Toward a 100% Power Electronics Interfaced Transmission Grid

………………

Xavier KESTELYN

L2EP
Laboratoire d'électrotechnique et d'électronique de puissance de Lille

Université de Lille
Arts et Métiers Sciences et Technologies
centralelille
JUNIA Grande école d'ingénieurs

1- Introduction

2- Research context

3- Overview of my lab activities about power electronic converters connected to power systems

4- A tool for a systematic assessment of stability?

5- Conclusion

1. Introduction

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Laboratoire d'électrotechnique et d'électronique de puissance de Lille

Xavier KESTELYN

Full Professor of Electrical Engineering (civil servant):

- Teaching (Half-time: 192h of lecture per year)
- Research / Transfer to socio-economic world (Half-time)
- Administrative tasks (The rest of the time ☺)

Arts et Métiers Institute of Technology - ENSAM

My Institution: Public School of Engineering

Laboratory of Electrical Engineering and Power Electronics- L2EP

My group of research (My lab): gathering of researchers from several private or public institutions around the town of Lille (North of France)

Arts et Métiers Institute of Technology – ENSAM

A single French public institution with eight campuses and three institutes founded in 1780

L2EP Laboratoire d'électrotechnique et d'électronique de puissance de Lille

Arts et Métiers Institute of Technology

11 SITES across France specialising in education and research

220 PHD STUDENTS in our "Engineering Sciences" doctoral school

1 BACHELOR'S DEGREE OF TECHNOLOGY

6000 STUDENTS across all courses

15 LABORATORIES and research teams

11 ENGINEERING PROGRAMMES: 1 Grande École engineering programme; 10 Apprenticeship engineering programmes

1100 PERSONNEL lecturers, technicians & administrative staff

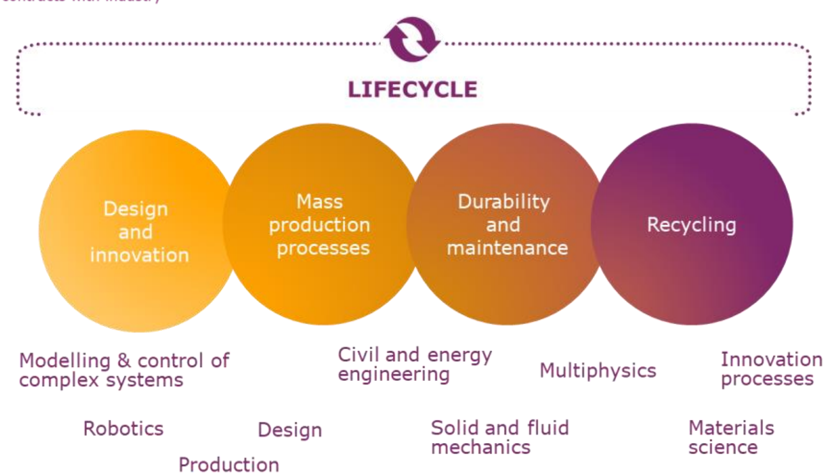
7 MILLION in revenue LIFELONG SKILLS DEVELOPMENT

+20 National research master's programmes

15 million in revenue generated through contracts with industry

2000 AUDITORS in lifelong skills development

17 MASTÈRES SPECIALISÉS © programmes



Laboratory of Electrical Engineering and Power Electronics- L2EP

Gathering 40 researchers and 40 PhD from four institutions of Lille:

Université de Lille | Arts et Métiers Institute of Technology | centralelille | JUNIA Grande école d'ingénieurs

Made up of four research teams:

- CONTROL Team
- POWER SYSTEM Team → Energy Management; 100% PE grids; Real-time simulation
- POWER ELECTRONIC Team
- NUMERICAL TOOLS AND METHODS Team

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2. Research context

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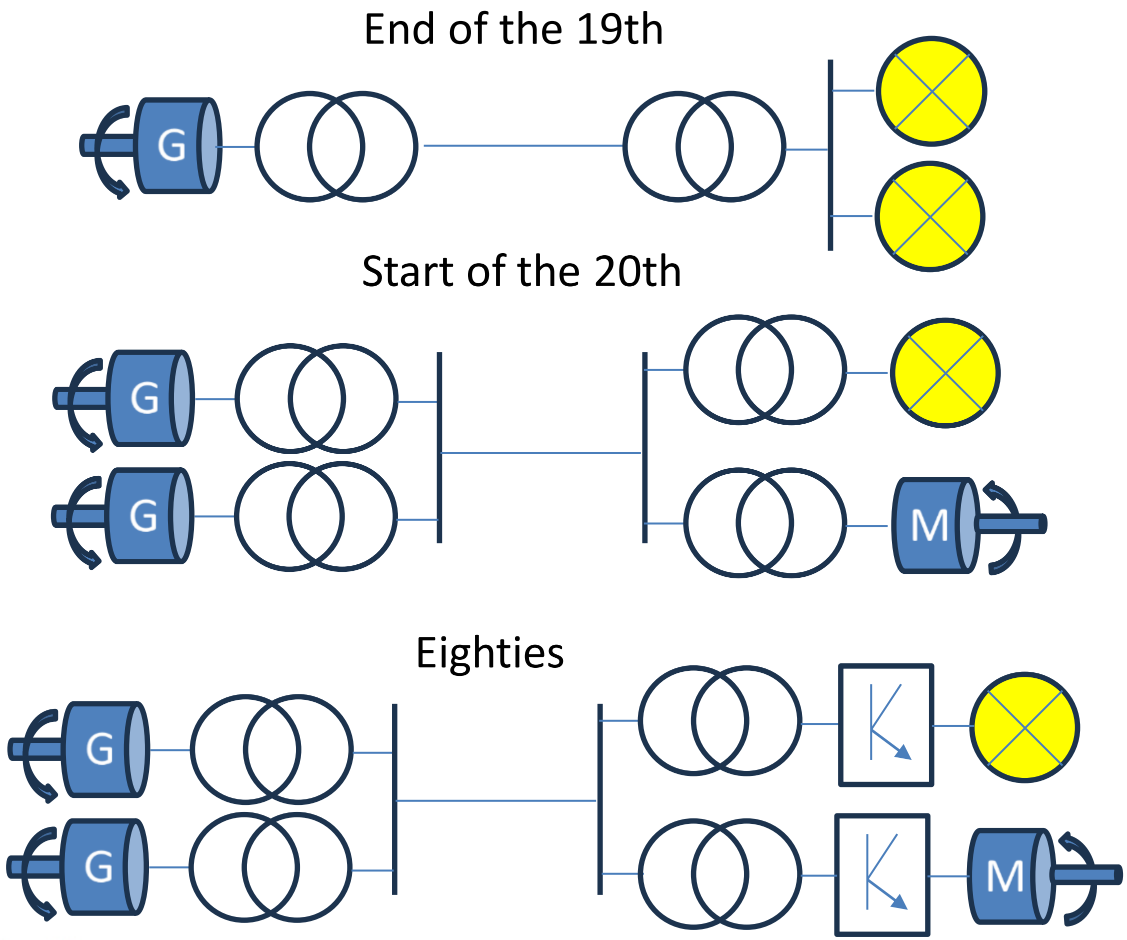
An evolving network



