Modular Multilevel Converter Modelling for Harmonic Stability Studies

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2021-05-25, Mats Larsson, Hitachi ABB Power Grids Research

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Agenda

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- Classical average modelling in stationary frame
- The Generalized Park's Transform
- MMC model in generalized dq system
- Accuracy

MMC Modelling – Classical Average Model in abc-frame

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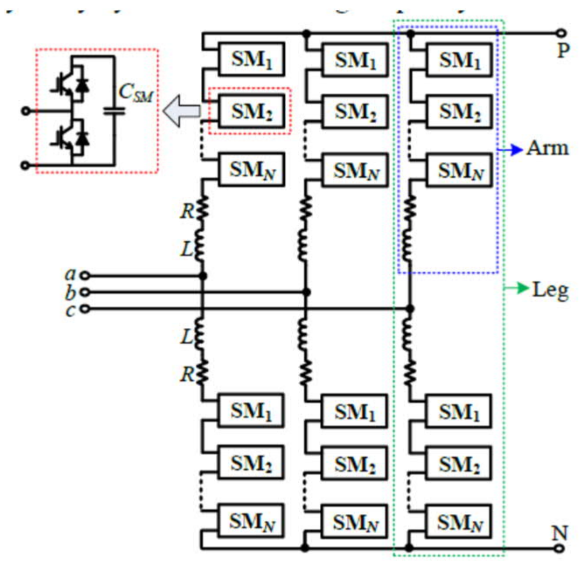
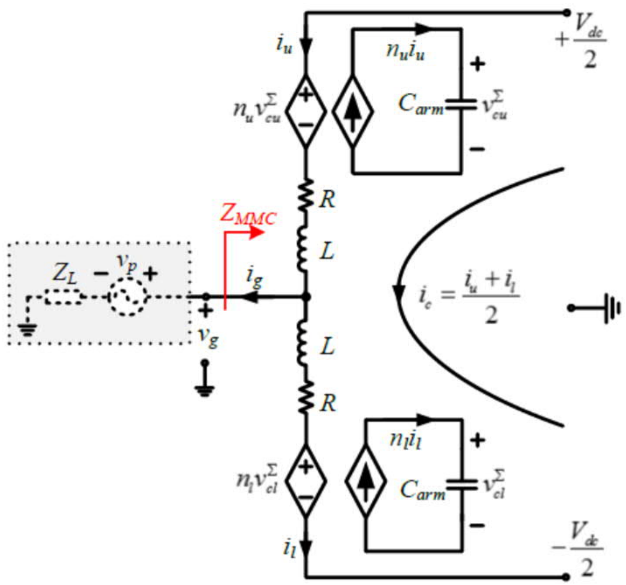
Physical Layout



Single Arm Equivalent



Mathematical Model

$$
\begin{aligned}
\mathbf{v_g} + L_{arm}\frac{d\mathbf{i_u}}{dt} + R_{arm}\mathbf{i_u} + \mathbf{diag}(\mathbf{n_u})\mathbf{v_{cu}} &= \mathbf{I_3}\frac{v_{dc}}{2} \\
\mathbf{v_g} - L_{arm}\frac{d\mathbf{i_l}}{dt} - R_{arm}\mathbf{i_l} - \mathbf{diag}(\mathbf{n_l})\mathbf{v_{cl}} &= -\mathbf{I_3}\frac{v_{dc}}{2} \\
C_{arm}\frac{d\mathbf{v_{cu}}}{dt} &= \mathbf{diag}(\mathbf{n_u})\mathbf{i_u} \\
C_{arm}\frac{d\mathbf{v_{cl}}}{dt} &= \mathbf{diag}(\mathbf{n_l})\mathbf{i_l} \\
\mathbf{i_c} &= \frac{\mathbf{i_u} + \mathbf{i_l}}{2} \\
\mathbf{i_g} &= \mathbf{i_u} - \mathbf{i_l}
\end{aligned}
$$

Internal dynamics

$$
\begin{aligned}
v_{dc}^{d} &= v_p - v_n \\
v_{dc}^{m} &= v_p + v_n \\
i_p &= \sum \mathbf{i_u} = \sum\left(\frac{2\mathbf{i_c} + \mathbf{i_g}}{2}\right) \\
-i_n &= \sum \mathbf{i_l} = \sum\left(\frac{2\mathbf{i_c} - \mathbf{i_g}}{2}\right) \\
-\mathbf{P}(\theta)\mathbf{i_g} &= \mathbf{i_g^{dqs}} \\
\mathbf{P}(\theta)\mathbf{v_g} &= \mathbf{v_g^{dqs}}
\end{aligned}
$$

