Optimal current reference calculation for MMCs considering converter limitations

InnoDC 2020 Autumn Meeting(Cinergia)

ESR 5 - Daniel Westerman Spier

daniel.westerman@cinergia.coop

Advisors

Eduardo Prieto-Araujo (UPC)

eduardo.prieto-araujo@upc.edu

Miquel Teixidó (Cinergia)

teixido@cinergia.coop

Oriol Gomis-Bellmunt (UPC)

oriol.gomis@upc.edu

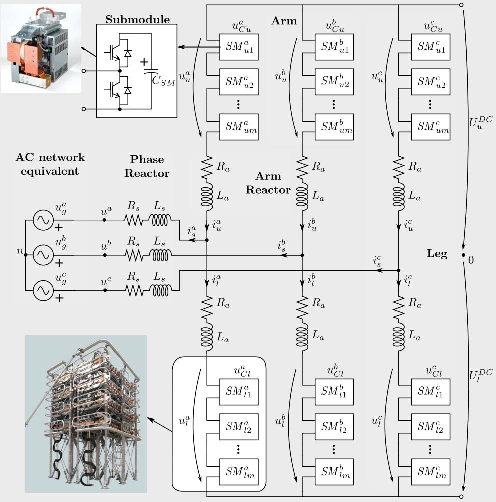
Marie Sklodowska-Curie funding European Union Horizon 2020 research & innovation. **This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement no. 765585. This presentation reflects only the author's view. The Research Executive Agency and European Commission are not responsible for any use that may be made of the information it contains.**

Oct. 2020

Outline of the presentation

Outline of the presentation

The Modular Multilevel Converter (MMC)



source: Siemens and [1].

VSC-MMC

- Active and reactive powers can be controlled independently
- "Black-start" capability
- Relatively lower losses (due to lower switching frequency)
- Higher output voltage quality
- More difficult to control (more degrees of freedom)

[1] D. Westerman Spier, E. Prieto-Araujo, J. Lopez-Mestre and O. Gomis-Bellmunt, "Optimal current reference calculation for MMCs considering converter limitations," in IEEE Transactions on Power Delivery, doi: 10.1109/TPWRD.2020.3020420.

Contributions

- Development of a natural *abc* reference frame steady-state model including all the MMC degrees of freedom
- Formulation of an optimization-based reference calculation problem to guarantee an optimal MMC operation under any network voltage conditions and grid operator requirements, considering the converter limitations.

Outline of the presentation

AC MMC circuit analysis

- Kirchhoff voltage law $\forall k \in (a, b, c)$

$$\underline{U}_{0n} = \underline{U}_g^k + \underline{Z}_s(\underline{I}_u^k - \underline{I}_l^k) + \underline{Z}_a \underline{I}_u^k + \underline{U}_u^k$$

$$\underline{U}_{0n} = \underline{U}_g^k + \underline{Z}_s(\underline{I}_u^k - \underline{I}_l^k) - \underline{Z}_a \underline{I}_l^k - \underline{U}_l^k$$

$$\underline{I}_s^k = \underline{I}_u^k - \underline{I}_l^k$$

$$\underline{I}_u^a + \underline{I}_u^b + \underline{I}_u^c = 0$$

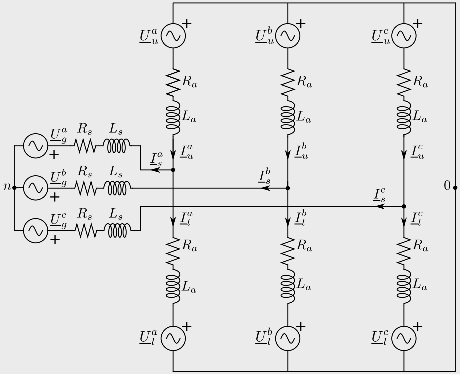
- Upper and lower arms power balancing $\forall k \in (a, b, c)$

$$P_u^k - P_l^k = 0$$

$$U_{u_r}^k I_{u_r}^k + U_{u_i}^k I_{u_i}^k = U_{l_r}^k I_{l_r}^k + U_{l_i}^k I_{l_i}^k$$

$$Q_u^k - Q_l^k = 0$$

$$U_{u_r}^k I_{u_i}^k - U_{u_i}^k I_{u_r}^k = U_{l_r}^k I_{l_i}^k - U_{l_i}^k I_{l_r}^k$$



