McGill University

Coming of Age?

Modular Multilevel Converter (MMC)

2003 to 2018

Prof. Boon Teck Ooi

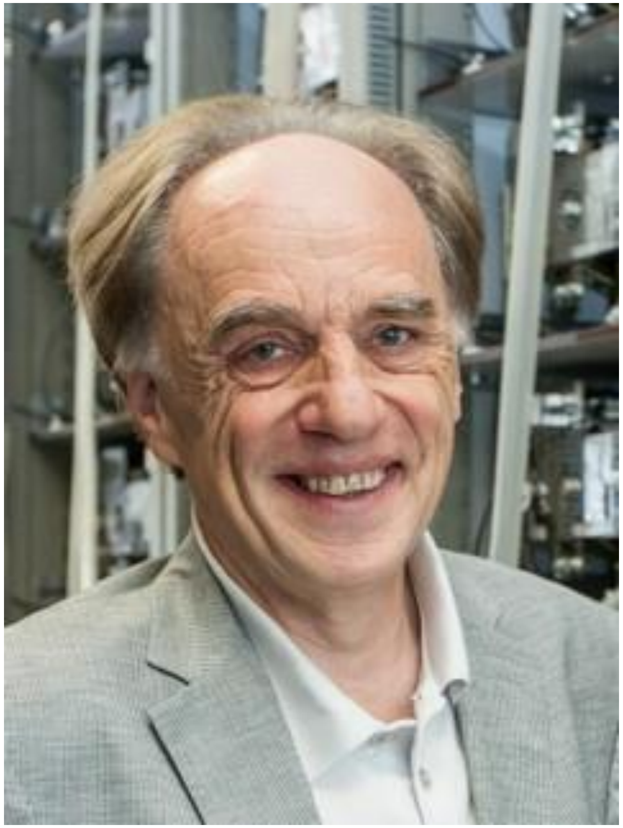
boon-teck.ooi@mcgill.ca

Electric Energy Systems Laboratory

June 2018

Handout of PPT available

Background



MMC inventor

Prof. Rainer Marquardt
Chair in power electronics
University of the Bundeswehr
Munich, Germany

Background

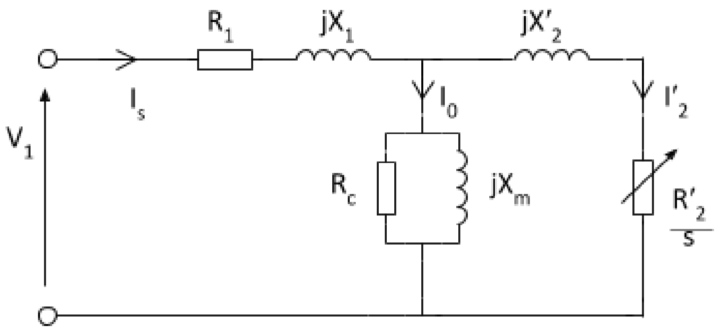
Definitive Formulation Based on Ordinary Differential Equations (ODE)

Royal Institute of Technology, Stockholm, Sweden

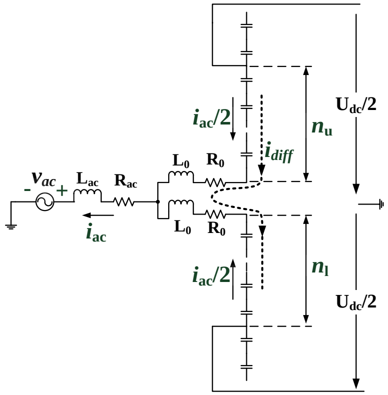
Antonopoulos, L. Angquist, and H. P. Nee, “On dynamics and voltage control of the modular multilevel converter,” Proc. Eur. Conf. Power Electron. Appl., Barcelona, Spain, 2009, pp. 1–10.

Historical perspective

- Induction Motor 1888
- Equivalent Circuit



- MMC 2003
- Detail Model



- ODE Equations

$$\begin{bmatrix} v_{qs} \\ v_{ds} \\ v_{qr} \\ v_{qr} \end{bmatrix} = \begin{bmatrix} R_s + sL_s & -\omega_s L_s & sL_m & -\omega_s Lm \\ -\omega_s L_s & R_s + sL_s & -\omega_s L_m & pL_m \\ sL_m & (\omega_s - \omega_r)L_m & R_r + sL_r & (\omega_s - \omega_r)L_r \\ -(\omega_s - \omega_r)L_m & sL_m & -(\omega_s - \omega_r)L_r & R_r + sL_r \end{bmatrix} \begin{bmatrix} i_{qs} \\ i_{ds} \\ i_{qr} \\ i_{qr} \end{bmatrix}$$

- ODE Equations

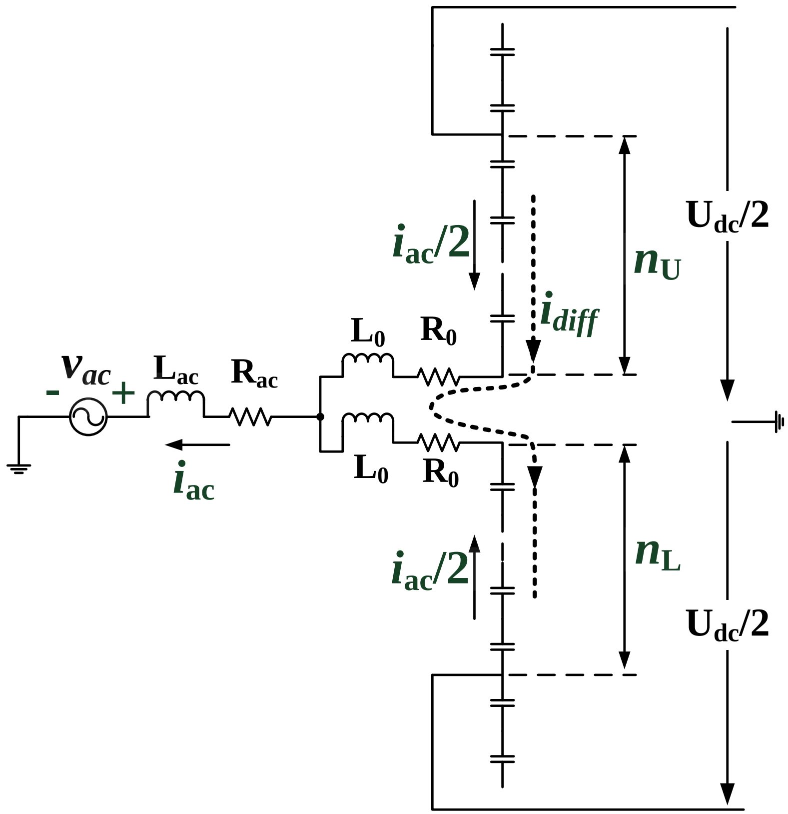
$$\frac{du_{U\ell,n}}{dt} = \frac{N}{C}\left(\frac{i_{ac\ell,n}}{2} + i_{diff\ell,n}\right)\left(\frac{1}{2} - \frac{u_{ref\ell,n}}{U_{dcl.n}}\right)$$

$$\frac{du_{L\ell,n}}{dt} = \frac{N}{C}\left(-\frac{i_{ac\ell,n}}{2} + i_{diff\ell,n}\right)\left(\frac{1}{2} - \frac{u_{ref\ell,n}}{U_{dc\ell,n}}\right)$$

$$\frac{di_{diff\ell,n}}{dt} = \frac{1}{2L_0}\left[U_{dc\ell,n} - (2R_0 + R_{dc})i_{diff\ell,n} - \frac{1}{2}(u_{U\ell,n} + u_{L\ell,n}) + \frac{U_{ref\ell,n}}{U_{dc\ell,n}}(u_{U\ell,n} - u_{L\ell,n})\right]$$

$$\frac{di_{ac\ell,n}}{dt} = \frac{1}{2L_{ac} + L_0}\left[-2v_{ac\ell,n} - (2R_{ac} + R_0)i_{ac\ell,n} + \frac{1}{2}(-u_{U\ell,n} + u_{L\ell,n}) + \frac{U_{ref\ell,n}}{U_{dc\ell,n}}(u_{U\ell,n} + u_{L\ell,n})\right]$$

ODE Derived from Series Capacitor Modulation



Definition of charge: $q = Cv$

Definition of current: $i = \frac{dq}{dt}$

$$i = C\frac{dv}{dt} + v\frac{dC}{dt}$$

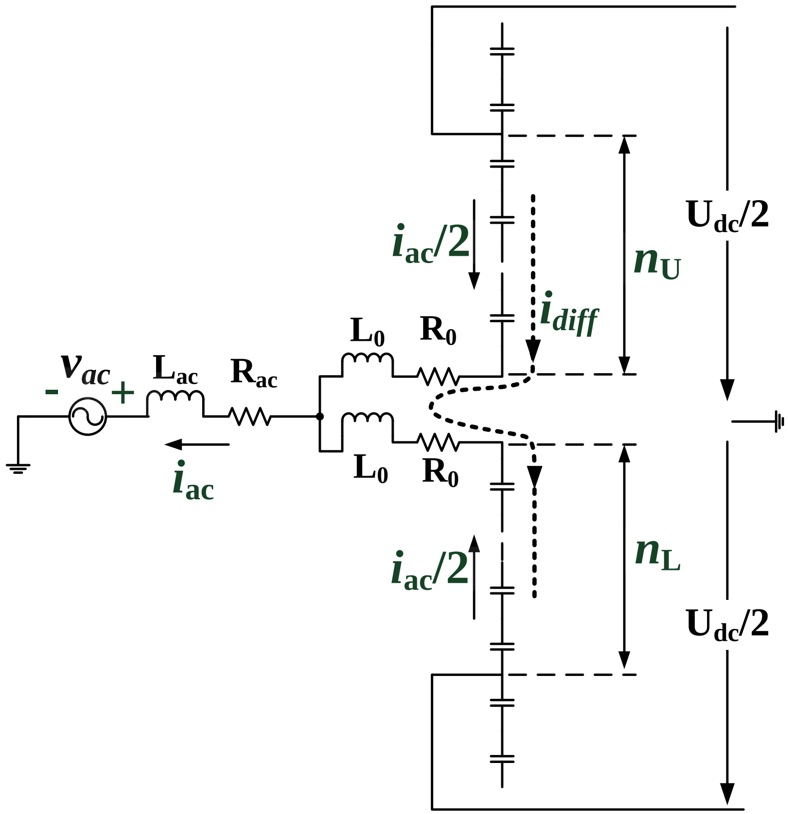
When $C = \frac{C_0}{n(t)}$

Then $$i = \frac{C_o}{n(t)}\frac{dv}{dt} + C_o v\frac{d\frac{1}{n(t)}}{dt}$$

$C_o v\frac{d\frac{1}{n(t)}}{dt}$ ---switching noise and is neglected.

$i = \frac{C_o}{n(t)}\frac{dv}{dt}$ is retained ----signal processing

Number of Capacitors commanded by Modulation Signal



$$n(t) = (\frac{1}{2} - \frac{U_{ref,l,n}}{Udcl,n})$$

$$i = \frac{C_o}{n(t)} \frac{dv}{dt}$$ is retained --- signal processing

$$i = \frac{C_o}{\left(\frac{1}{2} - \frac{U_{ref,l,n}}{Udcl,n}\right)} \frac{dv}{dt}$$

ODE equations

Number of capacitors $n(t) = (\frac{1}{2} - \frac{U_{ref,l,n}}{Udcl,n})$ commanded by Modulation signal

$$\frac{du_{U\ell,n}}{dt} = \frac{N}{C}(\frac{i_{ac\ell,n}}{2} + i_{diff\,\ell,n})(\frac{1}{2} - \frac{u_{ref\,\ell,n}}{U_{dcl.n}})$$

$$\frac{di_{diff\,\ell,n}}{dt} = \frac{1}{2L_0}[U_{dc\ell,n} - (2R_0 + R_{dc})i_{diff\,\ell,n} - \frac{1}{2}(u_{U\ell,n} + u_{L\ell,n}) + \frac{U_{ref\,\ell,n}}{U_{dc\ell,n}}(u_{U\ell,n} - u_{L\ell,n})]$$

$$\frac{du_{L\ell,n}}{dt} = \frac{N}{C}(-\frac{i_{ac\ell,n}}{2} + i_{diff\,\ell,n})(\frac{1}{2} - \frac{u_{ref\,\ell,n}}{U_{dc\ell,n}})$$

$$\frac{di_{ac\ell,n}}{dt} = \frac{1}{2L_{ac} + L_0}[-2v_{ac\ell,n} - (2R_{ac} + R_0)i_{ac\ell,n} + \frac{1}{2}(-u_{U\ell,n} + u_{L\ell,n}) + \frac{U_{ref\,\ell,n}}{U_{dc\ell,n}}(u_{U\ell,n} + u_{L\ell,n})]$$

Organization of Presentation

Engineering Science

- **Numerical prediction by ODE coincides with Detail Model**
- **Quantitative prediction from algebraic formulas**
- **Nonlinearity of MMC—treatment by linearization**

Engineering Practice

- **Siemens HVDC PLUS**
- **China State Grid and China South Grid**
- **Multiple controllability; Increase Transient Stability Limit and power transmissiblity**
- **Simulation platforms for planning studies that can PSSE, Power Factory, HYPERSIM, OPAL-RT, RTDS**

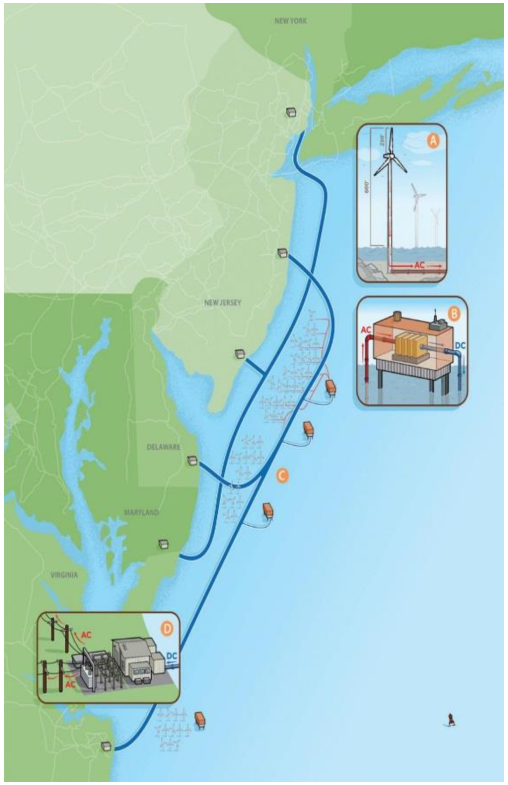
Simulation Tests

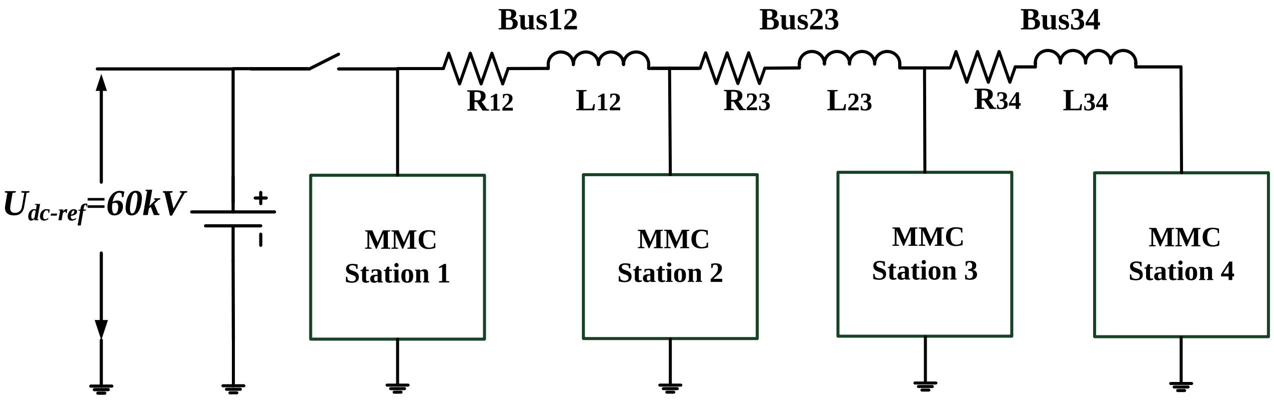
ODE predictions

Numerical prediction by ODE

Test: Multi-Terminal MMC HVDC ---- Atlantic Coast of USA

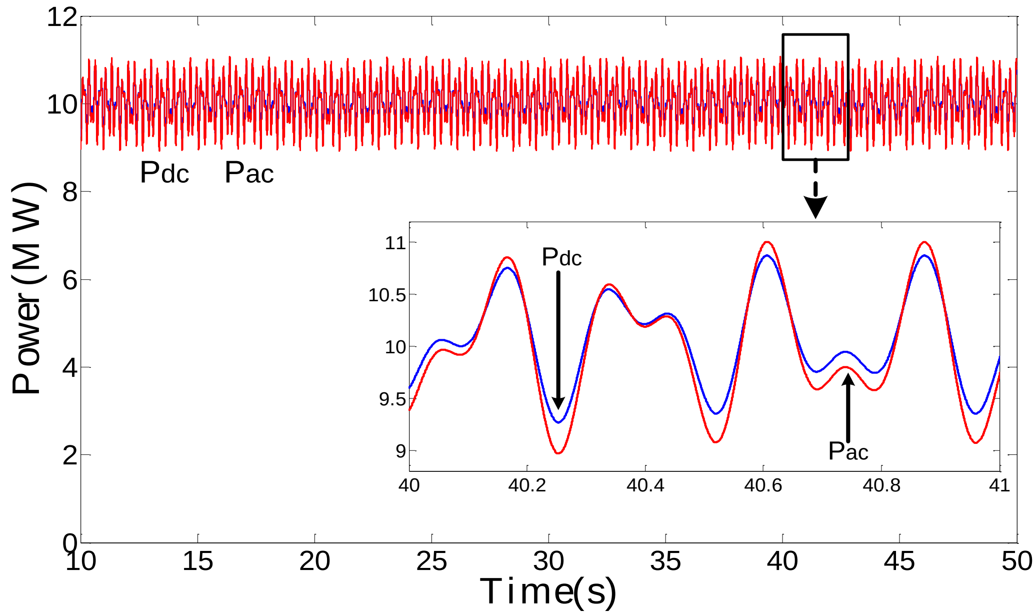
MMC-1 Energy Market
MMC-2 DC Voltage Regulator (Power Slack)
MMC-3 Wind Farm
MMC-4 Energy Market

