MMC-based audio amplifier

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> *As an informal challenge, we ambitioned to use an existing laboratory-scale Modular Multilevel Converter and build a powerful MMC-based audio amplifier!*

Modular Multilevel Converters (MMC) are best known for their suitability to high-voltage applications, notably large-scale HVDC facilities such as in sub-sea or long-distance energy transport.

In this context, the ability to block high voltages is key. Nevertheless, the high quality of the produced waveforms is also very beneficial to system design, thanks to reduced filtering requirements. Technically, this superior waveform quality is related to two simple yet fundamental benefits:

- The increase of the apparent switching frequency, which is often much higher than the actual switching frequency (typ. in the kHz range, while power semiconductors are actually switching at few tens of Hz).
- The reduced amplitude of the switching harmonics, thanks to a higher number of levels (typ. hundreds of levels/modules).

Read more
The technical note DC/AC Modular Multilevel Converter (MMC) (TN153) details an example of a three-phase inverter, using our MMC test bench.

Why use an MMC as an amplifier?

Switching audio amplifiers, often referred to as Class-D amplifiers, share the same need for superior voltage quality. Obviously, entirely different orders of magnitudes of power and frequencies are at stake, but MMCs are theoretically also able to bring attractive benefits for such applications.

Therefore, as an informal challenge, we ambitioned to use an existing laboratory-scale MMC as a powerful audio amplifier.

Operation parameters

The following operation parameters were selected. They simultaneously correspond to widely sufficient conditions for an excellent audio experience, as well as non-challenging parameters for our digital controller (B-Box RCP) and our power equipment:

- **Sampling** is made at **100kHz**, which isn't far from the typical 96kHz of professional audio equipment. That's anyway much larger than the typical audio spectrum, which covers 20Hz-20kHz.
- **Digital control** is also made at **100kHz**, because there are only a few PI controllers to run (16 in the selected control implementation), so that isn't a challenge at this frequency.
- **Switching** frequency is chosen as **25kHz**, because once accounting for the phase-shifting (interleaving), the apparent switching frequency becomes **400kHz**, which is largely sufficient to push switching harmonics away from the useful spectrum.
- The **number of modules** per arm is **N=4**, which is sufficient to benefit from **17 levels** on the load, namely the loudspeaker.

These parameters are summarized in the following table:

Symbol	Parameter	Value
N	Number of submodules per arm	4
f_{sw}	Actual switching frequency	25 kHz
$f_{sw,a}$	Apparent switching frequency ($f_{sw,a} = 16 \cdot f_{sw}$)	400 kHz
$f_s = f_{ctrl}$	Sampling and control frequency	100 kHz
n_a	Apparent number of levels ($n_a = 4N + 1$)	17

Downloads

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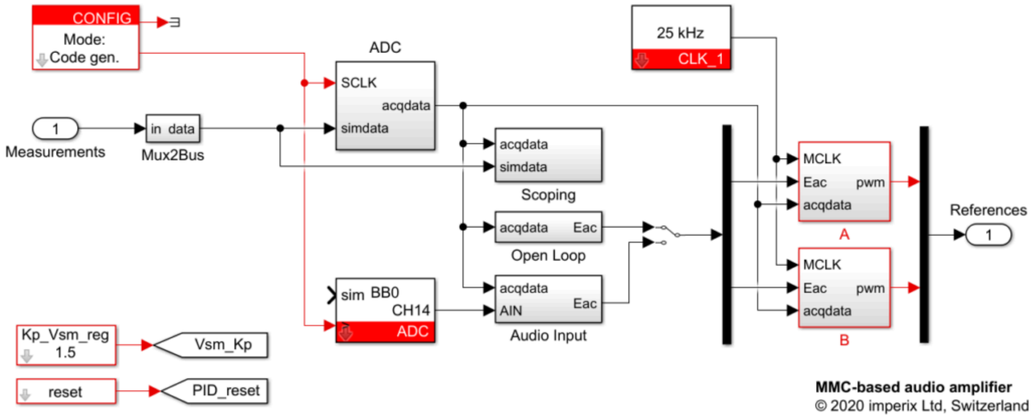
Control overview

The control of the Modular Multilevel Converter has been implemented in the simplest possible way. The requested converter voltage E_{AC} can be generated in a purely open-loop fashion, either using:

- A basic sinusoidal waveform generator, used for debug purposes (see block *Open Loop*).
- A signal input (see block *Audio Input*), which directly reads an analog input of the B-Box and to which a simple custom-made 3.5mm jack cable is connected.



General control overview of the developed application example

Submodules balancing

The generally delicate balancing of the converter submodules is here achieved using phase-shifted carrier-based modulators, whose duty cycles are slightly altered for balancing purposes.