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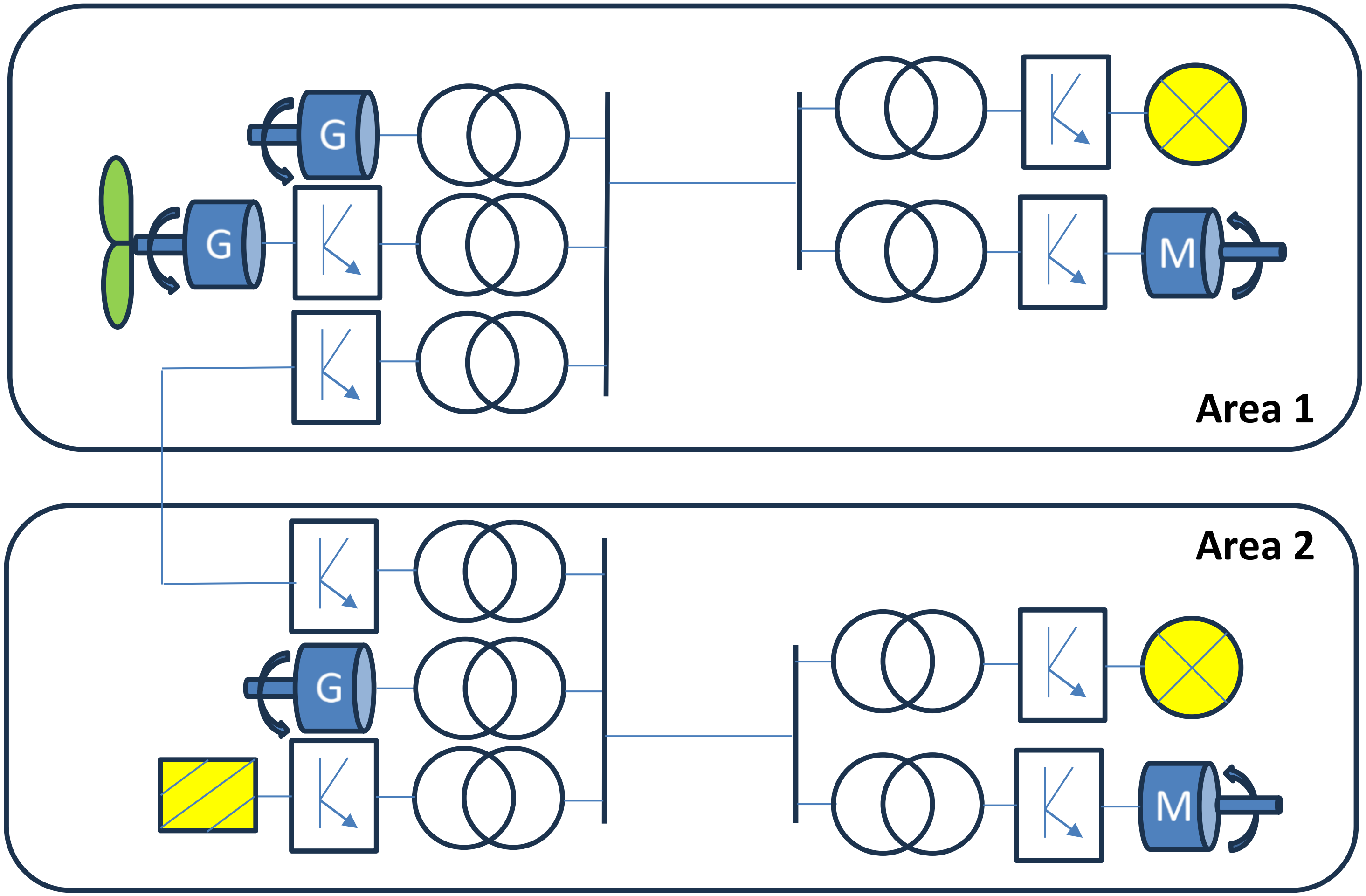
An evolving network

Start of the 21th



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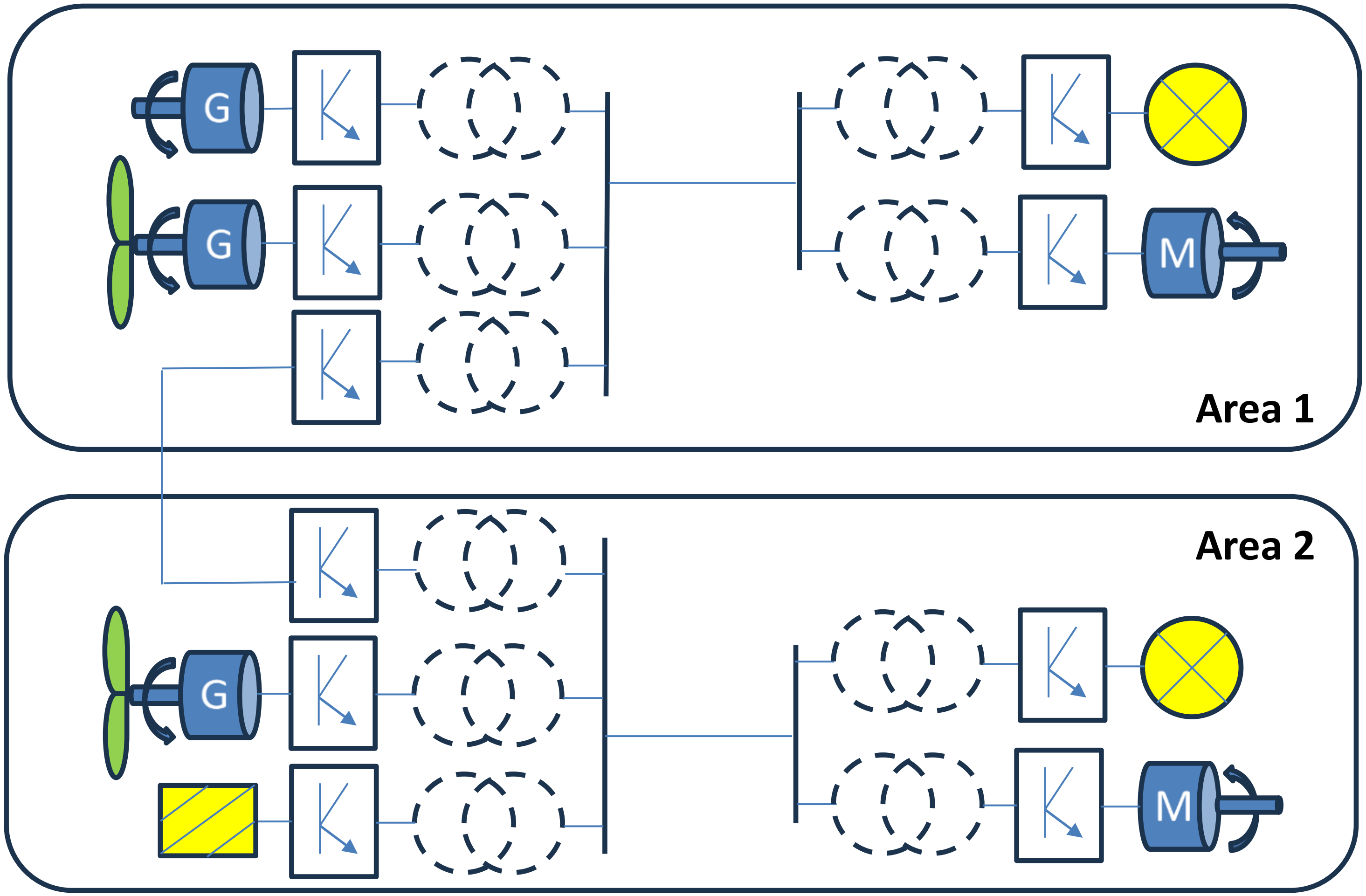
An evolving network

Near Future: A 100% PE-interfaced power grid?



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Mandatory technical needs of a transmission grid

Technical needs	Description
Sinusoidal waveform generation	Conversion of a primary energy resource into electrical energy on three-phase alternating currents
Transient voltage stiffness	The first voltage cycles following an event should have a limited amplitude and frequency drop from the nominal values
Hard transient resilience	The device must survive when stressing event occurs
Autonomous operation	Critical functions must be ensured only based on measurements available locally
Steady-state voltage amplitude control	The steady-state terminal voltage amplitude must be kept into acceptable range
Steady-state voltage frequency control	The steady-state terminal voltage frequency must be kept into acceptable range

Additional technical needs of a transmission grid

Technical needs	Description
Synchronization	All the electrical sources must converge into a consensus frequency
Load sharing	Load variation must be shared among generation units according to their ratings or a predefined law
Stability	Parallel electrical sources must remain stable after small or large disturbances

Some associated challenges to a 100% PE-interfaced grid

- **From PQ to PV:** Some converters must be able to impose a constant voltage, as synchronous generators do. **From Grid FoLlowing (GFL)/Grid Supporting to Grid ForMing (GFM).**
  - *How many GFM for a given number of GFL?*
  - *Where are the best locations for GFM?*
  - *Possible switching between GFL to GFM function?*

- **New topologies and tunings** for an **overall stability**: **dynamics are not the ones encountered with a synchronous generator-based grid.**
  - *What topology for GFM?*
  - *Do we have to modify classical GFL topologies?*
  - *How to tune GFM and GFL for small and large signal stability?*

- **Overcurrent capability:** How to **avoid oversizing** to cope with **overcurrent** during faults as synchronous generators intrinsically do?
  - *How to limit current fault without compromising the overall stability?*

3- Overview of L2EP activities about power electronic converters connected to the power systems

