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Control and Modulation of Modular Multilevel Converters

Thesis submitted in partial fulfilment of the requirement for the PhD Degree issued by the Universitat Politècnica de Catalunya, in its Electronic Engineering Program.

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Originality Statement

'I hereby declare that this submission is my own work and to the best of my knowledge it contains no materials previously published or written by another person, or substantial proportions of material which have been accepted for the award of any other degree or diploma at the Universitat Politècnica de Catalunya (UPC) or any other educational institution, except where due acknowledgement is made in the thesis. Any contribution made to the research by others, with whom I have worked at UPC or elsewhere, is explicitly acknowledged in the thesis. I also declare that the intellectual content of this thesis is the product of my own work, except to the extent that assistance from others in the project's design and conception or in style, presentation and linguistic expression is acknowledged.'

Signed:

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Dedicated to Antònia, Josep and Oriol.

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Abstract

The integration of renewable energy sources in the electrical grid is reducing our dependence on fossil fuels. However, to ensure feasibility and reliability of distributed energy generation, more efficient and higher power converters are required. The modular multilevel converter (MMC) is a modern topology of multilevel converter that is very attractive for medium- and high-voltage/power applications, including high-voltage direct current transmission systems and high-power motor drives.

The main features of the MMC are modularity, scalability to different power and voltage levels, redundancy and high quality output voltages and currents. However, the operation of the MMC is complex, and there are some issues that still have to be further investigated. One of these issues is the voltage ripples of the submodule (SM) capacitors. The voltage ripples define the minimum value of the capacitances needed for the converter, and therefore its overall size and cost. The use of a proper circulating current controller can reduce the voltage ripples. In this thesis, three techniques for calculating the circulating current reference are presented: two techniques based on optimization functions for minimizing the capacitor voltage ripples; and a fast-processing technique that provides results close to optimal.

The capacitor voltage ripples can also be reduced by adding a zero-sequence signal to the modulation signals. In this thesis, the application of discontinuous modulation to the MMC is proposed for the first time. This technique is based on the injection of a discontinuous zero-sequence signal and highly reduces the switching power losses and capacitor voltage ripples.

Real applications of the MMC are composed of a high number of SMs. This implies a challenge in the control system, including the data acquisition system. A new technique for measuring the capacitor voltages with only a few sensors has been presented in this thesis. From the output voltage provided by a group of SMs, the individual voltage of each one of them can be acquired. Since acquisition cannot be performed at each sampling time, the capacitor voltages are calculated between samples using an estimation algorithm.

Reliability is a feature required in industrial applications. The structure of the MMC facilitates the existence of redundant SMs, but faults need to be detected and localized for deactivating the faulty component. This thesis presents a robust and fast strategy for detecting, localizing and correcting faults in SMs and voltage sensors. The technique is based on three additional sensors per arm, which measure the output voltage of a group of SMs and compare it with the expected voltage.

Capacitance differences between the SMs can appear due to component tolerance or ageing of the capacitors. Capacitance mismatches cause uneven distribution of the power losses, thus increasing the thermal stress of some semiconductors, and therefore, their probability of failure. A power loss balancing technique has been proposed, equalising the losses in all the SMs and therefore avoiding the concentration of power losses in some SMs. Application of the MMC to motor drive applications has also been studied in this thesis. The operation of the MMC at low motor speeds/frequencies is still a challenge, since the capacitor voltage ripples are inversely proportional to the current frequency. In this thesis, it has been demonstrated that discontinuous modulation can help to reduce capacitor voltage ripples in motor drive applications, achieving very low speed operation. The technique is compared with other state-of-the-art methods, and it achieves similar capacitor voltage ripples and a significant reduction in power losses.

All the control and modulation techniques proposed in this thesis have been studied by simulation in the MATLAB/Simulink environment and corroborated experimentally on low-power laboratory prototypes.

Resum

La integració de fonts d'energia renovables a la xarxa elèctrica està reduint la nostra dependència dels recursos fòssils. Però per tal d'assegurar la viabilitat i fiabilitat de la generació d'energia distribuïda, fan falta convertidors estàtics més eficients i de més potència. El convertidor multinivell modular (MMC) és una topologia de convertidor multinivell recent, molt prometedora per aplicacions de mitja i alta potència, com són els sistemes de transmissió d'energia en corrent continua o els accionaments de motors d'alta potència.

Els principals avantatges del MMC són modularitat, escalabilitat en tensió i potència, redundància i gran qualitat de la tensió i corrent de sortida. El funcionament del MMC, però, és complex i encara hi ha alguns problemes que s'han d'investigar amb més profunditat. Un dels problemes és l'arrissat de tensió del condensador de sub-mòdul (SM). L'arrissat de tensió defineix el valor mínim d'aquests condensadors i per tant, el seu cost. L'ús d'un corrent circulant adequat pot reduir l'arrissat de tensió. En aquesta tesi es presenten tres tècniques per calcular la consigna del corrent circulant: dues tècniques basades en funcions d'optimització que minimitzen l'arrissat de tensió i una tècnica d'aplicació més simple, la qual proporciona resultats pròxims als òptims però que es pot calcular més ràpidament.

