The Modular Multilevel Converter

presented by

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Nanyang Technological University (NTU)
School of Electrical and Electronic Engineering
Singapore
QS World Univ. Ranking: 1st in Asia and 11th globally
Research Techno Plaza

- **Batteries / Solar Cell** - Printing, Deposition, Mats / Elec Characterization, electrochem testing (LIB, Supercap, CIGS, DSSC, OPV)
- **Smart Energy Systems** - Micro-grid simulator, Fuel cell grid interface system, Roof-top solar PV system and wind turbine, Flywheel energy storage and battery energy storage
- **Fuel Cells** – Materials processing, catalysis, electrochemical/materials characterization, feedstock conditioning
- **High Performance Computing Lab** - (dx360 M2 x 2400 cores, 2GB/core, 24TFlops)

Clean Tech One

- **Air Conditioning** - Solar thermal/liquid dessicant air conditioning (regenerator, evaporative cooler, liquid desiccant energy storage & recovery), radiant cooling test lab
- **Energy Systems** - Drive train lab (motor genset, 100-kW converter), wind/water tunnel testing, tribology
- **Prototyping Labs** - Fuel cells (1-5 kW PEMFC stacks)/Batteries, microgrids, control/management systems, wet chemistry (materials scale up), dry labs (smart sensors/energy harvesting)
Rolls-Royce@NTU Corporate Lab - Singapore

Electrical R&T Group

**Vision**

To support electrification in Rolls-Royce businesses with more electrical systems integration to deliver better power for a changing world

- **Aerospace**
- **Marine**
- **Power System**

**Facilities**

- Electrical Power System Integration Lab @ NTU EPSIL@N
  - Total floor area: 1000 m²
  - Equipped with state-of-the-art equipment and rigs
  - Largest cross sector electrical R&T lab within Rolls-Royce to serve development of current and future technologies
Outline

- Introduction
- Modular Multilevel Converter (MMC)
- Research Developed on the MMC
  - Capacitor Voltage Balance
  - Circulating Current Control
  - Modulation Techniques
  - Circulating Current Control Through Redundant Voltage Levels
- Future Research on the MMC
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Introduction

- High voltage direct current (HVDC) transmission:
  - For long distances, HVDC transmission is technically and economically more viable than AC transmission.
  - HVDC can interconnect asynchronous systems as well as systems with different frequencies.
  - HVDC transmission can be controlled faster so that the AC system stability can be improved.
  - The modular multilevel converter (MMC) is the most advanced power converter topology for HVDC transmission.
High Voltage DC (HVDC) Transmission

- HVDC versus HVAC
High Voltage DC (HVDC) Transmission

UHVDC Prospects 500kV-1100kV in China

New Constructions by 2015

±800 kV HVDC: 13 lines
±1100 kV HVDC: 1 line
Total HVDC (approx.): 30,000 km
50 HVDC lines

Solar Thermal
Power Plants
Photovoltaics
Wind
Hydro
Biomass
Geothermal

Vision
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Modular Multilevel Converter (MMC)

- Cascaded connection of sub-modules (SMs) or cells, usually made of half-bridges
- \( N \) SMs are connected in series to create an arm
- A phase-leg comprises two arms (upper and lower)
- Reactors \( L \) are inserted in the circuit to control the circulating currents and to limit the fault currents
Half-Bridge Sub-Modules (SMs)

- Operation of switches within an SM is complementary

<table>
<thead>
<tr>
<th>States</th>
<th>$s_1$</th>
<th>$\bar{s}_1$</th>
<th>$v_x$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM Activated</td>
<td>1</td>
<td>0</td>
<td>$v_c$</td>
</tr>
<tr>
<td>SM Deactivated</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

Half-bridge SM
Operation of the MMC

- Reference voltage for the SM capacitors:
  \[ V_C^* = \frac{V_{dc}}{N} \]

- On average, the number of SMs activated in a phase-leg equals \( N \).

