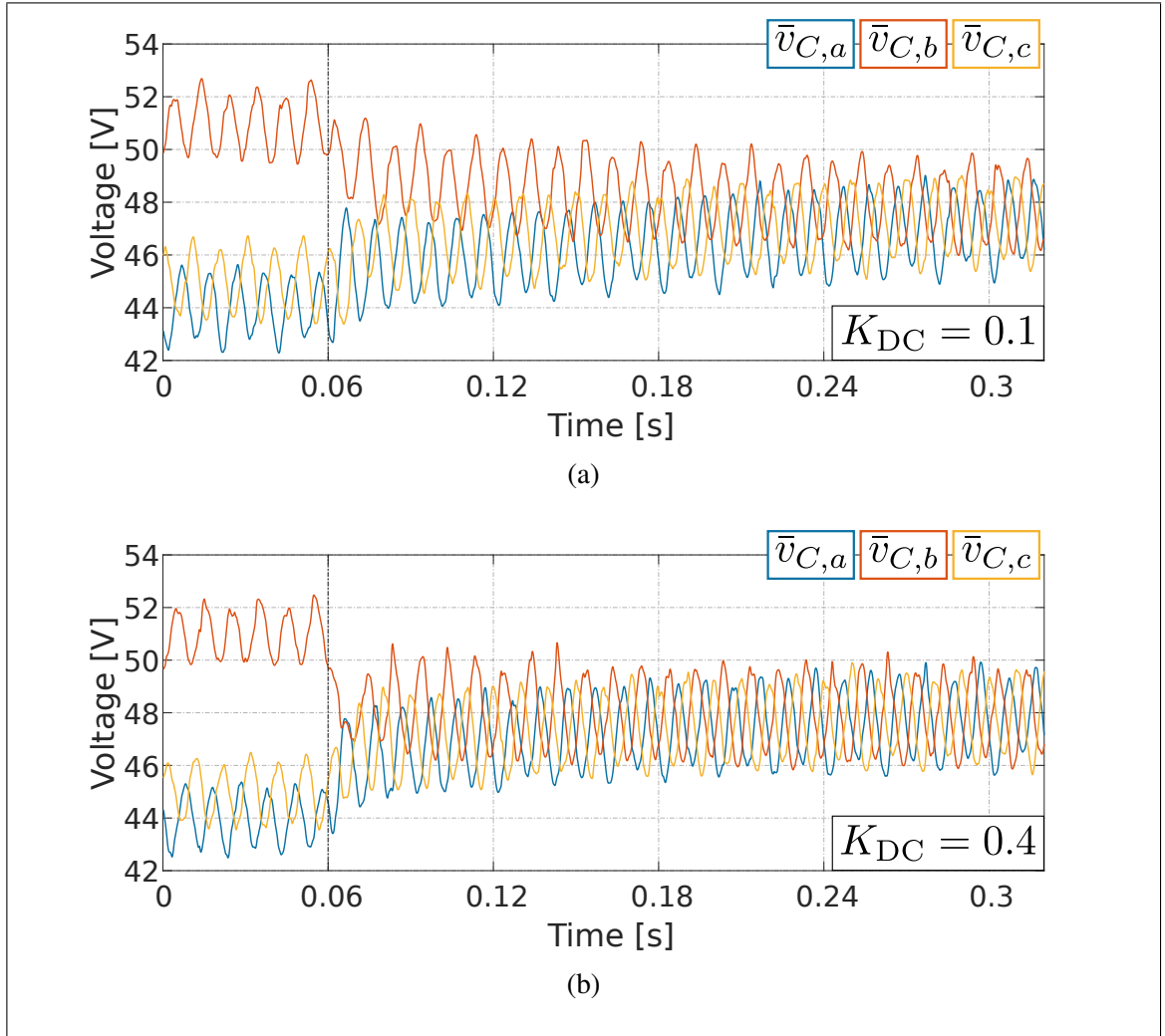


Figure 5.4. Phase average voltages for different values of the consensus controller gain. (a) $K_{DC} = 0.1$ (b) $K_{DC} = 0.4$

on the controller gain, having a higher speed if the proportional gain is higher, as seen in the trajectories of the two cases.

To show how other variables of the converter behave when performing the energy balance, Fig. 5.5 shows the results of the previous experiment, along with the output currents and circulating currents for both cases of the consensus controller gain. It can be observed that the output currents of the converter are initially unbalanced as a result of the voltages of the capacitors not being at their nominal value. However, the currents balance

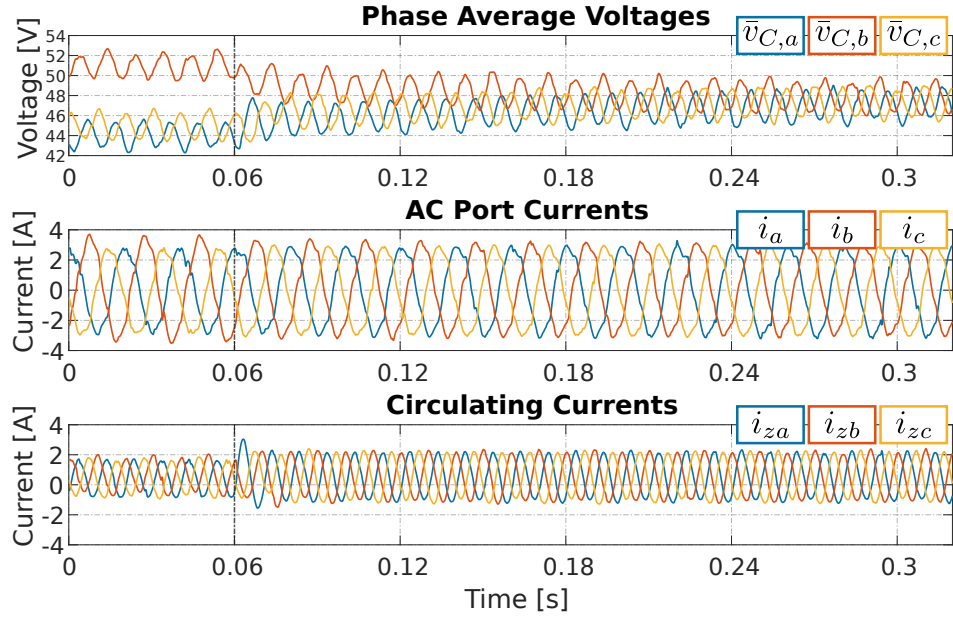
as the voltages approach their reference once the energy balancing control is enabled. This also verifies that performing the energy balance does not greatly affect the waveform of the output currents. This is because the control only provides references for the circulating currents, which can be controlled independently from the output currents.

Furthermore, it can be observed how the circulating currents increase their magnitude when the energy balancing scheme is activated, having a greater amplitude for the case in which the gain of the consensus controller is higher.

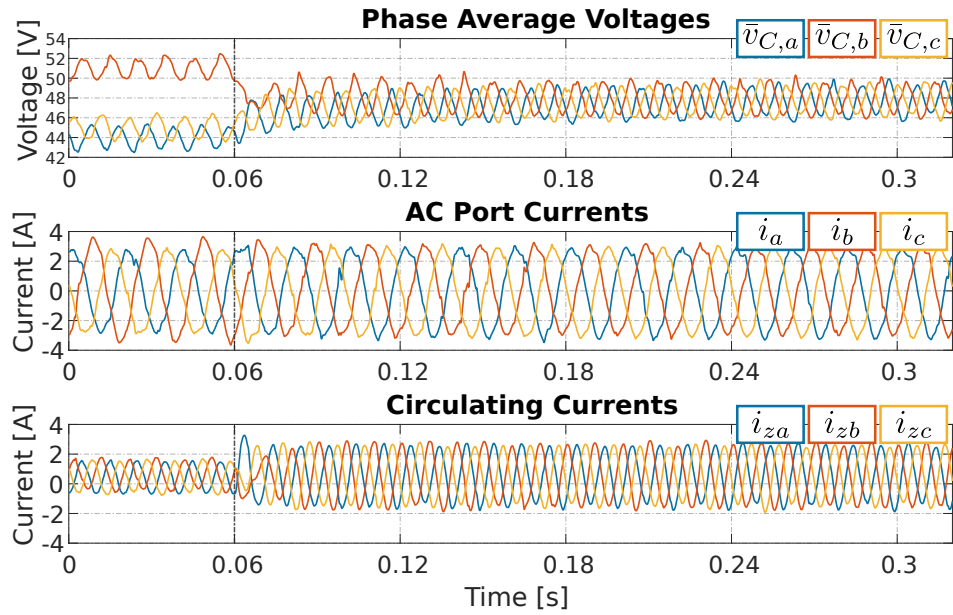
5.2.3. Effect of the circulating current suppressing controller

Based on the results shown in Fig. 5.5, the harmonic content of the circulating currents is analyzed. Fig. 5.6 shows the harmonic components of the circulating currents of each phase once the voltage balance has been reached in the converter capacitors, specifically for the case in which the controller gain is $K_{DC} = 0.4$. It can be observed how the circulating currents have an important second harmonic component of 100Hz. As discussed in section 2.1, if the second harmonic component is not controlled, this results in the presence of a second harmonic component in the cluster currents as well. This increases the losses in the converter and increases the voltage ripple in the capacitors of the submodules.

To eliminate this second harmonic component, the Circulating Current Suppressing Controller is implemented, utilizing the voltage components calculated at the CC, as described in section 3.6. To demonstrate the operation of this controller, the unbalance of the capacitors is executed again in the MMC prototype with a consensus controller gain of $K_{DC} = 0.4$. However, in this case the CCSC is enabled and the voltage components are calculated in each control period. Fig. 5.7 shows the results of both experiments, one with the CCSC disabled and the other with it enabled, graphing the trajectories of the phase average voltages, the upper and lower cluster currents from phase a, and the circulating currents of each phase.



