An MMC-based topology with Dual-Active-Bridge power channels for load balancing in 50Hz-railway applications

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An MMC-based topology with Dual-Active-Bridge Power Channels for load balancing in 50Hz Railway Applications

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Last but not least a deeply appreciation to my family and my girlfriend for their limitless support all these years

Ανδρέας Ζαφειρόπουλος
ABSTRACT

The purpose of this thesis report is to investigate challenges related to railway electrification. In ac-railway systems, trains are most often single-phase loads, which can create significant unbalances in the grid, when fed directly from two adjacent phases. To enhance power quality at the railway feeding point, one alternative is to design the system such as the power is fed to the catenary through Static Frequency Converters (SFCs), which can be a costly solution. Another option is to use Static Compensators (STATCOMs) in shunt connections, handling only the unbalanced amount of power, in order to symmetrize the railway load as seen from the grid side.

Modular multilevel converters (MMCs) are the state of the art solutions for medium- and high-voltage/power converter applications, such as load balancing and reactive-power compensation. This project will focus on analyzing Modular Multilevel Converter (MMC) topologies to be used as load balancers in railway systems. However, the specific requirements of this application reveal a potential weakness of MMCs. That is the asymmetrical character of the load may require much higher device rating in an MMC compared to a conventional converter, due to the symmetrizing components to rebalance the capacitor voltages in the submodules.

This project analyzes a reduced MMC-based topology with only two branches in order to meet the railway load-balancing characteristics. This chain-link compensator uses dc-dc converters to facilitate power channels in order to restore the power imbalance, without overrating the semiconductors in the main current path.

Keywords- Power electronics, STATCOM, MMC, power channel, power quality, negative-sequence compensation, high-speed trains.
SAMMANFATTNING

Syftet med detta examensarbete är att studera de svårigheter som elektrifierade järnvägar står inför. När systemet utgörs av växelström kan tågen ses som en enfas last, vilket kan skapa avsevärda obalanser i nätet då det matas från två intilliggande faser. En alternativ systemdesign för att uppnå en god effekt leverans uppnås då effekten är matad till kontaktledningen genom statiska frekvens omräknare (SFCs), detta kan dock vara en kostsam lösning. Ett annat alternativ är att använda statisk shunt kompensation (STATCOMs) som selektivt kan hantera den obalanserade effekten för att uppnå symmetri och balans i järnvägslasten, sett från nätets sida.

Modulära multiomriktare (MMCs) är en ledande teknik för omriktare till applikationer på mellan- och högspännings nivå, till exempel för lastbalans och reaktiv kompensering. Detta projekt analyserar modulära multiomriktare för lastbalansering i järnvägssystem. Kraven för denna applikation leder till en potentiell svaghet i MMCs där den asymmetriska karaktären på lasten kräver högre märkeffekt jämfört med konventionella omriktare. Detta på grund av de komponenter som återskapar symmetri och balans i kondensator spänningarna i submodulerna.

Här analyseras en reducerad variant av MMC-baserad topologi med endast två grenar för att möta kraven på järnvägens lastbalans. Denna kedjelänk-kompensator använder dc-dc omriktare för att styrja effektflödet till lasten vid obalanserad effekt, utan att för den skull överdimensionera halvledarna i den ordinarie strömvägen.

Sökord: Kraftelektronik, STATCOM, MMC, effekttunnel, effektkvalitet, negativ sekvenskompensation, höghastighetståg.
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<table>
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<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>APQC</td>
<td>Active Power Quality Conditioner</td>
</tr>
<tr>
<td>DAB</td>
<td>Dual Active-Bridge</td>
</tr>
<tr>
<td>DCMC</td>
<td>Diode-clamped Multilevel Converter</td>
</tr>
<tr>
<td>DHB</td>
<td>Dual Half-Bridge</td>
</tr>
<tr>
<td>EMI</td>
<td>Electromagnetic Interference</td>
</tr>
<tr>
<td>FACTS</td>
<td>Flexible AC Transmission Systems</td>
</tr>
<tr>
<td>FMC</td>
<td>Flying-capacitor Multilevel Converter</td>
</tr>
<tr>
<td>FRT</td>
<td>Fault Ride Through</td>
</tr>
<tr>
<td>HPQC</td>
<td>Hybrid Power Quality Conditioner</td>
</tr>
<tr>
<td>IGBT</td>
<td>Insulated-gate bipolar transistor</td>
</tr>
<tr>
<td>IGCT</td>
<td>Integrated gate-commutated thyristor</td>
</tr>
<tr>
<td>LPF</td>
<td>Low-Pass Filter</td>
</tr>
<tr>
<td>MFT</td>
<td>Medium Frequency Transformer</td>
</tr>
<tr>
<td>MMC</td>
<td>Modular Multilevel Converter</td>
</tr>
<tr>
<td>NS</td>
<td>Neutral Section</td>
</tr>
<tr>
<td>NSC</td>
<td>Negative-Sequence Component</td>
</tr>
<tr>
<td>PD</td>
<td>Phase Disposition</td>
</tr>
<tr>
<td>PETT</td>
<td>Power-electronic Traction Transformers</td>
</tr>
<tr>
<td>POC</td>
<td>Point of Connection</td>
</tr>
<tr>
<td>PSC</td>
<td>Positive-Sequence Component</td>
</tr>
<tr>
<td>PWM</td>
<td>Pulse-Width Modulation</td>
</tr>
<tr>
<td>RE</td>
<td>Railway Electrification</td>
</tr>
<tr>
<td>RLS</td>
<td>Recursive Least Squares</td>
</tr>
<tr>
<td>RPC</td>
<td>Railway Power Conditioner</td>
</tr>
<tr>
<td>SFC</td>
<td>Static Frequency Converters</td>
</tr>
<tr>
<td>SM</td>
<td>Submodule</td>
</tr>
<tr>
<td>SS</td>
<td>Section Separator</td>
</tr>
<tr>
<td>STATCOM</td>
<td>Static Compensator</td>
</tr>
<tr>
<td>STT</td>
<td>Substation Traction Transformer</td>
</tr>
<tr>
<td>SVC</td>
<td>Static Var Compensator</td>
</tr>
<tr>
<td>THD</td>
<td>Total Harmonic Distortion</td>
</tr>
<tr>
<td>VSC</td>
<td>Voltage Source Converter</td>
</tr>
</tbody>
</table>
**LIST OF SYMBOLS**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>$V_1$</td>
<td>Line to neutral grid side voltage</td>
</tr>
<tr>
<td>$V_2$</td>
<td>Line to neutral catenary side voltage</td>
</tr>
<tr>
<td>$\omega$</td>
<td>Angular grid frequency</td>
</tr>
<tr>
<td>$K$</td>
<td>Traction Transformer ratio</td>
</tr>
<tr>
<td>$\hat{I}_{tr1}$</td>
<td>Peak value of catenary section 1 load current</td>
</tr>
<tr>
<td>$\hat{I}_{tr2}$</td>
<td>Peak value of catenary section 2 load current</td>
</tr>
<tr>
<td>$I_{tr1}$</td>
<td>Load current at catenary section 1</td>
</tr>
<tr>
<td>$I_{tr2}$</td>
<td>Load current at catenary section 2</td>
</tr>
<tr>
<td>$\varphi$</td>
<td>Phase angle of load current at catenary section 1</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>Phase angle of load current at catenary section 1</td>
</tr>
<tr>
<td>$I_1$</td>
<td>Grid line current (peak value)</td>
</tr>
<tr>
<td>$P_1$</td>
<td>Active Power drawn at grid side of STT</td>
</tr>
<tr>
<td>$P_2$</td>
<td>Active Power at catenary side of STT</td>
</tr>
<tr>
<td>$I_{1}^{ref}$</td>
<td>Reference value of grid current after compensation</td>
</tr>
<tr>
<td>$I_{comva}$</td>
<td>Converter current at a-phase arm</td>
</tr>
<tr>
<td>$I_{comvb}$</td>
<td>Converter current at b-phase arm</td>
</tr>
<tr>
<td>$I_{ac}$</td>
<td>STT-current at catenary side 1</td>
</tr>
<tr>
<td>$I_{bc}$</td>
<td>STT-current at catenary side 2</td>
</tr>
<tr>
<td>$V_{comva}^{ref}$</td>
<td>Converter reference voltage at a-phase arm</td>
</tr>
<tr>
<td>$V_{comvb}^{ref}$</td>
<td>Converter reference voltage at b-phase arm</td>
</tr>
<tr>
<td>$I_{ac}$</td>
<td>STT-current at catenary side 1</td>
</tr>
<tr>
<td>$I_{bc}$</td>
<td>STT-current at catenary side 2</td>
</tr>
<tr>
<td>$L$</td>
<td>Buffer inductor of converter chain-link</td>
</tr>
<tr>
<td>$P_{load,a}$</td>
<td>Active power load demand at catenary side 1</td>
</tr>
<tr>
<td>$P_{load,b}$</td>
<td>Active power load demand at catenary side 2</td>
</tr>
<tr>
<td>$C$</td>
<td>Submodule capacitance</td>
</tr>
<tr>
<td>$U_{t1}$</td>
<td>Voltage at primary winding of MFT of DHB converter</td>
</tr>
<tr>
<td>$U_{t2}$</td>
<td>Voltage at secondary winding of MFT of DHB converter</td>
</tr>
<tr>
<td>$U_{c_{x}}$</td>
<td>Direct-voltage of a SM capacitor at $x$ catenary side</td>
</tr>
<tr>
<td>$U_{c_{x1}}$</td>
<td>Direct-voltage of a SM upper capacitor at $x$ catenary side</td>
</tr>
<tr>
<td>$U_{c_{x2}}$</td>
<td>Direct-voltage of a SM lower capacitor at $x$ catenary side</td>
</tr>
<tr>
<td>$P_t$</td>
<td>Active power transfer through each DHB ‘Power Channel’</td>
</tr>
<tr>
<td>$\delta$</td>
<td>Phase-shift angle between primary and secondary MFT voltages</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
</tr>
<tr>
<td>$f_{DHB}$</td>
<td>Switching frequency of DHB</td>
</tr>
<tr>
<td>$m_k$</td>
<td>Control signals of DHB PWM, $k = a, b, c$</td>
</tr>
<tr>
<td>$I_{+d}$</td>
<td>Converter reference current positive-sequence d-component</td>
</tr>
<tr>
<td>$I_{-d}$</td>
<td>Converter reference current negative-sequence d-component</td>
</tr>
<tr>
<td>$I_{+q}$</td>
<td>Converter reference current positive-sequence q-component</td>
</tr>
<tr>
<td>$I_{-q}$</td>
<td>Converter reference current negative-sequence q-component</td>
</tr>
<tr>
<td>$W_{DC}^\Sigma$</td>
<td>Sum of energy stored in SM capacitors in all branches</td>
</tr>
<tr>
<td>$V_{dc}^\Sigma$</td>
<td>Sum of direct-voltage submodule capacitors in all branches</td>
</tr>
<tr>
<td>$C_{eq}$</td>
<td>Equivalent capacitance of $2N$ series connected SM capacitors</td>
</tr>
<tr>
<td>$N$</td>
<td>Number of SM per chain-link</td>
</tr>
<tr>
<td>$N_{DHB}$</td>
<td>Number of DHB channels</td>
</tr>
<tr>
<td>$Z_{grid}$</td>
<td>Grid impedance</td>
</tr>
<tr>
<td>$L_{\sigma,STT}$</td>
<td>Leakage inductance of STT</td>
</tr>
<tr>
<td>$L_{\sigma,MFT}$</td>
<td>Leakage inductance of DHB MFT</td>
</tr>
<tr>
<td>$f_{MMC}$</td>
<td>Switching frequency of Phase Disposition PWM strategy of MMC</td>
</tr>
</tbody>
</table>
1. INTRODUCTION

In this introductory chapter a general background and the scope of the thesis will be presented. At the end of the chapter an outline of the thesis structure is also provided in order to support the reader with a brief insight on followings.

1.1 Background

During the last three decades, environmental awareness and concerns have been arisen worldwide due to excessive environmental pollution in combination with drastic climate changes and global warming. International organizations established for environmental protection are cooperating with regulatory authorities and world’s leading climate scientists in order to evaluate the damages and investigate feasible measurements to alleviate the problem and reverse the conditions back to normal. The most detrimental step towards environmental protection is to identify the roots of destruction and afterwards define appropriate actions in order to eliminate the impact of this causes. The European Union, as an indicative example, has set itself targets for reducing its greenhouse gas emissions progressively up to 2050, so as to achieve transformation towards a low-carbon economy [1].

According to [2], transportation is responsible for a quarter of EU greenhouse gas emissions, constituting a sector that can undertake further modifications for environmental improvements. Railway Electrification (RE) begun in the early 20th century [3]. In recent decades, the number of electrified railway operations has substantially increased with very high growth rates. The most significant reasons behind this expansion are that electrical locomotives are highly efficient trains and consist an environmental friendlier solution for massive public and freight transportation compared to their fossil-fuel engine counterparts.

