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Enhancing the Control of Modular Multilevel Converters in Smart Transformers Using Model Predictive Control

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ABSTRACT: Modern electrical networks have undergone significant transformations to accommodate various generation sources like gas turbines, wind turbines, and photovoltaic panels. Smart grids play a crucial role in managing electricity transmission from these diverse sources while coordinating the needs of loads with the capabilities of generators. Solid-state transformers are a key component of smart grids, specifically designed for efficient coordination and transmission.

These transformers are modular and can be divided into three sections: ACHV to DCHV using a modular multilevel converter MMC, DCHV to DCLV using a dual active bridge, and finally DCLV to ACLV utilizing a simple inverter. This modular design allows them to adapt to different generation sources.

This report delves deeper into the MMCand its functionalities within the solid-state transformer system.

Keywords: Modular multilevel converter, Solid-state transformer, model predictive control for MMC , Traditional control For the MMC

RÉSUMÉ: Les réseaux électriques modernes ont subi des transformations importantes pour accueillir diverses sources de production, telles que les turbines à gaz, les éoliennes et les panneaux photovoltaïques. Les réseaux intelligents jouent un rôle crucial dans la gestion du transport d'électricité à partir de ces sources diverses, tout en coordonnant les besoins des charges avec les capacités des générateurs. Les transformateurs statiques à semi-conducteurs sont un élément clé des réseaux intelligents, spécialement conçus pour une coordination et une transmission efficaces.

Ces transformateurs sont modulaires et peuvent être divisés en trois sections : du ACHV au DCHV en utilisant un convertisseur multiniveau modulaire MMC, du DCHV au DCLV en utilisant un pont actif doublée, et enfin du DCLV au ACLV en utilisant un simple onduleur. Cette conception modulaire leur permet de s'adapter à différentes sources de production.

Ce rapport approfondit le MMC et ses fonctionnalités au sein du système de transformateur statique à semi-conducteurs.

Mots clés : convertisseur multiniveau modulaire, Les transformateurs statiques à semi-conducteurs, Commande prédictive pour le CMM, les command traditionnelle pour le CMM

الملخص: شهدت الشبكات الكهربائية الحديثة تحولات كبيرة لاستيعاب مصادر توليد مختلفة مثل التوربينات الغازية وتوربينات الرياح والألواح الكهروضوئية. تلعب الشبكات الذكية دورًا حاسمًا في إدارة نقل الكهرباء من هذه المصادر المتنوعة مع تنسيق احتياجات الأحمال مع قدرات المولدات. تعتبر المحولات الحالة الصلبة عنصرًا رئيسيًا في الشبكات الذكية ، المصممة خصيصًا للتنسيق والنقل الفعال. هذه المحولات معيارية ويمكن تقسيمها إلى ثلاثة أقسام: التيار المتردد عالي الجهد إلى تيار مستمر عالي الجهد باستخدام محول متعدد المستويات المعياري (MMC) ، والتيار المستمر عالي الجهد إلى تيار مستمر منخفض الجهد باستخدام جسر نشط مزدوج ، وأخيرا التيار المستمر منخفض الجهد إلى تيار متردد منخفض الجهد باستخدام عاكس بسيط. يسمح هذا التصميم المعياري بالتكيف مع مصادر توليد مختلفة. يتعمق هذا التقرير في (MMC) والوظائف التي يؤديها داخل نظام المحول الحالة الصلبة.

كلمات مفتاحية :محول متعدد المستويات المعياري ,(MMC) محولات الحالة الصلبة ,(SSTs) تحكم تنبؤي لـ ,MMC تحكم تقليدي لـ(MMC)

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DEDICATION

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List of Abriviations and Symbolse

AC: Alternative current

DAB: Dual Active Bridge

DC: Direct Current

$\mathbf{e_k}$: Phase Voltage

FC: Flying Capacitors converter

HVT: High Voltage Transmission

$\mathbf{i_{uk}}$: Upper arm Current on modular multilevel converter

$\mathbf{i_{lk}}$: Lower arm Current on modular multilevel converter

$\mathbf{i_{lk}}$ Circulating Current on modular multilevel converter per phase

$\mathbf{i_k}$: greed Current on modular multilevel converter

$\mathbf{L_{arm}}$: Arm Inductance on modular multilevel converter

$\mathbf{L_{eq}}$: Equivalent Inductance on modular multilevel converter per phase

MMC: Modular multilevel converter.

NPC: neutral point clamped converter

$\mathbf{R_{arm}}$: Arm Resistance on modular multilevel converter

$\mathbf{R_{eq}}$: Equivalent Resistance on modular multilevel converter per phase

SM: Submodule

SST: Solid State Transformer

$\mathbf{V_{dc}}$: Output Voltage of the modular multilevel converter

$\mathbf{V_k}$: greed Voltage on modular multilevel converter

$\mathbf{V_{uk}}$: Upper arm Voltage on modular multilevel converter

$\mathbf{V_{lk}}$: Lower arm Voltage on modular multilevel converter

VSC: Voltage source converter

θ: the angular displacement between the stationary reference frame $\alpha\beta$ and the rotating reference frame dq

General Introduction

The evolving landscape of power transformation presents a significant challenge as traditional transformers struggle to keep up with the changing demands of today's energy systems. These transformers have long been relied upon to transfer electrical energy at different voltage levels while maintaining electrical isolation. However, the rise of renewable energy sources, the growing need for smart grids, and the demand for improved efficiency are pushing the boundaries of what classic transformers can achieve. One of the key issues faced by traditional transformers is their size and weight, limiting their adaptability to modern power transmission requirements [7].

In response to these challenges, the emerging technology of the solid-state transformer has entered the field to address the shortcomings of traditional transformers. Solid-state transformers offer a more efficient and adaptable solution for coordinating and transmitting power in today's diverse energy landscape. Their modular design allows for greater flexibility and efficiency, addressing also the problem of size and weight that plagues traditional transformers [14].

Optimizing the sensor requirements within the solid-state transformer's modular multilevel converter is essential for efficient operation. By reducing the number of sensors while maintaining efficiency, significant cost savings and reduced calculation time can be achieved. This strategic move towards sensor optimization is a key focus in addressing the primary challenge and enhancing the overall performance of power transformation systems.

Chapter I of the report delves into the comparison between traditional transformers section I.3and solid-state transformers section I.4, highlighting the need for more advanced technologies to meet the evolving demands of the power grid.

Chapter IIexplores the topology sectionII.2, operation section II.3 and working principle II.4 of the modular multilevel converter (MMC), a key component in the solid-state transformer system.

Chapter III focuses on different traditional control methods, including rotating subsection III.2.1 and sorting algorithms subsection III.2.2, used in power transformation systems. These control strategies play a crucial role in optimizing the performance of the MMC and ensuring efficient power transmission. The chapter emphasizes the importance of multiple sensors in the MMC's topology for efficient operation, raising the challenge of reducing the number of sensors for improved performance.

Finally, Chapter IVintroduces the concept Model predictive control, highlighting its significance in enhancing the performance of the modular multilevel converter.

Chapter I

The Evolving Landscape of Power Transformation

I.1 Introduction

For over a century, the work horse of the electrical grid has been the classic transformer. These passive devices, with their core of iron and windings of copper, have faithfully transferred electrical energy at different voltage levels while maintaining electrical isolation. However, the rise of renewable energy sources, the growing need for smart grids, and the demand for improved efficiency are pushing the boundaries of what classic transformers can achieve.

This presentation delves into the world of power transformation, exploring both the well-established classic transformer and the emerging technology of the solid-state transformer **SST**. We will begin by examining the core principles and operation of the classic transformer, highlighting its strengths and limitations. Subsequently, we will shift our focus to the innovative world of SSTs. We will explore their underlying technology, compare their performance with classic transformers, and discuss their potential to revolutionize the way we manage and distribute electrical power.

By the end of this chapter, you will gain a comprehensive understanding of both classic and solid-state transformers, allowing you to appreciate the evolution of power transformation technology and its potential impact on the future of our electrical grid but first you have to know the basic idea of smart grid.

I.2 From traditional to the smart grid

Nowaday, we are often hearing about smart grid, in the news and around all of us too but most of the people do not have the basic understanding of what a smart grid really is?

A smart grid is an electricity network that uses digital and other advanced technologies to monitor and manage the transport of electricity from all generation sources to meet the varying electricity demands of end users. Smart grids co-ordinate the needs and capabilities of all generators, grid operators, end users and electricity market stakeholders to operate all parts of the system as efficiently as possible, minimising costs and environmental impacts while maximising system reliability, resilience, flexibility and stability. Most of the technologies involved have already reached maturity, and so tracking investments provides insights on levels of deployment. and here a comparative Figure I.1 between traditional and smart grid where we can see the the many choices we can get from the smart one [7].

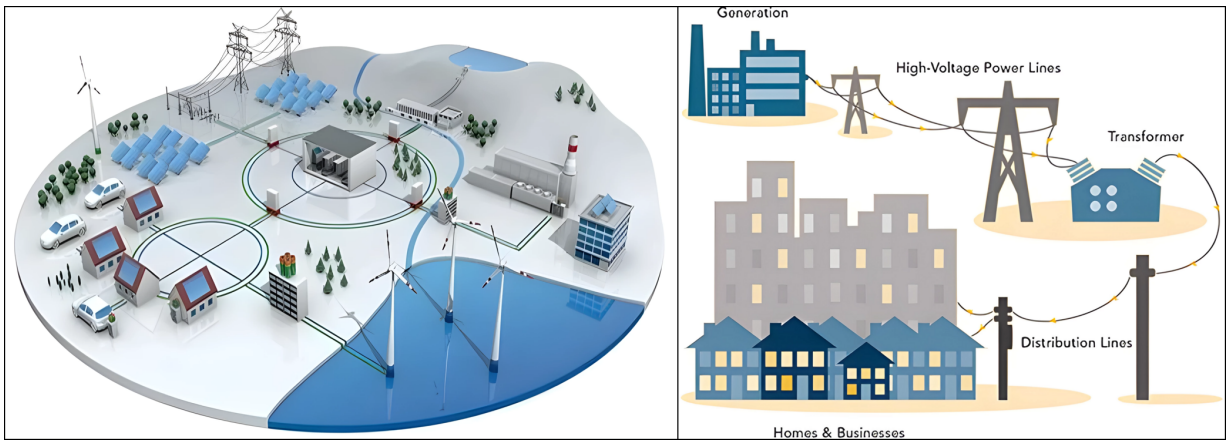


Figure I.1: Smart and Traditional grid

AS you can see we need a transformers that can update with the different in and out put which is our main subject in this chapter so we will offer this information and explain the traditional transformer first and than we go straight to the Solid State Transformer .

I.3 The Classic Transformers

A transformer is a static electrical device that transmits AC power from one circuit to another at a constant frequency, but the voltage level may be changed, implying the voltage can be increased or decreased depending on the requirement.

A transformer majorly consists of three parts:

core : The transformer core serves as a support for the winding. Additionally, it offers a magnetic flux flow channel with minimal resistance. As seen in the image, the winding is looped around the core. To cut down on losses in a transformer, it has a laminated soft iron core. Core composition is determined by variables including operational voltage, current, and power, among others. The core diameter is negatively correlated with iron losses and directly correlated with copper losses.

Windings : The copper wires that are wound over the transformer core are known as windings. Copper cables are used because Copper's high conductivity reduces transformer loss because resistance to current flow lowers as conductivity rises. And copper's high degree of ductility makes it possible to produce incredibly thin wires out of it.

The two basic types of windings are. windings for the primary and secondary coils. The primary winding is the group of winding turns that receive supply current. The number of winding turns from which output is derived is known as secondary winding. Insulation coating agents are used to insulate the primary and secondary windings from

one another.

Insulation Agents : Transformer require insulation to keep the windings apart and prevent short circuits. This makes mutual induction easier. Transformer stability and durability are influenced by insulation agents. In a transformer, the following are employed as insulating mediums: Insulating fluid, tape, Paper, and Lamination made of wood.

I.3.1 Types of Transformer

We can classify the type of transformers depend on deferent criterion [15] :

Based on Voltage Level:

There are primarily two types of Transformer based on the operating voltage. The following are some of them:

Step-down Transformer: The primary voltage is converted to a lower voltage across the secondary output using a step-down transformer. The number of windings on the primary side of a step-down transformer is more than on the secondary side. As a result, the overall secondary-to-primary winding ratio will always be less than one. Step-down transformer are used in electrical systems that distribute electricity over long distances and operate at extremely high voltages to ensure minimum loss and economical solutions. Step-down transformer are used to change high-voltage into low-voltage supply lines.

Step-up Transformer: The secondary voltage of a step-up transformer is raised from the low primary voltage. Because the primary winding has fewer turns than the secondary winding in this sort of transformer, the ratio of the primary to secondary winding will be greater than one. Step-up transformer are frequently used in electronics stabilizers, inverters, and other devices that convert low voltage to a significantly higher voltage. A step-up transformer is also used in the distribution of electrical power. For applications connected to power distribution, high voltage is necessary. In the grid, a step-up transformer is used to raise the voltage level prior to distribution.

Based on Core Material

Different types of Transformer are used in the power and electronics industries, depending on the core materials, which are:

Iron Core Transformer: Multiple soft iron plates are used as the core of an iron core transformer. The iron's strong magnetic properties of the iron core transformer have ex-

tremely high flux linkage. As a result, the iron core transformer has high efficiency. The soft iron core plates come in a variety of sizes and shapes. A few typical shapes include E, I, U, and L.

Ferrite Core Transformer: Due to its high magnetic permeability, a ferrite core transformer uses one. In the high-frequency application, this kind of transformer provides incredibly low losses. In high-frequency applications like switch mode power supplies (SMPS), RF-related applications, etc., ferrite core transformer are used as a result.

Toroidal Core Transformer: Iron core or ferrite core are two examples of toroid-shaped core materials used in transformer. For their excellent electrical performance, toroids, which have a ring- or donut-shaped core material, are frequently used. The ring form results in very low leakage inductance and extremely high inductance and Q factors.

Air Core transformer: The core material of an air core transformer is not a real magnetic core. The air is used solely in the air-core transformer flux linkage. The primary coil of an air-core transformer generates an alternating current, producing an electromagnetic field all around it.

Based on Usage

Transformer come in a wide range of variants, each of which operates in a distinct field. Thus, based on their proposed use, transformer can be categorized as follows:

Power Transformer: The energy is transferred to the substation or the general electrical supply using a larger power transformer. Between the major distribution grid and the power generator, this transformer serves as a link. Power Transformer can be further divided into three groups based on their power rating and specification- Small power transformer, Medium power transformer, and Large power transformer

Measurement Transformer: Instrument transformer is another name for measurement transformer. This is yet another measurement tool that is usually utilized in the power domain. To separate the primary power and convert the current and voltage in a smaller ratio to its secondary output, a measuring transformer is used.

Distribution Transformer: The distribution transformer function as a step-down transformer, converting high grid voltage to the appropriate voltage for the end user, typically 110V or 230V. Depending on the conversion capacity or ratings, the distribution transformer might be less in size or larger.

