Modular Multilevel Converter

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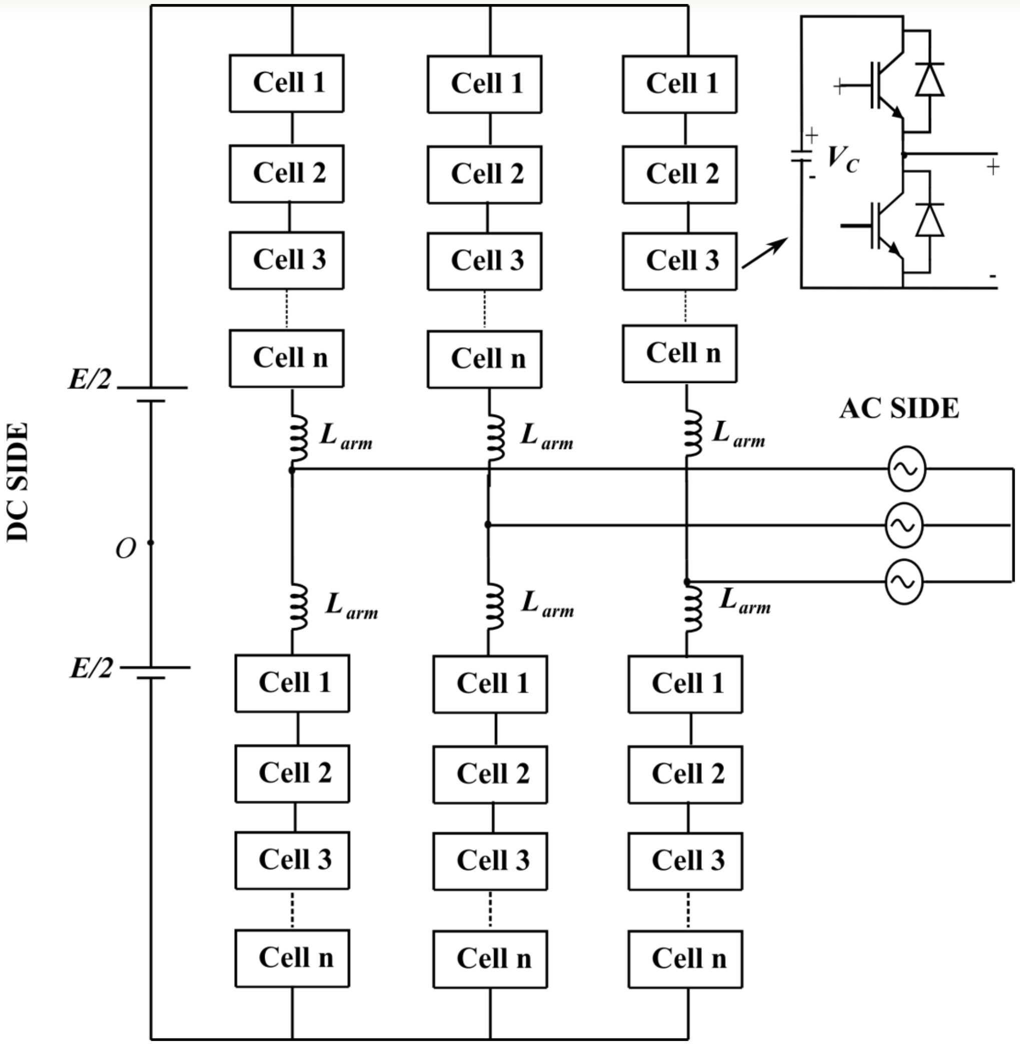
Modular Multilevel Converter

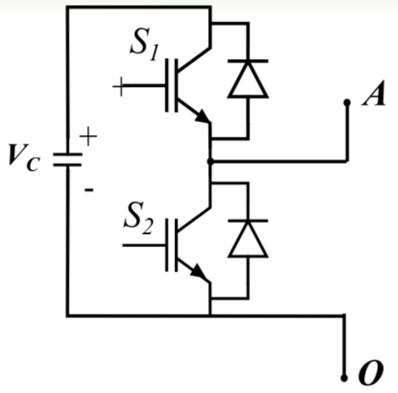
- Modular Multilevel Converter (MMC) is a new member of multilevel converter family, first proposed by Marquardt and others (2001).
- Many people say that this converter has immense potential for all applications in power electronics.



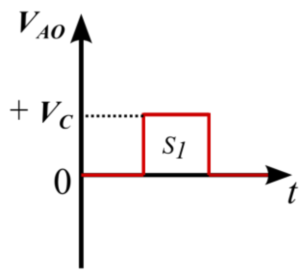
Drawback of Cascaded H-Bridge converter

- CHB requires many isolated sources. This is very challenging.
- MMC has only capacitors in the DC bus. It consists of full bridge or half bridge cells, capacitors in the DC bus and bypass switch.
- MMC is commercially implemented for HVDC, motor drives, Statcom or FACTS applications. It has potential for many more.
- Hundreds of cells can be connected in series e.g. for HVDC application.