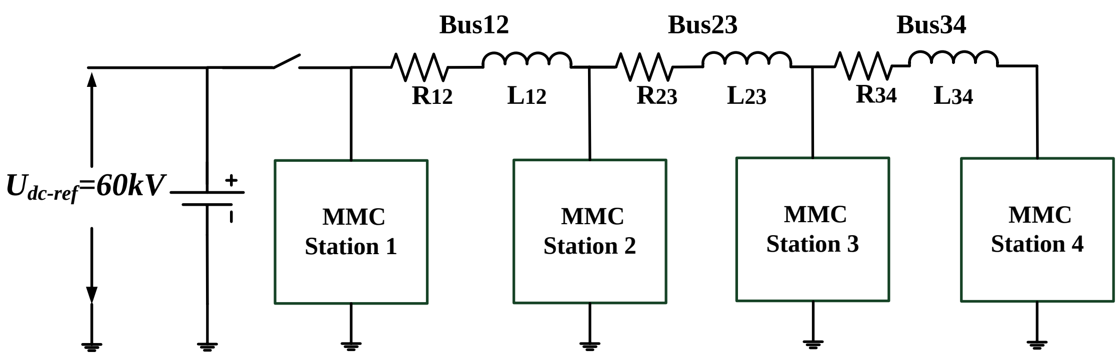




Stochastic Wind Control—AC-side of MMC operates as an infinite bus, regulate voltage magnitude and frequency

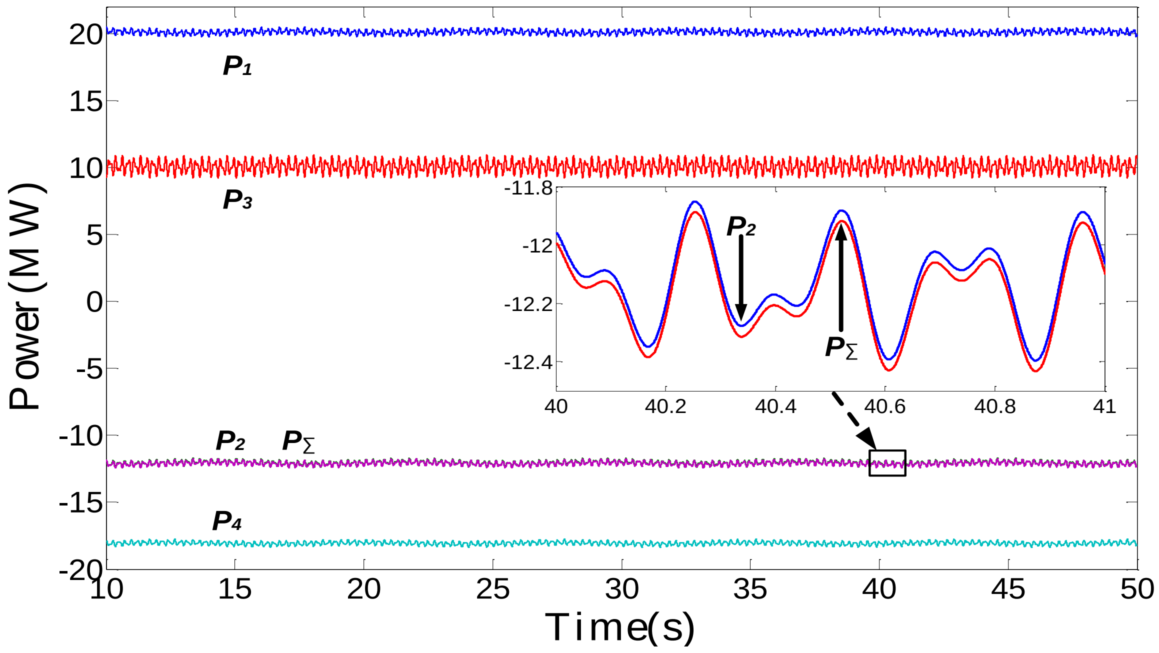
- MMC3 P_{dc} to track stochastic wind power P_{ac}.
- Wind stochasticity is seen as high frequency noise in P_{ac}.
- "Blow-up" in inset shows P_{dc} tracking P_{ac} closely

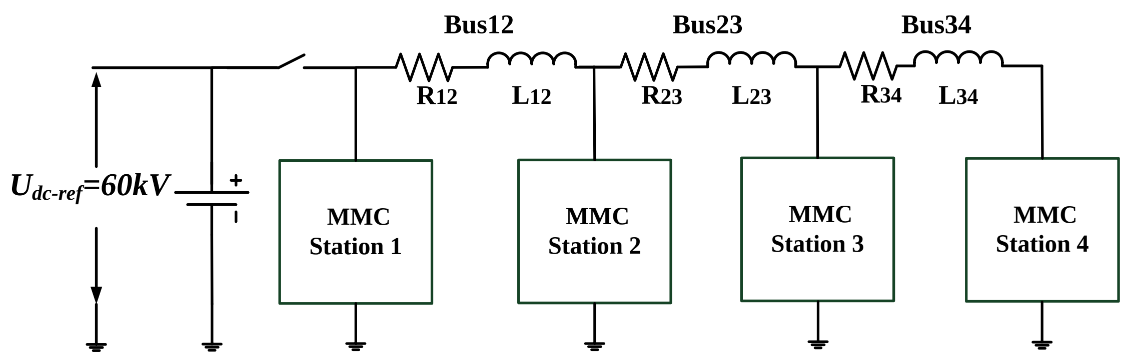




Numerical prediction by ODE

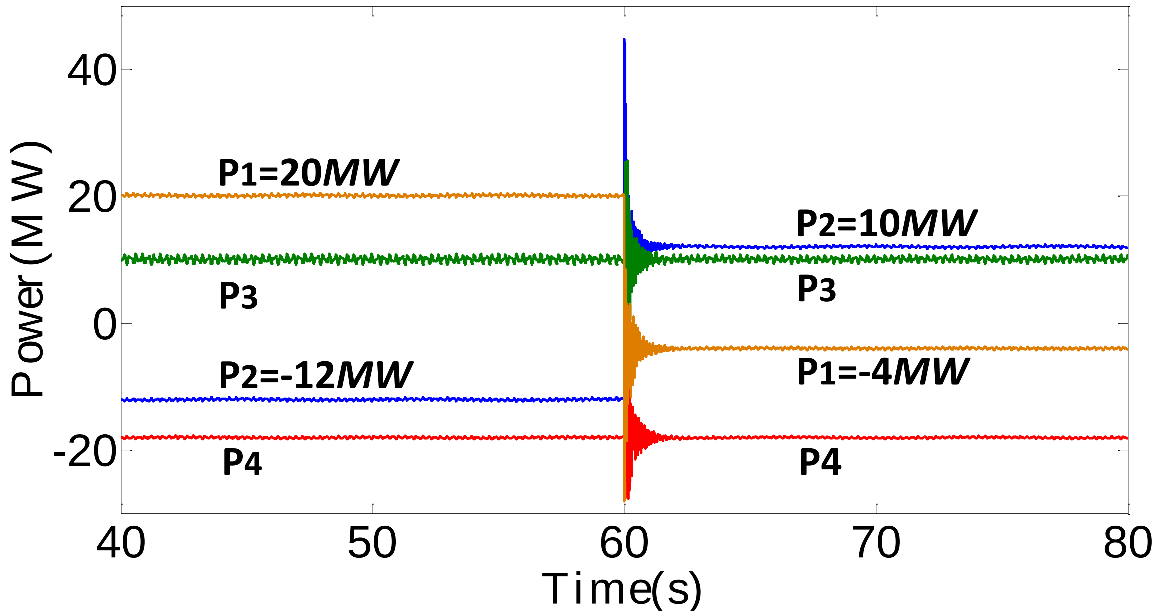
- Stochastic wind power P_3 makes the active powers P_1, P_2, P_4 noisy.
- MMC2 is the dc voltage regulator.
- Active power P_2 is equal to P_Σ the sum of active power of the other stations

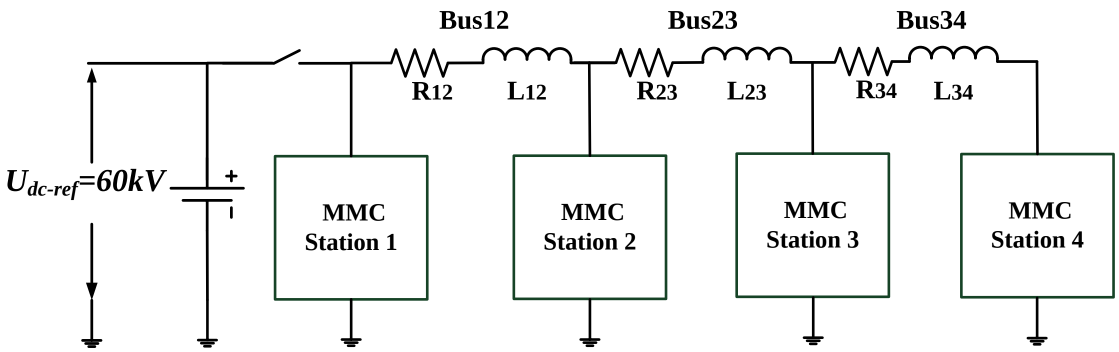




Numerical prediction by ODE

- Test on reversal of power by station shown as P_1.
- P_3 and P_4 remain unchanged.
- P_2 of dc voltage regulator as power slack accepts change of P_1.





Numerical prediction by ODE

The preceding "Atlantic coast" tests show that the ODE formulation can implement control strategies

simulations by both ODE and detail model.

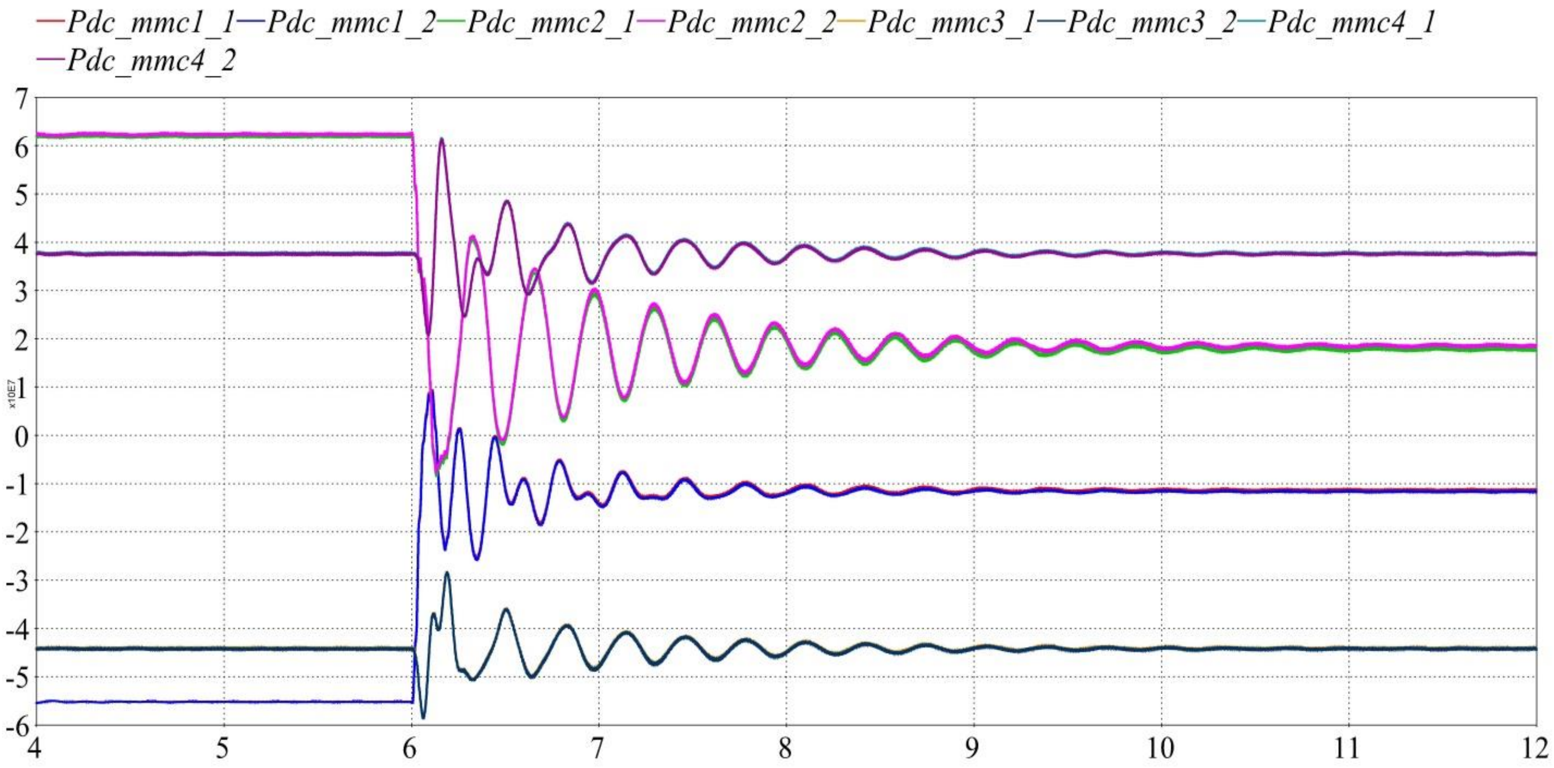
results coincide---very high accuracy.

