DC Microgrids
Modeling and Control

Dr. Daniele Bosich, PhD

About me

BSc (2007) MSc (2010)
Electrical Engineering

University of Trieste

PhD (2014)
Energy Engineering

University of Padova

detef
Digital Energy Transformation & Electrification Facility

Post-Doc (2014-2015)

Eindhoven University of Technology

Post-Doc (2015-2017)
Assistant Professor (2018-…)

University of Trieste

PIEN IE IEN GCSE MES

marine shipboard power systems

microgrid modeling

voltage control

nonlinear systems analysis

Contents

*Latest advancements in power electronics are forcing **DC technology** as a key enabling solution for newest islanded microgrids. In these systems, loads are supplied by **power converters** directly connected to the DC bus. Depending on the designed control bandwidth, load converters may exhibit the **Constant Power Load behavior**, thus forcing towards the system instability. The lesson wants to explore the CPL effect on the future **shipbboard DC microgrids**. Starting from the mathematical modeling, the **instability** will be solved basing on advanced control solutions.*

Introduction (1/2)

- **The classical paradigm** generation-transmission-distribution-utilization **must evolve**
- **Distributed Energy Resources + Storage Systems + Flexible Loads + Control = µG**
- More controllability, less power losses, more flexibility, better power quality, better use of energy **→ PROS**
- Latest advancements in power electronics are forcing **DC technology** as a key **enabling** solution for **newest microgrids (→ also on ships)**
- In DC µG, **loads are supplied by power converters** directly connected to the **DC bus**
- Depending on **control bandwidth**, load converters may exhibit the **Constant Power Load** (CPL) behavior **(→ load power constant under fast current/voltage variations)**

Introduction (2/2)

- By linearizing the CPL load in an equilibrium point → **negative incremental resistance (→ poles in the right half-plane system instability)**
- **Instability solution?** → DC/DC interface converters as **sources of stabilizing power (→ voltage actuator approach)**
- **Single converter case** → design of voltage control techniques
- Integration of several generating systems and controlled loads **→ multi-converter control!**
- Wrong control in presence of **parameters mismatch! →** how **to estimate** the parameters?
- High bandwidth controlled converter → **CPL** model is effective**? → new models**
- **Weighted Bandwidth Method + Digital Twin**

Microgrids (1/3)

*Microgrids comprise **LV distribution systems** with distributed energy resources **(DER)** (microturbines, fuel cells, PV, etc.) together with **storage devices** (flywheels, energy capacitors and batteries) and **flexible loads**. Such systems can be operated in **a non-autonomous way**, if interconnected to the grid, or in **an autonomous way**, if disconnected from the main grid. The operation of microsources in the network can provide distinct **benefits to the overall system** performance, if **managed and coordinated efficiently***

EU research projects

DER, storage, flexible loads, smart control and communication

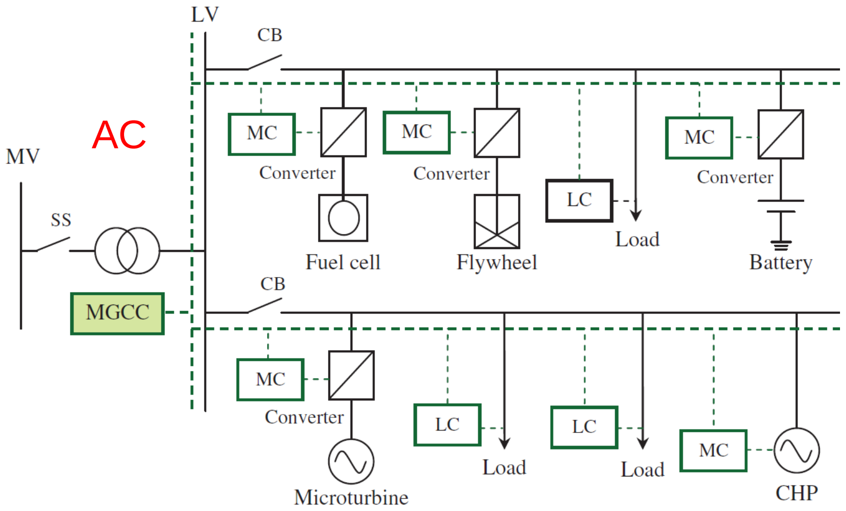
http://ieeetv.ieee.org/mobile/video/the-intergrid-safe-dependable-sustainable-iecon-2018?rf=events%7C157

Prof. Dushan Boroyevich, Virginia Tech (USA)

Nikos Hatziargyriou, "Microgrids: Architectures and Control", Wiley

Hassan Bevrani, Bruno Francois, Toshifumi Ise, "Microgrid Dynamics band Control", Wiley

Microgrids (2/3)



What can we get with a totally controlled power system?

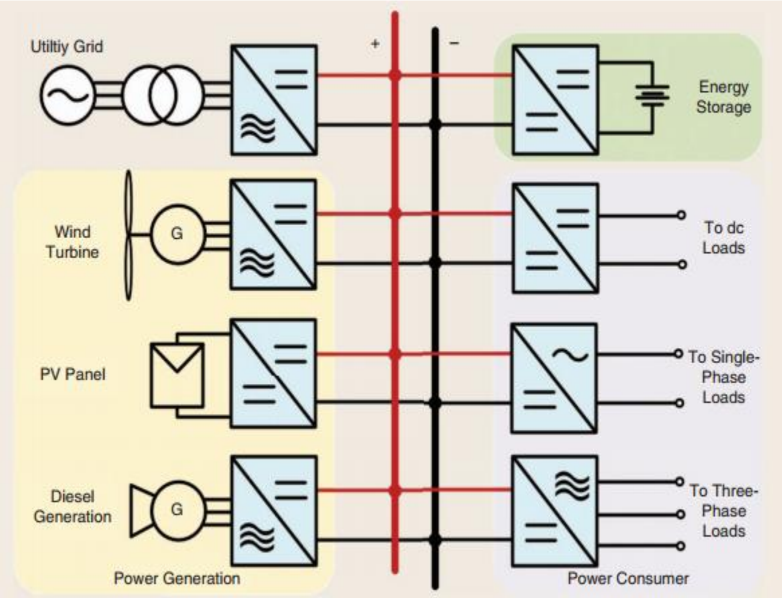
→ reliability UP, losses DOWN, V control UP, efficiency UP, voltage sags/drops DOWN, interruptibility, and so on and so forth…..

Better use of energy

- **Microgrid for system energy optimization**
- **Static switch** → connection to distribution VS islanded mode
- Power converters AC-DC, DC-AC → **interfaces between subsysems**
- **MGCC** → central controller for setting the low level controls + general MG management
- **Set-point** → Microsource Controller and Load Controller
- **Communication infrastructure** → monitoring and control
- **Exchanged information** from MGCC to MC/LC

control references, switch commands, V/I measurements

Microgrids (3/3)



Z. Jin, G. Sulligoi, R. Cuzner, L. Meng, J. C. Vasquez and J. M. Guerrero, "Next-Generation Shipboard DC Power System: Introduction Smart Grid and dc Microgrid Technologies into Maritime Electrical Networks," in IEEE Electrification Magazine, vol. 4, no. 2, pp. 45-57, June 2016.

Why DC Microgrids?

- **Smart integration** of Energy Storage Systems
- Feasible **islanded operation**
- System fully resistant to main grid blackouts
- No reactive power and synchronization
- **High overall efficiency**

Shipboard DC microgrids (1/10)

- Is the shipboard power system a microgrid?
- Is it possible to have the same advantages also onboard?
- Why don’t exploit DC technology also in shipboard microgrids?

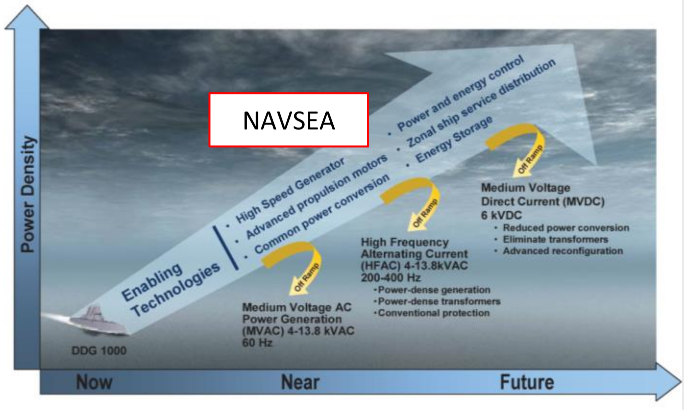
DC onboard!

→ **Medium Voltage DC Integrated Power System → MVDC IPS**
→ **MVDC shipboard power system is an islanded DC microgrid!**
→ **MVDC Large Ship project www.mvdc.it**

D. Bosich, A. Vicenzutti, R. Pelaschiar, R. Menis and G. Sulligoi, "Toward the future: The MVDC large ship research program," 2015 AEIT International Annual Conference (AEIT), Naples, Italy, October 14-16, 2015.

Shipboard DC microgrids (2/10)

- **High power density and enhanced quality of service** represent two main goals for a naval shipboard power system
- MVDC may constitute the **future technology** to guarantee these aims
- A **roadmap** (from U.S. Naval Sea Systems Command) and a standard (IEEE Std. 1709) have pushed the research in the MVDC direction



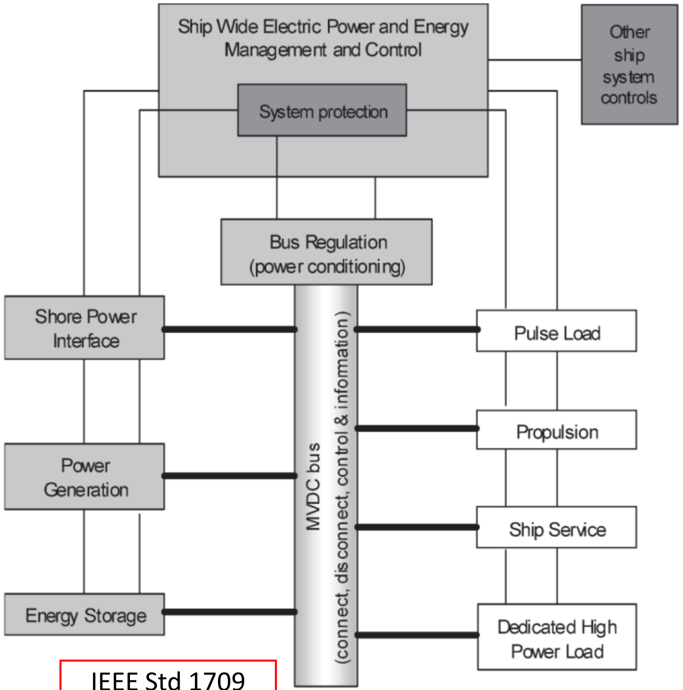

IEEE STANDARDS ASSOCIATION IEEE

IEEE Recommended Practice for 1 kV to 35 kV Medium-Voltage DC Power Systems on Ships

IEEE Industry Applications Society

IEEE Std 1709

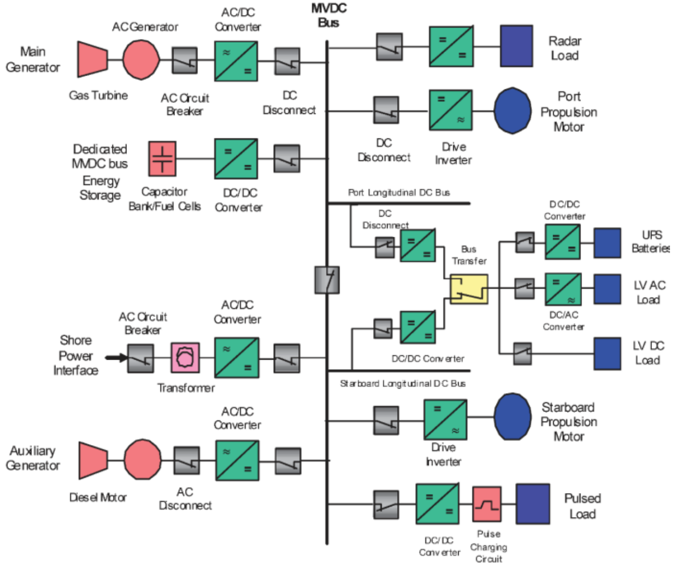
Shipboard DC microgrids (3/10)