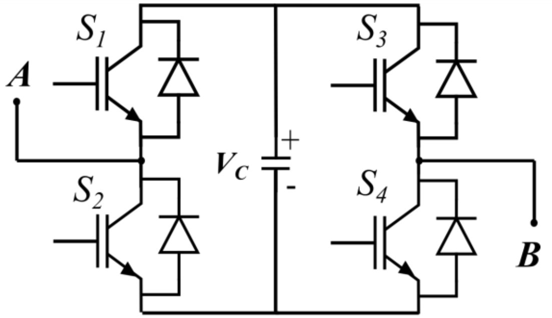
MMC and its cells



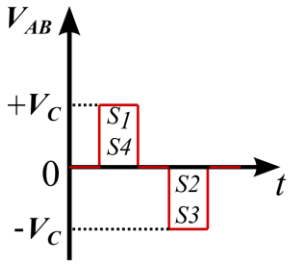
Half Bridge submodule



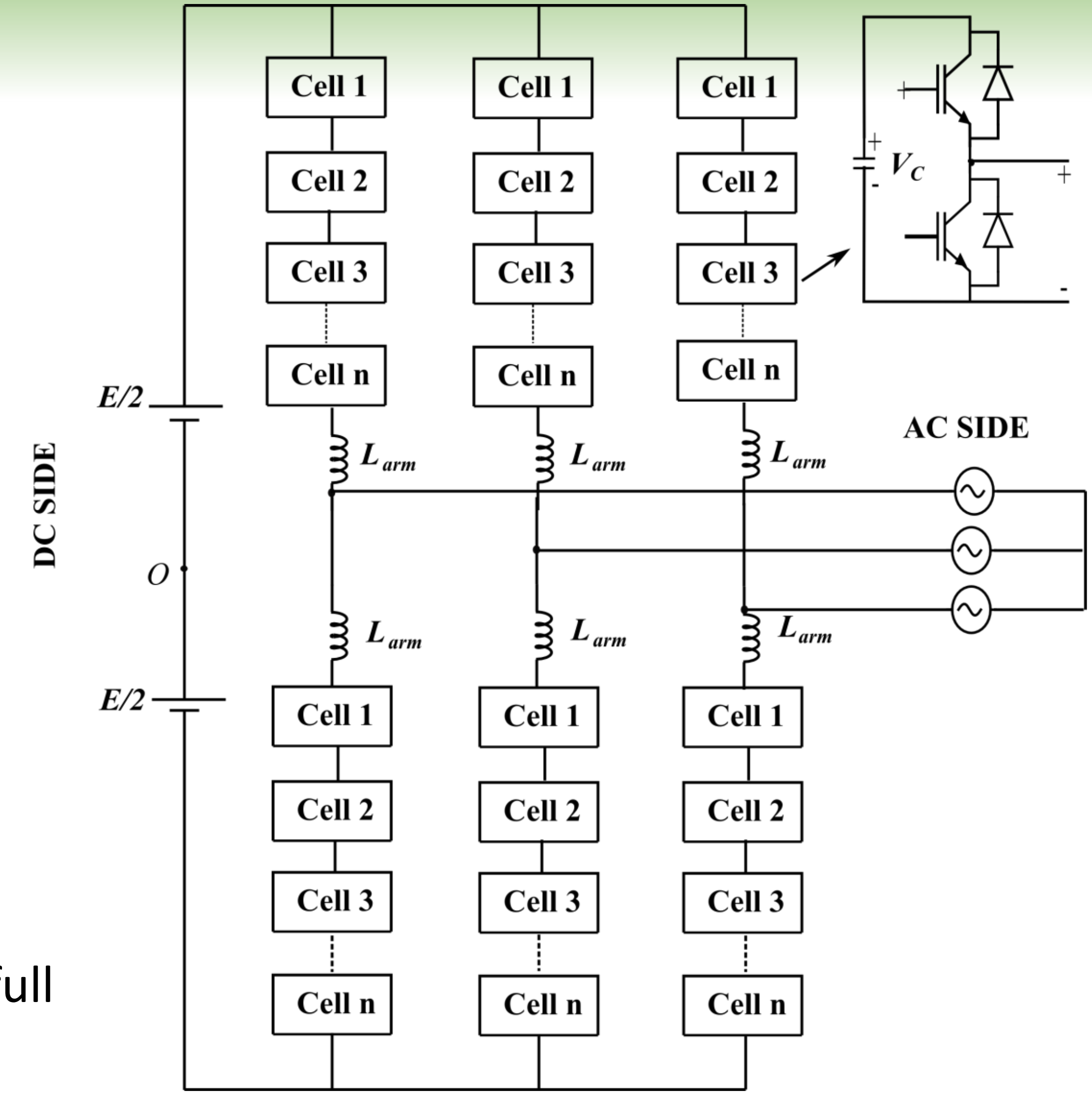
Output Voltage



Full Bridge submodule

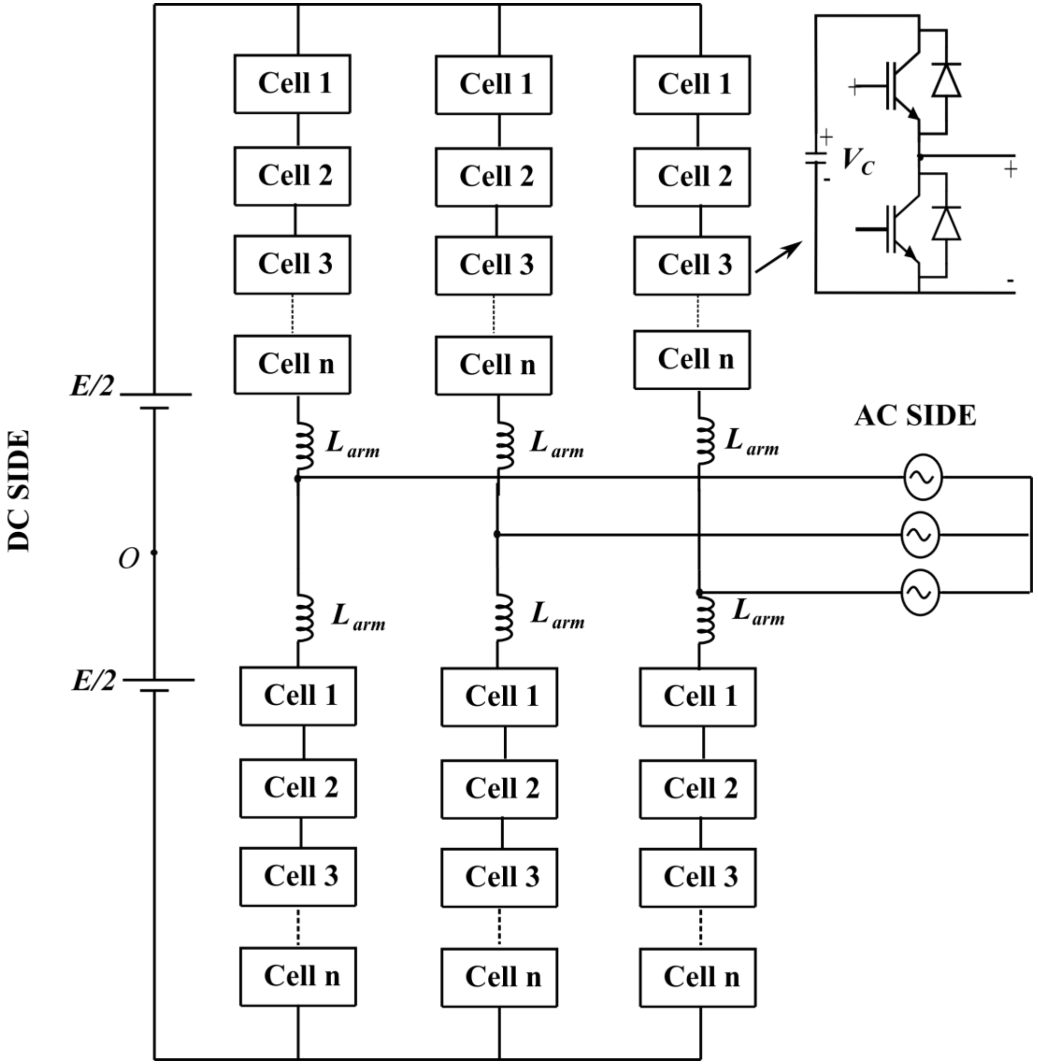


Output Voltage



- Cells (or Submodules) can be made with half bridges or full bridges.
- Each cell has a bypass mechanism, not shown.
- Cells are made up of capacitors.

Features



- Modular identical cells.
- Three upper arm and three lower arms.
- Each arm can contain more than hundred cells.
- Low voltage IGBTs are used in each cell.
- Fault tolerant operation is possible.
- Easy scalability of voltage and current.
- The same converter can be used for DC-AC or AC-DC applications.

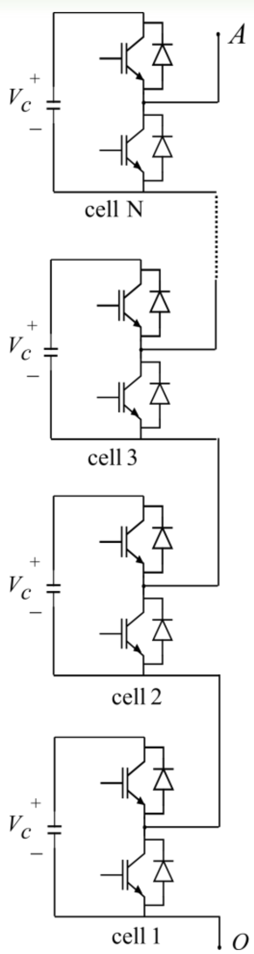
Advantages of MMC

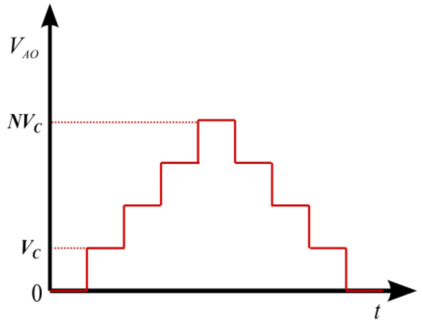
- Modular and simple converter cells.
- Easy bypass of faulty cells in case of a fault.
- Easy scalability of voltage and current.
- Very high quality of sine wave produced at the output, so the output filter is not needed. The common mode voltage is also low. Very low dv/dt at the output.
- The presence of the arm inductances also helps in limiting short circuit current.
- Good transient response, in particular during faulty conditions.
- The DC side can be fed from multi-pulse rectifiers, or AFE. The AC side can be fed from the grid.

Disadvantages of MMC

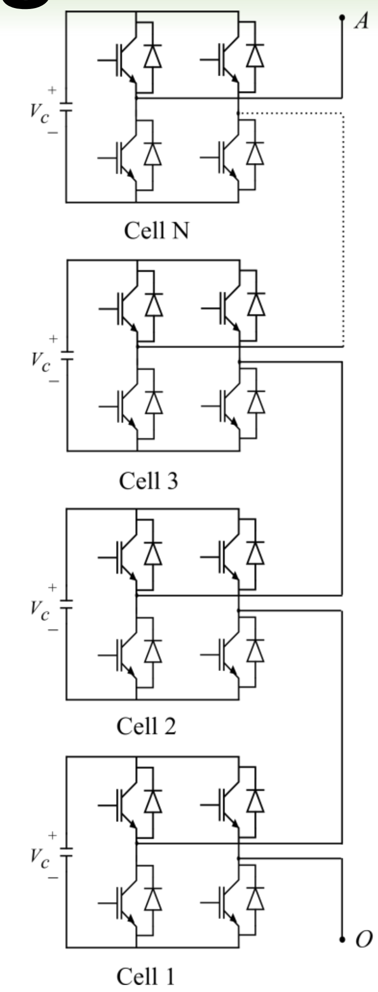
- Too many components, so control is complex. But the control strategy is repetitive for all cells. Cost is more.
- Reliability is less, but availability is more.
- Amount of capacitance is much more compared with other topologies.
- Control is complicated for vector controlled drives, where full load current is required at close to zero speed. But suitable for drives with fans or pumps.