L'arrissat de tensió també es pot reduir afegint un component homopolar en els senyals de modulació. En aquesta tesi es proposa per primera vegada l'ús de la modulació discontinua per al MMC. Aquesta tècnica, basada en la injecció d'un component homopolar, permet una gran reducció de l'arrissat de tensió i de les pèrdues de commutació.

Les aplicacions reals del convertidor MMC es componen per un gran nombre de SMs. Això implica un repte en el disseny del sistema de control, particularment en l'etapa d'adquisició de dades. Aquesta tesi presenta un nou sistema de mesura per a les tensions dels condensadors de SM, en el qual es necessiten pocs sensors. A partir de la tensió de sortida d'un grup de SMs, el sistema pot adquirir la tensió de cada un d'ells. Com que l'adquisició no es pot fer a cada període de mostreig, entre adquisicions la tensió es calcula mitjançant un algoritme d'estimació.

Un dels requisits de les aplicacions industrials és la fiabilitat. L'estructura del MMC permet l'ús de SMs redundants, però les fallades s'han de detectar i localitzar per tal de desactivar el component erroni. En aquesta tesi es presenta un sistema ràpid i robust de detecció, localització i correcció de fallades en SMs i sensors de tensió. El sistema es basa en l'ús de tres sensors addicionals per semi-branca, els quals mesuren la tensió de sortida d'un grup de SMs i la comparen amb la tensió esperada.

A causa de la tolerància o l'envelliment dels condensadors, poden aparèixer diferències en la capacitat dels SMs. Aquestes diferències causen una mala distribució de les pèrdues dels semiconductors, incrementant l'estrès tèrmic d'alguns dels components i la probabilitat de fallada. Per això, es proposa un algoritme d'equilibrat de pèrdues, el qual iguala les pèrdues dels SMs i n'evita la concentració en algun SM.

En aquesta tesi també s'ha estudiat l'aplicació del MMC en accionaments de motors. El funcionament del MMC a baixa velocitat/freqüència del motor és un repte encara no resolt, ja que l'arrissat de tensió dels condensadors és inversament proporcional a la freqüència del corrent. Aquesta tesi demostra que la modulació discontinua es pot utilitzar per reduir l'arrissat de tensió en aquesta situació, aconseguint un bon funcionament a molt baixa velocitat. En comparació amb altres tècniques actuals de baixa velocitat, la modulació discontinua aconsegueix un arrissat de tensió similar i una reducció de les pèrdues.

Totes les tècniques proposades en aquesta tesi s'han estudiat mitjançant simulació en l'entorn MATLAB/Simulink i s'han corroborat experimentalment en prototips de laboratori.

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List of Acronyms

Acronym	*Definition*
AAC	Alternative arm converter
ac	Alternating current
AERI	Australian Energy Research Institute
APOD-PWM	Alternative phase-opposition disposition pulse-width modulation
CB-SVPWM	Carrier-based space-vector pulse-width modulation
CL-DPWM	Closed-loop discontinuous pulse-width modulation
CMsin	Low-speed technique based on a sinusoidal zero-sequence
CMsqr	Low-speed technique based on a square zero-sequence
dc	Direct current
DEE	Departament d'Enginyeria Electrònica
DSP	Digital signal processor
EMI	Electro-magnetic interference
FACTS	Flexible alternating current transmission system
FC	Flying capacitors
FPGA	Field programmable gate array
HVDC	High-voltage direct current
IGBT	Isolated-gate bipolar transistor
IMB-CNM	Institute of Microelectronics of Barcelona - Centro Nacional de Microelectrónica
LS-PWM	Level-shifted pulse-width modulation
MEC	Modulated energy control
MMC	Modular multilevel converter
MOSFET	Metal-oxide-semiconductor field-effect transistor
MTTF	Mean time to failure

NLM	Nearest level modulation
NPC	Neutral point clamped
OC	Open-circuit
OL-DPWM	Open-loop discontinuous pulse-width modulation
PEMC	Power Electronics, Motors and Control (group)
PCB	Printed-circuit board
PD-PWM	Phase-disposition pulse-width modulation
PI	Proportional integral
PLL	Phase-locked loop
PMSM	Permanent magnet synchronous machine
POD-PWM	Phase-opposition disposition pulse-width modulation
PR	Proportional resonant
PS-PWM	Phase-shifted pulse-width modulation
PWM	Pulse-width modulation
rms	Root mean square
RL	Resistive-inductive
SC	Short-circuit
SHE	Selective harmonic elimination
SM	Submodule
SPWM	Sinusoidal pulse-width modulation
STATCOM	Static compensator
STB	Switching transition balancing (algorithm)
SVM	Space-vector modulation
THD	Total harmonic distortion
TIEG-P	Terrassa Industrial Electronics Group - Power
TLB	Total loss balancing (algorithm)
UNSW	University of New South Wales
UPC	Universitat Politècnica de Catalunya
VDPWM	Virtual discontinuous pulse-width modulation
VOC	Voltage oriented control
VSC	Voltage-source converter