IEEE Std 1709

- Power generation to convert energy from fuel into electric energy (e.g. prime mover + generator + AC/DC interface converter)
- Energy storage to face voltage oscillations in MVDC bus caused by step-loads (e.g. relevant load devices or the loss of a generator set)
- Pulsed load (e.g. electromagnetic aircraft launch system, rail gun and free electron laser)
- Propulsion constituted by electric motors, supplied from the DC distribution bus through variable speed drive inverters
- Ship service (e.g. hotel load)
- Dedicated High Power Load (e.g. military radar, large thruster, compressor)
- Shore power interface from the utility system on shore to MVDC power system (e.g. transformer + AC/DC interface converter)
- Ship-wide power and energy management control: to maximize the continuity-of-service of vital loads
- System Protection (e.g. circuit breakers in AC section, combination of converter control and solid state DC breakers in DC section)

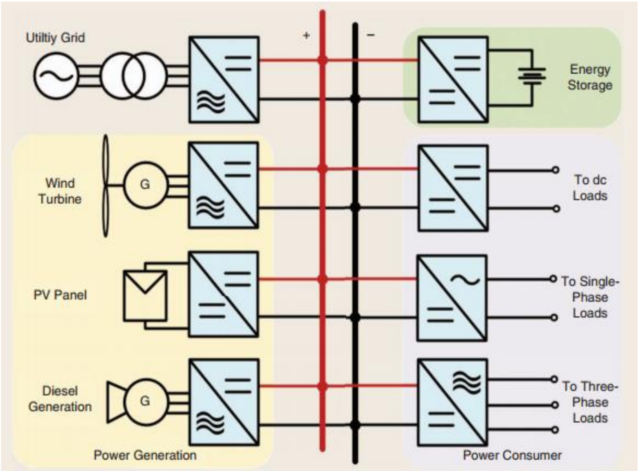
Shipboard DC microgrids (4/10)



IEEE Std 1709

Radial distribution

MVDC Integrated Power System
VS
MVDC microgrid

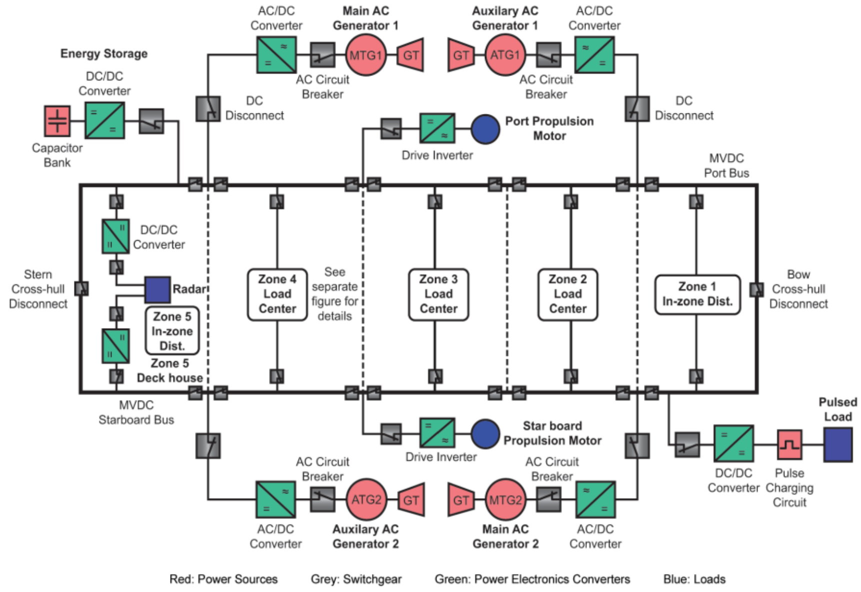


A Ship Is a Microgrid and a Microgrid Is a Ship: Commonalities and Synergies

By Antonello Monti and Marta Molinas

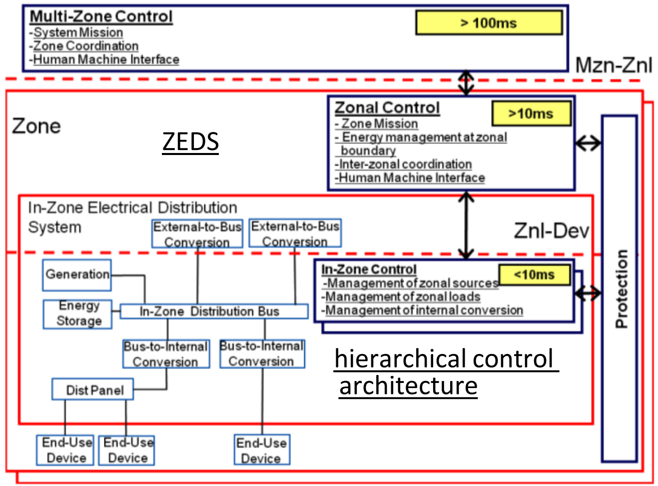
IEEE Electrification Magazine / DECEMBER 2019

Shipboard DC microgrids (5/10)

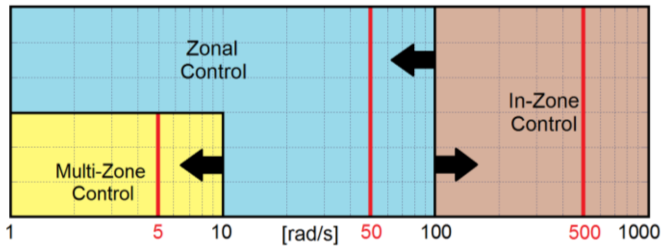


IEEE Std 1709

Zonal Electrical Distribution System



IEEE Std 1826



G. Sulligoi, D. Bosich, A. Vicenzutti and Y. Khersonsky, "Design of Zonal Electrical Distribution Systems for Ships and Oil Platforms: Control Systems and Protections," in IEEE Transactions on Industry Applications, vol. 56, no. 5, pp. 5656-5669, Sept.-Oct. 2020.

Shipboard DC microgrids (6/10)

DC technology → onboard benefits

- The DC distribution guarantees several benefits. **Two fundamentals:**
  - Eliminating large low-frequency (50 Hz or 60 Hz) transformers
  - Reducing power system weight by using **high-speed generators/converters/SST**

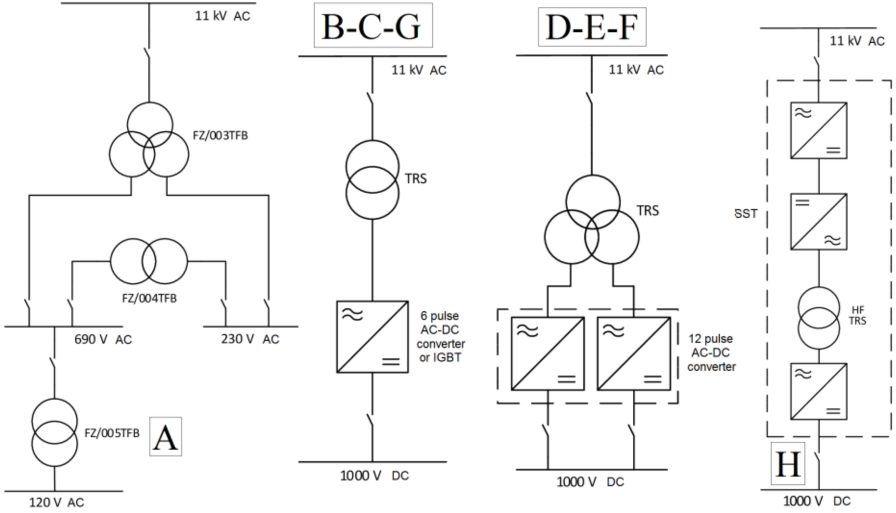
- The wide presence of power converters is requested to realize an onboard MVDC distribution. Converters ensure other advantages:
  - **Improving control of power flows**, especially in transient and emergency conditions
  - Limiting and managing fault currents and enabling reconfiguration

Shipboard DC microgrids (7/10)

DC technology → onboard benefits

- The discussed benefits are mandatory for **navies**, but their importance is evident also in case of **merchant ships**
- **New advanced products** to compete with rising economics!
- Smaller power system → **more space for payload (cabins)**
- **Smart redesign** of electrical distribution thanks to MVDC technology
- Transformers → **bulky components to be replaced!**

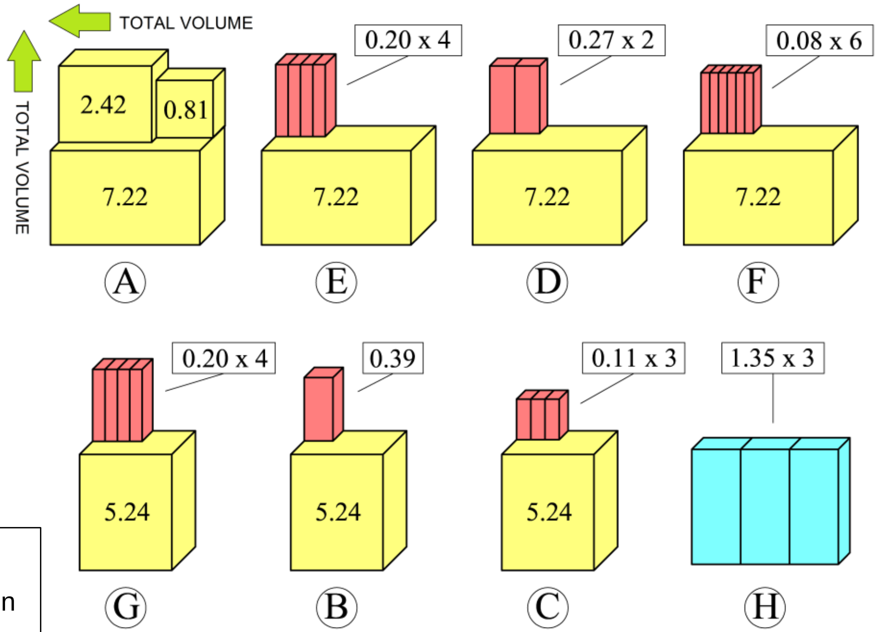
Shipboard DC microgrids (8/10)



DC distribution **redesign** from the main substation

V. Bucci, U. La Monaca, D. Bosich, G. Sulligoi, A. Pietra, "Integrated ship design and CSI modeling: A new methodology for comparing onboard electrical distributions in the early-stage design", International Conference on Ship and Shipping Research, NAV 2018, Trieste, Italy, 20-22 June 2018.

