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Nonlinear control of power converters for HVDC applications

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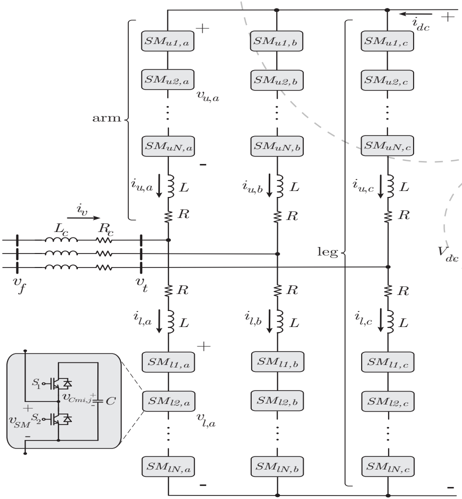
Introduction of MMC

- a large number of voltage cells connected in series
- by inserting desired number of cells, 'any' voltage level can be produced
- less harmonics
- no need for AC filters
- redundancy is higher
- lower switching frequency and semiconductor loss
- reduced manufacturing cost due to similarity of cells



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MMC in HVDC system

— Besides other applications, MMC has become the most promising converter topology for HVDC stations

— MMC-HVDC projects:

Project	Trans Bay	Nanhui	Southwest	Dalian	France	Zhoushan
DC Voltage	± 200 kV	±30 kV	±300 kV	±320 kV	±320 kV	±200 kV
Power	400 MW	20 MW	1440 MW	1000 MW	1000 MW	400 MW
Length	80 km	8.4 km	250 km	43 km	65 km	134 km
operated by	Siemens	C-EPRI	Alstom	C-EPRI	Siemens	C-EPRI
Year	2010	2011	2015	2013	2015	2015
Location	San Francisco	Shanghai	Sweden	China	France	China
type	underwater	offshore windfarm	city connection	under ground	under ground	multi terminal

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MMC in HVDC system

— Tennet off-shore wind farm complex

— in North Sea near to the German coast :

Wind Park	Power (MW)	Voltage (kV)	Cable length (km)	Commissioned by	State
Helwin 1	576	+/- 250	130	Siemens	Started operation in 2013
Dolwin 1	800	+/- 640	165	ABB	Tested during 2013
Borwin 2	800	+/- 300	200	Siemens	Tested during 2013
Sylwin 1	864	+/- 320	205	Siemens	Started operation in 2014
Dolwin 2	900	+/- 640	135	ABB	Started operation in 2015
Dolwin 3	900	+/- 320	162	Alstom	Started operation in 2017

MMC Control difficulties

— the control of the MMC converter is not as easy as other types of converters:

- Control of power transfer
- Balancing capacitor voltages
- Reducing circulating current
- Decrease switching frequency and loss
- Decrease communication load

— The control problem becomes a Multi-Input Multi-Output problem and classical PI controllers does not satisfy the objectives

— Advance control methods is introduced in recent years for MMC control:

- Repetitive control
- Model Predictive Control
- Proportional Resonant controller
- Optimization with Lagrange multipliers
- ...

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The idea

— The calculation load of the MPC methods is high for real time control of MMCs.

— **The idea:** a pre-defined cost function is calculated one step ahead *for all possible control actions* and the best control action, which minimizes the cost function, is selected.

— ac-side current, circulating current, and summation of capacitor voltages are controlled in each arm

— Cost function:

$$J_j = c_1 \left| i_{v,j,\mathrm{ref}} - i_{v,j} \right| + c_2 \left| i_{\mathrm{cir,ref}} - i_{\mathrm{cir},j} \right| + c_3 \left| v_{dc,\mathrm{ref}} - v^{\Sigma}_{u,j} \right| + c_4 \left| v_{dc,\mathrm{ref}} - v^{\Sigma}_{l,j} \right| .$$

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The ’traditional’ FCS-MPC for MMCs