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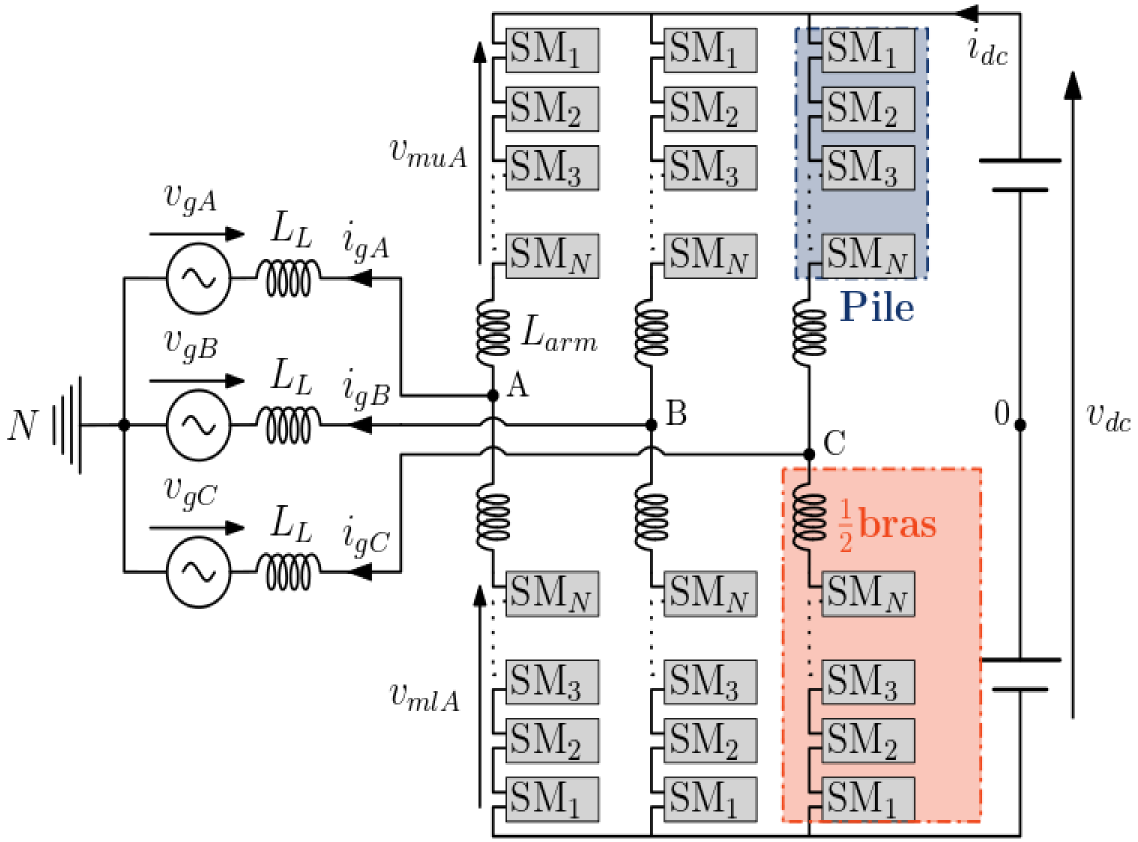
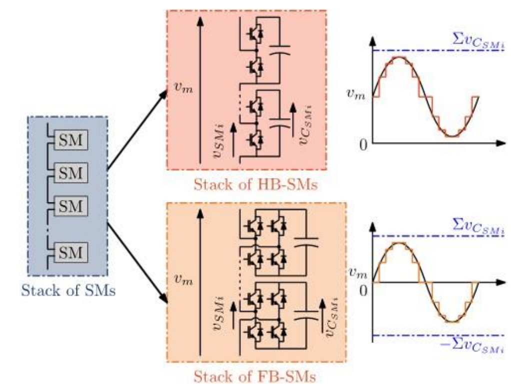
Control and Design of High Voltage Converters

Design of the Modular Multilevel Converter Control (MMC):
S. Samimi (PhD) 2012 – 2016 and **H. Saad (**PhD) 2012 – 2015





Control and Design of High Voltage Converters

Design of the Modular Multilevel Converter Control

In 2013, we were among the first team to propose a simplified model which is very useful to design the control of current and energy in the converter

Identification of 11 independent state variables :

- 6 voltages
- 5 currents

To have a full control of this system, 11 loops must be designed

Proposal of rigorous methodology to design all these loops

More recently : work to improve the control in case of unbalance situation or current source connection

Control and Design of High Voltage Converters

Design and Control of an Alternate Arm Converter: P. Vermeersch (PhD) 2017 – 2021

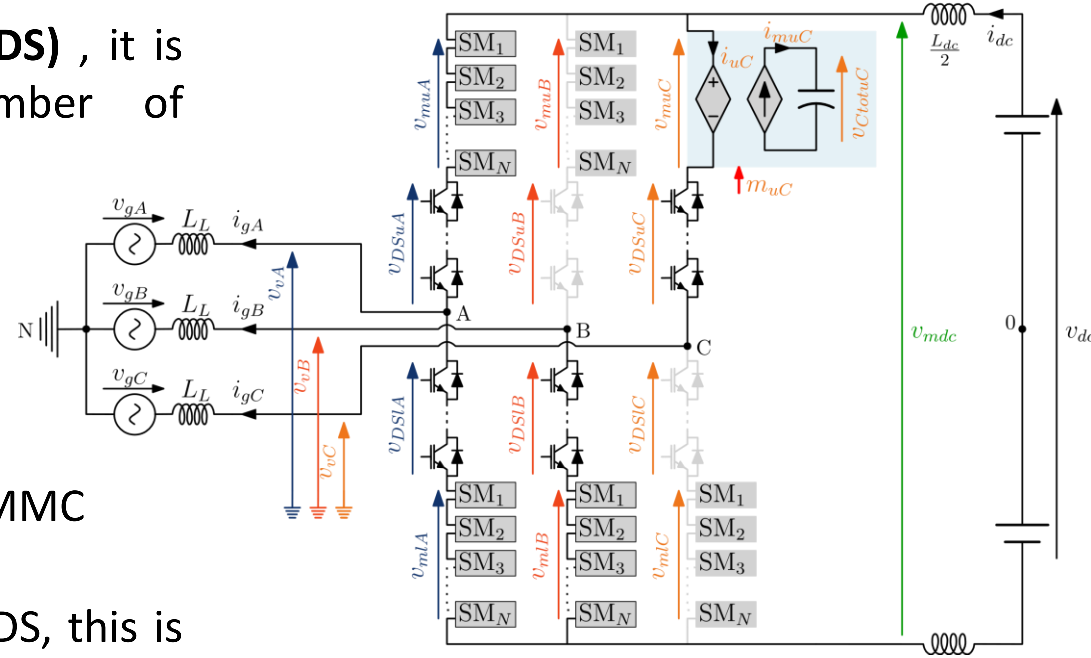
Thanks to the Director Switches **(DS)** , it is possible to decrease the number of submodules in an arm:

- Need of Full bridge submodules

- DC Fault Capability

- Similar losses compare to the HB-MMC

Due to the Boolean control of the DS, this is a sequential system.



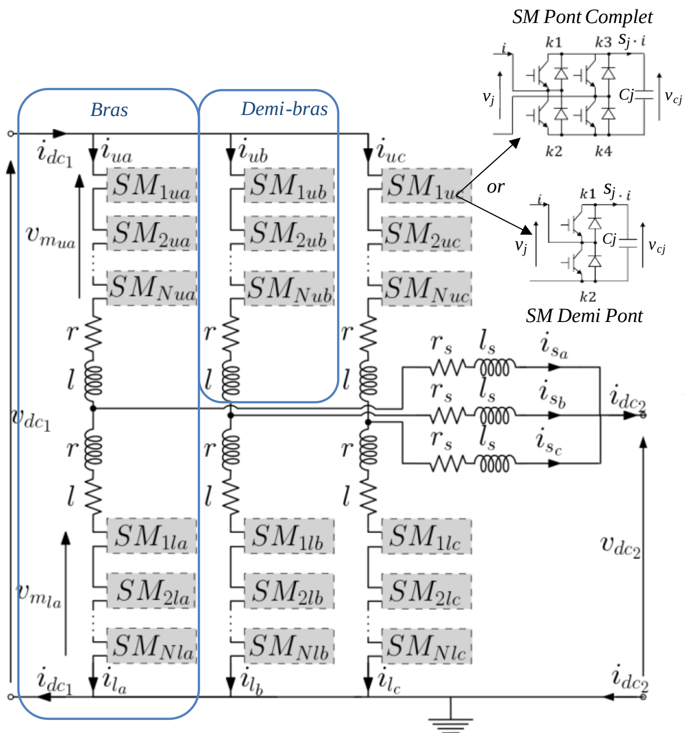
Proposal of a rigorous methodology to design a control adapted to an Extended overlap AAC (always an arm with 2 DS closed)

Control and Design of High Voltage Converters

Multi Terminal DC grid with DC/DC converter: Yafang Li's (PhD) : 2016 – 2019

Modular Multilevel Converter: M2DC

Similar control than the MMC with more possibilities



Identification of 11 independent state variables:

- 6 voltages
- 5 currents

AC circulating currents required:

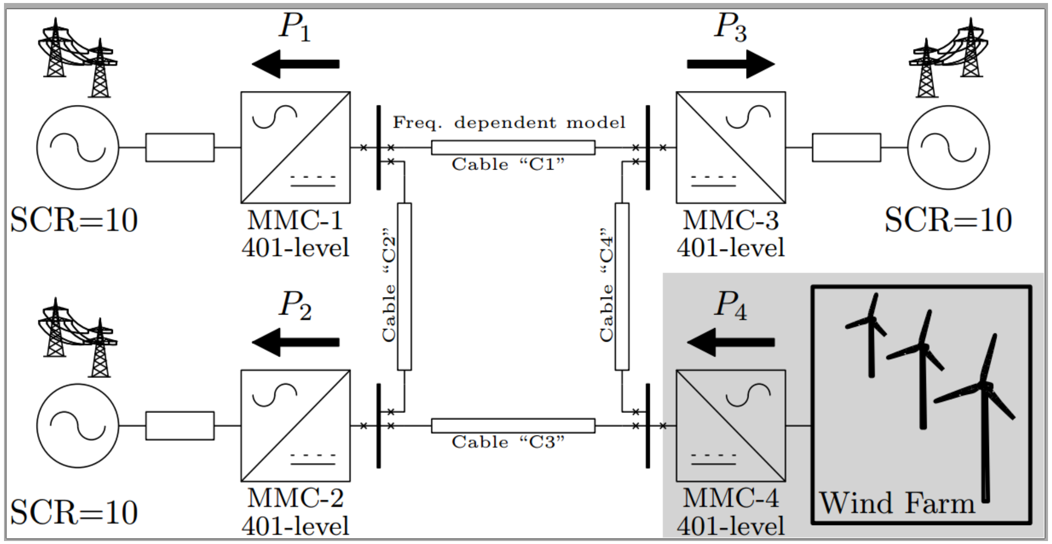
- frequency and amplitude free

Proposal of :

- Tools to design the converter depending on the circulation current frequency and amplitude
- Full state variable control with circulating currents and losses minimization

Multi Terminal DC grid

Pierre Rault (PhD) : 2011 – 2014 - within the European Project – Twenties – subcontractor of RTE
Julian Freytes (PhD) 2014 – 2017 - within the European Project – Bestpath – RTE workpage leader
Kosei Shinoda (PhD) 2014 – 2017 – with Supergrid Institute



Small signal stability study of a MTDC grid in collaboration with Sintef – NTNU - Trondheim

Industrial study within Betspath where the different MMC models were given by industrial manufacturers.

Multi Terminal DC grid

- The classical PI models of the cables are not relevant for this kind of studies.

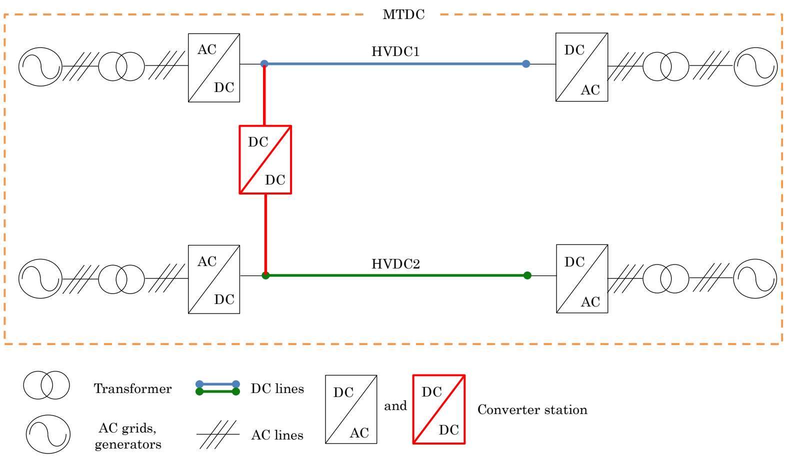
- More advanced models are needed but for the stability studies, they can be much simplified, and, at the end, they are more damped than PI models.

- Even if these systems seem quite complex, it is possible to catch the dominant behavior with very simple level of modeling (1st order) and then have a clear understanding of overall dynamics of the system.

With an appropriate control of the MMC, it is possible to enhance the stability of the DC grid: principle of the virtual capacitor.

Multi Terminal DC grid

DC/DC converter – on going work



HVDC grids or MTDC grids **interconnection:**
- Strengthen the grid (Power exchanges and stability)
- Integration of Huge renewable energy centers

- Interconnection of commissioned DC link:
  - similar to AC grid history
- Different voltage levels
  - Progressive investment and design
  - Permanent technological evolution
- Need for DC / DC converters:
  - Adapt the voltages / adapt the grounding.
  - Control the flow (bidirectional)
  - Act as a firewall in case of a short circuit

Multi Terminal DC grid

DC/DC converter – on going work

Ghazala Shafique (PhD) : 2021 – expected 2024 – ANR (French national research agency) funding

Integration of static DC / DC Converters for the Interconnection of high voltage DC Transmission grids

Objectives : management of power flows and the stability of a mesh DC grid integrating a DC / DC converter

Johan Boukhenfouf (PhD) : 2023 – 2025 – ANR (French national research agency) funding

DC/DC converter design and control for HVDC interconnection

Development of a demonstrator composed of :

- 2 DC/DC converters (M2DC and MMC Dual Active Bridge)
- MTDC Mock-up integration

High power converter in AC transmission grid: grid forming control

Guillaume Denis (PhD) : 2013 – 2017 RTE Funding
Taoufik Qoria (PhD) : 2017 – 2020 within Migrate Project

These works have been the opportunity to develop a theory about grid forming control:

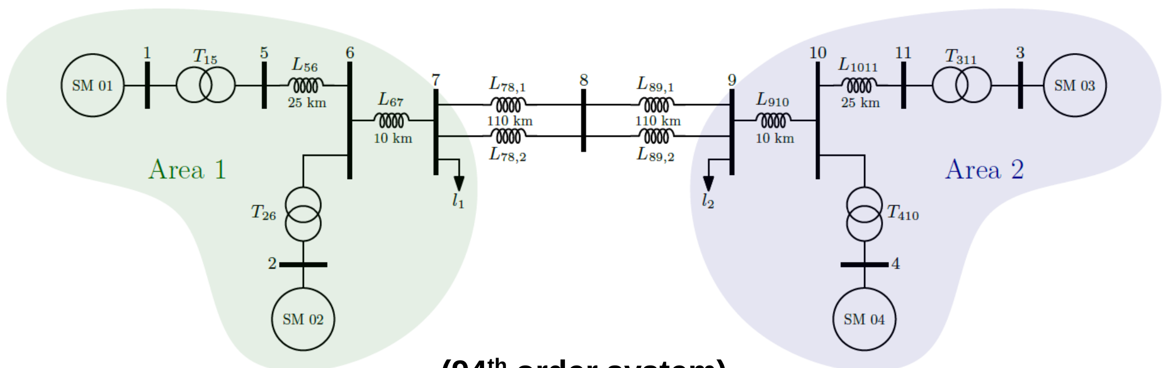
- starting from some basic considerations about power exchanges in the grid
- increasing the complexity by applying the theory to Modulator Multilevel Converter or VSC with LC filter connection

Some work have been done also about the question of the transient stability

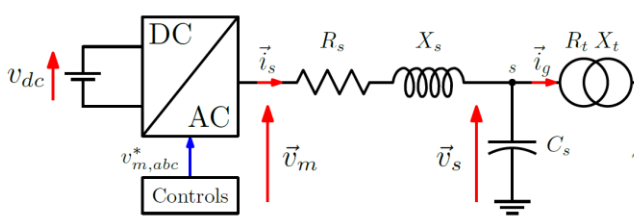
High power converter in AC transmission grid: grid forming control

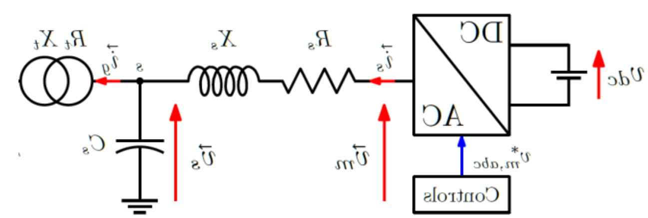
Guilherme Pereira (PhD) : 2017 – 2020 EDF Funding

Interaction between synchronous machines and power electronic converters



(94th order system)