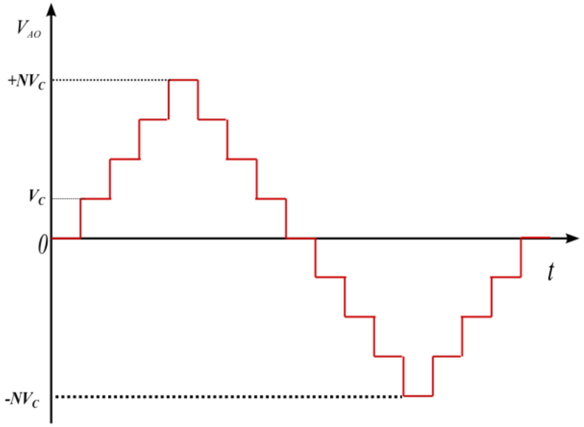
Cells as controllable voltage sources





Half bridge cells

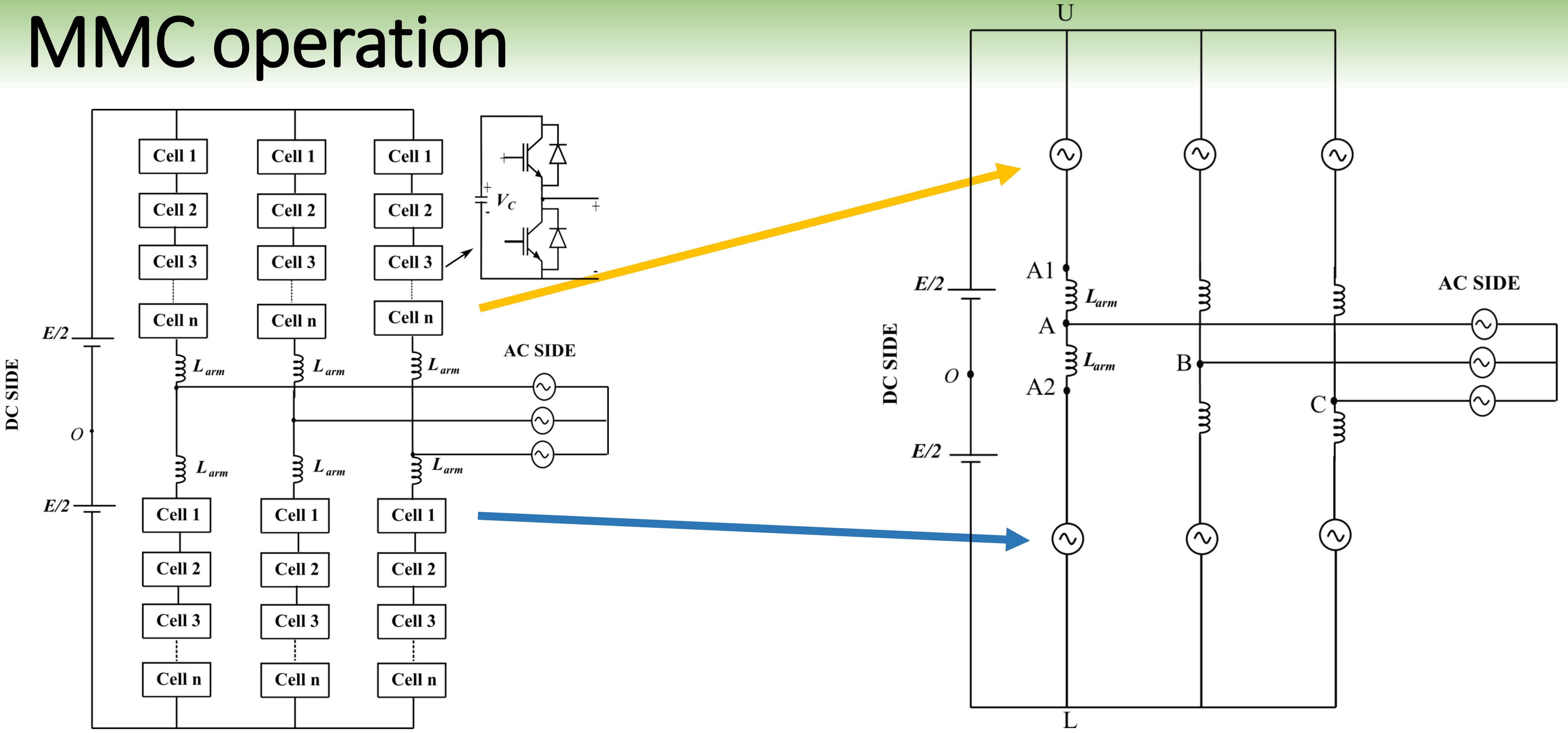




Full bridge cells

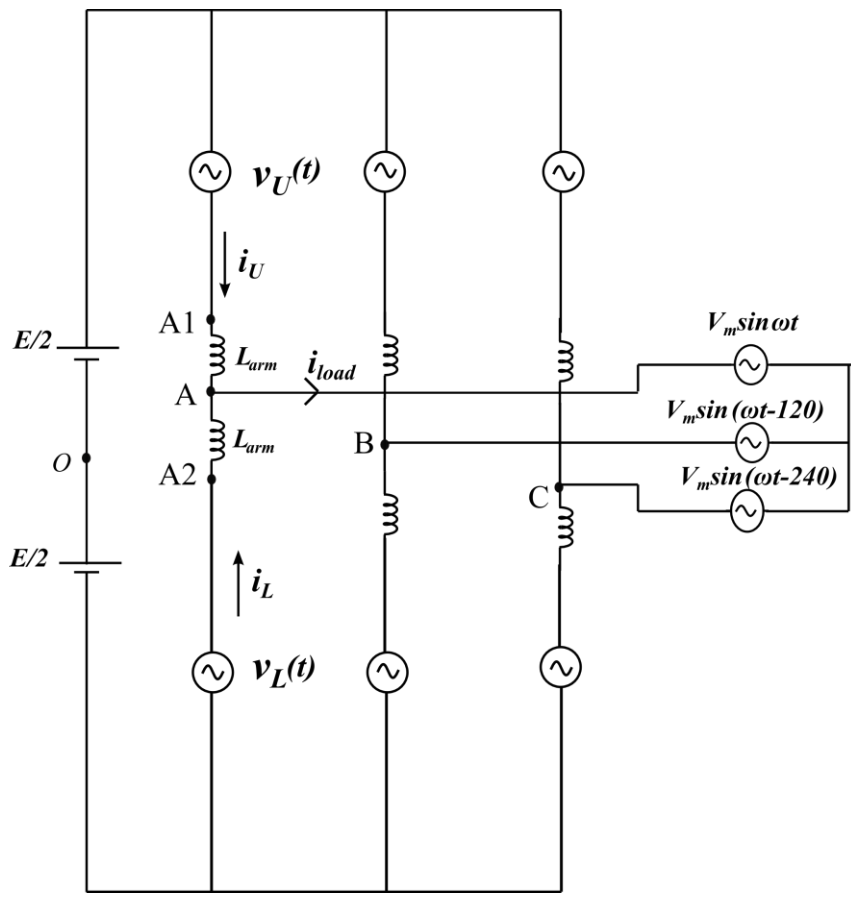
- With half bridges, the voltage produced has DC+AC components. With full bridges, the DC component in the voltage may be removed.
- With many cells, the output becomes smooth.

MMC operation



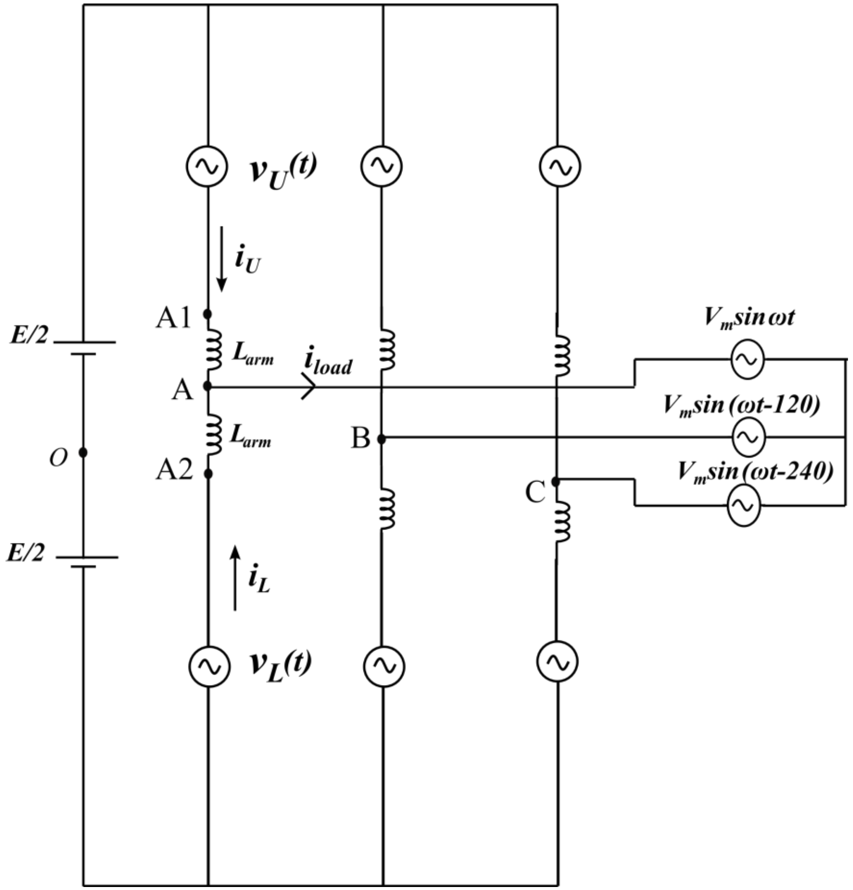
- Cells working together in an arm can be thought of as controllable voltage sources.

Steady state operation



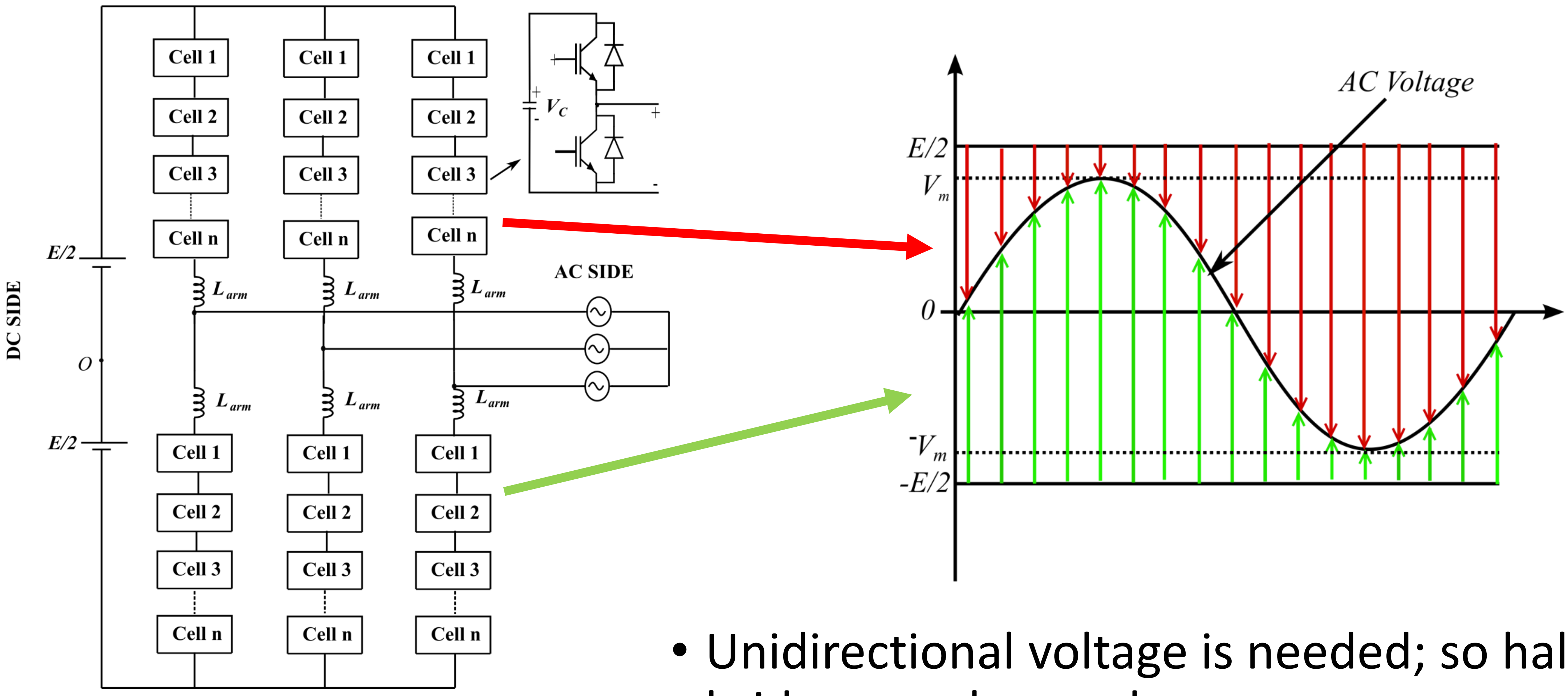
- Converter voltage equations:
- $\frac{E}{2} - v_U(t) - L\frac{di_U}{dt} = v_{AO}(t) = V_m \sin \omega t$
- Neglecting inductor drop,
- $\frac{E}{2} - v_U(t) = V_m \sin \omega t$
- This means, $v_U(t) = \frac{E}{2} - V_m \sin \omega t$.
- Similarly,
- $-\frac{E}{2} + v_L(t) - L\frac{di_L}{dt} = v_{AO}(t) = V_m \sin \omega t$
- This means, $v_L(t) = \frac{E}{2} + V_m \sin \omega t$.