DC technology → onboard benefits

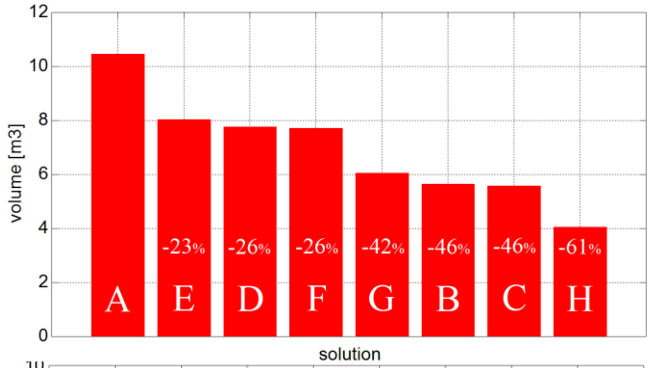


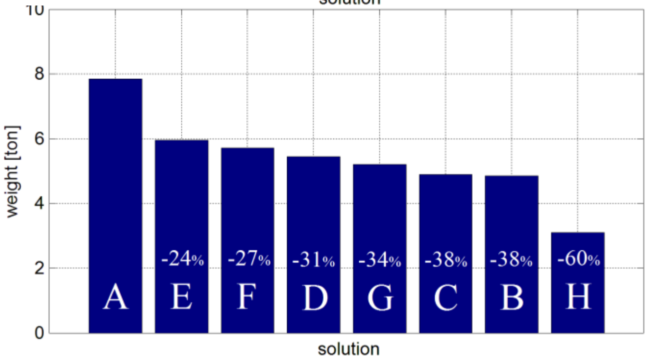
Shipboard DC microgrids (9/10)

S	Component	P [MW]	N_C [·]	N_{FC} [·]	N_F [·]	L_F [m]	W_F [m]	H_F [m]	V_F [m^3]	WE_F [ton]
A	Tr. 11/0.69/0.23 kV	2.35	1	1	1	2.90	1.36	1.83	7.22	5.24
	Tr. 690/230 V	0.60	1	1	1	1.80	0.91	1.48	2.42	1.97
	Tr. 690/120 V	0.16	1	1	1	1.11	0.65	1.12	0.81	0.62
B	Tr. 12/1.1 kV	2.50	1	1	1	1.79	1.30	2.25	5.24	4.70
	6 p. AC-DC conv.	2.50	1	1	1	0.56	0.56	1.23	0.39	0.15
C	Tr. 12/1.1 kV	2.50	1	1	1	1.79	1.30	2.25	5.24	4.70
	6 p. AC-DC conv.	0.80	3	1	3	0.28	0.49	0.78	0.11	0.07
D	Tr. 11/0.69/0.40 kV	2.35	1	1	1	2.90	1.36	1.83	7.22	5.24
	12 p. AC-DC conv.	1.50	2	1	2	0.49	0.42	1.31	0.27	0.1
E	Tr. 11/0.69/0.40 kV	2.35	1	1	1	2.90	1.36	1.83	7.22	5.24
	12 p. AC-DC conv.	2.52	1	4	4	0.24	0.58	1.40	0.20	0.18
F	Tr. 11/0.69/0.40 kV	2.35	1	1	1	2.90	1.36	1.83	7.22	5.24
	AC-DC conv. 12 p.	0.90	3	2	6	0.17	0.42	1.17	0.08	0.08
G	Tr. 12/1.1 kV	2.50	1	1	1	1.79	1.30	2.25	5.24	4.70
	AC-DC conv.IGBT	2.50	1	4	4	0.24	0.58	1.40	0.20	0.12
H	SST	2.20	1	3	3	0.95	0.64	2.22	1.35	1.03

P: single frame power
NC: components number
NFC: num. frame x comp.
NF: frames number
LF: frame length

WF: frame width
HF: frame height
VF: frame volume
WEF: total frame weight





DC technology → onboard benefits

DC distribution redesign from the main substation

V. Bucci, U. La Monaca, D. Bosich, G. Sulligoi, A. Pietra, "Integrated ship design and CSI modeling: A new methodology for comparing onboard electrical distributions in the early-stage design", International Conference on Ship and Shipping Research, NAV 2018, Trieste, Italy, 20-22 June 2018.

Shipboard DC microgrids (10/10)

DC technology → challanges

- Conversely, the main technical challenges to face are:
  - Difficulty in **interrupting DC current**
  - An effective grounding strategy to provide galvanic **isolation**
  - **Constant Power Loads stability issue**

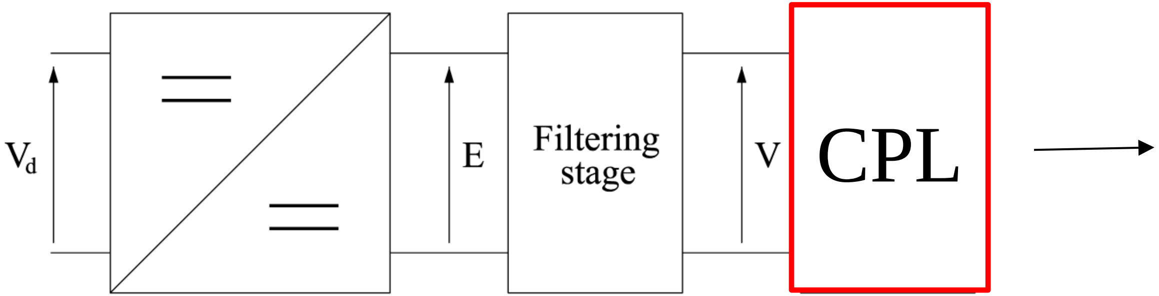
Pros VS Cons

- In particular the last point is the main topic of this **seminar**

CPL issue (1/7)

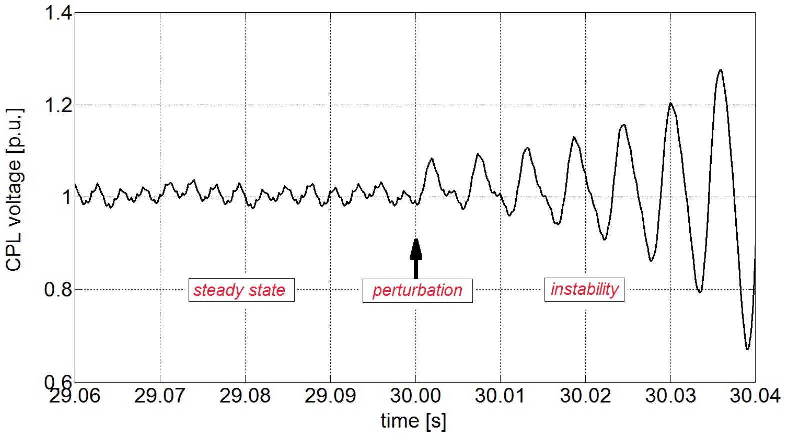
- MVDC power systems are to be based on a **widespread use of power converters**, in order to interface generating systems and loads to MVDC bus
- Their **tight control**, although desirable, tends to keep the **load power constant** even under perturbations
- Such an aspect reflects at the converter input terminals as a **Constant Power Load (CPL) behavior**
- The instability problem arises due to the **interaction between CPL and the DC filtering stage (2^{nd} order RLC)**
- This filter is indispensable to guarantee acceptable ripples in DC voltage and current (i.e. power quality)

CPL issue (2/7)



High performance drive

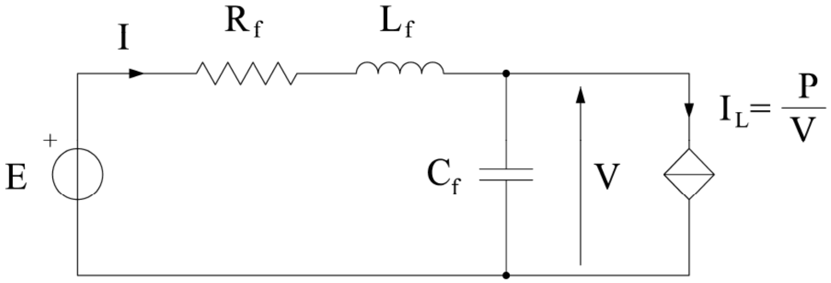
Infinite bandwidth controlled converter



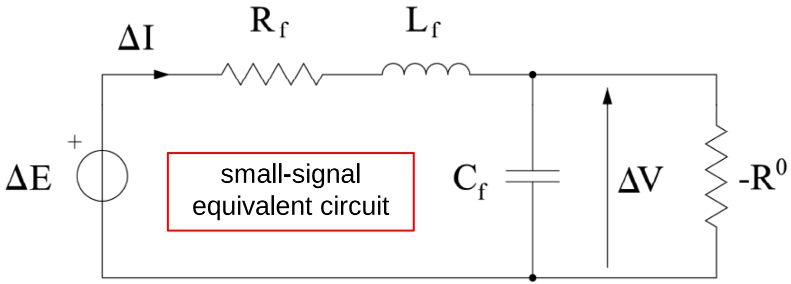
After a **perturbation (small or large),** the CPL combined with the DC filter determines **oscillations**, thus the **voltage instability**

WHY?

CPL issue (3/7)



1. perturbation V↓ IL↑
2. voltage drop ↑ V↓
3. system instability



$$\begin{cases} L_f \dfrac{d(\Delta I)}{dt} = \Delta E - R_f \Delta I - \Delta V \\ C_f \dfrac{d(\Delta V)}{dt} = \Delta I - \left(\dfrac{\partial I_L}{\partial V}\right)_0 = \Delta I - \left(-\dfrac{P}{V^2}\right)_0 \Delta V = \Delta I - \dfrac{\Delta V}{-R^0} \end{cases}$$

linearization in the equilibrium point

$$s^2 + \frac{1}{L_f C_f}\left(C_f R_f - \frac{L_f}{R^0}\right)s + \frac{1}{L_f C_f}\left(1 - \frac{R_f}{R^0}\right) = 0$$

$$\begin{cases} 1 - \dfrac{R_f}{R^0} > 0 \\ C_f R_f - \dfrac{L_f}{R^0} > 0 \end{cases} \Rightarrow \begin{cases} R^0 > R_f \\ R^0 > \dfrac{L_f}{R_f C_f} \end{cases}$$

In presence of a small perturbation, the **validity** of the two conditions assures a **stable damped** voltage behavior

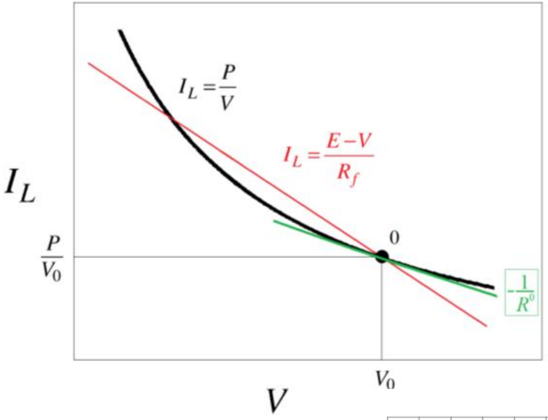
CPL issue (4/7)

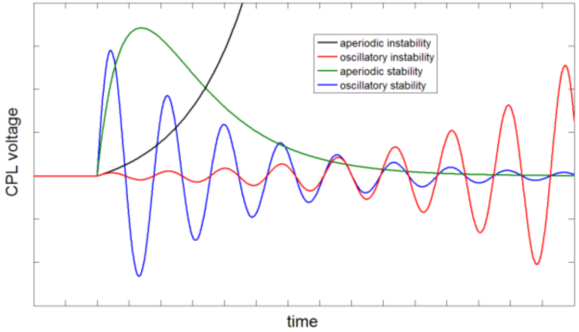
$$\begin{cases} L_f \dfrac{d(\Delta I)}{dt} = \Delta E - R_f \Delta I - \Delta V \\ C_f \dfrac{d(\Delta V)}{dt} = \Delta I - \left(\dfrac{\partial I_L}{\partial V}\right)_0 = \Delta I - \left(-\dfrac{P}{V^2}\right)_0 \Delta V = \Delta I - \dfrac{\Delta V}{-R^0} \end{cases}$$

$$s^2 + \frac{1}{L_f C_f}\left(C_f R_f - \frac{L_f}{R^0}\right)s + \frac{1}{L_f C_f}\left(1 - \frac{R_f}{R^0}\right) = 0$$

$$\begin{cases} 1 - \dfrac{R_f}{R^0} > 0 \\ C_f R_f - \dfrac{L_f}{R^0} > 0 \end{cases} \Rightarrow \begin{cases} R^0 > R_f \\ R^0 > \dfrac{L_f}{R_f C_f} \end{cases}$$

In presence of a small perturbation, the **validity** of the two conditions assures a **stable damped** voltage behavior





CPL issue (5/7)

