Research samples by the Power Electronics Research Group (GREP)
Outline

• Vision
• MAC converter
• Activity in SiC
• Control of multilevel back-to-back converters
Vision

• Research focused to **multilevel** power electronics converters:
  – Topologies.
  – Modulation.
  – Control.

• Applications in:
  – Renewable energy conversion.
  – Electric and hybrid vehicles technology.
  – Industry applications.
Outline

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Multilevel Active Clamped (MAC) Topology

- All flying capacitors are removed

Generalized Multilevel Topology

MAC Topology

ANPC Topology

Basic Cell
Operating Principle

Conduction losses are reduced

Fault-tolerance

SS1: Connection to node i_1

SS2: Connection to node i_2

Blocking Voltage = V

5-level leg

5 devices change their state

Switching losses concentrate on one device

SS3: Connection to node i_3

SS4: Connection to node i_4

SS5: Connection to node i_5

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Experimental Results

Four-Level Three-Phase Prototype

\[ m = 0.75, \quad V_{\text{dclink}} = 150 \text{ V}, \quad f_o = 50 \text{ Hz}, \quad f_s = 5 \text{ kHz}, \]
\[ C = 155 \ \mu\text{F}, \quad R_L = 16.5 \ \Omega, \quad \text{and} \quad L_L = 15 \ \text{mH} \]
Experimental comparison under a simple operating mode

Main objective

Compare the efficiency of the MAC converter with a two-level converter in low voltage

2-level converter

4-level MAC converter
Experimental comparison under a simple operating mode

Methodology

1) Estimation of Total Losses and Efficiency

Loss models

- Conduction losses.
- Switching losses (experimentally).
- Gate-driver losses.
- Other losses.

2) Experimental Tests to Measure Losses and Efficiency

- Measure input and output power.

Validation of Loss Models

Comparison of both results

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Experimental comparison under a simple operating mode

Efficiency Comparison Scenario

Two-level leg

\[ V_{dc} \]

\[ i_1 \]

\[ i_2 \]

\[ i_o \]

\[ L \]

\[ R \]

\[ v_o \]

Four-level MAC leg

\[ V_{dc}/3 \]

\[ i_1 \]

\[ i_2 \]

\[ i_3 \]

\[ i_4 \]

\[ L \]

\[ R \]

\[ v_o \]

Buck dc-dc converters

Output current constant

Switching state

1

2

\[ Ts/2 \]

\[ Ts \]

\[ Ts/2 \]

\[ Ts/4 \]

\[ Ts/8 \]

\[ Ts/8 \]

\[ Ts/8 \]

\[ Ts \]

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Experimental comparison under a simple operating mode

Analytical and experimental results

Conditions

$V_{dc} = 150 \, V$

$L = 60 \, \text{mH}$

$R = 16 \, \Omega$
Fault-Tolerance Analysis of the MAC converter

Motivation

Device Fault

Two-Level Converter

Cannot continue operating

MAC Converter

Can continue operating
Fault-Tolerance under Open-Circuit Faults

Open-circuit critical diagonals in an $m$-level leg

Which device faults imply to loose a level?

- Level $m$ is lost
- Level 1 is lost
- No levels are lost
Fault-Tolerance under Short-Circuit Faults

Short-circuit critical diagonals in an \( m \)-level leg

Which device faults imply to loose a level?

- Level \( m \) is lost
- Level 1 is lost
- New switching states can be defined to avoid losing levels, but the blocking voltage of some devices is increased.

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Experimental Results

Emulation of short-circuit and open-circuit faults

Emulation of a open-circuit fault in device $S_{p22}$.

Emulation of an short-circuit fault in device $S_{p12}$.

Emulation of a short-circuit fault in devices $S_{n21}$ and $S_{p22}$.

$V=50\text{ V}$
$L=5\text{ mH}$
$R=33\text{ }\Omega$
$f_s=20\text{ kHz}$
MAC Hardware Modifications

Solutions to improved the Fault-Tolerance Capacity

- Solution I: Parallelization of open-circuit critical diagonals.
- Solution II: Inclusion of two additional devices at input terminals $i_2$ and $i_{m-1}$.
- Solution III: Inclusion of one additional device at every input terminal.
Hardware Modifications

Solution I. Parallelization of open-circuit critical diagonals

- If an open-circuit fault occurs, the level is not lost thanks to the parallel device.
- Allows reducing the conduction losses and achieving a better loss distribution.
Hardware Modifications

Solution II: Inclusion of two additional devices at input terminals $i_2$ and $i_{m-1}$

- New extra devices are permanently ON under normal operation.
- If a short- or open-circuit fault occurs in a critical diagonal, the levels are not lost.
Solution III: Inclusion of one additional device at every input terminal

- New extra devices are permanently ON under normal operation.
- All levels available under any number of simultaneous short-circuit faults using the original switching states.
- Under open-circuit faults, no advantages compared to Solution II.