(a)



(b)

Figure 5.5. Experimental results for different values of the consensus algorithm gain. (a) $K_{DC} = 0.1$ (b) $K_{DC} = 0.4$

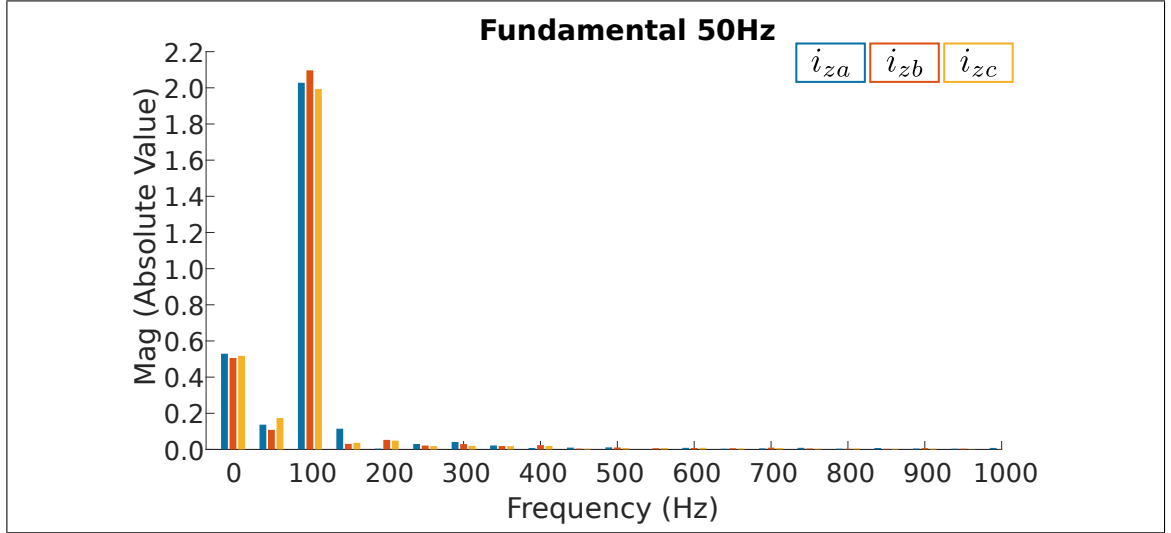


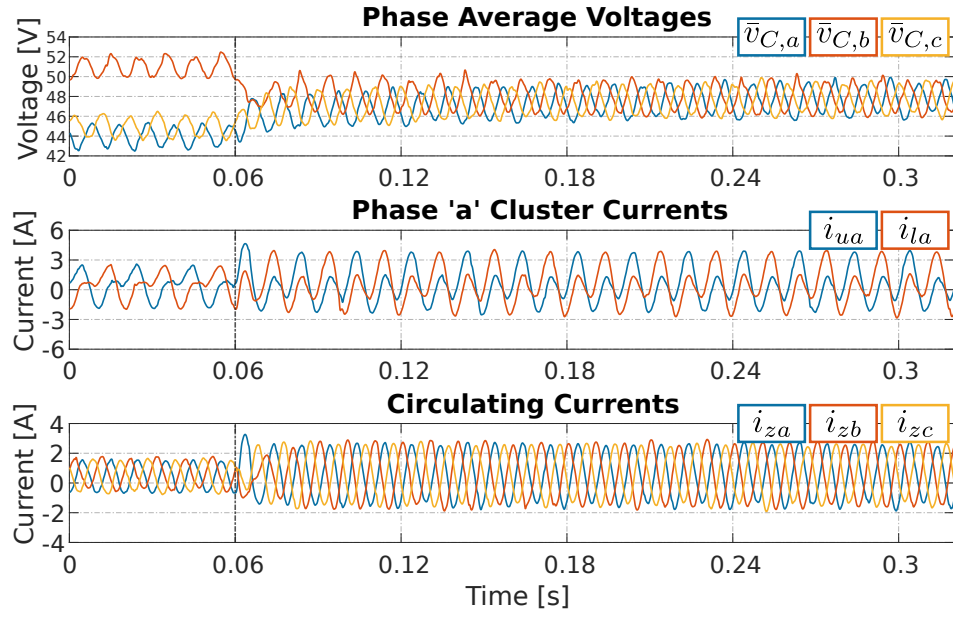
Figure 5.6. Harmonic components of circulating currents without CCSC and $K_{DC} = 0.4$.

It can be observed that both cases manage to balance the average voltages of the capacitors, but in the case in which the CCSC is not enabled, both the cluster currents and the circulating currents have a considerable second harmonic component. This is also reflected in the ripple of the phase average voltages, where a lower ripple can be observed when the CCSC is activated.

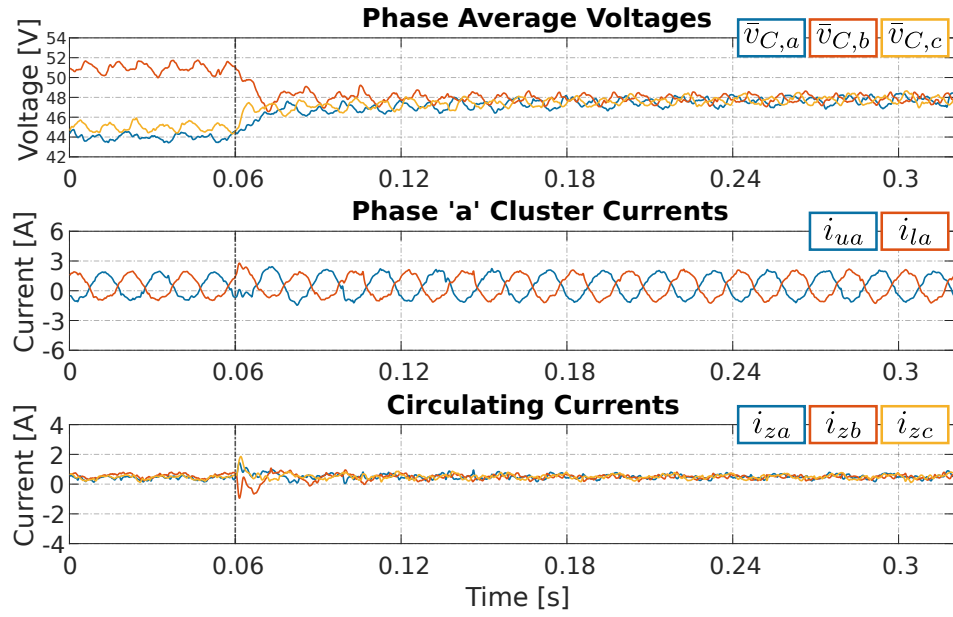
Furthermore, Fig. 5.8 shows the harmonic content of the circulating currents once the CCSC is activated. From these results, it can be observed that the second harmonic component is reduced from the circulating currents and consequently, the cluster currents as well. In this case, the circulating currents mainly possess a DC component due to the power balance of the converter, while the cluster currents have a DC and 50Hz component.

5.2.4. Operation as inverter

To validate the correct operation of the MMC utilizing the proposed distributed control scheme, the converter is tested in inverter operation, delivering power to the AC grid with unity power factor. In this experiment, a step reference change in the current delivered to



(a)



(b)

Figure 5.7. Experimental results for the CCSC implementation. (a) CCSC disabled (b) CCSC activated

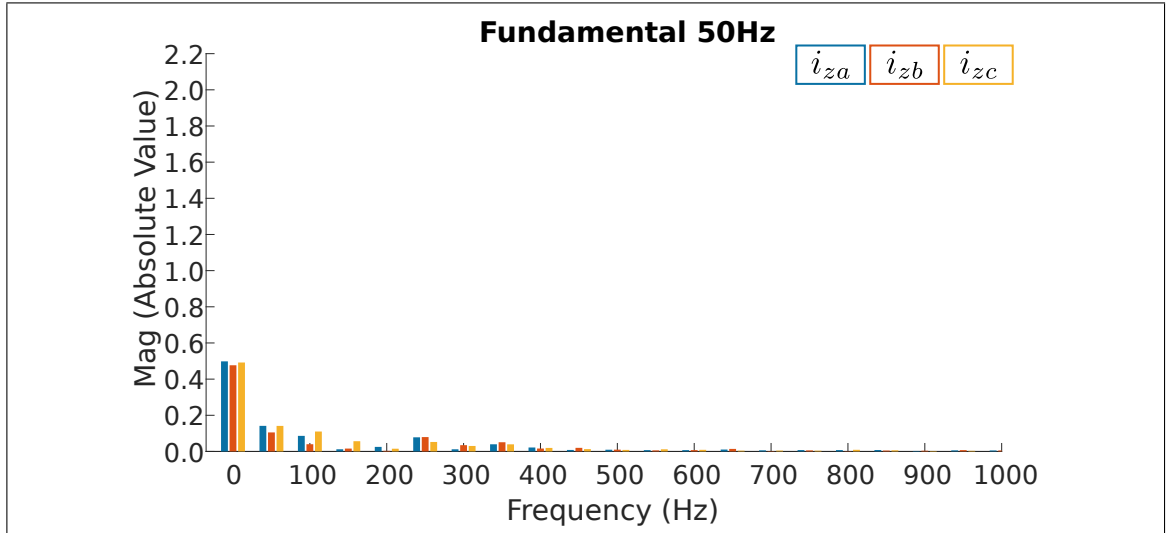


Figure 5.8. Harmonic components of circulating currents with CCSC activated $K_{DC} = 0.4$.

the AC port is applied to evaluate the voltage balance of the capacitors. Fig. 5.9 shows the experimental results of this test, where the AC grid voltages, the currents in the AC and DC ports of the converter, and the phase average voltages of the capacitors are illustrated.