However, electrified traction applications impose various power quality problems on the power grid described in more detail in next chapter. Typically, traction loads are single-phase, time-varying, and non-linear loads, resulting to system unbalance, reactive power, harmonics, etc [4]. The impact of those problems can often be detrimental for the safe operation of the grid. Therefore, in order to take advantage of the railway electrification benefits at maximum level, power-quality problems must be attenuated.

1.2 Thesis Scope

The main objective of this thesis is to design a converter compensator in order to attenuate load imbalances imposed by traction loads, and accomplish power-factor correction as it is seen from the grid at the feeder point. The proposed novel converter design will combine the features of:

- Modular Multilevel topology in cascade fashion
- Reduced chain-link configuration
- Bidirectional high-frequency power-channel links

Another significant part of the project is to specify the maximum power requirements with respect to the converter design for high-speed train applications utilized at industrial frequency of 50 Hz. In addition, one of the main challenges behind the novel converter design is the stable operation of the converter and equal voltage sharing among arm-branches and individual submodules as
well. The system is modeled and simulated in PSCAD software environment, while the data are extracted and plotted using MATLAB.

1.3 Outline

This master thesis report consists of following structure: The first part is composed by a literature review on the compensation techniques and devices used for load balancing and an introduction to Modular Multilevel Converters operation principles, system modeling, simulations and results. More specifically:

Chapter 1: Is a brief Introduction (this section) which describes the background and the scope of the project.

Chapter 2: Supports the reader with the appropriate background knowledge of Railway Electrification and the associated Power Quality Issues that are existing.

Chapter 3: Makes an introduction to Modular Multilevel Converters concepts and their STATCOM implementation used as load balancers.

Chapter 4: The System set-up description is provided and the proposed Converter Design challenges and control strategy are analyzed.

Chapter 5: Simulation and Results are given using PSCAD simulation environment.

Chapter 6: Discussions and Conclusions rising from the total project thesis work are analyzed.

Chapter 7: Future work insights are suggested.
2. RAILWAY ELECTRIFICATION AND POWER QUALITY ISSUES

In this chapter a historical overview about the evolution of electrified-rail operations since their start is given. Electrified railway applications have an influence on the power quality of the system. Especially, the unbalanced loading of the system creates negative-sequence components (NSC) of currents in the grid side, resulting in serious threats for the grid. The compensation techniques that have been implemented to tackle these problems since the early start of electric train operation are presented briefly in this chapter as well.

2.1 Historical background/overview

Railway Electrification (RE) was introduced during the end of the 19th century [5], as a promising solution for depleting the already heavily air-congested atmosphere, especially in over-populated metropolitan cities, as well as in industrial districts for transferring heavy cargos. The first electric railway was demonstrated at Berlin Trades Fair in 1879 and after two years the first electric tram line, Gross-Lichterfelde Tramway, was set into operation in Berlin, Germany. Meanwhile, the American electrified railroad began in 1888 when F. Sprague put the first trolley line into operation in Richmond, Va [6]. In 1890, the first electric Underground Railway (subway) opened in London and all the other subway systems soon followed. Early investigations, from H. M. Hobart [3], had already shown that under specific alternations in railway conditions, electrified traction can demonstrate better economic characteristics than its steam counterparts even for irregular and sparse traffic service of both freight and express passenger trains. In next few decades, the concept of RE of either passenger or freight services expanded gradually in most of industrially developed countries such as the U.S. [5], Sweden [7], Austria, Switzerland [8], Italy [9], and Japan [10], while street railway systems grew at a steady pace as well. However, the dominance of steamed-power trains would not end until the end of World War II.

2.1.1 Benefits and Drawbacks of RE

One of the main advantages of RE, is the high power-to-weight ratio which results in the ability for fast acceleration, lower amount of locomotives needed and high limits of speed and power. Another beneficial advantage is the regenerative properties that some electric trains are equipped with, which enables returning the excess of energy back to the grid or supplying heating inside the train during braking. Furthermore, electric trains are more environmentally friendly since carbon emissions are fewer, even for electricity generation based on fossil sources. Additionally, noise pollution is kept at low levels and lower maintenance requirements of traction units are necessary. Those profound advantages of the electrified locomotives over the other train types, accompanied with some periodical coal shortages, the oil crisis, the cost reduction of required material, and the cost of electrical energy gave further urge to the development and establishment of RE. On the other hand, RE for new line (or even upgrading existing ones) sets a high capital cost for installation. Also, from the beginning of RE, power quality-issues emerged, and thus appropriate compensation equipment must be installed to alleviate the adverse effects. However, during the last three decades the tendency towards RE is strong and efforts are recently focusing on sustainability issues.

2.1.2 Classification of Railway Supply systems

According to their power supply, railway systems can be classified to:
- Low-voltage DC systems
- Medium-voltage low-frequency (15 – 25 Hz) AC systems and
- Medium-voltage public-grid frequency (50/60 Hz) AC systems.

For contact line voltages various standard levels exist according to the type of connection and the application (tram, metro, trolley, high-speed train, etc.). The existence, development and expansion of all three types, from their beginning till nowadays, were subjected to both historical and techno-economic factors.

For historical and practical reasons, the first rail electrifications were designed as low-voltage DC systems, initially supplied by DC generators. Typical direct-voltage levels are 650 or 750 V for trams and metros, while 1.5 and 3 kV for feeding through overhead lines. In next stages, during mid-20th century, rotary converters and mercury rectifiers were used excessively for ac-to-dc voltage conversion [11]. In general, DC systems are simple in control, which is their main advantage. However, the low voltage levels, imposed mainly by safety reasons, result in high currents for a given power supply and thus excessive losses and higher voltage drops across the feeding line. To meet these specifications, thick cables and short distances between feeding points are needed, due to the large voltage drops [12]. Nowadays, because of their suitability to low-voltage levels, DC systems are more prone to be found in low-load trains like light rails, trams, subways, and trolleys [11].

In the early 20th century, the development of high-voltage AC systems gave the possibility of installing two sequential feeding points in larger distances. Until the 50s, the need of low frequency systems (16 2/3 Hz in Central and Northern Europe, 25 Hz in U.S.) was imperative in order to address problems related to ac motors. More specifically, early designs of large ac motors became impractical at standard public-grid-frequency due to the windings inductance limitations. In addition, alternating current induces eddy currents, particularly in non-laminated field pole pieces, which cause overheating and loss of efficiency [13]. By the end of World War II, the three-phase AC 50/60 Hz transmission and distribution grid systems had already been expanded and were available and capable of supply RE applications [11]. The simplicity of 50 Hz AC systems is achieved due to their structure as the power is transferred from the three-phase utility system to the single-phase traction system via power transformers [12]. Nowadays, 25 kV/50 Hz systems have become dominant in Europe, since there is no need for a frequency conversion and traction transformers are lighter as the frequency is higher [11].

### 2.2 Power Quality Issues

As it was mentioned previously, RE was rapidly developed in many countries because of its superior characteristics against steam-coal and diesel-powered counterparts. However, the operation of electric railways can influence the power quality of the public grid and in some cases even its own secure operation. The most significant culprit behind this fact is the characteristics of the traction load [14], as it possesses:

- Non-linear, and
- Time-varying behavior

The short-circuit capacity at the Point of Connection (POC) to the public-grid determines the size of impact of these effects. The weaker POC, the more sensitive to disturbances, and more prone to power-quality problems the system is. Especially in remote districts where a weak network
feeding point is common, traction load can account for 50% to 70% of the total load capacity, imposing higher influence on the public grid [15].

The main power-quality problems related with the operation of electric-railway traction are voltage fluctuations, voltage drops, voltage and current imbalance, reactive power, harmonics and arcing [16]. Furthermore, high-power electrification in trains can radiate and conduct significant amount of electromagnetic interference (EMI) due to undesired generation of harmonics, affecting the reliability and security of communication and control systems of the train. However, the emphasis of this master thesis is on improving the power quality of electric railway networks and their upstream public grid by correcting system imbalances and power factor. Thus, a brief focus on the root causes of the merged power imbalance problems, their associated impacts, and existing compensation solutions follow in next sections of this chapter.

2.3 System Imbalance causes and impacts

The system imbalance, which is described in the following as negative-sequence current injection, is mainly considered as the most severe power-quality issue in RE. In most of the cases, it is an inherent outcome of the railway network configuration and the nature of the traction load. Typically, railway networks begun as single-phase loads supplied by a traction transformer connected between two of the three phases of the public grid at the substation feeding point [17], [18]. More specifically, the transformer primary windings are connected to line-to-line grid voltage while the secondary windings are connected phase-to-ground, as it is shown in Fig. 1. That configuration can create significant asymmetries in the public grid, since the load is not equally distributed among the phases [19]. Regenerative-braking techniques and increased rail traffic can enhance the effect of these asymmetries [20].

![Fig. 2.1 Simple RE system configuration](image-url)

2.3.1 Negative-Sequence Component generation

A three-phase system is considered balanced when the three-phase voltages are sinusoidal with the same amplitude and 120° phase difference [21]. When a single-phase traction load is connected to a balanced system in an asymmetrical way as illustrated in Fig. 2.1, unequal voltage drops occur in different phases [22]. This leads to an unbalance in the utility network which in turn can be described as NSC of current flowing in the utility grid [16], [19] and [23]. In case of a strong grid, such a voltage unbalance on the primary side of a substation traction transformer (STT) is negligible. In this case, only NSC currents are injected into the power grid, since a slight change in the phase voltage can produce a larger unbalance in the current phase [22]. Therefore, a load imbalance can be directly translated to the generation of NSC of grid-currents.
2.3.2 Impacts of NSC

The NSC current injection in the main grid system hides serious hazards for electric devices of other upstream consumers and threatens the stable, secure and economic operation of the network. More precisely, it can lead to [24]:

- Voltage unbalances and dissimilar voltage drops
- Additional losses in power transformers
- Over-heat induction and synchronous machine’s rotor windings
- Malfunction of protective relay systems
- Incorrect operation of transmission line control systems
- Reduced transmission capability of lines
- Low power factors

All the aforementioned consequences are detrimental for the grid and most of the electrical apparatus. Under the existence of a heavy traction load and a relatively weak network, the current unbalance factor (the ratio of negative-sequence current over positive sequence) can reach up to 90% [25]. For this reason, negative-sequence currents must be tightly monitored and subsequently attenuated to avoid harming the power system and ensure high-quality power supply.

2.4 NSC of current compensation techniques

From the early start of RE, various methods have been implemented to compensate the NSC of currents and the generated load imbalances. These techniques aiming on power-quality improvement in rail-distribution systems. In this section a brief description and evaluation of those techniques is provided during the electric-railway evolution concluding to the state-of-the-art technological solutions.

2.4.1 Three-phase electric trains

In the early 20th century, in order to symmetrize the load, three-phase trains were designed in some countries (Italy, Switzerland, and U.S.). For this concept, two pantographs were used for the two phases and the running rails as the third phase. Despite the fact that this system resulted in negligible NSC of currents and voltages, the drawbacks of using a second pantograph and electrifying the rails were considerable to abandon this approach [16].

2.4.2 Phase-shift method

Later, in order to make the single-phase load of the system seen more symmetric, the overhead feeding lines (catenary sections) were sectionized in electrically isolated sections. The non-electrified zones are called neutral sections (NS) [26]. A NS’s length can vary between several meters to more than 1 km, while there is no power supply along the NS in order to avoid the risk of phase mixing. Each section is single-phase fed and the alternation of the phases of the utility grid occurs in each railway substation. This method is named as ‘phase-shift method’, and represents an inherent balancing technique where the in case of equal section loading, no unbalance occurs. Fig. 2.2 illustrates the phase-shift method in three adjacent single-phase traction substations.
2.4.3 Special types of Substation Traction Transformers

In most of the traction substations, the supply can be single- or three-phase based on the step-down transformer at the POC. Some special types of transformers developed for serving three-phase to two-phase connections are used in rail distribution networks systems as well. This is due to some particular performance characteristics that these transformers possess, such as reducing unbalanced currents on the grid side [26]. These types of transformers contribute to “local balancing enhancement” and several investigations have been made to evaluate their influence to the system [18], [23] and [27]. Among them, V-V, Wye-Delta (unbalanced transformers) or balanced transformers such as the Scott, Le Blanc, Modified-Woodbridge and impedance-matching are the most commonly used. In all of these transformer configurations, the requirement for NSs is considered as a significant drawback because locomotives loose power and velocity each time they are passing each cross-section [28].