List of Symbols

Symbol	Definition
A_{cr}	Amplitude of the carrier signal v_{cr}
C	Submodule capacitor
C_{dc}	dc-link capacitor
C_{est}	Estimated capacitance
C_{jz}	Arm equivalent capacitor, j being the phase identifier $j \in \{a, b, c\}$ and the arm identifier $z \in \{u, l\}$
C_{real}	Real capacitance
C'_{jz}	Equivalent submodule capacitor in the arm z of phase j of the equivalent energy model
$C_{jz_{eq}}$	Equivalent arm capacitor in the arm z of phase j of the equivalent energy model
$Cnt_{z(n)}$	Counter of cycles without updating the estimator, z being the arm identifier and (n) the number of submodule
$d_{jz(n)}$	Duty cycle of submodule (n) in arm z and phase j
$e_{exp\ z(k)}$	Expected set error in the arm z, k being the number of set
$e_{t\ z(k)}$	Theoretical set error in the arm z and set k
E_{on}	IGBT turn-on energy loss
E_{off}	IGBT turn-off energy loss
E_{rec}	Diode reverse recovery energy
f	ac-side current fundamental frequency
f_{cr}	Carrier frequency
f_{samp}	Sampling frequency
f_{sin}	Frequency of the zero-sequence voltage used in CMsin
f_{sqr}	Frequency of the zero-sequence voltage used in CMsqr

f_{sw}	Switching frequency
F_{opt}	Optimization function
h	Harmonic order identifier
i_{jcomm}	Common mode current at phase j
i_d	d-component of the stator current in a synchronous reference frame
i_d^*	i_d reference
i_D	Diode current
i_{dc}	dc component in the circulating current
i_{jdiff}	Differential or circulating current at phase j
i_j	ac-side current of phase j
i_{jz}	Current of arm z of phase j
i_q	q-component of the stator current in a synchronous reference frame
i_q^*	i_q reference
i_T	IGBT current
i_{Wjz}^*	Circulating current reference for controlling the energy in the arm z of phase j
I_{ac}	Amplitude of the ac-side current
I_{jdiff0}	Initial differential current at phase j
I_N	Rated current of the motor
j	Phase identifier, where $j \in \{a, b, c\}$
(k)	Number of the measuring set, where $k \in \{1, ..., nS\}$
k_{jz}	Ratio between the average measured submodule capacitor voltage and the theoretical submodule capacitor voltage of arm z of phase j
K_{device}	Gain of the TLB algorithm for a particular kind of device i.e., upper IGBT, upper diode, lower IGBT or lower diode
$K_{enforced}$	Gain of the enforced activation method
K_h	Amplitude of the hth harmonic component in the circulating current
K_{lim}	Gain of the CL-DPWM proportional limit
K_{RSF}	Gain of the feedback loop in the voltage balancing algorithm with reduced switching frequency
K_{sw}	Gain of the STB algorithm
l_j	Number of activated submodules in the lower arm of phase j
L	Arm inductor

L_{ac}	Grid inductor
L_{out}	Load inductor
L_d	Equivalent stator inductance in the d-component of a synchronous reference frame
L_q	Equivalent stator inductance in the q-component of a synchronous reference frame
m	Modulation index
M	Number of additional submodules per arm
n	Number of output levels of the converter
(n)	Number of the submodule, where $n = \{1, ..., N\}$
nS	Number of measuring sets per arm
nM	Number of submodules per measuring set
nT	Number switching transitions in a fundamental period
N	Number of basic submodules per arm
O_{lim}	Offset of the CL-DPWM proportional limit
p	Number of pole pairs of the motor
p_z	Instantaneous power in the arm z
P_{cond}	Conduction power losses
P_N	Nominal power of the motor
P_{out}	Output power
P_{sw}	Switching power losses
P_{tot}	Total power losses
R_{CE}	IGBT equivalent series resistor
R_D	Diode equivalent series resistor
R_{out}	Load resistor
R_s	Stator resistance
$R(t)$	Reliability function
$s_{jz(n)}$	Control function defining the state of the submodule (n) of arm z of phase j
$s_N(v_{Cz})$	Standard deviation of the submodule capacitor voltages of arm z
t	Time
T	Fundamental period
T_e	Rated torque of the motor
u_j	Number of activated submodules in the upper arm of phase j

U_{sin}	Amplitude of the zero-sequence voltage used in CMsin
U_{sqr}	Amplitude of the zero-sequence voltage used in CMsqr
v_{ac}	ac-voltage generated by the arms
v_{Az}	Supervisory arm sensor voltage of the arm z
$v_{Cjz(n)}$	Submodule capacitor voltage, j being the phase identifier, z the arm identifier and (n) the number of submodule
v_{jcomm}	Common mode voltage at phase j
v_{cr}	Modulation carrier signal
$v^*_{Cz(n)}$	Capacitor voltage of submodule (n) of arm z modified by the enforced measuring algorithm
v_{Czavg}	Average value of all the submodule capacitor voltages in the arm z
v_d	d-component of the stator voltage in a synchronous reference frame
v_{jdiff}	Differential voltage at phase j
v_j	ac-side voltage of phase j
v_{jd}	Discontinuous modulation signal of phase j
v_{jm}	Modulation signal of phase j
v_{jz}	Voltage provided by the arm z of phase j
v_{jzd}	Discontinuous modulation signal for the arm z
v_{jzff}	Arm z of phase j modulation signal after feed-forward compensation
v_{jzm}	Arm z of phase j modulation signal
v_q	q-component of the stator voltage in a synchronous reference frame
v_{SMjz}	Output voltage of the submodule (n) of arm z of phase j
$v_{Sz(k)}$	Measuring set voltage, z being the arm identifier and (k) the number of set
$v_{Sz(k)\ exp}$	Expected voltage of the set (k) of arm z
$v_{Sz(k)\ t}$	Theoretical voltage of the set (k) of arm z
v_{zs}	Zero-sequence voltage
V_{CE}	IGBT collector-emitter saturation voltage
$V_{Cjz(n)0}$	Initial voltage of the capacitor (n) of arm z and phase j
$V_{Cz(n)S}$	Submodule capacitor voltage acquired through a measuring set, z being the arm identifier and (n) the number of submodule
V_{dc}	dc-link voltage
V_F	Diode forward voltage