DC MMC circuit and steady-state analysis

DC analysis

- Kirchhoff voltage law
  $\forall k \in (a, b, c)$

$$U_u^{DC} + U_l^{DC} = U_u^{kDC} + U_l^{kDC} + 2R_a I^{kDC}$$

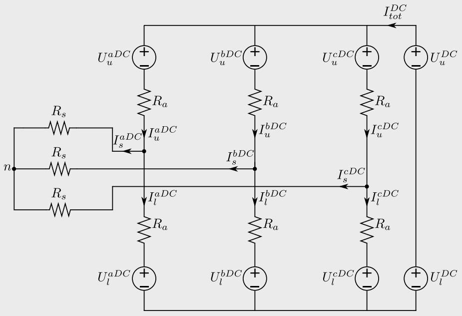
$$I_{tot}^{DC} = I^{aDC} + I^{bDC} + I^{cDC}$$

Steady-state analysis

- Assuming that the AC and DC active power exchanged in each arm are equal
  $\forall k \in (a, b, c)$

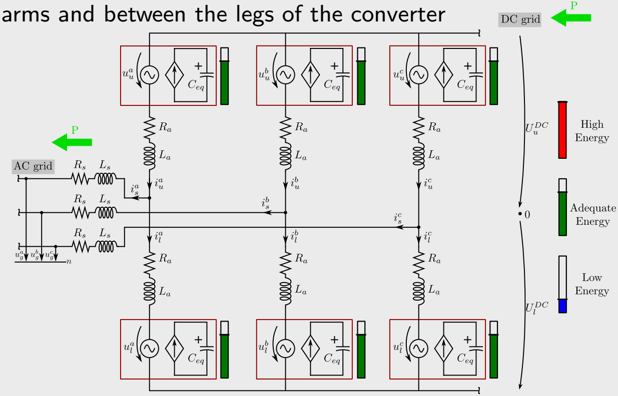
$$P_{u,l}^{kAC} = P_{u,l}^{kDC}$$

$$U_{u,l_r}^{k} I_{u,l_r}^{k} + U_{u,l_i}^{k} I_{u,l_i}^{k} = U_{u,l}^{kDC} I_{u,l}^{kDC}$$



Equivalent arm capacitor voltage fluctuation

- For the MMC, each arm can be represented as an equivalent capacitor, which its voltage will vary according to the power exchanged between the upper and lower arms and between the legs of the converter



Equivalent arm capacitor voltage fluctuation

Arm power and energy (steady-state)

- The active power stored in the upper and lower arms can be calculated as

$$p_{u,l}^{k}(t) = u_{u,l}^{k}(t) i_{u,l}^{k}(t) = \left(U_{u,l}^{kDC} + \hat{U}_{u,l}^{k} \cos(\omega t + \psi_{u,l}^{k}) \right) \cdot \left(I_{u,l}^{kDC} + \hat{I}_{u,l}^{k} \cos(\omega t + \delta_{u}^{k}) \right)$$

- Eliminating the zero frequency terms and integrating the result over time

$$E_{u,l}^{k}(t) = \frac{U_{u,l}^{kDC} \hat{I}_{u,l}^{k}}{\omega} \sin(\omega t + \delta_{u,l}^{k}) + \frac{I_{u,l}^{kDC} \hat{U}_{u,l}^{k}}{\omega} \sin(\omega t + \psi_{u,l}^{k}) + \frac{\hat{U}_{u,l}^{k} \hat{I}_{u,l}^{k}}{4\omega} \sin(2\omega t + \delta_{u,l}^{k} + \psi_{u,l}^{k})$$

- The equivalent arm capacitor's voltage fluctuation is directly related to its energy ripple
- The actual maximum energy stored in the equivalent arm capacitor, and consequently its maximum voltage ripple, cannot be found without interactive methods

Equivalent arm capacitor voltage fluctuation

Arm power and energy (steady-state) (cont.)