In Fig. 2.3 the configurations of the V-V, Scott, Le Blanc and Wye-Delta traction transformers are illustrated at the POC. V-V transformer has the same behavior with Wye-Delta as per NSC attenuation and since it saves one winding is preferred for railway applications. However according to [29], investigations revealed that the V-V connection causes more severe unbalanced disturbances than the Scott and the Le Blanc connection configurations, especially under a well-designed train-dispatch schedule. On the other side, the Scott, Le Blanc and Woodbridge schemes possess a significant drawback, i.e. operation in reduced utilization factor (iron and copper), with 81.6%, 84.5%, and 82.6% respectively [30], combined with their higher production cost, due to their non-mass production. Hence, the selection of appropriate STT is not trivial, but entails a trade-off between cost and power-quality performance and is highly dependent on the type of traction application. As a representative example, in high-speed railways with large-power locomotive loads, V-V traction transformers are preferred due to their simpler structure and higher power-rating utilization [31]. As a conclusion, various STT configuration schemes can be used to change the load as seen from the utility grid. However, in all these topologies a perfect load balancing can be achieved only under specific load conditions. Otherwise, only partial compensation is feasible.
2.4.4 Power Electronics in RE

A) Static Var Compensator (SVC)

An efficient solution was given in the late 70s, when power electronic based devices made their debut in railway power systems. Thyristor switched reactor/capacitor-based, named as Static Var Compensator (SVC), were implemented for reactive compensation [32]. Typically, SVCs can be modelled as a variable three-phase impedance, connected in delta- or wye-scheme, used for reactive-power compensation through voltage regulation. Even though the SVC contains reactive elements (reactors and capacitors), it has the capability of active power flow balancing and dynamic correction of voltage imbalances as well [20]. Hence, the operation range of traction-load conditions that can be attenuated is enhanced, compared to a system that is solely equipped with balanced traction transformers. By implementing Steinmetz’s theory for three phase power systems [33], the load can be balanced by adjusting independently the three phase impedances connected to POC. The installation of an SVC can be done via a step down transformer at the POC (high-voltage side) or directly connected to secondary winding of feeding STT (low-voltage side), as it is shown in Fig. 2.4. Two drawbacks using an SVC in traction systems are: a) the power factor correction and the NSC compensation contradict with each other [31] and b) the increase in amount and amplitude of harmonic injection to the grid. However, an SVC consists of a simple and low-cost dynamic compensator, and nowadays it can be placed close to giant power plants which can be both technically and economically beneficial [15].
During the last two decades, Flexible AC Transmission Systems (FACTS) devices have begun replacing the thyristor-based SVCs [34]. Due to the extreme progress of high-power switching devices, like IGBTs (insulated-gate bipolar transistor) and IGCTs (integrated gate-commutated thyristor), the STATic synchronous COMPensator (STATCOM), which is the main application of FACTS [32], has been considered as the next-generation power-compensator device [35]. Although several configurations exist, the STATCOM in its generic form is composed of a voltage source converter (VSC) with a dc-link capacitor, buffer inductances, and a coupling transformer on the ac-side. Thus, it can be modelled as a current-controlled voltage source, and its main objective is to exchange reactive power with the host ac-power system. Typically, a STATCOM is used to improve power quality in various ways such as: a) to increase the transmission capability of lines, b) to enhance angle/voltage stability of the system, c) to act as a damper for system oscillatory modes and d) to regulate voltage [36]. A STATCOM can also compensate for load imbalances in distribution networks by transferring active power between the phases in order to create a balanced load as seen from the utility grid [37]. Hence, a STATCOM can serve railway-power-system applications to mitigate load imbalances [38]. Compared to thyristor-based SVC, STATCOM at the same connection point as in Fig. 2.4, behaves not only with faster response and larger range of operation load, but also has lower harmonic footprint and more compact structure. Finally, the capability of bidirectional reactive-power compensation and phase active-power transformer makes the STATCOM more favorable than an SVC for reactive and NSC-current compensation [39].

C) Railway Power Conditioners (RPCs) in RE

During 1990s, various Railway Power Conditioners (RPCs) topologies were introduced by Japanese researchers in order to address unsolved power quality problems and improve the behavior of SVCs installations [40]. RPCs equipped with GCTs were first set into commercial operation in 2002 in each substation of the Tohoku-Shinkansen system [41]. Typically, an RPC (see Fig. 2.5) consists by two single-phase converters (full-bridge) in a back-to-back configuration,
sharing a common dc-link. Each ac-side is connected to a secondary winding of the feeding transformer (catenary side) via a step-down transformer for isolation of the converter from traction network and reduction of the converter’s voltage rating. In most installations a Scott or a Woodbridge scheme was used for the substation design [42], [43]. The RPC has the ability to transfer active power between the two railway sections due to the common dc-link, and inject/absorb reactive power to/from the LV side of the traction transformer. Hence, an RPC can act not only as a power-factor corrector, but also as NSC and harmonics current compensator simultaneously, through the control of its current injection at the catenary [40].

However, the main drawback of RPCs is that in order to fully compensate negative, reactive and harmonic currents both converters must be dimensioned with high-power capacity, which in turn increases substantially the cost of compensation. Given the fact that only under certain extreme conditions this high capacity is required, optimal control algorithms have been implemented based on prioritizing the compensation techniques (reactive, negative, and harmonic) according to traction loads, having as a goal to decrease the total capacity of the converters [28].

![Fig. 2.5 RPC installation for load balancing in electric railway system](image)

**D) Active Power Quality Conditioners (APQCs)**

The next generation of RPCs, Active Power Quality Conditioners (APQCs), were designed as an improvement to existing RPCs, reducing the number of power switching devices. The same compensation (reactive, negative, and harmonic) is achieved again, but now only by a three-wire three-phase converter connected to the secondary winding of STT via a step-down Scott transformer [44]. The Scott scheme of step-down transformer is necessary in case of a balanced transformer used as STT for a smooth interface among the three-phase ac side of converter and the orthogonal two-phase of traction system. In case of a commonly used in unbalanced V-V topology, a compensation method was implemented for $60^\circ$ difference in catenary-voltage sections. This topology is considered more advanced since cost reduction is achieved due to the simple single-phase step-down transformers to feed the converter and the lack of a special type of STT [31]. In Fig. 2.6, the two general APQC configurations are shown connected to a traction power system.
2.5 Recent advances in power quality

2.5.1 RPCs improvements

Recently, an enticing prospect was introduced in [45], where the RPC with half-bridge converters was investigated as an efficient compensation technique for both NSC and harmonic currents. Despite the gain from 50% or 33% reduction of switching devices from a conventional RPC or an APQC respectively, an additional complex control algorithm for dc-link voltage balancing is required to ensure the stability of converter. Another interesting approach has been presented in [46] where a multilevel power quality compensation configuration composed of two cascaded RPCs was proposed. High cost and complex control implementations are the shortcoming of that scheme.

2.5.2 Cophase system

Since 2009, some researchers have tend their attention towards configurations that combine the advantages of the previously mentioned methods in order to achieve further operational improvements. Those compensators, called Hybrid Power Quality Conditioners (HPQC) [47], [48] and [49], are usually implemented to the co-phase system. The main advantage of the co-phase power system supply, described in [50], is that the drawbacks of NSs are eliminated since half of them are no more needed, and the remaining ones are replaced by section separators (SSs) with less insulation requirements. The Co-phase system adopts single-phase feeding connection, thus two adjacent STT can feed with the same phase while the compensator is connected between the feeding phase and the other phase/s of STT [46]. In Fig. 2.7 a generic configuration of co-phase system is illustrated. A simple V-V or a special type balancing transformer can be applied as a substation transformer, while a common RPC or an APQC can be used as compensator. Furthermore, in [51], a more advanced version of co-phase system is proposed eliminating the remaining SPs from the catenary by feeding the single-phase traction load by a cascade connection.
of a step-down transformer, a three-to-two phase back-to-back converter configuration and a step-up converter to feed the catenary.

Despite the significant gain from NSs and SSs removal, the aforementioned co-phase systems require the installation of power conditioners in each traction substation, increasing tremendously the capital cost, and making the investment unreasonable in most of the cases. Thus, it is considered wise to seek for techniques and topologies that can improve power quality with the lowest possible cost.

![Fig. 2.7 Co-phase traction supply equipped with the concept of HPQC](image)

The family of modular multilevel converters (MMC or M2C) is considered to be the next-generation for medium- and high-power converters. Several STATCOM topologies, based on multi-modularity features, have been investigated and proposed for load balancing conditions. The aim of this thesis is to design a novel MMC-based STATCOM topology for addressing load imbalance issues in electric-railway transportation. Thus, in Chapter 3 basic concepts and operational principles of a multilevel VSC and particularly for MMC-based topologies are analyzed.
3. MODULAR MULTILEVEL CONVERTERS AS STATCOMS

As it was mentioned in the previous chapter, a STATCOM device is VSC system, and also a member of the so-called FACTS devices, applied for power-quality improvements of the system. By observing the tendency in market, the inference that the amount of VSC-based compensators will increase for industrial applications is quite reasonable. Multilevel converters and especially in their modular configuration seem to become dominant for future applications in both high and medium-power industrial applications. In this chapter basic principles behind multilevel concept are analyzed and particularly operational characteristics of MMCs are described. Additionally, challenges and drawbacks in existing MMC topologies used for NSC compensation will be discussed.

3.1 Introduction to Multilevel principles

The invention of the multilevel concept was patented in 1975 [52]. The need for complying the output current and voltage waveforms with grid harmonic distortion standards was hiding behind that concept. Keeping the power ratings of semiconductor devices as low as possible was one of the driving forces in the design [53]. The initial thought was that a cascaded connection of more devices with clamped voltages would present better performance than an existing conventional 2-level converter. Typically, a multilevel converter is capable of producing a staircase output voltage waveform via independent direct-voltage sources by a proper selection of their insertion, resulting in minimum Total Harmonic Distortions (THD). In turn, can contribute to substantial reduction of bulky passive filters used for harmonic compensation in 2-level VSCs [54]. In addition, due to the staircase waveform, the voltage stress \( \frac{dv}{dt} \) on power-switching devices is lower. Another significant advantage is that the multilevel concept can support lower switching frequencies resulting in overall lower switching losses. In most of the cases, total system reliability is high, since operation is ensured under component failure at a reduced power level. Even under emergency situations the converter can provide fault ride-through (FRT) capability. These significant properties combined altogether, can provide higher quality of voltage waveforms (almost sinusoidal) and higher converter overall efficiency.

However, some shortcomings still exist. The most significant one is the requirement for a large number of semiconductor devices, each one of them requiring a separate gate-drive system that increases both the capital and operational (cooling) cost of the converter. Another side effect is also the presence of large number of isolated capacitors (direct voltage sources), which makes their voltage balancing quite a challenging task. Hence, more sophisticated and complicated control strategies needs to be implemented.

During the last two decades, despite the aforementioned drawbacks, converters in multilevel topologies have been intensively investigated, and plenty of them have been proven to be beneficial alternatives and successfully implemented in various medium- and high-voltage applications as well [53]. Typically, multilevel scheme is more attractive for STATCOM applications, due to the improved dynamic behavior, and because bulky coupling transformers can be eliminated in some cases. Apart from the STATCOM applications, multilevel converters have found research and development potentials in High Voltage DC transmission systems (HVDC) and also in FACTS devices. Furthermore, multilevel converters can be utilized for other renewable-energy systems (PV, wind power, fuel cells) interface with the public grid, adjustable-speed drive systems, electric traction systems and active-power filtering [55].

In general, multilevel schemes can be classified into the following three groups:
Diode-clamped multilevel converter (DCMC)

Flying-capacitor or floating-capacitor or capacitor-clamped multilevel (FCM) converter

Modular multilevel converter (MMC)

The first two categories can shape a broader group, named as monolithic multilevel converters. A 3-level DCMC, known as neutral-point clamped, was introduced in 1981 [56], and since then it has been widely popular (and with higher numbers of voltage levels) in industrial applications for both low and medium frequencies, especially for ac motor-drive applications due to its high efficiency [57]. Meanwhile, the FCM converter was initially proposed by Maynard and Foch in 1992 [58]. Despite the fact that it is almost impractical at very low frequencies, the FMC has gained attraction in high speed-drives applications and test benches [55]. On the other hand, the basic configuration in modular topologies was suggested by Alesina and Venturini in 1981 [59], while a noticeable advance in the design and modeling of MMCs was proposed in 2002 by Marquardt and Lesnicar [60].

During the last decade, market interest has twisted towards MMC topologies, targeting to commercial high-power applications in HVDC systems [61] and [62]. However, MMC schemes as STATCOM have been found promising for compensation of unbalanced and distorted nonlinear loads [63]. Compared to MMCs, monolithic converters face problems with great complexity in structure and control, as well lower power utilization. Since the focus of this thesis is based on MMC-based converters, in next subsection a more detailed description for MMC-based STATCOM devices is given. For more details about monolithic converters, the reader is referred to [53] where a brief overview of specific features, advantages, drawbacks and operating principles is given.

3.2 Modular Multilevel Topologies for STATCOM

During the last decade, the modular multilevel concept has faced remarkable attention in both academia and industrial applications. Modularity is associated with the cascade connection of specific configuration of components (submodules), shaping larger systems. Due to the modular realization, the converter becomes insensitive to variable semiconductor parameters. In literature, the terms “cascade multilevel”, “series-connected multilevel” or “chain-link” can be found, referring to the MMC topology as different trade names. The distinct feature of such a converter is that it can be easily scaled up or down to several voltage and/or power levels according to the number of the submodules utilized. Apart from the general advantages that all multilevel topologies provide, MMCs especially offer simpler mechanical design and service, resulting in compact structures and lower maintenance cost.