V_g	Amplitude of the grid voltage
W_{Cjz}	Energy stored in the arm z of phase j
W^*_{Cjz}	Arm energy reference for the arm z of the phase j
x	Voltage level designed by the modulator
$\overline{y}$	Locally averaged value of the variable y
y_{norm}	Normalized value of the variable y
y_{rms}	rms value of the variable y
z	Arm identifier, where z indicates the upper arm (u) or the lower arm (l)
Z_{out}	Output impedance
δ	Variation of the capacitor voltages in the enforced measuring algorithm
δW_{Cjz}	Interval energy variation in the arm z
$\Delta v_{Cjz(n)}$	Submodule capacitor voltage ripple amplitude, j being the phase identifier, z the arm identifier and (n) the number of submodule
Δv_{est}	Estimated voltage variation in a submodule capacitor
Δv_{jm}	Differential control signal of phase j
Δv_{real}	Voltage variation in a submodule capacitor
Δv_{zs}	Zero-sequence compensation for the OL-DPWM
ΔW_{Cj}	Energy difference between upper and lower arms of phase j
ΔW^*_{Cj}	Energy difference reference for phase j
$\Delta\varphi$	Phase displacement between carriers in PS-PWM
λ_A	Failure rate of a supervisory arm sensor
λ_I	Failure rate of an individual submodule sensor
λ_m	Magnetic flux of the motor permanent magnets
λ_S	Failure rate of a supervisory set sensor
λ_{SM}	Failure rate of a submodule
ΣW_{Cj}	Total energy stored in the phase-leg j
ΣW^*_{Cj}	Phase-leg j total energy reference
φ	Output current phase angle
φ_h	Phase angle of an harmonic component in the circulating current, h being the harmonic order
ω	Fundamental angular frequency
ω_e	Electrical frequency of a motor
ω_N	Nominal speed of a motor

ω_o	Mechanical speed of a motor
ω_{sin}	Frequency, in rad/s, of the zero-sequence voltage used in CMsin
$\nabla F(x, y)$	Gradient of a multivariable function

Chapter 1

Introduction

This chapter presents the context and motivation for this research work. It includes a review of the previous research about modelling, modulation strategies, control techniques and fault-tolerant strategies for the MMC. This chapter also states the main objectives of this thesis and includes a list of the publications derived from it. To conclude, the thesis outline and the main contributions are presented.

1.1 Research Environment

The present thesis was developed in the Departament d'Enginyeria Electrònica (DEE) at the Universitat Politecnica de Catalunya (UPC), in the Terrassa Industrial Electronics Group – Power (TIEG-P). The main interests of the research group are:

- Electromagnetic compatibility: Electromagnetic interference (EMI) modelling, diagnostic and mitigation techniques for industrial environments, in vehicles, ships and aircraft.
- Renewable energy: Modelling and design of power converters for wind and photovoltaic (PV) systems.
- Power quality in electric systems: Measuring and correcting power supply disturbances in the generation and distribution systems.
- Control techniques for electric drives: Advanced techniques for matrix converters and multilevel converters.

This thesis has been funded mainly by the scholarship *Ayudas para contratos predoctorales para la formación de doctores 2013* (BES-2013-063590), which was granted by Spain's Ministerio de Economía y Competitividad.

Part of this thesis was developed during a research stay in the Power Electronics, Motors and Control (PEMC) group at the University of Nottingham, UK. The research stay was funded by the scholarship *Ayudas a la movilidad predoctoral para la realización de estancias breves en centros de I+D durante el año 2016* (EEBB-I-16-10672), which was also granted by Spain's Ministerio de Economía y Competitividad.

The research developed in this thesis was carried out in collaboration with researchers from the Energy Unit at Tecnalia Research and Innovation, Basque Country, Spain; the Australian Energy Research Institute at the University of New South Wales, Sydney, Australia; and the PEMC group at the University of Nottingham, UK.

This work is part of the activities developed under the projects RURALGRID, Consolider-Ingenio (CSD2009-00046) and CONNECT-DC (ENE2012-36871-C02-01).