Pulse Transformer: One of the most popular PCB-mounted transformer that gener-

ates electrical pulses with a consistent amplitude are pulse transformer. It is utilized in a number of digital circuits where the demand for isolated pulse creation exists.

Audio Output Transformer: Another frequent transformer in the electronics industry is the audio transformer. It is specifically usedin applications involving audio where impedance matching is necessary.

I.3.2 Working Principle of a Transformer

As shown in Figure I.2 the working of the transformer is based on the principle of mutual inductance between two coils which are magnetic coupled.

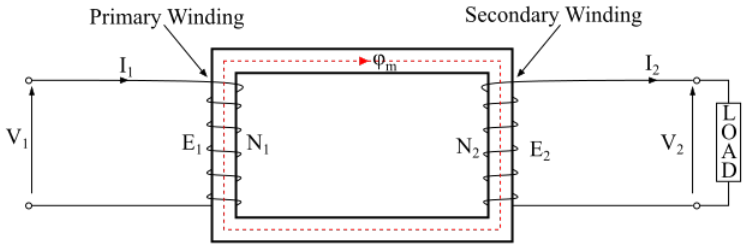


Figure I.2: classic transformer

According to the principle of mutual inductance, when an alternating voltage is applied to the primary winding of the transformer, an alternating flux ϕ which is called as the mutual flux is produced in the core. This alternating flux links both the windings magnetically and induces EMFs E1 in the primary winding and E2 in the secondary winding of the transformer according to Faraday's law of electromagnetic induction. The EMF (E1) is called as primary EMF and the EMF (E2) is known as secondary EMF and being given as :

$$E_1 = -N_1 \frac{d\varphi_m}{dt}$$
$$E_2 = -N_2 \frac{d\varphi_m}{dt}$$

$$\frac{E_2}{E_1} = \frac{N_2}{N_1} \tag{I.1}$$

From the above expression it can be seen that the magnitude of the Electromotive force **EMF** E1 and E2 depend upon the number of turns in the primary and secondary windings of the transformer respectively, i.e., if N2 > N1, then E2 > E1, thus the transformer will be a step-up transformer and if N2 < N1, then E2 < E1, thus the transformer will be a step-down transformer.

If a load is now connected across the secondary winding, the EMF E2 will cause a load current I2 to flow through the load. Therefore, a transformer enables the transfer of power from one electric circuit to another with a change in voltage level [16] .

We already said that this transformer can't avoid the needs of smart grid and development Demands. so the Solid State Transformer **SST** came to cover and replace the traditional transformers .

I.3.3 Advantages and Limitations

Of course every human made have some advantage and some limitation. We will acount some in this section.

Advantages:

Simplicity and Low Cost: Well-established design, readily available materials, and minimal maintenance requirements lead to lower manufacturing and maintenance costs.

High Reliability and Durability: Proven technology with minimal moving parts offers exceptional longevity and dependable operation.

Efficiency at High Power Loads: Ideal for high-voltage power transmission due to minimal energy losses at these levels.

Passive Operation: No external power source needed for operation. Robustness: Can withstand harsh environments and voltage fluctuations.

Limitations:

Bulk and Weight: Iron core makes them bulky and heavy, limiting their suitability for space-constrained applications.

Limited Control: Offer fixed voltage transformation based on winding ratios, with limited control over output parameters.

Energy Losses: Eddy currents and hysteresis in the core create energy losses, especially at lower power loads.

I.4 Solid State Transformer

A solid state transformer SST is an ac to ac converter that can replace conventional transformers used in distribution systems first idea mentioned proposed by McMurray in 1968 , however, the realization was difficult . After long years (about 50), using appropriate semiconductor devices with a novel topology configuration has come into play [10]. its main feature uses high frequency alternative current which make the transformer smaller in size and width and also meet the needs of the future smart grid .

I.4.1 Concept of solid state transformer

As said before, the solid-state transformer SSTis offered as a tool to meet the requirements of the smart grid. Solid-state transformers are comprised of three primary parts: converter to produce DC from input line frequency AC which represent the modular multilevel converter MMC , Dual Active Bridge DAB converter.isolation by a high-frequency transformer , and at last, converter to produce AC with line frequency from AC high frequency. Additionally, the isolation barrier partitions the transformer into two sections: high voltage and low voltage. In addition to being able to perform the same functions as a conventional transformer, SST provides a range of services to the grid, including reactive power compensation, power quality improvement, current limiting and voltage regulation power factor correction, etc., which can lead to improvements and establishing a connection between direct current DC and alternating current AC equipment

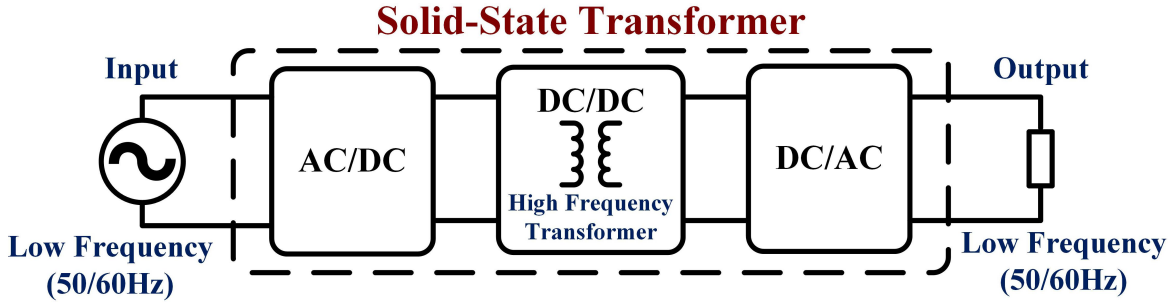


Figure I.3: Solide state transformer

There's an interesting trade-off between the frequency of the electrical signal and the size of a transformer. Traditionally, lower frequency AC power (like the 50 or 60 Hz used in homes) requires larger transformers. This is because the design relies on the core material to transfer energy efficiently. At higher frequencies, the same core can handle more power without reaching saturation, allowing for a smaller transformer. This principle is one of

the main concept used in solid-state transformers.

I.4.2 Types of SST Structures and Topologies

In general, SST configurations are classified into four categories according to the number of stages of voltage to DC conversion. Figure I.4 shows the types of presented configurations for SST [13]. Figure I.4A shows the single-stage SST with no DC link, Figure I.4B represents the two-stage SST with a DC link on the secondary side, Figure I.4C demonstrates the two-stage DC with a DC link on the primary side, and finally in Figure I.4D represents the three-stage with a DC link on both the primary and secondary sides[13]

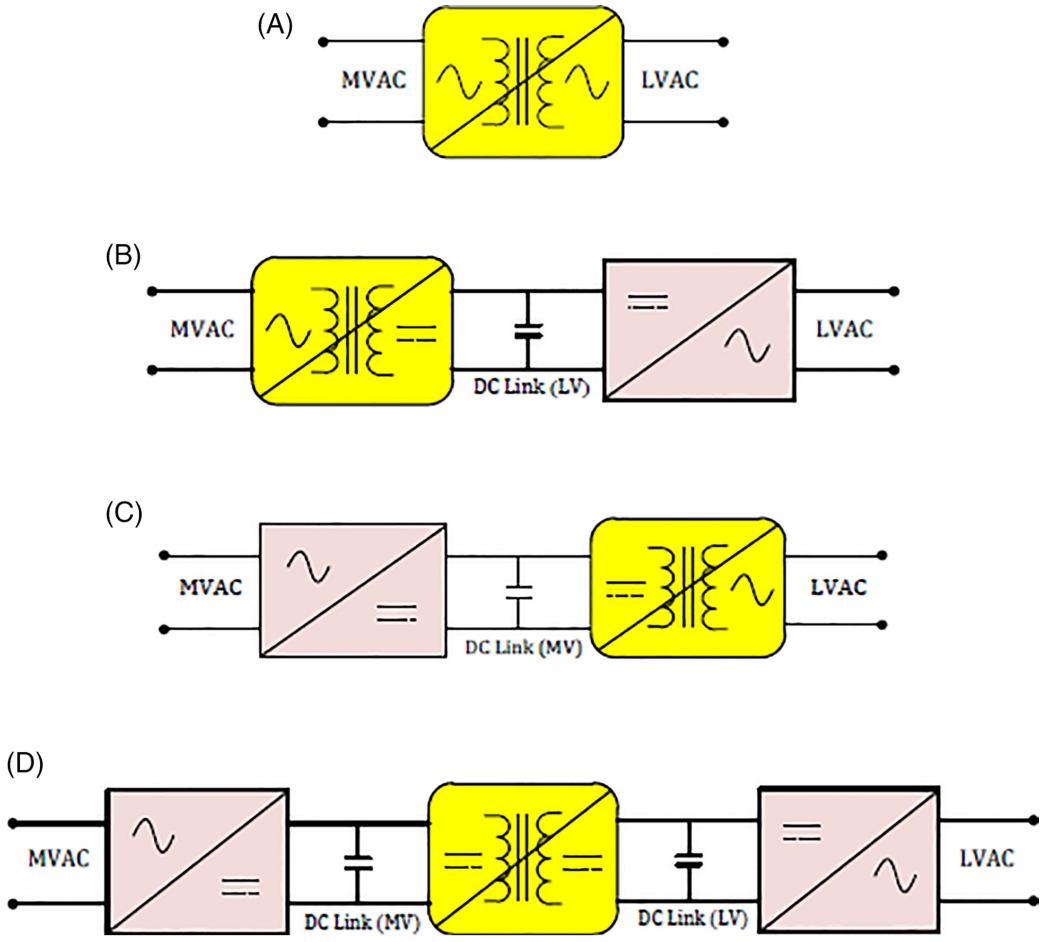


Figure I.4: Solide State Transformer Topologies

One Stage:

This structure comprises of converting high voltage AC to low voltage AC with an isolation stage. Having low cost and low weight because of its simple structure and also having the least losses due to the presence of fewer semiconductor switches and the use of minimal copper are the advantages of this structure. Disadvantages of this structure include the

following:

1. Due to lack of DC link, compensation of reactive power and direct connection of distributed renewable generation sources and energy storage are impossible and its control is difficult.

2. Need for large filters because of lack of regulation of input and output current.

3. Also in this structure, the disturbance on one side of the transformer can affect the other side, which is one of the major problems of the traditional transformers. The following two models are proposed for this structure.

4. AC-AC full-bridge converter This topology has a simpler control method than the other one-stage SST topologies, and its main drawback is the lack of a DC link and the capabilities provided by it.

5. AC-AC flyback This structure is the simplest topology of the isolated DC-DC converters. Disadvantages of this model include the large size of its filters and the lack of a DC link.

Two Stages:

In this structure, two models are proposed. In the first model, at first the AC voltage is converted to low voltage DC and then the low voltage DC is converted to low voltage AC. But in the second structure, first the AC voltage is converted to high voltage DC and then to low voltage AC. In these two models, there is an isolation stage (on the high voltage or low voltage side). The advantages of these two models include the ability to compensate for reactive power, support of their low voltage DC link LVDC from distributed energy storages and distributed energy resources , support of storage resource management, having an independent frequency and independent power factor, regulating the output voltage and input current, the ability to limit the input and output current and the possibility of isolating the ancillary loads of the network. Despite the mentioned advantages, zero voltage switching cannot be used in this structure in high voltage applications. Also, theLVDC link has more current ripples due to the lack of HVDC. In general, these two models have high switching losses, which can lead to reduced efficiency in the network. The details of the two mentioned models for SST with two stages structure are as follows:

1. AC-DC isolated boost + PWM inverter

   This topology of SST is based on the AC-DC isolated boost version.37 The disadvantages of this model are the need to use two different controls depending on the direction of power flow and also due to the lack of HVDC connection, its LVDC link will have a high ripple and on the other hand, its bandwidth is considerably lower than that of the input current because of the cascaded control.

2. AC-DC DAB + PWM inverter

   This topology of SST is based on DC-AC dual active bridges DAB version. The large signal medium model is the same as the DC-DC version. Each version of the DAB provides uniform control in both directions and zero voltage switching for a wide load range. The main disadvantage of this model is its high sensitivity to currents with high ripples. Also in this structure, due to the existence of a second-order filter, the design of the controls is very limited, leading to low bandwidth for the input current loop and even lower bandwidth for the **lvdc** link loop.

Three Stages:

This structure has a triple conversion in which high frequency isolation is performed in DC-DC stage. In this model, both HVDC and LVDC links are available. Most of the designs offered for intelligent transformers are of this type. This topology is able to compensate for reactive power and voltage regulation. In addition, it allows the connection of energy storage and renewable sources directly and the bidirectional power flow. In addition, other advantages of this model include high flexibility, better controllability, better regulation of output voltage and input current, and regulating of LVDC and HVDC links. Given the characteristics of all three models, it is easy to understand that the three stages structure has more advantages than the other two structures, and in addition, the important point is that in this model the existence of many switches in the switching circuits may lead to more losses, which reduces the efficiency of the network and impairs thermal management. Also in this structure, due to the high number of converter levels, the cost will be higher. For this structure, two models were proposed as follows.

1. PWM rectifier+ DC-DC DAB + PWM inverter

   This topology of the SST is most popular with researchers in the Future Renewable Electric Energy Delivery and Management field because of its better controllability, which allows several desirable functions for an SST. This topology consists of only

one module in two isolated DC-AC and DC-DC stages. The DC-AC stage of this topology is based on the full-wave rectifier. The isolated DC-DC stage of this topology is based on DAB modules that connect the HVDC link to the LVDC link. The main drawback of this topology is its complex structure, which results in reduction of network reliability.

2. Multilevel rectifier + DC-DC full-bridge converter + PWM inverter
   The DC-AC stage in this topology is based on a diode clamped multilevel rectifier. Therefore, in this structure, there is no need for modular configuration of input voltage division. A bi-directional modular version is used for the isolated DC-DC stage. In this topology, full-bridge converter supplies bi-directional power flow and injects low ripple currents into the LVDC link.

Now and before the chapter end we'd like to compare between the traditional and the solid state transformer on its development on this day .

I.4.3 Advantages and Limitations related to the SST

in this section we will talk about the goals we already reach and the challenge the SST is going throw.

Advantages:

Compact and Flexible: Power electronics enable a smaller footprint and modular design, offering scalability and customization.
Improved Efficiency: Power electronics facilitate efficient conversion across various load conditions, leading to lower overall energy losses.
Advanced Control Features: Precise control over output voltage, current, and power factor allows for grid integration of renewables and bi-directional power flow.
Smart Grid Integration: Communication interfaces enable real-time monitoring, data integration, and enhanced grid management functionalities.

Confrontation:

Cost and Complexity: Power electronics increase current costs compared to classic transformers. Additionally, their control systems require specific expertise for operation

and maintenance.

Reliability: While improving, power electronics have a higher potential for failure compared to classic transformers.

Limited Experience: A relatively new technology, with less established track record in long-term operation compared to classic transformers.

