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IRPWind

Grid Integration of High Definition MMC

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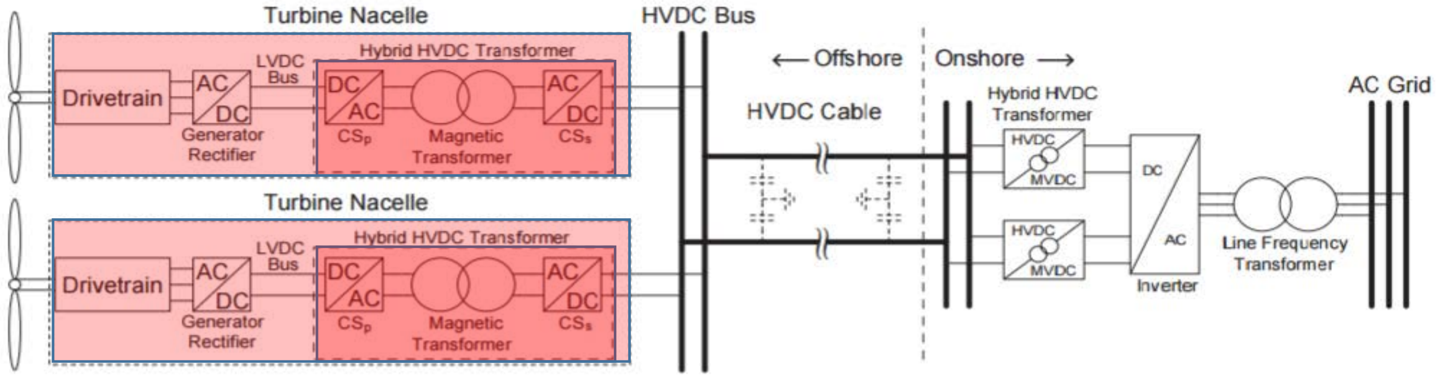
- Introduction to the High Definition Modular Multilevel Converter
- Joint Experiments organized by IRP Wind
- HD-MMC on the performance in 3 phase converter+ high level control
- Concluding remarks

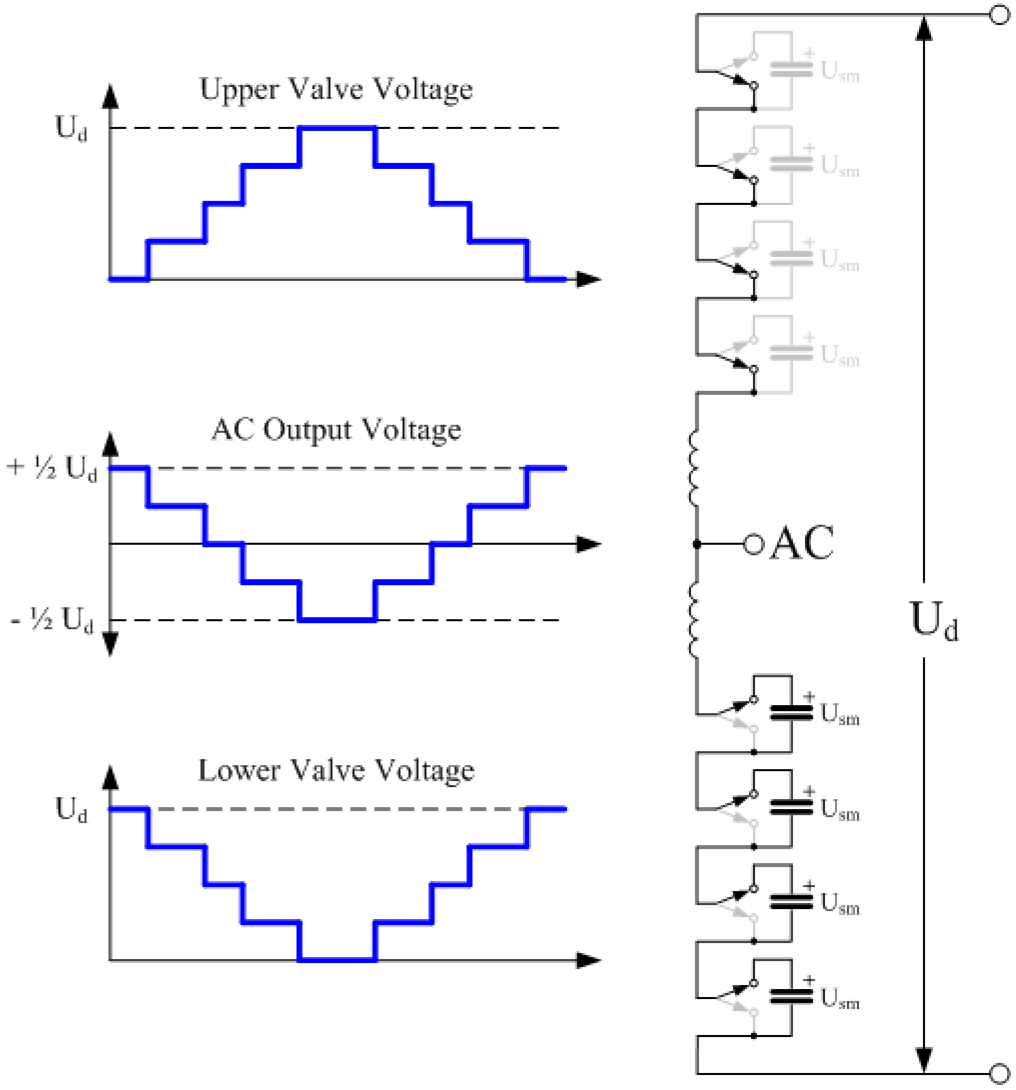
Introduction

- The outcomes of this work is expected to contribute to the reduction of offshore wind platform costs.
- A platform-less system, recently proposed by ORE Catapult, aims to reduce the cost of HVDC substation by modularizing and miniaturizing the HVDC converter to integrate it within the wind turbine nacelle.
- A high power density, low Total Harmonic Distortion (THD) converter was required to realize this concept due to the tight space requirements within the turbine.
- This led to the development of the High Definition – Modular Multilevel Converter (HD-MMC) which can generate a lower THD than Conventional –MMCs (C-MMCs) helping to increase power density and efficiency.



Introduction

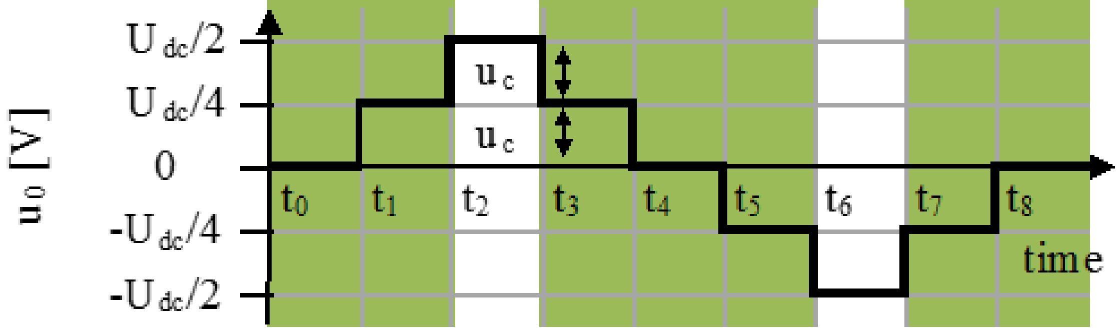
- MMC is emerging topology for offshore wind substations due to its black start capabilities, low Total Harmonic Distortion (THD) and high efficiency.
- The MMC uses a stack of identical modules.
- The multiple voltage steps make the MMC being capable of producing very small harmonic content



Introduction

- In the conventional MMC (C-MMC) each module create one level, so in order to produce a low THD many modules are required.
- What happen if MMC uses an uneven dc values?