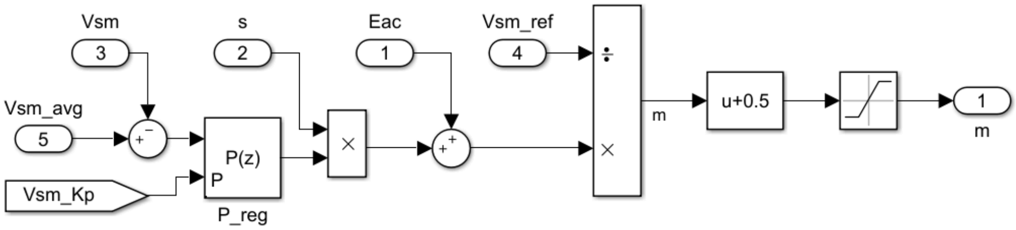
This technical approach, first proposed for MMC in [1], has proven since to be simple and effective. It consists in adding or subtracting a small amount of voltage to each submodule reference EMF, depending on the current sign.

However, as the reference voltage for each local control loop is here set to be the average capacitor voltage within one arm, it guarantees the balancing inside each arm, but not in-between the arms. This second stage of balancing is here addressed indirectly, using the fact that the duty-cycle m is computed by dividing the resulting reference EMF by $V_{SM,ref}$ instead of the actual measurement ($V_{SM,ref}$ is a constant setpoint, set for all submodules inside all arms).

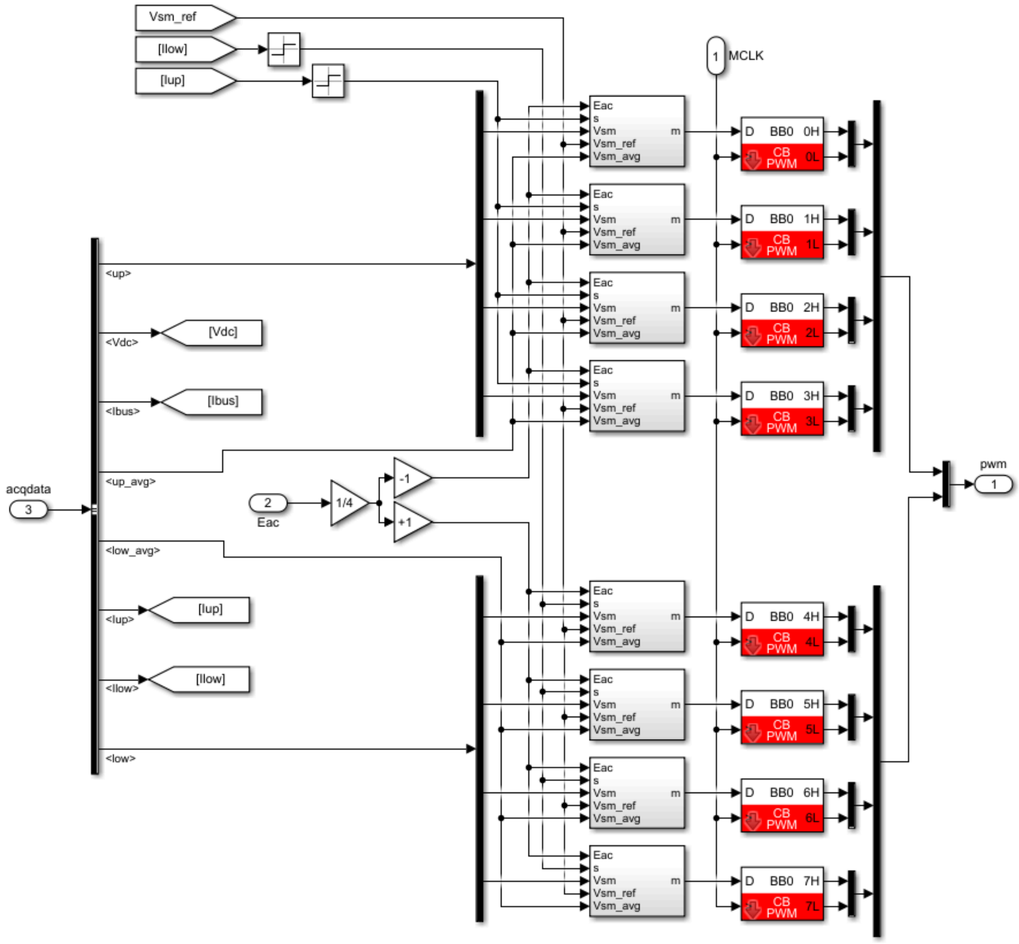
This simple technique is interesting as it was proven to be *asymptotically stable* [2]. However, it fails at properly rejecting the capacitor voltage fluctuations, which may impede the overall harmonic performance. As such, we would not recommend it for more serious use of an MMC in such an application.