- However, it is possible to calculate the absolute maximum energy bound for the MMC's upper and lower arms $E^{kAC}_{u,l_{max}}$ as

$$E^{kAC}_{u,l_{max}} \approx \sqrt{\left[\frac{U^{kDC}_{u,l}\,\hat{I}^{k}_{u,l}}{\omega}\cos(\delta^{k}_{u,l}) + \frac{I^{kDC}_{u,l}\,\hat{U}^{k}_{u,l}}{\omega}\cos(\psi^{k}_{u,l})\right]^2 + \left[\frac{U^{kDC}_{u,l}\,\hat{I}^{k}_{u,l}}{\omega}\sin(\delta^{k}_{u,l}) + \frac{I^{kDC}_{u,l}\,\hat{U}^{k}_{u,l}}{\omega}\sin(\psi^{k}_{u,l})\right]^2} + \left|\frac{\hat{U}^{k}_{u,l}\hat{I}^{k}_{u,l}}{4\omega}\right|$$

- Considering steady-state conditions, the equivalent arms' capacitors are also storing DC energy. Thus, the maximum and minimum values for the upper and lower arms energy can be calculated as

$$E^{k}_{u,l_{max,min}} = \underbrace{\frac{C_{SM}}{2} N^{k}_{u,l_{arm}} U^{2}_{SM}}_{\text{DC part}} \pm \underbrace{E^{kAC}_{u,l_{max}}}_{\text{peak of the AC part}}$$

- Finally, the admissible voltage magnitudes of the equivalent arms' capacitors can be expressed as

$$U^{k}_{Cu,l_{max,min}} = \sqrt{\frac{2E^{k}_{u,l_{max,min}} N^{k}_{u,l_{arm}}}{C_{SM}}}$$

Outline of the presentation

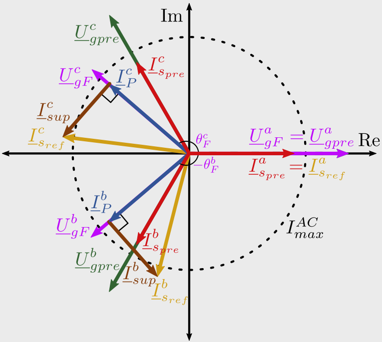
Grid support requirements

- During AC voltage sags, the HVDC system should be able to inject/absorb active and/or reactive current components to meet the grid code requirements
    1. $U_{min1} \leqslant U_g^k \leqslant U_{max1} \rightarrow \Delta I_r^k = 0$
    2. $U_{min2} \leqslant U_g^k < U_{min1} \rightarrow \Delta I_r^k = \frac{\Delta I_{rmax}(U_{min1} - U_g^k)}{U_{min1} - U_{min2}}$
    3. $U_g^k < U_{min2} \rightarrow \Delta I_r^k = \Delta I_{rmax}$
- Two candidate solutions to provide voltage support to the faulted phases are:
    - To consider only the positive sequence voltage component of the faulted three-phase system and based on its magnitude inject the required reactive current (Strategy I). However, this methodology is unable to provide full voltage support
    - To consider all the sequence voltage components and inject the required currents for each phase (Strategy II). The drawback is the possible imposition of zero sequence current components into the AC network