Valve	u_c	Logic								
	V	t_0	t_1	t_2	t_3	t_4	t_5	t_6	t_7	t_8
4p	$U_{dc}/4$	1	1	1	1	1	0	0	1	0
3p	$U_{dc}/4$	1	1	1	0	0	0	0	0	1
2p	$U_{dc}/4$	0	1	1	1	1	1	0	0	0
1p	$U_{dc}/4$	0	0	1	1	0	0	0	0	1
1n	$U_{dc}/4$	1	1	0	0	0	1	1	1	0
2n	$U_{dc}/4$	1	0	0	1	1	1	1	1	1
3n	$U_{dc}/4$	0	0	0	0	0	0	1	1	0
4n	$U_{dc}/4$	0	0	0	0	1	1	1	0	1



Introduction

By using uneven dc values in the C-MMC, the novel HD-MMC can produce 7 levels using the same number of modules.

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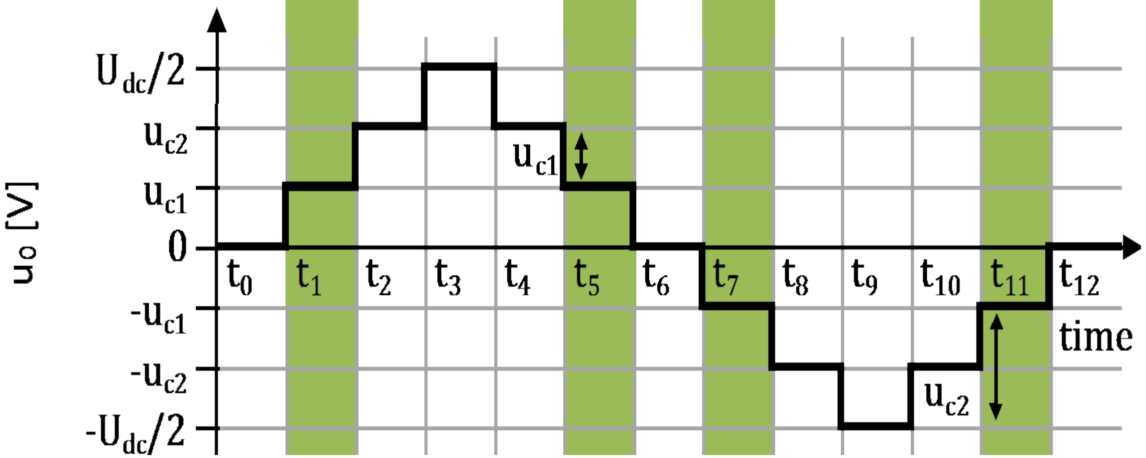
Some potential advantages:

- It can reduce the THD with the same number of modules
- A more compact converter can be achieved reducing size and cost
- the utilization of the MMC's resources could be improved, since redundant states can be repurposed.

SM	u_c	Logic												
	V	t_0	t_1	t_2	t_3	t_4	t_5	t_6	t_7	t_8	t_9	t_{10}	t_{11}	t_{12}
1	u_{c1}	0	1	0	0	1	0	1	1	1	1	0	0	0
2	u_{c1}	1	1	1	0	0	0	0	1	0	1	1	0	1
3	$u_{c2}\,(2u_{c1})$	0	0	0	0	0	1	1	1	1	1	1	1	0
4	$u_{c2}\,(2u_{c1})$	1	0	0	0	0	0	0	0	1	1	1	1	1
5	u_{c1}	1	1	1	1	0	0	0	1	0	0	1	0	1
6	u_{c1}	0	1	0	1	1	0	1	1	1	0	0	0	0
7	$u_{c2}\,(2u_{c1})$	1	1	1	1	1	1	0	0	0	0	0	0	1
8	$u_{c2}\,(2u_{c1})$	0	0	1	1	1	1	1	0	0	0	0	1	0



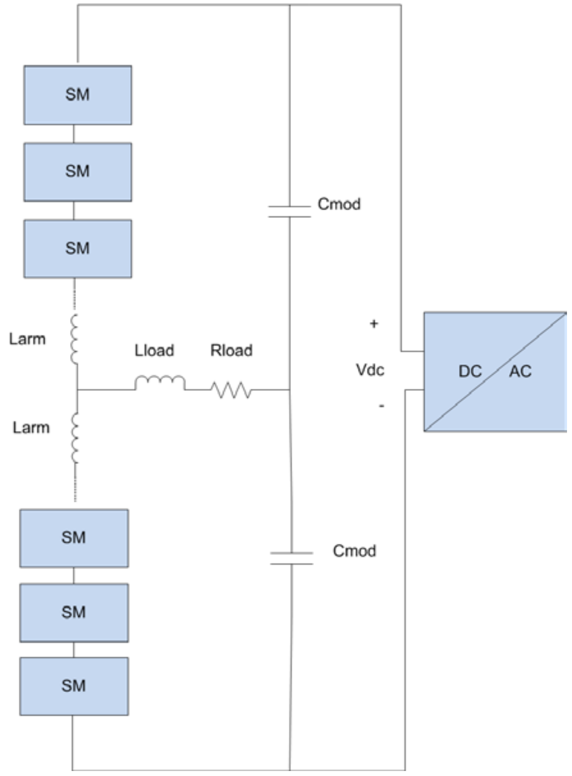
Joint Experiments within IRPWind

- This work is part of the **2nd call for Joint Experiments** organized within the Research Infrastructure WP of IRPWind.
- IRPWind is a European project, which it is aimed to foster better integration of European research activities in the field of wind energy research.
- In Europe, most large research facilities are being devoted to national activities that not necessarily matching the needs of Europe as a whole.
- **The Joint Experiments** has the objective of promoting alignment through joint experiments carried out in European research facilities and its effective use of resources.

Joint Experiments within IRPWind

- The HD-MMC control algorithm concept was successfully demonstrated in a project granted in **the first IRPWind Joint Experiment** call using a single phase, 18 module, half bridge MMC under controlled laboratory conditions

- The high level control was omitted to quantify the performance of the HD-MMC without any unnecessary complication. A simple RL load was used on the AC bus in place of an AC grid.