3.2.1 Basic Structure of an MMC chain-link

Typically, an MMC converter is more likely to be found as a three-phase-leg VSC. According to the converter inner configuration, each leg typically contains one or two arms. However, more than two arms have been placed in some heuristic topologies applied to special multi-phase applications. A typical leg schematic diagram composed of two arms (chain-links) is shown in Fig. 3.1. According to Marquardt and Lesnicar model theory [64], each chain-link consists of \( N \) identical series-connected submodules (SMs) with a small buffer inductor \( L \) and a modeling parameter resistor \( R \). The number of SMs can vary from less than ten up to several hundred depending on the application requirements. For instance, FACTS and HVDC systems require thousands of SM [65]. The inductor \( L \) is placed in order to limit arm-current harmonics and faults, while the resistor \( R \) represents both inner inductor and total arm resistive losses [66].
the arm is considered as a two-terminal device equipped with a local direct-storage capacitor, realizing the direct-voltage source.

![Schematic diagram of two-arm single-phase leg MMC](image)

Fig. 3.1 Schematic diagram of two-arm single-phase leg MMC

### 3.2.2 MMC Operational Principles

When half-bridge cells are used as fundamental building blocks of the converter only two quadrants operation is permissible with a two-level voltage output. In contrast, full-bridge cell allows four quadrant operation and the output voltage waveform now consists of three-levels. By controlling the states of the switches in each cell, a submodule capacitor can be connected (inserted) or elsewhere bypassed in/from the arm-circuit current path. In case of full-bridge cells implementation, there are two options for the capacitor insertion; either in positive or negative voltage direction. By controlling the number of capacitors inserted in the current path at every switching instant, the reference output voltage can be generated. Thus ideally, each arm can be considered as an independent ideal sinusoidal voltage source, which is the main goal of a VSC.

The harmonic components and the THD of the output alternating-voltage waveform $V_o$ are associated with the number of cells per arm. By selecting an adequately large number of submodules $N$, an (almost) ideal sinusoidal voltage waveform $V_o$ can be assumed at the output, without any loss in modelling accuracy. The low switching losses in an MMC converter can be explained by the low switching frequency $f_{sw}$ of the semiconductor devices implied by the large $N$. On the other hand, by increasing $N$, conduction losses may be increased as well, since the arm-current is flowing continuously in the arm and it is never disrupted.

### 3.3 MMC-Based STATCOM for Load Balancing

As mentioned previously, STATCOM in its generic form is composed of a VSC with a dc-link capacitor, buffer inductances and a coupling transformer in the ac-side. According to Prof. H.
Akagi [67], an MMC-based STATCOM designed with full-bridge cells, can have one of the following forms (see Fig. 3.2):

- Single Star
- Single Delta
- Double Star

When Single Delta [68] and Double Star [69] configuration are applied to STATCOM, the option of controlling negative-sequence reactive power is offered by means of a circulating current. On the other hand, Single Star configuration does not allow the generation of a circulating current, thus only positive-sequence current compensation can be achieved. Circulating current is useful for balancing the total stored arm-energy and consequently the arm direct-voltage. Typically, a circulating current flows among the legs and among the upper and lower arms for the cases of Single Delta (Fig. 3.2-b) and Double Star (Fig. 3.2-c) respectively. By regulating the circulating current, the active-power exchanged between the arms and legs of the converter is controlled, resulting in equal voltage sharing among the legs. In case of a Delta configuration, circulating current is an alternating component at fundamental frequency, while in the Double-Star it is composed by a direct current component [70]. Additionally, if it is properly controlled, the circulating current can be used for further suppression of capacitor-voltage ripple as it was proposed in [71].

Apart from keeping the total direct voltage among the arms and legs equal, another control task is also important to ensure equal voltage levels in the output waveform. That task entails that in each converter arm, equal voltage sharing among the dc-storage capacitors must be achieved. More accurately, it is enough if a reasonably tight tolerance band of voltage levels is followed by the capacitors [72]. This task is considered vital for the stable operation of the converter because when a capacitor is inserted in the current path it will enter a charging/discharging mode depending on the direction of arm-current and capacitors-voltage positive or negative insertion. That means if this process is not properly designed, some capacitors can be totally discharged while others will increase continuously their voltage levels. Therefore the implementation of this task, presupposes a balancing algorithm approach, whose role is to decide which of the $N$ SM-capacitors should be inserted or bypassed in current path at every switching instant according to sorting methods [60]. Another type of approach for dc-capacitor voltage level balancing instead of being algorithm-based, is an individual direct-voltage controller (PI-control) as implemented for each SM in [73]. The drawback of this type is that it is not easily applicable for higher values of $N$. 
3.4 Drawbacks of existing MMC-based STATCOMs for load balancing

Normally, operation with circulating currents has no impact on ac- and dc-side currents of the converter. However, the drawbacks of this method is an increase in the conduction and switching losses. Since circulating current is a current that is superimposed in the reference arm-currents, higher current ratings are imposed for all semiconductor devices as well. Furthermore, the higher the number of the SMs is, the higher the total cost of the converter becomes, and the overall efficiency declines as well. Thus, an alternative energy/voltage balancing technique that would not require the existence of circulating current would be an interesting aim towards decreasing the cost of total converter system and increasing the overall efficiency. The feasibility of this objective, requires a substantial change in the MMC-based STATCOM configuration that will be discussed in the following chapters.
4. SYSTEM DESCRIPTION AND CONVERTER TOPOLOGY DESIGN

As it was described in Chapter 1, the purpose of the thesis is to design a converter for load-balancing. Thus, equal phase-loading must be ‘seen’ from the grid side when compensating for the asymmetrical/non-linear traction load. In Chapter 3, MMCs were mentioned as the state-of-the-art solutions for load balancing and reactive-power compensation. However, the specific requirements of this application reveal a potential weakness of MMCs. The asymmetrical character of the load may require much higher device overrating in an MMC compared to a conventional converter, due to the symmetrizing components to rebalance the capacitor voltages in the submodules. In this chapter, an MMC-based topology with reduced arm chain-links is described in order to meet the railway load-balancing requirements.

4.1 System Description

In this section, the system behavior due to the asymmetrical loading is analyzed in order to determine the conditions that create the NSC of current generation. Afterwards, a method to provide the compensating references for the application requirements will be derived also.

4.1.1 Negative-Sequence grid current generation

A classical design for a traction substation that consists of a three-phase utility grid that supplies with power two single-phase train loads illustrated in Fig. 4.1. A V-V traction transformer configuration is selected to supply the traction load and is connected to two electrically-isolated catenaries.

![Traction power system supplied via a three phase V/v transformer](image)

As it was briefly explained in Chapter 2, when a balanced three-phase network is asymmetrically loaded, negative-sequence components in currents and voltages are emerging. Assuming an ideal three-phase balanced waveform for the grid-side voltages at the POC:

\[ V_A(t) = V_1 \cos(\omega t) \]
where $V_1$ is the amplitude of the line-to-neutral grid voltage (peak value) and $\omega$ the angular grid frequency. Thus, the feeding load voltages at the catenary side for a strong grid can be written as:

$$V_{ac}(t) = V_2 \cos(\omega t - \pi/6)$$
$$V_{bc}(t) = V_2 \cos(\omega t - \pi/2)$$

where $V_2$ is the amplitude of line-to-line load-voltage (peak value), while the c-node in the secondary winding is grounded,

$$V_c(t) = 0$$

For simplicity reasons, the train loads can be expressed as purely sinusoidal currents without containing any dc-offset or any other higher-harmonic component. Thus, without compensation, the load-currents are drawn directly from the transformer secondary and can be expressed as

$$I_{tr1}(t) = I_{ac}(t) = \hat{I}_{tr1} \cos(\omega t + \varphi)$$
$$I_{tr2}(t) = I_{bc}(t) = \hat{I}_{tr2} \cos(\omega t + \gamma)$$

where $\hat{I}_{tr1}$, $\hat{I}_{tr2}$ the amplitudes and $\varphi$, $\gamma$ the phases of load currents. Therefore, if $K = \frac{V_2}{V_{\sqrt{3}}}$ is the constant transformer turns ratio, the current relations between the primary and the secondary winding are

$$I_{ac}(t) = \frac{1}{K} I_A(t)$$
$$I_{bc}(t) = \frac{1}{K} I_B(t)$$
$$I_A(t) + I_B(t) + I_C(t) = 0$$

By solving the equation system of (9), (10) and (11) for $I_A$, $I_B$ and $I_C$ the three-phase grid side currents are

$$I_A(t) = K I_{ac}(t)$$
$$I_B(t) = K I_{bc}(t)$$
$$I_C(t) = -K [ I_{ac}(t) + I_{bc}(t) ]$$

Replacing with the general form of $I_{tr1}(t)$ and $I_{tr2}(t)$ from (7) and (8), the grid-side currents are given as

$$I_A(t) = K [ I_{tr1} \cos(\omega t + \varphi) ]$$
$$I_B(t) = K [ I_{tr2} \cos(\omega t + \gamma) ]$$
$$I_C(t) = -K [ I_{tr1} \cos(\omega t + \varphi) + I_{tr2} \cos(\omega t + \gamma) ]$$

The transformation from $abc$-sequence to positive-, negative-, and zero-sequence for the grid currents is derived by the following transformation matrix

$$\begin{bmatrix} I_0 \\ I_+ \\ I_- \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \cdot \begin{bmatrix} I_A \\ I_B \\ I_C \end{bmatrix}$$

where $a = e^{j2\pi/3}$, and after mathematical calculations yields
\[
I_o = I_A(t) + I_B(t) + I_C(t) = 0 \tag{19}
\]
\[
I_+ = \frac{K}{3} [(1 - a^2)I_{tr1}e^{j\varphi} + (a - a^2) I_{tr2}e^{j\gamma}] \tag{20}
\]
\[
I_- = \frac{K}{3} [(1 - a)I_{tr1}e^{j\varphi} + (a^2 - a) I_{tr2}e^{j\gamma}], \tag{21}
\]

where \(I_{tr1}\) and \(I_{tr2}\) denote the \textit{rms} values of load currents. Equations (xii) to (xvi) in Appendix prove that a minimum NSC will exist under any load condition. Therefore, it is valid to claim that asymmetry in loading, combined with the traction transformer structure, results in NSC existence in the power-grid. Without any means of further compensation, the presence of NSC in the grid currents is unavoidable.

### 4.1.2 Compensator reference currents

Due to its adverse effect described in Chapter 2, NSC of currents must be compensated for reasons of compliance with grid codes and improvement of power system quality. The objective of this thesis is to design a compensator connected at the catenary side which will make the load seen as balanced from the grid side at POC. This ‘load-balancer’ device must have the capability to transfer active power among catenary phases by injecting appropriate currents at the load-side (Fig. 4.2) and thus compensating for the negative sequence and reactive power as well.

Therefore, to ensure the above conditions the grid-side line currents drawn by the traction transformer should have equal amplitude and be in phase with grid-voltage at POC,

\[
I_A(t) = I_1 \cos(\omega t) \tag{22}
\]
\[
I_B(t) = I_1 \cos(\omega t - 2\pi/3) \tag{23}
\]
\[
I_C(t) = I_1 \cos(\omega t + 2\pi/3), \tag{24}
\]

where \(I_1\) denotes the amplitude of line grid-side current (peak value). With this condition, unity power factor at the POC is ensured as well, with total active power expressed as

\[
P_1 = 3 \frac{V_1 I_1}{\sqrt{2} \sqrt{2}} = \frac{3}{2} V_1 I_1 \tag{25}
\]

![Fig. 4.2 NSC and reactive power compensation at traction power system](image-url)
At the catenary-side, high-speed trains are typically driven by four-quadrant ‘ac-dc-ac’ converters (a full bridge connected back-to-back with three-phase converter) which are pulse-width-modulation- (PWM) controlled [74]. Hence, it is reasonable to assume that their reactive part can be neglected. However, in the general case the active power at the secondary winding can be expressed as

\[ P_2 = \frac{V_2}{2} \left( i_{tr1} \cos \left( -\frac{\pi}{6} - \varphi \right) + i_{tr2} \cos \left( -\frac{\pi}{2} - \gamma \right) \right) \]  

(26)

Assuming no resistive-losses in the traction transformer, \( P_1 \) should be equal to \( P_2 \), resulting in the required amplitude of the grid-side reference current as

\[ i_1^{\text{ref}} = \frac{K \sqrt{3}}{3} (i_{tr1} \cos \left( \frac{\pi}{6} + \varphi \right) + i_{tr2} \cos \left( \frac{\pi}{2} + \gamma \right)) \]  

(27)

By substituting \( i_1 \) in (22)-(24) with its reference value \( i_1^{\text{ref}} \), the three-phase balanced system can be derived as

\[ i_A^{\text{ref}}(t) = \frac{K \sqrt{3}}{3} (i_{tr1} \cos \left( \frac{\pi}{6} + \varphi \right) + i_{tr2} \cos \left( \frac{\pi}{2} + \gamma \right)) \cos(\omega t) \]  