The RURALGRID project, *Feasibility study in order to introduce renewable energies by means of microgrids in the Pyrenees Area*, was developed in the framework of the Comunidad de Trabajo de los Pirineos (CTP), which involved research organizations from Aragón (Universidad San Jorge and INYCOM), the Basque Country (Universidad del País Vasco/Euskal Herriko Unibertsitatea, Tecnalia Research and Innovation, and Jema Energy), Catalunya (UPC), Aquitaine (École Supérieure des Technologies Industrielles Avancées, IMS Bordeaux, and LOREKI), and Midi-Pyrénées (École Nationale d'Ingénieurs de Tarbes). In the case of Catalunya, the project was supported by the Secretaria d'Universitats i Recerca of the Departament d'Economia i Coneixement of the Generalitat de Catalunya. The RURALGRID project was devoted to studying the feasibility of implementing micro-grids in the Pyrenees area. New converter technologies were also analysed to improve the energy efficiency of micro-grids and distributed generation systems.

The project CSD2009-00046 of the Consolider-Ingenio Program, *Advanced wide band gap semiconductor devices for rational use of energy*, was funded by the Ministerio de Economía y Competitividad of Spain and was a collaboration between multiple research institutions, one of which was the UPC. It was led by the Institute of Microelectronics of Barcelona (Centro Nacional de Microelectrónica (IMB-CNM)). The CSD2009-00046 project was devoted to studying the use of wide band-gap semiconductor materials, such as silicon carbide (SiC) and Gallium Nitride (GaN), in a new generation of power semiconductor devices. The objectives of this project were to develop new semiconductor devices, characterize the new devices and implement power converters for demonstrating the advantages of the wide band-gap technology. The test converters have been selected to test characteristics such as operation at high temperature, extremely fast response or handling of high voltage.

The CONNECT-DC project, *Topologies and control of power electronic converters for offshore high voltage dc energy transmission*, funded by Spain's Ministerio de Economía y Competitividad, is a collaboration between two research organizations: the UPC and Tecnalia Research and Innovation. The CONNECT-DC project is devoted to analysing a medium-voltage dc transmission architecture for offshore applications. The main feature of this architecture is that the ac to dc current transformation is not located in an offshore platform but is instead distributed to each of the wind turbines. In this way it is possible to eliminate –or at least significantly reduce– the size of the offshore platform, thus reducing the costs of the transmission system. Other targets of this project are: development of control algorithms for wind turbine generators in order to optimize energy conversion efficiency; characterization of wind resources; and the development of control strategies for medium-voltage dc/ac onshore grid-connected power converters, including the modular multilevel converter (MMC).

1.2 Research Motivation

For a long time now, energy production has been dependent on fossil fuels. However, the paradigm has changed over recent decades as a result of the emergence of cleaner and cheaper energy resources. The development and improvement of renewable energy sources has lead to a distributed generation system, where multiple sources are connected to the electrical grid. Power converters allow integrating these energy sources from diverse origins into the electrical grid. The rise of renewable energy sources has led to requirements for higher power and more efficient converters.

Multilevel converters are indeed attractive power conversion topologies for medium- and high-voltage/power applications [1, 2]. The use of multiple semiconductor devices allows distribution of the voltage stress in each device, which increases the maximum ratings of the converter while using cheaper and more efficient semiconductors. Moreover, the multilevel output increases the quality of the ac-voltage, reducing the size and cost of the output filters. Some application fields of multilevel converters are: large electrical machine drives, such as offshore wind turbines; high-voltage direct current (HVDC) transmission systems; and flexible alternating current transmission systems (FACTS). The MMC [3], is a modern topology of multilevel converter that in just a few years has become the principal technology option for HVDC systems [4].

The main feature of the MMC is its modularity, which provides multiple benefits: scalability to different power and voltage levels; reliability with the use of redundant cells; compatibility with commercial semiconductors and easy manufacturing of the system [5, 6]. However, its internal performance is complex, and there are different issues that still must be improved and investigated further.

A very important aspect of the MMC is the so-called circulating current [7]. This inner current does not appear at the output, but is highly related to the system's stability, the efficiency of the converter and to the capacitor voltage ripples. The elimination of all the harmonic components in the circulating current increases the efficiency of the converter, but some studies indicate that the use of specific references can reduce the capacitor voltage ripples [8]. The MMC is composed of a high number of costly and bulky capacitors, and a reduction in the capacitor voltage ripples allows a reduction in the capacitances and in the cost of the converter. The use of circulating current references for reducing the capacitor voltage ripples is a worthy focus of research.

Multiple strategies can be used for controlling power converter switches. Due to the high number of MMC switches, the same output voltage can be obtained with multiple combinations. This degree of freedom in the modulation is usually used for balancing the capacitor voltages [9], but further targets can be considered. Moreover, adding a zero-sequence signal to the modulation or reference signals can also be studied with the objective of improving some of the previously mentioned aspects: effectiveness, capacitor voltage ripples and circulating current.

Industrial application aspects of the MMC are also an important point of study. Techniques for reducing the requirements of the MMC control system (such as simplifying the data acquisition system) and fault-tolerant techniques for allowing uninterrupted performance are topics that can be further studied.

This thesis attempts to contribute to all these topics.

1.3 Review of Previous Research

Although hough a similar topology was presented in 1981 [10], the current MMC topology was introduced in 2003 [3]. The MMC consists of two arms per phase-leg, where each arm comprises N series-connected submodules (SMs) and a series arm inductor L. Each SM consists of a capacitor C with a switching structure, which connects or disconnects the capacitor in-series within the arm. The main features of the MMC [5] are: its modularity and scalability to different power and voltage levels; its redundancy; and the high quality of the output voltages and currents. Those features make it one of the most attractive converters for high-power applications [2] like HVDC [4] and FACTS [11]. In recent years, the MMC has become a very important research topic and multiple alternative topologies, modulation strategies and control techniques have appeared [6, 12].