Steady state operation



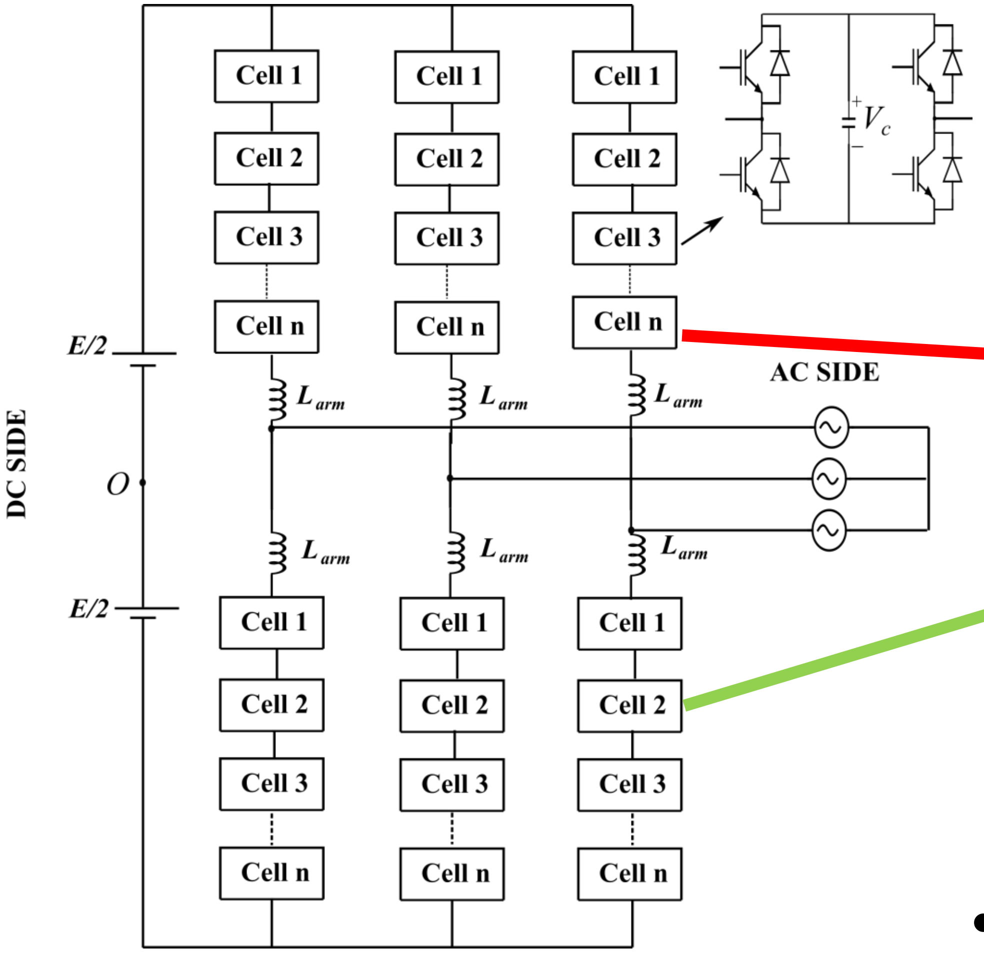
- In order to change the output AC voltages, the converter arm voltages can be modified as,
- $v_U^*(t) = \frac{E}{2}(1 - m \sin \omega t)$ where $0 \leq m \leq 1$ and $m = \frac{V_m}{\frac{E}{2}}$
- $v_L^*(t) = \frac{E}{2}(1 + m \sin \omega t)$
- How are the waveforms for $v_U^*(t)$?

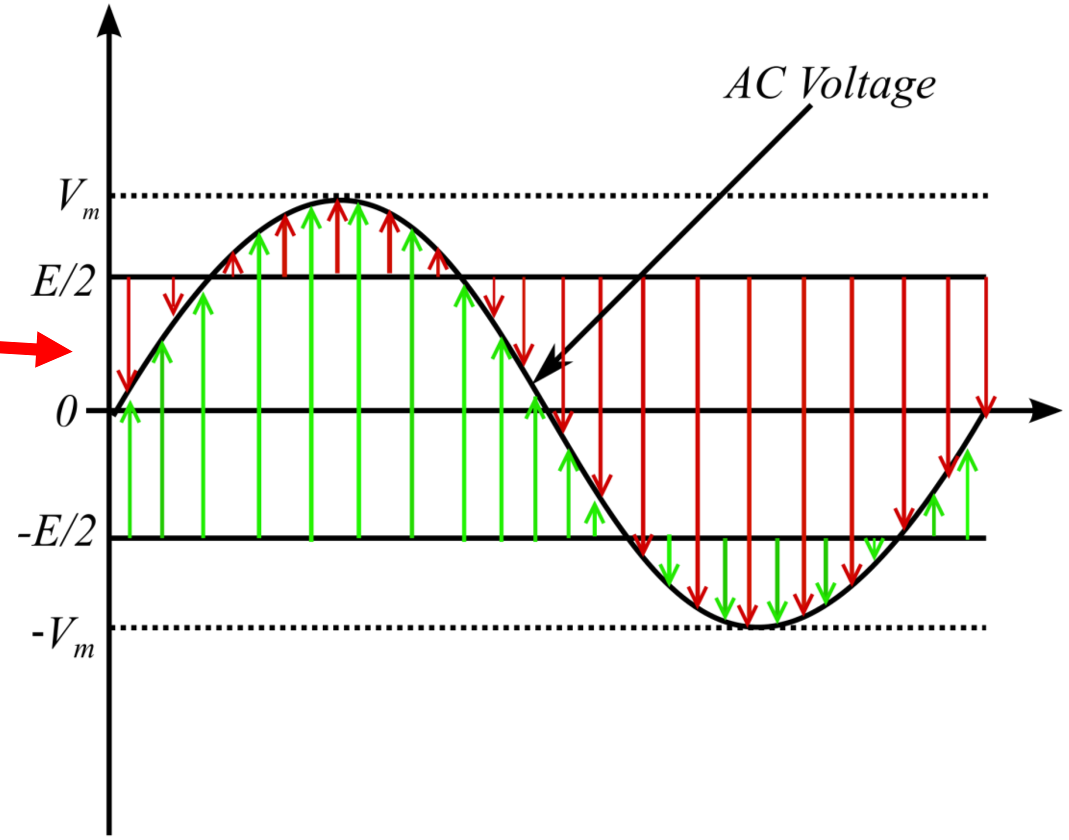
MMC operation (DC-AC or AC-DC)



- Unidirectional voltage is needed; so half bridges can be used.

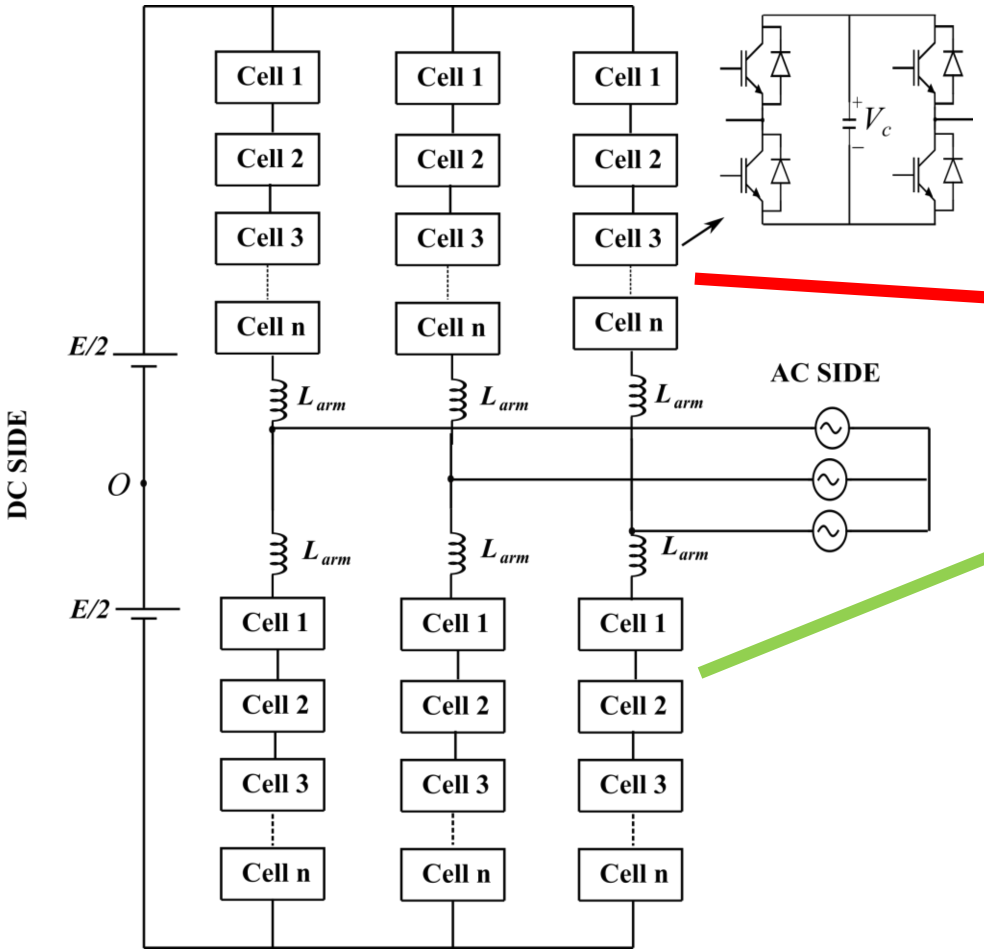
MMC operation (DC-AC or AC-DC)