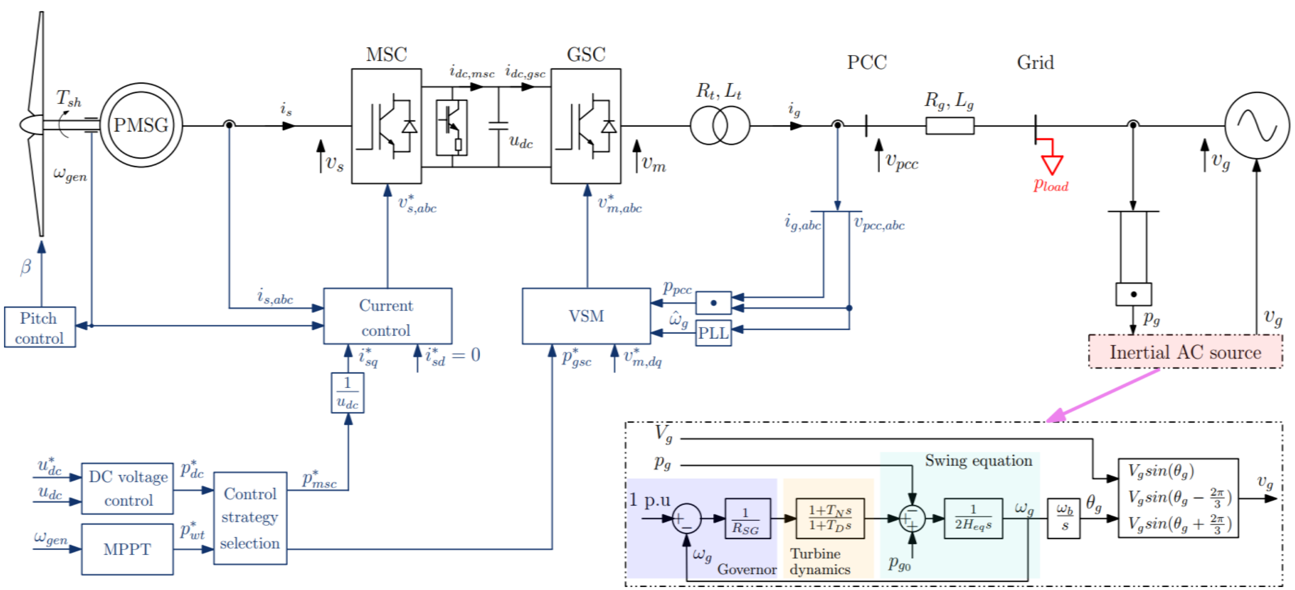
In case of grid forming control, it is possible to use some very simple models similar to simplified modelling of synchronous machines to capture the dominant behavior

High power converter in AC transmission grid: grid forming control

Artur Avazov (PhD) : 2018-2022 Joint doctorate with KU Leuven

1 - **Wind turbine and grid forming**

Double mass modeling for the mechanical system



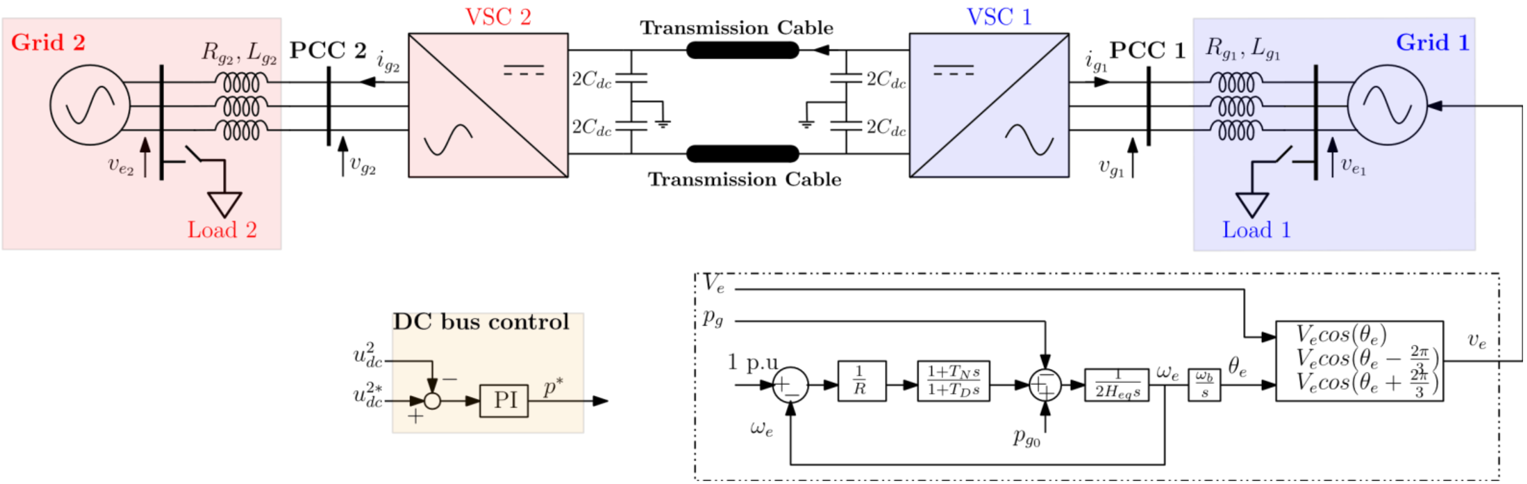
2 – **Equivalent model of a wind farm with grid forming control**

3 – **Integration of the wake effect to propose an equivalent model of the wind farm**

High power converter in AC transmission grid: grid forming control

Ebrahim Rokrok (PhD): 2018 – 2022 – Sintef (Norway) project funding

Grid forming and HVDC



Achieving one grid forming on one converter with an HVDC converter is quiet challenging but possible.

Achieving 2 grid forming controls on each side require a control on the DC bus

Improvement on the transient stability analysis + development of new control algorithm for grid forming control.

High power converter in AC transmission grid: grid forming control – One going works

Yahya Lamrani (PhD): 2021 – expected 2024 – RTE funding

Optimal position of Grid forming converter in transmission grid

Yorgo Laba (PhD): 2022 – expected 2025 – RTE/ENEDIS funding

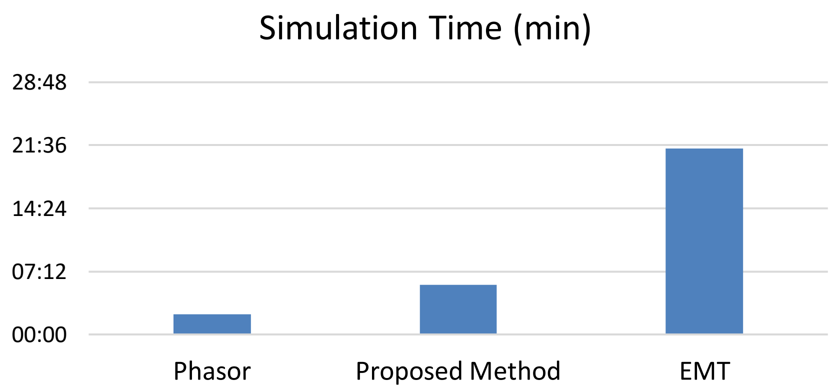
Use of distribution grid to re-energise the grid after a blackout