(28)

\[ i_B^{\text{ref}}(t) = \frac{K \sqrt{3}}{3} (i_{tr1} \cos \left( \frac{\pi}{6} + \varphi \right) + i_{tr2} \cos \left( \frac{\pi}{2} + \gamma \right)) \cos(\omega t - 2\pi/3) \]  

(29)

\[ i_C^{\text{ref}}(t) = \frac{K \sqrt{3}}{3} (i_{tr1} \cos \left( \frac{\pi}{6} + \varphi \right) + i_{tr2} \cos \left( \frac{\pi}{2} + \gamma \right)) \cos(\omega t + 2\pi/3) \]  

(30)

Therefore, according to the Kirchhoff Law in the secondary side, the compensation law that provides reactive and NSC attenuation can be derived as

\[ i_{\text{conva}}(t) = i_{tr1}(t) - i_{ac}(t) \]  

(31)

\[ i_{\text{convb}}(t) = i_{tr2}(t) - i_{bc}(t) \]  

(32)

Substituting \( i_{ac}(t) \) and \( i_{bc}(t) \) in (31) and (32) by equations (9) and (10) with their reference values from (28) and (29) respectively, the final form of the STATCOM compensating current is expressed as

\[ i_{\text{conva}}^{\text{ref}}(t) = i_{tr1} \cos(\omega t + \varphi) - \frac{\sqrt{3}}{3} (i_{tr1} \cos \left( \frac{\pi}{6} + \varphi \right) + i_{tr2} \cos \left( \frac{\pi}{2} + \gamma \right)) \cos(\omega t) \]  

(33)

\[ i_{\text{convb}}^{\text{ref}}(t) = i_{tr2} \cos(\omega t + \gamma) - \frac{\sqrt{3}}{3} (i_{tr1} \cos \left( \frac{\pi}{6} + \varphi \right) + i_{tr2} \cos \left( \frac{\pi}{2} + \gamma \right)) \cos \left( \omega t - \frac{2\pi}{3} \right) \]  

(34)

\[ i_{\text{convc}}^{\text{ref}}(t) = - [i_{\text{conva}}^{\text{ref}}(t) + i_{\text{convb}}^{\text{ref}}(t)] \]  

(35)

### 4.2 Converter Requirements for reduced branch

In Chapter 3, it is mentioned that each converter arm of an MMC-based STATCOM can operate as an independent ac-voltage source with controllable phase, magnitude and frequency behind a buffer inductor \( L \). By controlling the voltage across inductor’s terminals the reference converter current can be generated and injected into the catenary side (see Fig. 4.3). Thus, the converter reference-arm voltages in the phasor domain are given as

\[ V_{\text{conva}}^{\text{ref}} = V_{ac} + j \omega L \cdot i_{\text{conva}}^{\text{ref}} \]  

(36)
\[ V_{\text{conv} \text{ref}} = V_{bc} + j\omega L \cdot I_{\text{conv} \text{ref}} \] (37)

![Arm-equivalent of STATCOM device](image)

Fig. 4.3 Arm-equivalent of STATCOM device

Since the load on a TSS is normally a two-phase load or even in some cases a single-phase load (no load in a- or b-phase for some periods) and the c-node in the secondary winding of V-V transformer is grounded, it would be cost-efficient to eliminate the c-phase arm of STATCOM device. That is feasible because the c-phase is used as a return current path, and the current flowing is consequently dependent on the sum of a- and b-phase arm currents and not on its own arm voltage (see eq.(14)). Thus, if the induced currents at the secondary terminal of the traction transformer have the same amplitude and 120° phase difference, subsequently the return current will have the same amplitude and 120° phase difference from the other two phases as well. Therefore, a c-phase arm is not required, if the compensation is ensured.

An alternative structure for the proposed reduced-arm converter is illustrated in Fig. 4.4. Each phase-leg consists of a chain-link arm with \( N \) identical submodules (SM). Each submodule consists of a full-bridge converter. The points of connection of the device to the main circuit are denoted with circles in accordance with Fig. 4.2. It is obviously inevitable to generate a circulating current in this configuration. Therefore, the challenge with this modified topology is to find an alternative method in order to replace the NSC compensation feature that the circulating current was offering.

Depending on the load-current conditions (amplitude and phase), the converter-current reference is generated by the converter-voltage reference (eq. (33-37)). This implies that the generated reference power in each converter phase can be injected towards or from the catenary side in order to compensate for the load imbalance. Load balance is achieved by drawing equal power from each phase at the secondary winding terminals of the traction transformer, and thereafter redistributing this power among the STATCOM phase arms to cover the train-load power demand. The fulfillment of this condition presupposes that when there is a difference in load power demand\((P_{\text{load},a} \neq P_{\text{load},b})\), one arm converter must consume the half of their difference (i.e. \( \frac{1}{2} \cdot |P_{\text{load},a} - P_{\text{load},b}| \)) while the other phase must generate the same amount of power.
Because of the converter current and voltage reference nature, the power injected by the converter typically contains a dc-offset and some 2nd order (to the fundamental frequency) components. The dc-offset component is mainly associated with the energy that is stored/extracted in/from the dc-submodule capacitors. Since each arm chain-link can operate independently from the other and because it must inject the amount of power that the other arm-phase has to consume according to the traction loading, a different amount of energy is stored or extracted from the capacitors. Therefore, in order to accomplish the NSC compensation requirements, the capacitors in one side of the converter will be charged and in the other discharged, affecting the converter arm-voltage balancing. As the generated active powers in each arm chain-link have to be opposite, one side of the converter will be charged with the same rate that the other will be discharged. The existence of a controllable circulating current in the mentioned topologies of the Delta or the Double-Star STATCOM, could ensure a redistribution of the required energy/power transfer among the converter phases, in order to maintain equal the total arm voltages. The proposed topology in Fig. 4.4, does not offer this capability of energy redistribution between arm branches. Therefore, in next section an appropriate modification of this topology is described to tackle this problem.

### 4.3 Power Channel Design

In order to control the virtual “dc-link” voltage across the arm chain-links, the excess of energy stored in one converter phase must be transferred to the other, so as to cover the lack of energy there. That can be achieved by designing suitable “power channels” that are capable of controlling the direction and the amount of that active power flow. Since dc-capacitors are the only energy storage elements in the circuit, a potential way of implementing this task is to exchange power through them. The state of a dc-capacitor in the main circuit configuration is either a series, insertion to the converter current path or to be bypassed. In order to avoid interfering with the capacitors tasks and interrupting the current path, the required power exchange must be transmitted via a parallel path. Since the existing circuit path (Fig. 4.4) is reserved for generating the arm-voltage and current references, the only available alternative is paralleling dc-capacitors from a-phase to their corresponding pairs from b-phase. Thus, an appropriate dc-dc converter can intermediate to each pair of SMs to adjust the required power exchange via a “power channel” as it is shown in Fig. 4.5 in red boxes and lines respectively.
Some suitable candidates for a dc-dc converter that can operate with the above requirements are the Dual Half-Bridge (DHB) [75] or the Dual Active (Full) Bridge (DAB) [76], and Dual Bridge series resonant DC-DC [77] converters (Fig. 4.6). Typically, the concept of a resonant converter is adding a series (or other configurations) of an LC resonant bank in the output of a converter bridge in order to obtain the advantages of even higher frequency operation [78]. These types of converter with high-frequency modulation exhibit low cost, high-power density, and are attracting increasingly attention for applications such as energy conversion in dc-renewable energy sources [77], battery charging/discharging, Vehicle-2-Grid projects, and power-electronic traction transformers (PETTs) for medium-frequency transformers (MFTs) [79].

The DHB and DAB DC-DC topologies are composed of a primary and secondary half- or full-bridge respectively, requiring an isolated medium frequency transformer (MFT) with unity turns ratio (1:1), as an interface element. For reasons of compliance with the main circuit in Fig. 4.5,
primary and secondary sides of the MFT will be referred as a- and b-side respectively from now on. By using a T-equivalent circuit as the transformer’s model and considering the magnetizing inductance \( L_m \) negligible, the sum of the leakage inductances, denoted as \( L_s \), is utilized as a decoupling and energy transfer element between the dc-capacitor pairs. By controlling the state of power switches, a square waveform of voltage is applied on both sides of the transformer. For the case of DHB, in order to avoid a dc-offset in the voltage waveforms, the lower terminal of the isolated transformer must be connected to the mid-point of the dc-storage capacitor (Fig. 4.6). By this way, DHB can acquire a similar behavior as a DAB converter.

Since the DHB configuration demands half the number of power-switching devices, while still having the same power-rating requirements as the DAB, the DHB will be selected as a more cost-efficient implementation even though it offers less degrees of freedom.

### 4.3.1 Dual Half Bridge (DHB) Operation Principles

In [76], three different types of modulation are compared in a generalized method for DAB converters. As the simplest method, the phase-shift PWM modulation is applied to the DHB type here. Each side of the converter is PWM modulated with duty cycle \( D = 0.5 \), in order to keep equal voltage levels in both parts (upper and lower) of each dc-capacitor,

\[
U_{C_{x1}} = U_{C_{x2}} = \frac{U_{C_x}}{2}
\]  

where the subscript \( x \) refers to a- or b-phase. The power transfer from a- to b-side and vice versa is controlled by the phase-shift angle \( \delta \), which represents the phase difference between the a- and b-side square-voltage waveforms, as is shown in Fig. 4.7.

![Fig. 4.7 Phase-shift modulation in DHB converter (a) \( \delta > 0 \) Power transfer from a- to b-side, (b) \( \delta < 0 \) Power transfer from b- to a-side](image)
The power transferred between the phases is estimated in [80], where the concept of power channels is applied for suppressing fundamental-voltage fluctuations in the dc-storage capacitors for low output frequencies in MV-drives applications, and is expressed as

\[
P_t = Uc_a \cdot Uc_b \cdot \frac{\delta(\pi - |\delta|)}{\pi \omega_{DHB} L_s},
\]

where \(\omega_{DHB}\) denotes the switching frequency of DHB converter, \(Uc_a = Uc_{x1} + Uc_{x2}\) and \(\delta \in [-\pi, \pi]\). When the capacitor voltage in the a-side is higher than in the b-side \((Uc_a > Uc_b)\), then the transformer voltage at the a-side, \(U_{t1}\), should be leading the b-side, \(U_{t2}\), in order to transmit power from a- to b-phase \((P_t > 0)\). When the opposite condition is valid, the transformer voltage at the b-side is then leading, and the power flow changes direction \((P_t < 0)\). From eq. (39) for the positive range of \(\delta\), the transferred power is positive and has its maximum value at \(\pi/2\) which is also its symmetrical point. The same conditions with the opposite sign also exist for the negative range of \(\delta\). Therefore, it is reasonable to curtail further the range of the shift angle at \(\delta \in [-\pi/2, \pi/2]\), without losing any control capacity over the output.

### 4.3.2 Dual Half Bridge (DHB) Modulation Signals

As it is depicted in Fig. 4.7, in order to create the phase shifting between the transformer windings three control signals are required. Since, the duty ratio of each half bridge is constant at 0.5, the a-side is PWM controlled with a triangular carrier and a control signal \(m_a = 0.5\) constant, while the b-side requires two signals to create the phase difference. When the carrier value is lower than the control signal then the upper half capacitor direct-voltage is applied to transformer terminals, otherwise the lower half is inserted. For the b-side, \(m_b\) is the reference signal when the carrier is in ascending mode and as long as the carrier value becomes lower than the control signal then the upper half capacitor direct-voltage is applied to transformer terminals, until the triangular value in ascending mode becomes higher than the supplementary reference signal \(m_c\).

The relation between the reference phase-shift angle \(\delta\) and the controlled signals are given as

\[
m_b = m_a - \frac{\delta_{ref}}{\pi}
\]

\[
m_c = |1 - m_b|
\]

where \(\delta_{ref}\) is the reference phase-shift among the isolated transformer square waveforms expressed in radians.

### 4.4 Control Strategy

Fig. 4.8 shows the block diagram of the total control algorithm implemented to compensate the NSC of currents and adjust the power factor to unity. It consists of the main MMC circuit control strategy and the ‘Power Channel’ control. In the following subsections each component of the control system-block will be described with respect to its structure and its objectives. The output of the overall control block-diagram are the gate signal switching commands, \(S_{a,arm}\) and \(S_{b,arm}\), and \(S_{a,DHB}\) and \(S_{b,DHB}\), of the MMC chain-links and DHB power-channels respectively, as shown in Fig. 4.8.
4.4.1 Converter-Current Estimator

One of the main MMC circuit objectives is the external current control. Equations (33) to (35) provide current references for the MMC topology as functions of the load currents and the catenary-voltage phases. Therefore, in order to generate the converter reference currents, information about the amplitude, phase and frequency of those signals is necessary. Typically, grid-connected converters are equipped with Phase-Locked-Loop (PLL) systems in order to extract information parameters of a signal [81]. The control algorithm is implemented by setting the phase of grid line-to-neutral voltage $V_A$ as the reference set point. Therefore, all the phase angles of signals are referred with respect to the phase of $V_A$. Thus, the role of the PLL, which is a negative-feedback system, is to monitor the grid-voltage amplitude, frequency, and set the reference angle.