- **Filter parameters (R, L and C)** are to be determined by using standard equations, imposing the **percentage of losses, the current ripple and the voltage one**

$$
\begin{cases}
D_{nk} = \dfrac{V_{nk}}{U_{nk}} \\[2ex]
I_{nk} = \dfrac{P_{nk} - \Delta P_{\%k} \cdot P_{nk}}{V_{nk}}
\end{cases}
$$

$$
\begin{cases}
R_k = \dfrac{\Delta P_{\%k} \cdot P_{nk}}{I_{nk}^2} \\[2ex]
L_k = \dfrac{(U_{nk} - V_{nk}) \cdot D_{nk}}{f_{sk} \cdot I_{nk} \cdot \Delta I_{\%k}} \\[2ex]
C_k = \dfrac{1 - D_{nk}}{8 \cdot L_k \cdot f_{sk}^2 \cdot \Delta V_{\%k}}
\end{cases}
$$

ΔI% → L

ΔV% → C

ΔP% → R

CPL issue (6/7)

- It is important to analyze the CPL stability of each filtered DC/DC converter, calculating the **damping factor of the linearized system**:

$$\omega_{0fk} = \sqrt{\frac{1}{L_{fk} \cdot C_{fk}} \left(1 - \frac{R_{fk}}{R_k^0}\right)}$$

$$\xi_{fk} = \frac{1}{2\omega_{0fk} \cdot L_{fk} \cdot C_{fk}} \left(C_{fk} \cdot R_{fk} - \frac{L_{fk}}{R_k^0}\right)$$

- The filter may be designed to maintain a **positive damping factor**

- A positive damping factor is given by a **large C (small voltage ripple) and a small L (large current ripple)**

- On the other hand, **voltage actuator approach** makes possible an independent and feasible selection of filter

CPL issue (7/7)

- Islanded shipboard power systems are characterized by **loads power comparable to the generators one**

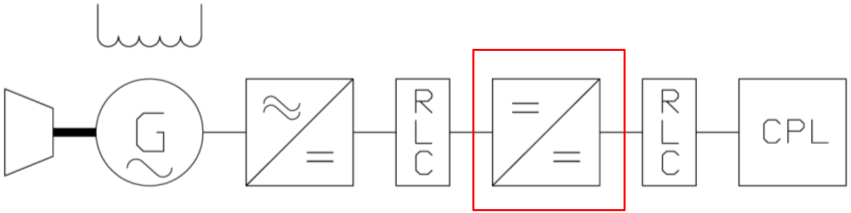
- **System perturbations are usually large**, caused by the connections and disconnections of high power loads

- **Small-signal analysis** (→ linearization) could be the **first step** to determine the system stability

- Conversely, **nonlinear studies (→ Lyapunov theory)** can be useful to determine the **system behavior in presence of large perturbation**

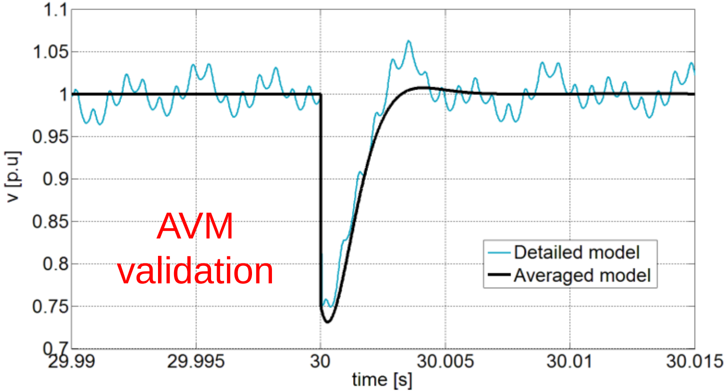
Voltage actuator approach (1/5)

- Voltage control techniques for **regulating the operation of DC/DC converter**
- DC/DC converter → **compensation of voltage instability!**
- Two models : detailed model (**generator dynamics and switching**) or Average Value Model AVM (**no generator dynamics or switching**) → cross test



Single converter case

source of stabilizing power



Voltage actuator approach (2/5)

- Three techniques are developed to solve the instability: **SF(State Feedback), AD (Active Damping) and LSF (Linearization via State Feedback)**

- **SF** is a basic technique: the aim is to **validate the small-signal stability conditions** by introducing two control constant

- **AD** is a non-dissipative method to **transiently increase the system damping factor** by adding a virtual filter resistance

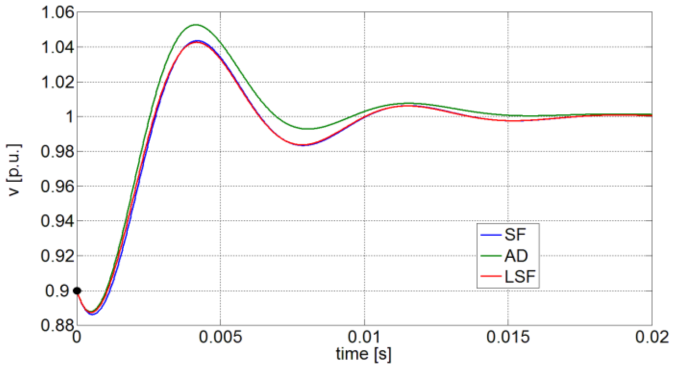
- **LSF** is a complex technique based on the introduction of a **suitable non-linear feedback to compensate the nonlinearity**. The controlled system is made **linear**

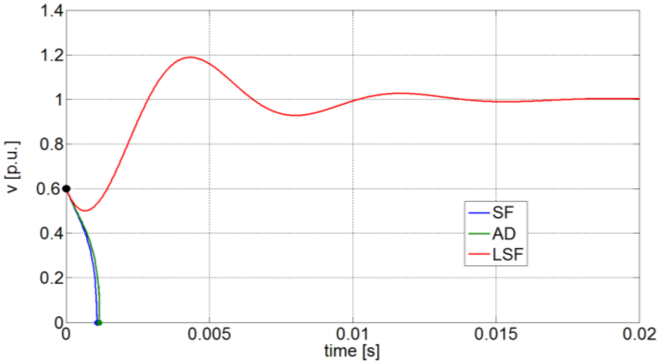
- A series of simulations is realized to verify the **effectiveness** of the techniques and to understand **pros and cons** → same voltage dynamics : csi=0.3, OM=895 rad/s

Voltage actuator approach (3/5)

- ✓ **Small** perturbation: **SF, AD and LSF** are able to keep the **bus stable**
- ✓ **Large** perturbation: small-signal hypothesis is violated and **SF-AD are not capable** to maintain stability. **LSF technique is able to restore** the rated voltage in accordance with the desired dynamics

D. Bosich, G. Giadrossi and G. Sulligoi, "Voltage control solutions to face the CPL instability in MVDC shipboard power systems," 2014 AEIT Annual Conference - From Research to Industry: The Need for a More Effective Technology Transfer (AEIT), Trieste, Italy, Sept. 18-19, 2014.





Voltage actuator approach (4/5)

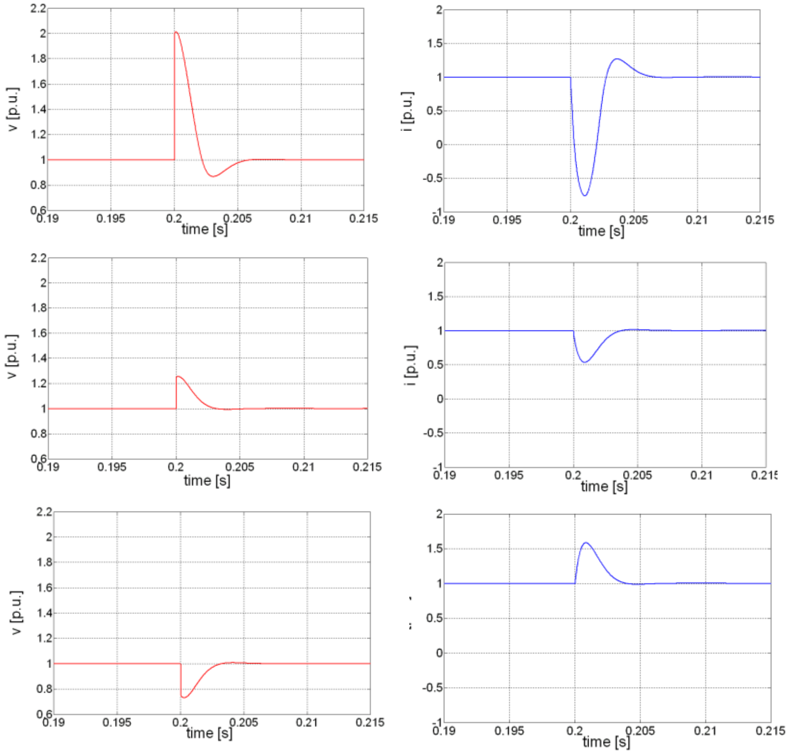
	PROS	CONS
SF - AD	• basic technique • feedback of standard real-time measurements • simple implementation on digital controllers	• stability ensured in presence of limited CPLs • non-linear damped system • stability guaranteed only for non critical system • stability ensured in presence of limited disturbance • system dynamics set considering stability issue
LSF	• any CPL non-linearity cancelled • standard linear system obtained • stability guaranteed even for critical system • stability ensured in presence of whichever disturbance • system dynamics set independently from stability issue	• complex technique • derivative variable calculus • partial non-linearity cancellation in presence of measurements errors • partial non-linearity cancellation in presence of system parameters uncertainty • voltage actuator saturation due to the derivative action of control signal

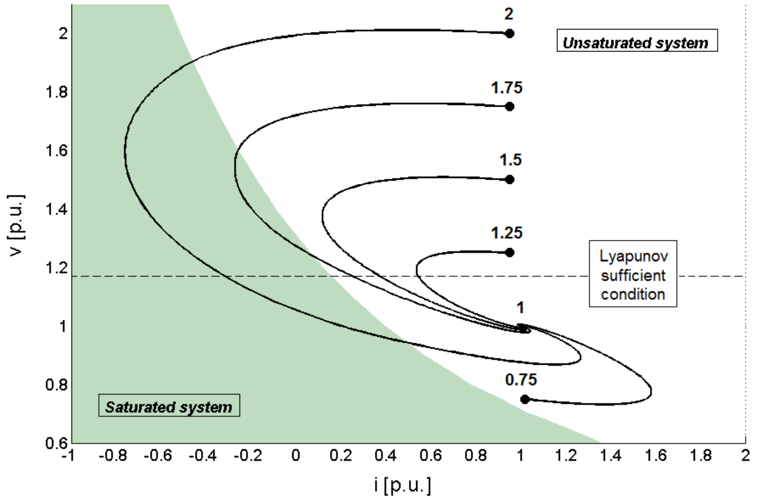
- **Basic controls (SF-AD) are not able** to compensate for the CPL destabilizing effect in **critical conditions (large CPL or large perturbation or small capacitance)**

- **LSF is a complex effective** control capable of solving instability also in **critical scenario**, but it may force the **voltage actuator saturation**

D. Bosich, G. Giadrossi and G. Sulligoi, "Voltage control solutions to face the CPL instability in MVDC shipboard power systems," 2014 AEIT Annual Conference - From Research to Industry: The Need for a More Effective Technology Transfer (AEIT), Trieste, Italy, September 18-19, 2014

Voltage actuator approach (5/5)





behavior during the **saturation**

of DC/DC converter

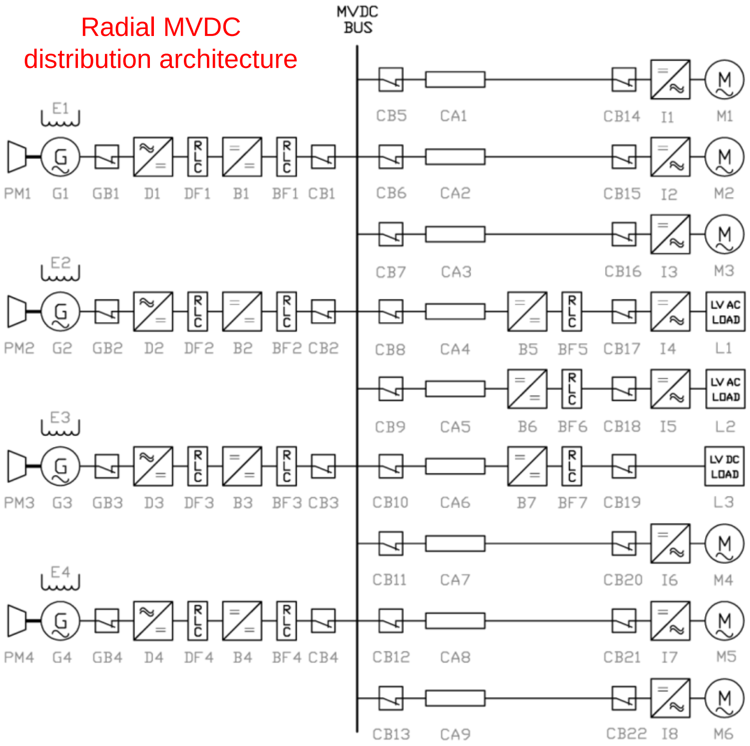
→ **nonlinear system**

….again!