- The voltage level at the midpoint of the phase-leg is defined by the number of SMs that are connected in the upper and lower arms of the converter.
States of the MMC. Example

State 1

State 2

State 1

State 2
States of the MMC. Example
States of the MMC. Example

State 3

State 4
States of the MMC. Example
States of the MMC. Example
MMC: Features and Applications

The MMC offers salient features such as:
- It is structurally scalable and can theoretically meet any voltage level requirement
- Capacitor voltage balancing task is relatively simple and no isolated DC sources are required
- There is no need for DC-link capacitor since the capacitances are embedded in the converter topology

Main applications of the MMC are:
- HVDC transmission systems
- Flexible AC transmission systems (FACTSs)
- High-power motor drives
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Capacitor Voltage Balance

- During the operation of the MMC, the arm current flows through the SM capacitors, which charge and discharge the capacitors.
- In order to ensure proper operation of the converter, the SM capacitor voltages have to be regulated to the reference value of

\[ V_C^* = \frac{V_{dc}}{N} \]

- An active voltage balancing method is essential for the operation of the MMC.
Capacitor Voltage Balance


- **Objectives:**
  - Proposing an efficient voltage balancing algorithm that can be adapted to MMCs with any number of levels.
  - Reducing the switching frequency of the power devices by limiting the number of transitions.
Capacitor Voltage Balance

- The voltage balancing algorithm uses measurements from the SM capacitor voltages and arm currents to select the next SM that will be connected or bypassed.

- If the arm current is in the charging direction:
  - and the PWM method requires the addition of one SM in the arm, the SM with the lowest voltage that is not connected to the arm will be selected and added to the arm.
  - and the PWM method requires the removal of one SM in the arm, the SM with the highest voltage that is connected to the arm will be selected and removed from the arm.
The voltage balancing algorithm uses measurements from the SM capacitor voltages and arm currents to select the next SM that will be connected or bypassed.

If the arm current is in the discharging direction:
- and the PWM method requires the addition of one SM in the arm, the SM with the highest voltage that is not connected to the arm will be selected and added to the arm.
- and the PWM method requires the removal of one SM in the arm, the SM with the lowest voltage that is connected to the arm will be selected and removed from the arm.
Voltage Balancing Algorithm

- Based on two sorting stages:

- Problem: More SMs than required may be activated/deactivated at any sampling instant, which increases the switching frequencies of the transistors and therefore reduces converter efficiency.
Reduction of the SM switching frequency can be achieved with the implementation of a simple feedback loop.

- Adding a constant voltage offset $\Delta K$ to the measured SM voltages as a function of their switching state.
Restricted Voltage Balancing Algorithm

Conventional voltage-balancing algorithm

Restricted voltage-balancing algorithm

\[ n_{up} \]

\[ 0 \quad 1 \quad 1 \quad 2 \quad 2 \]

SM Capacitor Voltages (V)

\[ V'_{Cap1} \quad V'_{Cap2} \quad V'_{Cap3} \quad V'_{Cap4} \quad V'_{Cap5} \]

\[ t_0 \quad t_1 \quad t_2 \quad t_3 \quad t_4 \]

\[ n_{up} \]

\[ 0 \quad 1 \quad 1 \quad 2 \quad 2 \]

SM Capacitor Voltages (V)

\[ V''_{Cap1} \quad V''_{Cap2} \quad V''_{Cap3} \quad V''_{Cap4} \quad V''_{Cap5} \]

\[ \Delta K \]
Comparison of Voltage Balancing Algorithms
Comparison of Voltage Balancing Algorithms

- Switching frequency reduction

![Graph showing comparison of voltage balancing algorithms with PD-PWM and Staircase Modulation. The x-axis represents time (s) ranging from 0.00 to 0.20, with nodes at 0.05, 0.10, 0.15, and 0.20. The y-axis represents total transitions in the MMC arm, ranging from 0 to 600. The graph includes lines for Conventional Voltage Balancing with PD-PWM, Restricted Voltage Balancing with PD-PWM, Conventional Voltage Balancing with Staircase Modulation, and Restricted Voltage Balancing with Staircase Modulation. The graph highlights switching frequencies at 260Hz, 165Hz, 145Hz, and 50Hz for PD-PWM, and 30Hz for Staircase Modulation.]