Numerical prediction by ODE coincides with Detail Model

Comparison of Detail Model with ODE

Detail Model Simulated by OPAL-RT

Numerical prediction by ODE coincides with Detail Model



- **Results of Detail Model and ODE Model coincide so that 8 graphs appear as 4 graphs.**
- **Transients from the demanding step change test demonstrate high accuracy of ODE.**

Organization of Presentation

Engineering Science

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- Quantitative prediction from algebraic formulas
- Nonlinearity of MMC—treatment by linearization

Engineering Practice

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Quantitative prediction from algebraic formulas

Prediction by harmonic analysis of ODE:

Algebraic Formulas

From Analytic Continuity

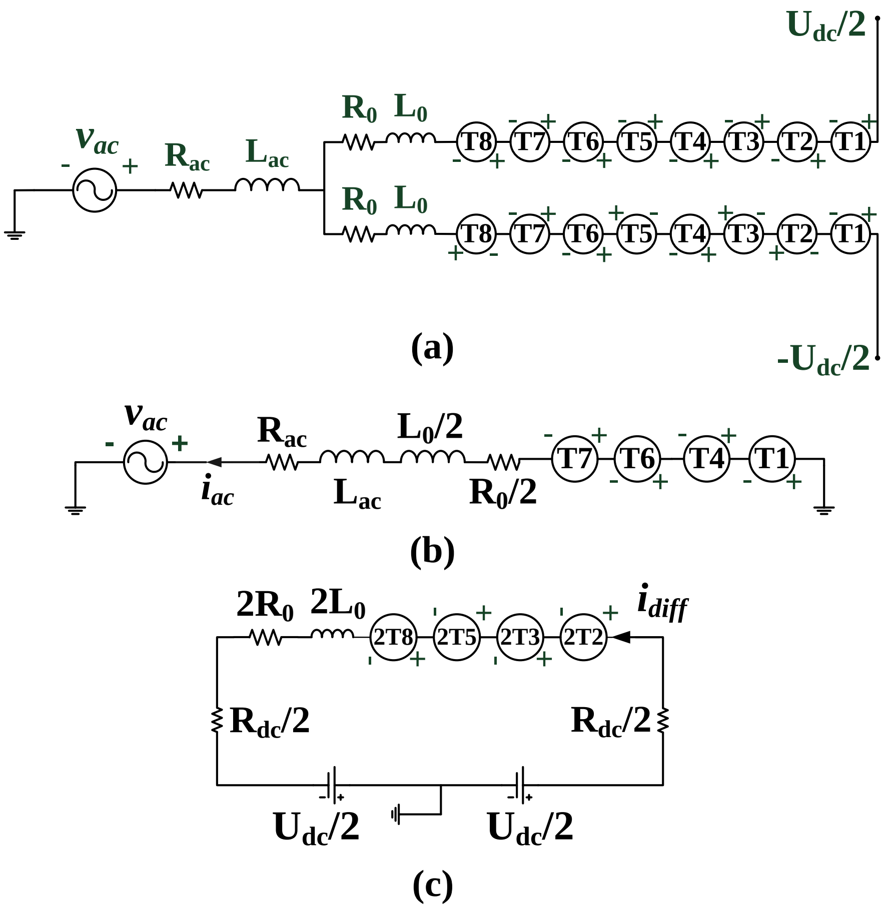
ODE Method succeeds or fails together

Harmonic Decomposition of MMC:
MMC---ideal voltage source equivalents connected in series

Dr. Can Wang
Assistant Professor
Harbin Institute of Technology, Shenzheng

Harmonic Decomposition of MMC:
MMC---ideal voltage source equivalents connected in series

- **Decomposition as ideal voltage sources of the upper half and the lower half.**
- **AC-side representation**
- **DC-side representation**



Quantitative prediction from algebraic formulas

AC-Side algebraic Voltages
Fundamental and 3rd harmonic

	Fundamental--ω	Third-Harmonic--3ω
T1	$\frac{NI_{ac}}{8\omega C}\sin(\omega t+\varphi_{ac})$	
T4	$-\frac{NU_{ref}I_d}{2\omega CU_{dc}}\sin(\omega t+\delta)$ $-\frac{NU_{ref}X}{4\omega CU_{dc}}\sin(\omega t+\varphi_2-\delta)$	$-\frac{NU_{ref}X}{12\omega CU_{dc}}\sin(3\omega t+\varphi_2+\delta)$
T6	$-\frac{NU_{ref}}{CU_{dc}}\cos(\omega t+\delta)\cdot\int_{-\infty}^{t}[\frac{I_d}{2}-\frac{U_{ref}I_{ac}}{4U_{DC}}\cos\left(\delta-\varphi_{ac}\right)]d\tau$	
T7	$-\frac{NU_{ref}X}{8\omega CU_{dc}}\sin\left(\omega t+\varphi_2-\delta\right)$ $\frac{NU_{ref}^2 I_{ac}}{16\omega CU_{dc}^2}\sin\left(\omega t+\varphi_{ac}\right)$	$-\frac{NU_{ref}X}{8\omega CU_{dc}}\sin\left(3\omega t+\varphi_2+\delta\right)$ $\frac{NU_{ref}^2 I_{ac}}{16\omega CU_{dc}^2}\sin\left(3\omega t+2\delta+\varphi_{ac}\right)$

Quantitative prediction from algebraic formulas

DC-Side algebraic voltages
DC and 2nd harmonic

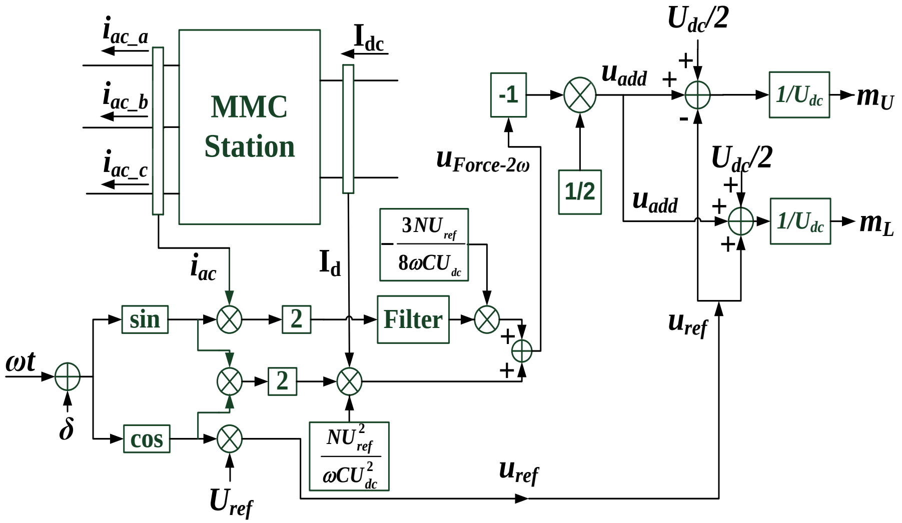
Original sources of 2nd Harmonic
二次谐波

	DC	2nd Harmonic
T2	$\int_{-\infty}^{t}[\frac{I_d}{2} - \frac{U_{ref}I_{ac}}{4U_{DC}}\cos(\delta-\varphi_{ac})]d\tau$	$\frac{NX}{8\omega C}\sin(2\omega t+\varphi_2)$
T3		$-\frac{NU_{ref}I_{ac}}{16\omega CU_{dc}}\sin(2\omega t+\delta+\varphi_{ac})$
T5	$-\frac{NU_{ref}I_{ac}}{8\omega CU_{dc}}\sin(\varphi_{ac}-\delta)$	$-\frac{NU_{ref}I_{ac}}{8\omega CU_{dc}}\sin(2\omega t+\delta+\varphi_{ac})$
T8	$\frac{NU_{ref}^2X}{4\omega CU_{dc}^2}\sin(\varphi_2-2\delta)$	$\frac{NU_{ref}^2I_d}{2\omega CU_{dc}^2}\sin(2\omega t+2\delta)$ $\frac{NU_{ref}^2X}{3\omega CU_{dc}^2}\sin(2\omega t+\varphi_2)$

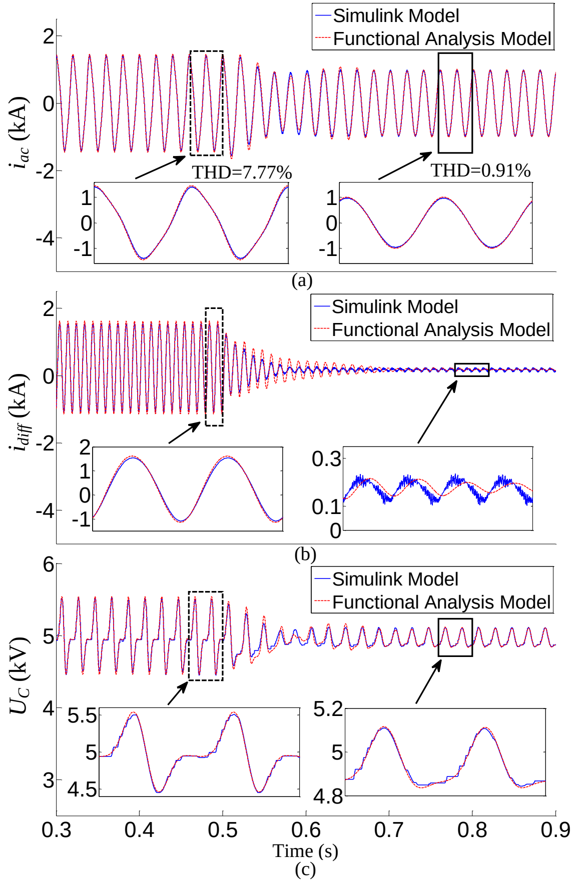
Quantitative prediction from algebraic formulas

- **Algebraic formulas give guidance to a Feedforward method to reduce "circulating current" 环流**

  - **circuitry of feedforward**
    前馈控制电路



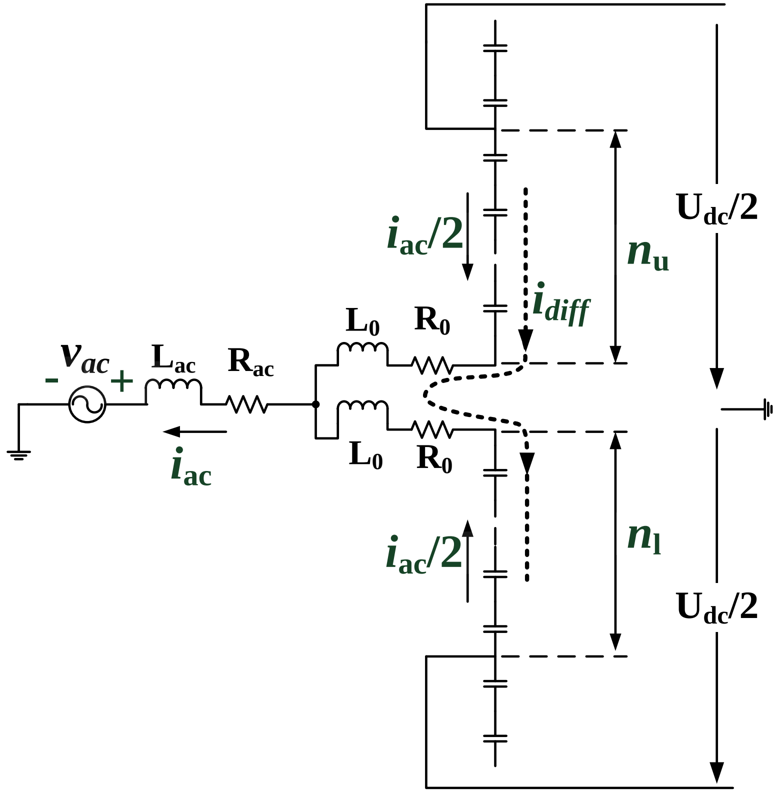
  - **simulation validation of claim**



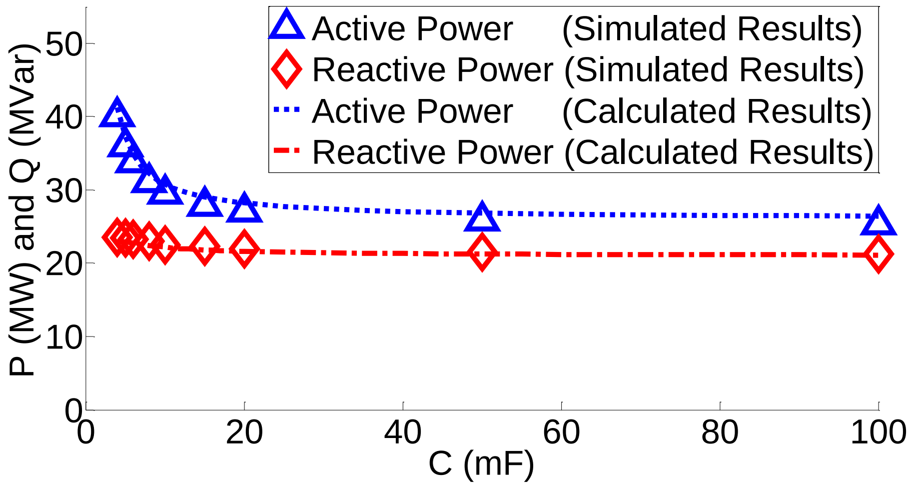
Quantitative prediction from algebraic formulas

- **ODE predicts: capacitor of sub-modules can reduce inductive reactance on AC-Side for power factor correction**

❑ **L_{ac} compensated by sub-module capacitors**

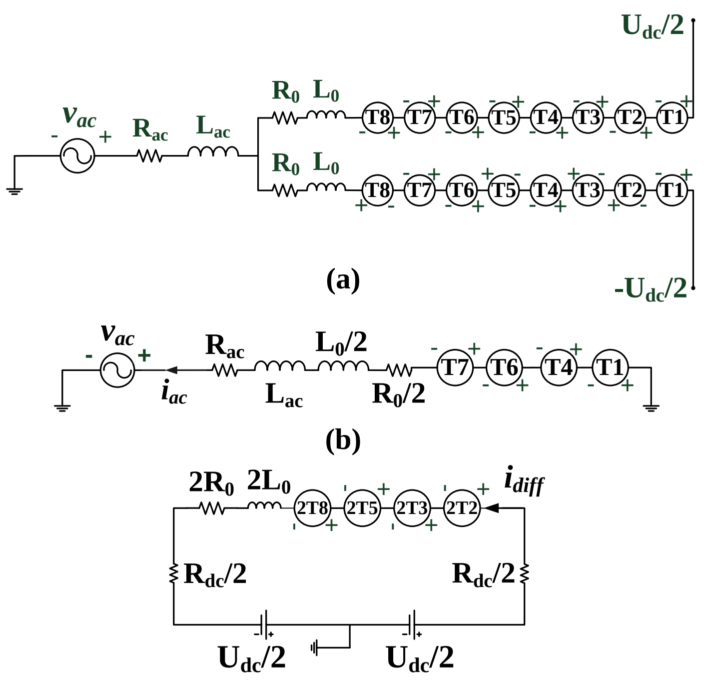


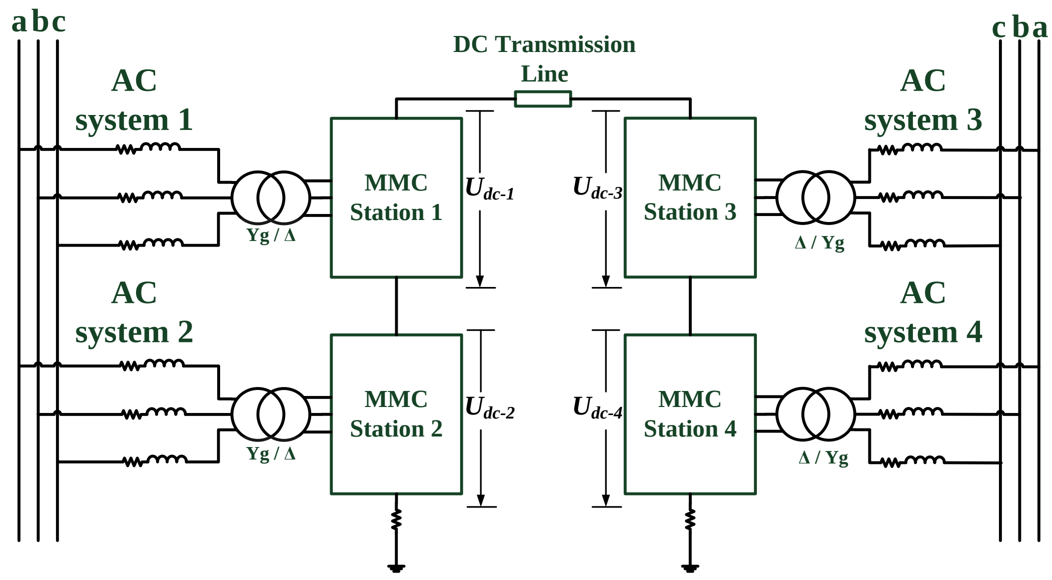
❑ ***P*** **and** ***Q*** **as function of capacitor size**



Quantitative prediction from algebraic formulas

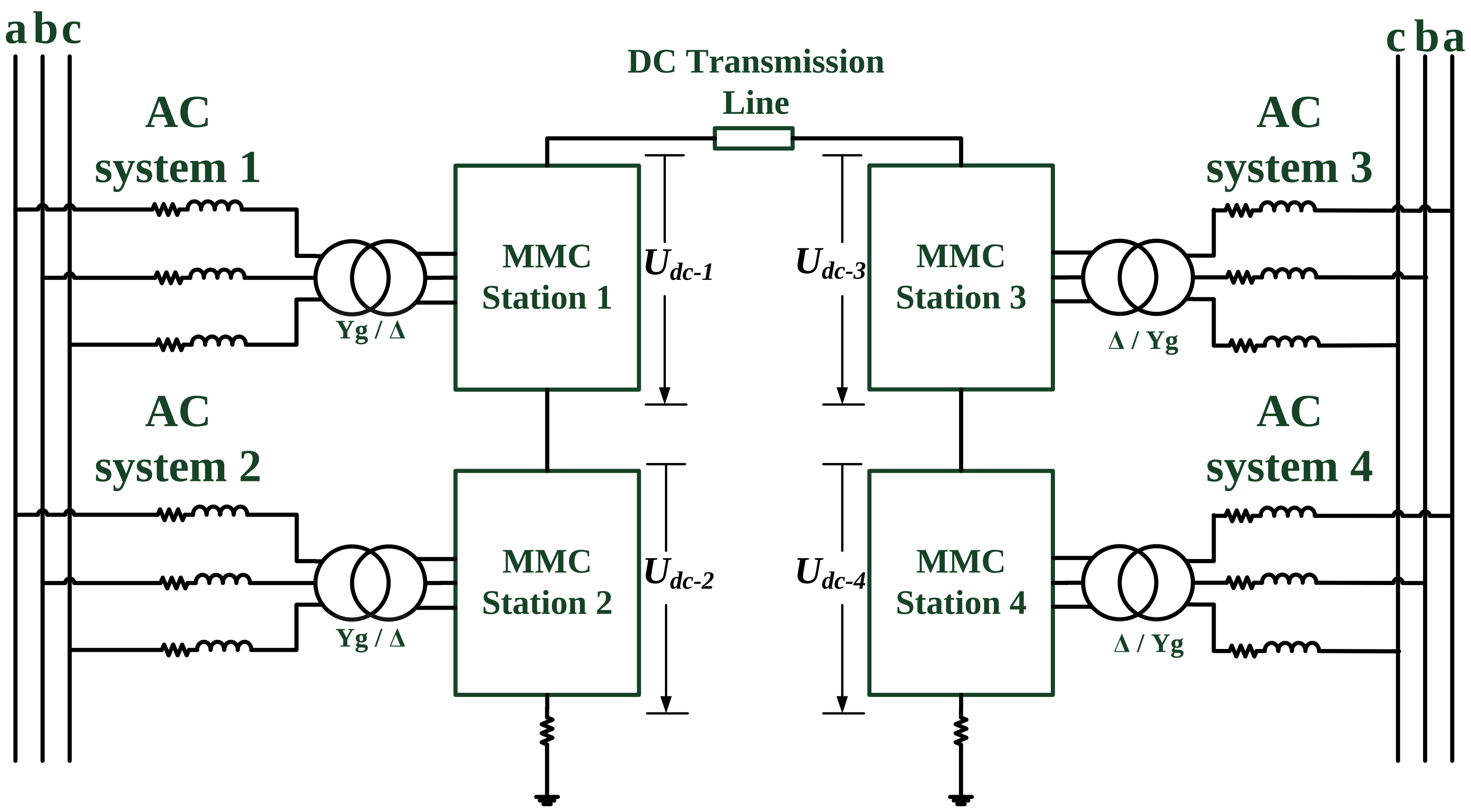
- **MMC equivalent as series connection of voltage sources:**
- **MMC-HVDC suitable for series connection on DC-Sides to form ultra MMC-HVDC**