Grid support requirements

- As an example, for a type C fault, the voltages and current vectors are depicted
- As it can be observed, the profile of the resultant currents $I^k_{s_{ref}}$ present an asymmetric profile (with zero sequence current component) and are exceeding the design limitations of the converter
- To adequate each current according to the limitations and the grid code, the coefficients α^k and β^k will be employed and calculated by the optimization algorithm (shown next)

$$\begin{bmatrix} I^k_{s_{ref_r}} \\ I^k_{s_{ref_i}} \end{bmatrix} = \begin{bmatrix} \cos(\theta^k_F) & -\sin(\theta^k_F) \\ \sin(\theta^k_F) & \cos(\theta^k_F) \end{bmatrix} \cdot \begin{bmatrix} \alpha^k \cdot I^k_P \\ \beta^k \cdot I^k_Q \end{bmatrix}$$



Outline of the presentation

Optimal reference calculation

- The proposed optimization algorithm in order to provide adequate grid support during balanced and unbalanced voltage conditions while ensuring that all the converter's quantities are kept within the design limitations
- The optimization algorithm can be divided into objective function, linear and non-linear constraints and inequalities
- Objective function

$$\text{minimize W } = \lambda_1 \left(R_a \left(\sum_{k=a}^{c} {I_u^k}^2 + {I_l^k}^2 \right) + R_a \left(\sum_{k=a}^{c} {I_u^{kDC}}^2 + {I_l^{kDC}}^2 \right) \right) - \lambda_2 \left(\sum_{k=a}^{c} \alpha^k \right) - \lambda_3 \left(\sum_{k=a}^{c} \beta^k \right)$$

- Non-linear equalities
- Linear equalities
- Linear inequalities

Outline of the presentation

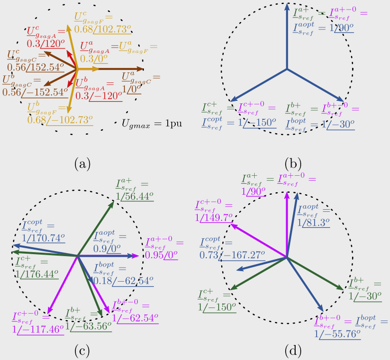
Optimal reference calculation

Table: System parameters

Parameter	Symbol	Value	Units
Rated power	S	526	MVA
Rated power factor	$\cos\phi$	0.95 (c)	-
AC-side voltage	$\underline{U}_{g\,RMS}$	184.75	kV
HVDC link voltage	U^{DC}	$\pm$320	kV
Phase reactor impedance	$\underline{Z}_s$	0.02+j 0.1	pu
Arm reactor impedance	$\underline{Z}_a$	0.01+j 0.08	pu
Converter modules per arm	$N^k_{u,l_{arm}}$	400	-
Average module voltage	U_{SM}	1.6	kV
Sub-module capacitance	C_{SM}	8	mF
Grid code voltage 1	U_{min1}	0.9	pu
Grid code voltage 2	U_{min2}	0.6	pu
Grid code voltage 3	U_{max1}	1.05	pu
Max reactive current	ΔI_{rmax}	1	pu
Optimal weighting factor 1	λ_1	10^{-9}	-
Optimal weighting factor 2	λ_2	1	-
Optimal weighting factor 3	λ_3	10^6	-
Maximum MMC arm current	I^{arm}_{max}	0.77	pu
Maximum AC grid current	I^{AC}_{max}	1	pu