So this is the end of the chapter and we think this is enogh of information to go throw our main report subject . Modulair Multi-level Converter **MMC**

I.5 Conclusion

In Chapter 1 we discusses the evolving landscape of power transformation, comparing traditional and solid-state transformers. The next chapter delves into the Modular Multilevel Converter MMC system.

Chapter II

Modulaire Multilevel Converter

II.1 Introduction

A multi-level converter is a method of generating high-voltage from lower-voltage components. it's origins go back over a hundred years. Neutral point clamped **NPC** and flying capacitor **FC** converters are some of the examples of multilevel converters [1, 11] .

The modular multilevel converters **MMC**s are the fourth-generation converters of the voltage source converter technology and they belong to the family of multilevel converters [8].This generation is one of the most attractive topologies in many medium and high voltage **AC-to-DC**, **DC-to-AC** and **AC-to-AC** conversion applications such as high voltage transmission **HVT**, motor drives, static synchronous compensator, back-to-back systems, wind/solar distributed power conditioning systems, energy collection and distribution, new matrix converters and so forth [3].

Having established the need for and potential benefits of MMCs, let's delve deeper into their fundamental building block: the converter topology.

II.2 Topology of Modular Multilevel Converter

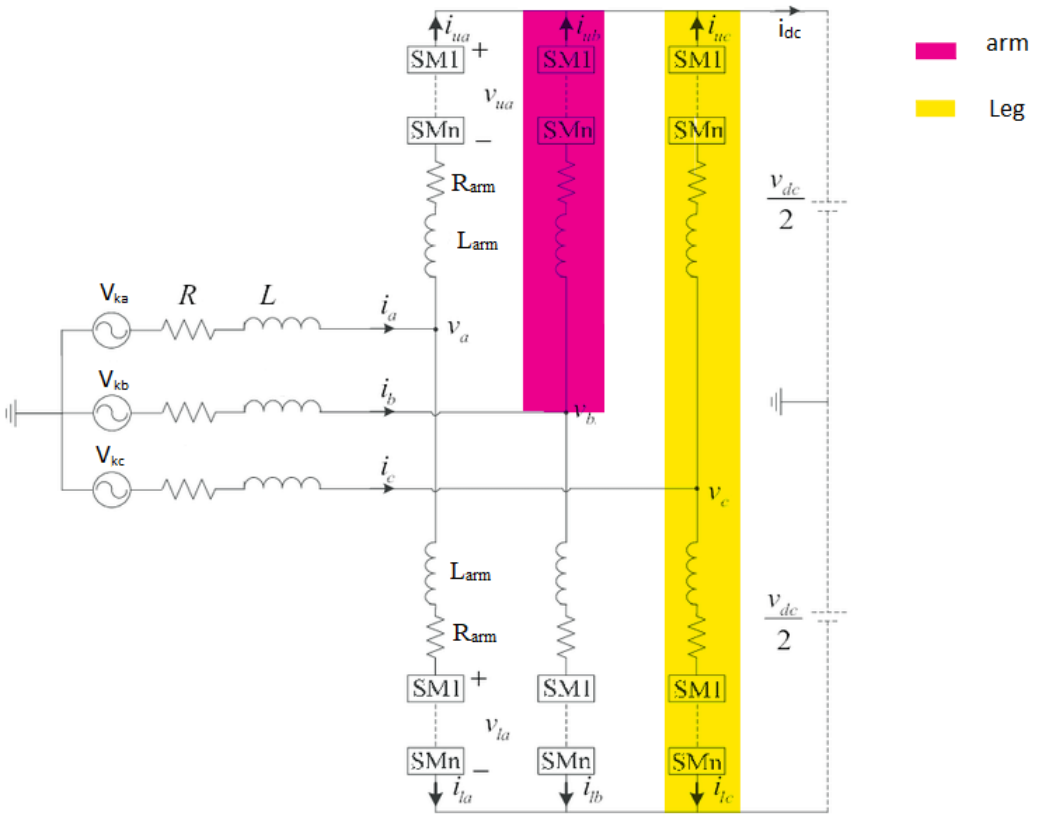


Figure II.1: Three-phase MMC topology

For a three-phase system, the MMC consists of three phase legs [12]. Each phase is split at a midpoint into two arms, an upper and lower arm, which connects one AC terminal to the DC terminal. Each arm contains multiple submodules (SM) and an inductor connected in series to help limit the current flow between phases. The SMs act as independently controllable voltage sources. Figure II.1 shows the basic topology for a three phase **MMC** in a configuration to rectify AC to DC. Having explored the modular structure of the MMC, consisting of interconnected submodules, we now delve into its operation, examining how these submodules interact to convert and control the flow of power.

II.3 Operation

The SMs are the heart of the MMC operation and are independently regulated by the MMC controller. The SMs can be a few different variations of topologies. The most popular is a half-bridge SM, shown in Figure II.2, which consists of two semiconductor devices, such as insulated gate bipolar transistors (IGBT), connected in series [6]. The capacitor connected across the two IGBTs for energy storage allows the SMs to act as a voltage source, but it also contributes to increasing the volume and weight of the converter. The SM connection terminals are to the midpoint between the two IGBTs and the lower IGBT terminal. For this study, the upper IGBT is referred to as "S1" and the lower IGBT is referred to as "S2."

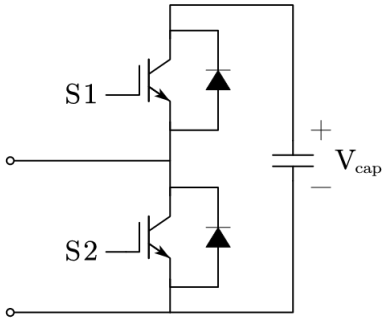


Figure II.2: Half-Bridge Sub-Module

Each SM produces two discrete voltages across its terminals which make each SM a controllable voltage source [2]. The half-bridge SM is controlled as a unipolar device so if S1 is on, then S2 must be off and if S1 is off, then S2 must be on. When S1 is on, regardless of the current direction, the voltage across the SM terminals will be equal to the voltage across the SM capacitor, Vcap. When S1 is off, regardless of current direction, the voltage across the SM terminals will be equal to 0 V [6]. Therefore, for N number of SMs connected in series per arm, the total arm voltage output can be in the range of 0 V to NVcap.

Here is a Figure II.3 to simplify the operation principle

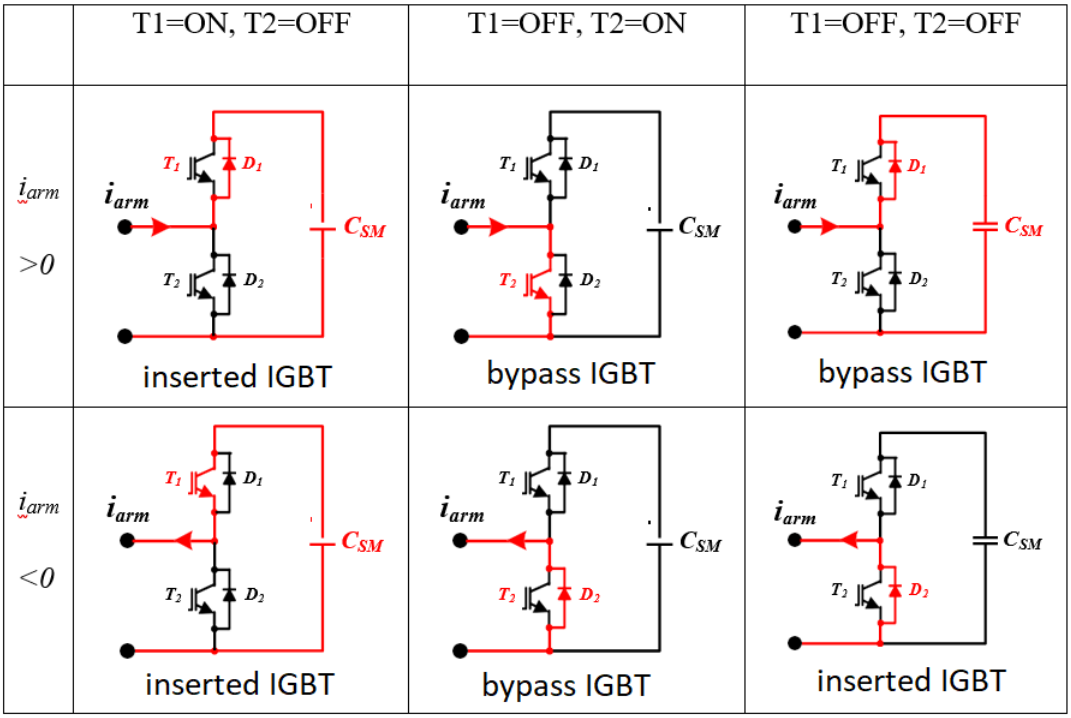


Figure II.3: Submodule states and current paths

It can be deduced that charging and discharging of submodule capacitor occur when T1 is turned on. If the arm current is positive, then the capacitor is charged and if it is negative, then the capacitor is discharging. This fact will be useful when discussing capacitor voltage balancing. In addition, the ideal value of the capacitor voltage is given by :

$$V_{cap} = \frac{V_{dc}}{n} \tag{II.1}$$

V_{cap} represent the voltage of the capacitor in the submodule and n is the number of capacitors per arm.

Unveiling the inner workings of the MMC, this section delves into the fundamental principles behind its operation. We'll explore how the interactions between submodules and their switching strategies translate into the overall power conversion and control functionalities of the MMC.

II.4 MMC Working Principle

Even while **MMC** operates on a more complicated idea, The basis idea similar to the fundamental two Level voltage source converter **2L-VSC** . The output voltage is constructed based on the submodule number in multiple steps.

The modulator converts the control signals into gate signals for the IGBTs; to produce the desired voltage at the output,there for some submodules are inserted while the others are bypassed

Another important point to mention is the capacitors in submodules that are not fed by an external power source. Therefore, they are called floating. Charging and discharging should cancel out each other over a period and all submodule capacitor voltages should be close or ideally equal to each other. Therefore, capacitor voltages in an arm should be equalized in all the operating time by an active balancing control. In any proposed control method, the balancing basically depends on the current paths and the states given in Figure II.3, for example, if it is desired to increase the voltage of a submodule, then its on-duration may be increased when arm current is positive. The condition of turned-on T1 determines the charging process. Also, turn-on of a submodule is equivalent o turn-on of T1. As a result, the charging of a submodule capacitor is coupled with insertion of submodules.

By deconstructing the underlying principles that govern the system's operation in the previous section , we can now establish a mathematical model. This model will capture the key relationships between variables and allow us to analyze and predict the system's behavior quantitatively and help us on the control of the MMC.

II.5 Mathematical model of the MMC

II.5.1 Electric Equations

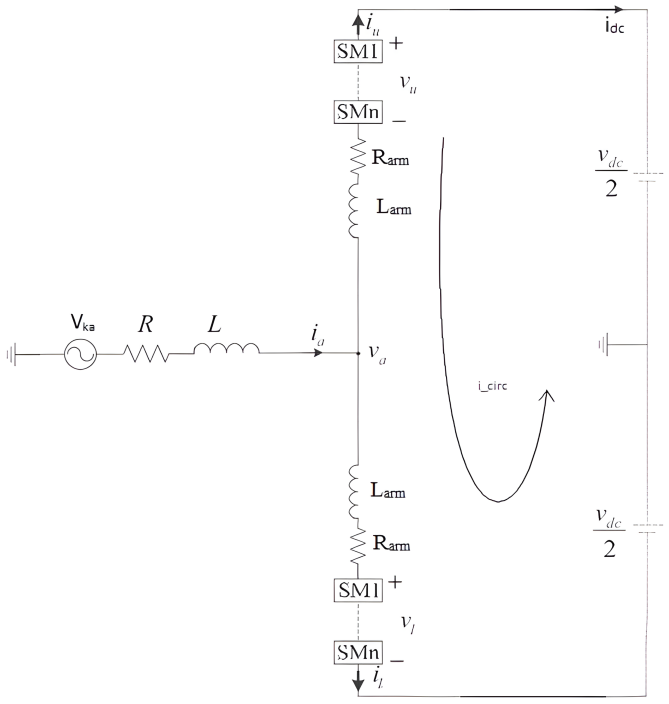


Figure II.4: Single phase MMC

For a better analysis of the MMC model on the medium-voltage side, considering a single Leg corresponding to a single phase Figure II.4, (the behavior is identical for the other phases).and by using Kirchhoff's Voltage Law and assuming the voltage drop across the arm inductors is negligible, a set of equations relating the voltages of an MMC can be derived as follow [5]:

$$i_{uk} = i_{circ} - \frac{i_k}{2} \tag{II.2}$$

$$i_{lk} = i_{circ} + \frac{i_k}{2} \tag{II.3}$$

Where i_{uk} and i_{lk} are respectively the currents of the upper and lower arms of the phase. i_k is the mains-side phase current given by:

$$i_k = i_{lk} - i_{uk} \tag{II.4}$$

i_{circ} is the circulation current, which can be obtained by adding II.2 and II.3 :

$$i_{circ} = \frac{i_{lk} + i_{uk}}{2} \tag{II.5}$$

For the different voltages characterizing the arm of MMC, they are expressed by :

$$V_k + R_{arm}.i_{uk} + L_{arm}.\frac{di_{uk}}{dt} + V_{uk} - \frac{Vdc}{2} = 0 \tag{II.6}$$

$$V_k - R_{arm}.i_{lk} - L_{arm}.\frac{di_{lk}}{dt} - V_{lk} + \frac{Vdc}{2} = 0 \tag{II.7}$$

Building on the previous equations, we obtain

$$V_{uk} = \frac{Vdc}{2} - V_k - R_{arm}.i_{uk} - L_{arm}.\frac{di_{uk}}{dt} \tag{II.8}$$

$$V_{lk} = \frac{Vdc}{2} + V_k - R_{arm}.i_{lk} - L_{arm}.\frac{di_{lk}}{dt} \tag{II.9}$$

By replacing II.2 and II.3 we obtain :

$$\begin{cases} V_{uk} &= \frac{Vdc}{2} - V_k - R_{arm}.i_{circ} + \frac{R_{arm}}{2}.i_k - L_{arm}.\frac{di_{circ}}{dt} + \frac{L}{2}.\frac{di_k}{dt} \\ V_{lk} &= \frac{Vdc}{2} + V_k - R_{arm}.i_{circ} - \frac{R_{arm}}{2}.i_k - L_{arm}.\frac{di_{circ}}{dt} - \frac{L}{2}.\frac{di_k}{dt} \end{cases} \tag{II.10}$$

the addition of the equations in II.10 gives :

$$V_{dc} = V_{uk} + V_{lk} + 2\left(R_{arm}.i_{circ} + L\frac{di_{circ}}{dt}\right) \tag{II.11}$$

by subtracting the same equations we got :

$$V_k = \frac{V_{lk} - V_{uk}}{2} + \frac{R_{arm}}{2}.i_k + \frac{L_{arm}}{2}.\frac{di_k}{dt} \tag{II.12}$$

$$e_k = \frac{V_{lk} - V_{uk}}{2} \tag{II.13}$$

V_k: is the voltage of phase k on the mains side.