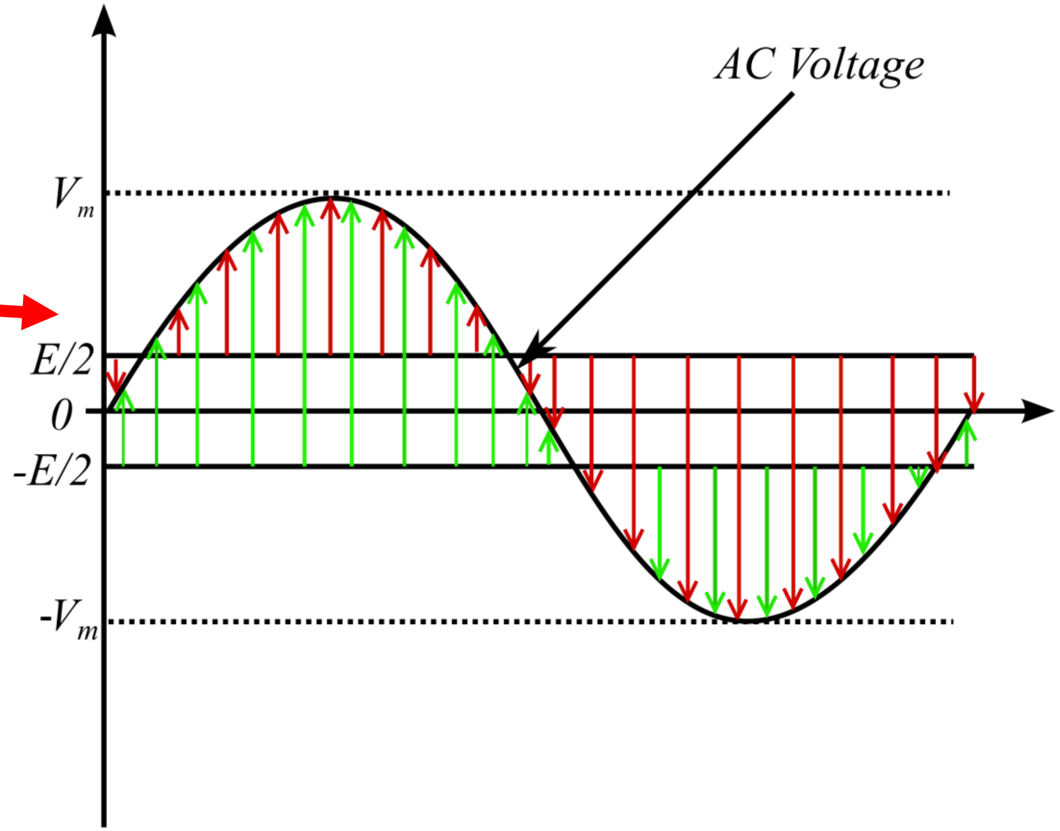




- Bidirectional voltage is needed; so full bridges must be used.

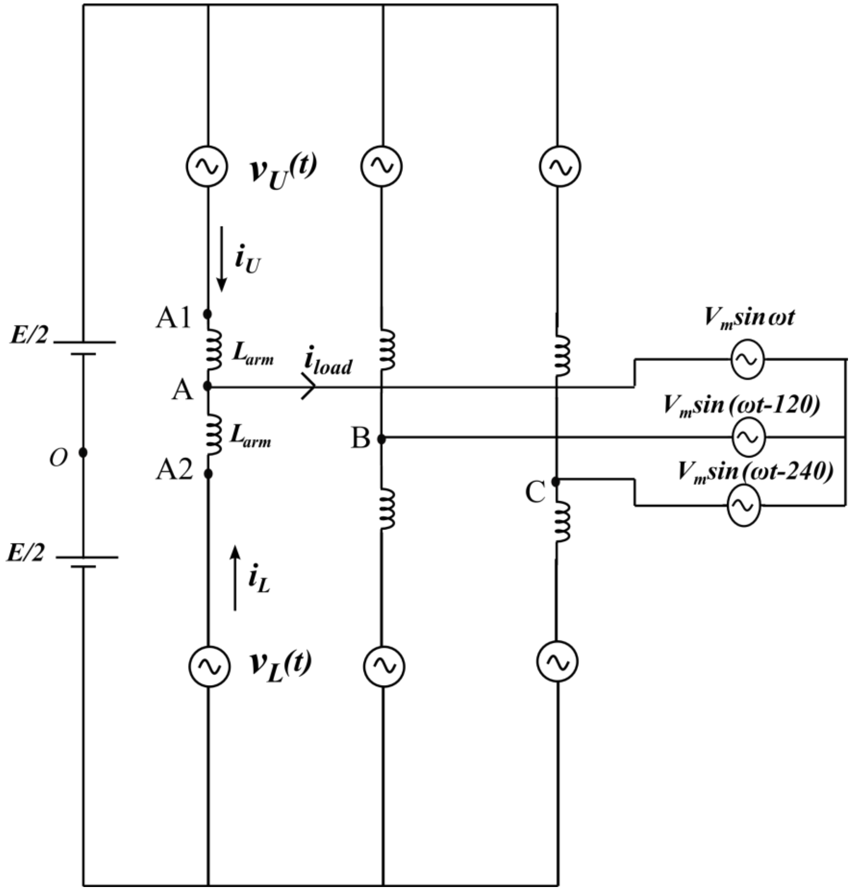
MMC operation (DC-AC or AC-DC)





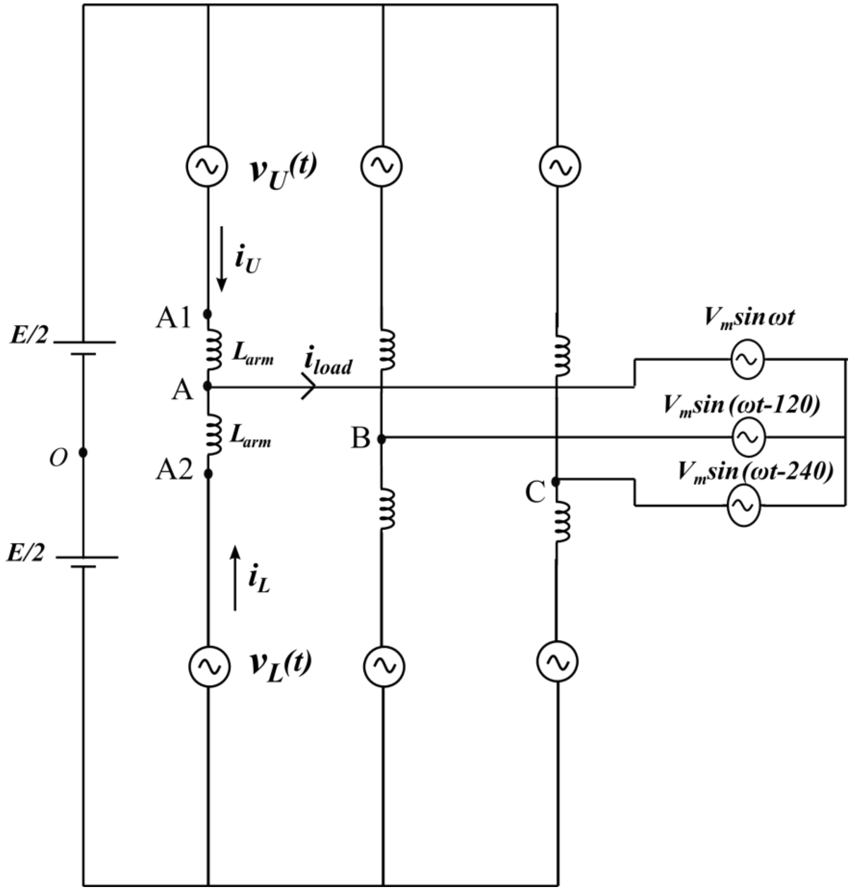
- What happens when E=0 or a very small value?

Arm voltage rating



- Converter voltage equations:
  - $v_U(t) = \frac{E}{2} - V_m \sin \omega t$
  - $v_L(t) = \frac{E}{2} + V_m \sin \omega t$
- If $V_m \leq \frac{E}{2}$ then $0 \leq v_U \leq E$.
- Similarly, $0 \leq v_L \leq E$.
- Thus voltage rating of upper and lower arm is the total DC link voltage.
- Voltage rating of each cell (and capacitor) is *E/N*, where N is the number of submodules in any arm.