Since the reference angle and the fundamental frequency are given, the amplitudes and phases of the load-currents are also necessary for the converter current estimator. A proposed methodology in [82] based on a Recursive Least-Squares (RLS) algorithm is used to estimate the remaining unknown values in run-time.

![Fig. 4.8 Overall control system block of the MMC-based STATCOM with DHB modulation](image)

4.4.2 Converter-Current Controller

From (33) – (34) it can be observed that the compensation currents are asymmetrical and are composed by positive- and negative-sequence as it is mathematically proven in Appendix II. As a simple method, PI controllers are considered as an adequate control strategy to set the converter arm-currents to their reference values, extracted from eq. (33) and (34). In order to apply PI controllers, the input quantities must be constants and not sinusoidal, so that accurate reference tracking is feasible. Applying Park transformation $(abc/dq)$, the three-phase compensation current signals are converted to constant quantities in the $dq$-rotational reference frame. Because the three-phase currents are unbalanced, the $dq$-quantities contain both dc- and ac-components. Therefore, it is necessary to extract the positive and negative sequence components of the $dq$-frame in order to obtain constant values [83]. In addition, each component is low-pass filtered in order to remove any harmonic-wave distortion. The positive-sequence current in $q$ direction, $I_{+dq}$, and the negative-sequence reference currents in both $d$ and $q$ directions, $I_{-dq}$, are obtained by the converter-current
estimator, as shown in Fig. 4.8. Furthermore, the positive-sequence of d-current converter component \( I_{+d} \) is determined by the output of the overall direct voltage controller. At the output of the PI controllers, the cross-coupling terms are removed, while the voltage of secondary side of traction transformer is fed forward to the positive-sequence controllers (see Fig. 4.9). In this way, current control loops are forcing the measured converter currents to their reference values. The outputs of current controllers are comprising the phase-arm voltage reference-commands for the converter.

![Fig. 4.9 Current control system block of the MMC-based STATCOM (a) positive- and (b) negative-sequence](image)

4.4.3 Overall Direct-Voltage Control

Typically, in grid-connected converters the d component of the current is adjusted in order to control the active power transferred to or from the grid. Thus, a total-energy controller can be implemented in order to set the total-energy level stored in the SM capacitors to a desired value, \( V_{dc}^* \). Assuming constant direct voltage level in all SM capacitors, the desired energy can be translated to a total desired dc-link voltage for both phases according to

\[
W_{dc}^* = W_{dc,a}^* + W_{dc,b}^* = \frac{1}{2} C_{eq} (V_{dc}^*)^2, \tag{42}
\]

where \( C_{eq} \) is the equivalent capacitance of 2N series connected SM capacitors, and \( V_{dc}^* \) is the sum of all SM direct voltages in both chain-link arms. Since the dc-capacitors are typically suffering from 2\(^{nd}\) harmonic voltage fluctuations, the measured total dc-link voltage is passed through a low-pass filter (LPF) in order to extract the mean voltage value and feed it back to the controller.

Since the converter is selected to operate as STATCOM, the overall power flow of the converter should be zero. This condition is valid because the converter consumes the required amount of active power in one phase, and injects the same amount from the other phase, making the total active power exchange seen from the terminals equal to zero. Equation (xxiv) in Appendix II reveals that in steady state, the real part of positive-current sequence of the converter, \( I_{+d} \), is zero. Hence, the output of the total dc voltage controller can determines the reference for the positive-sequence of the d-current converter component, \( I_{+d} \), as shown in Fig. 4.10. When the overall direct-voltage level reaches its reference value, there is no need for energy transferred from/by the host grid and the controller error becomes zero. However, in practical applications in order to
cover power (conducting and switching) losses, there must be a small amount of active-power injection to the converter, and the overall direct-voltage controller can serve this demand.

![Overall direct-voltage Controller](image)

**4.4.4 DHB Power-Channel control as Arm Balancer**

The basic idea behind DHB “power channels” is to exchange the required amount of power between phase-arms, so as to keep the direct-voltage levels constant in each converter branch. The DHB “power channels” can act as arm balancers forcing equal direct-voltage on both sides. Assuming that the overall direct-voltage level has been achieved in the converter, a simple PI controller that sets the direct-voltage difference of each a- and b-side dc-capacitor pair to zero is required. Thus, the output of the arm balancer provides the phase-shift angle command, $\delta^{ref}$, which is the input to the DHB modulator. Using a fast and adequate modulation in the converter arms, the same $\delta^{ref}$ can be used for all $N$ “power channels”. Therefore, a PI controller that tries to set eliminate total direct-voltage difference between the converter arms ($V_{dc,a} - V_{dc,b}$) provides the $\delta^{ref}$ command. For the reasons described in the previous section, the measured voltages are passed through a LPF to extract and control only their dc components, as it is depicted in Fig. 4.11.

![Arm-balancer direct-voltage Controller](image)

**4.4.5 Individual Voltage-Balancing Control and MMC Modulation Strategy**

As mentioned in Chapter 3, there are different ways of achieving equal direct-voltage among the individual SM capacitors in each branch. The dc-capacitor voltage balancing is achieved by exchanging energy among the cells of the same phase without grid interaction. For this project the algorithm selection strategy that was presented in [82] was selected. In order to conduct the modulation, all SM direct-voltage values are assumed to be known through measurement at each switching instance. For multilevel topologies, multicarrier PWM techniques involve a modulating reference signal (sinusoidal voltage command in our case), which is compared with $N$ triangular carrier signals comprising multilevel bands [84]. A Phase Disposition (PD) strategy is selected, as
illustrated in Fig. 4.12, where all carriers are in phase across all bands. According to the voltage command the number of SM that must be inserted/bypassed is determined, which is the first step of the algorithmic procedure. The selection process is achieved according to the direction of the arm current and the command of “insert or bypass” an SM, derived after the first step. When a current is flowing in the positive direction, i.e. the SM capacitors will get charged, if a SM has to be inserted, then the one with the lowest dc-capacitor voltage will be selected in order to increase its voltage level. Otherwise, if a SM has to be bypassed, the SM with the highest voltage will be chosen for the opposite reason. On the other hand when a current is flowing in the negative direction, i.e. the SM capacitors will get discharged (if connected with positive polarity), the opposite selection strategy will be followed. This algorithm combined with the selection of a fairly large SM capacitance and a relatively high carrier frequency can ensure equal voltage sharing among the arm’s SM.

Fig. 4.12 N-level carrier-based PD-PWM modulation using a triangular carrier
5. SIMULATION AND RESULTS

In order to verify the power-quality compensation capability of the proposed MMC-based STATCOM design, the power system software of PSCAD was used as a simulation tool under various traction-loading conditions. Apart from that, the investigation of the dynamic response of the ‘Power Channel’ on arm-voltage balancing with respect to the power transfer through the ‘Power Channels’ is another crucial focus of the project. In the following sections, the parameters used to model the system are given, and different case studies are investigated in simulation.

5.1 System Parameters

Initially, the utility grid illustrated in Fig. 4.1, which supplies the traction loads is modelled as an ideal sinusoidal three-phase voltage source with, $V_1$ of 110 kV, 50 Hz line-to-line rms value behind a grid impedance $Z_{grid}$. The V-V traction configuration consists of two 25 MVA single-phase transformers at 110 kV/25 kV voltage terminal levels, modelled by a leakage inductance of $L_{\sigma,STT} = 0.15$ H without any active or core losses.

In literature, various methods to model a train system exist. For instance, an inductive load $Z_L$ [34] or a resistive load $R_L$ can be placed in parallel with an uncontrollable rectifier [74]. However, in this project the train loads will be modelled as sinusoidal-current sources with a lagging power factor. The reason behind this decision is that the regenerative mode of operation of a train can be considered in the study cases, referred as ‘active-load’, and for compatibility reasons in comparison with the ‘passive-load’ conditions as well. A typical value of the maximum active power that each load can consume/generate is 10 MVA for high-speed trains.

The 25-kV, 25-MVA MMC branches of the STATCOM consist of $N = 5$ cascaded SM each and a buffer inductor $L = 0.2$ mH. Therefore, an eleven-level line-to-line voltage waveform is generated by each converter-arm. In addition, each SM is composed by a full bridge VSC with four IGBTs as semiconductor power-switching devices, and of two dc-storage 6.6 mF capacitors connected in series. Each IGBT is equipped with an anti-parallel diode. Switching devices are represented by a small value of resistance $R_{on}$ during conduction, and by an enormous value in the off-state. A five-band Phase Disposition PWM strategy, naturally sampled, is applied with a triangular carrier at $f_{MMC} = 2.5$ kHz.

Each ‘Power Channel’ consists of an isolated 2 MVA MFT. Each transformer is modelled by a leakage inductance $L_{\sigma,MFT} = 0.5$ mH, without any active or core losses. A phase-shifted PWM strategy, described in sections 4.3.1-2, is applied with a carrier at $f_{DHB} = 1$ kHz. The converter design parameters are concentrated in Table I.

Table I. Simulation parameters of proposed MMC-based STATCOM

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Notation</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of cells/arm</td>
<td>$N$</td>
<td>5</td>
</tr>
<tr>
<td>Buffer arm inductor</td>
<td>$L$</td>
<td>0.2 mH</td>
</tr>
<tr>
<td>SM dc-capacitance</td>
<td>$C$</td>
<td>3.3 mF</td>
</tr>
</tbody>
</table>
### Quantity | Notation | Value
--- | --- | ---
Rated SM direct-voltage | $U_c$ | 8 kV
Switching frequency of MMC branch | $f_{MMC}$ | 2.5 kHz
Number of ‘Power Channels’ | $N_{DHB}$ | 5
Leakage inductance of MFT | $L_{\sigma,MFT}$ | 0.5 mH
Switching frequency of DHB | $f_{DHB}$ | 1 kHz

#### 5.2 Identification of different load cases

The proposed compensation technique for load balancing is evaluated by simulating different cases of loading. The phasor diagram of the system without any compensation is shown in Fig. 5.1. These phasor diagrams represent a graphical illustration of the imposed load imbalances that was described analytically in Section 4.1. Taking into account the regenerative braking operation of a train four, different combinations of train-loading can emerge because the operation of each train is independent. The corresponding load power factors $\cos \varphi_p$, $\cos \gamma_p$, $\cos \varphi_a$, and $\cos \gamma_a$ are selected in the range of $0.86–1$ lagging, with $p$ and $a$ subscripts denoting passive and regenerative mode of the train respectively. In order to achieve active power generation with a corresponding lagging power factor $\cos \varphi_a$ or $\cos \gamma_a$, the load current must be leading the opposite phasor of the load voltage $V_{ac}$ and $V_{bc}$ respectively.

![Fig. 5.1 Phasor diagram of load currents for train 1 and 2 without STATCOM compensation](image-url)

- (a) both ‘passive’
- (b) ‘active’-‘passive’
- (c) both ‘active’ (regenerating)
- (d) ‘passive’-‘active’ loading
5.3 NSC Current Evaluation According to Different Loading

In order to investigate the impact of asymmetrical traction loading on the generation of NSC in the grid currents, the system is simulated without the compensation device. Therefore, the profile of the current unbalance on the grid-side can be evaluated based on the four different load conditions described in previous section. The positive-sequence components (PSC) and NSC can be retrieved from equations (20) – (21), as functions of the load-current amplitudes and phases for both ‘passive -load’ and ‘active-load’ conditions. The analytical expressions of the PSC and NSC for each one of the (a), (b), (c) and (d) cases have been calculated in Appendix I. In Fig. 5.2 and Fig. 5.3 the amplitude of NSC and PSC grid-currents are plotted by setting the load-current amplitudes in \( xy \) plane for various power factors using MATLAB software. The positive range of current amplitudes lies between 0 to 1 \( \text{pu} \) (corresponding in 0 to 10 MVA) and stands for “passive”, while the negative range represents “active” load conditions. The amplitude of the current is considered as the per unit base.

![Fig. 5.2 Amplitude of NSC of grid-currents in [pu] without STATCOM compensation (a) both ‘passive’ (b) ‘active’-‘passive’ (c) both active and (d) ‘passive’-‘active’ loading](image)

A general observation from Fig. 5.2 is that in all cases the higher the current amplitude is (maximum load), the higher values in magnitude of NSC are obtained. For each case, the power factors illustrated in Fig. 5.2, have been estimated according to the Appendix I equations in a way that each combination of power factor values would create the highest or the lowest overall NSC magnitude. All the other possible combinations of power factors in their determined range will create surfaces that lay between the plotted ones. Among all cases, case (b) generates the highest overall NSC current amplitude, while case (d) generates slightly lower values of NSC for the majority of power factors.