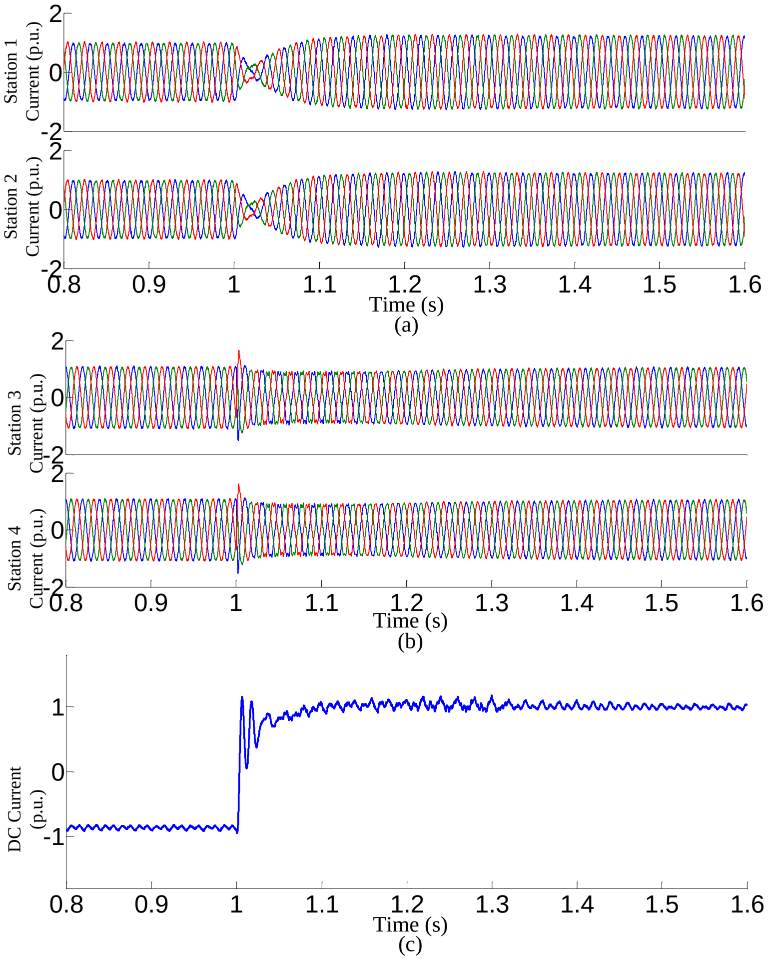
Quantitative prediction from algebraic formulas

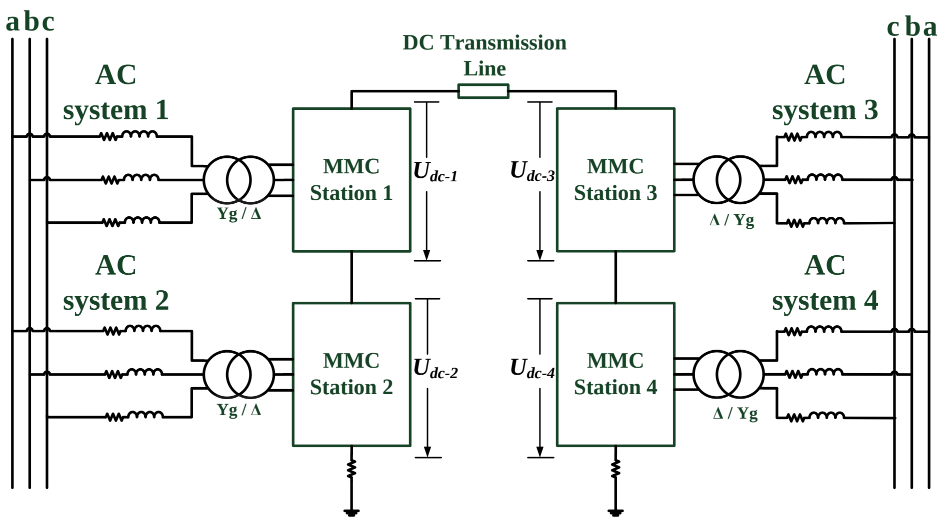
- **Simulation test to demonstrate suitability of Ultra MMC HVDC**



Quantitative prediction from algebraic formulas

- **Simulation of Instantaneous Power Reversal in Ultra-MMC HVDC (DC voltage equalization control required)**





Quantitative prediction from algebraic formulas

HVDC Station based on single-phase MMC H-Bridges connected in series

Dr. Quanrui Hao,
Associate Professor,
Shandong University

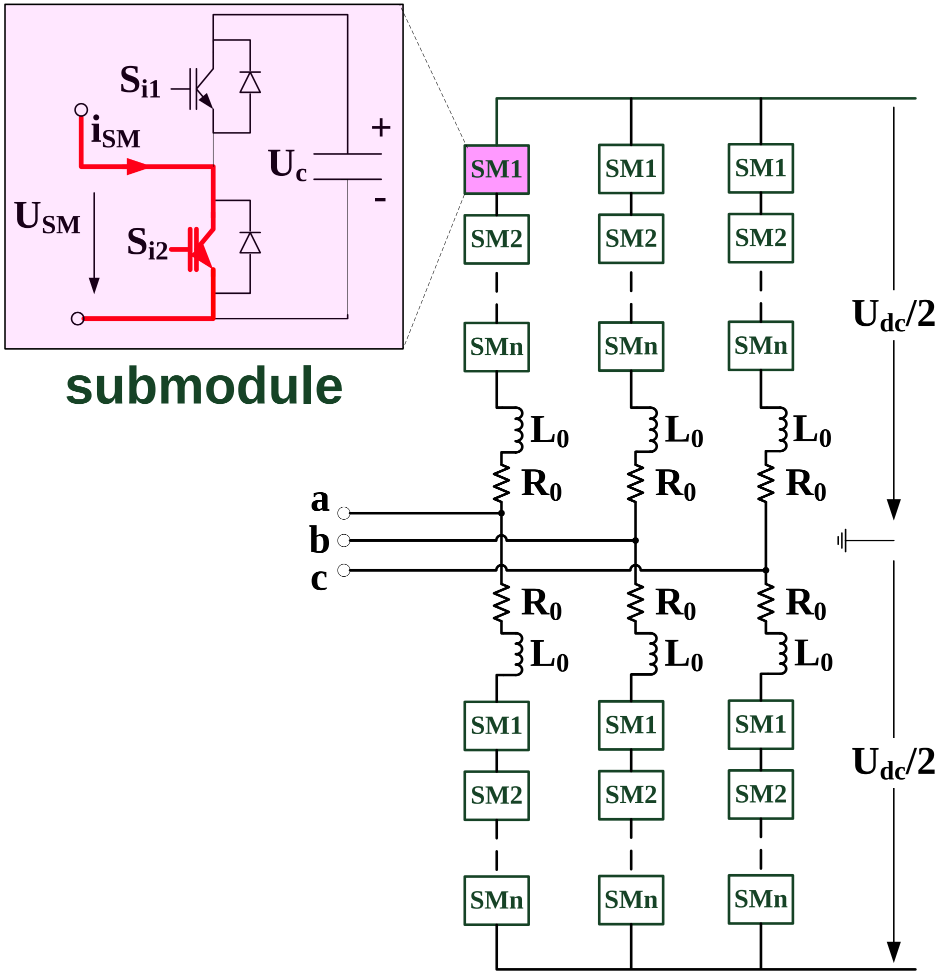
McGill

SHANDONG UNIVERSITY 1901

山东大学

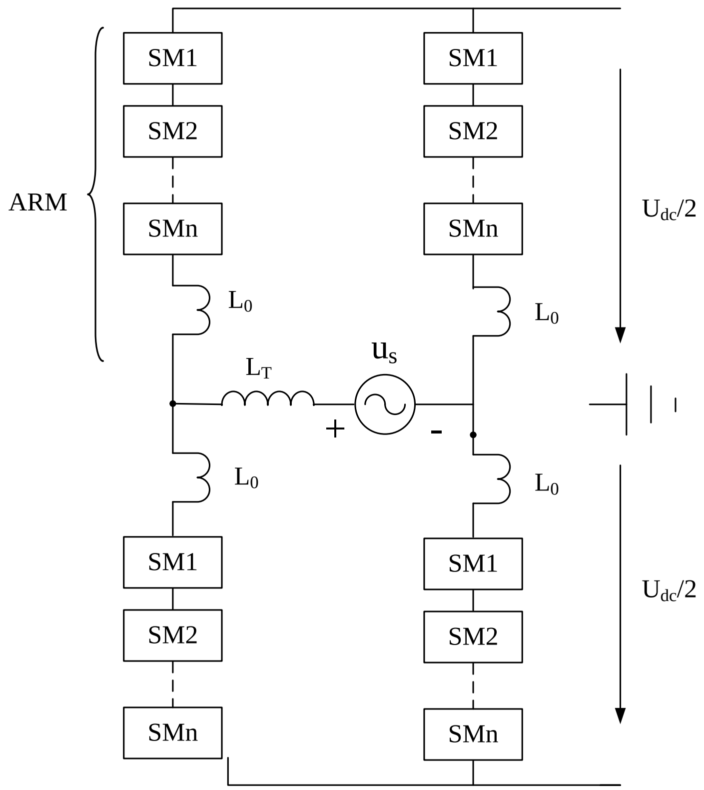
Quantitative prediction from algebraic formulas

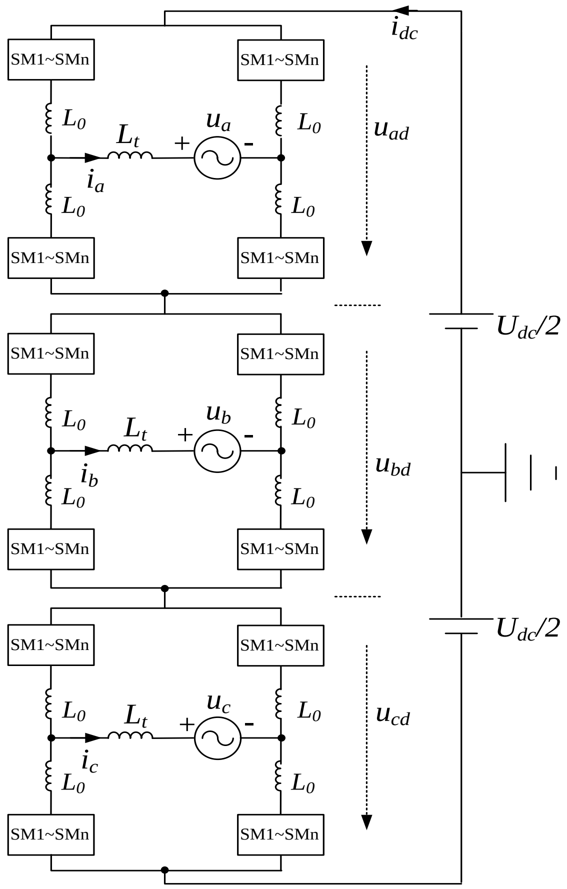
- **Each leg has voltage withstand of U_{dc}**



Quantitative prediction from algebraic formulas

- **Reorganize two legs as three-phases of MMC Based on Single-Phase H-Bridge Modules in Series**





Quantitative prediction from algebraic formulas

Need engineering science

To answer existing puzzles

Quantitative prediction from algebraic formulas

Why is multi-terminal HVDC is less successful with LCC thyristor technology (modelled as ideal voltage source on dc side) compared to IGBT-MMC technology (modelled as ideal voltage source on dc side) ?

shibai

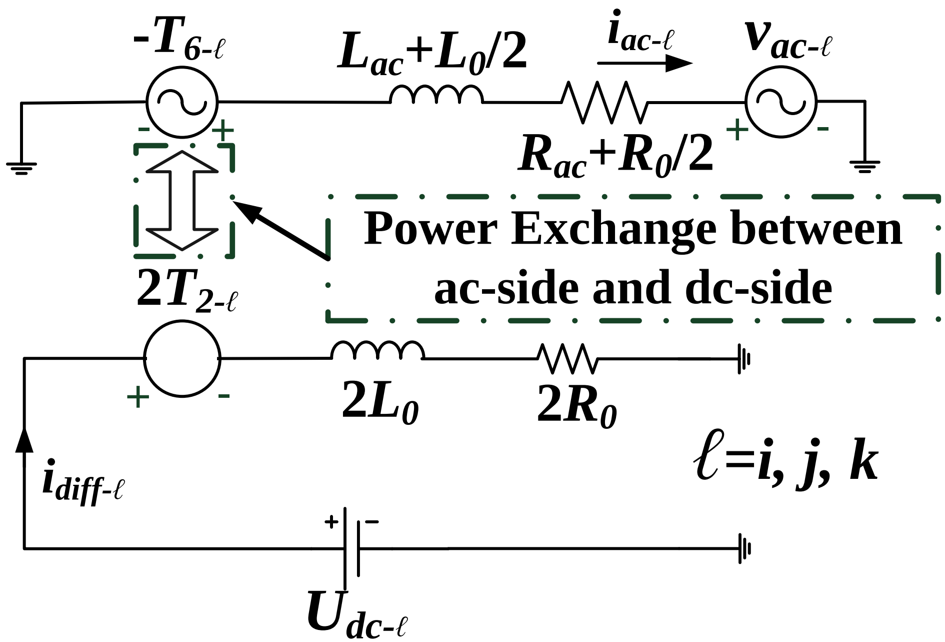
CHENG
gong

Quantitative prediction from algebraic formulas

- **Algebraic formulas show instantaneous power balance of ac-side ideal voltage source with dc-side ideal voltage source**

Voltages T_6 and $2T_2$ dominate.

$$T_6 \cdot i_{ac} \Leftrightarrow 2T_2 \cdot i_{diff}$$



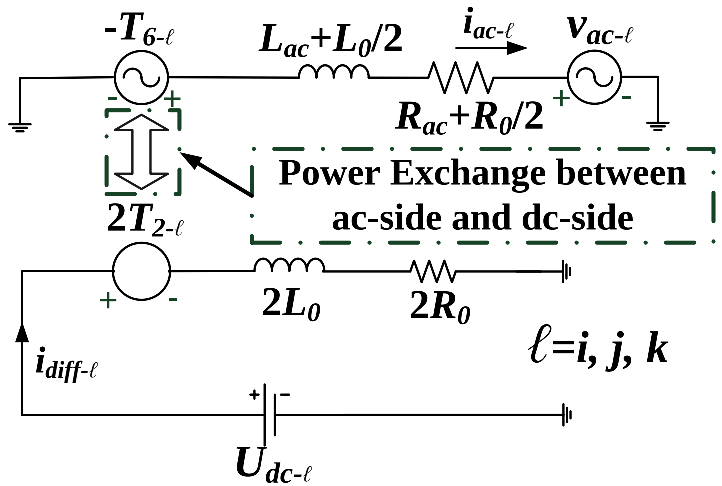
$$T_6 = -\frac{NU_{ref}}{CU_{dc}} \cos(\omega t + \delta) \cdot \int_{-\infty}^{t} [\frac{I_d}{2} - \frac{U_{ref} I_{ac}}{4U_{dc}} \cos(\delta - \varphi_{ac})] d\tau$$