1. All possible control actions are evaluated, and the optimal action selected
2. Gives the switch settings directly
3. Complexity grows exponentially with number of SMs and with prediction horizon
4. Has been shown to work satisfactorily for low number of SMs, prohibitively complex for the number of SMs used in industrial applications

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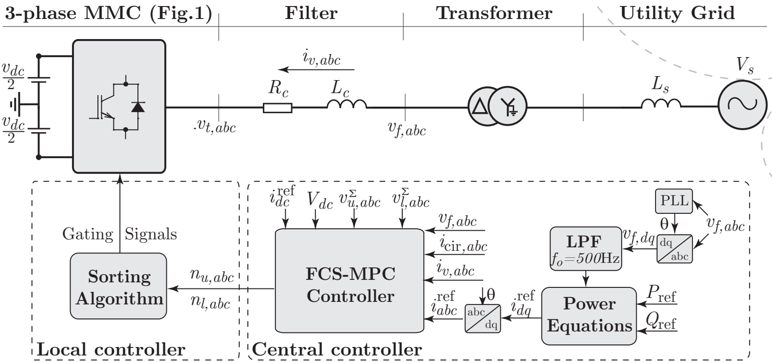
Our approach to FCS-MPC for MMCs

1. All SMs are treated as equal
2. Evaluate the cost function only to find the optimal *number* of inserted SM's (the optimal insertion index)
3. Individual switch settings determined by a sorting algorithm and the insertion index. The sorting algorithm is designed to balance capacitor voltages.
4. Complexity linear in the number of SM's, still exponential in horizon length

Control block diagram

— The following systems is simulated in PLECS/MATLAB.



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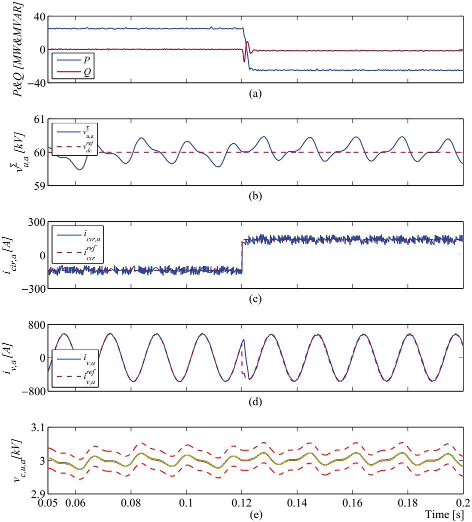
Simulation result

— Power reversal command, switching frequency=3.5 kHz



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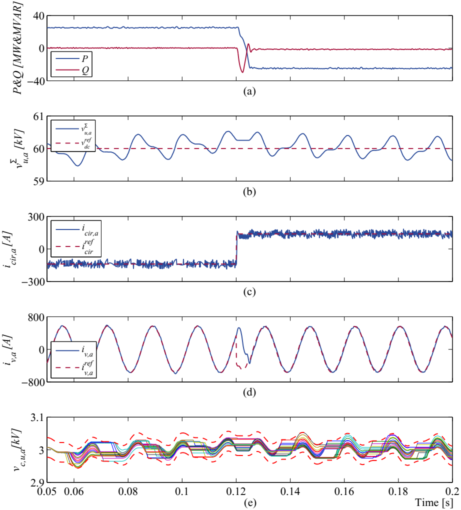
Simulation result

— By reducing switching frequency to 200 Hz



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Variations of the FCS-MPC

— Adding a constraint on the maximum change in insertion number for each timestep

— Works acceptably in simulations, but causes slower response to quick disturbances

— Reduces the exponential growth in complexity with horizon length

Shortcomings of FCS-MPC

— The computational complexity - in particular for the high number of SMs used in industrial applications

— No stability guarantee (common for finite horizon optimal control). Stability assessed by simulation

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The goal

— The MMC is modeled as a discrete-time bilinear system

$$x_{k+1} = Ax_k + \sum_{i=1}^{m}(B_i x_k + b_i)u_{i,k} = Ax_k + (B_x + B)u_k$$

— the nonlinearity consists of products between the states and input

— To stabilize the system, the Lyapunov inequality

$$V(x_k) - V(x_{k+1}) = x_k^T P x_k - x_{k+1}^T P x_{k+1} > 0$$

should be fulfilled.