The PSC grid currents are depicted in Fig. 5.3 for the same sets of power-factor values. According to their analytical equations in Appendix I, case (a) will present the same behavior as (c) for PSC currents. The same condition stands between cases (b) and (d). Typically, the profile of PSC follows similar trend as the NSC surfaces. One crucial load condition is when one train is operating as consumer while the other traction side is feeding back power to the grid ((b) and (d)), with unity power factors at both sides. Under this load condition only NSC of current exists, since the PSC is completely eliminated.
5.4 System simulation without NSC compensation

The system response for maximum active-power requirements on loads ($|I_{tr1}| = |I_{tr2}| = 1$ pu) is simulated in PSCAD for both worst- and best-case scenarios in each case and the results are illustrated in Fig. 5.4 and 5.5 respectively. The worst-case scenarios are defined as the cases that create the highest ratios of $|I_{NSC}|/|I_{PSC}|$. On the other hand the best-case ones are related with the lowest ratios of $|I_{PSC}|/|I_{NSC}|$. In the following figures, the impact of asymmetrical loading is evident in the generation of NSC on grid side. The grid current becomes highly unbalanced in all cases. More specifically, it can be observed in Fig. 5.4 (b) and (d), that the grid-side current has completely changed its fundamental sequence from $abc$ to $acb$ (negative) as it was expected from the previous analysis in Fig. 5.2 and Fig. 5.3. Despite the fact that moving from worst-scenarios for each case to the associated better ones the quality of current waveforms is improved, the NSC compensation is still considered to be vital for the secure operation of the system.

---

**Fig. 5.3** Amplitude of PSC of grid-currents in [pu] without STATCOM compensation (a) both ‘passive’ (b) ‘active’-‘passive’ (c) both active and (d) ‘passive’-‘active’ loading

**Fig. 5.4** Grid-side currents without STATCOM compensation for worst scenarios (a) both ‘passive’ (b) ‘active’-‘passive’ (c) both active and (d) ‘passive’-‘active’ loading
Another crucial task of the project is the dimensioning design of the converter according to the application requirements and restrictions. Apart from its voltage ratings, which are specified due to the application parameters inputs, the maximum required amplitude of current flow through the converter must be investigated. According to equations (33) and (34), the converter currents are functions of the load-current amplitudes and phases. Therefore, the load-conditions that are generating the maximum arm currents must be specified according to these equations for all cases of traction loading. Fig. 5.6 shows various case-scenarios for four sets of power-factor combinations. The reference amplitude converter-branch currents are plotted by setting the load-current amplitude in the xy plane for various power factors using MATLAB software. The reason for not identifying the worst-case scenarios is complex trigonometrical formulas that were derived in Appendix II.
It can be observed that the converter currents are asymmetrical due to the unbalanced loads. The maximum current amplitude for the a- and b-branch are observed for two loading cases respectively as

\[
\max(|I_{conva}^e|) = 1.067 \text{ pu},
\]

for

\[
\begin{align*}
I_{tr1} &= 1 \text{ [pu]} \text{ and } \cos \varphi_p = 0.86, \\
I_{tr2} &= -1 \text{ [pu]} \text{ and } \cos \gamma_a = 1
\end{align*}
\]

\[
\max(|I_{convb}^e|) = 1.067 \text{ pu}
\]

for

\[
\begin{align*}
I_{tr1} &= 1 \text{ [pu]} \text{ and } \cos \varphi_p = 1, \\
I_{tr2} &= -1 \text{ [pu]} \text{ and } \cos \gamma_a = 0.86
\end{align*}
\]

Therefore, the current dimensioning of the converter is determined by the maximum amplitude of the expected load currents when the trains are operating in opposite modes. On the other hand, if the regenerative braking is not an option, the maximum expected converter current is 0.62 pu in the case where one of the trains is operated at its maximum power while the other is standing still. In that case the converter can be rated for substantially lower current values.
5.5.2 Converter Power Requirements

As was mentioned in Chapter 4, from a power perspective, the load balancing is accomplished by injecting active power in one phase and absorbing the same amount in the other phase as

\[ p_{\text{conva}}^{\text{ref}} = \frac{1}{2} (P_{\text{load,b}} - P_{\text{load,a}}) \]  
\[ p_{\text{convb}}^{\text{ref}} = \frac{1}{2} (P_{\text{load,a}} - P_{\text{load,b}}) \]  

Thus, the total power exchange of the converter with the power-grid system is zero which validates its operation as STATCOM. The power that each converter chain link produces/consumes can be estimated as

\[ S_{\text{conva}}^{\text{ref}} = V_{\text{conva}}^{\text{ref}} \cdot \{i_{\text{conva}}^{\text{ref}}\}^* = p_{\text{conva}}^{\text{ref}} + jQ_{\text{conva}}^{\text{ref}} \]  
\[ S_{\text{convb}}^{\text{ref}} = V_{\text{convb}}^{\text{ref}} \cdot \{i_{\text{convb}}^{\text{ref}}\}^* = p_{\text{convb}}^{\text{ref}} + jQ_{\text{convb}}^{\text{ref}} \]

The reference active powers of the converter arms are plotted in Fig. 5.7, by setting the load-current amplitudes in the xy plane for two cases of power factor combinations using MATLAB software. Applying unity power factor in both loads, results in the maximum power requirements for both phases, when the loads are operating at opposite modes and maximum currents. The same occurs for 0.86 lagging power factors, but with lower value of power requirements (0.86 times lower). Observing the graphs of Fig. 5.7 (c), it can be verified that the overall active power is always zero. Furthermore, in the worst-case scenario, the converter chain-links must generate/consume power equal with their phase active load.

In Fig. 5.8, the required reactive-power injection from each converter arm is illustrated for the same conditions that were investigated for the active power. It is observed that the reactive-power requirements are not the same for both phases. Reactive-power is the dominant factor that affects the voltage level at the POC. The unequal reactive-power injection that is determined by the compensation method can result in significant unequal voltage drops or boosts in the secondary side of traction transformer, especially for cases of weak POC.
Fig. 5.7 Converter active power requirements for two power factor combination sets (a) a-phase, (b) b-phase, (c) sum of a- and b-phase.

Fig. 5.8 Converter reactive power requirements for two power factor combination sets (a) a-phase, (b) b-phase, (c) sum of a- and b-phase.
The total apparent power requirements of the converter phases are shown in Fig. 5.9 for various power-factors, in order to obtain the required dimensioning of the convert. From the graphs below it is proven that the STATCOM should be dimensioned 1.005 times the value of total load.

![Converter apparent power requirements for four power factor combination sets (a) a-phase and (b) b-phase](image)

**Fig. 5.9 Converter apparent power requirements for four power factor combination sets (a) a-phase and (b) b-phase**

### 5.6 System Simulation with Proposed MMC STATCOM Installed

In this section the system response will be simulated in the PSCAD environment with the proposed MMC STATCOM topology installed at the catenary side. The first goal is to show that the proposed compensation method can balance the three-phase grid-currents for different loading cases. The combination of train operation modes that is investigated in the rest of the project are:

(a) both ‘passive’,
(b) opposite modes (i.e. Train 1 behaves as ‘active’ and Train 2 as ‘passive’ and
(c) both ‘active’.

#### 5.6.1 Steady-State Operation

In this section the load balancing of the system is shown during rated-load conditions. In section 5.3 the power factors that resulted in highest grid current NSC were obtained and will be applied as the worst-case scenarios, to evaluate the compensation capability of the converter. Fig. 5.10 shows the grid currents according to the simulation results.

In the following graphs it is observed that the load balance at the POC has been accomplished for all cases. In case (b), where operation in opposite modes is evaluated, the grid currents are
completely eliminated since Train 1 (decelerating) can supply Train 2 (accelerating) through the converter, and no power from the grid is required.

Fig. 5.10 Balanced grid-currents after STATCOM compensation (a) Train 1 & 2 ‘passive’, (b) Train 1 ‘active’ –Train 2 ‘passive’ and (c) Train 1 & 2 ‘active’ loading at $|I_{tr1}| = |I_{tr2}| = 1 \text{pu}$

In order to validate the load balancing capabilities during this operation case also, Train 1 is set at one fourth of its maximum generating power ($I_{tr1} = -0.25 \text{pu}$). The grid-current response in Fig. 5.11 has the same behavior as described for the cases in Fig. 5.10. Therefore, the compensation strategy has been proven to be adequate to balance the load as seen from the POC for all modes of operation.

Fig. 5.11 Balanced grid-currents after STATCOM compensation (c) Train 1 & 2 ‘active’ loading at $|I_{tr1}| = 1, |I_{tr2}| = 0.25 \text{pu}$

The next step is to show that the converter operation is stable for the cases (a), (b), and (c). Since, the converter lacks a common dc-bus, the direct-voltage level of the SM capacitors is a critical
feature for stable operation of the converter. As it can be observed in the following figures (Fig. 5.11 - 5.13), equal direct-voltage sharing is achieved at the SM dc-capacitors of the converter. Within 2 sec, the capacitors reach their steady-state voltage of 8 kV, and get stabilized in both phases even starting from a non-energized state. The dc-capacitor voltage at a- and b- branches phases are denoted as $V_{dc}^{SM,a}$ and $V_{dc}^{SM,b}$ in the graphs. The MMC modulator strategy arranges sufficiently the equal voltage splitting among the capacitors in the same chain-link. During the start-up procedure of the converter, the capacitors have the capability of reaching their direct-voltage reference value from a completely discharged state without any extra auxiliary power supply.

![Fig. 5.11 Voltage response in dc-capacitors for case (a)](image)

![Fig. 5.12 Voltage response in dc-capacitors for case (b)](image)
In cases (a) and (c) there is no power transfer through the DHB ‘Power Channel, due to the equal active-power demand in both traction-transformer sides, while in case (b) the active power generated in a-side is transferred to supply the load of Train 2. This is shown in Fig. 5.14, where the reference angle $\delta^{ref}$ is plotted. According to (39) a zero angle for (a) and (c) cases corresponds to zero power transfer through the channel, while a 0.478 rad phase difference corresponds to 2 MVA per power channel and to 10 MVA totally.

5.6.2 Load step response

In order to assess the performance of the converter during transient phenomena, a step response is applied to the Train 2 load. At 2.45 sec the Train 2 stops from consuming power and brakes with full power, feeding back energy to the system. This means that all the power generated at Catenary 1 (see Fig. 4.1) will flow through the power channel to supply the Train 1. As it can be seen in Fig. 4.15 the system returns to its reference value after the initial transient. The corresponding shift angle $\delta^{ref}$ response, and the power transferred $P_t$ in each channel are shown in Fig. 5.16. The
$\delta_{ref}$ is 0 during case (a) since no power needs to be exchanged between converter chain-links. After case (b) is applied, it reaches its steady-state value 0.478 rad in order to transfer 2 MVA per power channel. Because this is the maximum load-step change, stable operation of the converter is ensured for any other smaller load changes.

![Graph showing voltage dc-capacitors step response](image1)

**Fig. 5.15 Voltage dc-capacitors step response subjected to load change from case (a) to (b)**

![Graph showing response in angle $\delta_{ref}$](image2)

**Fig. 5.16 Response in angle $\delta_{ref}$, subjected to load change from case (a) to (b)**

### 5.6.3 Power Channel reduction

It is interesting to investigate a case where a number of DHB channels can be eliminated. This situation either represents a case with a faulty DHB, or the number of DHBs os intentionally lowered than the number of SMs in order to evaluate the feasibility of the concept with a reduced number of ’Power Channels’. Assuming in this simulation a faulty DHB, in order to keep the initial design parameters of the ‘Power Channels as shown in Table 1, the maximum amount of active power that can be transferred through the power channel at steady state occurs when phase angle becomes $\delta = \pi/2$ and is given as

$$\begin{align*}
P_{t,\text{max}} &= V_{dc}^a \cdot V_{dc}^b \cdot \frac{\delta(\pi - \delta)}{\pi \omega_s L_s} = V_{dc}^a \cdot V_{dc}^b / 8 f_{DHB} L_s \sigma_{MFT} = 3.876 [\text{MVA}] 
\end{align*}$$

(47)
The maximum power $P_{t,\text{max}}$ required to be transferred through four out of five channels is 2.5 MVA per power channel. As shown in (47), the maximum power limits of DHB channel are enough to cover those worst case power-transfer requirements. Deactivating one DHB converter at 0.5 sec, during the loading conditions of case (b), the phase shift angle $\delta^{\text{ref}}$ is increased from 0.478 to 0.63 rad (Fig. 5.17). Those phase-shift angles correspond to $5 \times 2 = 10$ MVA and $4 \times 2.5 = 10$ MVA total active power transfer. Fig. 5.18 shows the dc-capacitors voltage response to that change, where stable operation can be observed. The converter is capable of transferring the required active power and perform load balancing through four DHB channels, fact that increases converter’s inherent redundancy.

Fig. 5.17 Phase shift angle $\delta^{\text{ref}}$ step response during one ‘Power Channel’ reduction for load case (b)

Fig. 5.18 Voltage dc-capacitors response during one ‘Power Channel’ reduction for load case (b)
6. DISCUSSION AND CONCLUSIONS

The main objective of this thesis is the design of a converter for alleviating traction-load unbalances in 50-Hz railway applications. As it is described in Chapter 2, the asymmetrical and heavily time-varying character of the traction loads imposes critical load imbalances to the power-grid system. The STT topology in railway supply networks is an additional cause of increasing this inherent imbalance. The direct impact of these load imbalances, as described in Chapter 2 & 4, is a negative-sequence current injection on the grid side, threatening the secure operation of the system. Therefore, a compensation device accounting for NSC and reactive power compensation is necessary for power-quality improvements, especially in a weak POC. A comprehensive review of compensation techniques and devices is given in Chapter 2 as well.