Cell voltage rating



- Voltage rating of each cell (and capacitor) is *E/N*, where *N* is the number of submodules in any arm.
- Number of submodules is also related to capacitor stored energy.
- A low value of *N* will increase the voltage rating on each switch and capacitor ripple.
- A high value of *N* will increase the cost.

Arm currents

- Arm current has both DC and AC component.
- If we neglect the capacitor voltage ripple, then
  - half of load current will flow through arms at fundamental frequency
  - Arm currents will have DC to maintain power balance
- But a 2^{nd} harmonic voltage ripple appears on the capacitor voltage due to single phase power flow. It causes second harmonic voltages to appear in the arms. It causes additional harmonic currents.
- So the arm currents have,
  - half of load current flowing through arms at fundamental frequency
  - Arm currents will have DC to maintain power balance
  - Higher harmonic currents due to capacitor voltage ripple

Arm currents at steady state

- Arm current expression:
- $i_U(t) = \frac{1}{2} i_{load}(t) + i_{circ}(t)$
- $i_L(t) = \frac{1}{2} i_{load}(t) - i_{circ}(t)$
- $i_{load}(t) = I_m sin(\omega t - \varphi)$
- $i_{circ}(t)$ has a DC component and higher harmonics (predominantly fundamental and 2nd harmonics).

Arm energy balancing at steady state

- We have to ensure that power flow through the cell is zero over a certain period of time i.e. $\int_0^T v_{cell} i_{cell}\, dt = 0$ to maintain capacitor voltages constant.
- This means arm energy should also be zero

$$\text{i.e. } W_{arm} = \int_0^T p_{arm}\, dt = \int_0^T v_{arm} i_{arm}\, dt = 0.$$

- The instantaneous power for upper arm is given as

$$p_U(t) = v_U(t) i_U(t)$$

$$= \left(\frac{E}{2}(1 - m \sin \omega t)\right)\left(\frac{1}{2} i_{load}(t) + i_{circ}(t)\right)$$

$$= \left(\frac{E}{2}(1 - m \sin \omega t)\right)\left(\frac{1}{2} I_m \sin(\omega t - \varphi) + i_{circ}(t)\right)$$

Arm energy balancing at steady state

$$p_U(t) = \frac{E}{2}\frac{1}{2}I_m \sin(\omega t - \varphi) + \frac{E}{2}i_{circ}(t) - m\frac{E}{2}\frac{1}{2}I_m \sin\omega t \sin(\omega t - \varphi) - m\frac{E}{2}\sin\omega t i_{circ}(t)$$

$$= \frac{E}{2}\frac{1}{2}I_m \sin(\omega t - \varphi) + \frac{E}{2}i_{circ}(t) - m\frac{E}{2}\frac{1}{4}I_m\,(2\sin\omega t \sin(\omega t - \varphi)) - m\frac{E}{2}\sin\omega t i_{circ}\,(t)$$

$$= \frac{E}{2}\frac{1}{2}I_m \sin(\omega t - \varphi) + \frac{E}{2}i_{circ}(t) - m\frac{E}{2}\frac{1}{4}I_m\,(\cos\varphi - \cos(2\omega t - \varphi)) - m\frac{E}{2}\sin\omega t i_{circ}(t)$$

$$= \frac{E}{2}i_{circ}(t) - \frac{mEI_m}{8}\cos\varphi + \frac{EI_m}{4}\sin(\omega t - \varphi) - \frac{mE}{2}i_{circ}(t)\sin\omega t + \frac{mEI_m}{8}\cos(2\omega t - \varphi)$$

The instantaneous arm power has both DC and AC components and can be written as

$$p_U(t) = p_{U\_DC}(t) + p_{U\_AC}(t)$$

Arm energy balancing at steady state

$$p_{U\_DC}(t) = \frac{E}{2} i_{circ}(t) - \frac{mEI_m}{8} \cos\varphi$$

$$p_{U\_AC}(t) = \frac{EI_m}{4} \sin(\omega t - \varphi) - \frac{mE}{2} i_{circ}(t) \sin \omega t + \frac{mEI_m}{8} \cos(2\omega t - \varphi)$$

In steady state, to ensure arm energy balance, the average DC power of each arm must be equal to zero

$$p_{U\_DC}(t) = 0$$

This gives DC component of circulating current , $i_{circ}(t) = \frac{1}{4} mI_m cos\varphi$

The instantaneous power for lower arm is given as

$$p_L(t) = v_L(t) i_L(t)$$
$$= (\frac{E}{2}(1 + m \sin \omega t))(\frac{1}{2} i_{load}(t) - i_{circ}(t))$$

Arm energy balancing at steady state

$$p_L(t) = (\frac{E}{2}(1 + m\sin\omega t))(\frac{1}{2}I_m\sin(\omega t - \varphi) - i_{circ}(t))$$

$$p_L(t) = -\frac{E}{2}i_{circ}(t) + \frac{mEI_m}{8}\cos\varphi + \frac{EI_m}{4}\sin(\omega t - \varphi) - \frac{mE}{2}i_{circ}(t)\sin\omega t - \frac{mEI_m}{8}\cos(2\omega t - \varphi)$$

The instantaneous arm power has both DC and AC components and can be written as

$$p_{L\_DC}(t) = -\frac{E}{2}i_{circ}(t) + \frac{mEI_m}{8}\cos\varphi$$

$$p_{L\_AC}(t) = \frac{EI_m}{4}\sin(\omega t - \varphi) - \frac{mE}{2}i_{circ}(t)\sin\omega t - \frac{mEI_m}{8}\cos(2\omega t - \varphi)$$

In steady state, to ensure arm energy balance, the average DC power of lower arm must be equal to zero

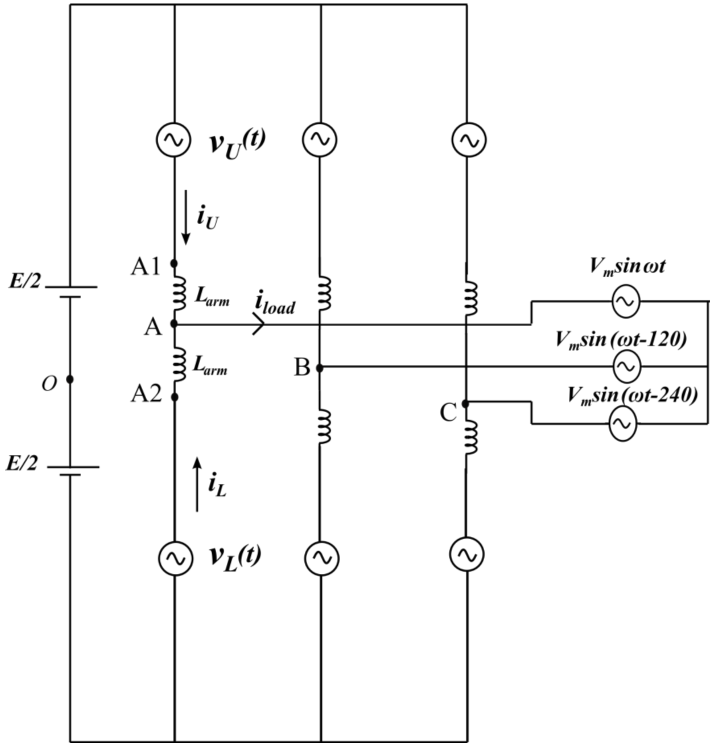
$$p_{L\_DC}(t) = 0$$

This gives, $i_{circ}(t) = \frac{1}{4}mI_m cos\varphi$

Relation between AC and DC side current

- Let the current drawn from DC source (E) be I_d. Then, EI_d is the power drawn (or power flows) from (into) DC side.
- Under no losses in the converter, it should be equal to AC power.
- Thus, $EI_d = 3\frac{V_m}{\sqrt{2}}\frac{I_m}{\sqrt{2}}cos\varphi$
- Hence, $I_d = \frac{3}{4}mI_m cos\varphi$
- Thus I_d is three times the circulating current. Ideally I_d is pure DC.

- Another way of writing the arm currents is: $i_U(t) = \frac{1}{2}I_m sin(\omega t - \varphi) + \frac{I_d}{3}$



Arm energy balancing at steady state

AC power components of arm power will cause energy variation in each arm. The upper arm energy can be written as

$$W_U(t) = \int p_{U_{AC}}(t)\,dt = \int \left(\frac{EI_m}{4}\sin(\omega t - \varphi) - \frac{mE}{2} i_{circ}(t)\sin\omega t + \frac{mEI_m}{8}\cos(2\omega t - \varphi)\right) dt$$

Assuming $i_{circ}(t) = \frac{I_d}{3}$

$$W_U(t) = \int \left(\frac{EI_m}{4}\sin(\omega t - \varphi) - \frac{mE}{2}\frac{I_d}{3}\sin\omega t + \frac{mEI_m}{8}\cos(2\omega t - \varphi)\right) dt$$

Solving the above equation, the upper arm energy variation obtained is

$$W_U(t) = -\frac{EI_m}{4\omega}\cos(\omega t - \varphi) + \frac{mEI_d}{6\omega}(\cos\omega t) + \frac{mEI_m}{16\omega}\sin(2\omega t - \varphi) + c1$$

Where $c1$ is the integration constant

Arm energy balancing at steady state

The value of $c1$ can be obtained by assuming at $t = 0$, $W_U(t) = W_{U0}$

$$c1 = W_{U0} + \frac{EI_m}{4\omega}\cos(\varphi) - \frac{mEI_d}{6\omega} + \frac{mEI_m}{16\omega}\sin(\varphi)$$