From these results, it can be observed that the converter reaches the new output current reference in less than two cycles of fundamental frequency. The increase of the currents in the AC port also implies an increase of the input current in the DC port to balance the transferred power, which can be corroborated from these results. Furthermore, it can be observed how the phase average voltages of the capacitors decrease as the output currents increase, and then gradually converge again to their nominal value with an increased ripple value. This demonstrates that the energy balance control effectively maintains the phase average voltages at their nominal value when the MMC is in inverter operation, even with changes in the AC current reference.

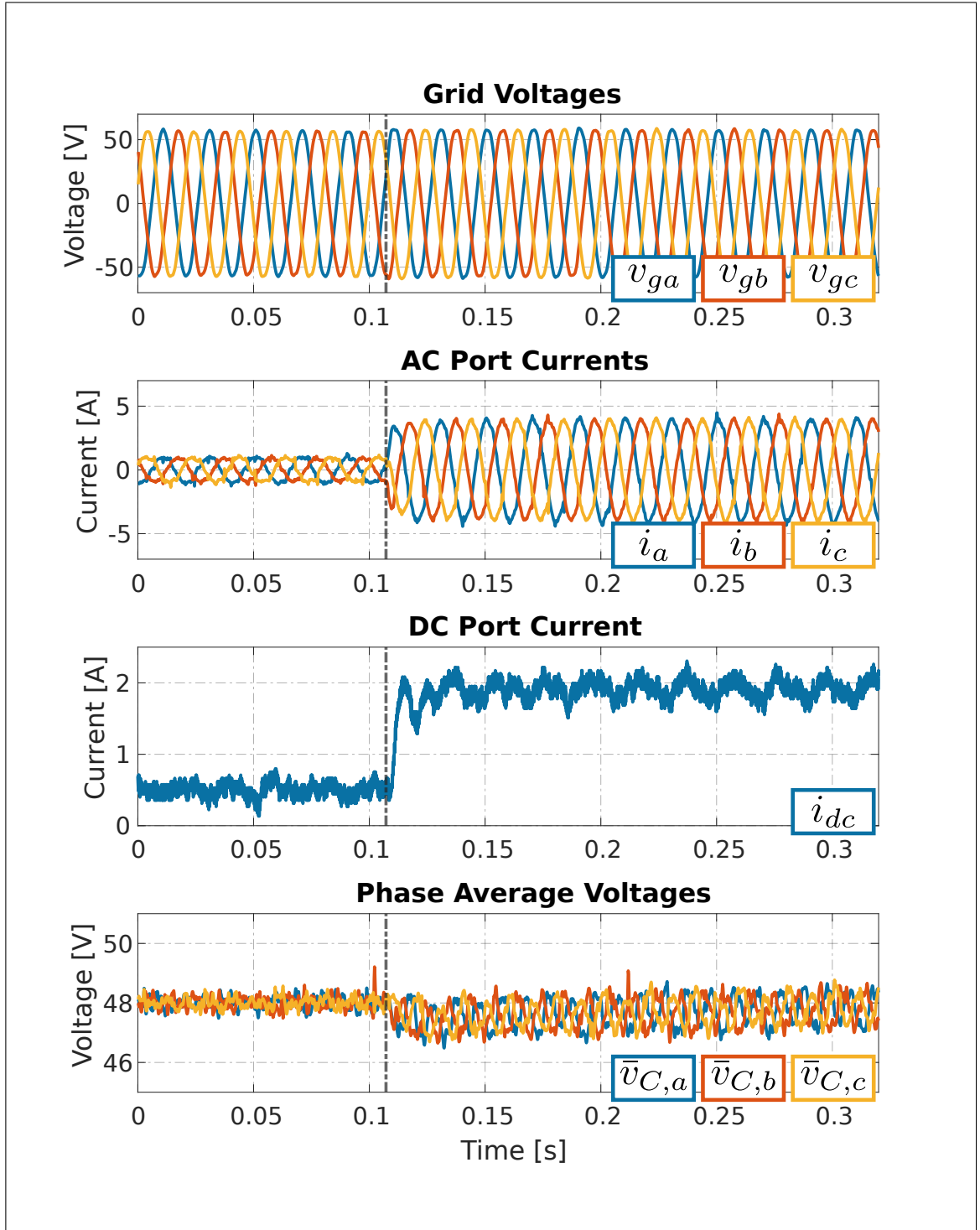


Figure 5.9. Experimental results for operation as inverter with AC current step from 1A to 4A.

5.2.5. Operation as rectifier

The performance of the converter is also evaluated in the case in which the MMC is in rectifier operation, delivering power from the AC grid to the DC port. In a similar way to the previous experiment, the performance of the voltage balancing controller and the overall system are evaluated by performing a step change in the reference current of the AC port, producing a corresponding change in the current of the DC port. Fig. 5.9 shows the experimental results, graphing the AC grid voltages, the currents in the AC and DC ports of the MMC, and the phase average voltages of the capacitors.

Similar to the results of the previous experiment, the AC port currents reach the new reference in less than two cycles of fundamental frequency. In this case, the AC network delivers power to the DC port of the converter, since the current in the DC port is negative. Furthermore, the phase average voltages increase as the current reference change occurs, and then return to their nominal value of 48V. From these results, it is demonstrated that the energy balance control successfully maintains the capacitor voltages at their nominal values when the MMC operates as a rectifier, even after changes in the reference currents.

5.3. Conclusion

This chapter analyzes the results of the conducted simulations and experiments to verify the operation of the proposed distributed control. First, the objective of the simulations is to test different communication structures between LCs, which affect the calculations of the consensus algorithm and consequently, the references for the circulating currents. By defining and testing 3 different communication structures, it is concluded that each one influences the convergence speed and the trajectory of the phase average voltages of the capacitors to their nominal value. The structure that communicates all the LCs between them provides the fastest convergence speed, so it is implemented in the MMC laboratory prototype.

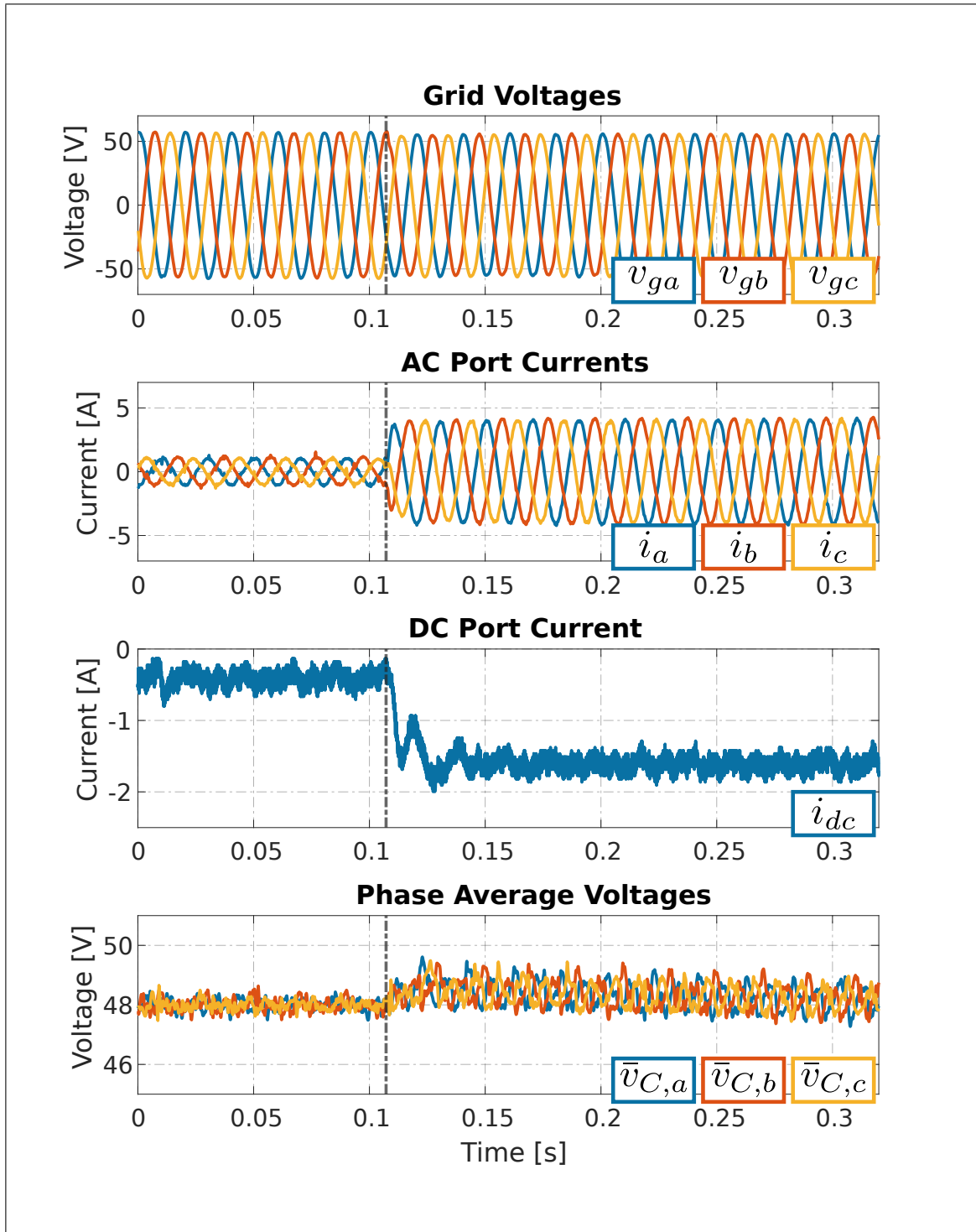


Figure 5.10. Experimental results for operation as rectifier with AC current step from 1A to 4A.