G. Sulligoi, D. Bosich and G. Giadrossi, "Linearizing voltage control of MVDC power systems feeding constant power loads: Stability analysis under saturation," *2013 IEEE Power & Energy Society General Meeting*, Vancouver, BC, 2013, pp. 1-5.

Voltage control solutions in multiconverter MVDC system (1/14)

Radial MVDC distribution architecture



- The plant layout rearranges the MVAC distribution of a **large all-electric ship** into MVDC using IEEE Std 1709 proposal
- **Four generating systems:**
  - Alternators (G1-G4)
  - Diode rectifiers (D1-D4)
  - DC-DC interface converters (B1-B4)
- **Six CPLs** directly connected to the MVDC bus (I1-I3, I6-I8)
  → **critical scenario**
- **Three load lines** (L1-L3), fed by dedicated buck converters, modeling in an equivalent way the remaining **low voltage shipboard users**
- Second order **RLC filtering stages** (DF1-DF4, BF1-BF7)

Voltage control solutions in multiconverter MVDC system (2/14)

- The proposed power system is characterized by lots of **CPLs**
- **Supply of CPLs → worst case scenario →** the related instability must be solved!
- **Which solution?**
- To assure voltage stability, **two control strategies (global and local)** may be developed
- The **global strategy** is used to stabilize the **MVDC bus** voltage by controlling the **power station** (→ power converters at the left)
- The **local strategy** is useful to **locally solve** the instability of **highly impacting loads** (right)

Voltage control solutions in multiconverter MVDC system (3/14)

- Two different voltage controls are designed to **stabilize the multi-converter MVDC power system**
- **1st →** combination of a g**lobal AD** and of a **local LSF**
- **2nd → global LSF**
- Each control solution is analyzed by means of **numerical simulations**
- **Weak points** of each solution: **dynamics interactions (1st solution)** and instability due to system **parameters mismatching (2nd solution)**

Voltage control solutions in multiconverter MVDC system (4/14)

Global AD+Local LSF

- **AD** on **generating** DC/DC converters, **LSF** on **load** DC/DC converters
- **Limited AD action** → generating system **filters** are designed **for ensuring a low voltage ripple (1%)** → damping factor greater than **-0.2** (not very critical case)
- **AD virtual resistances** → positive damping factor ξ_{ADk} **(0.18)**
- **Local LSF technique** → control of **highly impacting CPLs** (about 1/4 of the total power)
- **LSF method** → CPL cancellation by feeding back a proper **nonlinear control function Fc**
- Control function = **nonlinear term + state feedback** (for imposing the dynamics)

LSF $F_c = f_l + f_d$

$$\begin{cases} f_l = R_f \dfrac{P}{V} - L_f \dfrac{P}{V^2}\dfrac{\mathrm{d}V}{\mathrm{d}t} \\ f_d = k_1 \cdot V + k_2 \cdot I_c \end{cases}$$

Voltage control solutions in multiconverter MVDC system (5/14)

Global AD+Local LSF

G. Sulligoi, D. Bosich, V. Arcidiacono and G. Giadrossi, "Considerations on the design of voltage control for multi-machine MVDC power systems on large ships," 2013 IEEE Electric Ship Technologies Symposium (ESTS), Arlington, VA, USA, April 22-24, 2013.

- **Matlab/Simulink simulations tests** are carried out in order to verify the effectiveness of the comprehensive control, assuming **AVMs** and two possible **perturbations (i.e. load variations)**

- **First perturbation**

  Contemporaneous step insertion (in t=4 s, **25%** of generating rated power) of CPLs **I1** and **I8** (directly connected to the bus) is used to **check external control AD loops**

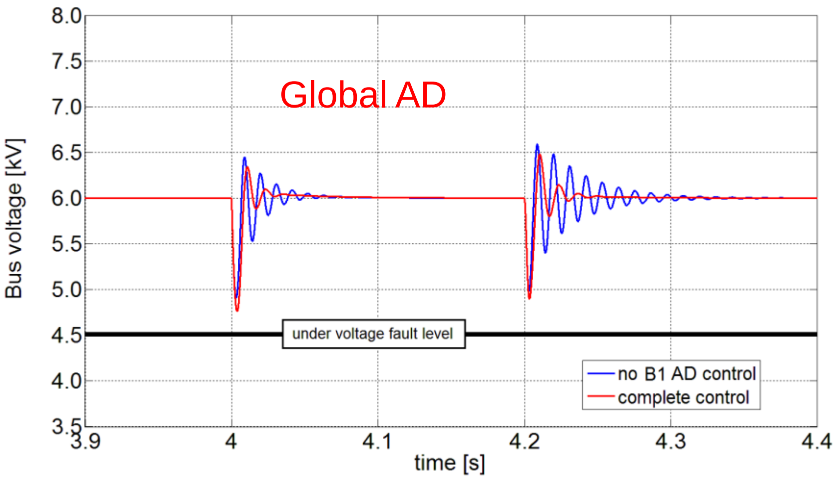
- **Second Perturbation**

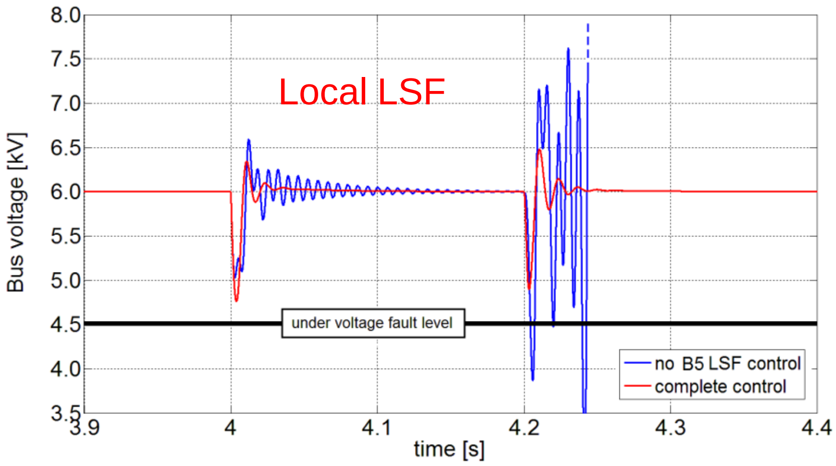
  Later, **I4 highly impacting CPL** is connected (in t=4.2 s, **15%** of generating rated power) to **test the Local LSF voltage control**

Voltage control solutions in multiconverter MVDC system (6/14)

G. Sulligoi, D. Bosich, V. Arcidiacono and G. Giadrossi, "Considerations on the design of voltage control for multi-machine MVDC power systems on large ships," 2013 IEEE Electric Ship Technologies Symposium (ESTS), Arlington, VA, USA, April 22-24, 2013

- **In absence of AD** control, perturbations determine **limited bus voltage oscillations**
- **Local Instability** (dashed lines) due to the **LSF lack** burdens the MVDC bus by the B5 DC/DC converter → **ship black-out or under-voltage protection intervention**



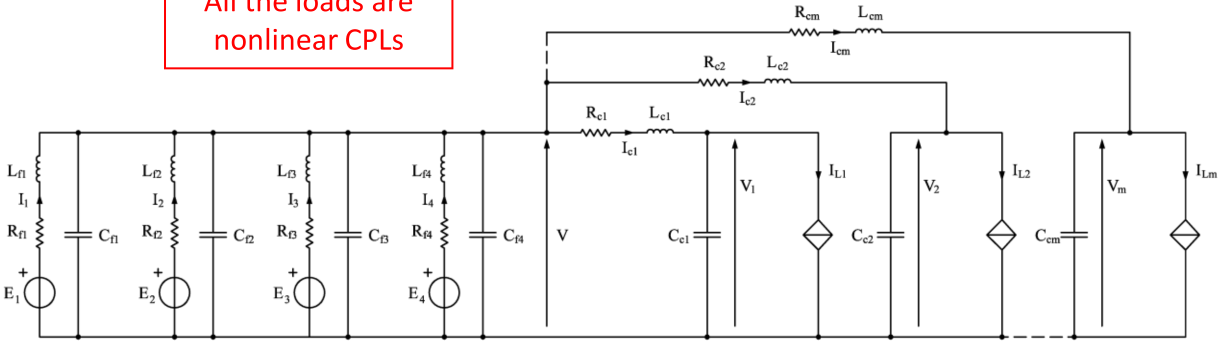


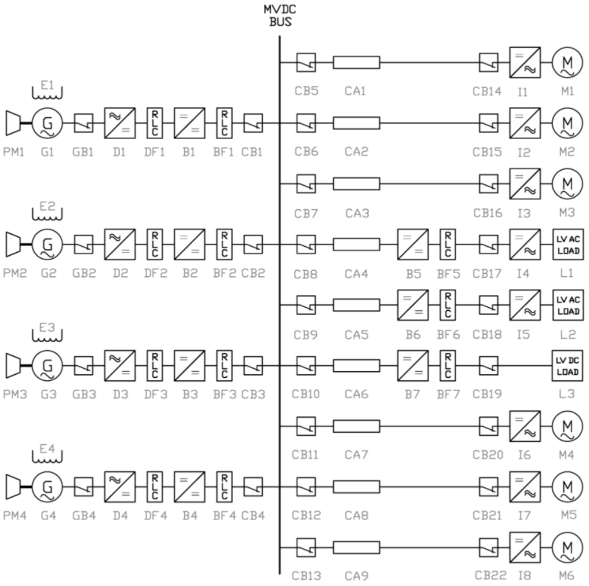
Voltage control solutions in multiconverter MVDC system (7/14)

Global LSF

- Common practice for size-limited DC power systems
  → to **neglect cable longitudinal parameters Rch and Lch** with respect to other longitudinal elements

All the loads are nonlinear CPLs



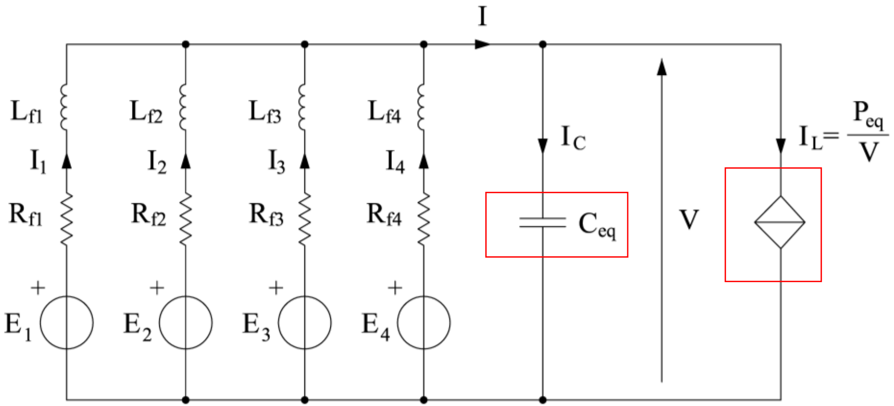


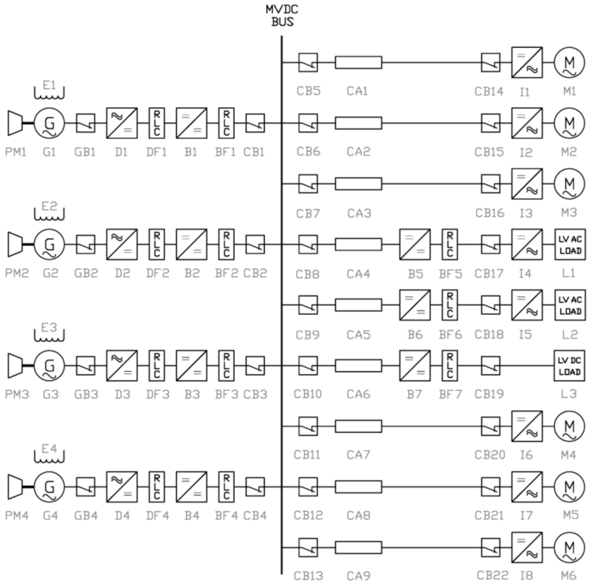
Voltage control solutions in multiconverter MVDC system (8/14)