# of cells per arm	**18**
DC Voltage	776V
Rated power	60 kVA
Load power	5 kW
Cell capacitance per module	19.8mF
Arm inductance (Larm)	1.5 mH
Load resistance (Rload)	3.2 Ω
Load inductance (Lload)	33mH

Previous experiment setup

18 level single-phase half bridge MMC

Variac+rectifier and capacitor filters

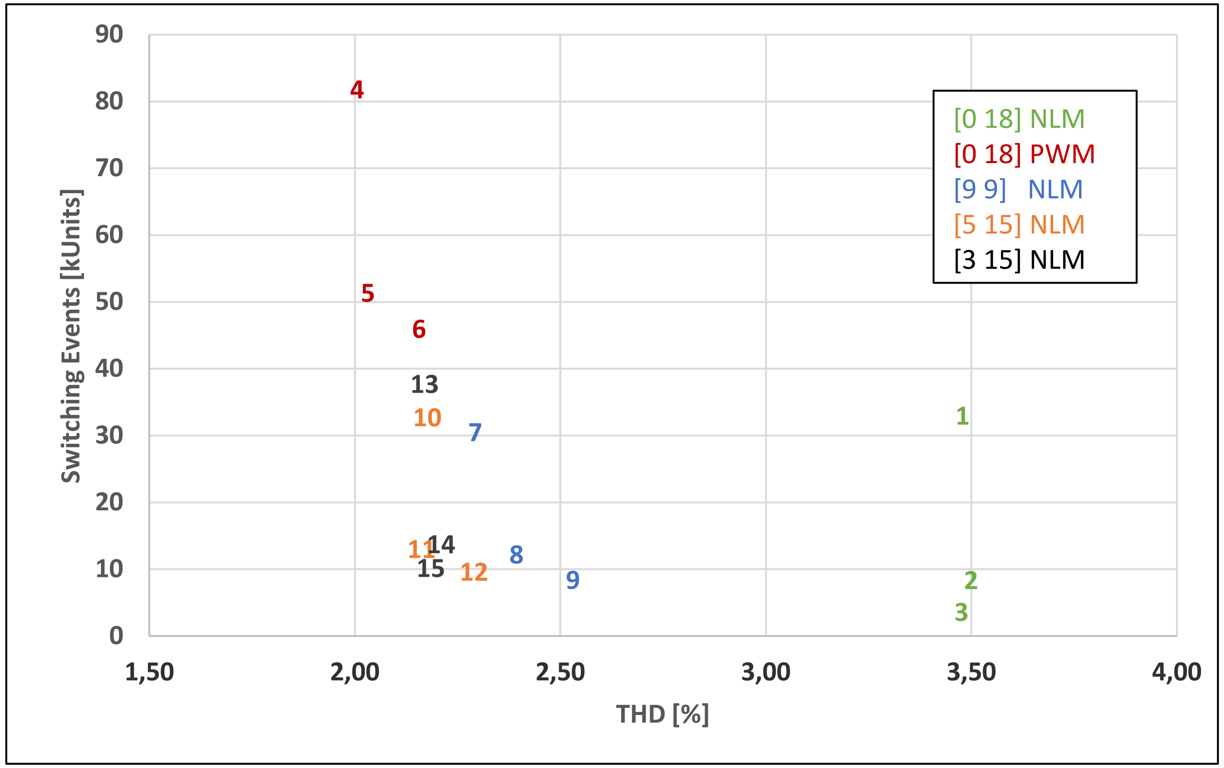
Arm inductors

Group card board

A RL load

Previous results (1st Joint experiments)

The figure shows switching events SE (efficiency) vs THD. C-MMC with PWM has the lowest THD but with the highest SE. C-MMC with NLM has the lowest SE, but the highest THD. HD-MMC is a good trade-off between THD and efficiency.



2nd Joint Experiments within IRPWind

- This second project will build on the results of that project and it will focus on the real world application of the HD-MMC. The project will be split into two stages:
  - The first stage will evaluate the impact of the HD-MMC on the performance of a 3 phase converter with high level control integration.
  - The second stage will look at the real world application of the HD-MMC converter under two scenarios. One connected to an offshore wind turbine generator and the other one connected to an AC inter-array grid

- **SINTEF** is the host institution, and ORE Catapult and Tecnalia are users. The control algorithm for a HD-MMC was developed at **ORE Catapult** in a simulation environment. MMC implementation was made by **SINTEF. ORE Catapult, Tecnalia and SINTEF** performed the experiments in November. **Tecnalia/IREC** acts as an impartial referee during the comparison of both techniques C-MMC vs HD-MMC since it has no conflict of interest in the project.

Access to SINTEF lab

SINTEF Energy Research has three different MMCs:

- MMC unit with half bridge cells with 18 cells per arm
- MMC unit with full bridge cells with 12 cells per arm
- MMC unit with half bridge cells with 6 cells per arm

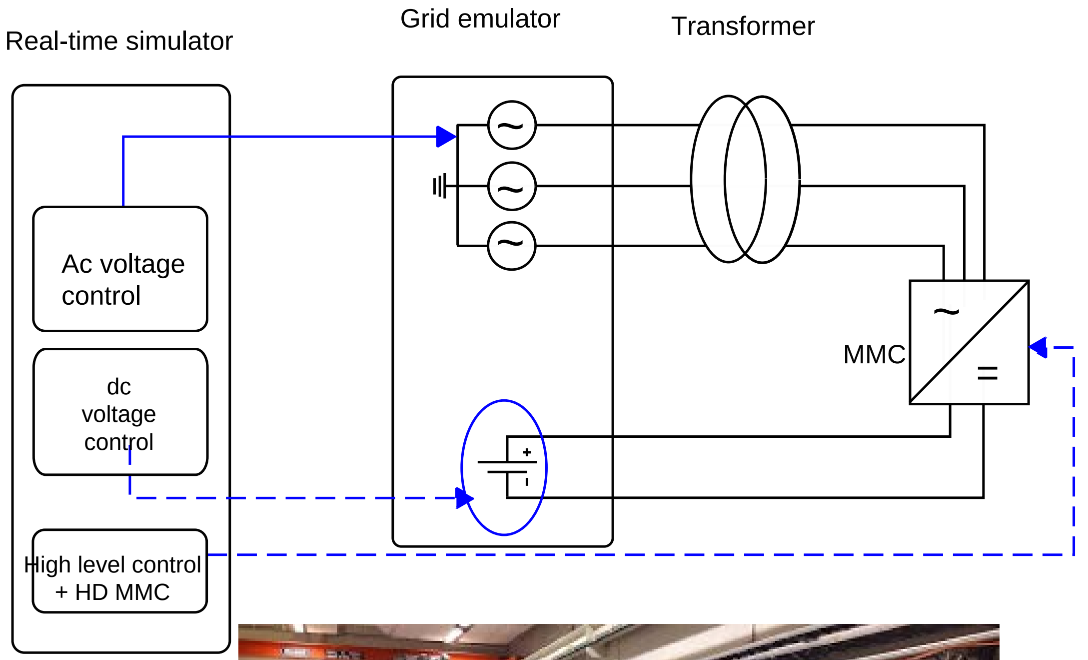
HD-MMC on the performance in 3 phase converter

Objectives

- Ensure proper operation of the HD-MMC in 3-phases with high level power control
  - Correct voltage levels created
  - Module voltages are stable and correct
- Compare Efficiency/THD trade off compared to C-MMC using PWM and NLM

Set-Up

- GES creates constant, stable AC grid
- GES creates constant, stable DC bus
- MMC operates in PQ mode.