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Circulating Current Control

- There is a circulating current in each phase of the MMC that does not appear at the output of the converter.
- The circulating current is composed of a DC component plus AC components. The DC component is essential for the operation of the converter.
- The circulating current can be controlled to improve the performance of the MMC.
Common and Differential Modes

Based on the superposition theorem, two circuits can be distinguished:

\[ v_{\text{comm}} = \frac{v_u + v_l}{2} \]
\[ i_{\text{comm}} = \frac{i_u + i_l}{2} = \frac{i_a}{2} \]

\[ v_{\text{diff}} = \frac{v_u - v_l}{2} \]
\[ i_{\text{diff}} = \frac{i_u - i_l}{2} = i_{\text{circ}} \]
Control of the Circulating Current

- The common and differential circuits can be analyzed independently. The differential voltage defines the differential (circulating) current:

\[ i_{\text{diff}} = \frac{1}{L} \int_0^t v_{\text{diff}} \, dt + I_{\text{diff}0} \]

- A differential voltage can be introduced to control the circulating current without affecting the output current.
Circulating Current Components

- If the only reference for the circulating current is the DC component, the arm currents become the minimum and this reduces power losses in the MMC.
  \[ i_{\text{diff}} = I_{DC} \]

- A second order harmonic can be added to the DC component to reduce the capacitor voltage ripples.
  \[ i_{\text{diff}} = I_{DC} + I_2 \cos(2\omega t + \varphi_2) \]

- The amplitude and phase of the output current need to be found to inject the second harmonic into the circulating current.
Circulating Current Reference Based on Instantaneous Information

J. Pou, S. Ceballos, G. Konstantinou, V.G. Agelidis, R. Picas, and J. Zaragoza

- Objectives:
  - Defining the second order harmonic to be injected into the circulating current from instantaneous information.
  - Evaluation of capacitor voltage ripple reduction with the methods proposed.
Circulating Current Reference Based on Instantaneous Information

Method 1:

– Reduction in the SM capacitor voltage ripple can be achieved by forcing a larger current through the arm with the lower number of connected SMs.

– Based on the instantaneous values of the reference waveform and the load current, the circulating current reference is defined as:

\[ i_{circ} = \frac{i_a v_{am}}{2} \]

with \( i_a \) : Output current

\( v_{am} \) : Normalized reference signal
Circulating Current Reference Based on Instantaneous Information

- **Method 2**
  - If the capacitances of the deactivated SMs are considered, the equivalent capacitances become larger than the actual capacitances inserted in the arm.
  - The circulating current reference becomes:

\[
i_{\text{circ}} = \frac{i_a v_{am}}{1 + v^2_{am}}
\]

![Diagram of circulating current reference](image)
Experimental Results

DC Circulating Current

Method 1

Method 2
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Multicarrier pulse-width modulation (PWM) techniques are commonly used in MMCs.

Phase-disposition PWM (PD-PWM) yields the best harmonic performance.
PD-PWM Carrier Dispositions

Upper Arm
- No Interleaving
- Interleaving
  - $N$ Carriers

Lower Arm
- No Interleaving
- Interleaving
  - $N$ Carriers
PD-PWM - No Interleaving

- An MMC with \( N \) SMs per arm generates \( N+1 \) levels without interleaving
An MMC with $N$ SMs per arm generates $2N+1$ levels with interleaving.
Interleaving between Upper and Lower Arms

Output voltage

Output current

Interleaving enabled

Voltage (kV)

Current (A)

time (s)

time (s)
Discontinuous Modulation of the MMC


- Objectives:
  - Implementing a discontinuous modulation technique to the MMC.
  - Evaluation of the SM capacitor voltage ripple reduction.
Discontinuous Modulation of the MMC