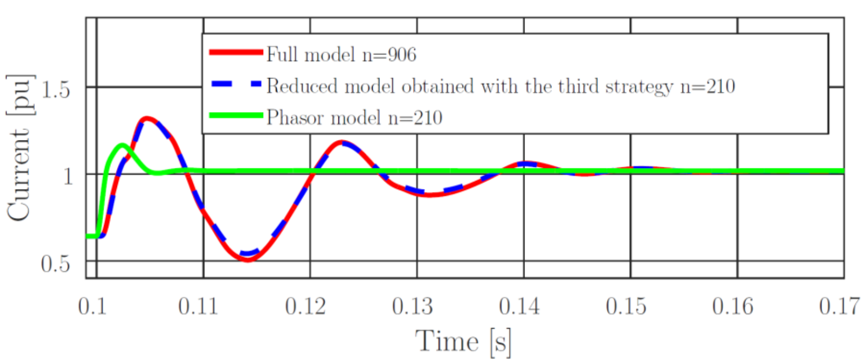
Model Order Reduction

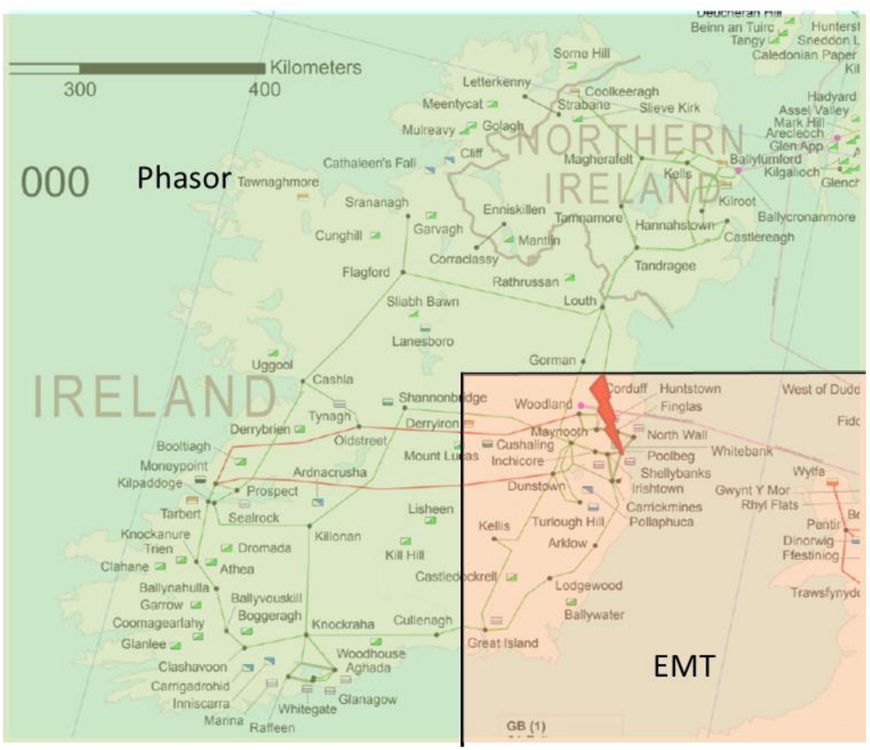
Q. Cossard (PhD): 2016 – 2019 European Migrate Project

Model Order Reduction that:

- preserves the physical variables of the system.
- is easily applicable.
- gives better results than the classicaly used phasor approximation.







Conclusive remark

12 years of experience in the field of PE-interfaced grids:

- Power electronic converter in High Voltage application
- Multi Terminal DC grid
- Power electronic converter in power system

Always guided by the same drivers:

- *Trying to develop the simplest models as possible in order to be understandable as much as possible and build a bridge between the "power electronic world" and "power system world"*

- *Willing to develop a new theory of the power system integrating power electronic converters*

Among on going works, a tool for assessing the overall stability of transmission grids with a high penetration of power electronic converters is needed

4- A tool for a systematic assessment of stability?

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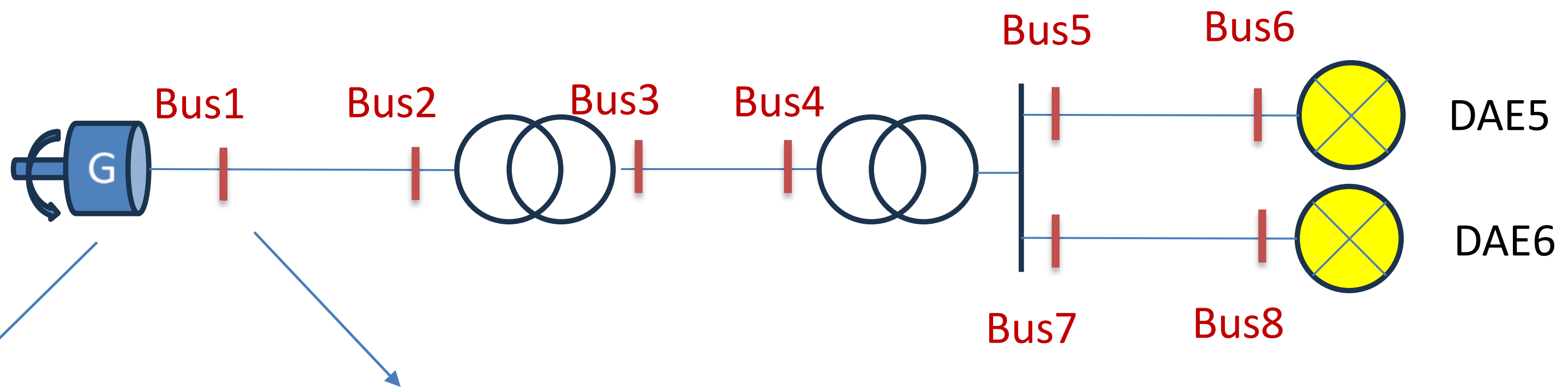
Power System modelling

Power systems are usually modelled by nonlinear Differential Algebraic Equations (DAE):

$$\dot{x} = f(x, y)$$
$$0 = g(x, y)$$



$$\dot{\delta} = \omega_n(\omega - \omega_s)$$
$$\dot{\omega} = \frac{p_m - p_e}{2H}$$
$$\cdots$$

$$p_1 = p_{B1}$$
$$q_1 = q_{B1}$$

Where *x, y, f* and *g* are obtained by assembling all models of connected elements.

Large and small signal stability

Large signal stability analysis :

Large signal stability is usually based on time simulations, where at each step time the original system is numerically solved, using:

- ElectroMagnetic Transients Programs (EMTP): When small dynamics are considered
- Transient Simulation Programs (TSP): When middle and large range dynamics are considered

Very few tools are available for analytical analysis of large signal stability (Equal Area Criterion and Lyapounov based techniques)

Small signal stability:

- The original system is linearized around an operating point
- The eigenvalues and eigenvectors of the linearized system are analyzed.

NB: Small signal stability is usually embedded with some TSP

Large signal stability by time simulation

EMTP are based on PhD works of Hermann Dommel (Nodal Analysis):

- Each element is modelled by an equivalent circuit obtained by a temporal discretization of each basic model (R,L,C, …) composing the system.
- At each time step there is a system as *Ax=z* to be solved
  - *If linear elements, constant time step and static topology (constant A): easy to be solved. Otherwise not…*
  - *No direct link to small signal stability (even if possible)*

TSP is based on the assumption of neglecting the fast dynamics of the lines:

- Each subsystem connected to the grid is modelled by DAE
- Lines serve as connecting equations between subsystems
- The DAE are discretized and convert to a set of nonlinear algebraic equations
- The nonlinear set of equations is solved at each step time (NR, …)
  - *Large matrices to invert at each time step*
  - *Direct link with small signal stability (since the Jacobians give, at each step time, a snapshot of the linearized system)*

Neither EMTP nor TSP give an analytical way to assess to nonlinear large signal stability

Normal Form Theory for nonlinear stability assessment

Introduced by Poincaré, Normal Forms are (mainly in the mechanical engineering domain) used for:

- Classification of dynamical systems;
- Qualitative study of dynamical systems;
- Quantitative study of dynamical systems.

The main idea is closed to the classical (Linear) EigenValues analysis:

The DAE system model:

$$\begin{aligned} \dot{x} &= f(x,y) \\ 0 &= g(x,y) \end{aligned} \qquad (1)$$

Is first recast to an ODE one:

$$\dot{x} = \hat{f}(x,y) \qquad (2)$$

The results presented in these section come mainly from Tian TIAN (PhD 2014-2017) and Nnaemeka UGWUANYI (PhD 2017-2020)

Normal Form Theory for nonlinear stability assessment

(2) is expanded to its Taylor series around an operating point x_0:

$$\Delta \dot{x} = A\Delta x + \sum_{k=2}^{\infty} T_k(\Delta x) \qquad (3)$$

where T_k are composed of homogeneous polynomial terms related to partial derivatives of $\hat{f}$.

Jordan form of (3) is obtained by applying a transformation $\Delta x = Uy$:

$$\dot{y} = \Lambda y + \sum_{k=2}^{\infty} F_k(\mathrm{y}) \qquad (4)$$

where Λ is a diagonal matrix composed of all (linear) eigenvalues of the system.

NB: To apply the Normal Form Theory, it is not necessary to diagonalize the system. However, it makes possibles to find again the well-known notion of linear modes.

Normal Form Theory for nonlinear stability assessment

The idea of Poincaré was to eliminate nonlinear terms by a sequence of near-identity changes of coordinates:

$$\mathrm{y} = \mathrm{z} + h_m(\mathrm{z}) \quad (5)$$

where h_m are homogeneous polynomial terms ($m > 2$) .

Let's consider in a first approach the change of coordinates:

$$\mathrm{y} = \mathrm{z}_2 + h_2(\mathrm{z}_2) \quad (6)$$

where h_2 are homogeneous second-order polynomial terms .