The modelling of the MMC is a complex task, since it includes a high number of non-linear elements. In order to study the dynamic performance of the MMC, simplified models of the converter are required. For this reason, modelling of the MMC has been a common research topic [13, 14]. Multiple assumptions and calculations in this thesis are based on the averaged model presented in [15].

Like in most converter topologies [1], the modulation of the MMC [16] is a widely studied field. The MMC was originally presented with a space vector modulation (SVM) [3], which can be calculated on a plane or in a three-dimensional space [17, 18]. However, this technique becomes too complicated when the number of levels increases, and the most common modulation techniques are based on multicarrier pulse-width modulation (PWM) [19, 20]. The common multicarrier techniques use as many carriers as SMs (N), but some strategies based on interleaving [21] use $2N$ carriers for obtaining more output voltage levels. The multiple PWM carriers can be distributed along the modulation range (level-shifted) [9] or phase-shifted in a sampling period [22, 23]. The nearest level modulation (NLM) [24, 25] has also been considered for the MMC, but only in converters with a high number of levels. Selective harmonic elimination (SHE) is another technique considered in multiple articles [26–28], but the hard-processing requirements of this technique make it feasible only for converters with a low number of levels. Some papers have proposed new modulation techniques specifically designed for the MMC, such as a modified PWM [29] and another technique that switches at fundamental frequency [30].

Modulation techniques usually define the output voltage level, but not which SMs to activate. This degree of freedom can be used to balance the capacitor voltages in the arms. This task is performed by the voltage balancing algorithm. The most common voltage balancing algorithm is based on sampling the capacitor voltages, sorting them, and selecting those that balance the voltages [3, 9, 31]. Some papers present improved versions of the algorithm for reducing the switching frequency [24, 32]. Voltage balancing algorithms for modulation techniques that directly link the SMs to a particular carrier have also been developed [23, 33]. Those techniques modify the modulation signal or the carrier of each SM in order to balance the voltages.

Another widely studied topic is the dynamic analysis and control of the circulating current [34, 35]. This current flows through the arms of the converter without appearing at the output, and it is naturally composed of a dc component and low order harmonics [7, 36], mainly the second one. In order to ensure system stability and improve converter performance, the circulating current must be controlled. It can be controlled through the voltage applied to the arm inductors, usually by adding a differential reference in the upper and lower arm modulation signals [7]. Since the voltage is applied over inductances, a proportional controller is commonly used [37]. More complex controllers can be used, such as: resonant controllers [38, 39], repetitive controllers [40, 41] or controllers operating with d-q variables [32, 42].

The circulating current reference can be defined according to multiple objectives. Some studies propose eliminating all the harmonic components, which reduces the arm rms current and therefore the power losses [32,38]. A fundamental frequency component can also be added to balance the energy stored in the upper and lower arms [7, 39]. Other studies propose injecting second and/or fourth harmonic components to reduce the capacitor voltage ripples [8,43]. Reducing the capacitor voltage ripples is important for reducing the size of the capacitors [44] and, therefore, the overall cost of the converter.

The circulating current can also be combined with a zero-sequence voltage. Some studies propose using a fixed frequency zero-sequence and circulating current in order to translate the power oscillations to a higher frequency [45]. This technique is very useful for reducing capacitor voltage ripples at low frequencies, which is especially interesting in motor drive applications [46,47]. Zero-sequence signals have been used for motor drive applications and for extending the linear operating range, such as third harmonic injection or those based on SVM [48]. However, apart from those, the topic of zero-sequence signal has not been studied further in relation to the MMC. In this thesis, discontinuous zero-sequences, which have been widely studied in other converter topologies [49–52], are applied to the MMC for the first time.

In real applications of the MMC, such as in HVDC applications, the voltage specifications require the use of hundreds of SMs [4]. With the common voltage balancing algorithms, the voltage of each SM has to be measured in order to sort and select the SMs to be activated. Acquisition and conditioning of such a large number of signals is a challenge, and some techniques have appeared in recent years. Some studies try to solve this challenge with open-loop voltage balancing algorithms [19, 30, 53], but those methods can become unstable. Other studies develop simpler voltage balancing algorithms for a high number of SMs, but many voltage sensors are still required [33, 54, 55]. A possible solution for reducing the number of voltage sensors is to use observers and estimators [56, 57]. However, the reliability of the measuring system is reduced. A first approach to reducing the hardware complexity is presented in [58], where the acquisition system is highly simplified, but not the number of sensors.

A very important requirement of real applications is the reliability of the system, and a lot of research has recently been conducted on fault-tolerant solutions. Failures in the dc-link [59–61] and on the ac-side [62] have been highly studied. However, the most common failures in power converters are due to faults in switching devices [63]. The MMC can easily provide redundancy of the SMs with the use of additional SMs [64–66], but the fault has to be detected and localized before disabling the faulty SM. Some techniques have emerged for detecting faults in the SM switching devices, and these are based on the use of additional sensors [67–69] or on the use of estimators and observers [70–72]. Another focus for improving converter reliability is to study the failure mechanisms of the switching devices [73, 74]. The failures are usually related to power losses, which, if not controlled, can be unevenly shared among the SMs in the arms [31].