- Application of discontinuous modulation to the MMC:
  - Leads to a significant reduction in the SM capacitor voltage ripples, especially when operating with low modulation indices.
  - Requires a dedicated circulating current control strategy.
The control strategy uses two main loops that are mutually coupled:
- Calculation of the circulating current reference,
- Circulating current controller and
- Clamping controller.
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- Control of the circulating current is one of the main requirements for the operation of the MMC
- Interleaving between the upper and lower arms produces redundant states that can be used to control the circulating current
Traditional Carrier Dispositions

Upper Arm

Non-Interleaving
\((N+1)\) levels

Interleaving
\((2N+1)\) levels

Lower Arm

\(N\) Carriers

\(N\) Carriers
Proposed Carrier Disposition

A single set of carriers for both arms (upper and lower)

Interleaving (2N+1 levels)

2N Carriers
Circulating Current Control

\[ V_{diff} \approx 0 \]

Activated SMs

\[ N \]

Level \( k + 2 \)

Level \( k + 1 \) (Redundant)

Level \( k \)

\[ V_{diff} > 0 \]

\[ V_{diff} < 0 \]

\[ N - 1 \]

Activated SMs

\[ N + 1 \]

Activated SMs

\[ N \]

Activated SMs

\[ N \]

Activated SMs
Differential Mode

- Equivalent circuits of the two redundant states for the same voltage level.
Proposed Method

➢ Implementation:
  - Generate the circulating current reference.
  - Determine whether the actual current is above or below the reference.
  - Select the redundant state that regulates the circulating current towards its reference.
  - Generate $n_u$ and $n_l$ (activated SMs in the upper and lower arms, respectively)
Extended Implementation

- Utilising additional redundancies in voltage levels.
  - Deviating from $N$ by more than one for the whole phase-leg ($N\pm2$, $N\pm3$, ...)

- Switching frequency considerations:
  - Transitions only during level changes and between adjacent states.
Experimental Setup

Circuit diagram

Laboratory prototype

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of SMs per arm, $N$</td>
<td>5</td>
</tr>
<tr>
<td>dc-link voltage, $V_{dc}$</td>
<td>250 V</td>
</tr>
<tr>
<td>SM reference voltage, $V_C$</td>
<td>50 V</td>
</tr>
<tr>
<td>SM capacitor, $C$</td>
<td>3.6 mF</td>
</tr>
<tr>
<td>Arm inductors, $L$</td>
<td>3.6 mH</td>
</tr>
<tr>
<td>Load $R_L$ &amp; $L_L$</td>
<td>15.6Ω &amp; 5mH</td>
</tr>
<tr>
<td>Carrier frequency $f_{car}$</td>
<td>2 kHz</td>
</tr>
</tbody>
</table>
Simulation and Experimental Results

Simulation Results

Experimental Results
Experimental Results

- Load and circulating currents under two circulating current references

- DC circulating current

- DC + 2\textsuperscript{nd} harmonic circulating current
Experimental Results

- SM capacitor voltages under the two circulating current references

DC circulating current

DC + 2\textsuperscript{nd} harmonic circulating current
Discussion

- The proposed method utilises redundancies in the voltage levels under $2N+1$ modulation to control the circulating current and is capable of tracking different circulating current references (DC and AC references).

- It does not require:
  - differential voltage injection to the reference of the phase-legs and
  - tuning of parameters in the control loops.

- Control action is limited by the volt-sec at the redundant states. An extended implementation might be necessary for MMCs with large numbers of SMs.
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Future Research on the MMC

- MMCs with reduced capacitances
- Advanced control techniques, especially predictive control
- Embedded energy storage in the MMC
- Modulation and control using different SM configurations
- Back-to-back-connected MMCs. Interaction between circulating current controllers
- Control of HVDC multiterminals
- MMC shortcircuit protection
- HV DC-DC converters
- Other applications of the MMC (motor drives, STACOMs, solar PV generation, etc.)
- Study of other modular configurations, including the alternate arm converter (AAC)
MMC Prototype

- Two three-phase MMCs
- Each MMC rated at 10kW
- 8 SMs (full-bridge) per arm
- Can be reconfigured to four three-phase MMCs with 4 SMs per arm