— The SOS method designs the controller, by YALMIP package (in MATLAB) in the form of ratio of two polynomials as:

$$u_i(x) = \frac{c_i(x_k)}{c_0(x_k)}$$

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Controller design by SOS method in YALMIP

Theorem

Region of convergence: Given a quadratic function $V(x) = x^T Px$, polynomials $c_i(x), i \in [1,\ldots,m]$, and SOS polynomials $\acute{c}_0(x)$ and $s_1(x,z)$, a bilinear discrete time system in closed loop with the control law

$$u_i(x) = \frac{C(x)x}{(\acute{c}_0(x)+1)}$$

is stable $\forall x | x^T Px < \gamma$, provided

$$\begin{bmatrix} x \\ z \end{bmatrix}^T M(x) \begin{bmatrix} x \\ z \end{bmatrix} - s_1(x,z)(\gamma - x^T Px) > 0$$

where

$$M(x) = \begin{bmatrix} (\acute{c}_0(x)+1)P & ((\acute{c}_0(x)+1)A + (B_x+B)C(x))^T P \\ P((\acute{c}_0(x)+1)A + (B_x+B)C(x)) & (\acute{c}_0(x)+1)P \end{bmatrix} > 0$$

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List of variables

— states:
- $\mathbf{i}_{v,dq}$ ac-side currents in *dq* reference frame
- $\mathbf{i}_{cir,dq}$ circulating currents in *dq* reference frame
- i_{d0} dc component of the circulating current
- W the total stored energy in the converter
- ΔW energy difference between the upper and lower arms

— inputs
- $\mathbf{V}_{u,dq}$ upper arm voltage in the *dq* reference frame
- $\mathbf{V}_{l,dq}$ lower arm voltage in the *dq* reference frame
- V_{d0} the dc component of arm voltages

— Other parameters
- ω rotating frequency of source voltage
- $\mathbf{v}_{f,dq}$ the ac-side voltage of the converter

MMC model in the dq frame

— for the ac side current in *dq* reference frame:

$$\frac{d\mathbf{i}_{v,dq}}{dt} = \begin{bmatrix} -\frac{R+2R_c}{L+2L_c} & \omega \\ -\omega & -\frac{R+2R_c}{L+2L_c} \end{bmatrix} \mathbf{i}_{v,dq} + \frac{\mathbf{v}_{u,dq} - \mathbf{v}_{l,dq}}{L+2L_c} + \frac{2\mathbf{v}_{f,dq}}{L+2L_c}.$$

— Circulating current: $\frac{d\mathbf{i}_{\text{cir},dq}}{dt} = \begin{bmatrix} -\frac{R}{L} & \omega \\ -\omega & -\frac{R}{L} \end{bmatrix} \mathbf{i}_{\text{cir},dq} - \frac{1}{2L}(\mathbf{v}_{u,dq} + \mathbf{v}_{l,dq}),$

— dc component of circulating current: $\frac{di_{d0}}{dt} = -\frac{R}{L} i_{d0} - \frac{1}{2L} V_{d0} + \frac{1}{2L} V_{dc}$