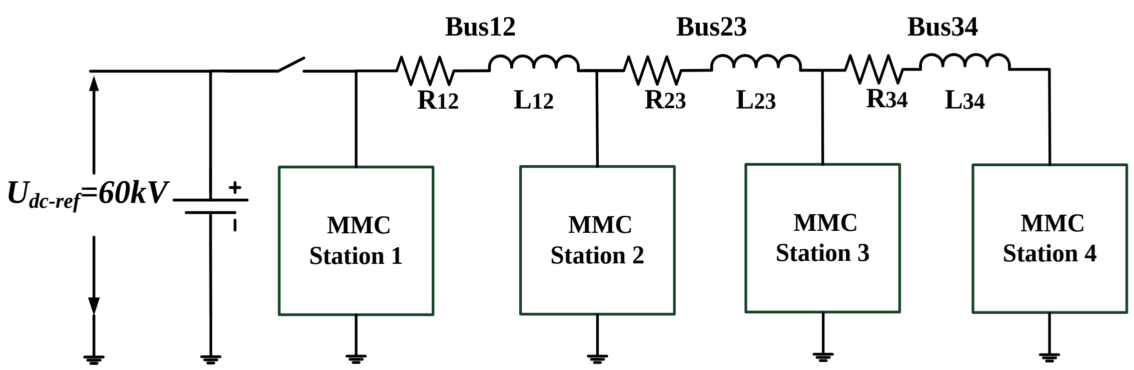
$$2T_2 = U_{dc} = 2\int_{-\infty}^{t} [\frac{I_d}{2} - \frac{U_{ref} I_{ac}}{4U_{dc}} \cos(\delta - \varphi_{ac})] d\tau$$

Quantitative prediction from algebraic formulas

- **Power balance of ac-side and dc-side facilitates multi-terminal MMC-HVDC**

$$T_6 \cdot i_{ac} \Leftrightarrow 2T_2 \cdot i_{diff}$$

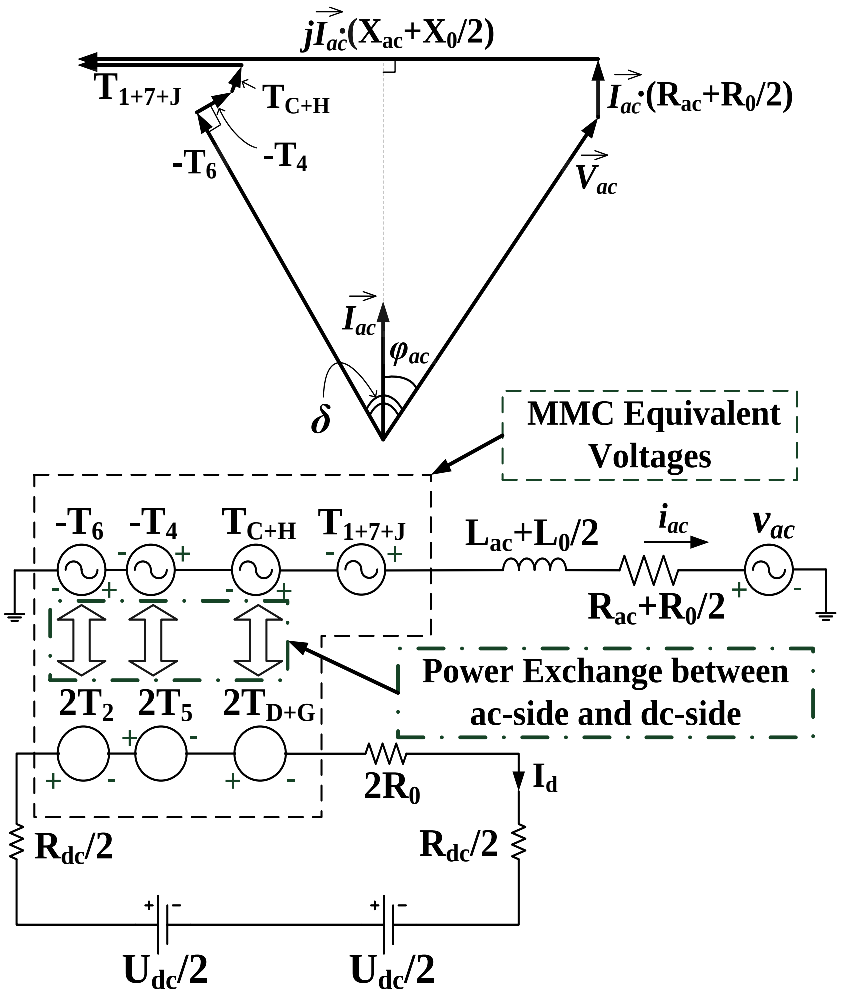




Quantitative prediction from algebraic formulas

- **After circulating current is eliminated, algebraic formulas show that MMC operation can be followed by Phasor Diagrams**

Composite Phasor Diagram of MMC



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Engineering Practice

- **Siemens HVDC PLUS**
- **China State Grid and China South Grid**
- **Multiple controllability; Increase Transient Stability Limit and power transmissiblity**
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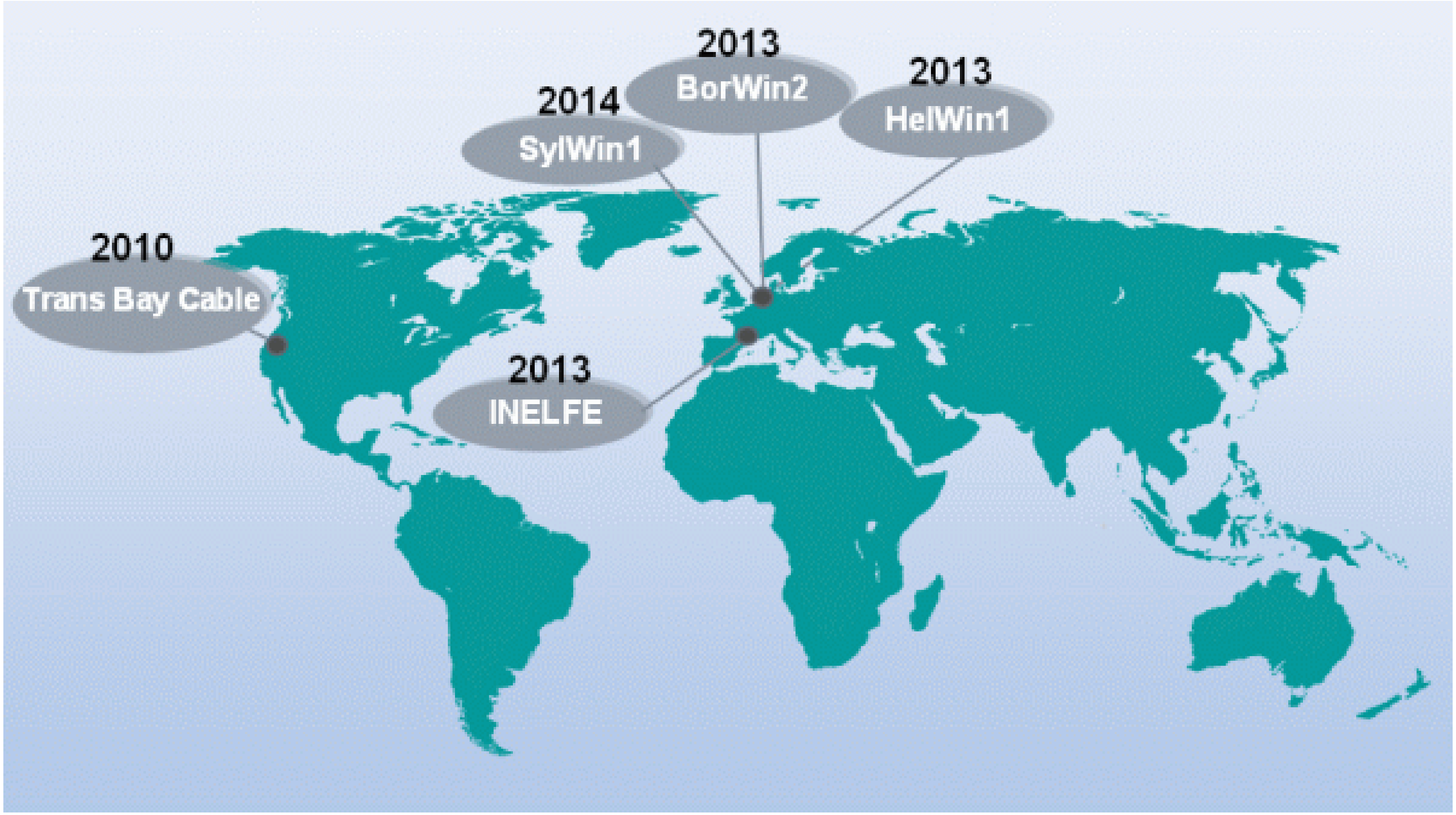
Siemens HVDC PLUS



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China State Grid and China South Grid

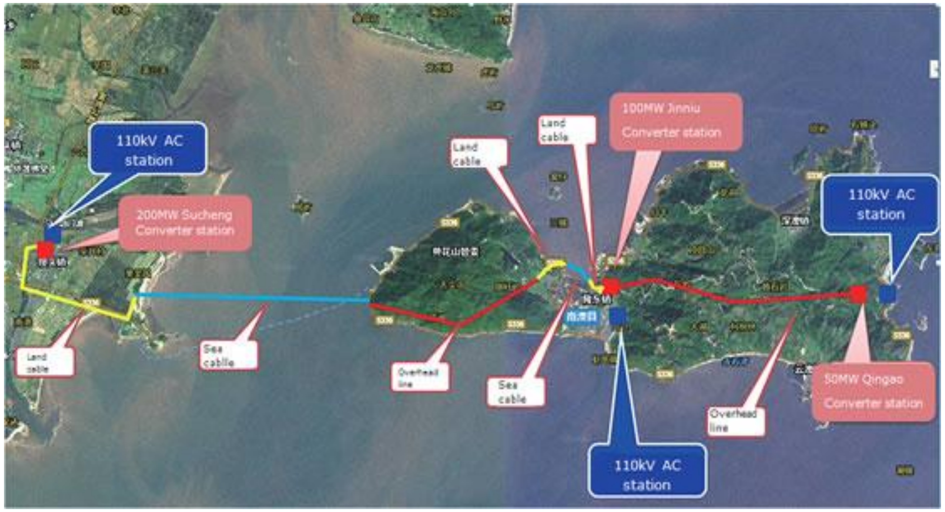
- **Yunnan----Luxi**

  ±350 kV/1000 MW MMC
  Based Back-to-Back VSC-HVDC
  Asynchronous Networking Project
  AC grid voltage of either units: 500 kV
  VSC-HVDC unit :
  Two modular multilevel converters (MMCs)

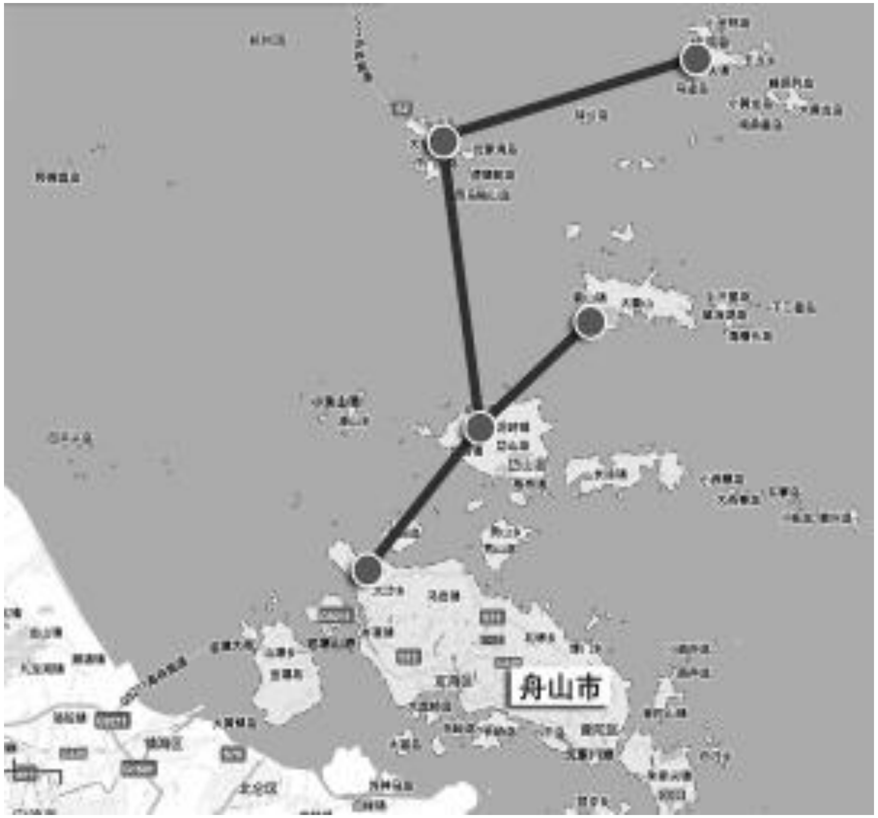
China State Grid and China South Grid

- **Multi-Terminal MMC-HVDC**

3-terminal Nan'Ao



5-terminal Zhoushan



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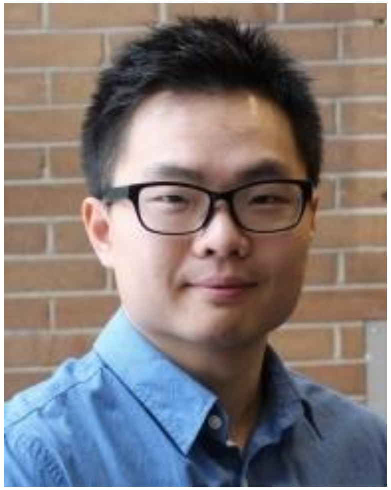
Researchers

Mr. Haihao Jiang



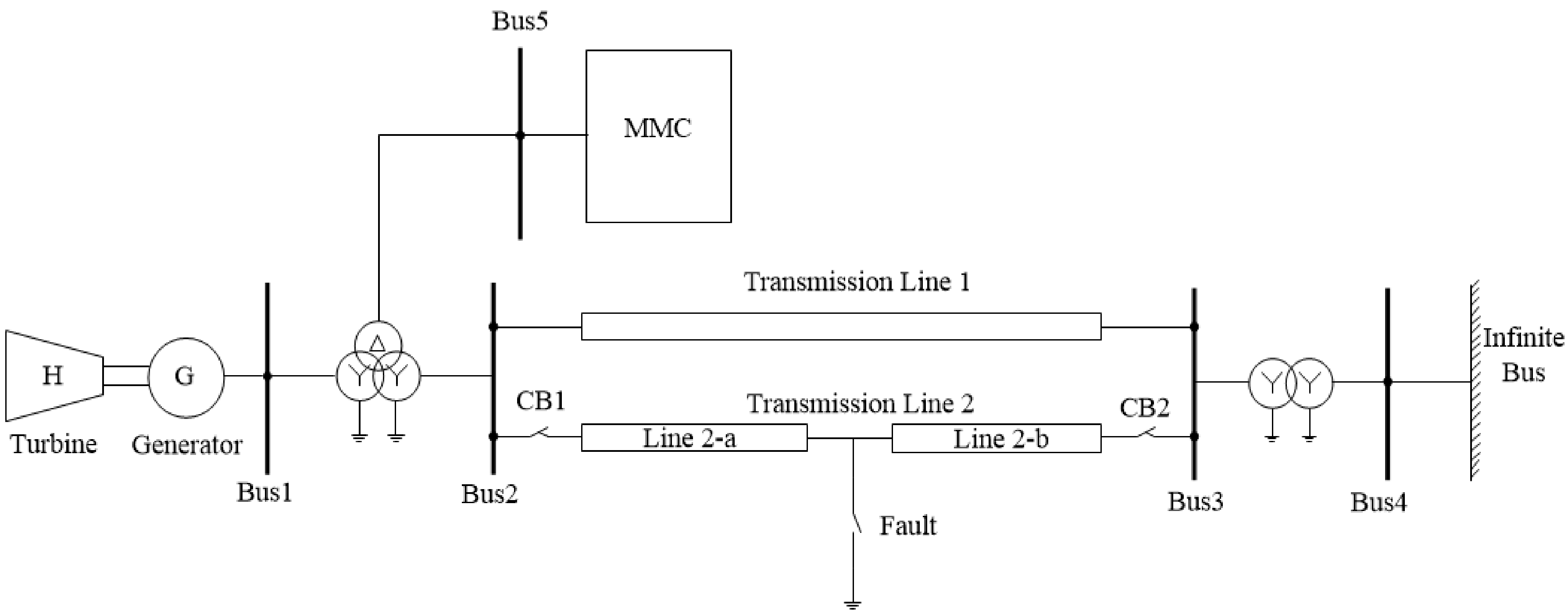
Dr. Can Wang

Multiple controllability

- Suppression of "Circulating Current"
- Decoupled P-Q control
- Protection against low voltage ride-through due to faults by Individual Phase Deadbeat
- Protection against overcurrent due to faults by Individual Phase Deadbeat
- Damping of power oscillation