1.4 Thesis Objectives

This thesis focuses on the study and development of new control and modulation techniques that improve some practical issues with the MMC. The developed techniques aim to fulfill three general purposes: (1) reducing the capacitor voltage ripples, (2) simplifying the MMC hardware and (3) improving its reliability. Furthermore, this thesis is devoted to studying and developing techniques for the application of the MMC to motor drives.

For these purposes, the following objectives are defined in this thesis:

- To define a circulating current reference that reduces the capacitor voltage ripples while also developing a method for calculating the optimal reference that minimizes the voltage ripples.
- To study the suitability of using discontinuous modulation in the MMC; evaluate its performance; and improve the technique with the goal of reducing power losses and capacitor voltage ripples.
- To develop a technique for measuring capacitor voltages while reducing the number of voltage sensors required by the MMC.
- To define a mechanism for detecting and localizing faults in both the SMs and the voltage sensors of the MMC while also developing a method for substituting the faulty sensors.
- To study the distribution of power losses in the switching devices when considering different capacitance values, and to also develop an algorithm for balancing these same power losses.

- To study the application of the MMC to motor drives and application of capacitor voltage ripple reduction techniques in order to allow MMC operation at low speeds/frequencies.

1.5 List of Publications

The following papers are as a result of the research developed in this thesis and have been published in different journals and conference proceedings.

1.5.1 Journal Papers

The following journal papers have been published or are already accepted for publication:

[1] J. Pou, S. Ceballos, G. Konstantinou, V. G. Agelidis, R. Picas, and J. Zaragoza, "Circulating current injection methods based on instantaneous information for the modular multilevel converter," *IEEE Trans. Ind. Electron.*, vol. 62, no. 2, pp. 777-788, Feb. 2015.

[2] R. Darus, J. Pou, G. Konstantinou, S. Ceballos, R. Picas, and V. G. Agelidis, "A modified voltage balancing algorithm for the modular multilevel converter: Evaluation for staircase and phase-disposition PWM," *IEEE Trans. Power Electron.*, vol. 30, no. 8, pp. 4119-4127, Aug. 2015.

[3] R. Picas, S. Ceballos, J. Pou, J. Zaragoza, G. Konstantinou, and V. G. Agelidis, "Closed loop discontinuous modulation technique for capacitor voltage ripples and switching losses reduction in modular multilevel converters," *IEEE Trans. Power Electron.*, vol. 30, no. 9, pp. 4714-4725, Sep. 2015.

[4] R. Picas, J. Zaragoza, J. Pou, S. Ceballos, and J. Balcells, "New measuring technique for reducing the number of voltage sensors in modular multilevel converters," *IEEE Trans. Power Electron.*, vol. 31, no. 1, pp. 177-187, Jan. 2016.

[5] G. Konstantinou, J. Pou, S. Ceballos, R. Picas, J. Zaragoza, and V. G. Agelidis, "Control of circulating currents in modular multilevel converters through redundant voltage levels," *IEEE Trans. Power Electron.*, vol. 31, no. 11, pp. 7761 - 7769, Nov. 2016.

[6] R. Picas, J. Zaragoza, J. Pou, and S. Ceballos, "Reliable modular multilevel converter fault detection with redundant voltage sensor," *IEEE Trans. Power Electron.*, vol. 32, no. 1, pp. 39-51, Jan. 2017.

1.5.2 Conference Papers

The following papers have been presented in international conferences:

[7] R. Picas, J. Pou, S. Ceballos, V. G. Agelidis, and M. Saeedifard, "Minimization of the capacitor voltage fluctuations of a modular multilevel converter by circulating current control," in *Proc. IECON 2012 - 38th Annual Conference of the IEEE Industrial Electronics Society*, Montréal, Canada, 2012, pp. 4985–4991.

[8] R. Picas, J. Pou, S. Ceballos, J. Zaragoza, G. Konstantinou, and V. G. Agelidis, "Optimal injection of harmonics in circulating currents of modular multilevel converters for capacitor voltage ripple minimization," in *Proc. ECCE Asia Downunder (ECCE Asia), 2013 IEEE*, Melbourne, Australia, 2013, pp. 318–324.

[9] R. Picas, S. Ceballos, J. Pou, J. Zaragoza, G. Konstantinou, and V. G. Agelidis, "Improving capacitor voltage ripples and power losses of modular multilevel converters through discontinuous modulation," in *Proc. IECON 2013 - 39th Annual Conference of the IEEE Industrial Electronics Society*, Vienna, Austria, 2013, pp. 6233–6238.

[10] R. Picas, S. Ceballos, J. Pou, J. Zaragoza, G. Konstantinou, V. G. Agelidis, and J. Balcells, "Discontinuous modulation of modular multilevel converters without the need for extra submodules," in *Proc. IECON 2015 - 41st Annual Conference of the IEEE Industrial Electronics Society*, Yokohama, Japan, 2015, pp. 2538–2543.