Case A: Optimal reference calculation in AC voltage sags

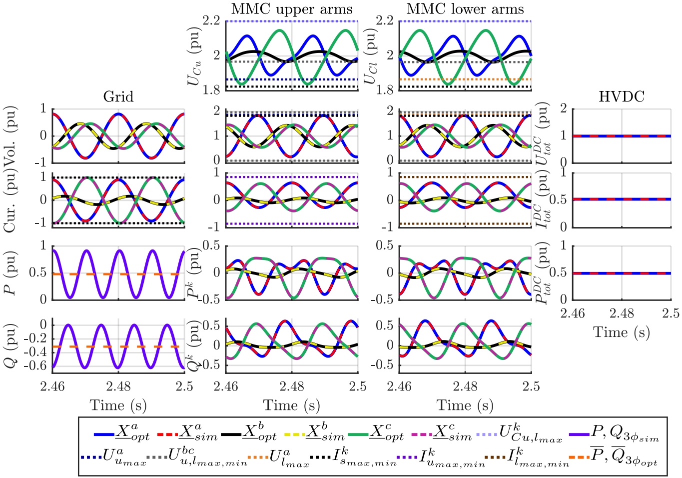
- Three different faults are analyzed in this case study: Type A, C and F [2]
- The phasorial representation of the voltages and the currents for Strategy I (only positive sequence component), Strategy II (all the three components) and the optimized strategy are shown



[2] M.H.J. Bollen, L.D. Zhang, "Different methods for classification of three-phase unbalanced voltage dips due to faults," in Electric Power Systems Research, Volume 66, Issue 1, 2003, Pages 59-69.

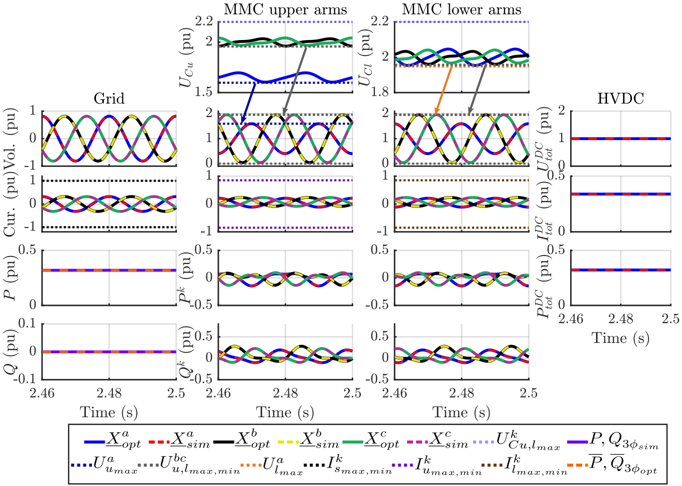
Case A: Optimal reference calculation in AC voltage sags

- Comparison between average model of the MMC and the optimization algorithm for fault type C



Case B: Saturation in the MMC arm voltages

- In this case study the number of available sub modules in the upper arm for phase a $\left(N^{a}_{u_{arm}}\right)$ is reduced from 400 to 330



Case B: Saturation in the MMC arm voltages

Observations

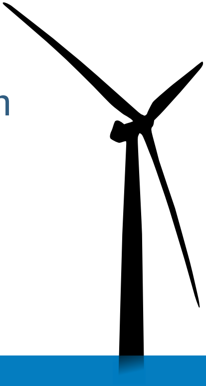
- The stored energy in phase *a* is importantly reduced impacting its DC and AC voltage levels
- To avoid over-modulation, the applied voltages in the arm of phase *a* are decreased (lower arm is also affect to comply with the optimization constraints)
- The applied voltages for phases *b* and *c* are increased, as the optimization algorithm targets to meet the pre-contingency active and reactive power set-points

Outline of the presentation

Conclusions

- An optimization-based reference calculation method for MMCs operating under normal and constraint scenarios has been presented
- The optimization algorithm has been formulated as an multi-objective problem, allowing to prioritize between active power, reactive power or converter arm losses reduction
- Different case studies have been presented and the results indicated that the proposed approach can be potentially used to obtain the MMC references in both normal and fault conditions

Thank you for your attention



Marie Sklodowska-Curie funding
European Union Horizon 2020 research
& innovation. **This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement no. 765585. This presentation reflects only the author's view. The Research Executive Agency and European Commission are not responsible for any use that may be made of the information it contains.**