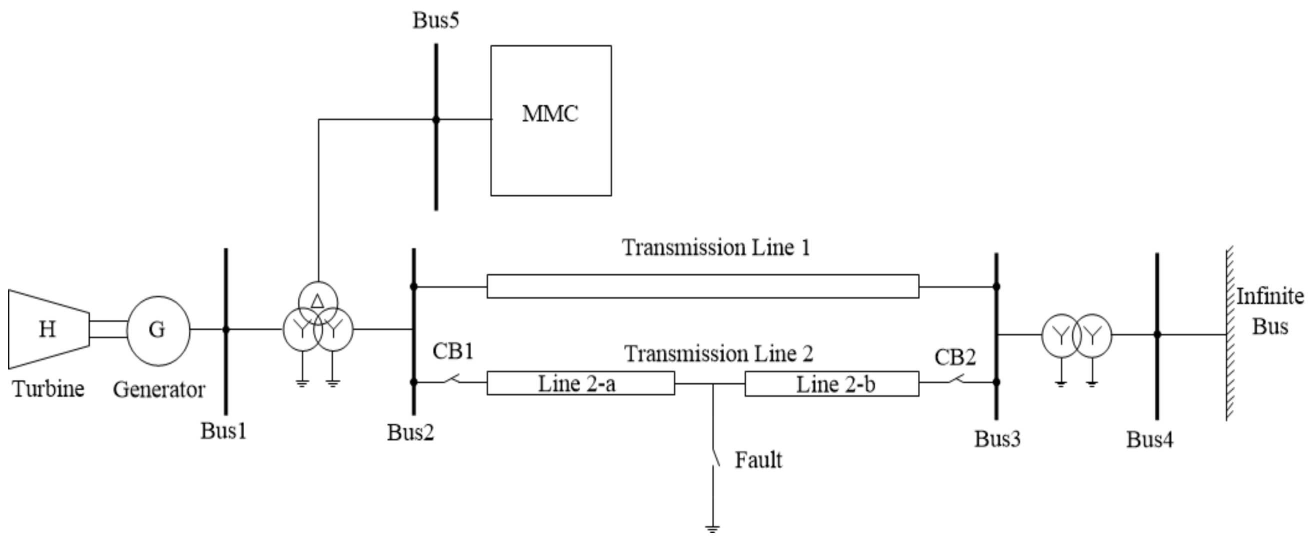
Multiple controllability; Increase Transient Stability Limit and power transmissibility

- **Demonstration of multiple controllability**
- **Transient stability test in radial transmission line**



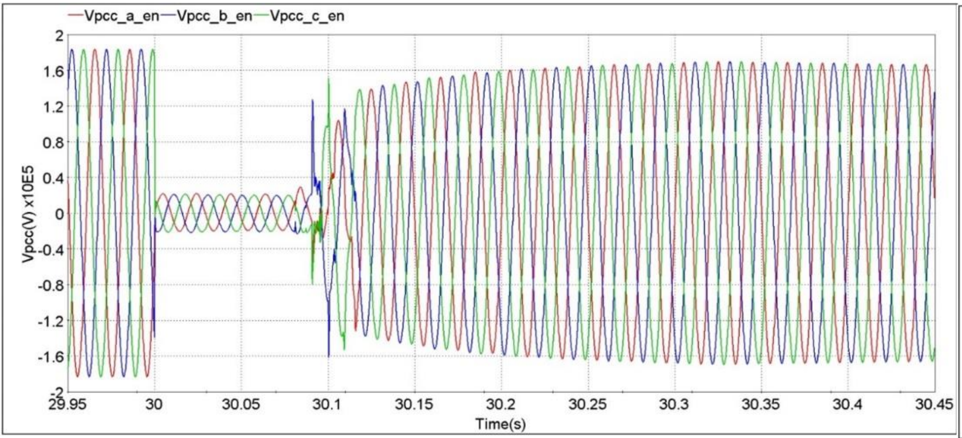
Transient Stability Test Scenario

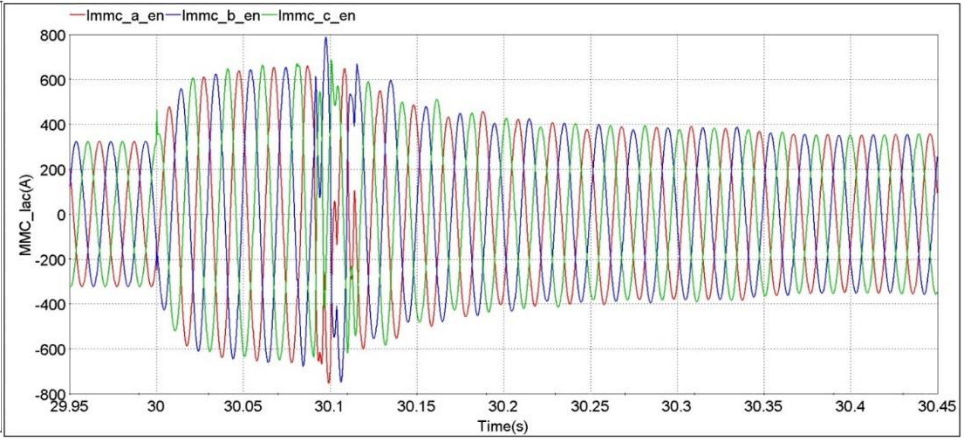
1. Power transfer from turbine-generator to infinite bus
2. System inertia represented by *H* of turbine-generator
3. MMC damps swing of turbine-generator
4. 3-phase short circuit fault
5. MMC protected by Deadbeat
6. Circuit-Breakers CB1, CB2 clear fault in Line 2
7. Power transmitted by Line 1
8. MMC damps power oscillation



Multiple controllability; Increase Transient Stability Limit and power transmissibility

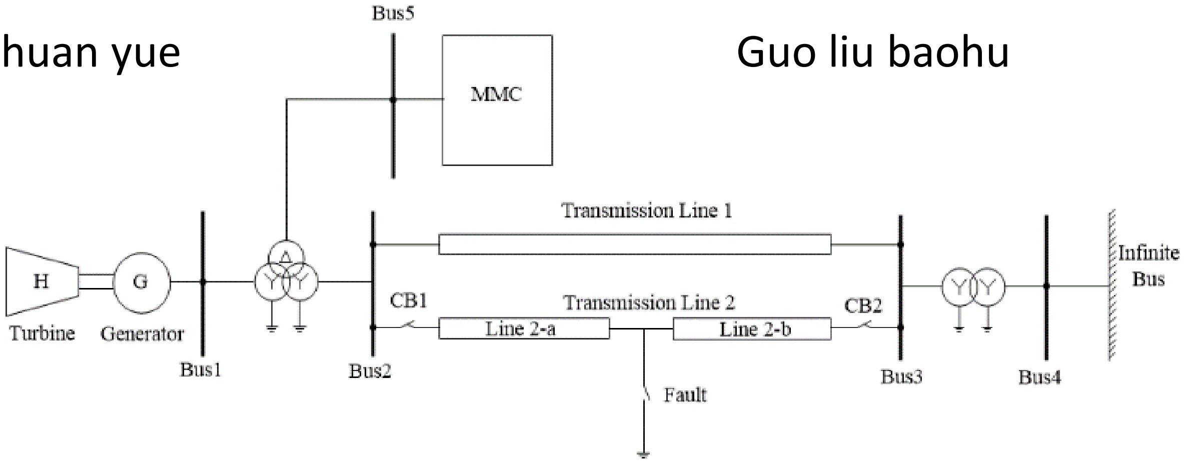
- **Demonstration of dead-beat control**
  left: voltage at point of common coupling (PCC)
  right: ac-current from MMC





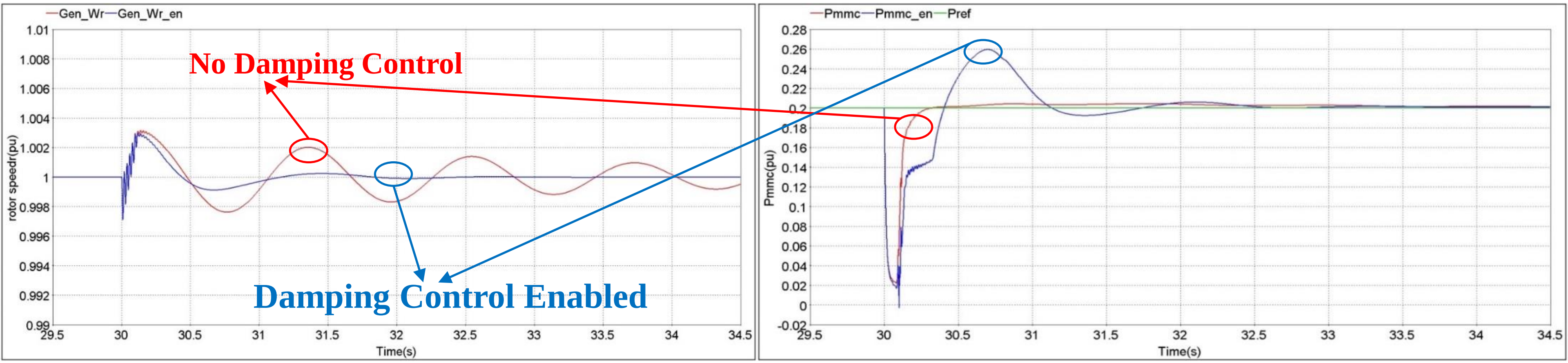
Di ya chuan yue

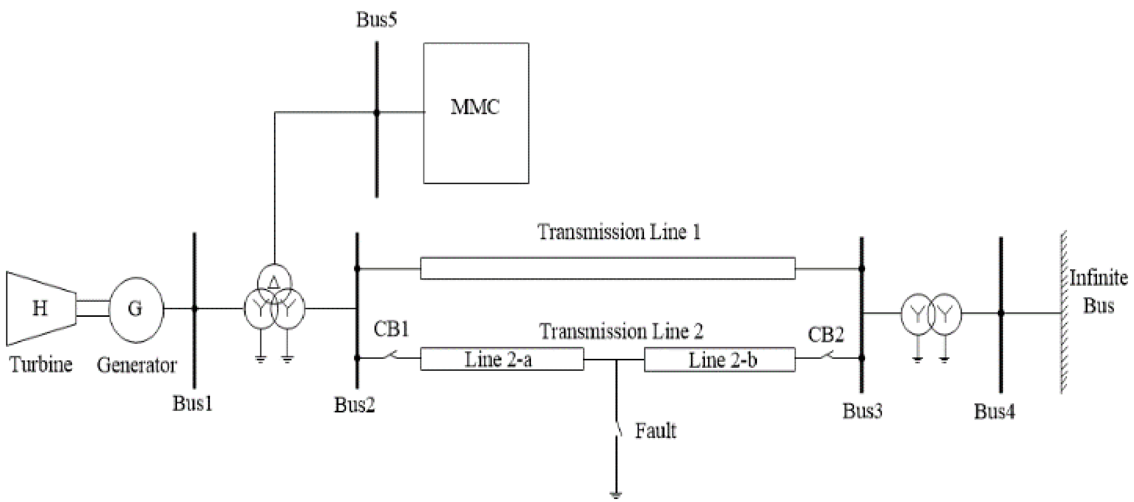
Guo liu baohu



Multiple controllability; Increase Transient Stability Limit and power transmissibility

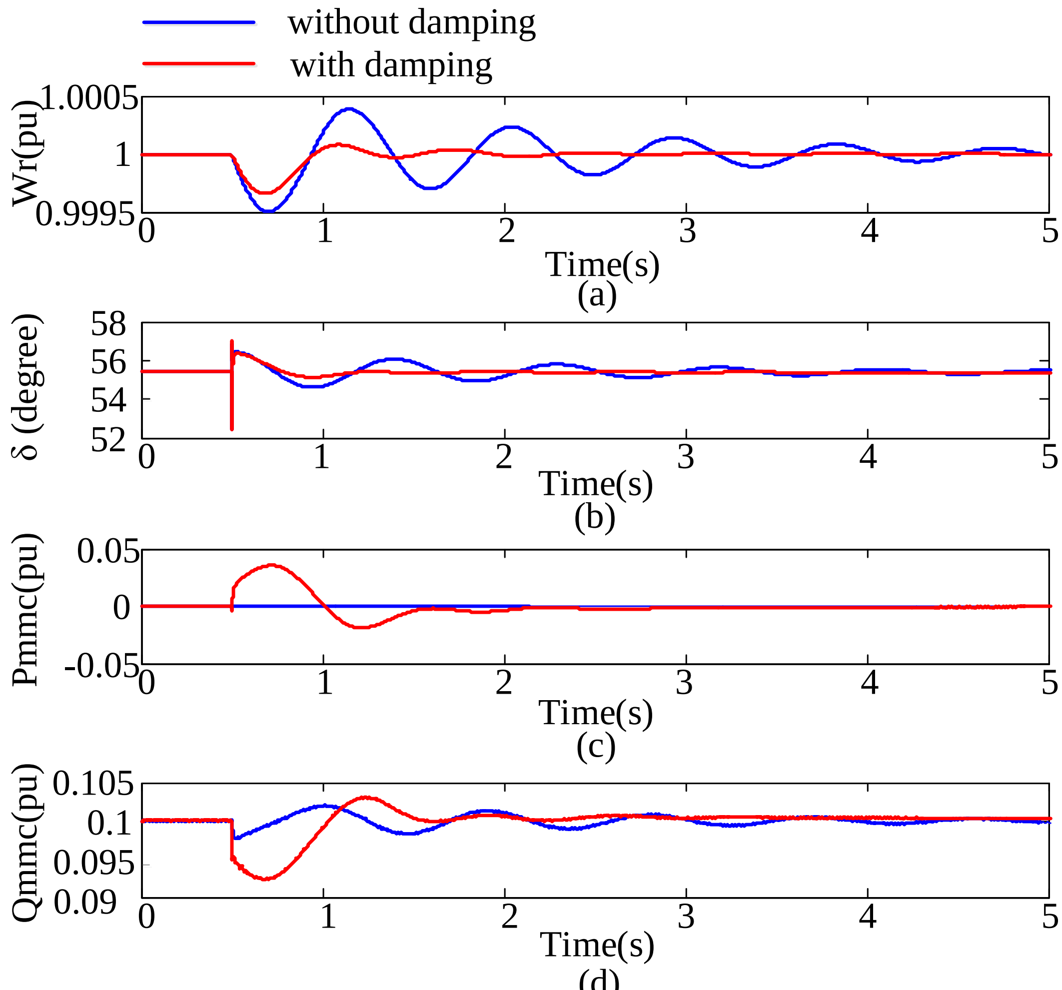
- **Turbine-Generator Speed (System Frequency)**
- **Active Power from MMC**



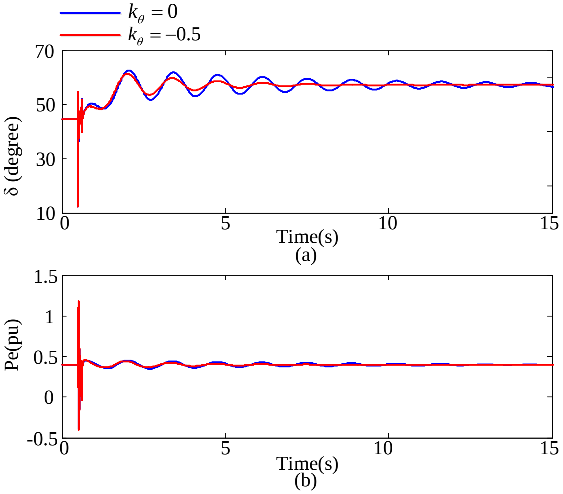


Multiple controllability; Increase Transient Stability Limit and power transmissibility

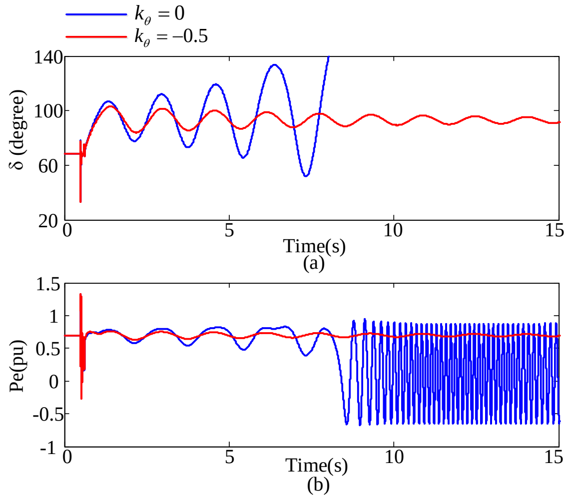
- **Damping can raise transient stability limit, raise transmissibility of power**



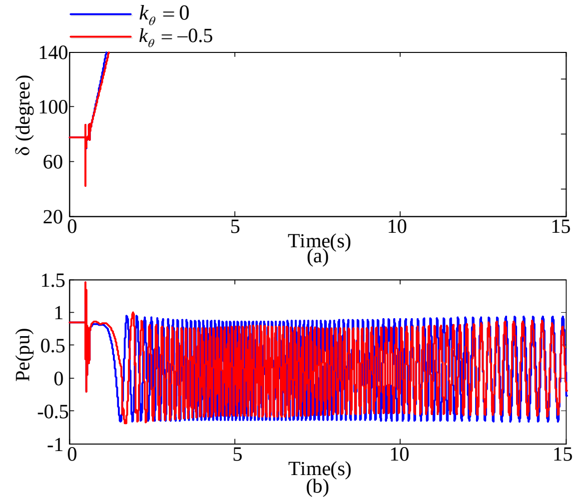
Simulation experiment on power oscillation