Putting the value of $c1$, the upper arm energy obtained is

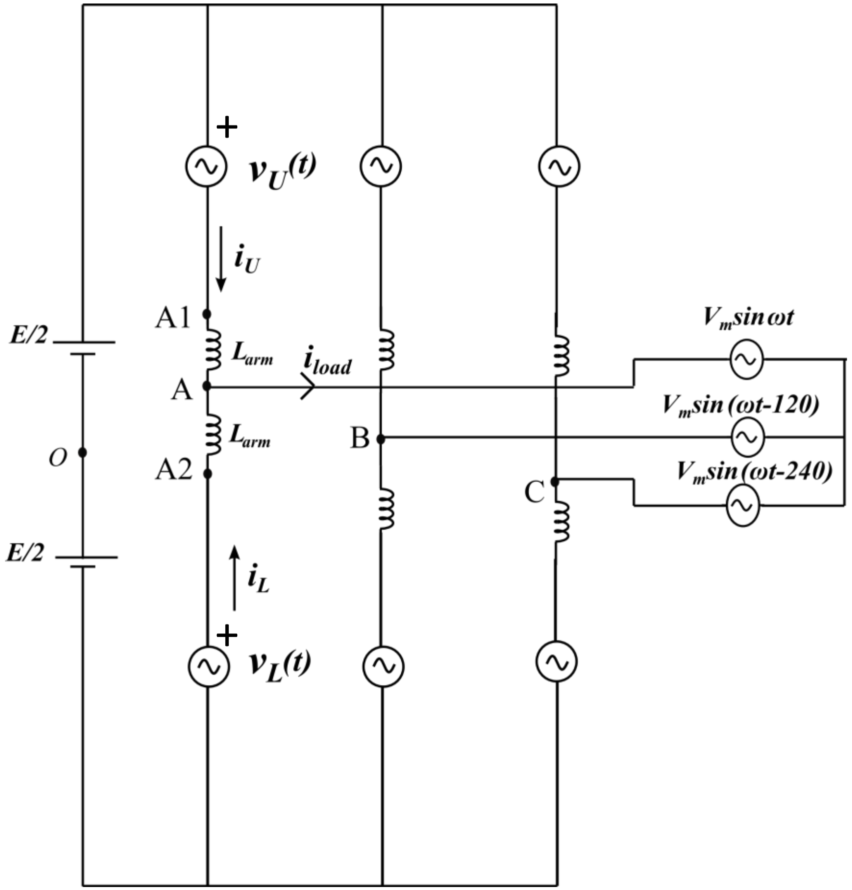
$$W_U(t) = W_{U0} + \frac{EI_m}{4\omega}\cos(\varphi) - \frac{mEI_d}{6\omega} + \frac{mEI_m}{16\omega}\sin(\varphi) - \frac{EI_m}{4\omega}\cos(\omega t - \varphi) + \frac{mEI_d}{6\omega}(\cos \omega t) + \frac{mEI_m}{16\omega}\sin(2\omega t - \varphi)$$

Similarly, the lower arm energy can be written as:

$$W_L(t) = \int p_{L_{AC}}(t)\, dt = \int \left(\frac{EI_m}{4}\sin(\omega t - \varphi) - \frac{mE}{2}\frac{I_d}{3}\sin \omega t - \frac{mEI_m}{8}\cos(2\omega t - \varphi)\right) dt$$

$$W_L(t) = W_{L0} + \frac{EI_m}{4\omega}\cos(\varphi) - \frac{mEI_d}{6\omega} - \frac{mEI_m}{16\omega}\sin(\varphi) - \frac{EI_m}{4\omega}\cos(\omega t - \varphi) + \frac{mEI_d}{6\omega}\cos \omega t - \frac{mEI_m}{16\omega}\sin(2\omega t - \varphi)$$

Lower arm energy



From the circuit diagram and the sign convention used, the arm energy variation expression in the lower arm should be negative of the arm energy variation expression in the upper arm.

$$W_L(t) = -W_{L0} - \frac{EI_m}{4\omega}\cos(\varphi) + \frac{mEI_d}{6\omega} + \frac{mEI_m}{16\omega}\sin(\varphi) + \frac{EI_m}{4\omega}\cos(\omega t - \varphi) - \frac{mEI_d}{6\omega}\cos\omega t + \frac{mEI_m}{16\omega}\sin(2\omega t - \varphi)$$

Upper and lower arm energy expressions

The upper arm energy obtained earlier is

$$W_U(t) = W_{U0} + \frac{EI_m}{4\omega}\cos(\varphi) - \frac{mEI_d}{6\omega} + \frac{mEI_m}{16\omega}\sin(\varphi) - \frac{EI_m}{4\omega}\cos(\omega t - \varphi) + \frac{mEI_d}{6\omega}(\cos\omega t) + \frac{mEI_m}{16\omega}\sin(2\omega t - \varphi)$$

$$W_L(t) = -W_{L0} - \frac{EI_m}{4\omega}\cos(\varphi) + \frac{mEI_d}{6\omega} + \frac{mEI_m}{16\omega}\sin(\varphi) + \frac{EI_m}{4\omega}\cos(\omega t - \varphi) - \frac{mEI_d}{6\omega}\cos\omega t + \frac{mEI_m}{16\omega}\sin(2\omega t - \varphi)$$

- We note that the fundamental component in the upper and lower arms are equal.
- However their sum cancel each other indicating that energy exchange takes place at fundamental frequency between upper and lower arms. It does not go out of the arms.

Phase energy balancing at steady state

Each phase energy variation can be written as

$$W(t) = W_U(t) + W_L(t)$$

$$W(t) = \frac{2mEI_m}{16\omega}\sin(\varphi) + \frac{2mEI_m}{16\omega}\sin(2\omega t - \varphi)$$ (Assuming $W_{U0} = W_{L0}$)

$$W(t) = W_0(t) + \Delta W(t)$$

- We also note that there is a constant term and a 2nd harmonic term in phase energy expression.
- The constant term indicates the energy stored in the capacitors in the phase.
- The 2nd harmonic component indicates the energy that is exchanged among the three phases.
- If we add the 2nd harmonic component of three phases, then the sum comes out be zero.

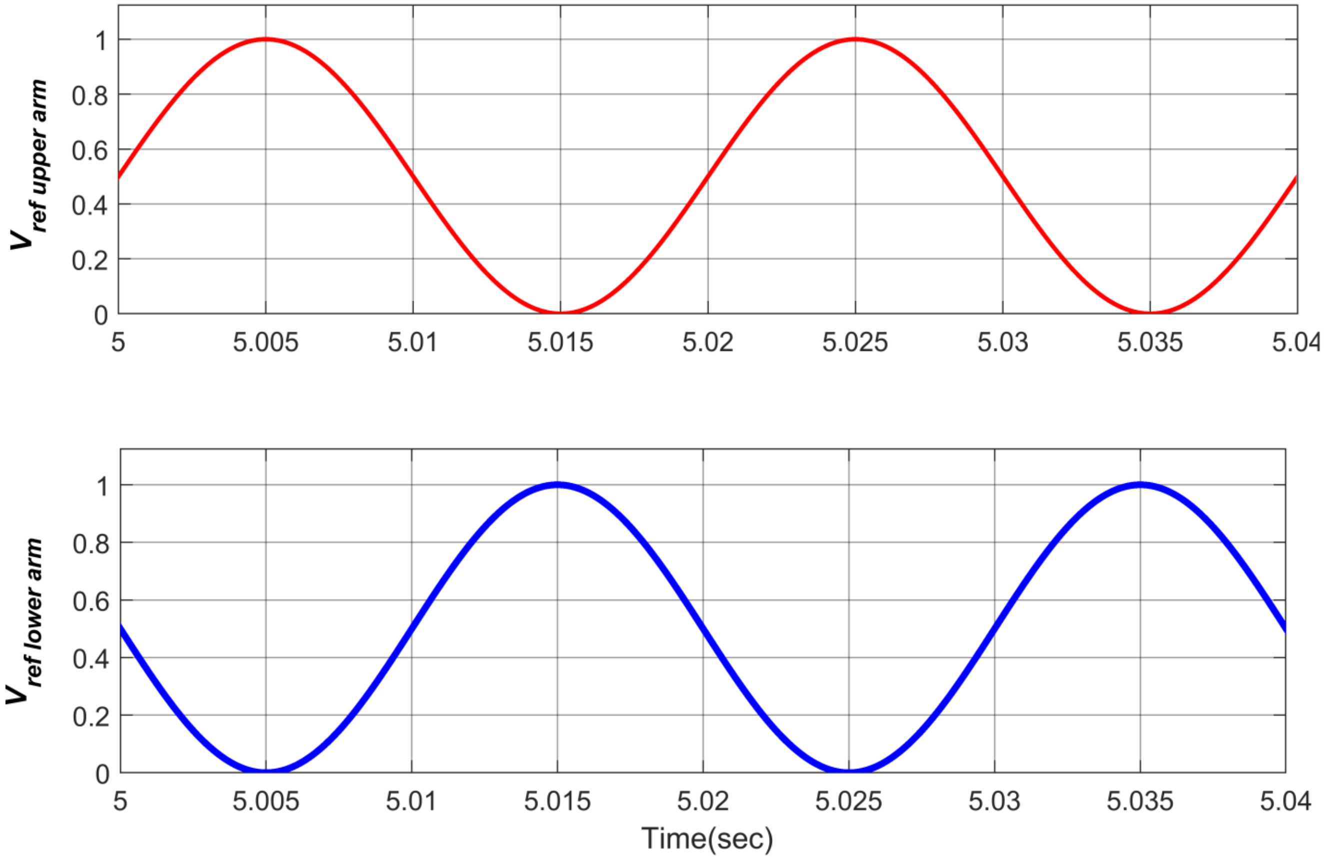
Energy Deviation

Summarizing:

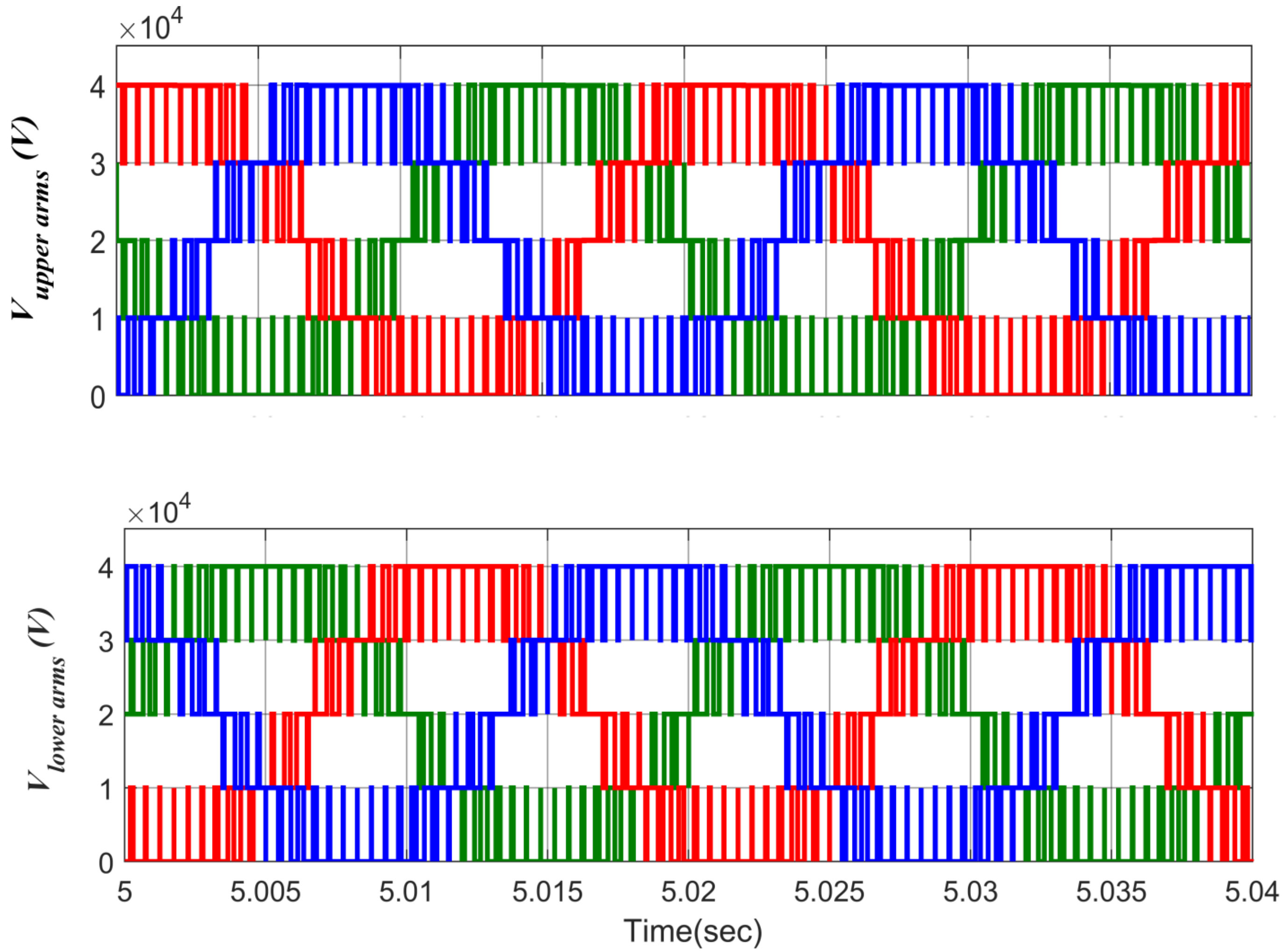
- The DC and AC power in each arm should cancel to ensure that capacitors are balanced.
- Each arm energy deviation consists of two components: one fundamental frequency component and other second harmonic component.
- The fundamental frequency component causes energy exchange between the upper and lower arm of the same leg.
- The second harmonic component causes energy exchange between phases, it does not flow into DC or AC side.

Simulation Results

Parameters	Values
Power Rating	6 MW
DC bus voltage	40KV
Number of cells	4
Arm inductance (Larm)	3mH
Cell capacitance (C)	12mF
Fundamental Frequency	50 Hz
Switching Frequency	1Khz
Load (R,L)	100Ω, 20mH

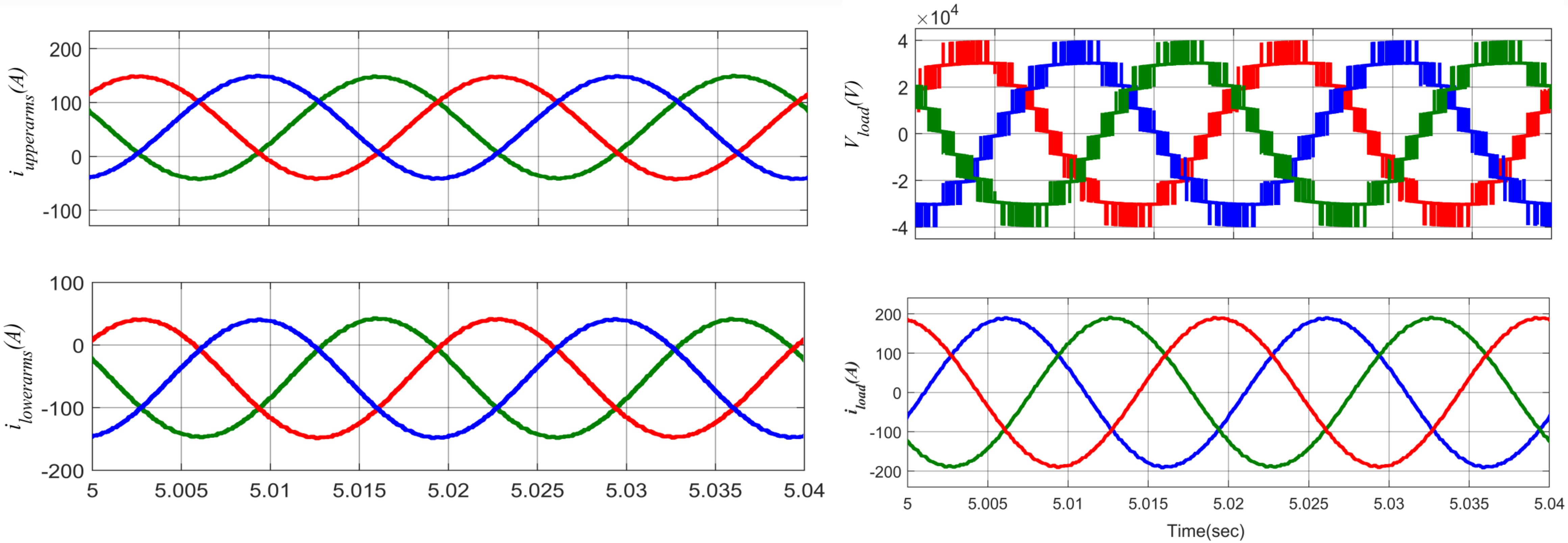


Waveforms of MMC



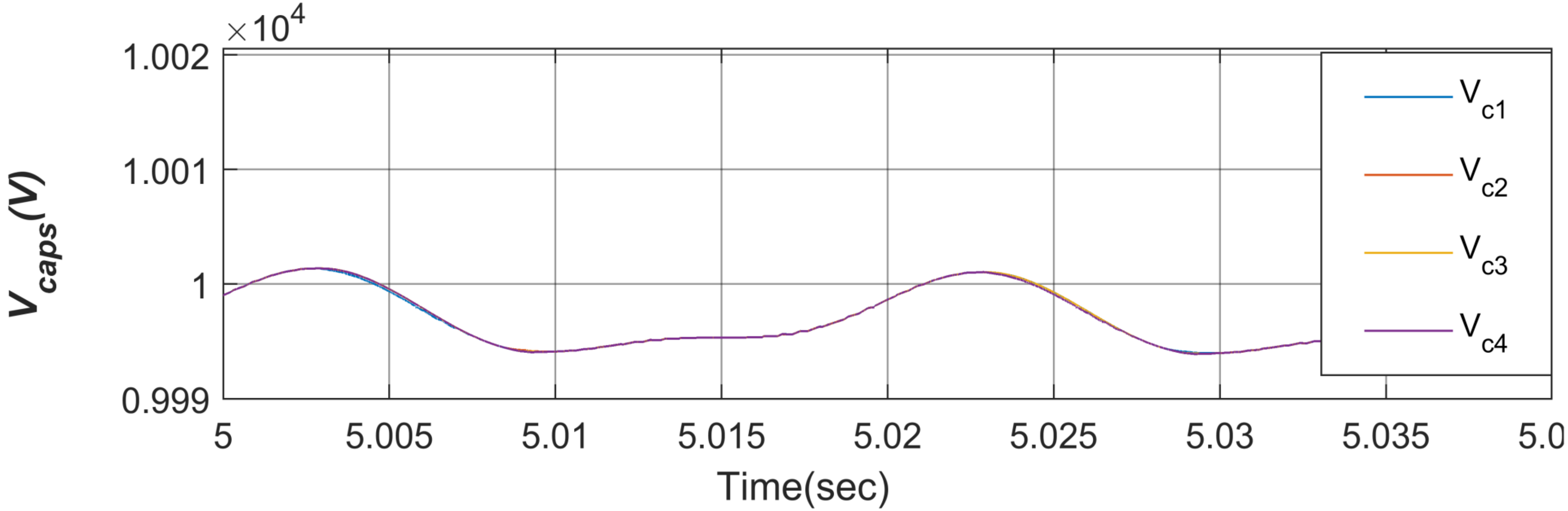
- Simulation is shown with 4 cells in each arm. Upper and lower arm voltages are identical. They have a DC and an AC component.

Waveforms of MMC



- Arm currents have a DC and an AC component.
- The line voltages and currents are perfectly balanced and have only AC component.

Waveforms of MMC



- Capacitor voltages are balanced.