V_{uk}, V_{lk}: are the voltages at the upper and lower arms, respectively.

V_{dc}: is the voltage on the DC side of the MMC.

R_{arm} and L_{arm}: are respectively the resistance and inductance of the MMC arm

Combining the results of equation II.12 and the equation II.13, we arrive at the conclusion that:

$$e_k = \frac{V_{lk} - V_{uk}}{2} = V_k - \frac{R_{arm}}{2}.i_k - \frac{L_{arm}}{2}.\frac{di_k}{dt} \tag{II.14}$$

For all the three phase:

$$\begin{cases} e_a &= V_a - \frac{R_{arm}}{2}.i_a - \frac{L_{arm}}{2}.\frac{di_a}{dt} \\ e_b &= V_b - \frac{R_{arm}}{2}.i_b - \frac{L_{arm}}{2}.\frac{di_b}{dt} \\ e_c &= V_c - \frac{R_{arm}}{2}.i_c - \frac{L_{arm}}{2}.\frac{di_c}{dt} \end{cases} \tag{II.15}$$

e_k : represent the inner electromotive force generated in the phase (voltage of phase) and also used as reference at the control, will be discuss III.2.1.

We can notice also :

$$\begin{cases} R_{eq} &= R + \frac{R_{arm}}{2} \\ L_{eq} &= L + \frac{L_{arm}}{2} \end{cases}$$

R and L: is the input filter resistance and inductance respectively

R_{eq} and L_{eq}: is the equivalent resistance and inductance of the phase

Kirchhoff law provide a simplification for the system in this way in Figure II.5 :

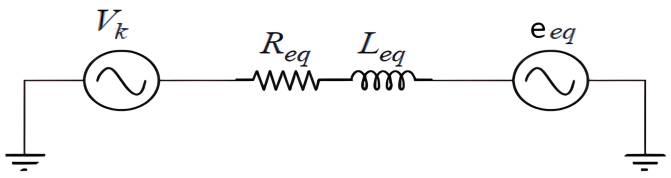


Figure II.5: Circuit equivalent for one phase from the MMC

So if we consider the AC filter (input filter) :

$$\begin{cases} e_a &= V_a - R_{eq}.i_a - L_{eq}.\frac{di_a}{dt} \\ e_b &= V_b - R_{eq}.i_b - L_{eq}.\frac{di_b}{dt} \\ e_c &= V_c - R_{eq}.i_c - L_{eq}.\frac{di_c}{dt} \end{cases} \tag{II.16}$$

II.5.2 Transformation de park

Also known with abc-to-dq, used specifically in the analysis of three-phase systems. The Park transformation simplifies the analysis of three-phase AC power systems by converting the three-phase quantitiesof the voltage and/or the current from a stationary reference frame abc to a rotating reference frame dq0. And It's not directly related to parks or transformations in the general sense. The Park transformation proses goes from $abc$to$\alpha\beta$(Clarke) than from $\alpha\beta$ to dq (park).

Clarke Transformation:

The Park transformation is often applied in conjunction with the Clarke transformation. which takes the three-phase quantities (a, b, c) and converts them to two-phase quantities (alpha, beta).

$$\begin{bmatrix} \alpha \\ \beta \\ 0 \end{bmatrix} = \frac{2}{3}. \begin{bmatrix} 1 & \frac{-1}{2} & \frac{-1}{3} \\ 0 & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} \tag{II.17}$$

α and β are the transformed two-phase components in the stationary reference frame.
0 is the zero-sequence component (usually negligible).
a b and c are the original three-phase quantities (currents or voltages)

Park Transformation

The Park transformation then takes these two-phase quantities (alpha, beta) and transforms them into a rotating reference frame (d, q, 0).
By converting to a rotating reference frame that moves with the rotor, the analysis becomes more intuitive as some complex calculations in the stationary frame are simplified.

$$\begin{bmatrix} d \\ q \\ 0 \end{bmatrix} = \begin{bmatrix} \cos(\theta) & \sin(\theta) & 0 \\ -\sin(\theta) & \cos(\theta) & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} \alpha \\ \beta \\ 0 \end{bmatrix} \tag{II.18}$$

d is the Direct axis component.

q is the Quadrature axis component

θ represents the angular displacement between the stationary reference frame $\alpha\beta$ and the rotating reference frame dq

So now by applying the park transformation on the equation II.16 we simplify the system to :

$$\begin{cases} e_d &= V_d - R_{eq}.i_d - L_{eq}.\frac{di_d}{dt} - \theta L_{eq}.i_q \\ e_q &= V_q - R_{eq}.i_q - L_{eq}.\frac{di_q}{dt} + \theta L_{eq}.i_d \end{cases} \tag{II.19}$$

In order to implement the Clarke-Park transformation on the measured currents, the measurement of the angle of the phase voltage is required. There are several ways to measure this angle, for input grid voltage, one of the most usual ways to do it is by using a Phase-Locked-Loop PLL block Figure II.6.

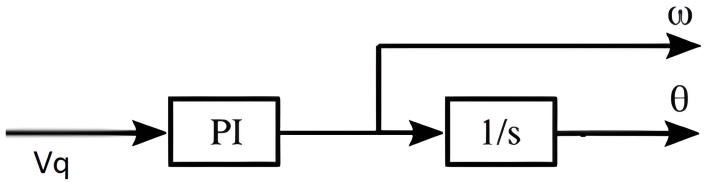


Figure II.6: Phased_Locked Loop control

The key is to select adequate values for the PI controller parameters. As a first guess, the values for K_{IPLL} and K_{PPLL} can be chosen as:

$$\begin{cases} PI_{PLL} & = K_{PPLL}\left(1 + \frac{K_{IPLL}}{s}\right) \\ K_{PPLL} & = \frac{2BW_{PLL}}{V_m} \\ K_{IPLL} & = \frac{BW_{PLL}^2}{V_m} \end{cases} \tag{II.20}$$

where B_{WPLL} is the bandwidth of the PLL. For reference, a value of $Bw_{PLL} = 10H_Z$ can be initially targeted [4].

II.6 Conclusion

Chapter 2 explores the Modular Multilevel Converter MMC system, detailing its topology, operation, and mathematical model. The following chapter focuses on the control strategies for the MMC system.

Chapter III

Control of the MMC

III.1 Introduction

Control theory works with the dynamic systems and modifies their behaviours by an external controller. The aim of the control theory is to make a system to follow a desired reference signal. In power electronics, generally inductor current, capacitor voltage and motor speed is controlled. Their basic electrical and mechanical equations that describe the dynamics determine the controlled variable and control action to be utilized.
Switching and control issues of MMC are similar to the conventional 2L-VSCs. Output current, DC-link voltage, and active and reactive power control methods are fundamentally the same as the 2L-VSC. However, it has some unique aspects also. The fact that MMC has floating capacitors is the main reason for the extra control requirement. The major control difference lies in the capacitor voltage balancing. If this is not successfully handled, the MMC perhaps loses stability and cannot operate. Additionally, the presence of the circulating current leads to another control, the suppression of harmonic content of circulating current. In this way, efficiency improvement in the converter and usage of components with low ratings may be possible. Furthermore, in the literature, several types of PWM methods for MMC are proposed.

Apart from output current, DC-link voltage, and power control, which are fundamentally common to all VSCs, in the literature, there are mainly two types of inner control which deals with the special control aspects of MMC. First one is based on sorting algorithm and proposed by Lesnicar and Marquardt will be discussed in subsection III.2.2. The other one is based on phase-shifted PWM and proposed by Hagiwara and Akagi III.2.1.

III.2 Traditional Control

The goal of any control as we know is to follow the desired output in the respect of some constraint. in this case:

1. Follow the voltage reference on the out put (desired output)
2. Limited balancing voltage on the capacitors.
3. Limited circulating current per arm
4. Number of inserted submodule(capacitors) in the same time equal to n per phase

III.2.1 Rotating algorithm Control

Figure III.1: Block diagram of phase-shifted

In a simple explanations this method is divided in three main parts:
First part: calculate the reference in each arm, which is effected on the first place by the desired output and the charge implemented with the MMC and its calculated which the output current control block as you can see in Figure III.1.
second part: comparing the reference with identical triangles (PWM technique) to make the capacitor related to the triangle inserted or bypassed. Which represented by PWM block of Figure III.1.
third part: here phase−shifted block in Figure III.1 force the desired output additionally to a simplification on the control.

Current control block

This method, also known as Voltage Oriented Control VOC, is widely used in inverters and adopted by MMC to calculate phases reference.
considering the reference from equation II.19, the d component of the current will control the active power demanded from the grid (source without filter), while the q component will fix the reactive power. This enables then for full power factor control of the input power.
The control scheme can be understood as in Figure III.2. The grid voltage and current magnitudes are transformed into dq coordinates, also obtaining the grid voltage phase and frequency information from the **pll** block. These parameters, together with the Vdc voltage are used as measured magnitude in the control stage.

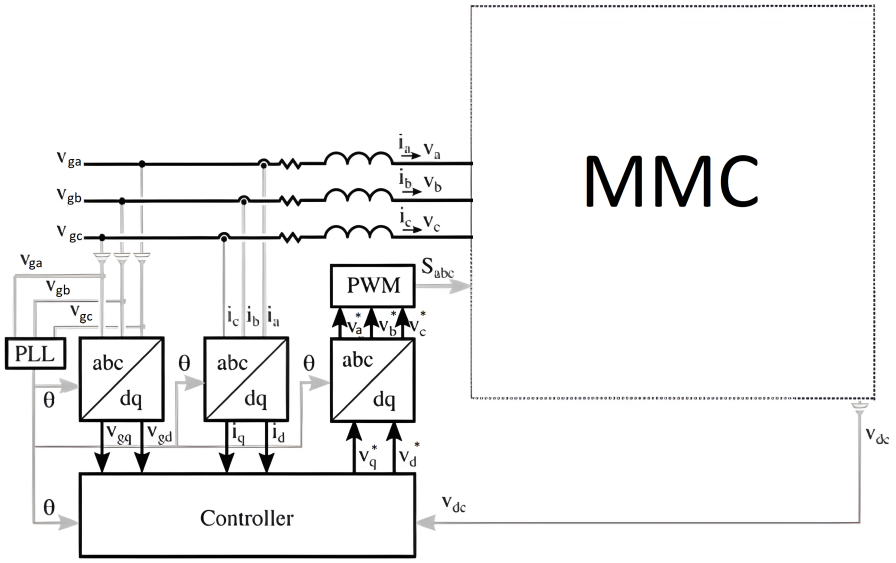


Figure III.2: Block control diagram

The idea is to control the output DC link voltage, vdc, by means of a voltage control loop. The output of this external loop provides the reference for the grid id current. Indeed, this id current is in phase with the grid voltage, as stated below, and takes into account the active power entering to the system. Thus, if the power demand at the load suddenly increases, the DC link voltage will decrease, and the voltage control must increase the reference for the d current id*, so as to provide more active power to the load and, consequently, increase back to the nominal value the DC link voltage level.

The reference for the iq* component is defined as a function of the desired power factor at the input of the rectifier. In case unity power factor is required, this reference can be set to 0.

This way, the reference for the grid d and q coordinates is now fixed; two internal current control loops can be therefore schematized as in Figure III.3 [9, 17].

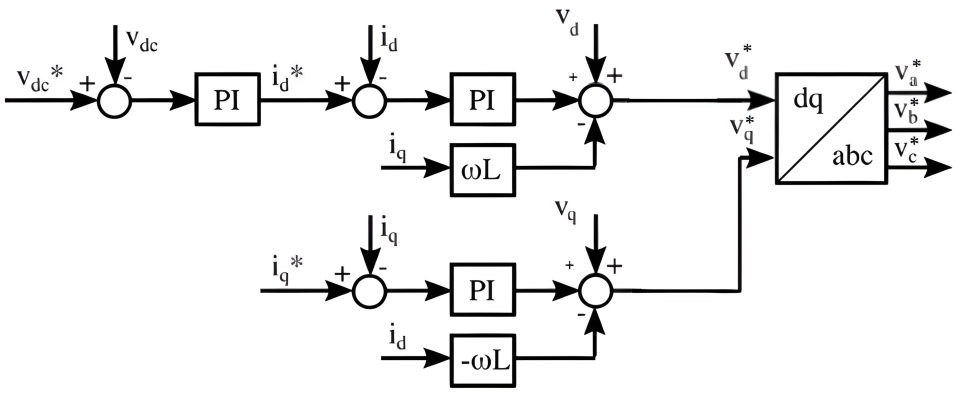


Figure III.3: Decoupled control diagram

Pulse Width Modulation block

As we know the basic idea of the PWM technique for effectively controlling the power supplied to electrical devices. In order to attain a desired average voltage or power level, the principle of pulse width modulation PWM is used for a periodic signal.

We utilize PWM technique by comparing the arm reference with n triangle waves, These carrier waves have a phase difference $2\pi/n$ radians between them. the instantaneous result of comparing give back State of submodules.

To maintain a total of n submodules per phase, opposite references (with a π radian phase difference) are applied to the upper and lower arms.

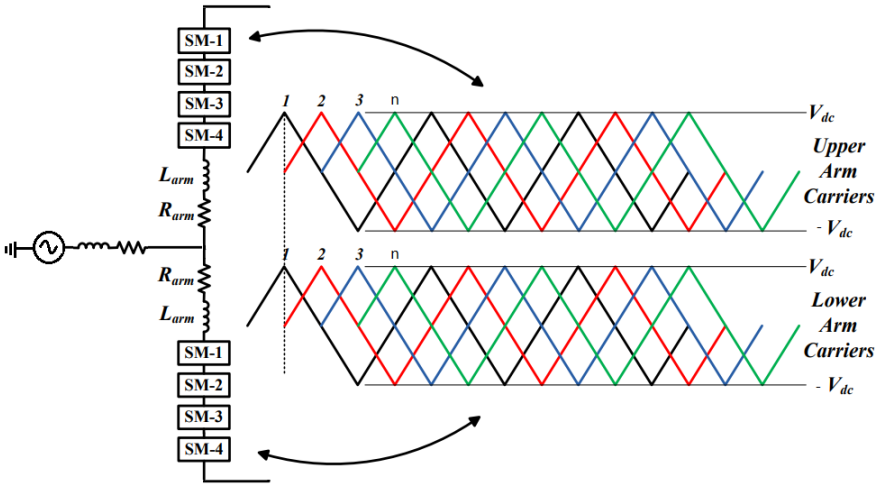


Figure III.4: Phase-shifted identical triangular carriers

Pulse Width Modulation block

Only a limited number of the total swishing state possibilities are taken. he main idea of choosing the switching state is guarantee the desired output tracking and at the same time division of labor by the IGBT's

Simulation results

While this technique improves on the MMC output characteristics Figure III.5 and III.6, it compromises capacitor voltage balancing Figure III.7 and Figure III.8. This imbalance create a circulating current Figure III.9 which injects harmonics back into the power grid Figure III.11 and Figure III.10 , potentially causing damage. Additionally, if the maximum voltage rating of the capacitors is lower than the required balancing voltage, capacitor failure becomes a risk.