The results of the experimental tests are presented, which aim to validate the operation of the proposed distributed control in an MMC laboratory prototype. From these results, it is concluded that a variation of the proportional gain of the consensus controller K_{DC} modifies the convergence speed of the phase average voltages to the nominal voltage reference. In this case, a higher proportional gain increases the convergence speed of the average voltages.

The operation of the Circulating Current Suppressing Controller is validated, which reduces the second harmonic component of the circulating currents and cluster currents of the converter. The suppression of the second harmonic also reduces the ripple in the voltages of the submodules, which is verified through the experimental results in the MMC laboratory prototype.

Finally, it is concluded that the proposed distributed control scheme is capable of performing the energy balance during both inverter and rectifier operations of the MMC. The experimental results demonstrate that the voltages of the capacitors are maintained near their nominal values during current step changes at the DC and AC ports of the converter.

6. CONCLUSIONS

The MMC operates effectively under both inverter and rectifier conditions utilizing the proposed control scheme. By employing a distributed control strategy, the operation of the converter was managed using seven low-cost controllers, one CC and six LCs located at cluster level of the converter. This approach distributes the computational load among these controllers, as opposed to a centralized control scheme. The CAN protocol is utilized for the communication between the controllers, which is characterized by its low cost and simplicity of implementation. Furthermore, the proposed control strategy ensures the correct operation of the MMC even with the low data transmission speed of this protocol. Additionally, the implemented consensus algorithm manages the inter-cluster energy balance of the MMC through communication between the LCs, eliminating the need to transmit capacitor voltage measurements to the CC.

Based on the present literature and the state of the art, this work adopts a classification regarding the different distributed control schemes applied in MMCs, distinguishing between decentralized and cooperative schemes. Consensus-based distributed control schemes belong to the category of cooperative strategies, which operate based on the exchange of variables between agents or LCs for the calculation of the converter control signals.

The proposed distributed control strategy specifically utilizes one CC and six LCs implemented at cluster level of the MMC to control the submodules of each cluster. The CC is responsible for the control of specific internal and external variables of the converter, such as the output currents and the circulating currents suppressing control. Meanwhile, the LCs are responsible for calculating the necessary control signals to achieve the energy balance of the MMC, such as the inter-cluster and intra-cluster energy balance, in addition to the generation of the switching signals of their respective submodules. The energy balancing control of the MMC is achieved by regulating the circulating currents of the converter, task that is assigned to the LCs. This reduces the total computational load of the

CC compared to the centralized control scenario. Furthermore, the balancing algorithms are performed without transmitting capacitor voltages from the LCs to the CC.

Considering the proposed control strategies, the horizontal energy balance of the converter is interpreted as a consensus problem. For this, a mathematical model is introduced that represents a multi-agent system with double-integrator dynamics and control input given by a distributed PI controller. By developing the equations of the MMC and the proposed controller, it is concluded that this model can be represented by the introduced multi-agent system, analyzing the similarities between both systems. Furthermore, different communication structures between phases are analyzed, verifying how these impact the calculation of the consensus algorithm for the horizontal energy balance of the MMC.

Regarding the physical implementation of the system, the proposed distributed control scheme employs the CAN communication protocol for the data transmission between the controllers, which operates on a bus-type topology. While this protocol and communication topology are not preferred in the literature in the context of power converters, its characteristics are suitable for its implementation in the proposed control scheme. The distributed control strategy is compatible with the communication speed of the CAN protocol, while the bus topology allows consensus variables to be shared between all the LCs.

Implementing the distributed control scheme requires additional considerations to coordinate the control tasks between controllers. These tasks must be performed in a determined order in each control period to ensure the proper operation of the MMC. The proposed synchronization scheme enables the coordination of the executed tasks, utilizing the messages transmitted by the CC to adjust the carriers of the LCs. Furthermore, the message size limit due to the characteristics of the CAN protocol, does not restrict the operation of the converter, establishing a message structure compatible with the proposed control scheme.

The simulations and experiments validate the operation of the distributed control strategy for the energy balance of the MMC. The simulations verify that the different communication structures successfully regulate the voltages of the capacitors to the reference value imposed by the controller. The convergence speed and voltage trajectories differ based on the implemented scheme. The results indicate that the communication structure that communicates all LCs with each other achieves the fastest convergence speed when the same proportional gain of the consensus controller is utilized for the simulation of the communication schemes.

Experimental tests validate the energy balancing strategy in an MMC laboratory prototype, showing that increasing the gain in the consensus controller leads to a faster convergence speed to the voltage reference. These results also verify the operation of the Circulating Current Suppressing Controller, reducing the second harmonic component of the circulating currents while maintaining their DC components to ensure the energy balance of the capacitors and the power balance between the DC and AC ports of the MMC. Finally, the results validate the effectiveness of the proposed energy balancing control during inverter and rectifier operations of the MMC, maintaining the voltages of the capacitors at their nominal value despite step changes in the output current references.

Based on the obtained experimental results, the main hypothesis of this thesis is validated

H A consensus-based distributed control scheme can effectively achieve the inter-cluster energy balance in a three-phase Modular Multilevel Converter (MMC) by utilizing a control topology that integrates Local Controllers (LCs) at the cluster level of the converter.

For future work, the system stability for lower sampling periods could be improved by implementing a communication protocol that allows the transmission of all required control variables within a single control period. For this, one possibility is to utilize the

CAN-FD protocol, which has a similar connection structure to the CAN protocol implemented in this work, but offers a higher data transmission speed and a greater amount of data per message. Furthermore, the representation of the horizontal energy balance as a consensus problem could be improved by considering the full non-linear power equations in the analysis, which could be utilized to obtain an approximation of the convergence zone to the consensus.

REFERENCES

- Abu-Rub, H., Holtz, J., Rodriguez, J., & Baoming, G. (2010). Medium-voltage multilevel converters—state of the art, challenges, and requirements in industrial applications. *IEEE Transactions on Industrial Electronics*, 57(8), 2581-2596. doi: 10.1109/TIE.2010.2043039
- Andreasson, M., Dimarogonas, D. V., Sandberg, H., & Johansson, K. H. (2014). Distributed control of networked dynamical systems: Static feedback, integral action and consensus. *IEEE Transactions on Automatic Control*, 59(7), 1750-1764. doi: 10.1109/TAC.2014.2309281
- Burgos-Mellado, C., Gutierrez, J., Pineda, C., Donoso, F., Watson, A., Sumner, M., ... Mora, A. (2020). Distributed control strategy based on a consensus algorithm for the inter-cell and inter-cluster voltage balancing of a cascaded h-bridge based statcom. In *2020 IEEE 21st Workshop on Control and Modeling for Power Electronics (COMPEL)* (p. 1-8). doi: 10.1109/COMPEL49091.2020.9265758
- Burgos-Mellado, C., Pereda, J., Mora, A., Cardenas-Dobson, R., & Dragicevic, T. (2023). Distributed control for modular multilevel cascaded converters: Toward a fully modular topology. *IEEE Industrial Electronics Magazine*, 2-15. doi: 10.1109/MIE.2023.3299080
- Corrêa, T. P., Almeida, L., & Rodriguez, F. J. (2018). Communication aspects in the distributed control architecture of a modular multilevel converter. In *2018 IEEE International Conference on Industrial Technology (ICIT)* (p. 640-645). doi: 10.1109/ICIT.2018.8352253
- Cui, S., Kim, S., Jung, J.-J., & Sul, S.-K. (2014). A comprehensive cell capacitor energy control strategy of a modular multilevel converter (MMC) without a stiff dc bus voltage source. In *2014 IEEE Applied Power Electronics Conference and Exposition - APEC 2014* (p. 602-609). doi: 10.1109/APEC.2014.6803370

- Debnath, S., Qin, J., Bahrani, B., Saeedifard, M., & Barbosa, P. (2015). Operation, control, and applications of the modular multilevel converter: A review. *IEEE Transactions on Power Electronics*, 30(1), 37-53. doi: 10.1109/TPEL.2014.2309937
- Donoso, A. (2022). *Modulación y control distribuido basados en consenso para convertidores modulares multinivel en cascada con almacenamiento de energía* (Master's thesis, Pontificia Universidad Católica de Chile). Retrieved from <https://repositorio.uc.cl/handle/11534/66157>
- Du, S., Dekka, A., Wu, B., & Zargari, N. (2018). *Modular multilevel converters: Analysis, control, and applications*. Wiley.
- Dwivedi, S., Jain, S., Gupta, K., & Chaturvedi, P. (2018). *Modeling and control of power electronics converter system for power quality improvements*. Elsevier Science.
- Gonzalez, S., Verne, S., & Valla, M. (2013). *Multilevel converters for industrial applications*. Taylor & Francis.
- Hagiwara, M., Maeda, R., & Akagi, H. (2011). Control and analysis of the modular multilevel cascade converter based on double-star chopper-cells (mmcc-dscc). *IEEE Transactions on Power Electronics*, 26(6), 1649-1658. doi: 10.1109/TPEL.2010.2089065
- Isik, S., Burugula, V., Alharbi, M., Azidehak, A., & Bhattacharya, S. (2022). Implementation of a modular distributed fault-tolerant controller for mmc applications. *Energies*, 15(22). doi: 10.3390/en15228427
- Kadandani, N. B., Dahidah, M., & Ethni, S. (2021). Review of circulating current control methods in modular multilevel converter. *Bayero Journal of Engineering and Technology*.
- Mathe, L., Burlacu, P. D., & Teodorescu, R. (2017). Control of a modular multilevel converter with reduced internal data exchange. *IEEE Transactions on Industrial Informatics*, 13(1), 248-257. doi: 10.1109/TII.2016.2598494