Grid interface

Frequency mixing gives rise to harmonics in circulating current and equivalent capacitor voltages
Single dq-frame model previously used no longer appropriate

The Generalized dq Transform

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Definitions

The generalized dq model is based on a generalized Park transform defined by

$$\mathbf{T_n}(\theta) = \begin{pmatrix} 1 & \cos(\theta) & \sin(\theta) & \cdots & \cos(n\theta) & \sin(n\theta) \\ 1 & \cos(\theta - \frac{2\pi}{3}) & \sin(\theta - \frac{2\pi}{3}) & \cdots & \cos(n\theta - \frac{2n\pi}{3}) & \sin(n\theta - \frac{2n\pi}{3}) \\ 1 & \cos(\theta - \frac{4\pi}{3}) & \sin(\theta - \frac{4\pi}{3}) & \cdots & \cos(n\theta - \frac{4n\pi}{3}) & \sin(n\theta - \frac{4n\pi}{3}) \end{pmatrix}$$

$$\mathbf{s^{abc}}(t) = \mathbf{T_n}(\theta)\mathbf{s^{dq}}(t)$$

where

$$\mathbf{s^{abc}}(t) = \begin{pmatrix} s_a(t) \\ s_b(t) \\ s_C(t) \end{pmatrix}$$

and

$$\mathbf{s^{dq}}(t) = \begin{pmatrix} s_0(t) \\ s_{d1}(t) \\ s_{q1}(t) \\ \vdots \\ s_{dn}(t) \\ s_{qn}(t) \end{pmatrix}$$

Model Transformation

$$\frac{d\mathbf{T_n}}{dt} = \mathbf{T_n}\mathbf{K}$$

where

$$\mathbf{K} = \begin{pmatrix} 0 & 0 & 0 & \cdots & 0 & 0 \\ 0 & 0 & \omega_s & & 0 & 0 \\ 0 & -\omega_s & 0 & & 0 & 0 \\ \vdots & & & \ddots & & \\ 0 & 0 & 0 & & 0 & n\omega_s \\ 0 & 0 & 0 & & -n\omega_s & 0 \end{pmatrix}$$

$$\frac{d}{dt}\mathbf{s^{abc}}(\mathbf{t}) = \frac{d}{dt}(\mathbf{T_n}(t)\mathbf{s^{dq}}(t)) = \mathbf{T_n}(t)(\mathbf{K}\mathbf{s^{dq}}(t) + \frac{d}{dt}\mathbf{s^{dq}}(t)))$$

Source: M. Larsson: WindStab User's Guide – Harmonic Stability Analysis Toolbox for Offshore wind Farms, Tech. Report 2019/CTR/TR22, 2019.

MMC Model Transformation

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Stationary Frame

$$\begin{aligned}
\mathbf{v_g} + L_{arm}\frac{d\mathbf{i_u}}{dt} + R_{arm}\mathbf{i_u} + \mathbf{diag}(\mathbf{n_u})\mathbf{v_{cu}} &= \mathbf{I_3}\frac{v_{dc}}{2} \\
\mathbf{v_g} - L_{arm}\frac{d\mathbf{i_l}}{dt} - R_{arm}\mathbf{i_l} - \mathbf{diag}(\mathbf{n_l})\mathbf{v_{cl}} &= -\mathbf{I_3}\frac{v_{dc}}{2} \\
C_{arm}\frac{d\mathbf{v_{cu}}}{dt} &= \mathbf{diag}(\mathbf{n_u})\mathbf{i_u} \\
C_{arm}\frac{d\mathbf{v_{cl}}}{dt} &= \mathbf{diag}(\mathbf{n_l})\mathbf{i_l} \\
\mathbf{i_c} &= \frac{\mathbf{i_u} + \mathbf{i_l}}{2} \\
\mathbf{i_g} &= \mathbf{i_u} - \mathbf{i_l}
\end{aligned}$$