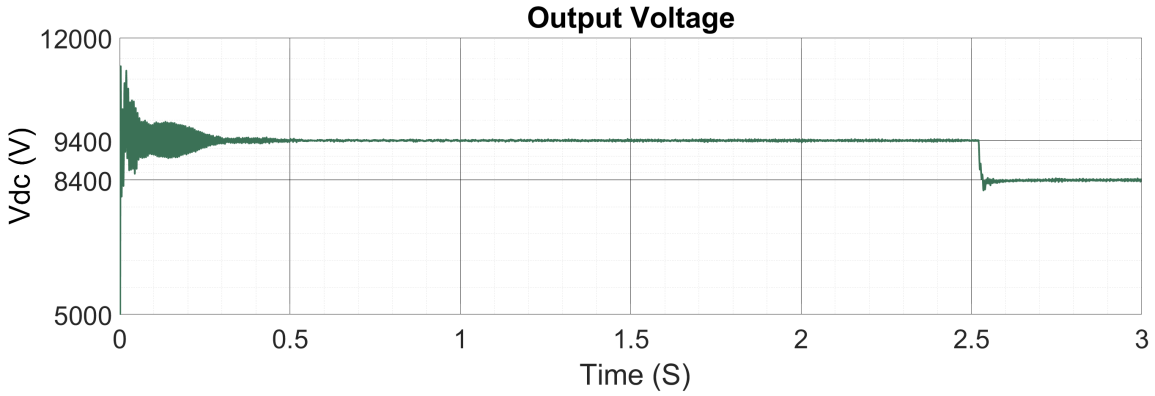


Figure III.5: V_{dc} Transient and Steady state on the Rotating Algorithm control

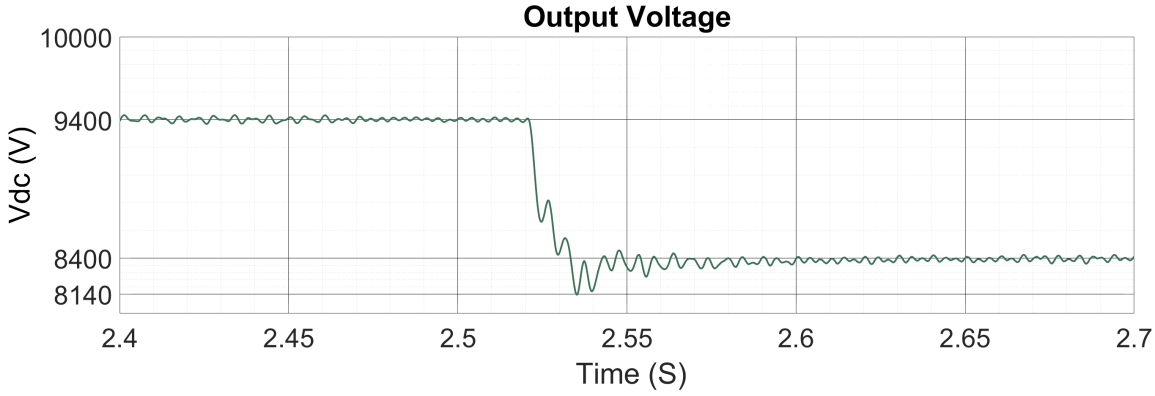


Figure III.6: V_{dc} Commutation state on the Rotating Algorithm control

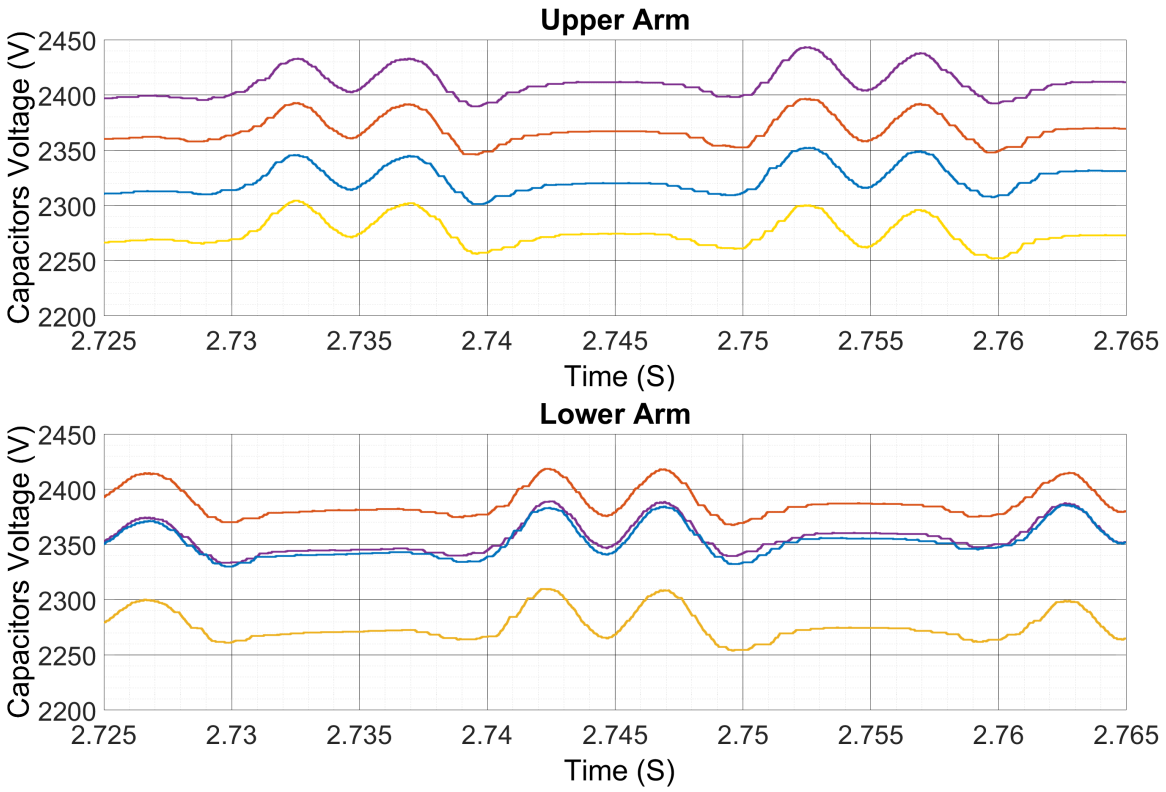
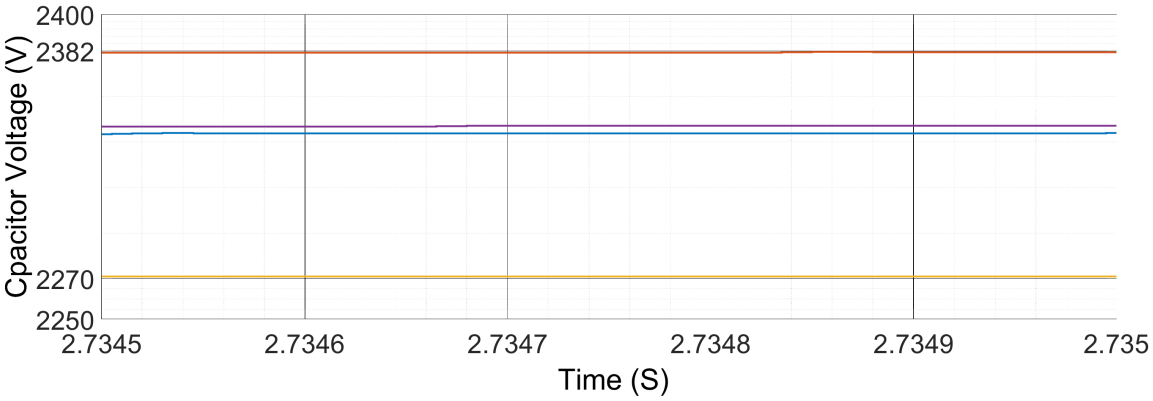


Figure III.7: Capacitors Voltage balancing on the Rotating Algorithm control



c

Figure III.8: Capacitors Voltage different on the Rotating Algorithm control

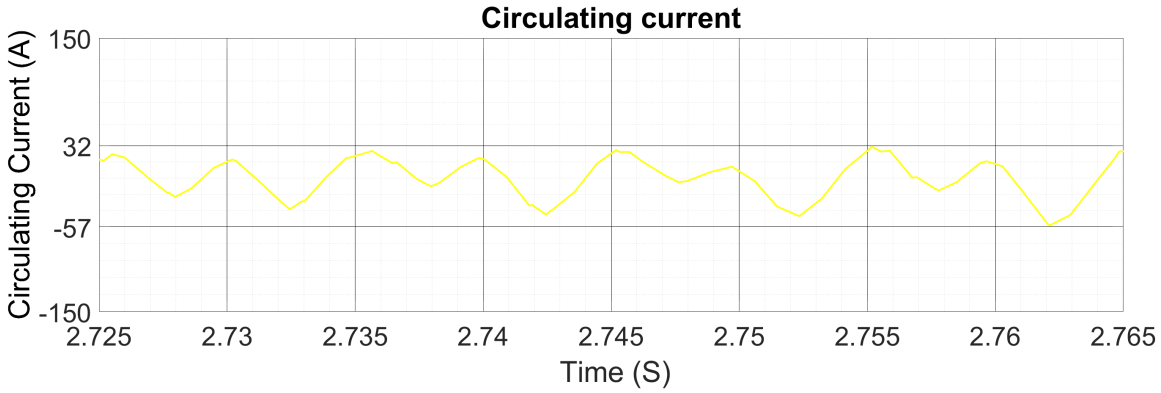


Figure III.9: Circulating Current on the Rotating Algorithm control

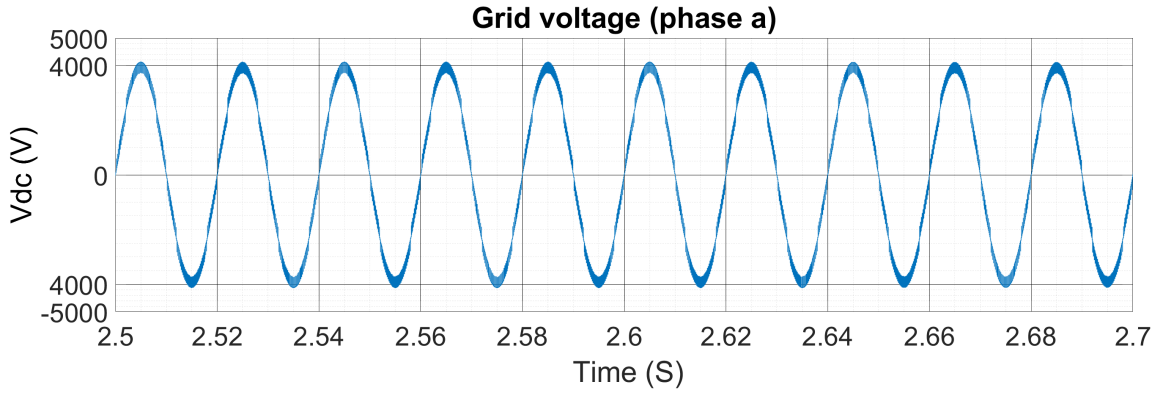


Figure III.10: Grid voltage on the Rotating Algorithm control

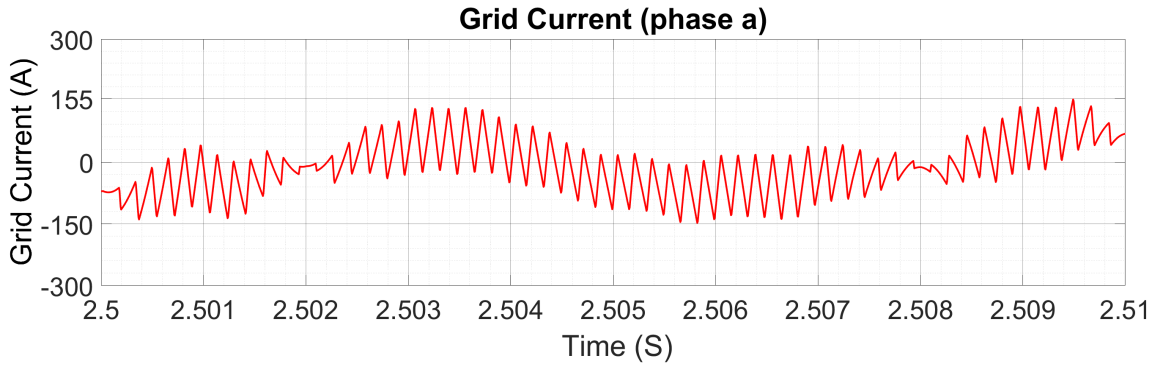


Figure III.11: Grid Current on the Rotating Algorithm control

To enhance the efficiency of the Modular Multilevel Converter MMC, improved capacitor voltage balancing and reduced circulating current are crucial. This can be achieved by implementing a new control algorithm, which will be discussed in detail in the following subsection.

III.2.2 Sorting algorithm control

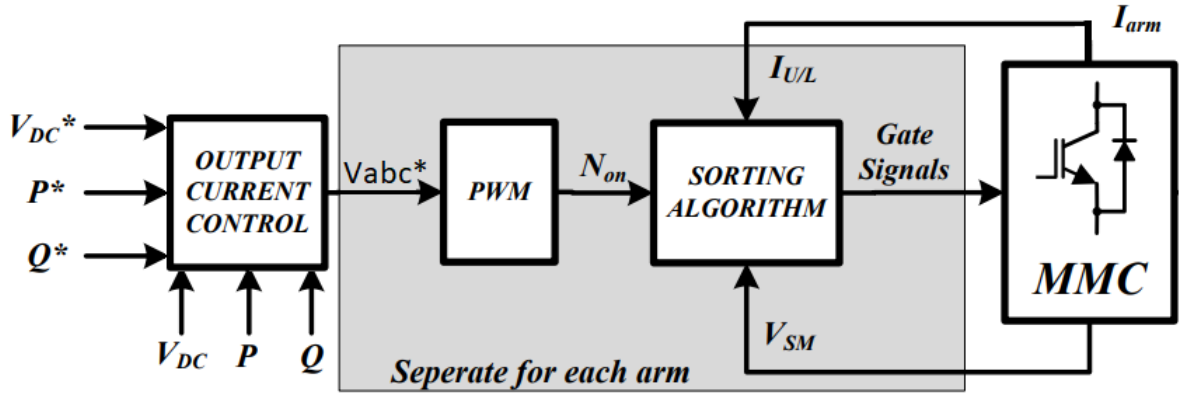


Figure III.12: Block diagram of sorting algorithm

This algorithm method in a simple explanation is divided in three main parts:

First one: calculate the reference in each arm, which is effected on the first place by the desired output and the charge implemented with the MMC and its calculated with the output current control block as you can see in Figure III.12.

Second part: fix number of submodules inserted in upper and low arm per each phase, using PWM block in Figure III.12.