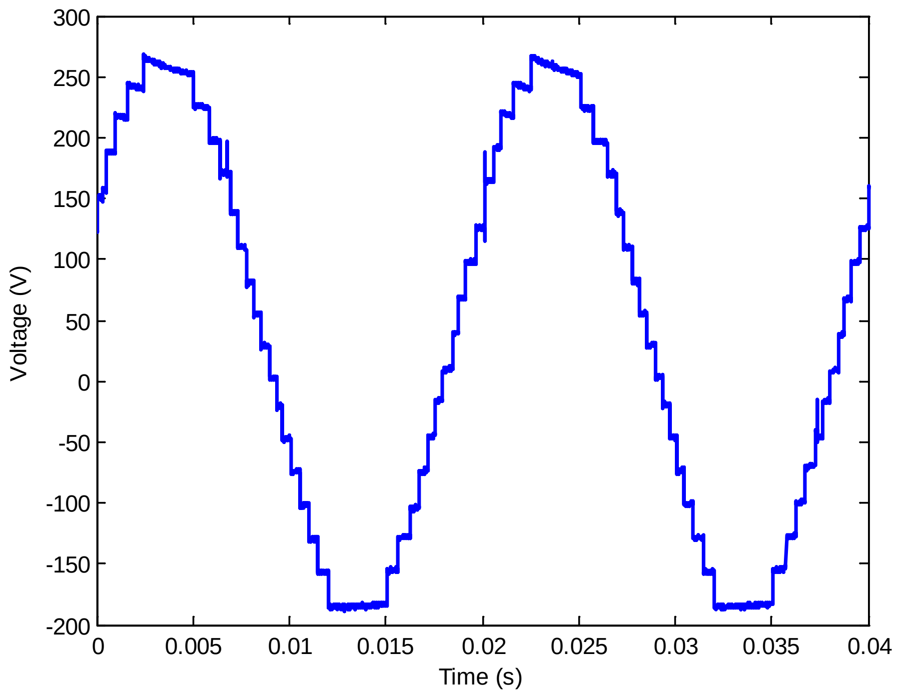


HD-MMC on the performance in 3 phase converter

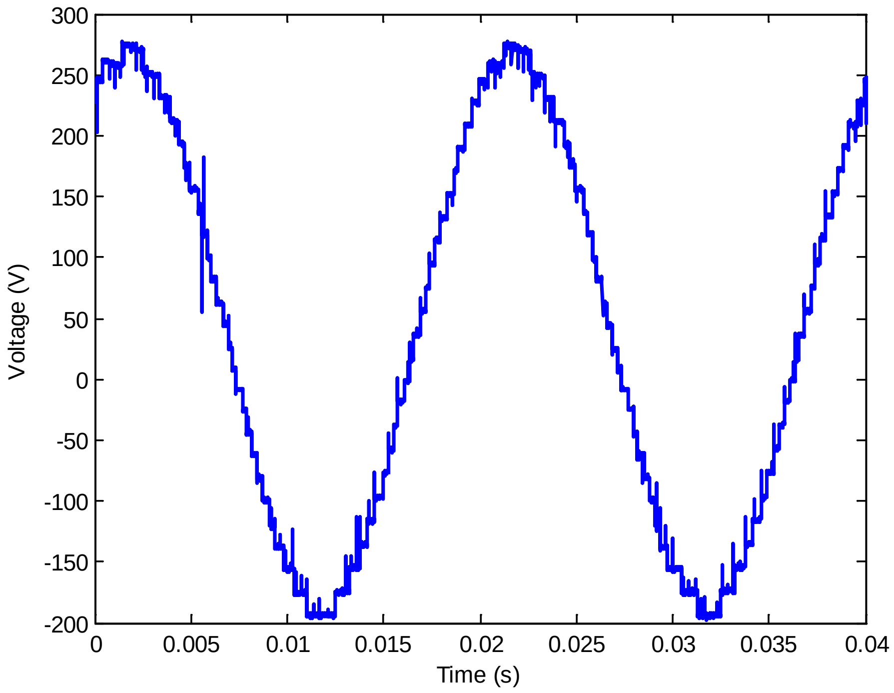
- 18 cases were performed.
- It includes C-MMC with NLM and PWM (As reference case)
- Different combination with HD-MMC
- The weight value is a mechanism that helps the sorting process by giving priority to capacitor voltage balancing or efficiency.

Experiment No	Converter	Configuration	Weighting Factor	Modulation Strategy
1.00	C-MMC	[18 00]	0	NLM
1.01	C-MMC	[18 00]	500	NLM
1.02	C-MMC	[18 00]	5000	NLM
1.03	C-MMC	[18 00]	0	PWM
1.04	C-MMC	[18 00]	500	PWM
1.05	C-MMC	[18 00]	5000	PWM
1.06	HD-MMC	[09 09]	0	NLM
1.07	HD-MMC	[09 09]	500	NLM
1.08	HD-MMC	[09 09]	5000	NLM
1.09	HD-MMC	[12 06]	0	NLM
1.10	HD-MMC	[12 06]	500	NLM
1.11	HD-MMC	[12 06]	5000	NLM
1.12	HD-MMC	[14 04]	0	NLM
1.13	HD-MMC	[14 04]	500	NLM
1.14	HD-MMC	[14 04]	5000	NLM
1.15	HD-MMC	[15 03]	0	NLM
1.16	HD-MMC	[15 03]	500	NLM
1.17	HD-MMC	[15 03]	5000	NLM