Time derivative of (6) gives:

$$\dot{\mathrm{y}} = \dot{z_2} + DH_2(z_2)\dot{z_2} = [I + DH_2(z_2)]\dot{z_2} \rightarrow \dot{z_2} = [I + DH_2(z_2)]^{-1}\dot{\mathrm{y}}$$

Where $DH_2(z_2)$ is the Jacobian of $h_2(\mathrm{z}_2)$.

Normal Form Theory for nonlinear stability assessment

Considering that $I + DH_2(z_2) \approx I - DH_2(z_2) + O(2)$, where $O(n)$ stands for terms at order *n* or higher and using (4), it comes:

$$\dot{z}_2 = [I - DH_2(z_2) + O(2)][\Lambda y + F_2(y) + O(3)]$$

Adding (6), we get:

$$\dot{z}_2 = [I - DH_2(z_2) + O(2)][\Lambda z_2 + \Lambda h_2(z_2) + F_2(z_2) + O(3)]$$

Or

$$\dot{z}_2 = \Lambda z_2 + \Lambda h_2(z_2) + F_2(z_2) - DH_2(z_2)\Lambda z_2 + O(3) \qquad (7)$$

Terms of order 2 are cancelled if $\Lambda h_2(z_2) + F_2(z_2) - DH_2(z_2)\Lambda z_2 = 0$, that is by cancelling all coefficients of $z_1^2, z_1 z_2, {z_2}^2$ of (7).

NB: In case of $\boldsymbol{\Lambda_k + \Lambda_l - \Lambda_j = 0}$ **(resonance conditions) some second order terms of (7) can not be cancelled.**

Normal Form Theory for nonlinear stability assessment

If the condition $\Lambda_k + \Lambda_l - \Lambda_j \neq 0$ holds, coefficients of h_2 are determined such:

$$h2^j_{kl} = \frac{F2^j_{kl}}{\Lambda_k + \Lambda_l - \Lambda_j}$$

And (7) becomes, if third order terms or higher are neglected,

$$\dot{z}_2 = \Lambda z_2 \quad (8)$$

which is the same dynamical equation as the linearized system!

In case of resonnances ($\Lambda_k + \Lambda_l - \Lambda_j = 0$), the associated terms can not be cancelled and (7) becomes:

$$\dot{z}_2 = \Lambda z_2 + R_2(z_2) \quad (9)$$

Where $R_2(z_2)$ are remaining second order terms that can not be cancelled.

NB: The same procedure can be sequentially applied for cancelling higher order terms.

Normal Form Theory for nonlinear stability assessment

Normal form (8) or (9) is far simpler than (2) and makes possible to easily characterized the nonlinearities of the system in an easy manner.

For example, it can be computed:

- *Mode frequency/amplitude dependence*
- *Nonlinear Participation Factors*
- *Nonlinear indexes*
- *Nonlinear Modal Persistence Measures*
- *Stability indexes*
- *…*

NB: In his simplest form (8) no more information on stability are available compared to a classical linear modal approach and (9) offers a nice option to assess stability.

Normal Form Theory for nonlinear stability assessment

Analysis/Remarks/Questions :

- *Not always possible to recast DAE into ODE, how to tackle with DAE systems?*

- *Normal Form comes from an approximation of an approximation, what is the domain of validity of the approximate model?*

- *Normal Form procedure implies a lot of computations, how to reduce them?*

- *Applying Normal Form Theory up to third order terms seems to be a good compromise for Power System analysis, but why not using more than third order terms?*

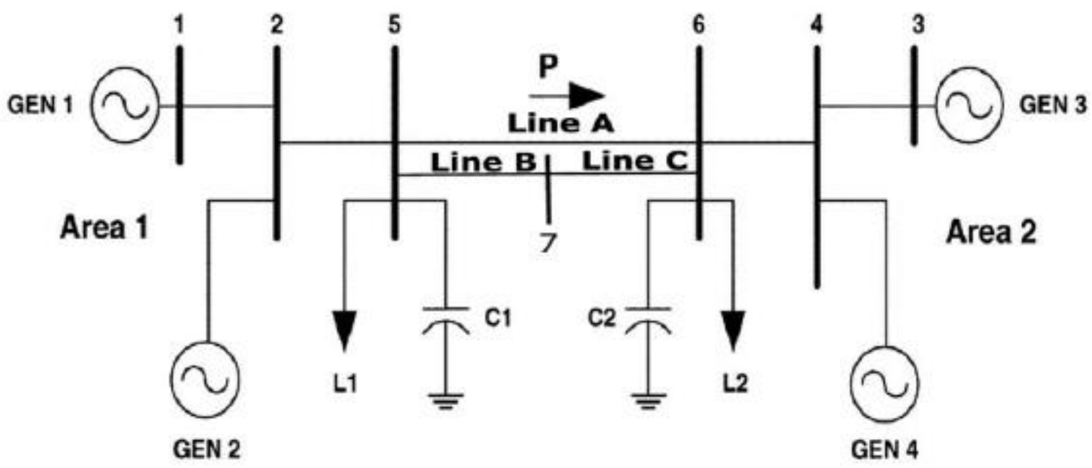
- *Normal Form OK for free oscillations systems but what about forced systems?*

Our ongoing works try to answer (some of) the listed points

Example of Normal Form Theory applied to power systems

Nonlinear Stability assessment

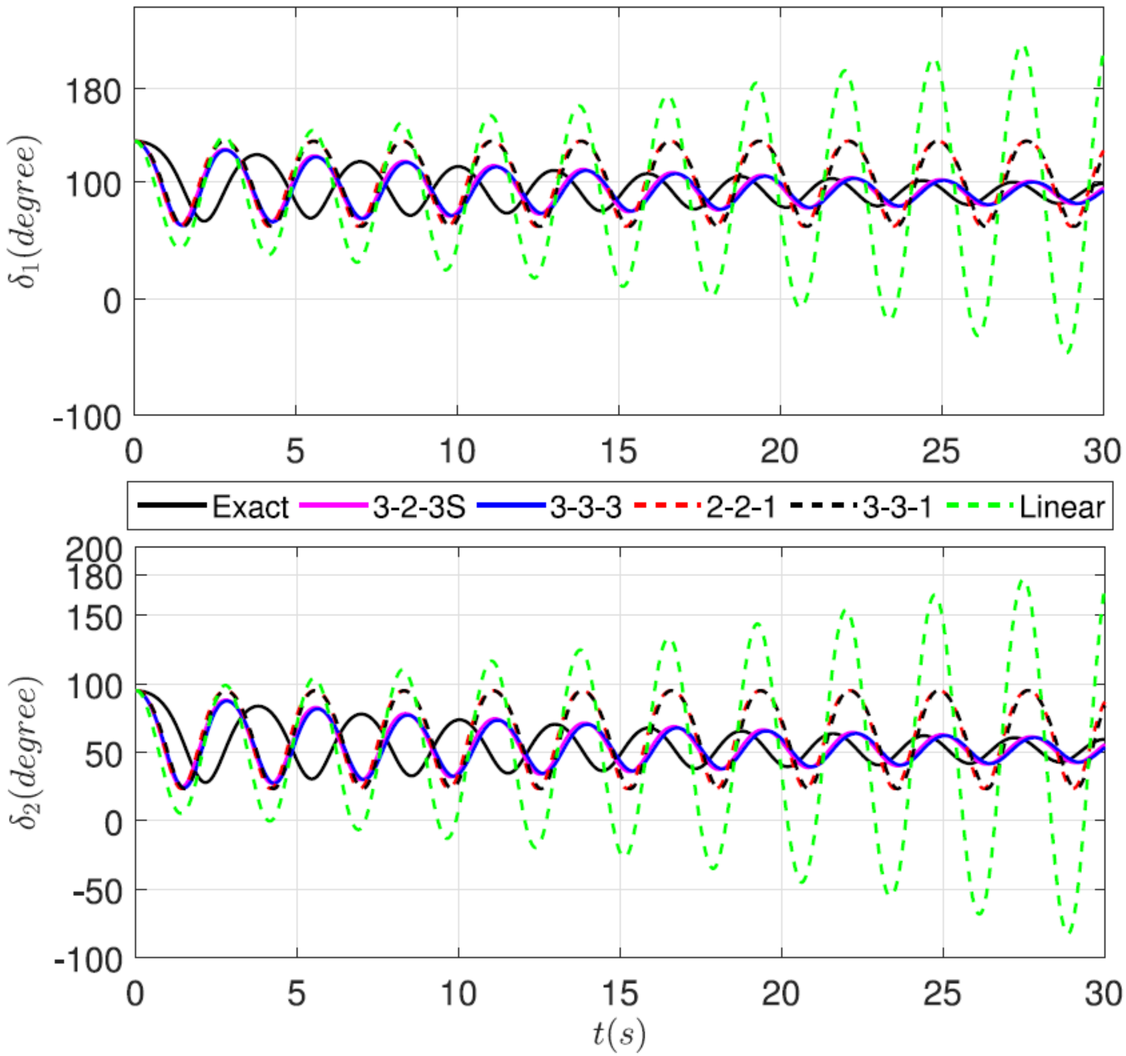
Let’s consider the well-known IEEE 4 machine test system 2-area 4-generator.