Conduction losses are highly increased.
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GREP - Work Objective in SiC

Efficiency comparison

ANPC built upon 1200 V Si IGBTs + Si diodes
Device IRG7PH30K10PbF + diode DSEI 30
Driver IXYS IXDN609

ANPC built upon 1200 V SiC MOSFETs + SiC diodes
Device Cree C2M0080120D + diode C4D20120D
Driver IXYS IXDN609
Efficiency Results

Vdc-link = 500 V
P ≈ 3 kW
Rg = 6.7 Ω

SiC (analytical)  SiC (experimental)  Si (analytical)  Si (experimental)

Efficiency vs. Frequency [kHz]
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Introduction: wind generation system

Trends in wind power generation point to increase power and voltage:
• Multilevel converters well suited
• Full power converter to achieve complete system control

Wind power generation variable speed system:
Permanent magnet synchronous generator + back-to-back NPC

Advantages:
• Optimum power control
• 100% speed variability
• Without Gearbox

Drawbacks:
• Converter size
• Generator size and weight
• Expensive
Motivation

Steady-state operation (or "normal" operation):

\[ P_{GRID} = P_{GEN} \]

\[ P_{GEN} \] given by the MPPT

Operation under grid fault condition (to meet LVRT requirements)

\[ P_{GEN} \] given by the MPPT
\[ P_{GRID} , Q_{GRID} \] set by the GCR

\[ P_{GEN} > P_{GRID} \]

Active power surplus under grid fault

Motivation:

- Minimize the use of the dc-link brake chopper by storing energy in the rotor inertia.
- Predictive current control applied to both converters and dc-link balance control.
Proposed control block diagram

Normal operation

Operation under grid dip
Predictive control method

• Measure variables at $t_k$: $x(t_k)$
• Apply the switching state $S_k$ during the 1$^{st}$ step
• Calculate the predicted value $x_p(t_{k+1})$ at $t_{k+1}$ with $x(t_k)$ and the current switching state $S_k$ by using the discrete model
• Calculate the predicted value $x_{pi}(t_{k+2})$ at $t_{k+2}$ for all the possible switching states, with $x_p(t_{k+1})$ by using the discrete model
• Evaluate the quality function $g$ for all the predicted values $x_{pi}(t_{k+2})$ at $t_{k+2}$
• The switching state that minimizes $g$ is selected and applied during the 2$^{nd}$ step
Simulation results

PMSG data: $J = 0.0812 \text{ kg} \cdot \text{m}^2$; $L_s = 10 \text{ mH}$; $R_s = 0.5 \Omega$; $\psi_r = 0.382 \text{ Wb}$; $p = 4$

Dc-link data: $C = 2200 \ \mu\text{F}$; $V_{pn} = 250 \text{ V}$

Grid-side data: $L = 10 \text{ mH}$; $R_L = 0.1 \Omega$; $V_{GRID} = 72 \text{ V}_{\text{RMS}}$; $f = 50 \text{ Hz}$

Grid voltages (V) ($V_a$ drops 55%)

Grid abc currents (A)

Grid dq currents (A)

P and Q grid power (W, VAR)

Generator abc currents (A)

Generator dq currents (A)

P and Q generator power (W, VAR)

Dc-link capacitor voltages (V)

Shaft speed (rpm)
Simulation results

Current reference tracking

Phase $\alpha$ load current spectrum for SVM

Number of commutations

Phase $\alpha$ load current spectrum for predictive control
Experimental results: Grid side converter

Experimental setup overview

V_{po} = 300 \, V \; ; \; C = 2.2 \, mF \; ; \; L = 5.5 \, mH \; ; \; R = 0.5 \, \Omega \; ; \; V_{grid} = 152 \, V_{RMS} \; ; \; f_{grid} = 50 \, Hz \; ; \; T_s = 100 \, \mu s.
Conclusions

- PMSG + back-to-back NPC applied to wind generation
  - no gearbox, 100% speed variability, well suited for high voltage/power
- Low Voltage Ride-Through compliance
  - Slow generator-side power regulation due to the mechanics
  - Fast grid-side power regulation
  - Active power excess during the dip must be dissipated/stored
  - Dc-link brake chopper allows power excess dissipation
- Proposed control approach:
  - Active power excess is stored in the rotor inertia
  - Dc-link brake chopper activation can be avoided if the rotor speed is below the limit (cut-off speed)
  - Pitch control should work concurrently to reduce rapidly the generated active power
  - Predictive converter current control allows reduced number of converter commutations with same performance as conventional control
Thanks for your attention!!!