P_e=0.4pu, both are stable



P_e=0.7pu, unstable, stabilized by damping



P_e=0.85pu, cannot be stabilized by damping increase

Multiple controllability; Increase Transient Stability Limit and power transmissibility

- Damping can increase power transmissibility by **49% (提高49%功率传输)**

Damping Constant (k_0)	Transient Stability Limit	Power Angle	Power Transmissibility Gain
	Transmitted Power(pu) P_{base}=800MW	δ (degree)	Per Unit Gain Base Power 0.53x800MW
0	0.53	72.85	1
-0.1	0.58	78.71	1.09
-0.2	0.63	84.50	1.19
-0.3	0.69	91.93	1.30
-0.4	0.78	104.65	1.47
-0.5	0.78	104.65	1.47
-0.6	0.78	104.65	1.47
-0.7	0.78	104.65	1.47
-0.8	0.79	106.45	1.49
-0.9	0.79	106.45	1.49

Organization of Presentation

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- Numerical prediction by ODE coincides with Detail Model
- Quantitative prediction from algebraic formulas
- **Nonlinearity of MMC—treatment by linearization**

Engineering Practice

- Siemens HVDC PLUS
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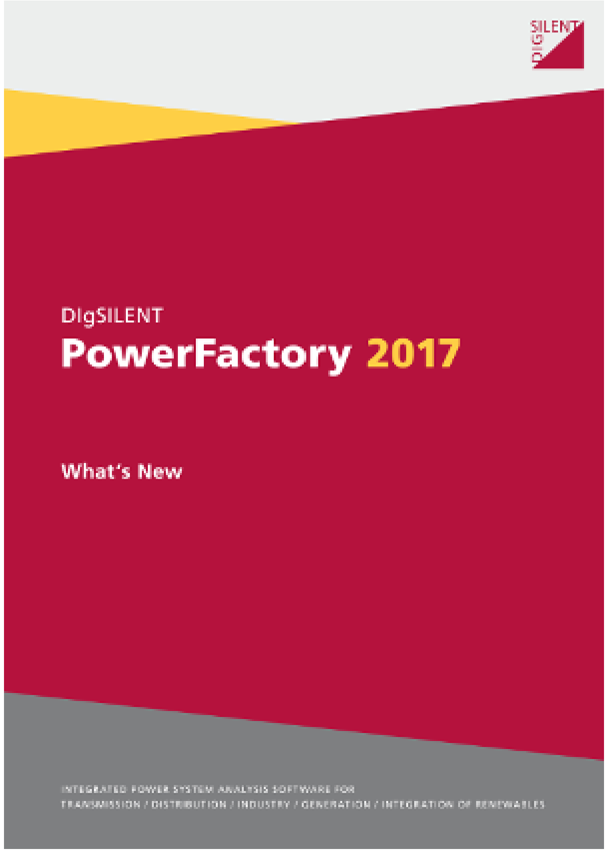
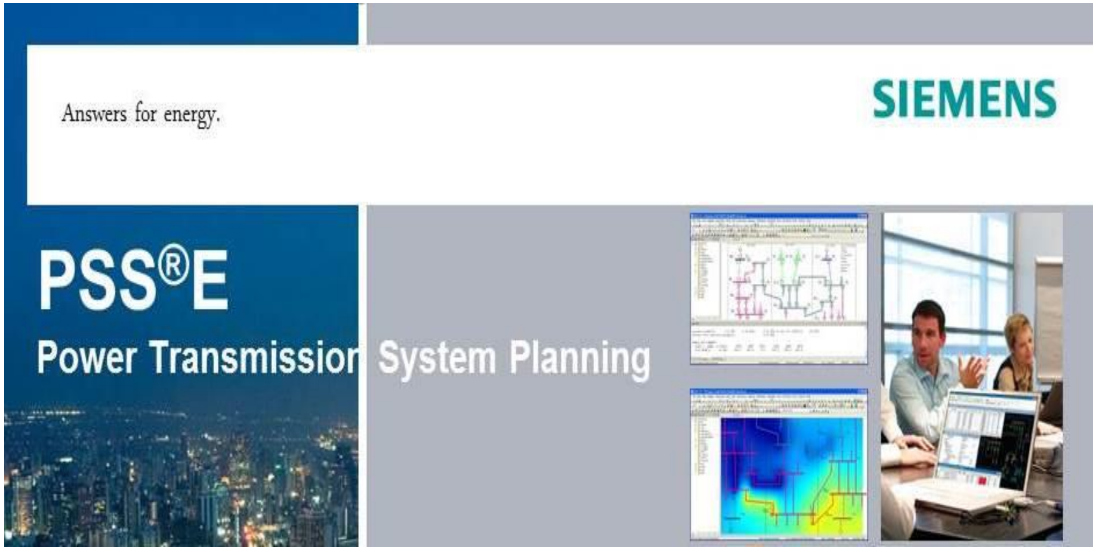
- **Simulation platforms for planning studies that can PSSE, Power Factory, HYPERSIM, OPAL-RT, RTDS**

Software for power transmission planning





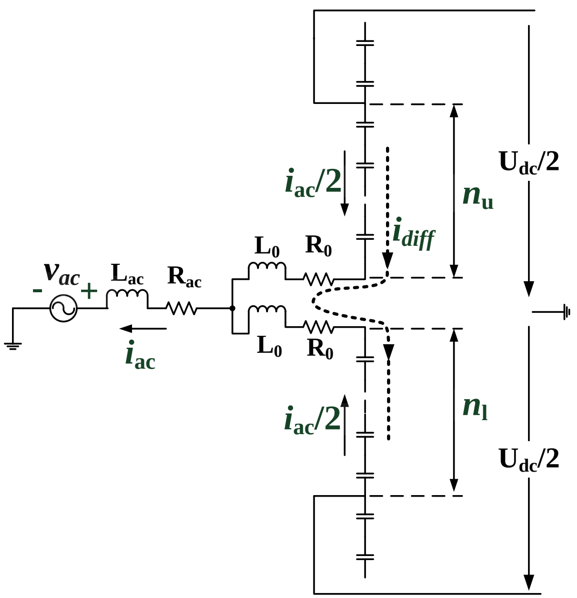
power transmission planning using digital simulation

RTDS Technologies

OPAL-RT

HYPERSIM

- Representing MMC in hybrid AC-DC Power Transmission planning
  - Simulating Detail model is time intensive
  - Each sub-module requires one ODE, there are hundreds of modules
  - ODE: Each phase has 4 equations---**10 times faster**



$$\frac{du_{U\ell,n}}{dt} = \frac{N}{C}\left(\frac{i_{ac\ell,n}}{2} + i_{diff\ell,n}\right)\left(\frac{1}{2} - \frac{u_{ref\ell,n}}{U_{dcl.n}}\right)$$

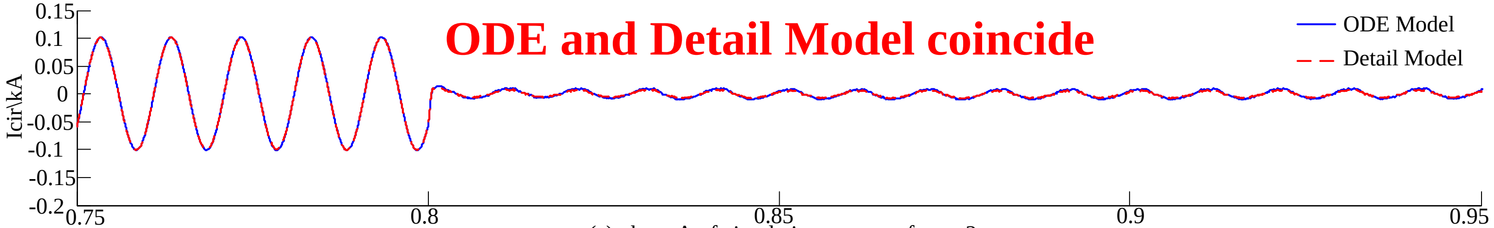
$$\frac{du_{L\ell,n}}{dt} = \frac{N}{C}\left(-\frac{i_{ac\ell,n}}{2} + i_{diff\ell,n}\right)\left(\frac{1}{2} - \frac{u_{ref\ell,n}}{U_{dc\ell,n}}\right)$$

$$\frac{di_{diff\ell,n}}{dt} = \frac{1}{2L_0}\Big[U_{dc\ell,n} - (2R_0 + R_{dc})i_{diff\ell,n} - \frac{1}{2}(u_{U\ell,n} + u_{L\ell,n}) + \frac{U_{ref\ell,n}}{U_{dc\ell,n}}(u_{U\ell,n} - u_{L\ell,n})\Big]$$

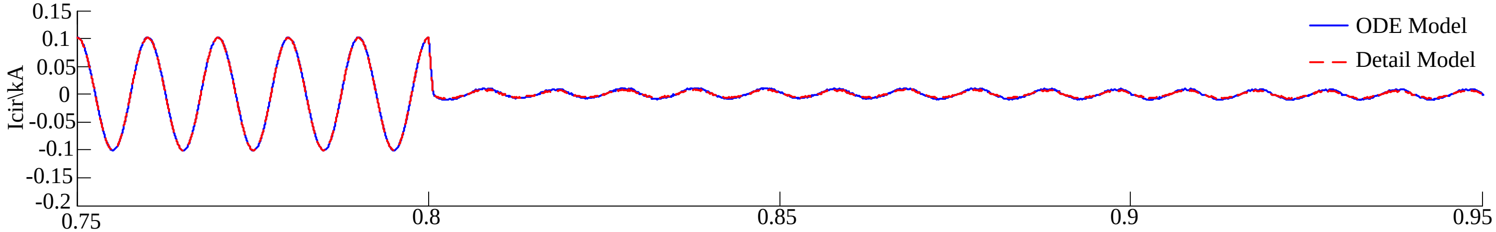
$$\frac{di_{ac\ell,n}}{dt} = \frac{1}{2L_{ac} + L_0}\Big[-2v_{ac\ell,n} - (2R_{ac} + R_0)i_{ac\ell,n} + \frac{1}{2}(-u_{U\ell,n} + u_{L\ell,n}) + \frac{U_{ref\ell,n}}{U_{dc\ell,n}}(u_{U\ell,n} + u_{L\ell,n})\Big]$$

➢ Accuracy test of ODE against detail simulation

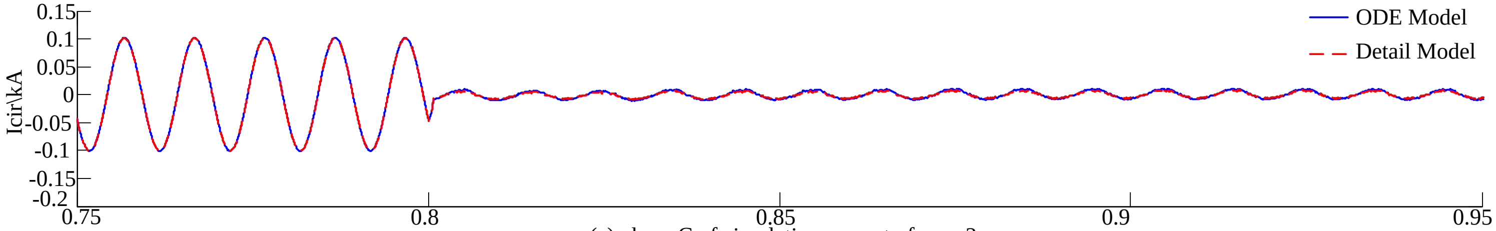
Example: circulating current of a, b and c phase of mmc.
no suppression 0.8s ≤ t. suppression enabled: t ≥ 0.8s



(a) phase A of circulating current of mmc2



(b) phase B of circulating current of mmc2



(c) phase C of circulating current of mmc2

- **Represent MMC by ODE in**
  - **POWER FACTORY**
  - **PSS-E**
  - **RTDS**
  - **OPAL-RT**
  - **HYPERSIM**

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Nonlinearity of MMC—treatment by linearization

- **ODE predicts nonlinearities of MMC**

  Existence of circulating current and its suppression by feedback.

- **ODE are nonlinear equations**

  Linearization about equilibrium solution yields time varying periodic matrix.

- **Result of Linearization**

  Linearized equation is time varying. Periodic in 50 or 60 Hz supply.

Nonlinearity of MMC—treatment by linearization

$$\frac{d\underline{x}}{dt} = \underline{f}(\underline{x}, \underline{u})$$

defining $\underline{x}=\underline{X_0}+\Delta\underline{x}$ where $\underline{X_0}$ is the vector of steady-state solution

$$\frac{d\underline{X}_0}{dt} + \frac{d\Delta\underline{x}}{dt} = \underline{f}(\underline{X}_0, \underline{u}) + \left.\frac{\partial(\underline{f}(\underline{x}, \underline{u}))}{\partial\underline{x}}\right|_{\underline{X_0}} \Delta\underline{x} + \left.\frac{\partial(\underline{f}(\underline{x}, \underline{u}))}{\partial\underline{x}}\right|_{\underline{u_0}} \Delta\underline{x}$$

$$\frac{d\Delta\underline{x}}{dt} = \left.\frac{\partial(\underline{f}(\underline{x}, \underline{u}))}{\partial\underline{x}}\right|_{\underline{u_0}} \Delta\underline{x} = [A(t)]\Delta\underline{x}$$

$$[\mathrm{A}(t)]=[A(t+T)].$$

Nonlinearity of MMC—treatment by linearization

- **Linearized Matrix is time varying because U_{ref} is time varying in 50 or 60 Hz.**
- **Nonlinearity is known as Bi-linear**

$$[A(\mathrm{t})] =$$

$$\begin{pmatrix} 0 & 0 & \frac{N}{C}(\frac{1}{2}-\frac{u_{ref}}{U_{dc}}) & \frac{N}{2C}(\frac{1}{2}-\frac{u_{ref}}{U_{dc}}) \\ 0 & 0 & \frac{N}{C}(\frac{1}{2}+\frac{u_{ref}}{U_{dc}}) & -\frac{N}{2C}(\frac{1}{2}+\frac{u_{ref}}{U_{dc}}) \\ -\frac{1}{2L_0}(\frac{1}{2}-\frac{u_{ref}}{U_{dc}}) & -\frac{1}{2L_0}(\frac{1}{2}+\frac{u_{ref}}{U_{dc}}) & -\frac{1}{2L_0}2R_0 & 0 \\ -\frac{1}{L'}(\frac{1}{2}-\frac{u_{ref}}{U_{dc}}) & \frac{1}{L'}(\frac{1}{2}+\frac{u_{ref}}{U_{dc}}) & 0 & -\frac{1}{L'}(R') \end{pmatrix}$$

Nonlinearity of MMC—treatment by linearization

Aleksandr Lyapunov

Gaston Floquet

Nonlinearity of MMC—treatment by linearization

Stability: eigenvalues of state-transition matrix lies within unit circle

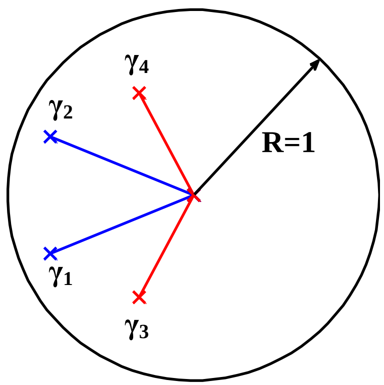
$$\Delta\dot{\underline{x}} = [A(t)]\Delta\underline{x}$$

Form state-transition matrix [Φ(T,0)]

[A(t)]=[A(t+T)]

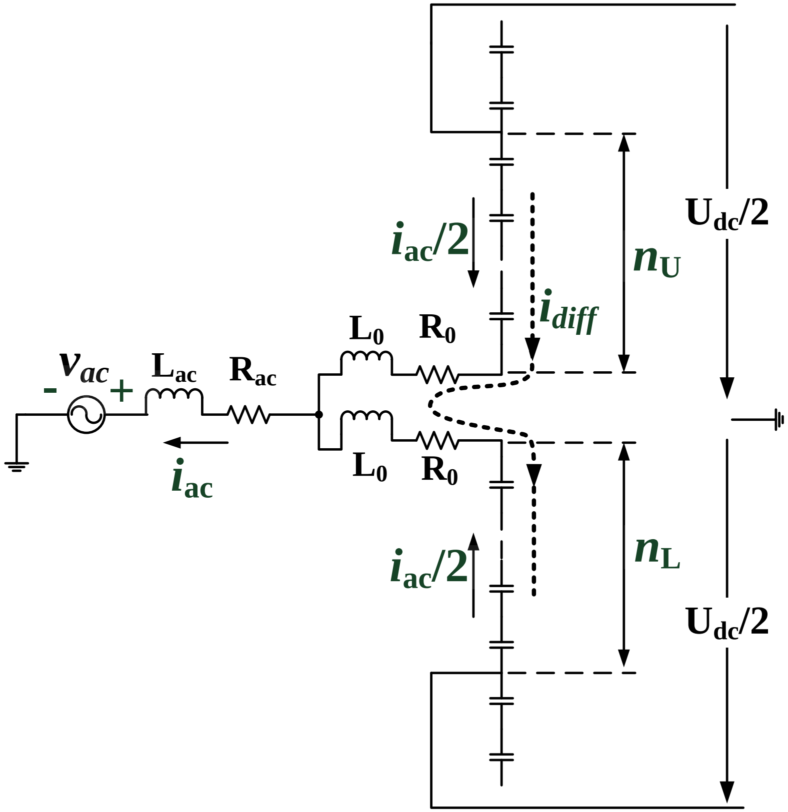
$$\Delta\underline{x}(t) = [\Phi(t,0)]\Delta\underline{x}(0)$$

$$\frac{d[\Phi(t,0)]}{dt} = [A(t)][\Phi(t,0)]$$



Nonlinearity of MMC—treatment by linearization

- **Liapunov-Floquet Theory yields graphs to choose parameter values for best damping.**