Last part: now the sorting algorithm block in the same Figure III.12 can pick which submodule is inserted and which one is not.

Now Let's have a better understanding how each block works:

Current Control block

This block is common between phase shifted and sorting algorithm method. Subsubsection explain it with details III.2.1.

Pulse with modulation block

Similar to the rotating algorithm we use PWM technique and comparing the identical triangles with the reference but we get in return the number will be inserted and not the state on every single submodule.

Sorting algorithm block

This block sorts capacitors based on their voltage levels. It then determines which submodules to activate or bypass based on both the sorted voltage and the direction of the

current (positive or negative).

When a capacitor is inserted into the circuit with positive current , it discharges as current flows through it from the negative plate to the positive plate.

When a capacitor is inserted into the circuit with negative current , it charges as current flows through it from the positive plate to the negative plate.

Simulation results

The following figures present the simulation results for a sorting algorithm that controls the output voltage V_{dc} (Figures III.13 and III.14) from the AC source (Figures III.19 and III.18). A key feature of this algorithm is its ability to balance the capacitor voltages, minimizing both the minimum and maximum values and reducing the difference between the highest and lowest instantaneous voltages (Figures III.16 and III.16), lead to limited circulating Current .

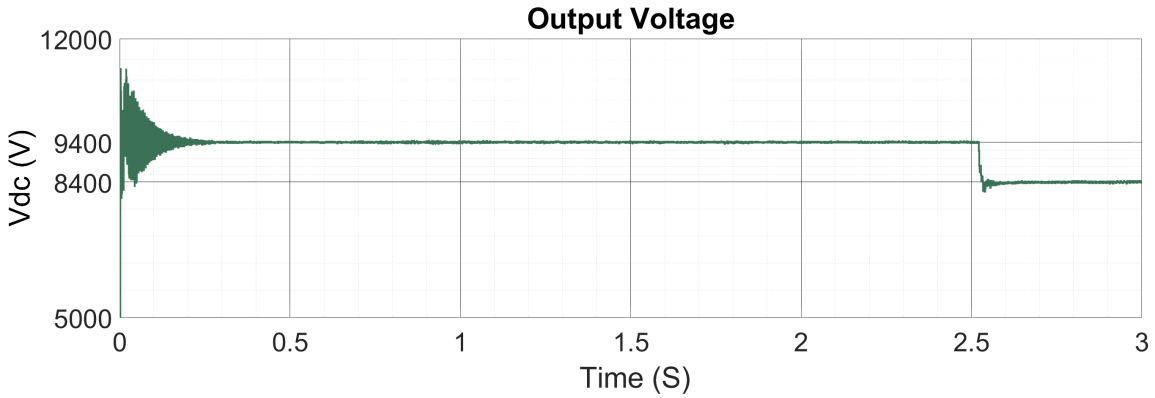


Figure III.13: V_{dc} Transient and Steady state on the Sorting Algorithm control

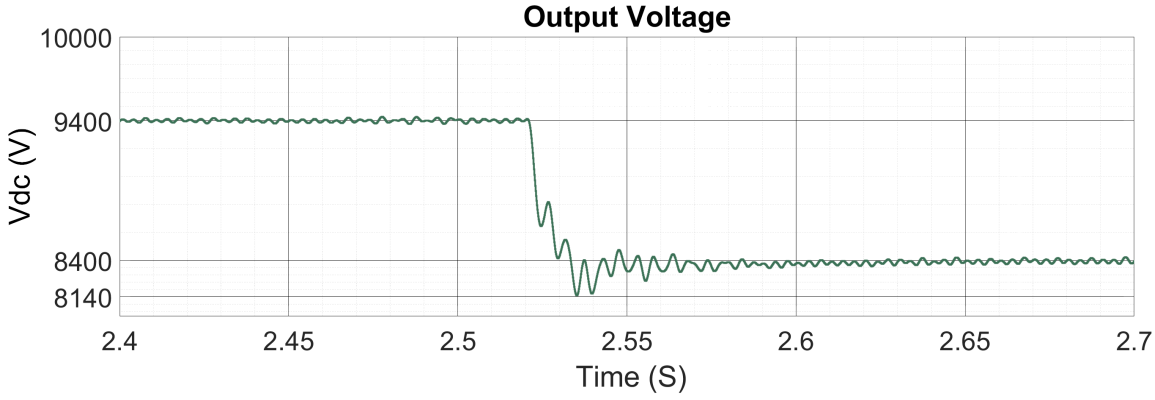


Figure III.14: V_{dc} Commutation state on the Sorting Algorithm control

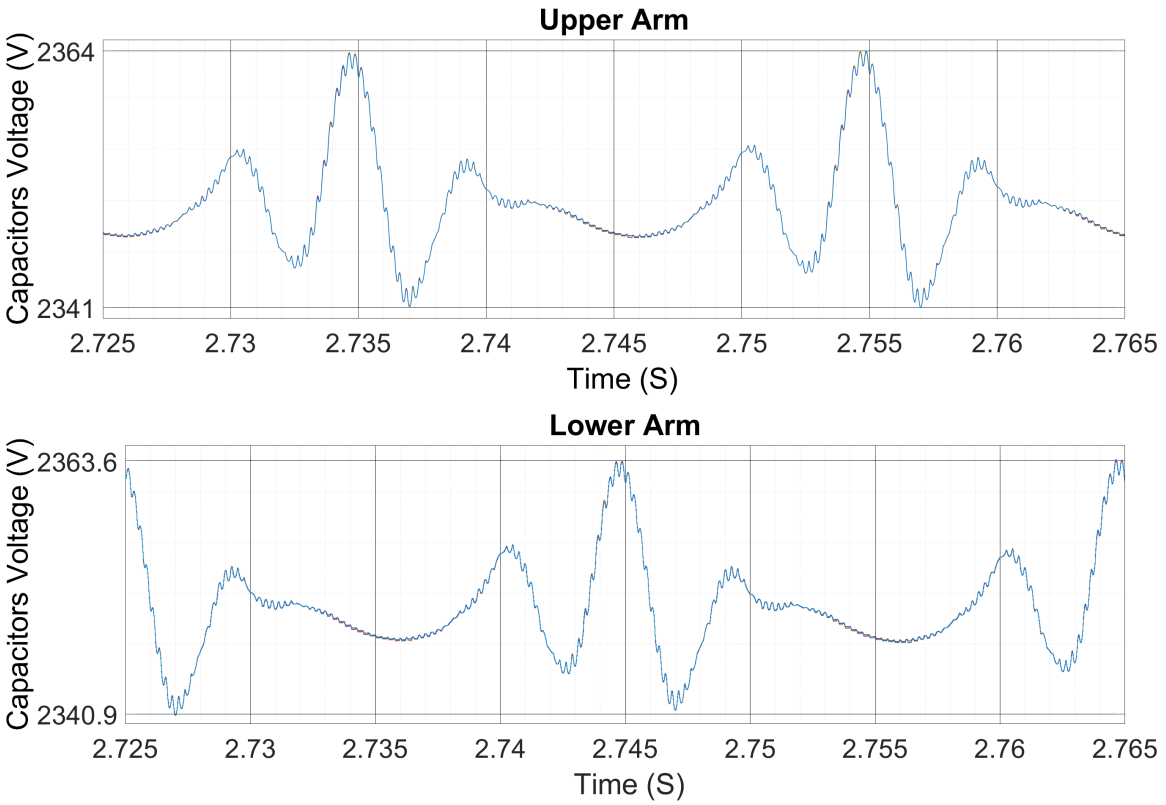


Figure III.15: Capacitors Voltage different on the Sorting Algorithm control

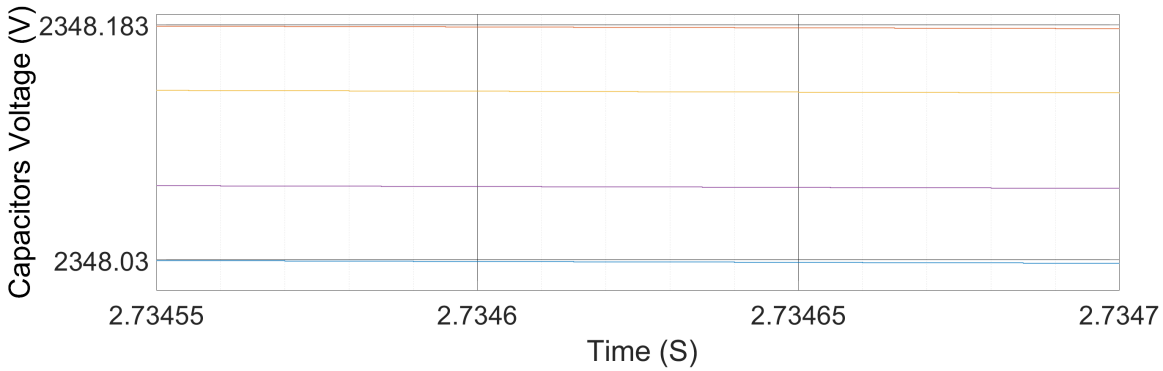


Figure III.16: Capacitors Voltage balancing on the Sorting Algorithm control

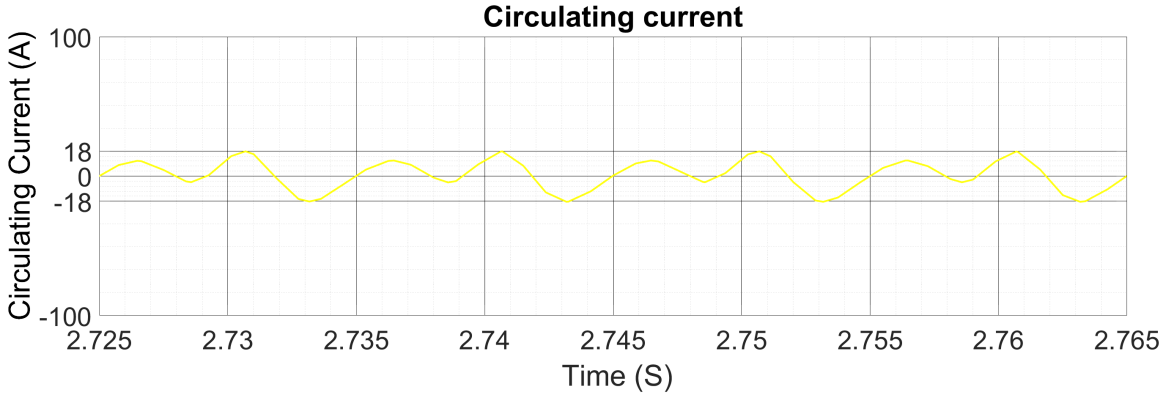


Figure III.17: Circulating Current on the Sorting Algorithm control

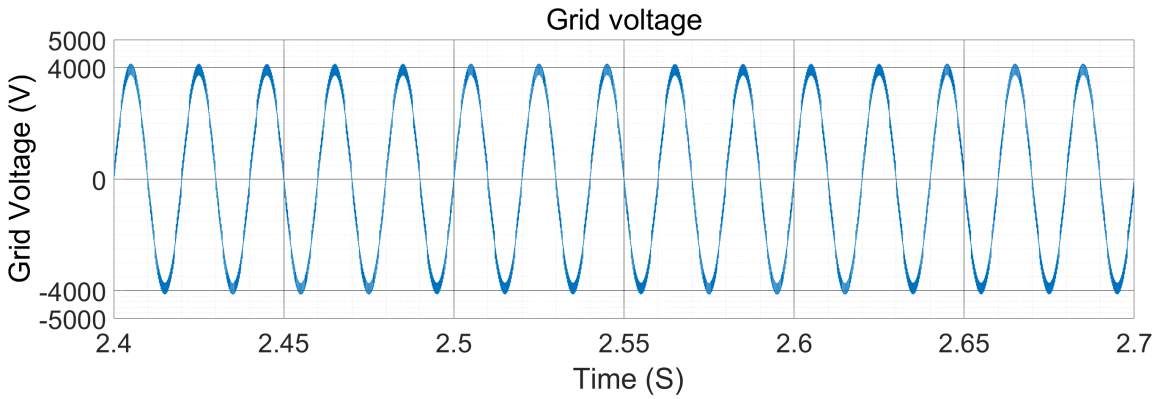


Figure III.18: Grid voltage on the Sorting Algorithm control

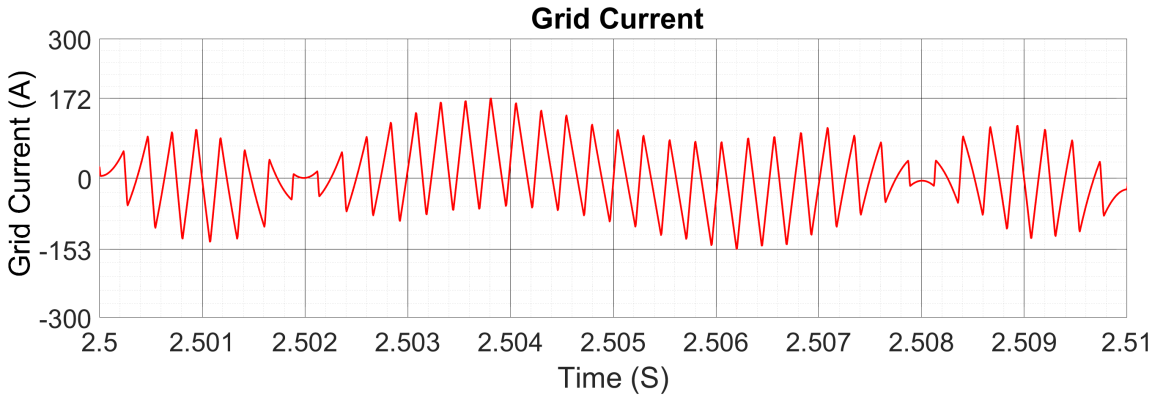


Figure III.19: Grid Current on the Sorting Algorithm control

III.3 Conclusion

While this control method boasts high efficiency, it comes at the cost of requiring a significant amount of sensors. This not only increases the overall cost of the system but also leads to longer calculation times. These longer calculation times can then manifest as slower response to transients, reduced control accuracy, and even potential for instability. Therefore, we propose a model-predictive control approach in Chapter 3. This method aims to strike a balance between the faster response times and lower cost of the first traditional control method and the high efficiency of the second method discussed earlier.

Chapter IV

Model Predictive Control for Modular Multilevel Converter

IV.1 Introduction

This chapter explores novel predictive control strategies for enhancing the performance of modular multilevel converters. We will delve into these innovative approaches and present the obtained results. Implementing predictive control requires two fundamental elements:

1. A predictive model of the system
2. Cost function that minimizes undesirable output behaviour (error).
3. Considering relevant references

Developing these elements presented a significant challenge in our case, due to the unconventional nature of the cost function, which differs from those used in typical converter applications.

IV.2 Predictive Model

Predictive models, as is widely recognized, rely on mathematical equations.Discretization of differential equations often serve as a powerful foundation for their development.