Generalized dq frame

$$\begin{aligned}
\mathbf{v_g^{dq}} + L_{arm}(\mathbf{K}\mathbf{i_u^{dq}} + \frac{d\mathbf{i_u^{dq}}}{dt}) + R\mathbf{i_u^{dq}} + \mathbf{f}(\mathbf{n_u^{dq}}, \mathbf{v_{cu}^{dq}}) &= \mathbf{I_n^{dq}}\frac{v_{dc}}{2} \\
\mathbf{v_g^{dq}} - L_{arm}(\mathbf{K}\mathbf{i_l^{dq}} + \frac{d\mathbf{i_l^{dq}}}{dt}) - R\mathbf{i_l^{dq}} - \mathbf{f}(\mathbf{n_l^{dq}}, \mathbf{v_{cl}^{dq}}) &= -\mathbf{I_n^{dq}}\frac{v_{dc}}{2} \\
C_{arm}(\mathbf{K}\mathbf{v_{cu}^{dq}} + \frac{d\mathbf{v_{cu}^{dq}}}{dt}) &= \mathbf{f}(\mathbf{n_u^{dq}}, \mathbf{i_u^{dq}}) \\
C_{arm}(\mathbf{K}\mathbf{v_{cl}^{dq}} + \frac{d\mathbf{v_{cl}^{dq}}}{dt}) &= \mathbf{f}(\mathbf{n_l^{dq}}, \mathbf{i_l^{dq}}) \\
\mathbf{i_c^{dq}} &= \frac{\mathbf{i_u^{dq}} + \mathbf{i_l^{dq}}}{2} \\
\mathbf{i_g^{dq}} &= (\mathbf{i_u^{dq}} - \mathbf{i_l^{dq}})
\end{aligned}$$

Multiplication in dq-frame cuts off harmonics of order larger than n
All dq quantities constant in steady state

Model Accuracy

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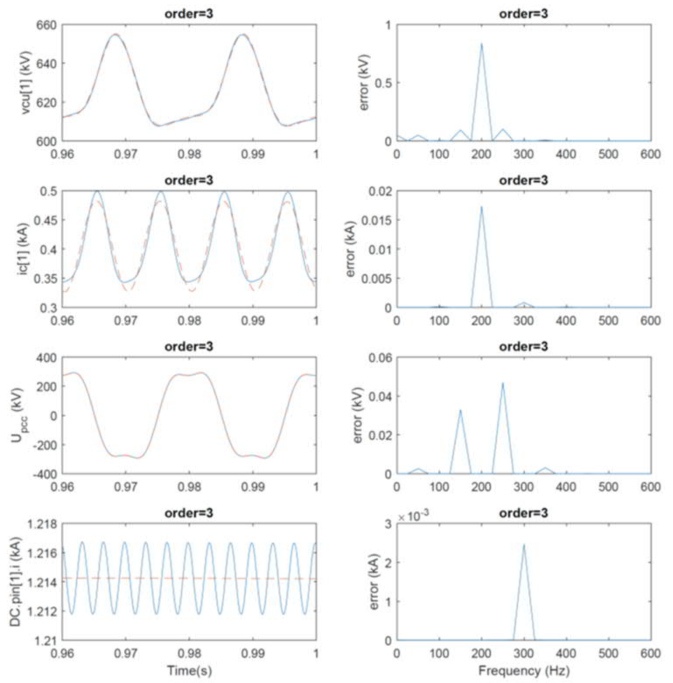
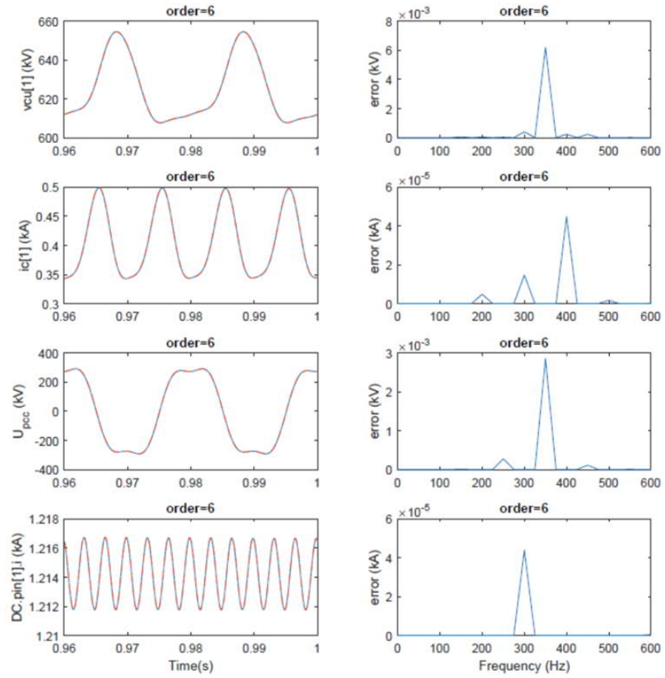
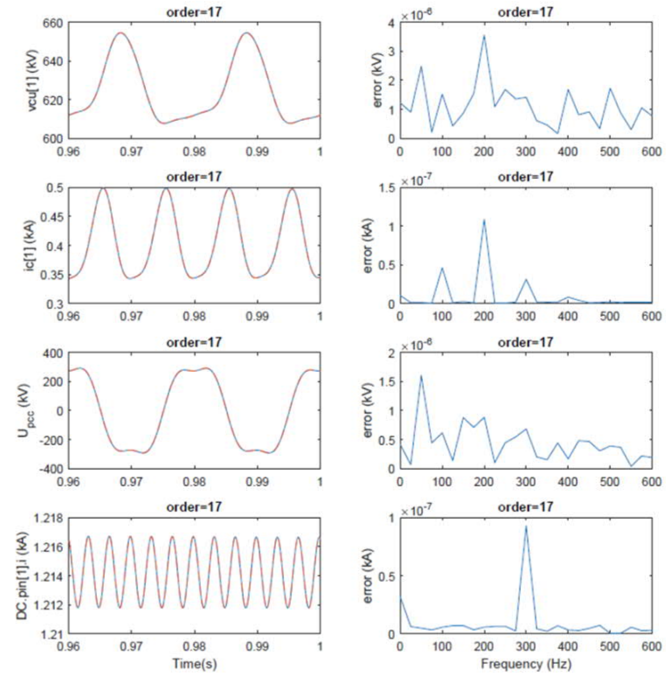
Approximation order 3