Neira, S., Poblete, P., Pereda, J., & Nuñez, F. (2020). Consensus-based distributed control of a multilevel battery energy storage system. In *2020 IEEE 21st Workshop on Control and Modeling for Power Electronics (COMPEL)* (p. 1-7). doi: 10.1109/COMPEL49091.2020.9265850

Olfati-Saber, R., & Murray, R. (2004). Consensus problems in networks of agents with switching topology and time-delays. *IEEE Transactions on Automatic Control*, 49(9), 1520-1533. doi: 10.1109/TAC.2004.834113

Raju, M. N., Sreedevi, J., P Mandi, R., & Meera, K. (2019). Modular multilevel converters technology: a comprehensive study on its topologies, modelling, control and applications. *IET Power Electronics*, 12(2), 149-169. doi: <https://doi.org/10.1049/iet-pel.2018.5734>

Salvadores, T., Pereda, J., & Rojas, F. (2024). Power imbalance analysis of modular multilevel converter with distributed energy systems. *IEEE Open Journal of the Industrial Electronics Society*, 5, 109-121. doi: 10.1109/OJIES.2024.3361167

Santos, E., & da Silva, E. (2014). *Advanced power electronics converters: Pwm converters processing ac voltages*. doi: 10.1002/9781118886953

Song, S., & Liu, J. (2019). Interpreting the individual capacitor voltage regulation control of psc-pwm mmc via consensus theory. *IEEE Access*, 7, 66807-66820. doi: 10.1109/ACCESS.2019.2917320

Soomro, J., Akhter, F., Hussain, R., Ansari, J., & Munir, H. (2022). A detailed review of mmc circuit topologies and modelling issues. *International Transactions on Electrical Energy Systems*. doi: 10.1155/2022/8734010

Talon Louokdom, E., Gavin, S., Siemaszko, D., Biya-Motto, F., Essimbi Zobo, B., Marchesoni, M., & Carpita, M. (2018). Small-scale modular multilevel converter for multi-terminal dc networks applications: System control validation. *Energies*, 11(7). doi: 10.3390/en11071690

The, A., Bruening, C., & Dieckerhoff, S. (2015). Can-based distributed control of a mmc optimized for low number of submodules. In *2015 IEEE Energy Conversion Congress and Exposition (ECCE)* (p. 1590-1594). doi: 10.1109/ECCE.2015.7309884

Thitichaiworakorn, N., Hagiwara, M., & Akagi, H. (2012). Experimental verification of a modular multilevel cascade inverter based on double-star bridge-cells (mmci-dsbc). In *2012 IEEE Energy Conversion Congress and Exposition (ECCE)* (p. 4196-4202). doi: 10.1109/ECCE.2012.6342253

Toh, C. L., & Norum, L. E. (2012). A performance analysis of three potential control network for monitoring and control in power electronics converter. In *2012 IEEE International Conference on Industrial Technology* (p. 224-229). doi: 10.1109/ICIT.2012.6209942

Tu, Q., Xu, Z., & Xu, L. (2011). Reduced switching-frequency modulation and circulating current suppression for modular multilevel converters. *IEEE Transactions on Power Delivery*, 26(3), 2009-2017. doi: 10.1109/TPWRD.2011.2115258

Xu, B., Tu, H., Du, Y., Yu, H., Liang, H., & Lukic, S. (2021). A distributed control architecture for cascaded h-bridge converter with integrated battery energy storage. *IEEE Transactions on Industry Applications*, 57(1), 845-856. doi: 10.1109/TIA.2020.3039430

Yang, S., Liu, S., Huang, J., Su, H., & Wang, H. (2020). Control conflict suppressing and stability improving for an mmc distributed control system. *IEEE Transactions on Power Electronics*, 35(12), 13735-13747. doi: 10.1109/TPEL.2020.2995898

Yang, S., Tang, Y., & Wang, P. (2018). Distributed control for a modular multilevel converter. *IEEE Transactions on Power Electronics*, 33(7), 5578-5591. doi: 10.1109/TPEL.2017.2751254

Yinghong, H., Peng, S., Zimeng, L., & Qing, G. (2022). Circulating current suppression for modular multilevel converter based on predictive control. In *2022 4th International Conference on Power and Energy Technology (ICPET)* (p. 1261-1266). doi:

10.1109/ICPET55165.2022.9918416

APPENDIX

A. LIST OF SYMBOLS AND ABBREVIATIONS

MMC Parameters

R_s	Cluster resistance
L_s	Cluster inductance
R_o	Phase output resistance
L_o	Phase output inductance
N	Number of submodules per MMC cluster
V_{dc}	MMC DC-link voltage

MMC Variables

i_χ	Output current of phase $\chi \in \{a, b, c\}$
$i_{z\chi}$	Circulating current between the DC link and phase $\chi \in \{a, b, c\}$
$i_{y\chi}$	Cluster current of position $y \in \{u, l\}$ and phase $\chi \in \{a, b, c\}$
$v_{y\chi}$	Cluster voltage of position $y \in \{u, l\}$ and phase $\chi \in \{a, b, c\}$
$\bar{v}_{C,y\chi}$	Cluster average voltage of the capacitors in position $y \in \{u, l\}$ and phase $\chi \in \{a, b, c\}$
$\bar{v}_{C,\chi}$	Phase average voltage of the capacitors of phase $\chi \in \{a, b, c\}$
$v_{g\chi}$	AC grid voltage of phase $\chi \in \{a, b, c\}$

Control Variables

$U_{DC,y\chi}$	Error signal for horizontal energy balancing of LC in position $y \in \{u, l\}$ and phase $\chi \in \{a, b, c\}$
$U_{AC,y\chi}$	Error signal for vertical energy balancing of LC in position $y \in \{u, l\}$ and phase $\chi \in \{a, b, c\}$
$\Delta V_{z,y\chi}$	Inter-cluster balancing component of LC in position $y \in \{u, l\}$ and phase $\chi \in \{a, b, c\}$
$\Delta V_{intra,y\chi}$	Intra-cluster balancing component of LC in position $y \in \{u, l\}$ and phase $\chi \in \{a, b, c\}$
v_{χ}^*	Phase voltage reference of phase $\chi \in \{a, b, c\}$
$v_{z\chi}^*$	Circulating current suppressing component of phase $\chi \in \{a, b, c\}$
$v_{y\chi,i}^*$	Final modulating signal of submodule $i \in \{1, \dots, N\}$ in position $y \in \{u, l\}$ and phase $\chi \in \{a, b, c\}$

Abbreviations

ADC	Analog-to-Digital Converter
CAN	Controller Area Network
CC	Central Controller
CCSC	Circulating Current Suppressing Controller
LC	Local Controller
MCU	Micro-Controller Unit
MMC	Modular Multilevel Converter
MMCC	Modular Multilevel Cascaded Converter
SM	Submodule

B. ALTERNATIVE DERIVATION OF POWER EQUATIONS

The power entering the upper $P_{u\chi}$ and lower $P_{l\chi}$ clusters of phase χ of the MMC can be expressed by equations (B.1) and (B.2) respectively. In this relationships, the $\Sigma\Delta$ transform defined in (3.10) is utilized to represent the cluster voltages, while the cluster currents are defined as (3.4) and (3.5).

$$P_{u\chi} = v_{u\chi} i_{u\chi} = (v_{\chi}^{\Sigma} - v_{\chi}^{\Delta}) \left(i_{z\chi} + \frac{i_{\chi}}{2} \right) \quad (\text{B.1})$$

$$P_{l\chi} = v_{l\chi} i_{l\chi} = (v_{\chi}^{\Sigma} + v_{\chi}^{\Delta}) \left(i_{z\chi} - \frac{i_{\chi}}{2} \right) \quad (\text{B.2})$$

For the following analysis, based on (Salvadores, Pereda, & Rojas, 2024), it is considered that the circulating current $i_{z\chi}$ only contains a DC component and an AC component of fundamental frequency for the operation of the converter. The reason of this is because these two components are directly controlled for the horizontal and vertical energy balance, while other components have comparatively lower amplitudes, especially since the circulating current suppression controller is utilized. Considering this, the following system variables can be defined for phase χ , assuming without loss of generality, that the converter operates with unitary power factor.

$$v_{g\chi} = V_g \sin(\omega t + \theta_{\chi}) \quad (\text{B.3})$$

$$i_{\chi} = I_{\chi} \sin(\omega t + \theta_{\chi}) \quad (\text{B.4})$$

$$i_{z\chi} = I_{z\chi,0} + I_{z\chi,1} \sin(\omega t + \phi_{z\chi}) \quad (\text{B.5})$$

Where $v_{g\chi}$ corresponds to the grid voltage, i_{χ} is the phase current, $i_{z\chi}$ denotes the circulating current with its DC and fundamental AC component, θ_{χ} is the AC grid voltage phase angle, and $\phi_{z\chi}$ corresponds to the circulating current angle. By replacing the

previous definitions in the dynamic equations of the converter, (3.11) and (3.12), the relationships (B.6) and (B.7) for the values of the converter voltages v_χ^Σ and v_χ^Δ respectively.

$$v_\chi^\Sigma = -R_s (I_{z\chi,0} + I_{z\chi,1} \sin(\omega t + \phi_{z\chi})) - I_{z\chi,1} L_s \omega \cos(\omega t + \phi_{z\chi}) + \frac{V_{dc}}{2} \quad (\text{B.6})$$

$$v_\chi^\Delta = I_\chi R_\epsilon \sin(\omega t + \theta_\chi) + I_\chi L_\epsilon \omega \cos(\omega t + \theta_\chi) + V_g \sin(\omega t + \theta_\chi) \quad (\text{B.7})$$