All the loads are nonlinear CPLs

Global LSF

- **All capacitors and nonlinear loads become parallel connected** → equivalent capacitor **Ceq** and equivalent load current generator **IL=Peq/V**





Voltage control solutions in multiconverter MVDC system (9/14)

Global LSF

- DC/DC generating converters controlled (**Fk**) for "cancelling" the **total CPL (power Peq**)

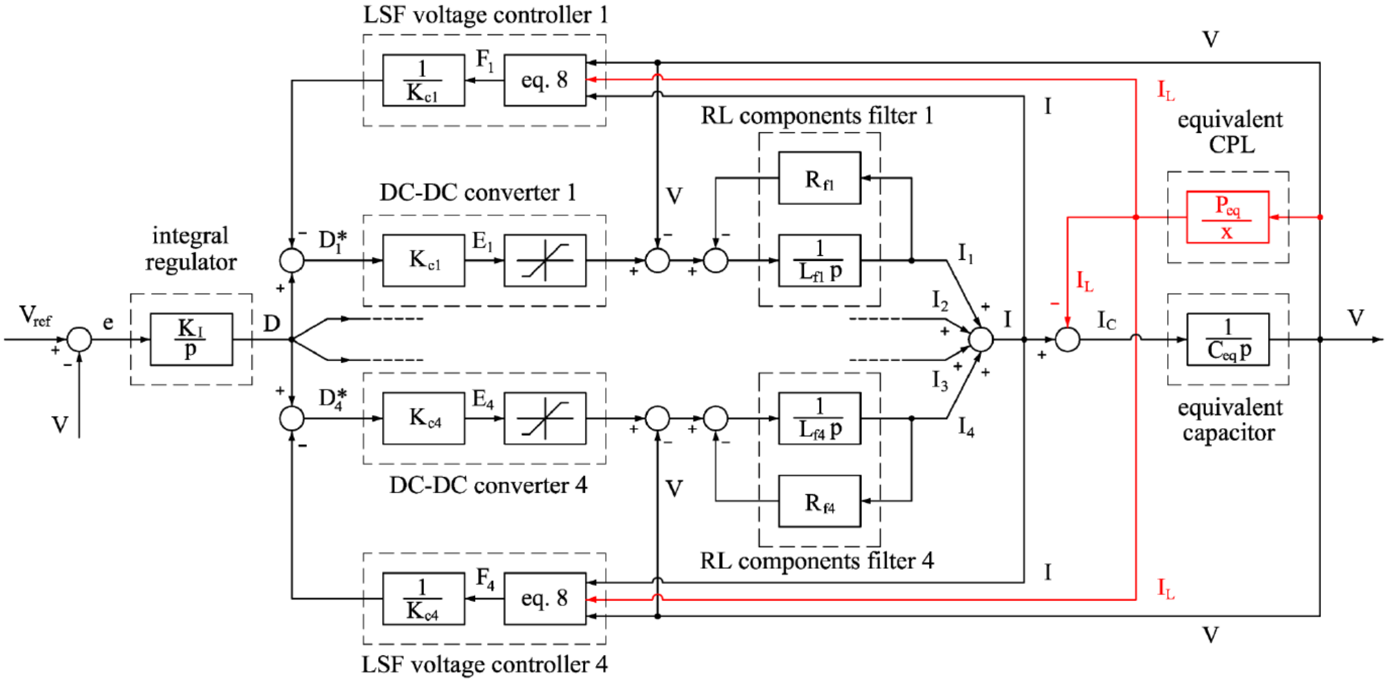
$$\begin{cases} f_l = -\frac{P_{eq}}{C_{eq}\cdot T_f \cdot V} + \frac{P_{eq}}{C_{eq}\cdot V^2}\frac{dV}{dt} = -\frac{I_L}{C_{eq}\cdot T_f} + \frac{I_L}{C_{eq}\cdot V}\frac{I-I_L}{C_{eq}} \\ f_c = K_1 \cdot (V - V_0) + K_2 \frac{dV}{dt} = K_1 \cdot (V - V_0) + K_2 \frac{I-I_L}{C_{eq}} \end{cases}$$

$$F_k = S_k \cdot (f_l + f_c) \cdot C_{eq} \cdot L_{fk}$$

Equation 8

- The combined control action of functions **fl** and **fc** can be split in **four contributions Fk** over the four generators, using the **load sharing coefficients Sk (ΣSk=1)**
- **LSF is designed to be a well-performing control technique also in critical situation**
- Thus generating system filters (BF1/BF3, BF2/BF4) can be **designed** assuming **quite large voltage ripple (3%) and tiny current ripple (30%)**, determining a **very low (and then dangerous!) damping factor (-0.48)**

Voltage control solutions in multiconverter MVDC system (10/14)



G. Sulligoi, D. Bosich, G. Giadrossi, L. Zhu, M. Cupelli and A. Monti, "Multiconverter Medium Voltage DC Power Systems on Ships: Constant-Power Loads Instability Solution Using Linearization via State Feedback Control," in IEEE Transactions on Smart Grid, vol. 5, no. 5, pp. 2543-2552, Sept. 2014.

Voltage control solutions in multiconverter MVDC system (11/14)

- Using **AVM** assumption, it is possible to model the MVDC power system in a simple way. **Matlab/Simulink** simulations tests are used to **test the control action**

- A sudden **generating system disconnection** actually represents one of the most **dangerous events** in shipboard power systems

Global LSF

Perturbation

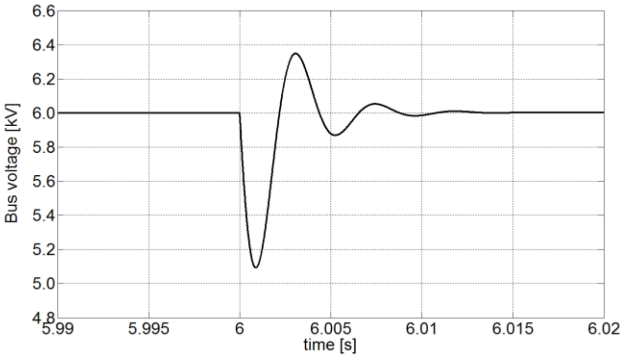
- At the **beginning** the **MVDC shipboard microgrid** supplies a **CPL load (Peq=18.5 MW)**, by using **3** DC generating systems **(total rated power Pn=42 MW)**

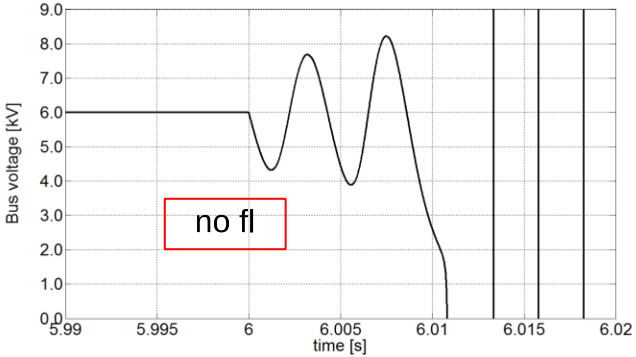
- **At t=6 s**, the sudden commutation of **CB3** is used to simulate **the disconnection of B3**, therefore the total rated power becomes **Pn=26.25 MW**

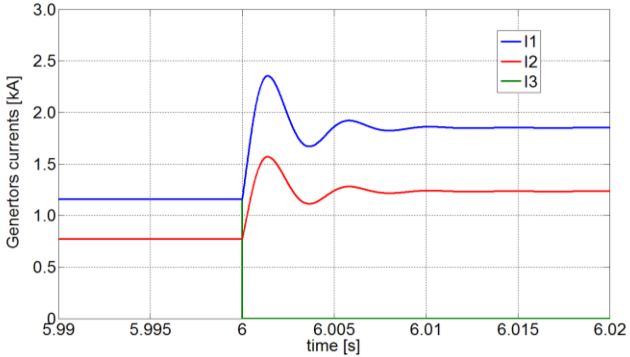
- **After the disconnection**, load sharing coefficients **S_k are automatically calculated and adapted** to guarantee a **proper sharing** over each remaining DC generating system

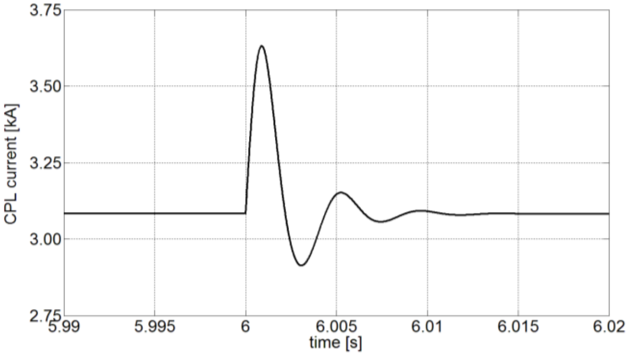
G. Sulligoi, D. Bosich, G. Giadrossi, L. Zhu, M. Cupelli and A. Monti, "Multiconverter Medium Voltage DC Power Systems on Ships: Constant-Power Loads Instability Solution Using Linearization via State Feedback Control," in IEEE Transactions on Smart Grid, vol. 5, no. 5, pp. 2543-2552, Sept. 2014

Voltage control solutions in multiconverter MVDC system (12/14)







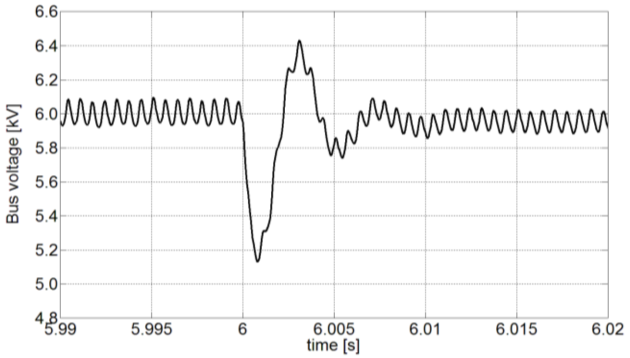


Global LSF

AVM

G. Sulligoi, D. Bosich, G. Giadrossi, L. Zhu, M. Cupelli and A. Monti, "Multiconverter Medium Voltage DC Power Systems on Ships: Constant-Power Loads Instability Solution Using Linearization via State Feedback Control," in IEEE Transactions on Smart Grid, vol. 5, no. 5, pp. 2543-2552, Sept. 2014

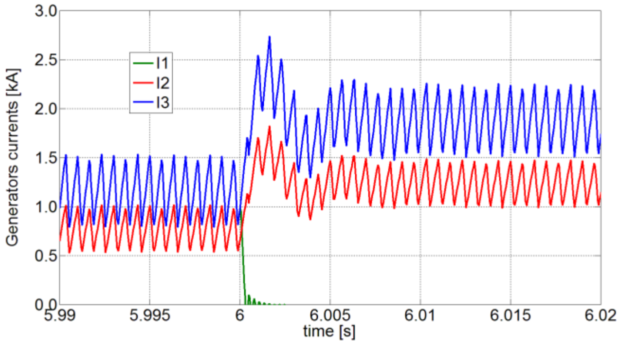
Voltage control solutions in multiconverter MVDC system (13/14)