In Chapter 3, operational principles of MMC-based topologies are analyzed, as MMCs consist the next generation of power converters. Applying the existing topologies of MMC-based STATCOM devices as load balancers, some major challenges are arising. The main drawbacks are the need for a third phase leg in the converter, and also that all three legs need to be overrated in order to handle a circulating component, which is responsible for energy exchange among the legs, and thus ensures stable operation for the converter.

The general requirements and the necessary topology modifications required for designing a reduced arm chain-link MMC compensator are described in Chapter 4. As the third leg now is missing from the converter topology, an alternative mean of power exchange should be invented. Therefore, a high-frequency ‘Power Channel’, incorporated by a DHB converter, is designed to connect each SM of a branch phase with a corresponding SM of the other phase. Instead of using circulating current that increases the device ratings, the required energy exchange between the two branches is controlled by a DHB converter operation. However, the proposed novel MMC topology has an increased complexity in structure and control, which are the main drawbacks of the device.

The evaluation of the converter behavior is investigated in the PSCAD software environment. Three different cases of traction loading have been considered and their impact on the negative-sequence grid-current injection was investigated for different load-power factors. The most crucial situation for the system load unbalances is emerging when the train load on one catenary side operates as a consumer, while on the other side the train is braking. Especially, for some loading cases the PSC gets eliminated and only NSCs of current exist in the system (Fig. 5.2). Furthermore, the required active-power generation/consumption of the MMC branches, and the required energy/power exchanged via the ‘Power Channels’ is also investigated with respect to the traction load cases. Once again, the maximum power requirements exist when on one catenary side the train load operates as a consumer while on the other side the train is braking with its maximum power (10 MVA).

The proposed MMC topology was proven capable of achieving load balancing and reactive power compensation as ‘seen’ from grid side at the POC for all different types of loading cases. The DHB ‘Power Channels’ can effectively act as arm balancers, providing the path for the required energy exchange among arm chain-links and ensuring equal voltage sharing among the converter branches. Their operation does not contradict with the modulator sorting algorithm, which ensures the equal voltage sharing inside each chain-link individually. The converter has a start-up capability and can operate effectively under maximum load-step changes. The designing parameters of the ‘Power Channel’ have been selected properly in order to afford higher amounts of energy transfer, and thus stable operation can be ensured with fewer channels than the number of SMs in the chain-link. In this thesis project, the MMC converter was consisted of $N = 5$ SMs per chain-link, and by
reducing the number of ‘Power Channels’ to \( N_{DHB} = 4 \), the converter was able to manage its compensation tasks and retain its stability.

In conclusion, the basic concept discussed in this thesis is how to exchange energy among SMs of different branches in order to obtain equal voltage sharing among the branches was proven that is feasible with the use of DHB converters in the railway application for NSC and power-factor compensation.
7. **FUTURE WORK**

The main goal of the thesis was to design a reduced MMC converter equipped with appropriate ‘Power Channels’ for energy exchange among the branches in order to compensate for load imbalances, and correct the power factor in 50-Hz railway applications. The basic challenges to overcome were the investigation of channels’ possible structure and their control strategy to ensure voltage arm balancing. The concept of energy exchange among arm chain-links was proven and some future work can focus on:

- **Catenary Voltage control:** The overall control block diagram can be enhanced with voltage control at the connection point of the converter. Therefore, the voltage level of the catenary can be adjusted and the distance between two subsequent STT can be increased.

- **Individual SM voltage control:** Instead of using a sorting algorithm, the performance of the proposed converter topology can be evaluated for individual SM voltage control by applying PI or Proportional Resonant control theory.

- **Analytical loss investigation:** Converter losses should be analytically derived, including the ‘Power-Channels’ behavior in order to optimize the design parameters of the converter.

- **Further reduction of DHB links:** It was proven that the converter can operate with fewer power channels than the number of SMs in the chain-link. One condition to achieve that, is to dimension the active-power channels for the maximum required energy transferred according to the application requirements. However, the limitation aspects to what extent the number of channels can drop down must be further investigated.

- **Comparison with other compensators:** Another important aspect of a future project is a comprehensive study comparing different existing MMC STATCOM topologies with the proposed one with respect of losses, cost, volume, and the overall efficiency of the converter.
APENDIX

1. CALCULATION OF PSC AND NSC AMPLITUDE OF LOAD-CURRENT

By replacing in the equation (21) and (22) the functions identities $1 - a^2 = \sqrt{3}e^{j\pi/6}$, $a - a^2 = \sqrt{3}e^{j\pi/2}$, $1 - a = \sqrt{3}e^{j11\pi/6}$, $a^2 - a = \sqrt{3}e^{j3\pi/2}$, it yields to

\[
I_+ = \sqrt{3} \frac{K}{3} \left[ I_{tr1} e^{j(\phi + \pi/6)} + I_{tr2} e^{j(\gamma + \pi/2)} \right] \quad (i)
\]
\[
I_- = \sqrt{3} \frac{K}{3} \left[ I_{tr1} e^{j(\phi - \pi/6)} + I_{tr2} e^{j(\gamma - \pi/2)} \right] \quad (ii)
\]

By replacing in (i) and (ii) the trigonometric identity $e^{j\theta} = \cos \theta + jsin\theta$

\[
I_+ = \frac{K\sqrt{3}}{3} \left[ I_{tr1} (\cos (\phi + \pi/6) + jsin (\phi + \pi/6)) + I_{tr2} (\cos (\gamma + \pi/2) + jsin (\gamma + \pi/2)) \right] \quad (iii)
\]
\[
I_- = \frac{K\sqrt{3}}{3} \left[ I_{tr1} (\cos (\phi - \pi/6) + jsin (\phi - \pi/6)) + I_{tr2} (\cos (\gamma - \pi/2) + jsin (\gamma - \pi/2)) \right] \quad (iv)
\]

When loads are passive then the phase angle of the current is expressed as

\[
\phi = -\frac{\pi}{6} - \phi_p \quad (v)
\]
\[
\gamma = -\frac{\pi}{2} - \gamma_p \quad (vi)
\]

While when they are active

\[
\phi = -\frac{\pi}{6} + \pi + \phi_a \quad (vii)
\]
\[
\gamma = -\frac{\pi}{2} + \pi + \gamma_a \quad (viii)
\]

For case (a), i.e. $\phi = -\pi/6 - \phi_p$ and $\gamma = -\pi/2 - \gamma_p$, the magnitude of sequence components are

\[
|I_+|_{(a)} = \frac{K\sqrt{3}}{3} \sqrt{[I_{tr1} \cos(\phi_p) + I_{tr2} \cos(\gamma_p)]^2 + [I_{tr1} \sin(\phi_p) + I_{tr2} \sin(\gamma_p)]^2} \quad (ix)
\]
\[
|I_-|_{(a)} = \frac{K\sqrt{3}}{3} \sqrt{[I_{tr1} \cos(\pi/3 + \phi_p) + I_{tr2} \cos(\pi + \gamma_p)]^2 + [I_{tr1} \sin(\pi/3 + \phi_p) + I_{tr2} \sin(\pi + \gamma_p)]^2} \quad (x)
\]

And after mathematical calculations it yields to,

\[
|I_+|_{(a)} = \frac{K\sqrt{3}}{3} \sqrt{I_{tr1}^2 + I_{tr2}^2 + 2I_{tr1}I_{tr2}\cos(\phi_p - \gamma_p)} \quad (xi)
\]
\[
|I_-|_{(a)} = \frac{K\sqrt{3}}{3} \sqrt{I_{tr1}^2 + I_{tr2}^2 + 2I_{tr1}I_{tr2}\cos(\phi_p - \gamma_p - 2\pi/3)} \quad (xii)
\]

Following the previous procedure for the cases (b), (c) and (d) the magnitudes of sequence components are expressed as,
For case (b),

\[
|I_+|(b) = \frac{K\sqrt{3}}{3} \sqrt{I_{tr1}^2 + I_{tr2}^2 + 2I_{tr1}I_{tr2}\cos(\varphi_a + \gamma_p + \pi)} \tag{xiii}
\]

\[
|I_-|(b) = \frac{K\sqrt{3}}{3} \sqrt{I_{tr1}^2 + I_{tr2}^2 + 2I_{tr1}I_{tr2}\cos(\varphi_a + \gamma_p + 5\pi/3)} \tag{xiv}
\]

For case (c),

\[
|I_+|(c) = \frac{K\sqrt{3}}{3} \sqrt{I_{tr1}^2 + I_{tr2}^2 + 2I_{tr1}I_{tr2}\cos(\varphi_a - \gamma_a)} \tag{ xv }
\]

\[
|I_-|(c) = \frac{K\sqrt{3}}{3} \sqrt{I_{tr1}^2 + I_{tr2}^2 + 2I_{tr1}I_{tr2}\cos(\varphi_a - \gamma_a + 2\pi/3)} \tag{xvi}
\]

For case (d),

\[
|I_+|(d) = \frac{K\sqrt{3}}{3} \sqrt{I_{tr1}^2 + I_{tr2}^2 + 2I_{tr1}I_{tr2}\cos(\varphi_p + \gamma_a + \pi)} \tag{ xv }
\]

\[
|I_-|(d) = \frac{K\sqrt{3}}{3} \sqrt{I_{tr1}^2 + I_{tr2}^2 + 2I_{tr1}I_{tr2}\cos(\varphi_p + \gamma_a + \pi/3)} \tag{xvi}
\]
2. CALCULATION OF CONVERTER-CURRENT AMPLITUDE PSC AND NSC

Equations (32) and (33) can be written in phasor representation as

\[
I_{\text{conv}}^{\text{ref}} = I_{tr1} e^{j\phi} - Le^{j0} \quad \text{(xviii)}
\]

\[
I_{\text{conv}}^{\text{ref}} = I_{tr2} e^{j\gamma} - Le^{-j2\pi/3} \quad \text{(xviii)}
\]

where the constant \( L \) substitutes the following expression as

\[
L = \frac{\sqrt{3}}{3} \left( I_{tr1} \cos \left( \frac{\pi}{6} + \phi \right) + I_{tr2} \cos \left( \frac{\pi}{2} + \gamma \right) \right) \quad \text{(xix)}
\]

The amplitude of the converter can be written as

\[
|I_{\text{conv}}^{\text{ref}}| = \sqrt{|I_{tr1}|^2 \cos \phi - L|^2 + (|I_{tr1}| \sin \phi)^2 = \sqrt{|I_{tr1}|^2 + L^2 - 2L|I_{tr1}| \cos \phi} \quad \text{(xx)}
\]

\[
|I_{\text{conv}}^{\text{ref}}| = \sqrt{|I_{tr2}| \cos \gamma + L/2|^2 + (|I_{tr2}| \sin \gamma + L/2)^2 = \quad \text{(xxi)}
\]

\[
= \sqrt{|I_{tr2}|^2 + \frac{L^2}{4} + \frac{L}{2} |I_{tr2}| \gamma + siny} \]

If the converter currents were analyzed in positive and negative sequence by applying the inverse transformation of eq. (18) then

\[
I_{\text{conv}}^+ = \frac{\sqrt{3}}{3} \left[ I_{tr1} e^{j(\phi + \frac{\pi}{6})} + I_{tr2} e^{j(\gamma + \frac{\pi}{2})} + Le^{j\frac{\pi}{3}} + Le^{-j\frac{\pi}{3}} \right] \quad \text{(xxii)}
\]

\[
I_{\text{conv}}^- = \frac{\sqrt{3}}{3} \left[ I_{tr1} e^{j(\phi - \frac{\pi}{6})} + I_{tr2} e^{j(\gamma - \frac{\pi}{2})} + Le^{j\frac{\pi}{3}} + Le^{-j\frac{\pi}{3}} \right] \quad \text{(xxiii)}
\]

After mathematical calculations it yields to

\[
I_{\text{conv}}^+ = \frac{\sqrt{3}}{3} \left[ I_{tr1} \sin(\phi + \frac{\pi}{6}) + I_{tr2} \sin(\gamma + \frac{\pi}{2}) \right] \quad \text{(xxiv)}
\]

\[
I_{\text{conv}}^- = \frac{\sqrt{3}}{3} \left[ I_{tr1} \cos \left( \phi + \frac{\pi}{6} \right) + \cos \left( \gamma - \frac{\pi}{2} \right) \right] + \frac{\sqrt{3}}{3} \left[ I_{tr1} \sin \left( \phi - \frac{\pi}{6} \right) + I_{tr2} \sin \left( \gamma - \frac{\pi}{2} \right) \right] + \frac{\sqrt{3}}{3} \left[ I_{tr1} \cos \left( \phi + \frac{\pi}{6} \right) + I_{tr2} \cos \left( \gamma + \frac{\pi}{2} \right) \right] \quad \text{(xxv)}
\]
8 REFERENCES