By substituting (B.6) and (B.7) in the cluster power definitions (B.1) and (B.2), it is possible to obtain the expression for the power entering each phase P_χ , as shown in (B.8). During the derivation of these relationships, various oscillating terms are obtained that are discarded, since only the average power variation of each phase is analyzed.

$$\begin{aligned} P_\chi &= P_{u\chi} + P_{l\chi} \\ &= V_{dc} I_{z\chi,0} - \frac{1}{2} V_g I_\chi - 2R_s I_{z\chi,0}^2 - R_s \left(I_{z\chi,1}^2 + \frac{I_\chi^2}{4} \right) - \frac{1}{2} R_o I_\chi^2 \end{aligned} \quad (\text{B.8})$$

It can be observed that the average power entering each phase is influenced by different terms due to the effect of the circulating current and the phase current. If it is assumed that the losses are negligible in the converter, it can be considered that the cluster resistance R_s and the output resistance R_o have small values, so these components can be neglected compared to the first and second terms. Therefore, defining the first term of this relationship as ΔP , it can be noted that the power entering the phase can be controlled directly utilizing the corresponding circulating current, specifically its DC component, as shown in (B.9).

$$\Delta P_\chi = V_{dc} i_{z\chi,0} = \dot{\omega}_{c,\chi} \quad (\text{B.9})$$

Where $\dot{\omega}_{c,\chi}$ represents the change in the energy stored in the capacitors of phase χ due to this power flow. This indicates that the capacitors of each phase can be charged or discharged by controlling the circulating currents. By comparing this result with equation (3.40), it can be observed that this alternative derivation yields a similar result.

C. CC AND LC PRINTED CIRCUIT BOARDS

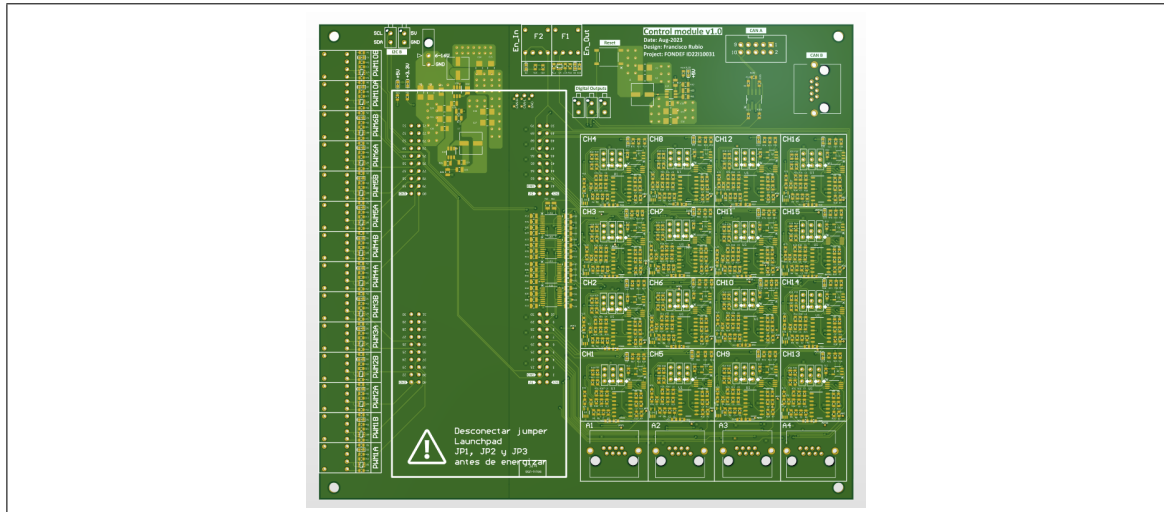


Figure C.1. CC and LC printed circuit board from project ID22I10031.

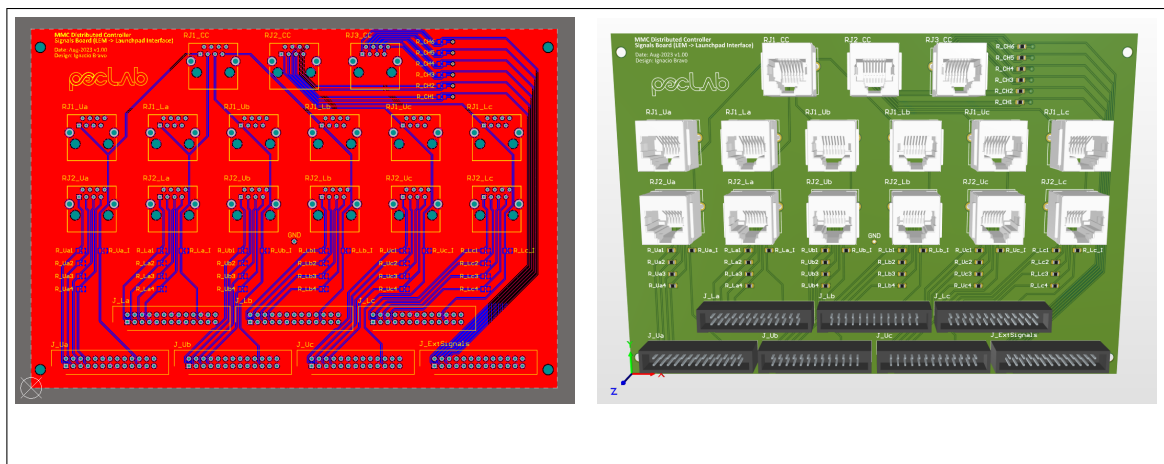


Figure C.2. MMC measurements board.

D. EXPERIMENTAL RESULTS WITH MODULATION ADJUSTMENT

This appendix presents the results of the experiments performed in chapter 5, but considering a modification in the modulation of the control signals. In the original experiments, the modulating signals for the submodules were normalized by dividing by the constant nominal voltage of each capacitor $\frac{V_{dc}}{N}$. However, in this case, the modulating signals are normalized by the measured voltage of the corresponding capacitor within each submodule.

As part of these experiments, a compensation current scheme is implemented to reduce the effect of the vertical energy balance on the DC port current, as described in (Salvadores et al., 2024). In this scheme, the LCs exchange the AC references of their respective circulating current $i_{z\chi,AC}^*$ through the CAN communication bus to calculate the compensating components. However, this implementation could be improved by adopting a communication protocol with a higher data transmission rate to support shorter sampling periods, since the transmission of these references are affected by the communication delay and the sequential transmission of the LCs.

D.1. Validation of the voltage balancing control

The results for the two proposed controller gain scenarios utilizing the modulation adjustment are presented in Fig. D.1. It can be observed that in both cases, the control scheme continues to balance the capacitor voltages to their nominal value. Furthermore, the convergence speed of the voltages to the reference value varies depending on the controller gain, having a higher speed if the proportional gain is higher.

Fig. D.2 presents the results of the previous experiment, displaying the output currents and circulating currents for both cases of the consensus controller gain. Conclusions are similar to the original modulation, achieving voltage balance while controlling the AC port currents. However, in this case, the AC port currents are less balanced compared to