— the stored energy dynamics:

$$\frac{dW}{dt} = \frac{dW_u}{dt} + \frac{dW_l}{dt} = -\frac{3}{4} v_{u,d} i_{v,d} + \frac{3}{2} v_{u,d} i_{\text{cir},d} - \frac{3}{4} v_{u,q} i_{v,q} + \frac{3}{2} v_{u,q} i_{\text{cir},q} + \frac{3}{4} v_{l,d} i_{v,d} + \frac{3}{2} v_{l,d} i_{\text{cir},d} + \frac{3}{4} v_{l,q} i_{v,q} + \frac{3}{2} v_{l,q} i_{\text{cir},q} + 3 V_{d0} i_{cir,0},$$

$$\frac{d\Delta W}{dt} = \frac{dW_u}{dt} - \frac{dW_l}{dt} = -\frac{3}{4} v_{u,d} i_{v,d} + \frac{3}{2} v_{u,d} i_{\text{cir},d} - \frac{3}{4} v_{u,q} i_{v,q} + \frac{3}{2} v_{u,q} i_{\text{cir},q} - \frac{3}{4} v_{l,d} i_{v,d} - \frac{3}{2} v_{l,d} i_{\text{cir},d} - \frac{3}{4} v_{l,q} i_{v,q} - \frac{3}{2} v_{l,q} i_{\text{cir},q}.$$

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MMC model in the dq frame

the bilinear model of MMC

$$
\dot{\mathbf{x}}(t) = \underbrace{\begin{bmatrix} -\frac{R+2R_c}{L+2L_c} & w & 0 & 0 & 0 & 0 & 0 \\ -w & -\frac{R+2R_c}{L+2L_c} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -\frac{R}{L} & w & 0 & 0 & 0 \\ 0 & 0 & -w & -\frac{R}{L} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -\frac{R}{L} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}}_{A_c} \mathbf{x}(t) + \underbrace{\begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ -\frac{3}{4} & 0 & \frac{3}{2} & 0 & 0 & 0 & 0 \\ -\frac{3}{4} & 0 & \frac{3}{2} & 0 & 0 & 0 & 0 \end{bmatrix}}_{B_{1c}} \mathbf{x}(t)u_1
$$

$$
+ \underbrace{\begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -\frac{3}{4} & 0 & \frac{3}{2} & 0 & 0 & 0 \\ 0 & -\frac{3}{4} & 0 & \frac{3}{2} & 0 & 0 & 0 \end{bmatrix}}_{B_{2c}} \mathbf{x}(t)u_2 + \underbrace{\begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ \frac{3}{4} & 0 & \frac{3}{2} & 0 & 0 & 0 & 0 \\ -\frac{3}{4} & 0 & -\frac{3}{2} & 0 & 0 & 0 & 0 \end{bmatrix}}_{B_{3c}} \mathbf{x}(t)u_3 + \underbrace{\begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & \frac{3}{4} & 0 & \frac{3}{2} & 0 & 0 \\ 0 & -\frac{3}{4} & 0 & -\frac{3}{2} & 0 & 0 \end{bmatrix}}_{B_{4c}}
$$

$$
+ \underbrace{\begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 3 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}}_{B_{5c}} \mathbf{x}(t)u_5 + \underbrace{\begin{bmatrix} \frac{1}{L+2L_c} \\ 0 \\ -\frac{1}{2L} \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}}_{b_{1c}} u_1 + \underbrace{\begin{bmatrix} 0 \\ \frac{1}{L+2L_c} \\ 0 \\ -\frac{1}{2L} \\ 0 \\ 0 \\ 0 \end{bmatrix}}_{b_{2c}} u_2 + \underbrace{\begin{bmatrix} -\frac{1}{L+2L_c} \\ 0 \\ -\frac{1}{2L} \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}}_{b_{3c}} u_3 + \underbrace{\begin{bmatrix} 0 \\ -\frac{1}{L+2L_c} \\ 0 \\ -\frac{1}{2L} \\ 0 \\ 0 \\ 0 \end{bmatrix}}_{b_{4c}} u_4 + \underbrace{\begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ -\frac{1}{2L} \\ 0 \\ 0 \end{bmatrix}}_{b_{4c}} u_5 + \underbrace{\begin{bmatrix} \frac{2v_{f,d}}{L+2L_c} \\ \frac{2v_{f,q}}{L+2L_c} \\ 0 \\ 0 \\ \frac{V_{dc}}{2L} \\ 0 \\ 0 \end{bmatrix}}_{d_c}
$$