HD-MMC on the performance in 3 phase converter

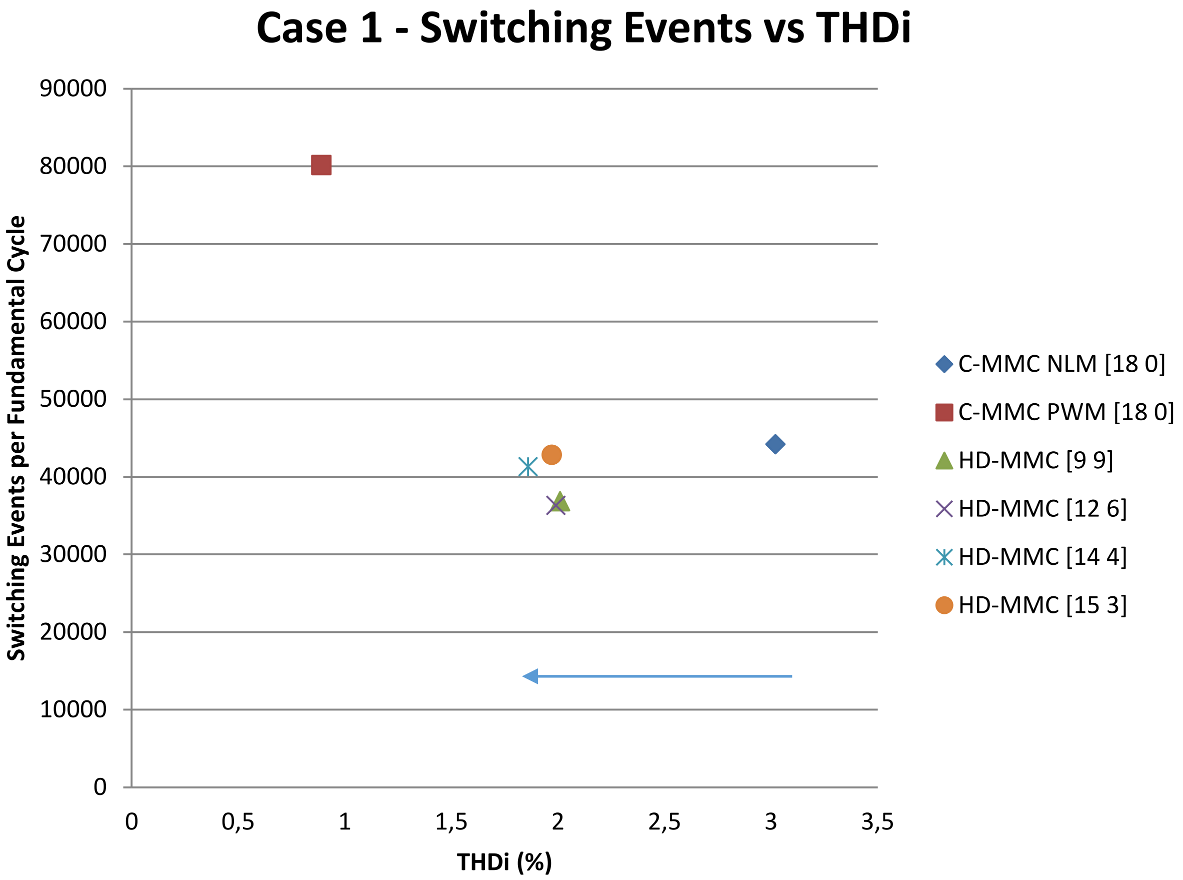


In C_MMC, 19 levels are produced in each arm voltage

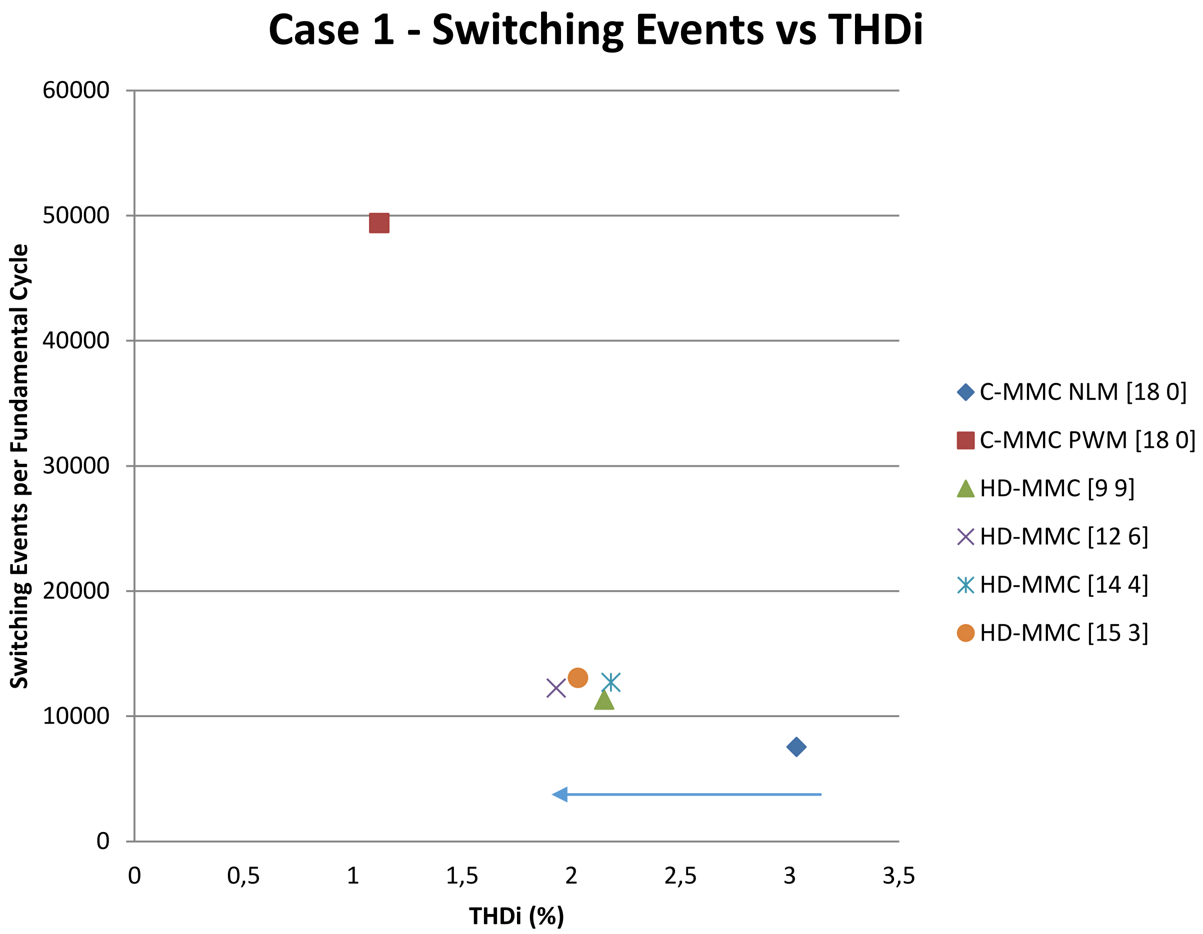


In HD-MMC [9, 9], 28 levels are produced in each arm voltage

HD-MMC on the performance in 3 phase converter



Weighting Factor0



Weighting Factor 5000

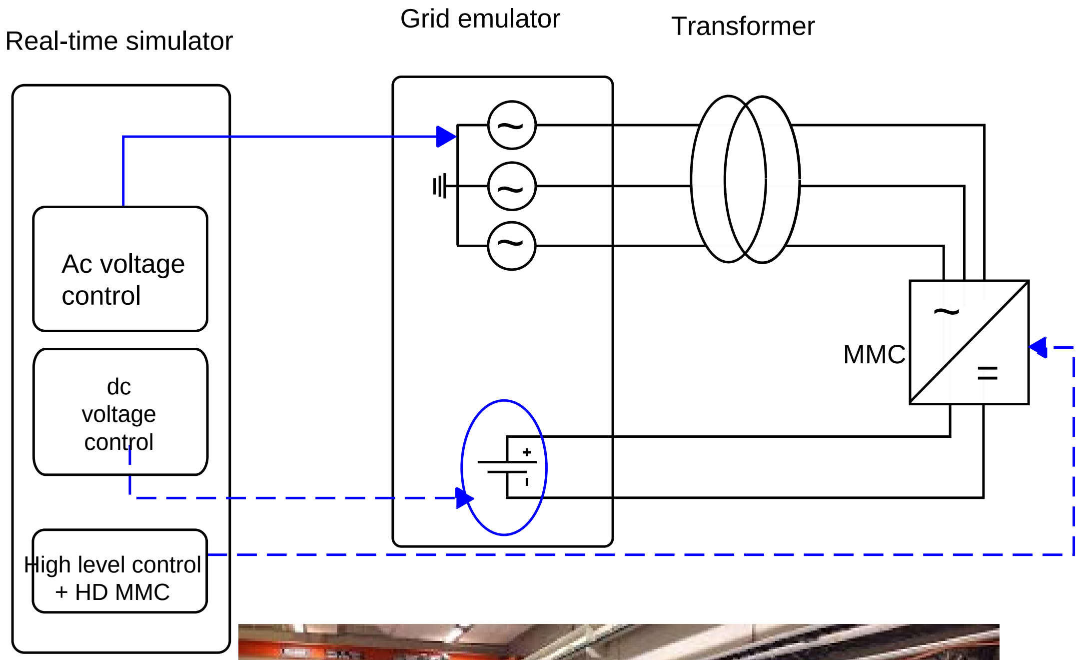
HD-MMC on the performance of a 3 phase converter with high level control integration

Objectives

- Determine stability of HD-MMC to sudden control point changes
- Determine the impact the HD-MMC has on the time taken to reach new operating point
- Ensure module voltages remain stable after each step change

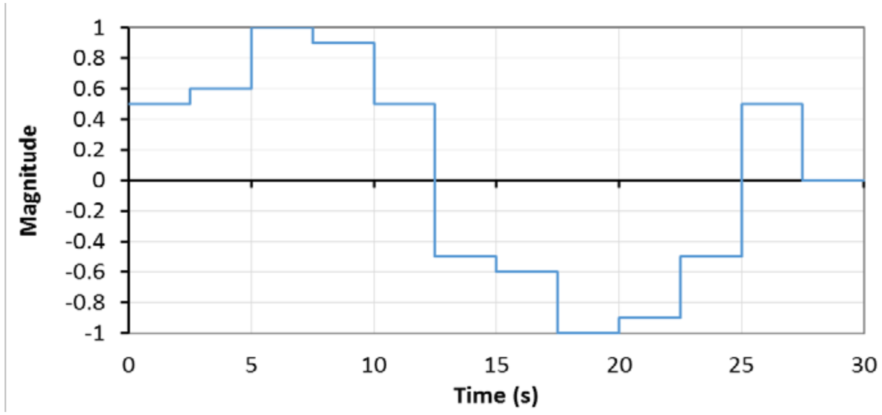
Set-Up

- GES creates constant, stable AC grid
- GES creates constant, stable DC bus
- MMC operates in PQ mode. PQ references are used to create step changes in Apparent Power (S) magnitude or angle.