IV.2.1 Capacitors Voltage Prediction

$$V_{cap}(t + T_s) = V_{cap}(t) + \frac{T_s}{C}.i_{jk}(t)S_k \tag{IV.1}$$

i_{jk} is the currents of upper or lower arms of the phase j=$\{u/l\}$.
S_k refer to the state of submodule (capacitor) inserted equal to 1 or bypassed equal to 0.
T_s is the discretization simple time
Equation (IV.1) allows us to predict individual capacitor voltages. Furthermore,enable the predictions of arm voltage based on the number and configuration of capacitors. These predictions formed the basis for our initial predictive control model.

IV.2.2 Circulating Current Prediction

Equation (II.11) enables the derivation of the predicted circulating current equations for each phase.

$$i_{circ_j}(t+T_s) = i_{circ}(t) + \frac{T_s}{L_{arm}}\left(\frac{V_{dc}}{2} - \frac{(V_{uk_j} + V_{lk_j})}{2} - R_{arm}.i_{circ}\right) \tag{IV.2}$$

These equations (IV.2) employed in model predictive control lead to the achievement of optimal results.

IV.3 Application of MPC

IV.3.1 Objective function base on capacitors balancing

This strategy is proposed in order to track individual capacitors voltage in real time,to maintain desired output voltage V_{dc} base on the equation II.1 as an reference.

$$g = min\left(S_k \sum_{x=1}^{n} (V_{cap_pux} - V_{cap})^2 + S_k \sum_{x=1}^{n} ((V_{cap_plx} - V_{cap})\right) \tag{IV.3}$$

x is just a reference to the capacitors.
V_{cap_pux} and V_{cap_plx} represent the voltage value of capacitor related to x in real time.
V_{cap} is the reference and ideal value to capacitor voltage.
g is the objective function.

This approach proved ineffective results because the objective function combined capacitor voltage tracking. Consequently, minimizing g at all times did not necessarily guarantee the optimal switching state for maintaining the desired voltage
and at the same time we can't tracking capacitor voltage independently because it will not be related to the output and don't respect the constraint said "n capacitors inserted at the same time".

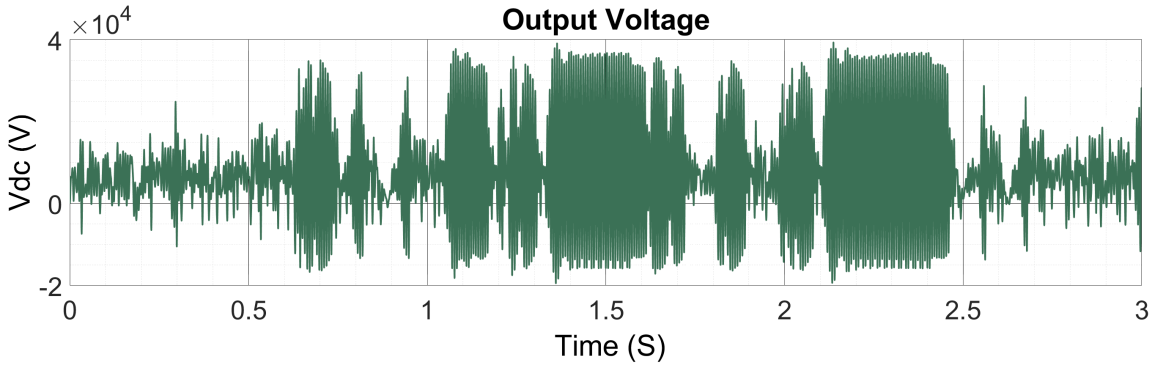


Figure IV.1: Output Voltage using the balancing strategy

This Figure IV.1 represent the output voltage of simulation using balancing strategy.

IV.3.2 Objective function base on phase voltage

This strategy is proposed in order to track phase voltage in real time,to maintain desired output voltage V_{dc} base on the equation II.13 as an reference.

$$g = min\,(e_k - V_{ref})^2 \tag{IV.4}$$

e_k is the phase voltage.
V_{ref} is the desired phase reference.

In this strategy e_k it considers every combination of submodules inserted in the upper and lower arms, so more submodule the MMC carry more calculating state will be, for example in 4 submodule per arm give 72 switching state per phase.
the strategy have better result compare to the first one and converge to the desired output but not stable cause the capacitors balancing is not considered as you can see in IV.2.

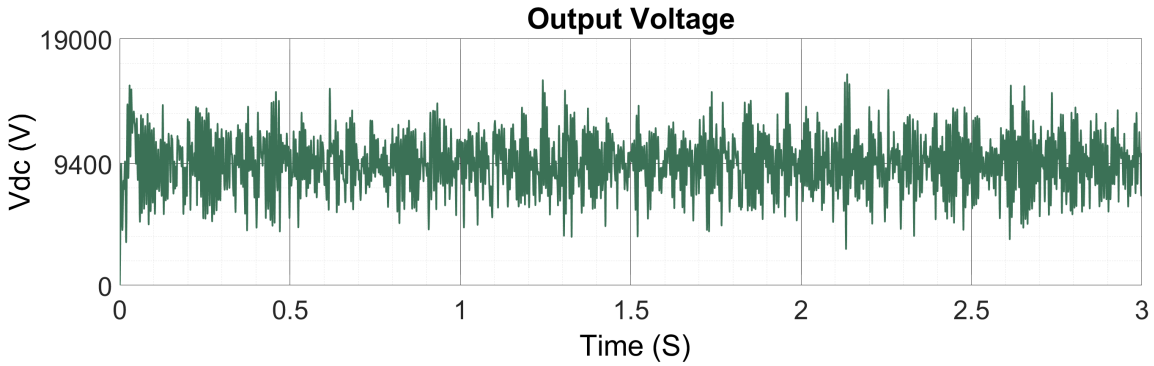


Figure IV.2: Output Voltage using the phase reference strategy

IV.3.3 Objective function base on circulating current

This is the optimal result we got out of the strategy we go throw it's basis on rotating algorithm using a model predictive for the selection of switching state to limit the circulating current equation IV.2.

In simple explication the switching state that are rotating from rotating algorithm III.2.1, now been selected by minimization of the objective function IV.5.

$$g = min\left(i_{circ_j}(t + T_s) - 0\right)^2 \tag{IV.5}$$

At first we apply the objective function base on circulating Current out of the rotating algorithm and of course it limit the circulating current IV.3, but also at the same time this objective function is not related with the output, so we had ineffective results at v_{dc} Figure IV.4.

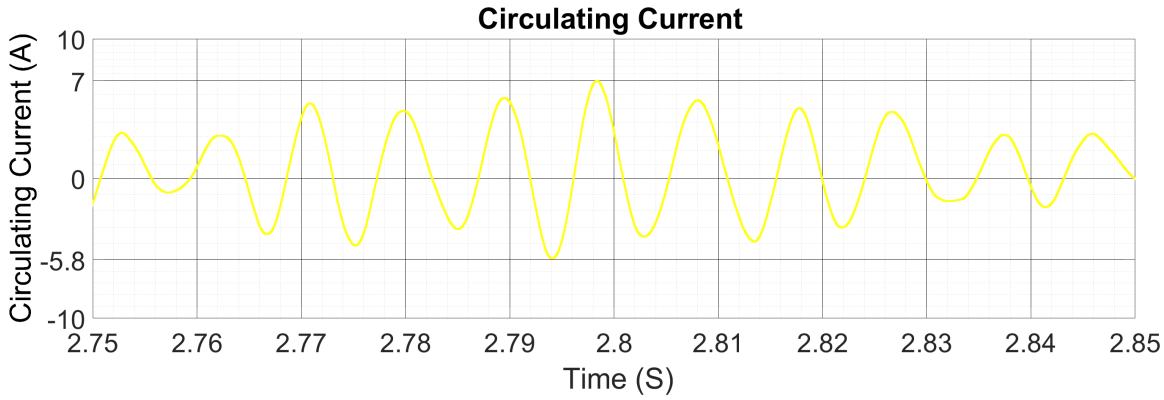


Figure IV.3: circulating current using pure MPC base on circulating current strategy

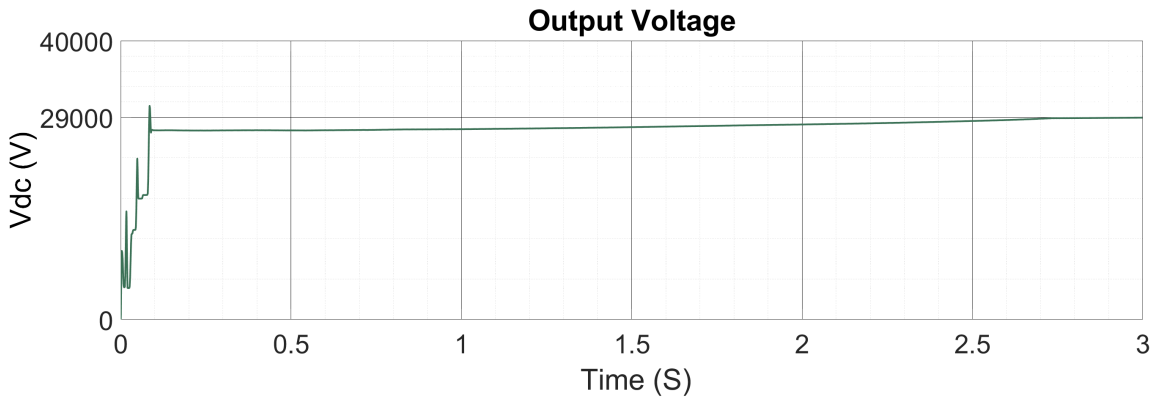


Figure IV.4: Output Voltage using pure MPC base on circulating current strategy

Than we had the idea of having a good basis for the control algorithm and of course related to the output voltage, there where we use the switching state related to the rotating algorithm. and here are the results we had.

IV.3.4 Simulation and results

Simulation

For the simulation here are the screen shots from Matlab Simulink :

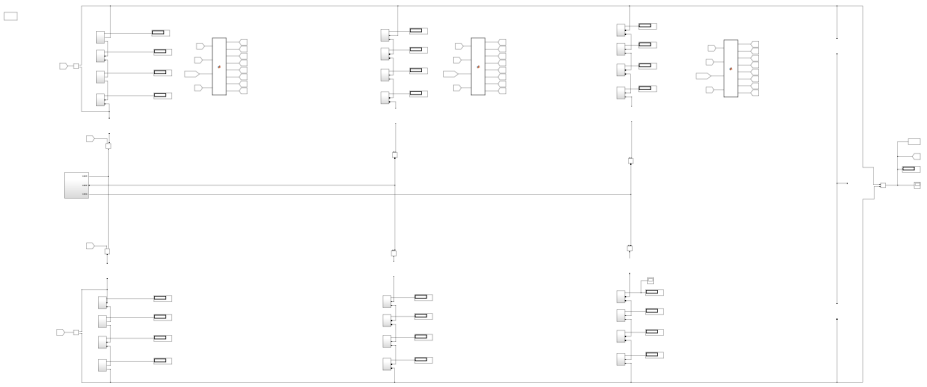


Figure IV.5: Simulation Circuit for MPC with rotating algorithm

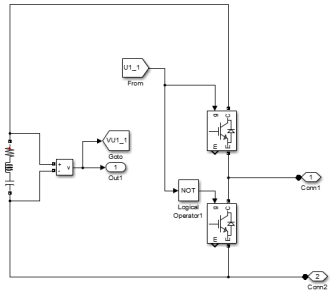


Figure IV.6: Sub-Module Simulation Circuit for MPC with rotating algorithm

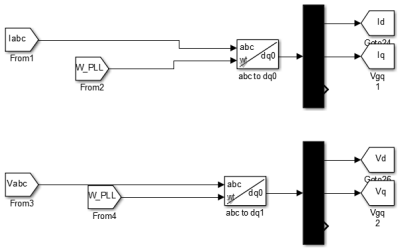


Figure IV.7: Simulation dq Transformation for MPC with rotating algorithm

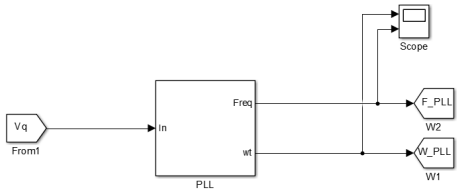


Figure IV.8: Simulation Phase Locked Loop for MPC with rotating algorithm

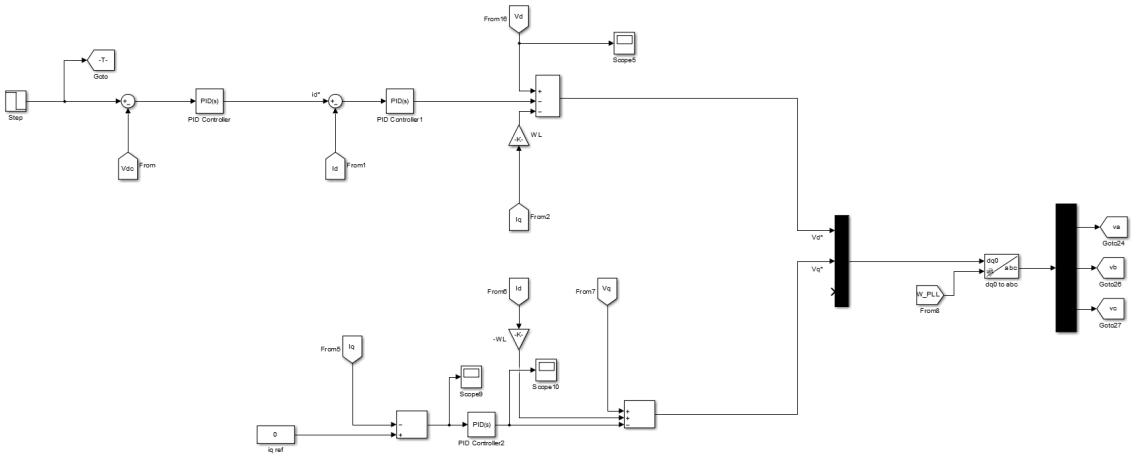


Figure IV.9: Simulation Voltage Oriented Control for MPC with rotating algorithm

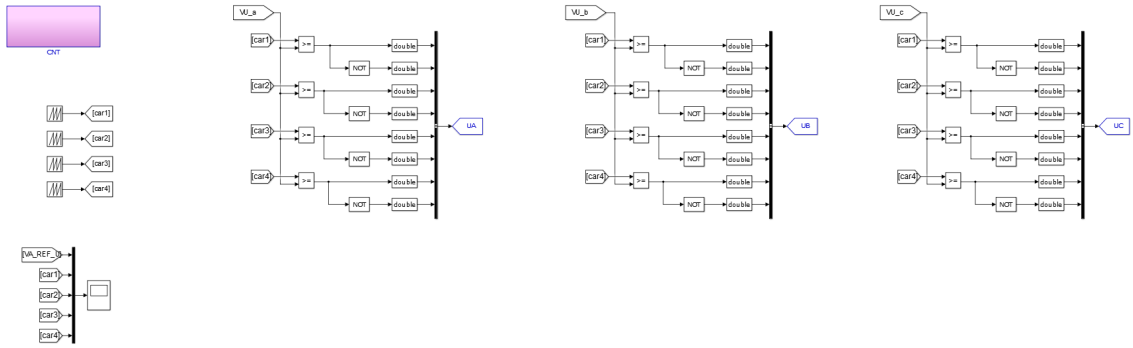


Figure IV.10: Simulation PWM technique for MPC with rotating algorithm

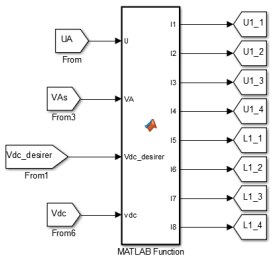


Figure IV.11: Matlab function to generate the model predicted for MPC with rotating algorithm

In the previous Figures we present the simulation circuit of the modular multilevel converter and it's sub-module Figures IV.5 and IV.6.

we go throw the dq transformation where we use a Simulink-made block Figures IV.7 and IV.8.