Approximation order 6



Approximation order 17



Modal Analysis

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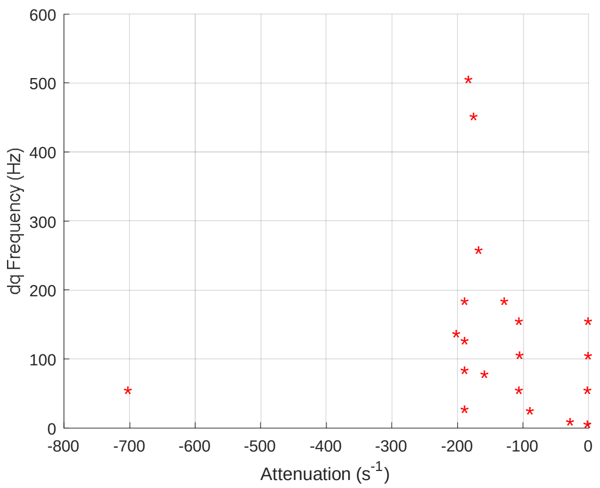
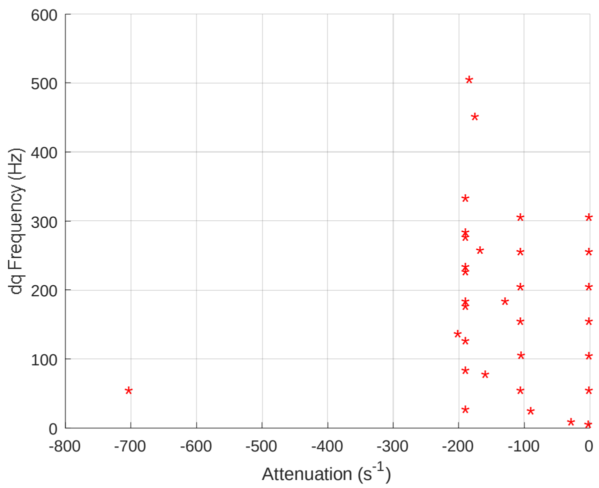
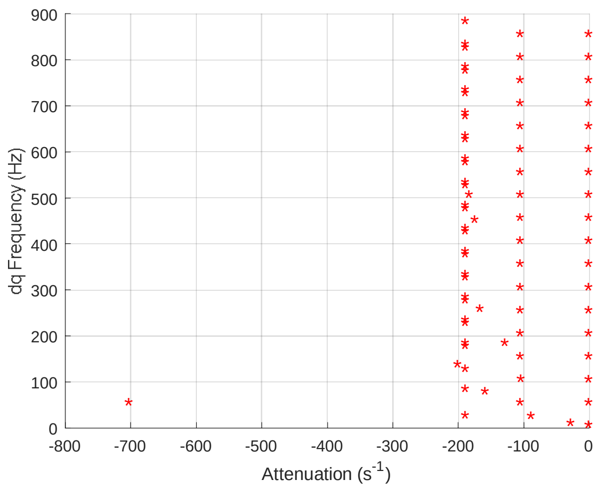
Approximation order 3



Approximation order 6



Approximation order 17



Model order and frequency range increases significantly with approximation order

Conclusion

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A Generalized dq frame MMC model has been derived

The generalized dq frame is compatible with modal analysis frameworks

For model accuracy on the AC side side, approximation order 3 is often enough

Higher order approximations enable accurate modelling of the converter also from the DC side

Model complexity increases quickly with approximation order