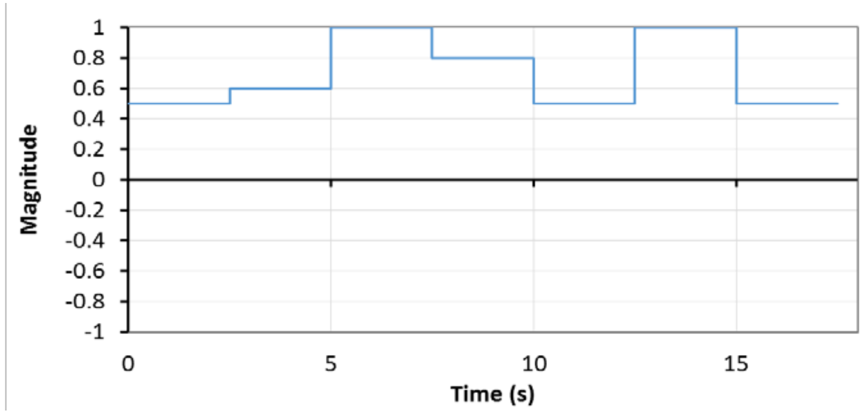


HD-MMC on the performance of a 3 phase converter with high level control integration

No	Converter	Configuration	Weight	Modulation Strategy	Variable	Pattern
2.00	HD-MMC	[14 04]	0	NLM	S	1
2.01	HD-MMC	[14 04]	0	NLM	θ	1
2.02	HD-MMC	[14 04]	0	NLM	V	2
2.03	C-MMC	[18 00]	0	NLM	S	1
2.04	C-MMC	[18 00]	0	NLM	θ	1
2.05	C-MMC	[18 00]	0	NLM	V	2



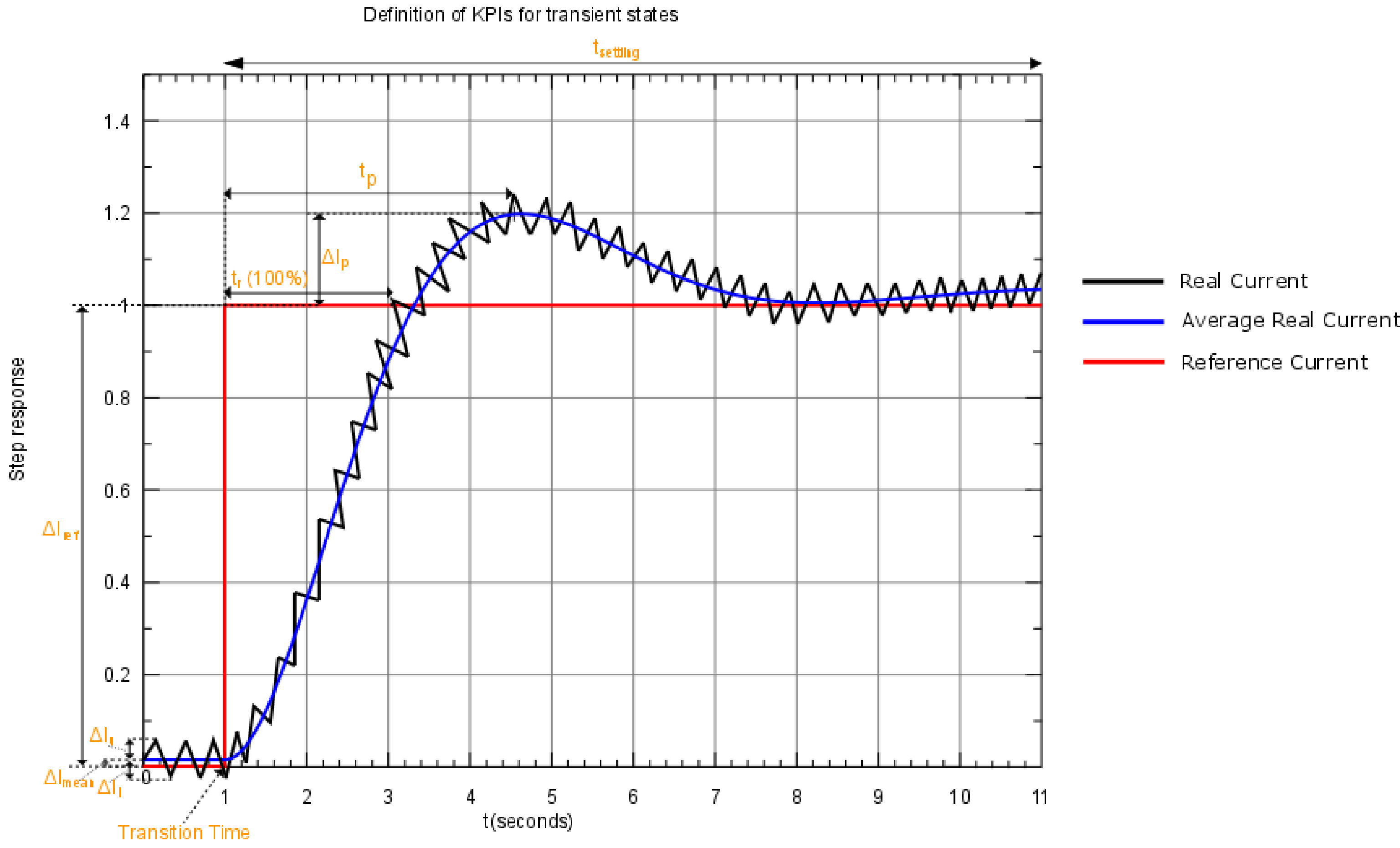
Profile for S, angle



Profile for V

HD-MMC on the performance of a 3 phase converter with high level control integration