Control block diagram

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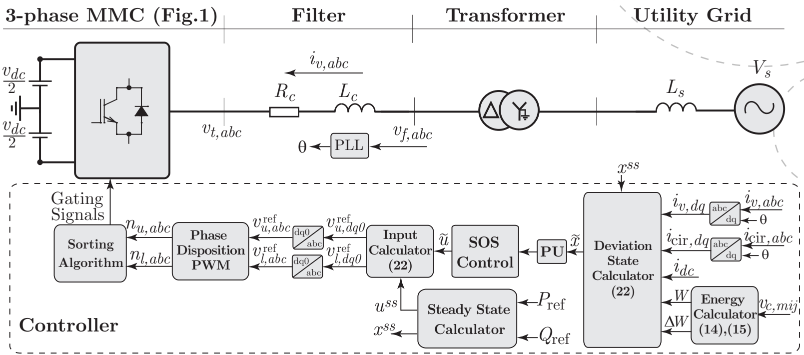

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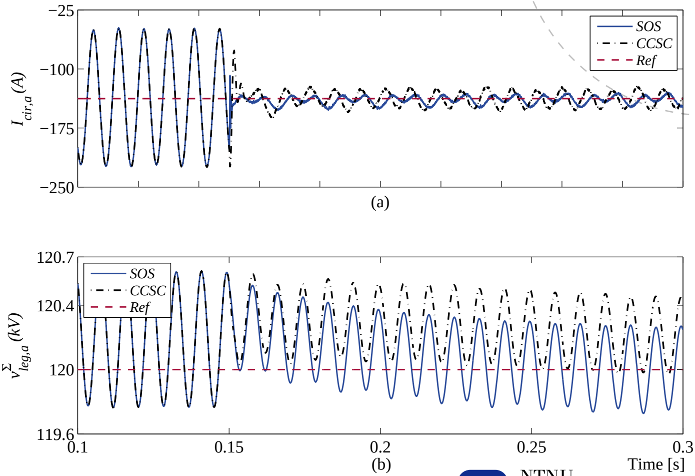
Activation of controller

— Activation of controller at $t = 0.15$ s



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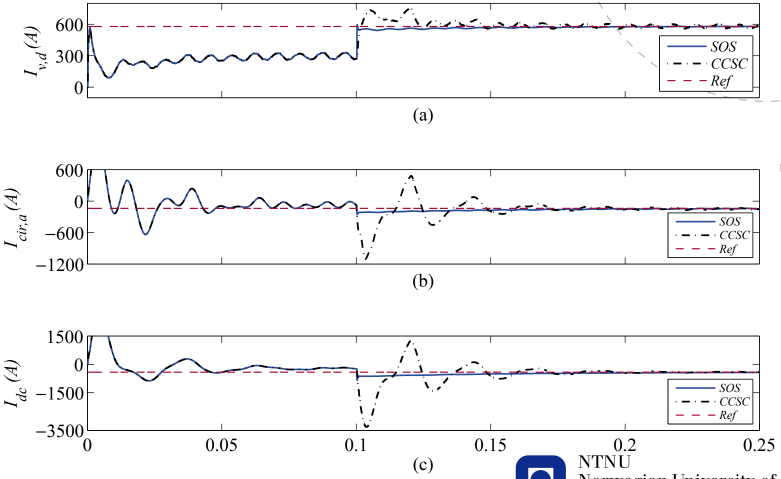
Convergence to the operating point

— Before activation of the controller, the states are far from their references.