[11] G. Konstantinou, J. Pou, S. Ceballos, R. Picas, J. Zaragoza, and V. G. Agelidis, "Utilising redundant voltage levels for circulating current control in modular multilevel converters," in *Proc. IECON 2015 - 41st Annual Conference of the IEEE Industrial Electronics Society*, Yokohama, Japan, 2015, pp. 2213–2218.

[12] R. Picas, J. Pou, J. Zaragoza, A. Watson, G. Konstantinou, S. Ceballos, and J. Clare, "Submodule power losses balancing algorithms for the modular multilevel converter," in *Proc. IECON 2016 - 42nd Annual Conference of the IEEE Industrial Electronics Society*, Florence, Italy, 2016.

1.5.3 Patents

[13] R. Picas, J. Zaragoza, and J. Pou, "Sistema y método de medida de las tensiones de las disposiciones capacitivas de los sub-módulos de un convertidor de potencia multinivel con almacenamiento distribuido de energía (MMC) y convertidor MMC," Patent ES P201430893, 11 June 2014.

Table 1.1: Relationship between chapters and publications.

Chapter	**Publication**
Chapter 2 The Modular Multilevel Converter	[2],[5],[7],[11]
Chapter 3 Circulating Current References for Capacitor Voltage Ripple Reduction	[1],[7],[8]
Chapter 4 Discontinuous Modulation	[3],[9],[10]
Chapter 5 Voltage Measurement System	[4],[13],[14]
Chapter 6 Fault Tolerant Topology	[6]
Chapter 7 Balancing Algorithms for Submodule Power Losses	[12]
Chapter 8 Application of the MMC in Low-Speed Motor Drives with Discontinuous Modulation	[15]

[14] R. Picas, J. Zaragoza, and J. Pou, "System and method for measuring the voltages of the capacitive arrangements of the sub-modules of a multilevel power converter with distributed energy storage (MMC) and an MMC converter," Patent WO/2015/189453, 10 June 2015.

1.5.4 Papers under Revision

The following paper has been submitted to a journal and it is currently under consideration for publication:

[15] R. Picas, J. Zaragoza, J. Pou, S. Ceballos, G. Konstantinou, and V.G. Agelidis, "Study and comparison of discontinuous modulation for modular multilevel converters in motor drive applications," submitted to *IEEE Trans. Ind. Electron.*

The selected journal and conference papers are associated with the chapters of the thesis that are shown in Table 1.1.

1.6 Thesis Outline and Main Contributions

This thesis is composed of nine chapters. The following summary indicates the main contents of each one.

- Chapter 2 presents the MMC with details of its operating principles, a mathematical model and an explanation of the main control strategies. Within these strategies, a scalable algorithm for the level-shifted PWM (LS-PWM) is implemented; a new implementation of the voltage balancing algorithm is detailed; and a novel method for controlling the circulating current is presented. It also reviews the main applications of the MMC and presents the MMC prototypes used in this thesis.

- Chapter 3 presents three methods for calculating the circulating current reference. All these methods have the objective of reducing the capacitor voltage ripples. The first one defines an approximated continuous function of the capacitor voltage ripples and obtains an optimal function for the second harmonic of the circulating current. The second method applies an iterative optimization method by evaluating all the combinations of the second and fourth harmonics and selecting the optimal ones. The third technique calculates the theoretical optimal reference from a simplified model of the converter and obtains a nearly optimal reference that can be calculated on-line.

- Chapter 4 presents the discontinuous modulation for application in the MMC. This technique reduces the switching power losses and the capacitor voltage ripples, especially for low modulation indices. Three approaches to discontinuous modulation are presented. The first approach consists of an open-loop technique that uses a pre-defined modulation signal. The second approach uses a closed-loop algorithm for defining the zero-sequence signal, thus further reducing power losses and capacitor voltage ripples. Finally, the third approach is adapted to medium-power applications by reducing the number of required SMs.

- Chapter 5 presents a new voltage measuring system, where only two sensors per arm are required. The sensors measure the voltage provided by a set of SMs and acquire the capacitor voltages when only a single SM in the set is activated. Between actual measurements, the system performs an estimation of the capacitor voltages.

- Chapter 6 presents a fault detection and localization system for the MMC. The topology is based on three additional sensors per arm, which compare the expected voltage with the measured one. The system is able to detect open-circuit and short-circuit faults in the switching devices and faults in the voltage sensors. The use of additional sensors allows substituting the faulty sensors with the measuring algorithm presented in Chapter 5.

- Chapter 7 studies the distribution of power losses in an MMC when the SM capacitances are not equal. The inequalities in the capacitances can be caused by the manufacturing tolerance or by a degradation of the capacitors. A system for balancing the losses between the SMs is also presented.

- Chapter 8 deals with the application of the MMC to a variable-speed motor drive. This application presents problems at low speeds/frequencies, where the capacitor voltage ripples can become excessive. Discontinuous modulation is applied in order to reduce the capacitor voltage ripples, presenting a good performance of the motor at 1% of the nominal speed. The technique is compared with other state-of-the-art low-speed operation techniques, and discontinuous modulation is found to be the one that presents the lowest power losses with similar capacitor voltage ripples.

- Finally, Chapter 9 summarizes the main contributions of the thesis and includes some discussion of possible future research.