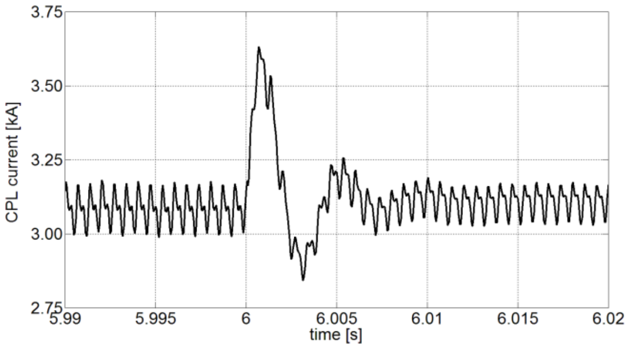


- **Good matching** of the simulation results in Simulink (AVM) and RTDS (detailed model)

Global LSF

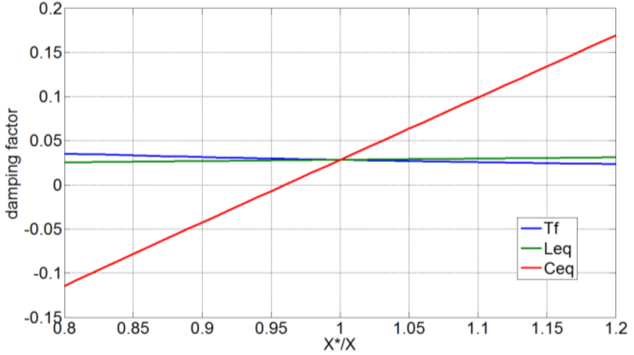
Detailed model simulations – RTDS

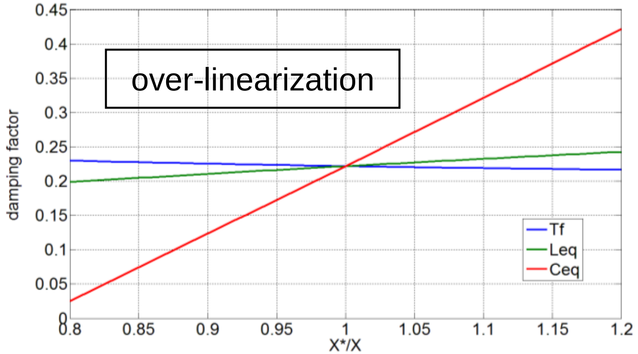




G. Sulligoi, D. Bosich, G. Giadrossi, L. Zhu, M. Cupelli and A. Monti, "Multiconverter Medium Voltage DC Power Systems on Ships: Constant-Power Loads Instability Solution Using Linearization via State Feedback Control," in IEEE Transactions on Smart Grid, vol. 5, no. 5, pp. 2543-2552, Sept. 2014

Voltage control solutions in multiconverter MVDC system (14/14)



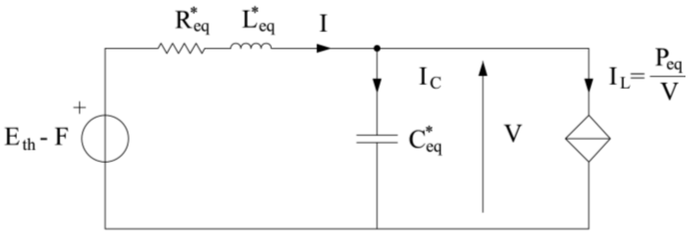


Global LSF

- **Worst case scenario (deactivation of f_c)**
  Sensitivity analysis to verify how the **system parameters mismatching** impacts on the **stability**
- The **control** assumes a **parameter X** lower or upper the **actual system parameter X***
- The stability issue is strictly linked to **system capacitor mismatch**, while others mismatch are irrelevant
- **Global LSF control technique is unable** to guarantee stability (so $\xi_t<0$) if the power system presents a real equivalent capacitor **C_{eq}^*smaller than 0.95 the designed one C_{eq}**
- An **over-linearization strategy** can be applied, determining the **f_l function on a reduced equivalent capacitor (e.g. 0.8 C_{eq}):** the system stability is **ensured**

Model parameters estimation (1/6)

- Thanks to a **linearizing (nonlinear!) function perfectly calibrated** on the system, **LSF** can establish an **input-output linear relationship**
- Then, a **control function** for performing the desired **pole placement**
- **Parameter mismatch → partial linearization → insufficient? → instability**



Evidently, the complete compensation is achievable only when the nonlinear feedback F is perfectly tuned to the function Λ. That means on one hand the perfect correspondence among control parameters (R^c_{eq}, L^c_{eq} and C^c_{eq}) and the parameters of the installed filters (R^*_{eq}, L^*_{eq} and C^*_{eq}), and on the other one precise knowledge about the time-varying functions (P_{eq}, V, dV/dt).

Second-order reduced model

$$\begin{cases} \dot{V} = \frac{1}{C^*_{eq}}\left(I - \frac{P_{eq}}{V}\right) \\ \dot{I} = \frac{1}{L^*_{eq}}\left(E_{th} - F - V - R^*_{eq} I\right) \end{cases}$$

$$\ddot{V} = \frac{1}{C^*_{eq}}\left(\dot{I} + \frac{P_{eq}}{V^2}\dot{V}\right)$$

$$\ddot{V} + \left(\frac{R^*_{eq}}{L^*_{eq}}\right)\cdot\dot{V} + \left(\frac{1}{L^*_{eq}C^*_{eq}}\right)\cdot V + \Lambda = \frac{1}{L^*_{eq}C^*_{eq}}\left(E_{th} - F\right)$$

$$\Lambda = -\left(\frac{1}{C^*_{eq}}\frac{P_{eq}}{V^2}\right)\cdot\dot{V} + \left(\frac{R^*_{eq}}{L^*_{eq}C^*_{eq}}\right)\cdot\frac{P_{eq}}{V}$$

$$\frac{F}{L^*_{eq}C^*_{eq}} = \left(\frac{1}{C^c_{eq}}\frac{P_{eq}}{V^2}\right)\cdot\dot{V} - \left(\frac{R^c_{eq}}{L^c_{eq}C^c_{eq}}\right)\cdot\frac{P_{eq}}{V} \cong -\Lambda$$

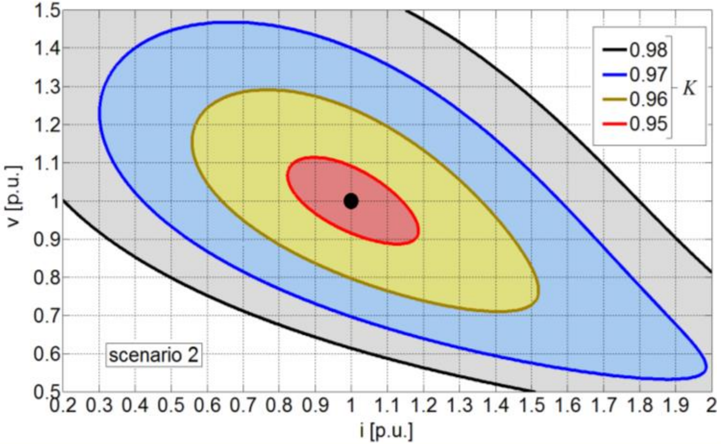
Model parameters estimation (2/6)

$$\ddot{V} + \left(\frac{R^*_{eq}}{L^*_{eq}}\right)\cdot\dot{V} + \left(\frac{1}{L^*_{eq}C^*_{eq}}\right)\cdot V + \left(\frac{1}{C^c_{eq}} - \frac{1}{C^*_{eq}}\right)\frac{P_{eq}}{V^2}\dot{V} + \left(\frac{R^*_{eq}}{L^*_{eq}C^*_{eq}} - \frac{R^c_{eq}}{L^c_{eq}C^c_{eq}}\right)\cdot\frac{P_{eq}}{V} = \frac{E_{th}}{L^*_{eq}C^*_{eq}}$$

$$\begin{cases} \Psi = \frac{1}{2}\left\{\dot{V} + \int_{V_0}^{V} h(\vartheta)d\vartheta\right\}^2 + \int_{V_0}^{V} g(\vartheta)d\vartheta \\ \dot{\Psi} = -g(V)\int_{V_0}^{V} h(\vartheta)d\vartheta \end{cases}$$

$$\Psi(V,I) = \frac{1}{2}\left\{\frac{I}{C^*_{eq}} - \frac{P_{eq}}{C^*_{eq}V} + \frac{R^*_{eq}}{L^*_{eq}}(V - V_0) + \frac{P_{eq}}{C_F V} - \frac{P_{eq}}{C_F V_0}\right\}^2 + \frac{1}{L^*_{eq}C^*_{eq}}\left\{\frac{V^2 - V_0^2}{2} + R_F P_{eq}\log_e\left|\frac{V}{V_0}\right| - E_{th}(V - V_0)\right\}$$

$$\dot{\Psi}(V,I) = \frac{1}{L^*_{eq}C^*_{eq}}\left[V + R_F\frac{P_{eq}}{V} - E_{th}\right] \cdot \left[-\frac{R^*_{eq}}{L^*_{eq}}(V - V_0) - \frac{P_{eq}}{C_F V} + \frac{P_{eq}}{C_F V_0}\right]$$



Lyapunov analysis for nonlinear systems

$$K = C^*_{eq}/C^c_{eq}$$

$$\begin{cases} \dot{\Psi}(V) \leq 0 \\ V \geq \dfrac{P_{eq}}{V_0\cdot\left(\frac{R^*_{eq}C_F}{L^*_{eq}}\right)} := V_{\min} \end{cases}$$

$$\begin{cases} \Omega(I) = \Psi(V_{\min}, I) \\ \dfrac{d\Omega(I)}{dI} = 0 \Rightarrow I_t = \dfrac{R^*_{eq}C_F}{L^*_{eq}}V_0 \end{cases}$$

$$k = \Psi(V_{\min}, I_t)$$

$$RAS = \{(V,I) : \Psi(V,I) \leq k\}$$

Model parameters estimation (3/6)

D. Bosich, G. Sulligoi, E. Mocanu and M. Gibescu, "Medium Voltage DC Power Systems on Ships: An Offline Parameter Estimation for Tuning the Controllers' Linearizing Function," in IEEE Transactions on Energy Conversion, vol. 32, no. 2, pp. 748-758, June 2017.