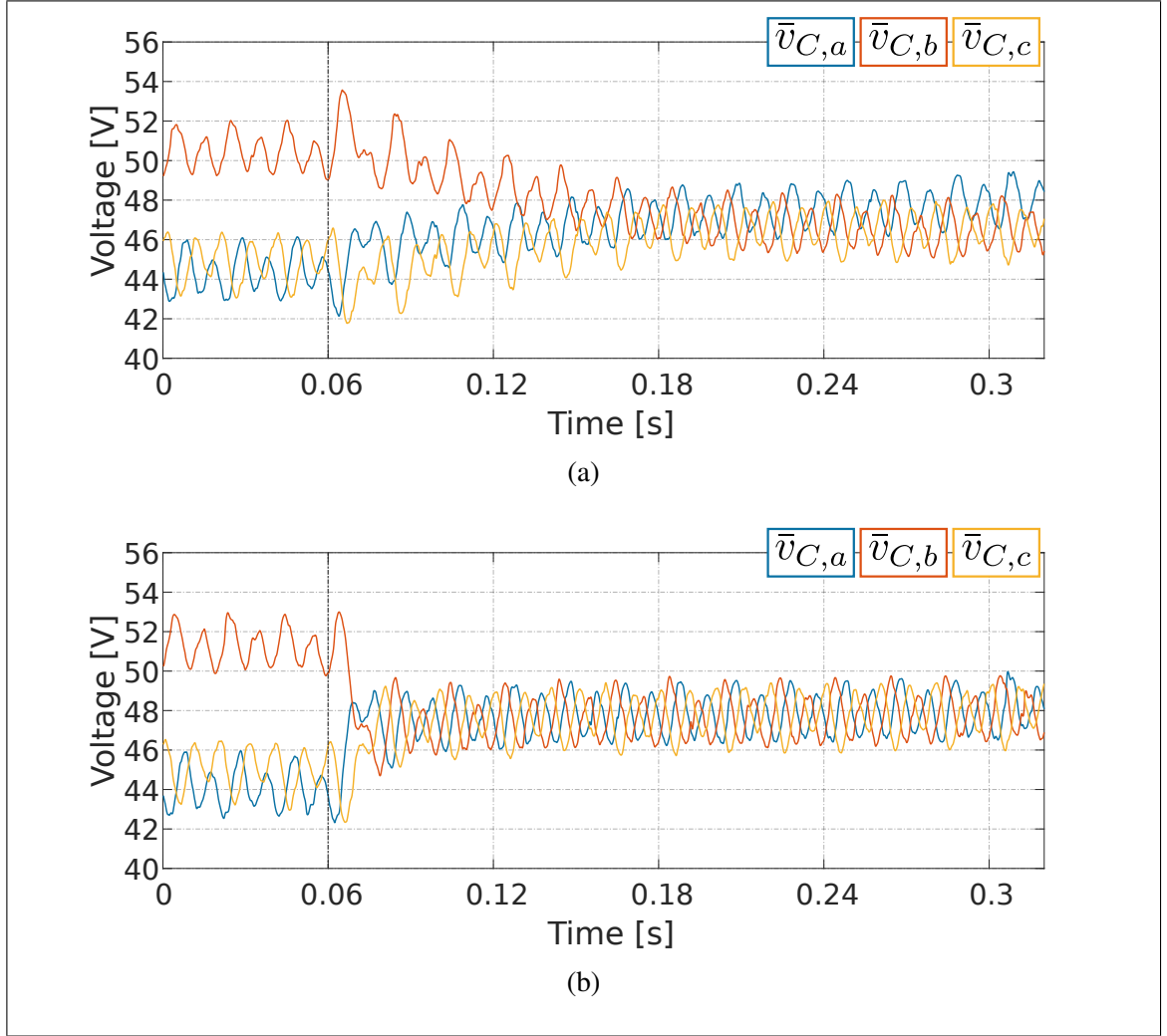
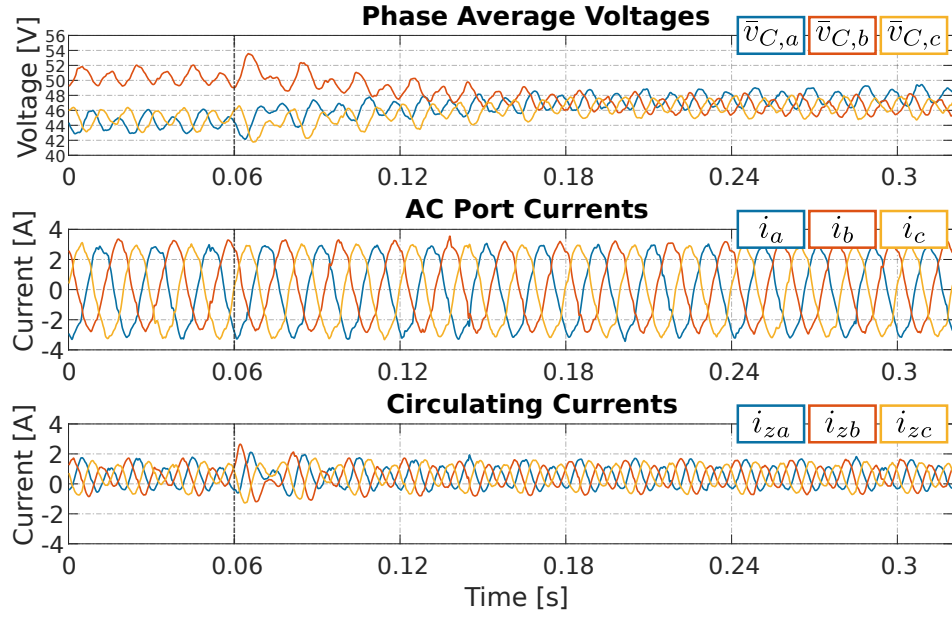


Figure D.1. Phase average voltages for different values of the consensus controller gain. (a) $K_{DC} = 0.1$ (b) $K_{DC} = 0.4$

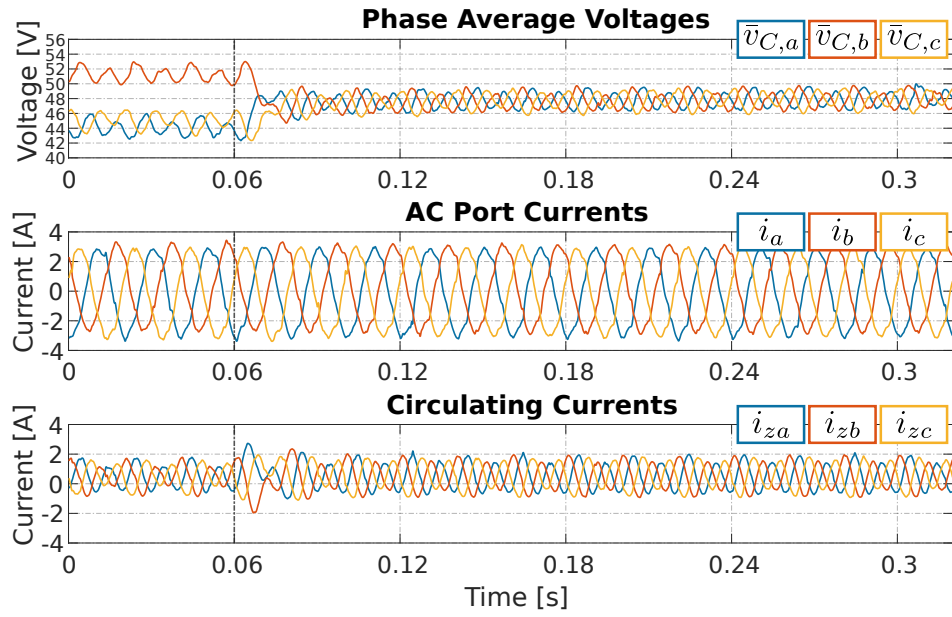
the original modulation scenario. This could be improved by adopting a communication protocol with a higher data transmission rate, but further tests are required.

D.2. Effect of the circulating current suppressing controller

Fig. D.3 shows the harmonic components of the circulating currents of each phase from the results shown in Fig. D.2. This considers the case in which the controller gain



(a)



(b)

Figure D.2. Experimental results for different values of the consensus algorithm gain. (a) $K_{DC} = 0.1$ (b) $K_{DC} = 0.4$

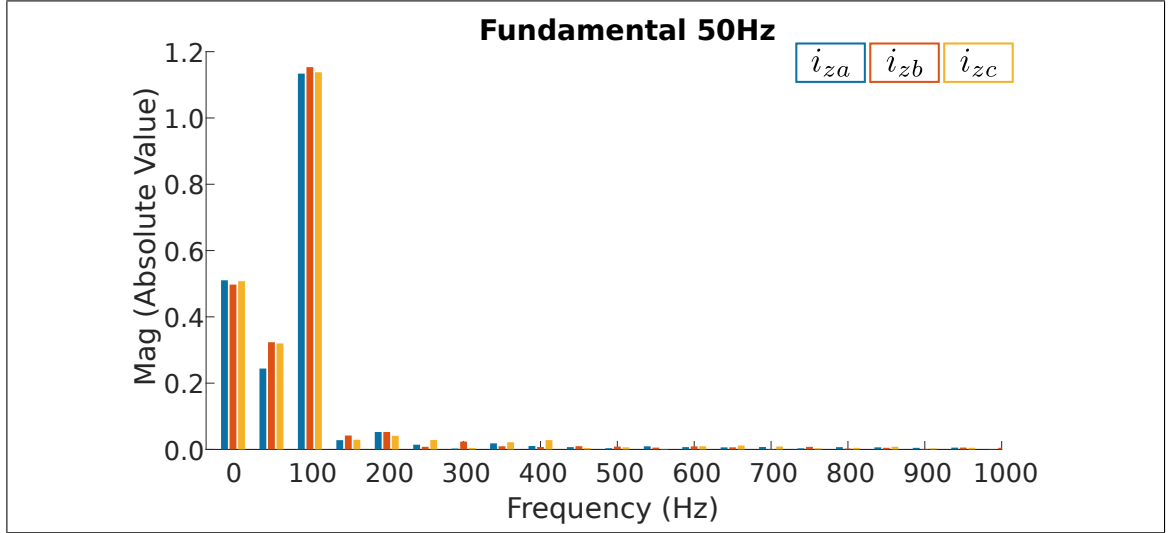


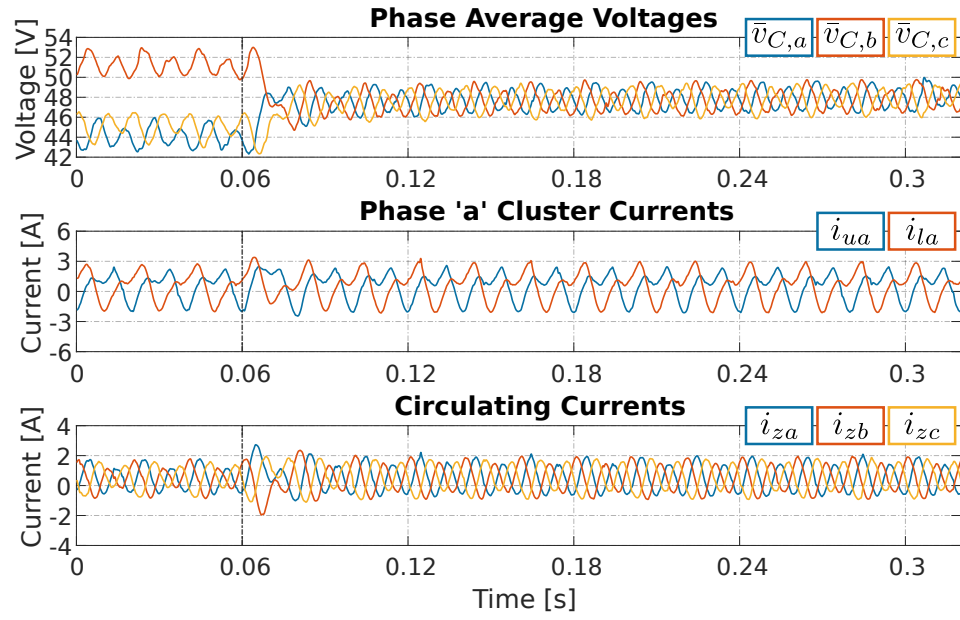
Figure D.3. Harmonic components of circulating currents without CCSC and $K_{DC} = 0.4$.

is $K_{DC} = 0.4$, after the voltage balance has been achieved in the capacitors of the converter. It can be observed how the circulating currents have an important second harmonic component of 100Hz, which should be regulated with the CCSC.