We present the voltage oriented control which made for the reference calculation IV.9.

Than we show you the PWM and the block function that generate the switching state Figures IV.10 and IV.11.

Results

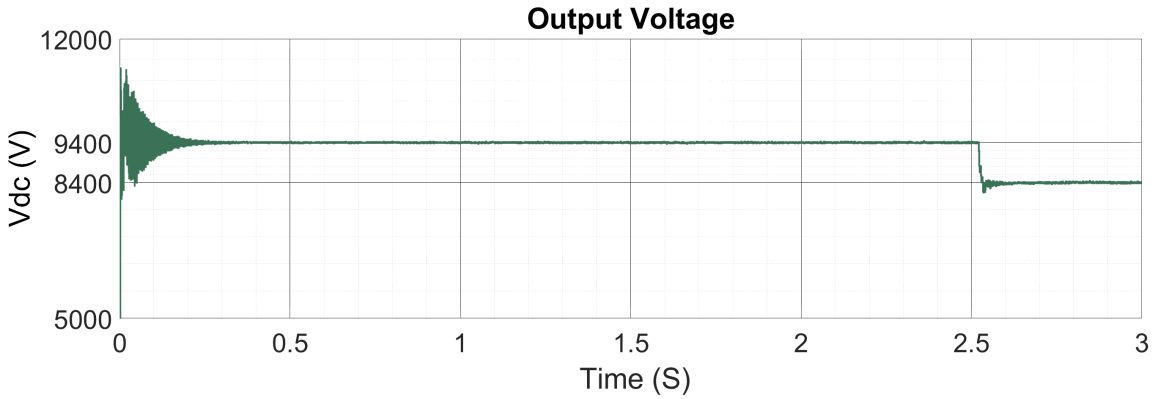


Figure IV.12: V_{dc} Transient and Steady state on MPC with rotating algorithm

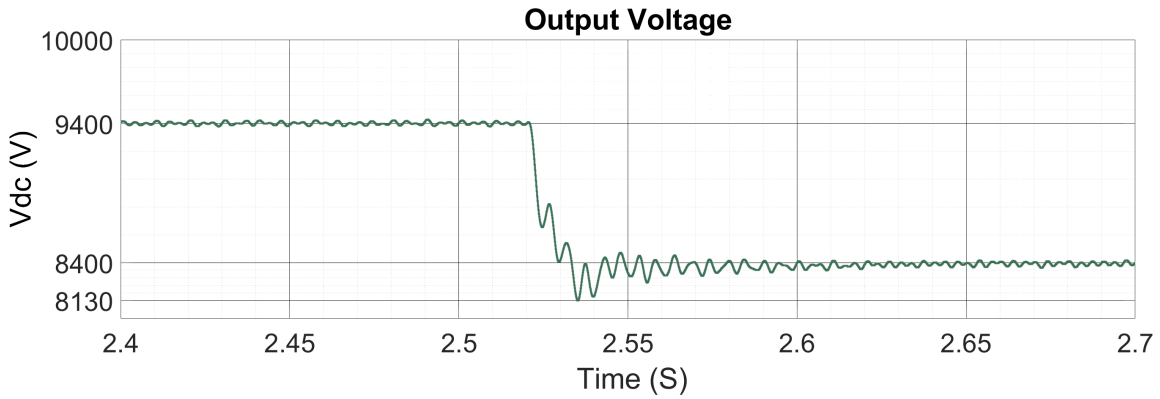


Figure IV.13: V_{dc} Commutation state on MPC with rotating algorithm

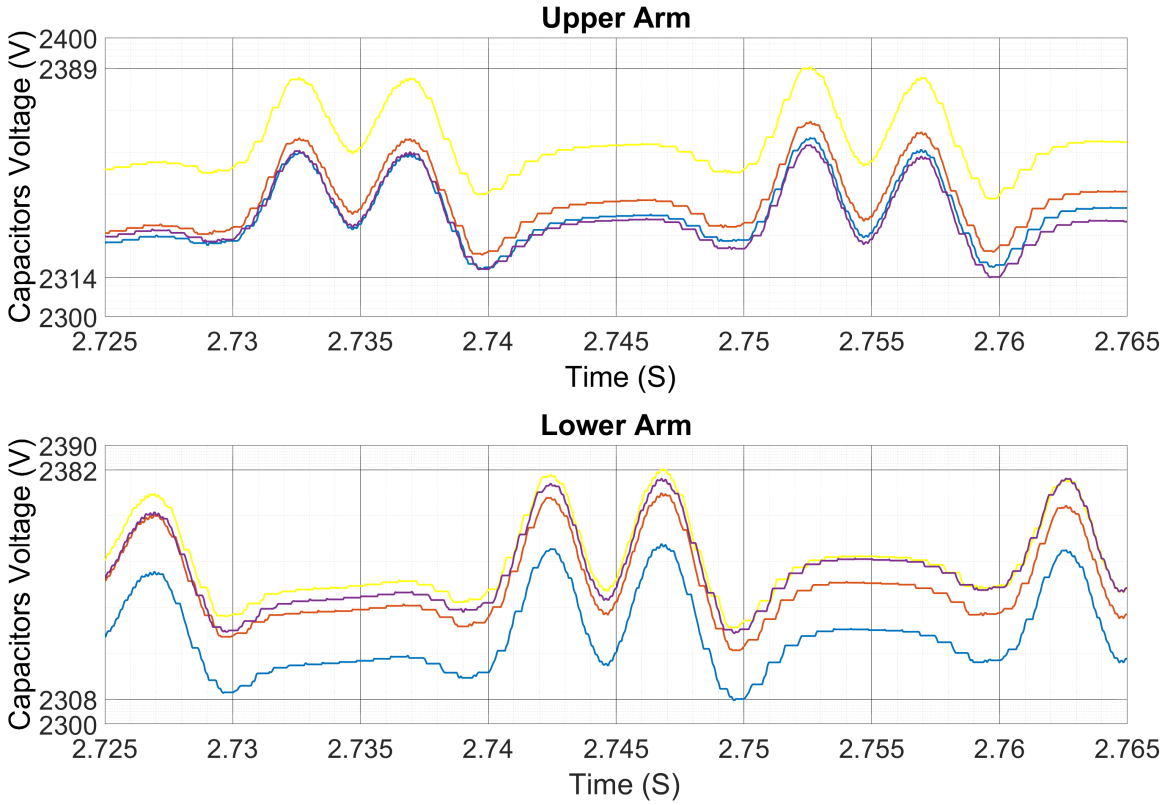


Figure IV.14: Capacitors Voltage different on MPC with rotating algorithm

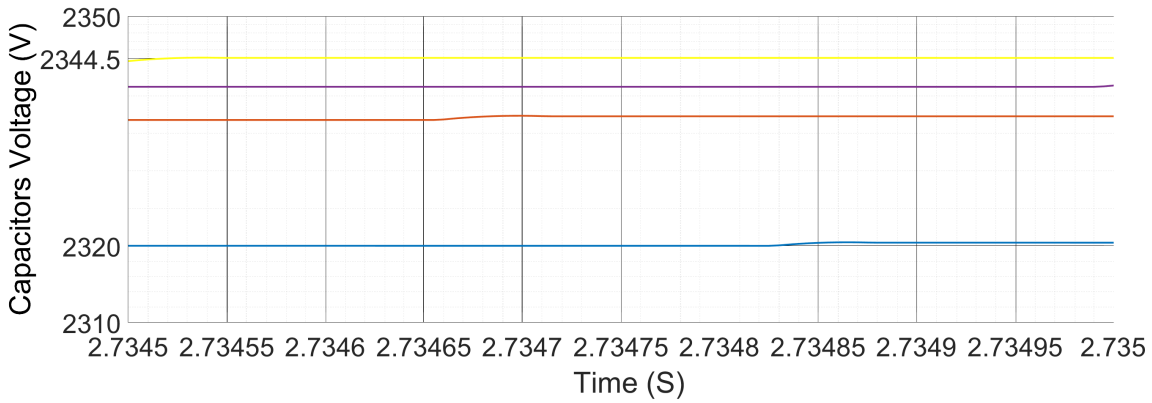


Figure IV.15: Capacitors Voltage balancing on MPC with rotating algorithm

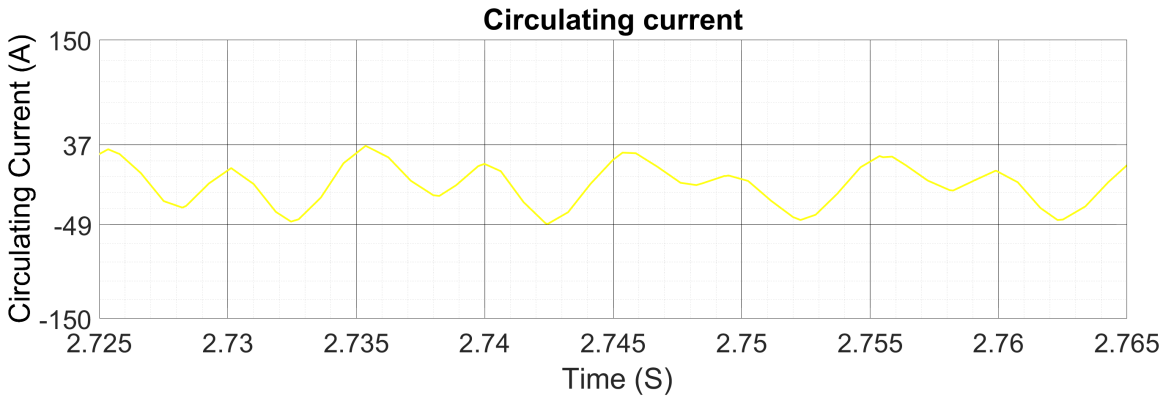


Figure IV.16: Circulating Current on MPC with rotating algorithm

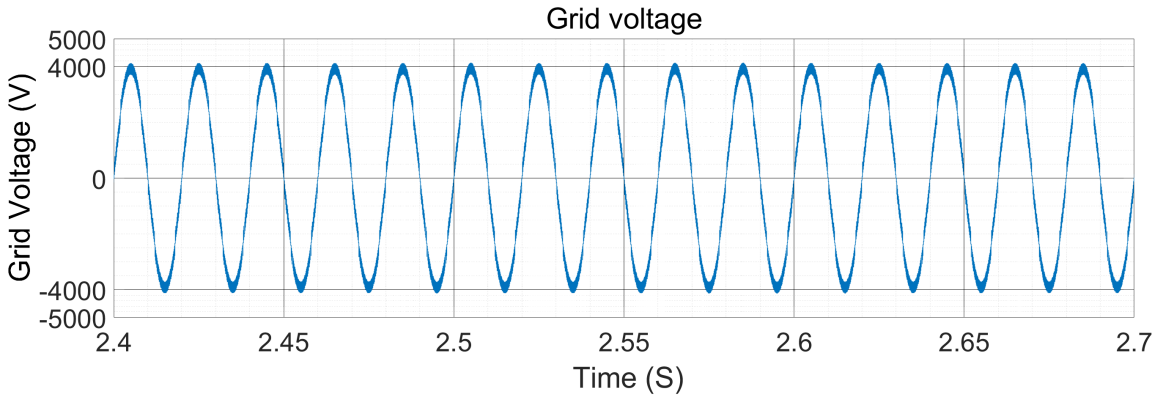


Figure IV.17: Grid voltage on MPC with rotating algorithm

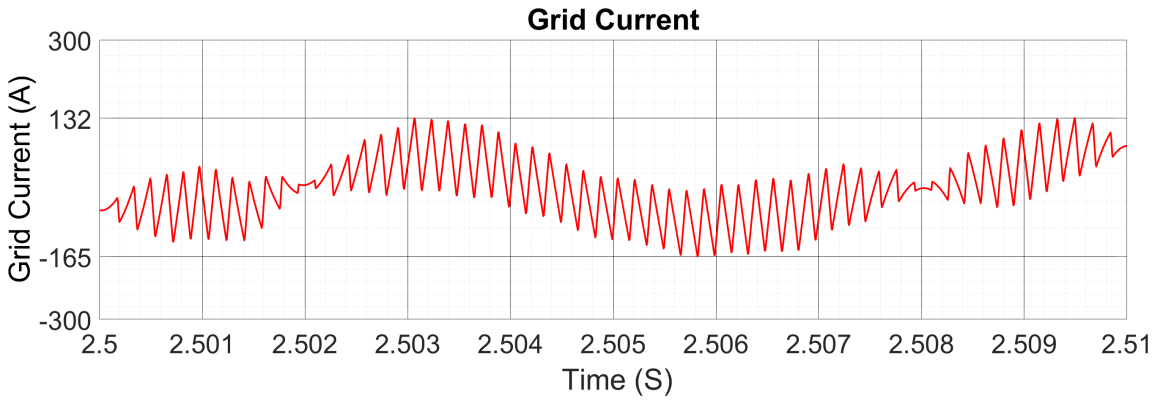


Figure IV.18: Grid Current on MPC

Now as you can see the desired output is well tracked Figures IV.12 and IV.13. Additionally, capacitors voltage balancing Figure IV.14 and IV.15 performance higher to rotating algorithm is much better and at the same time is not compare to sorting algorithm but without using sensors on the MPC. So of course the circulating current IV.16 variation in between the two traditional control algorithm.

IV.4 Conclusion

The Chapter four introduces Model Predictive Control MPC with a cost function base on circulating current for the Modular Multilevel Converter, highlighting its significance in enhancing system performance with out using sensors.

General Conclusion

This thesis successfully demonstrated a new control system for Modular Multilevel Converters MMCc utilizing Model Predictive Control MPC.

Model predictive control, especially with a rotating algorithm, offers a significant advantage by requiring fewer sensors. This translates to a more cost-effective system throughout its lifecycle.

Minimizing sensors not only reduces the amount of data that needs transmission but also streamlines the computational demands on the system, leading to overall greater efficiency.

For future work, exploring the integration of MPC with a sorting algorithm presents a promising avenue for further improvement. Such a combination could potentially achieve near-perfect output results. Additionally, investigating the possibility of adopting this enhanced control system by a leading company in the power electronics industry holds immense potential for real-world implementation and impact.

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