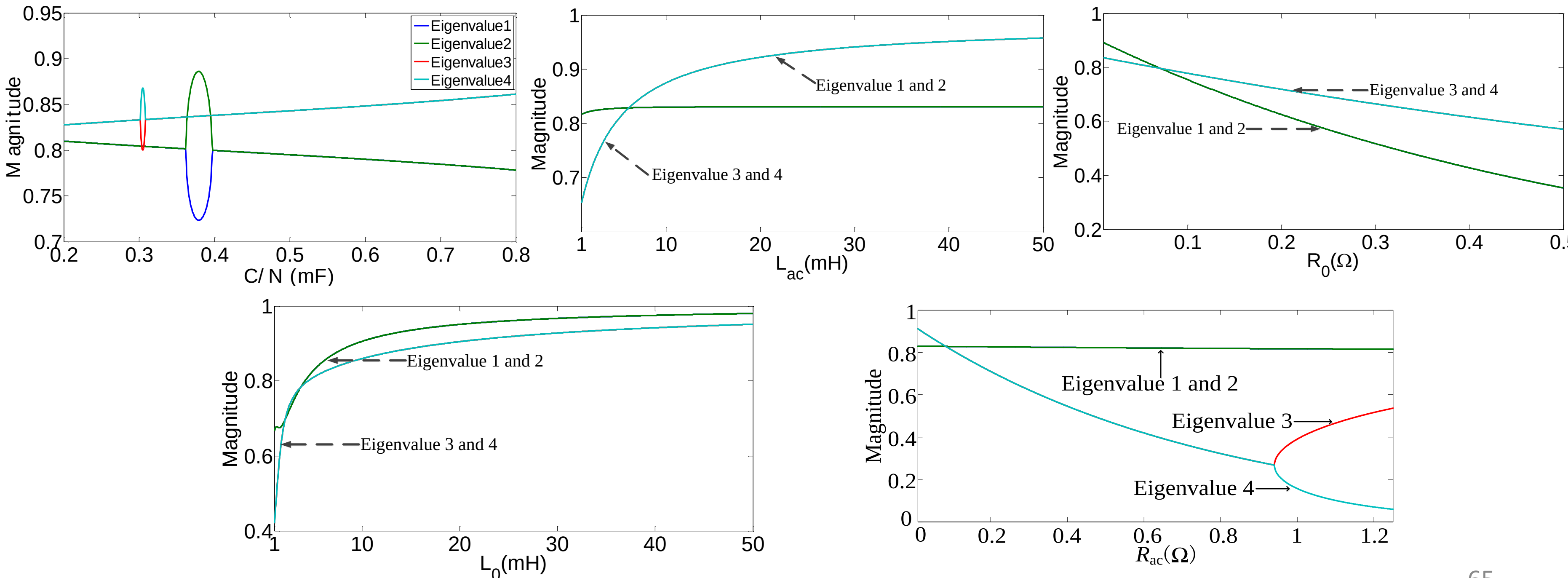
MMC parameters are

C/N, L_{ac}, L_o, R_{ac}, R_o,

Choose the parameter values with lowest magnitudes of all eigenvalues predicted by Liapunov-Floquet Theory .

Nonlinearity of MMC—treatment by linearization

- **Liapunov-Floquet Theory yields graphs on damping coefficients as functions of** ***C/N, L_{ac}, L_o, R_{ac}, R_o***
- For best damping, the magnitude should be as low as possible.
- The designer chooses parameters such that the largest of the 5 magnitudes is as small as possible. (Min-Max).



Nonlinearity of MMC—treatment by linearization

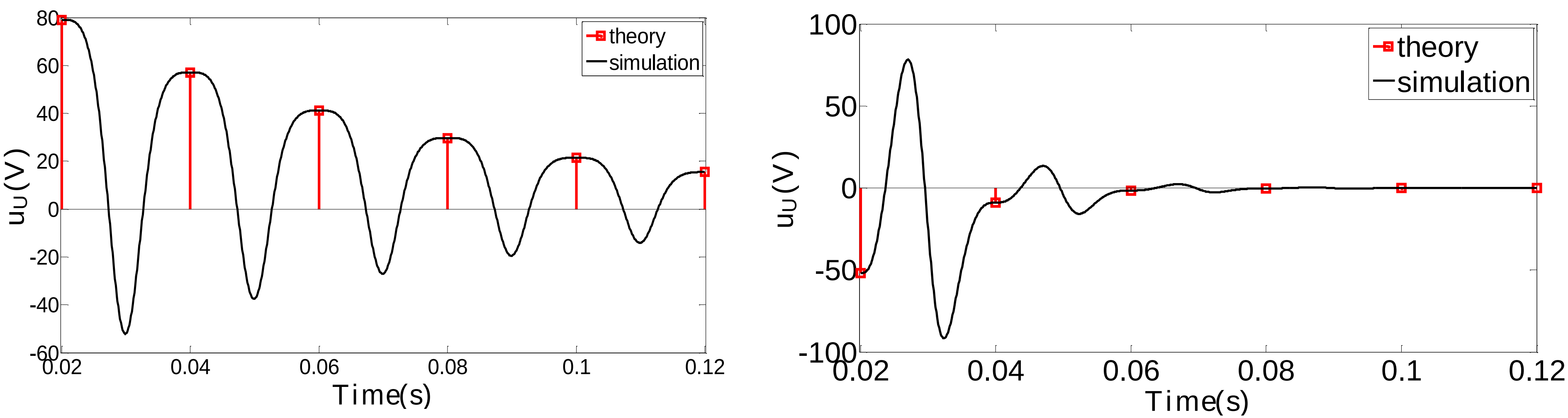
➢ Validation of Formulas from Liapunov-Floquet Theory (公式验证)

- ❑ Agreement of simulations of time-domain linearized state-variable with Liapunov-Floquet Theory predictions

Validation of Liapunov-Floquet Theory against simulated transient

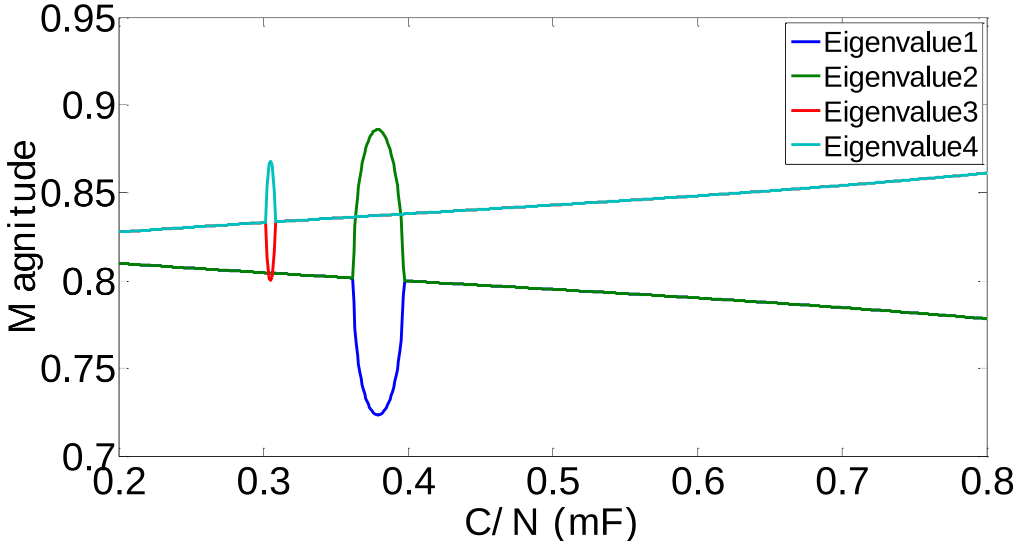
Magnitude 0.721

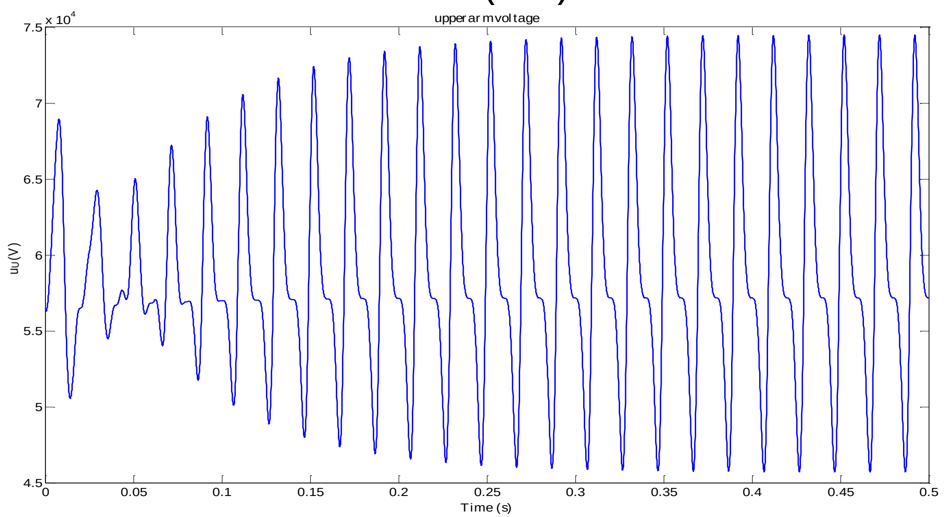
Magnitude 0.172



Nonlinearity of MMC—treatment by linearization

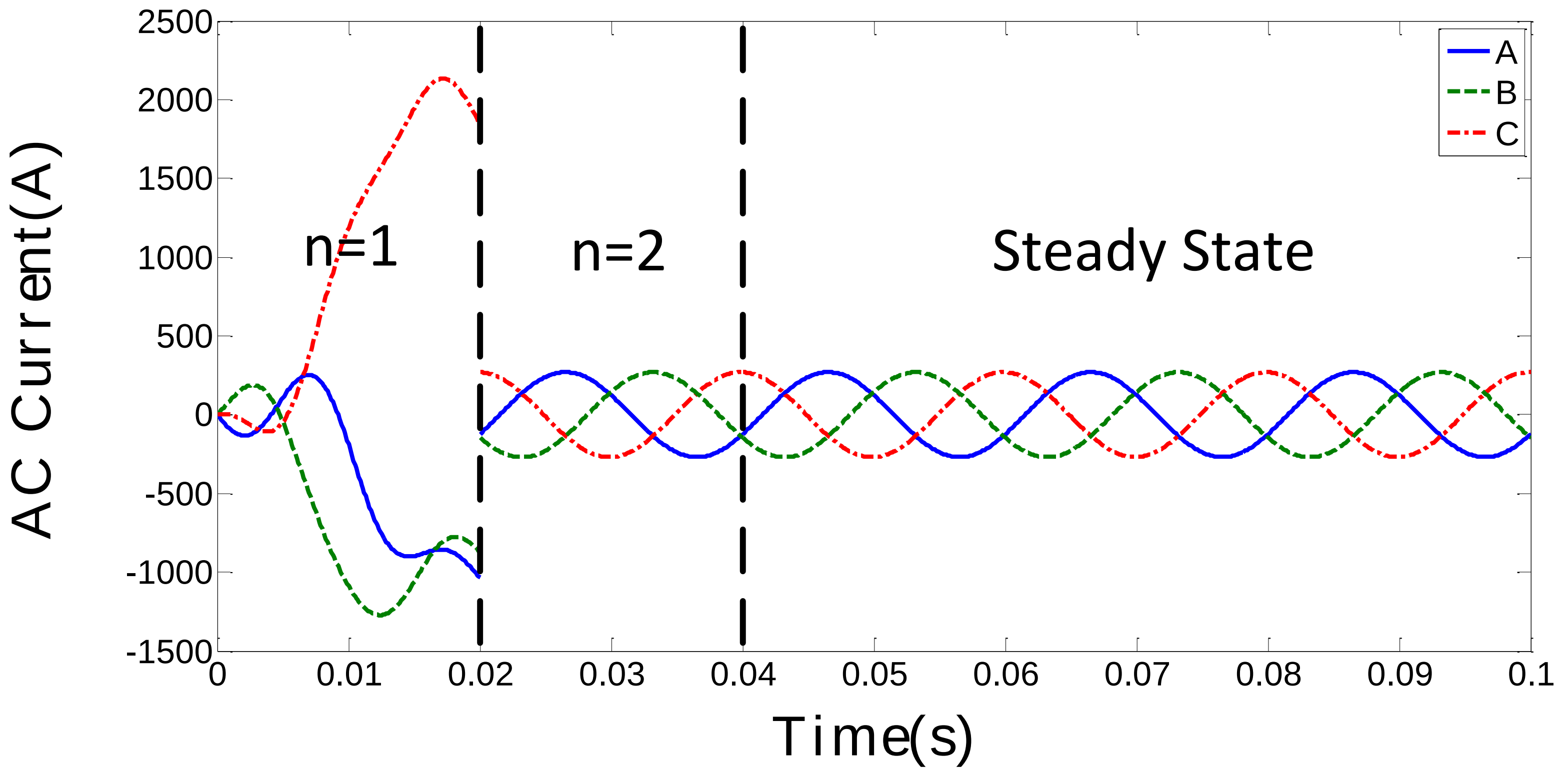
➢ **Wrong parameter choice results in forced oscillation**





Nonlinearity of MMC—treatment by linearization

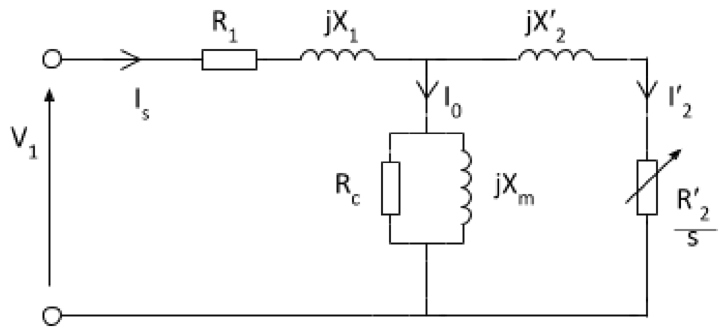
- **Reaching steady-state solution within 1 cycle of supply frequency**
- Save waiting time for transients to be damped out
- Applying algorithm of Aprille and Trick



Conclusion

Requirements of coming of age are satisfied.

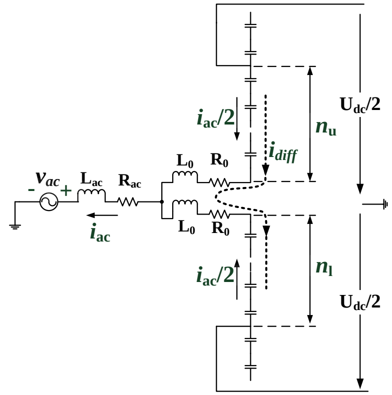
- **Induction Motor 1888**
- **Equivalent Circuit**



- **ODE Equations**

$$\begin{bmatrix} v_{qs} \\ v_{ds} \\ v_{qr} \\ v_{qr} \end{bmatrix} = \begin{bmatrix} R_s+sL_s & -\omega_e L_s & sL_m & -\omega_e Lm \\ -\omega_e L_s & R_s+sL_s & -\omega_e L_m & pL_m \\ sL_m & (\omega_e-\omega_r)L_m & R_r+sL_r & (\omega_e-\omega_r)L_r \\ -(\omega_e-\omega_r)L_m & sL_m & -(\omega_e-\omega_r)L_r & R_r+sL_r \end{bmatrix} \begin{bmatrix} i_{qs} \\ i_{ds} \\ i_{qr} \\ i_{qr} \end{bmatrix}$$

- **MMC 2003**
- **Detail Model**



- **ODE Equations**

$$\frac{du_{U\ell,n}}{dt} = \frac{N}{C}\left(\frac{i_{ac\ell,n}}{2} + i_{diff\ell,n}\right)\left(\frac{1}{2} - \frac{u_{ref\ell,n}}{U_{dcl.n}}\right)$$

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$$\frac{di_{ac\ell,n}}{dt} = \frac{1}{2L_{ac} + L_0}\left[-2v_{ac\ell,n} - (2R_{ac} + R_0)i_{ac\ell,n} + \frac{1}{2}(-u_{U\ell,n} + u_{L\ell,n}) + \frac{U_{ref\ell,n}}{U_{dc\ell,n}}(u_{U\ell,n} + u_{L\ell,n})\right]$$

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Thank you

For your patience