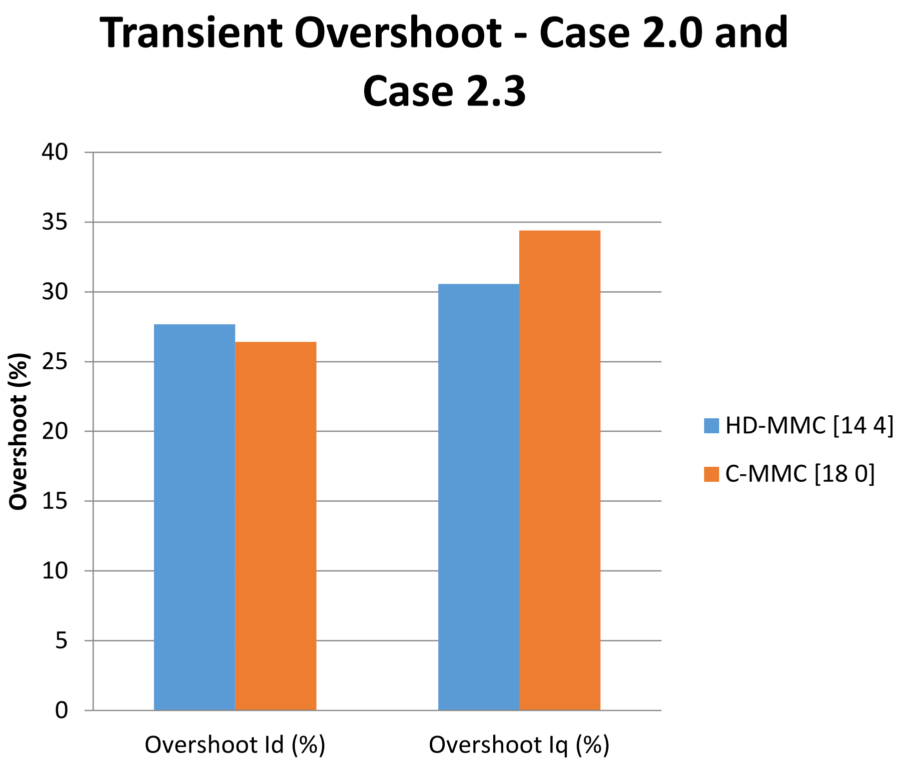
- Overshoot_Id (%) (ΔI_p in Figure):
- Overshoot_Iq (%) (ΔI_p in Figure):
- Peak Time Id (s) (t_p in Figure):.
- Peak Time Iq (s) (t_p in Figure):
- Rise Time Id (s) (t_r in Figure):
- Rise Time Iq (s) (t_r in Figure):
- Settling Time Id (s) ($t_{settling}$ in Figure):
- Settling Time Iq (s) ($t_{settling}$ in Figure):
- Steady State Mean Error Id (A) (ΔI_{mean} in Figure):
- Steady State Mean Error Iq (A) (ΔI_{mean} in Figure):
- Steady State Ripple Id Upper Level (A) (ΔI_u in Figure):
- Steady State Ripple Id Lower Level (A) (ΔI_l in Figure):
- Steady State Ripple Iq Upper Level (A) (ΔI_u in Figure):
- Steady State Ripple Iq Lower Level (A) (ΔI_l in Figure):

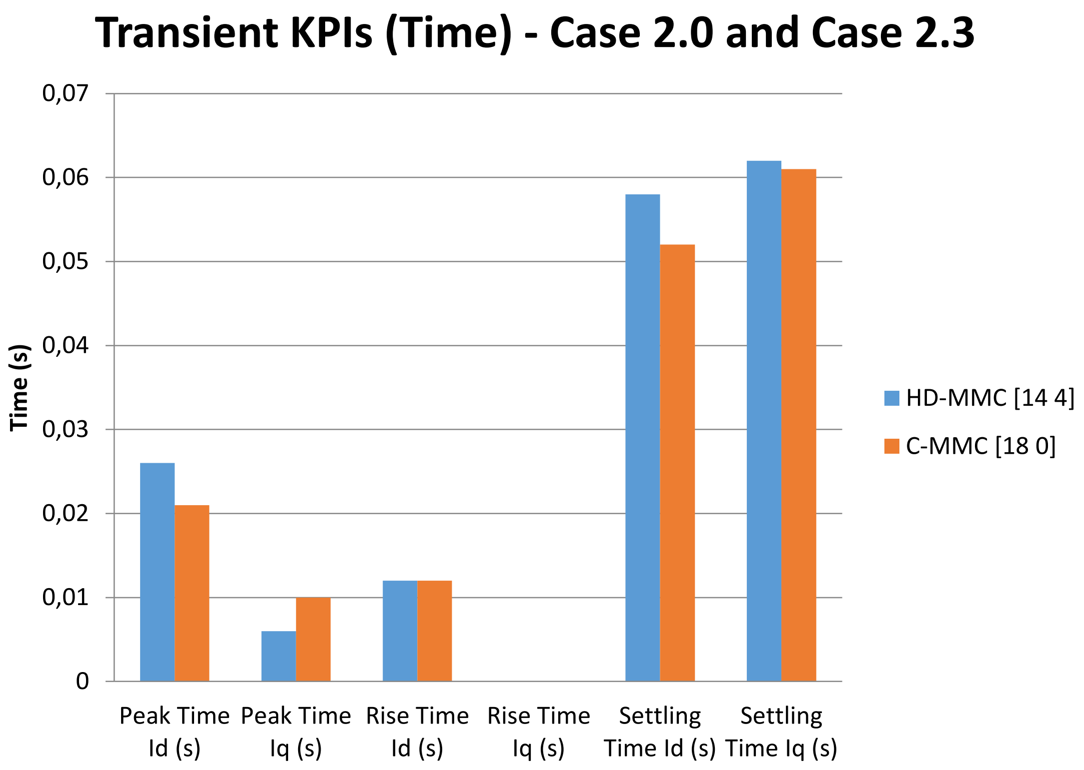


HD-MMC on the performance of a 3 phase converter with high level control integration

Experiment. No	2.00	2.01	2.03	2.04
Converter	HD-MMC	HD-MMC	C-MMC	C-MMC
Modulation	NLM	NLM	NLM	NLM
Configuration	[14 4]	[14 4]	[18 0]	[18 0]
Weighting Factor	0	0	0	0
OvershootId (%)	27.67	33.16	26.41	28.05
OvershootIq (%)	30.56	23.23	34.40	25.82
Peak Time Id (s)	0.026	0.017	0.021	0.019
Peak Time Iq (s)	0.006	0.035	0.010	0.034
Rise Time Id (s)	0.012	0.007	0.012	0.008
Rise Time Iq (s)	0.000	0.016	0.000	0.020
Settling Time Id (s)	0.058	0.066	0.052	0.056
Settling Time Iq (s)	0.062	0.063	0.061	0.055
Steady State Mean Error Id (A)	0.43	0.37	0.47	0.28
Steady State Mean Error Iq (A)	0.19	0.39	0.31	0.69
Steady State Ripple Id Upper Level (A)	1.93	2.25	3.14	3.20
Steady State Ripple Id Lower Level (A)	2.18	2.81	2.80	3.06
Steady State Ripple Iq Upper Level (A)	2.81	1.82	3.16	3.30
Steady State Ripple Iq Lower Level (A)	2.23	1.98	3.24	3.44

HD-MMC on the performance of a 3 phase converter with high level control integration