A three-phase short-circuited fault is applied at Bus 7 and after 0.10s, line B and line C are tripped.

Example of Normal Form Theory applied to power systems

Nonlinear Stability assessment



The frequency of the real system is lower than the one given by a linear approximation.

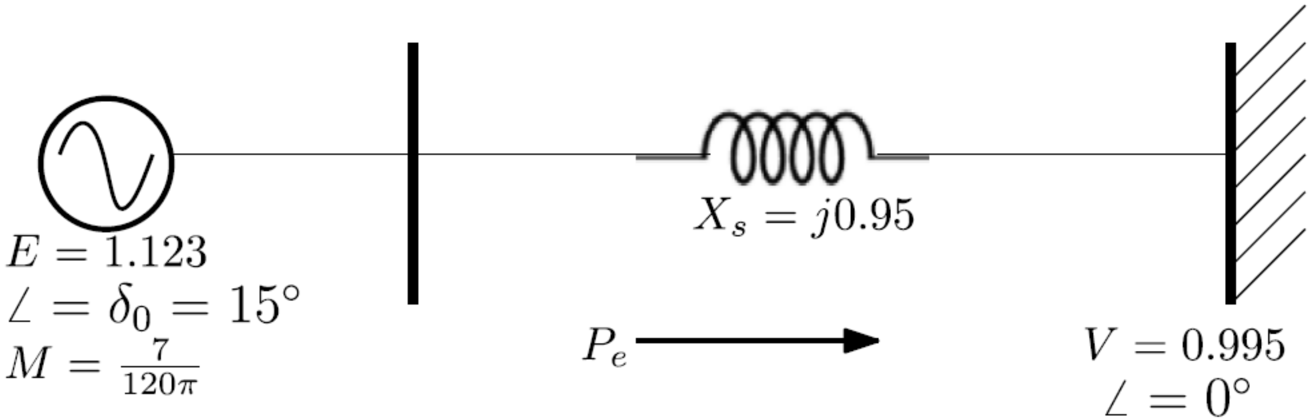
A linear approach gives wrong results concerning the stability of the system.

Normal Form Theory is able to capture the dynamics of the system and can be used for stability assessment.

Example of Normal Form Theory applied to power systems

Nonlinear Stability assessment

Let's consider the simplest power system composed of one generator connected to a large electrical grid.



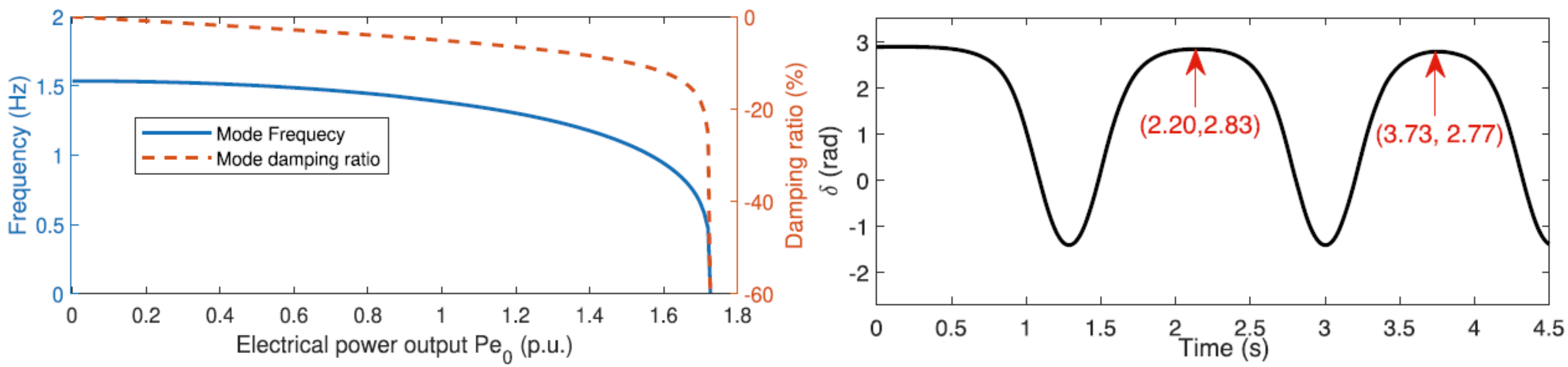
Modelled by the following ODE:

$$\dot{\delta} = \Omega_b \omega$$
$$\dot{\omega} = \frac{1}{2H}\left(p_m - \frac{ev}{x_e}\sin\delta - D\omega\right)$$

Example of Normal Form Theory applied to power systems

Nonlinear Stability assessment

The more the system is stressed, the more it has a “nonlinear” behavior with a low frequency



It has been observed that at a certain level of stress, the frequency “drops” and the system becomes unstable.

Normal Form makes possible to analytically determine the level of stress at which the system will become unstable. Even it is based on approximations, it seems easier to be implemented compared to Lyapunov-based methods.
Last (but not least), it keeps the notion of Linear modes (Basics of engineers!)

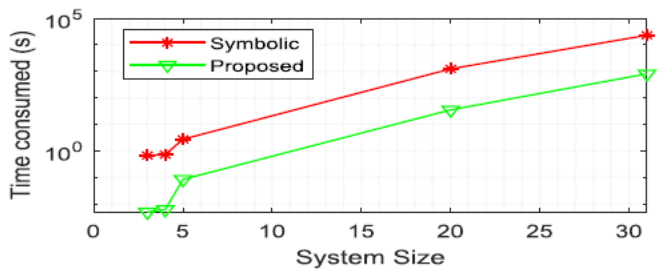
Example of Normal Form Theory applied to power systems

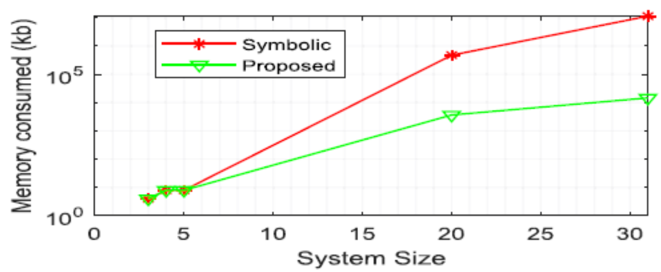
Computational burdens

Even if simple to use, Normal Form Theory needs an incredible number of coefficients to be computed.

$$N_c = N\left[\frac{(N+1)!}{2!(N-1)!} + \frac{(N+2)!}{3!(N-1)!}\right] = \frac{N^4}{6} + N^3 + \frac{5N^2}{6}.$$

Some ways have been found to compute these coefficients in an easier way and to be able to know what are the coefficients that can not be computed without affecting too much the results.





Test on IEEE 50-Machine System

Example of Normal Form Theory applied to power systems

Working with DAE (instead of ODE): Ongoing research

Up to now, Normal Form Theory is limited to systems modelled by ODE. However, power systems are usually modelled by DAE.

Systems that are considered are modelled by: $$\mathbf{A}\dot{\mathbf{y}} = \mathbf{L}\mathbf{y} + Q(\mathbf{y}, \mathbf{y})$$

Where *y* is the *N*-dimensional state (and algebraic) variables vector, *A* and L are *NxN* matrices (*A* can be singular to consider algebraic variables) and *Q* is a purely quadratic application.

Even if it seems to be restrictive since Q must be quadratic, by adding dummy variables many of applications can be modelled by Q.

A common paper with Dr. Bin is under redaction for submission to PSCC 2024
The ultimate aim is to embed NFT in TSP for analytical assessment of nonlinear stability

5- Conclusion

Renewables, Interconnexions, People concerns -> Power Electronics = power systems pushed to their limits -> Nonlinearities

100% Power Electronics Grids -> New tools to develop to analytically assess the nonlinear stability

Normal Theory = Continuation of Linear Approach (Eigenvalues) that could be “naturally” inserted in Transient Simulation Programs

Still research works to do:

- Working with DAE (instead of ODE)
- Reducing the necessary resources to get the Normal Form system
- Applying Normal Form to forced systems
- Be sure of the domain of validity
- …

Still many exciting research works to do!
You are very welcome to collaborate ☺

Thanks for your attention

……………………

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