To go further

An alternative approach, using sort-&-select balancing and modulation would be possible. Some hints about the functioning of the pre-implemented modulators are given in TN160.



Subsystem dedicated to the control of each submodule



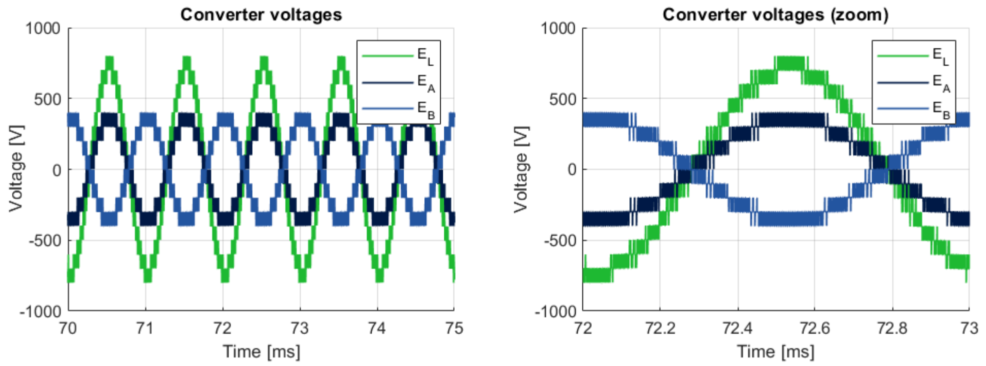
Subsystem dedicated to the control of each phase-leg

Modulation and interleaving

Having $N = 4$ modules per arm, the carrier-based modulators are phase-shifted as follows:

- $\phi_{modules} = \frac{2\pi}{4}$ in-between modules of the same arm. The resulting arm-level EMF therefore possesses N+1 levels, with an apparent switching frequency of $f_{sw,a} = 4 \cdot f_{sw}$.
- $\phi_{arms} = \frac{2\pi}{8}$ in-between arms of the same phase-leg. The resulting arm-level EMF (e.g. E_A or E_B) therefore possesses $2N + 1$ levels, with an apparent switching frequency of $f_{sw,a} = 8 \cdot f_{sw}$.
- $\phi_{legs} = \frac{2\pi}{16}$ in-between phase-leg. The resulting converter-level EMF (E_L) therefore possesses $4N + 1$ levels, with an apparent switching frequency of $f_{sw,a} = 16 \cdot f_{sw}$.

These waveforms can be analyzed from the following simulation results:



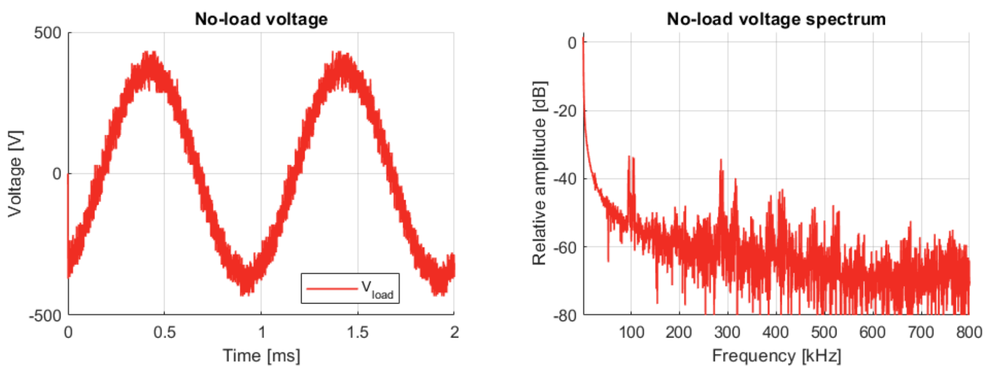
Simulated converter EMFs

As all B-Boxes are automatically synchronized down to ±2ns, no specific configuration is needed for managing the arm-level or converter-level interleaving. More information on the related topic can be found in the technology section: distributed modulation.

Experimental results

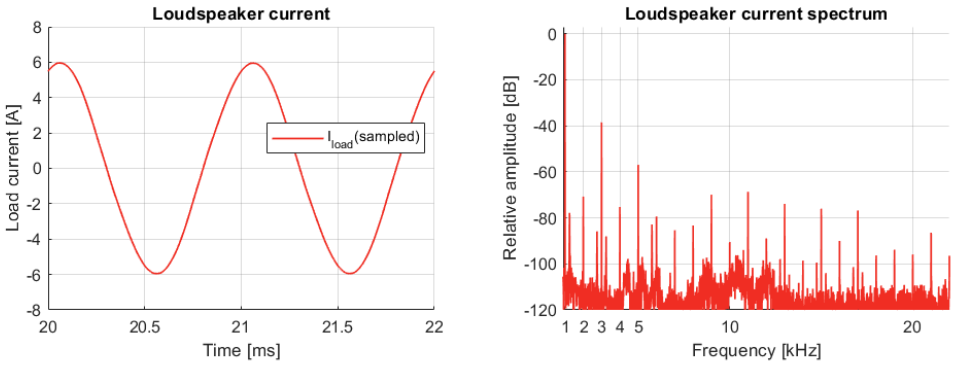
Experimental results are reported below. They correspond to measurements made for a pure sine wave at 1kHz.