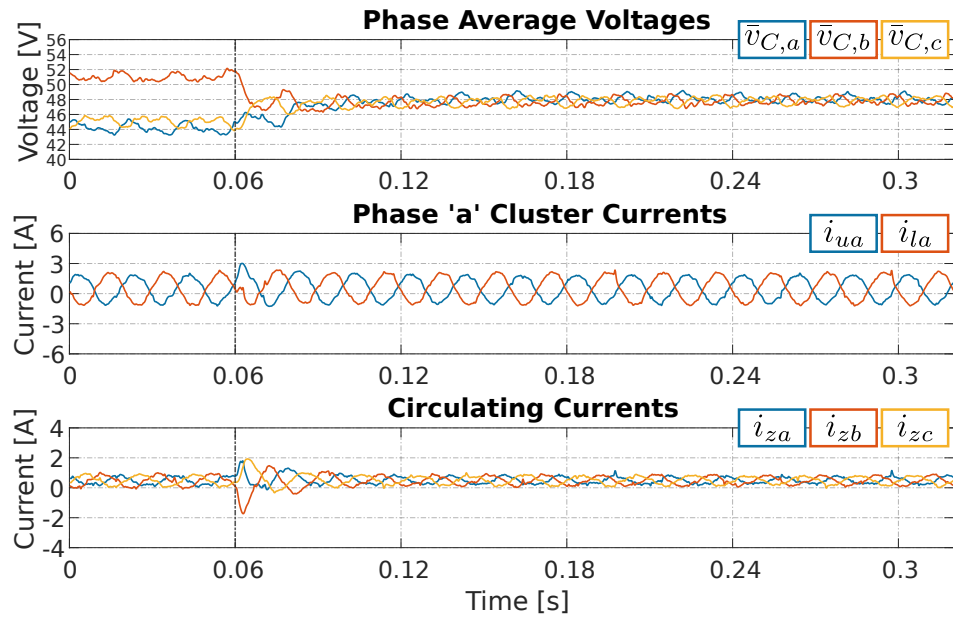
Fig. D.4 shows the results of the previous experiment, comparing the system with the CCSC disabled and enabled, and graphing the trajectories of the phase average voltages, the upper and lower cluster currents from phase a, and the circulating currents of each phase. Similar to the original experiments, both cases manage to balance the average voltages of the capacitors. However, when the CCSC is disabled, both the cluster currents and the circulating currents have a considerable second harmonic component. Furthermore, when the CCSC is activated, the second harmonic component is reduced in the circulating and cluster currents. This can also be concluded from Fig. D.5, which shows the harmonic content of the circulating currents once the CCSC is activated.

D.3. Operation as inverter

As in the original experiment, a step reference change in the current delivered to the AC port is applied to evaluate the voltage balance of the capacitors. Fig. D.6 presents



(a)



(b)

Figure D.4. Experimental results for the CCSC implementation. (a) CCSC disabled (b) CCSC activated

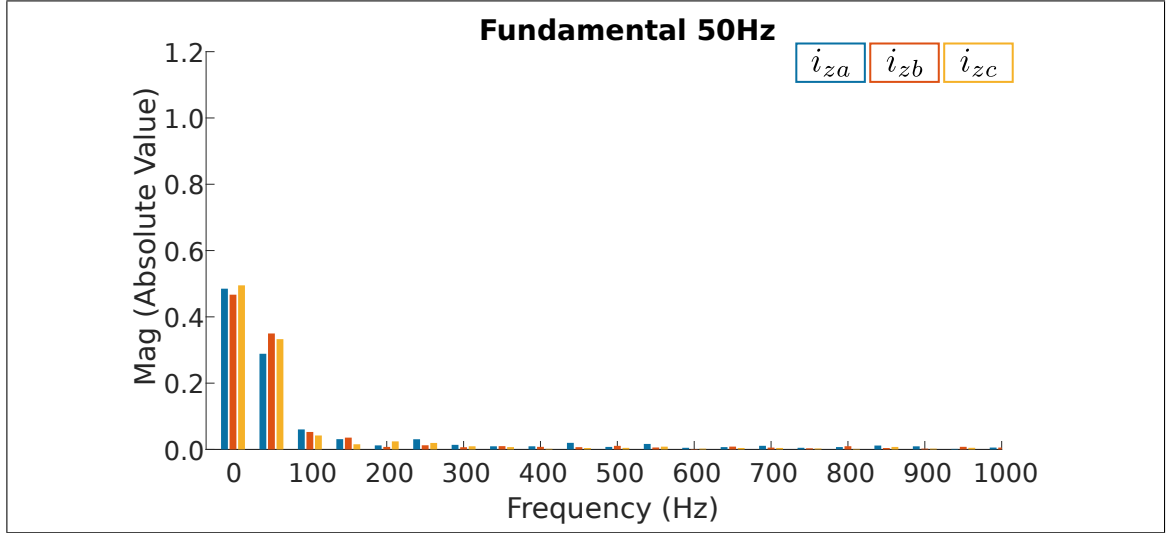


Figure D.5. Harmonic components of circulating currents with CCSC activated $K_{DC} = 0.4$.

these results when the MMC is in inverter operation, showing the AC grid voltages, the currents in the AC and DC ports of the converter, and the phase average voltages of the capacitors.

It can be observed that the AC port currents and the DC current increase as a result of the step reference change, while the phase average voltages are maintained close to their nominal value. However, in this case, a 50Hz AC component can be noted in the DC port current. This could be improved by reducing the sampling period of the control system by implementing a faster communication protocol, such as the CAN-FD protocol.

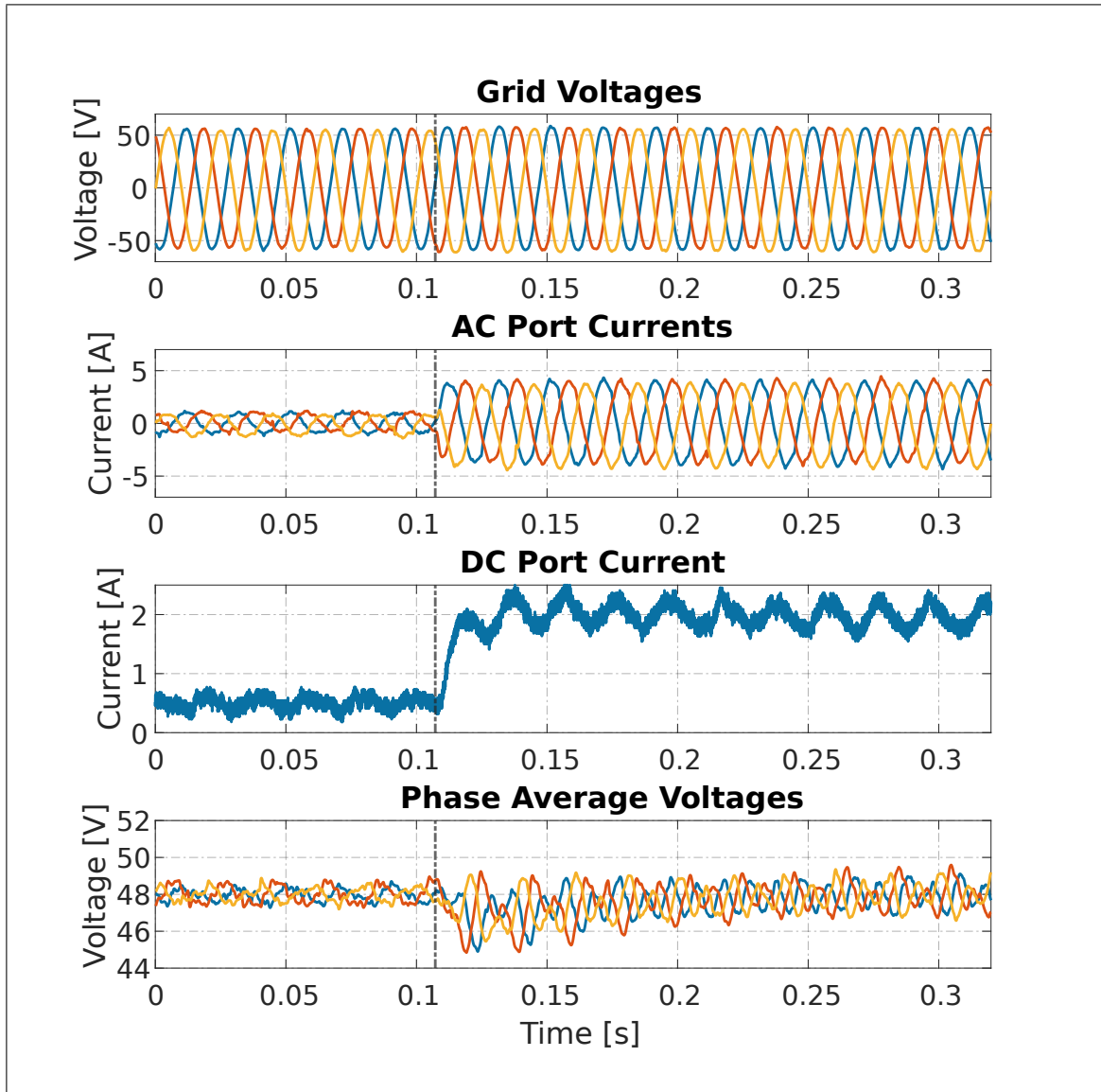


Figure D.6. Experimental results for operation as inverter with AC current step from 1A to 4A.