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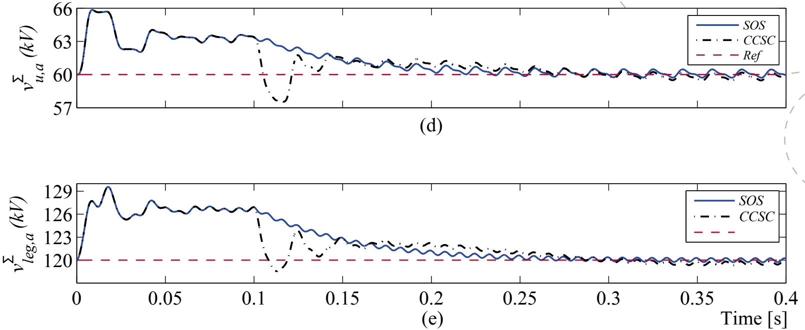

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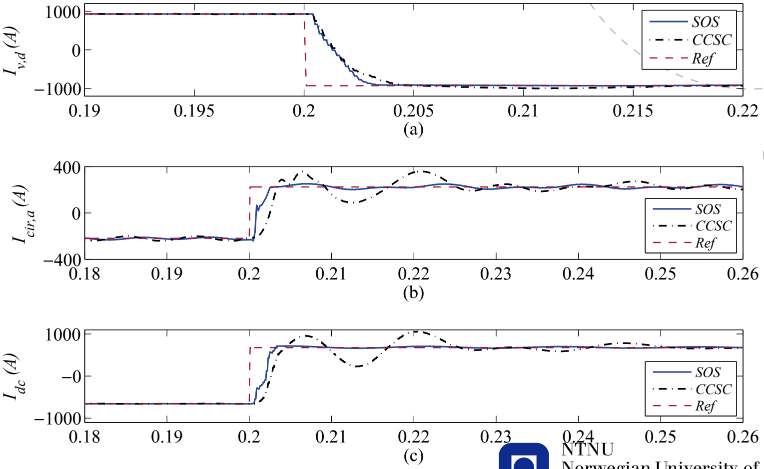
Real power flow reversal command

— Initially, the MMC system is in a steady-state condition, transferring $P = 40$ MW to the ac grid. At $t = 0.2$ s, the real power flow is reversed to $P = -40$ MW.



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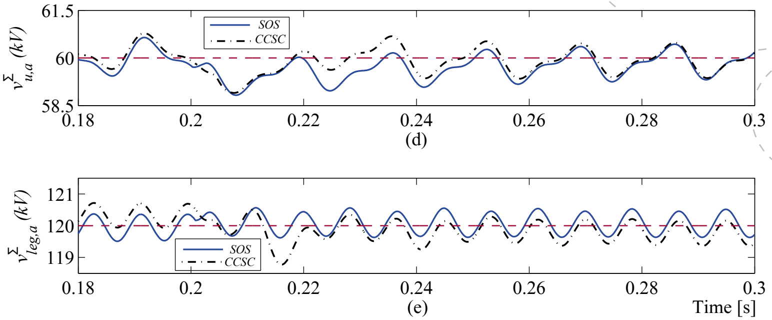

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Related work

— Application to buck-boost converters. Also a bilinear system for the averaged model with the duty cycle as input.

— Introducing integral action in the SOS design.

— Studying operating point changes. For non-linear systems, stability is not (necessarily) independent of the operating point.

— Studying robustness to parameter changes in the system

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Ongoing and future work

- Application to MMC controllers in *abc* frame
- Handling of sinusoidal references
- Experimental verification

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Conclusion

— Modular Multilevel Converters have several advantages for AC/DC conversion

— These promising features made them the best converter topology for HVDC stations

— The main disadvantage is the control difficulty and the need for advanced control methods

— Finite Control Set Model Predictive Control method introduce a controller which is optimal for next sampling instant

— Using Sum of Squares decomposition method along with a Lyapunov function gives both a guarantee for stability of the converter and a good performance for the response

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Questions?

— Thank you for your attention

— Questions?

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