First, the voltage waveform at no load is presented. The various levels can be identified, although the imperfect balancing prevents from clearly identifying all levels distinctively. The provided Fourier transform also shows that switching harmonics are still present at 100kHz and 300kHz, at levels that are still higher than the 400kHz ones.



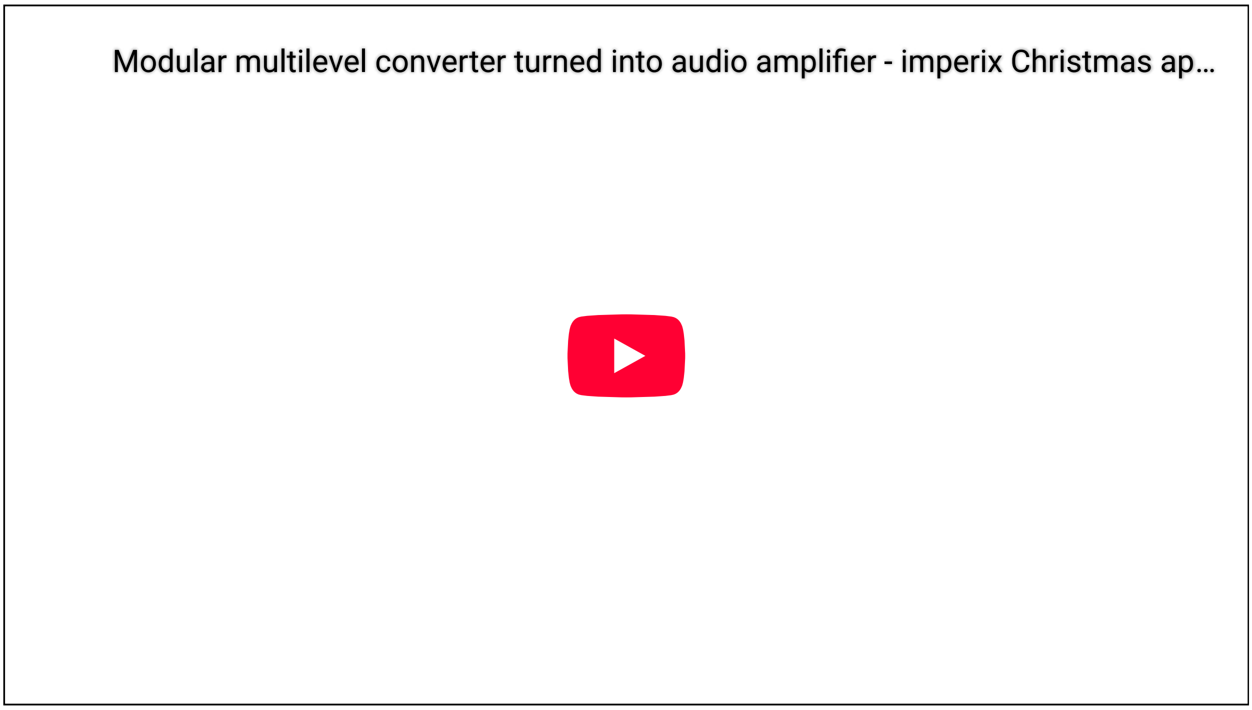
Bridge voltage measured without load

Second, the current waveform is presented when the loudspeaker is physically connected, corresponding to more reasonable operating conditions. In this case, switching harmonics become naturally filtered by the low-pass behavior of the loudspeaker itself (resonant circuit) and imperfections of the sine wave become barely visible. Nevertheless, harmonic distorsion is still present (about 1%), mostly constituted by third-order harmonics).



Experimental measurement of the loudspeaker current

Short presentation video



Academic references

[1] M. Hagiwara and H. Akagi, “PWM Control and Experiment of Modular Multilevel Converters,” in Proc. PESC Conference, Rhodes, Greece, 2008. https://doi.org/10.1109/PESC.2008.4591917

[2] L. Harnefors, S. Norrga, A. Antonopoulos and H.-P. Nee, “Dynamic modeling of modular multilevel converters,” in Proc. EPE Conference, Birmingham, Sept. 2011. https://ieeexplore.ieee.org/document/6020628