A similar dynamic behaviour between HD-MMC and C-MMC

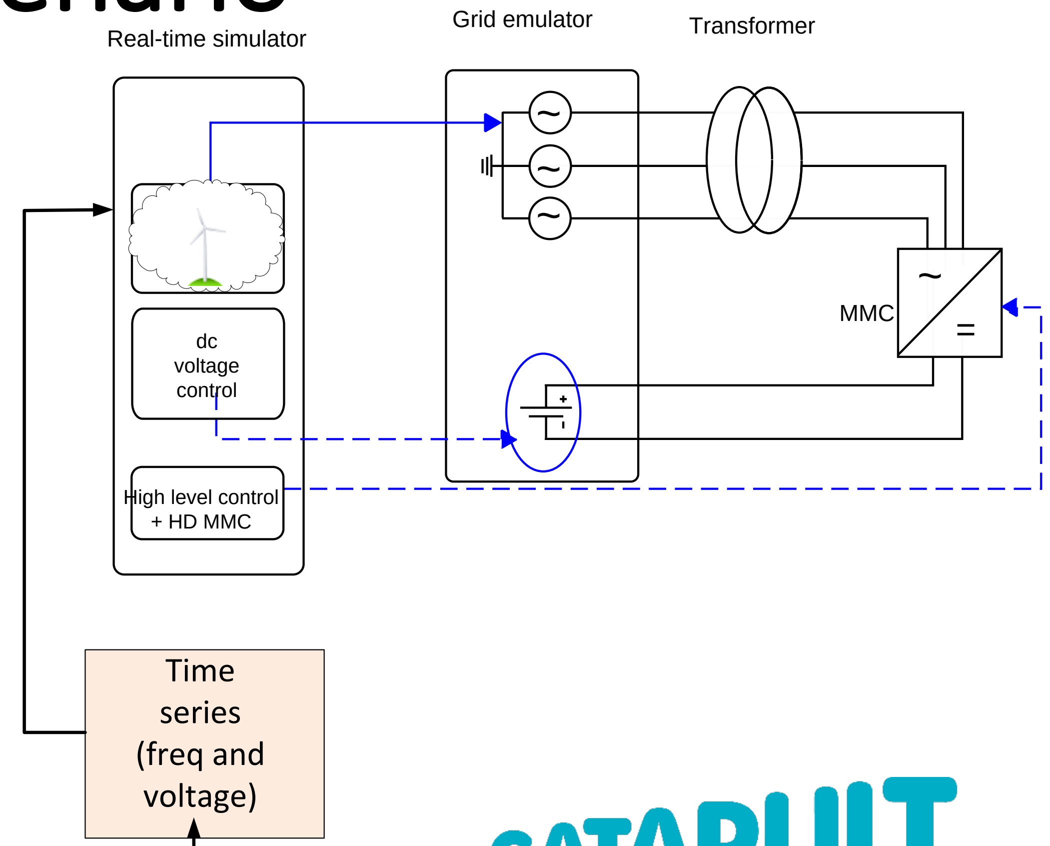
HD-MMC on the performance of a 3 phase converter in a more realistic scenario

Objectives

- This case determined the HD-MMC's performance when used as a generator facing converter.
- Using the non-dimensionalized generator output voltage and current waveforms saved by the Levenmouth Demonstration Turbine's (LDT's) SCADA.
- A time series with the voltages and frequencies to be produced by SINTEF's Grid Emulation System (GES) will be created.

Set-Up

- GES should follow the voltage magnitude and frequencies given to it in a csv file
- GES should create a stable DC voltage

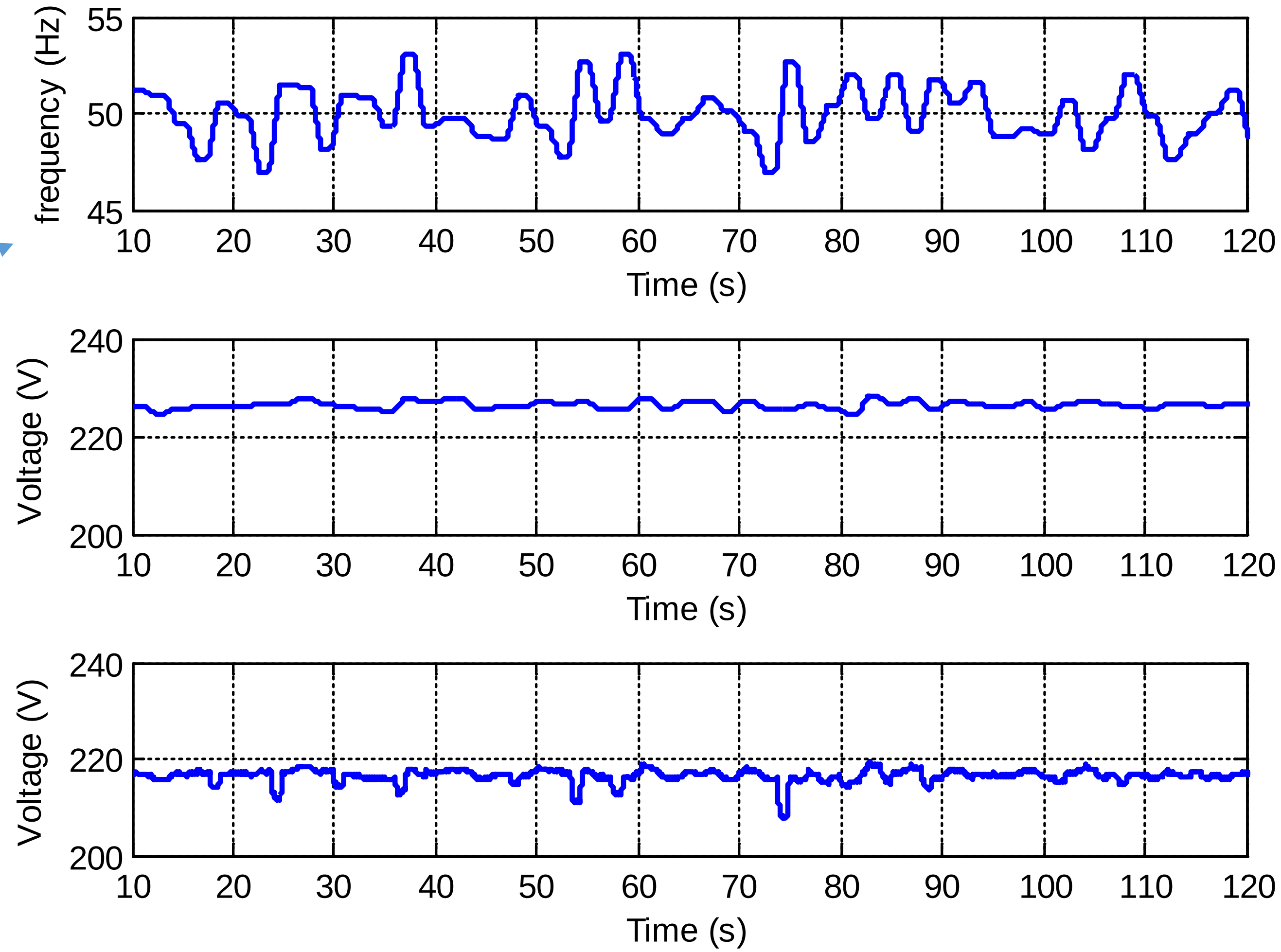


HD-MMC on the performance of a 3 phase converter in a more realistic scenario

HD-MMC should create an AC grid at the same voltage and frequency of that created by the GES

References

Produced by HD-MMC



Conclusions

This work was part of the **2nd call for Joint Experiments** organized within The Research Infrastructure WP of IRPWind.

The main goals were achieved:

(i) The performance of a 3 phase converter with HD-MMC with high level control integration was demonstrated. The performance of the HD-MMC to a C-MMC using THD and efficiency was verified. While the primary goal of HD-MMC, which is to reduce the THD was achieved.

(ii) The control stability and system response was verified through stepping the control set points and rapid changes in grid voltage and frequency to emulate potential grid variation and disturbances

(iii) The HD-MMC concept was tested in more real world conditions such as the connection of an emulated generated with real data.

THANKS