- One possibility to solve the inaccurate linearization is offered by the **off-line parameter estimation.**
- Once obtained a **snapshot (voltage transient)** of the system, **deterministic and stochastic methods** may be exploited for **calibrating the parameters of a reduced system model.**
- Then, LSF technique can be **perfectly tuned** to successfully linearize the DC power system → **stability!**

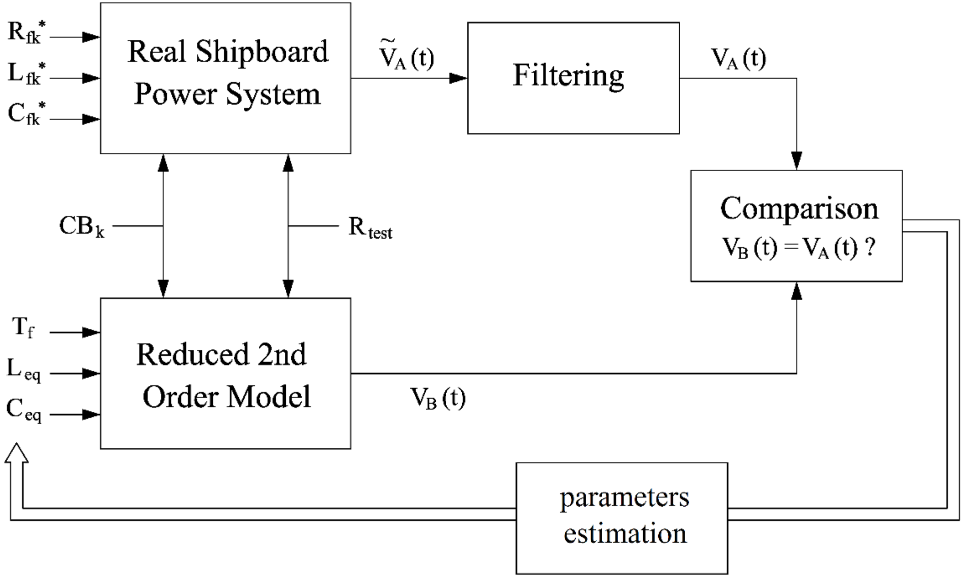
perfect convergence

reference voltage transient
==
model output

estimated parameters
==
real parameters

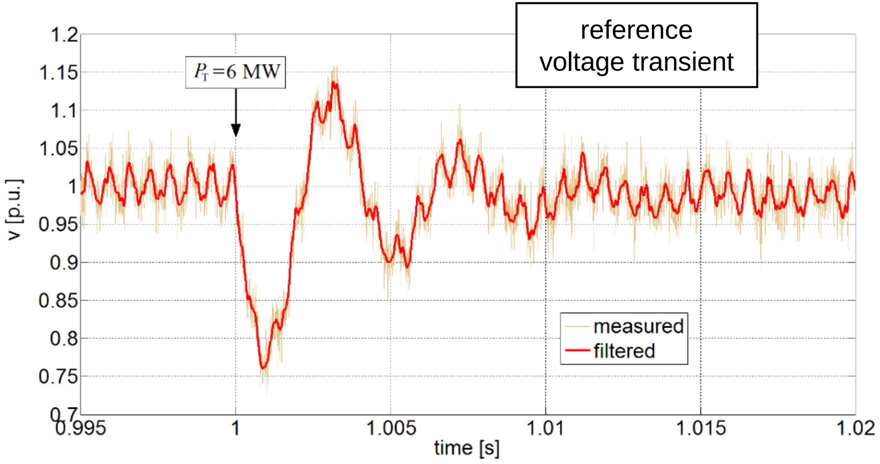
Model parameters estimation (4/6)

D. Bosich, G. Sulligoi, E. Mocanu and M. Gibescu, "Medium Voltage DC Power Systems on Ships: An Offline Parameter Estimation for Tuning the Controllers' Linearizing Function," in IEEE Transactions on Energy Conversion, vol. 32, no. 2, pp. 748-758, June 2017.



Estimation based on comparison among transients

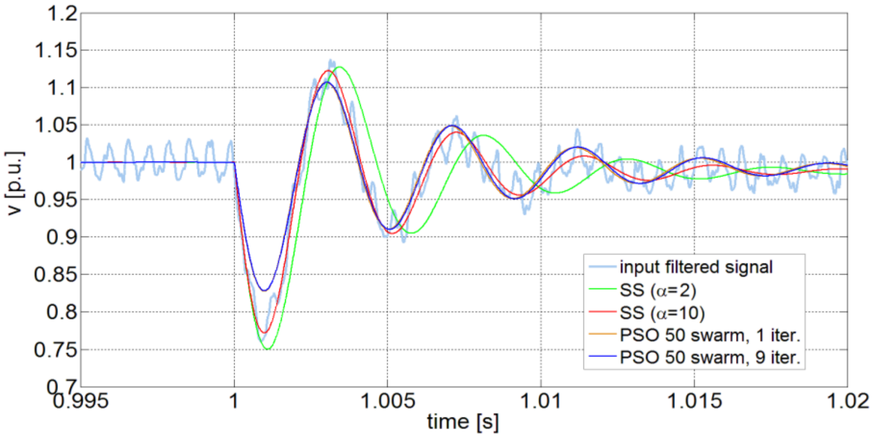
Model parameters estimation (5/6)



Methods for parameter estimation on reduced order model

Selective Search (SS)

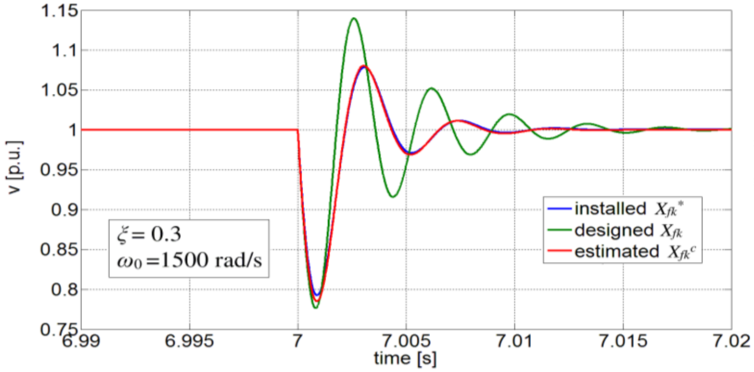
Particle Swarm Optimization (PSO)

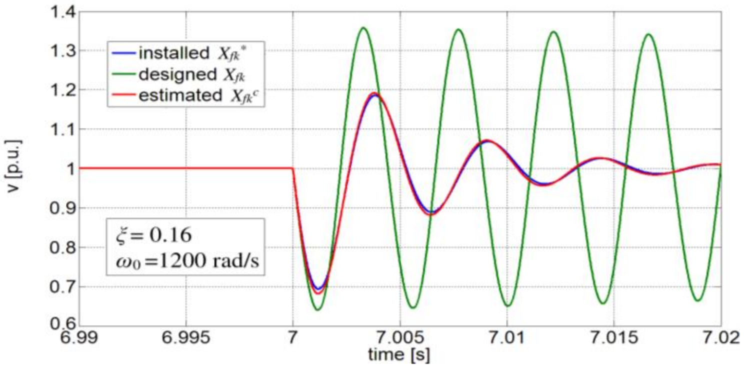


SS (10 iterations α)
perfect correspondance
reference vs. model output

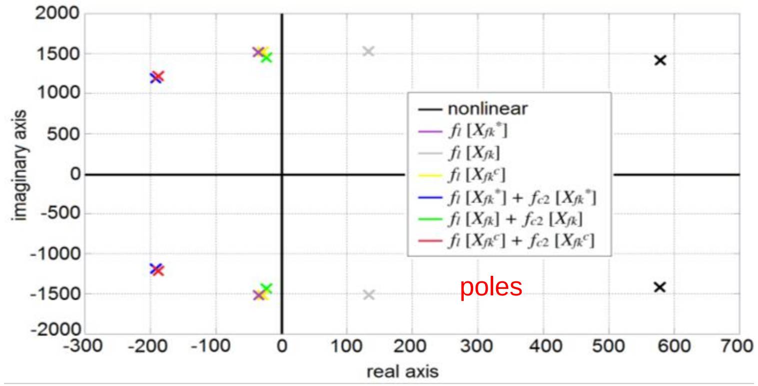
Control parameters may be tuned on the estimated ones!

Model parameters estimation (6/6)





Estimation solves **stability issues** even in case of low performance controlled systems



1a) **Partial linearization** (X_{fk} designed parameters)
→ from black to grey → **system instability**

2a) **Control function**
→ from grey to green → **NO control specifications**

1b) **Linearization** (X_{fk}^c estimated parameters
→ from black to yellow → **system stability**

2b) **Control function**
→ from yellow to red (near blue) → **control specification** ξ=0.16 and ω_0=1200 rad/s

Last studies → Weighted Bandwidth Method (1/2)

energies MDPI

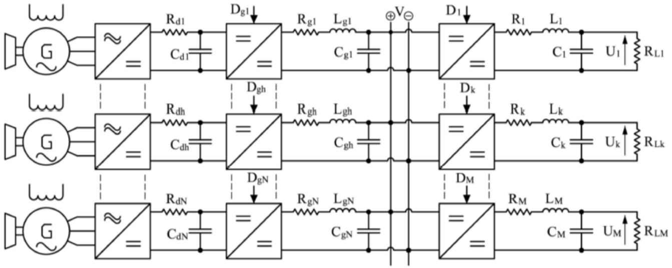
Article

Weighted Bandwidth Method for Stability Assessment of Complex DC Power Systems on Ships

Daniele Bosich *, Giovanni Giadrossi, Stefano Pastore and Giorgio Sulligoi

$$\begin{cases} \dot{I} = \frac{1}{L}(E - V) \\ \dot{V} = \frac{1}{C}(I - I_L) \\ \dot{D}_k = \omega_k D_{k0} - \frac{\omega_k}{V_0} D_k V \\ I_L = \sum_{k=1}^{M}\left[\frac{1}{R_{Lk}} D_k^2 V\right] \end{cases}$$

$$\begin{cases} \Delta\dot{I} = \frac{1}{L}(\Delta E - \Delta V) \\ \Delta\dot{V} = \frac{1}{C}(\Delta I - \Delta I_L) \\ \Delta\dot{D}_k = -\omega_k \Delta D_k - \frac{\omega_k D_{k0}}{V_0}\Delta V \\ \Delta I_L = \sum_{k=1}^{M}\left[\frac{2D_{k0}V_0}{R_{Lk}}\Delta D_k + \frac{D_{k0}^2}{R_{Lk}}\Delta V\right] \end{cases}$$



$$D_k(s) = -\frac{\omega_k D_k(s)}{s} - \frac{\omega_k D_{k0}}{sV_0}V(s) \Rightarrow D_k(s) = -\frac{\omega_k}{s+\omega_k}\frac{D_{k0}}{V_0}V(s)$$

$$I_L(s) = \sum_{k=1}^{M}\left[\frac{2D_{k0}V_0}{R_{Lk}}D_k(s) + \frac{D_{k0}^2}{R_{Lk}}V(s)\right] = \sum_{k=1}^{M}\left[\frac{D_{k0}^2}{R_{Lk}}\cdot\frac{s-\omega_k}{s+\omega_k}\right]V(s)$$

$$Z_o(s) = \frac{V(s)}{-I_L(s)} = \frac{sL}{1+s^2LC} = \frac{1}{C}\frac{s}{\omega_0^2+s^2}$$

$$Y_i(s) = \frac{I_L(s)}{V(s)} = \sum_{k=1}^{M}\left[\frac{D_{k0}^2}{R_{Lk}}\cdot\frac{s-\omega_k}{s+\omega_k}\right]$$

$$Y_i(j\omega) = \sum_{k=1}^{Ms}\left[G_k\frac{j\omega-\omega_k}{j\omega+\omega_k}\right] = \sum_{k=1}^{Ms}\left[G_k\frac{-2\omega_k}{j\omega+\omega_k}\right] + G_S$$

$$Y_S(j\omega) = G_S\frac{j\omega-\omega_S}{j\omega+\omega_S} = G_S\frac{-2\omega_S}{j\omega+\omega_S} + G_S$$

$$\omega_S = \sum_{k=1}^{Ms} m_k\omega_k$$

$$\omega_D = \sum_{k=Ms+1}^{M} m_k\omega_k$$

$$\Im\left(\overline{Z_o}\cdot\overline{Y_i}\right) = -\frac{\omega_{cr}}{C\left(\omega_0^2-\omega_{cr}^2\right)}\cdot\left[G_S\frac{\omega_S^2-\omega_{cr}^2}{\omega_S^2+\omega_{cr}^2} + G_D\frac{\omega_D^2-\omega_{cr}^2}{\omega_D^2+\omega_{cr}^2}\right] = 0$$

$$\Re\left(\overline{Z_o}\cdot\overline{Y_i}\right) = -\frac{2\omega_{cr}^2}{C\left(\omega_0^2-\omega_{cr}^2\right)}\cdot\left[G_S\frac{\omega_S}{\omega_S^2+\omega_{cr}^2} + G_D\frac{\omega_D}{\omega_D^2+\omega_{cr}^2}\right] = -\Psi$$

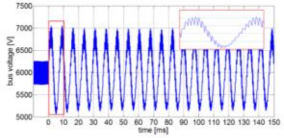


Figure 9. Bus voltage transient in Case 1 (each Y-division is 500 V in zoomed gr

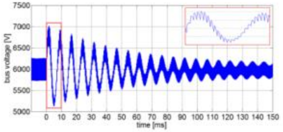


Figure 10. Bus voltage transient in Case 3 (each Y-division is 500 V in zoomed g

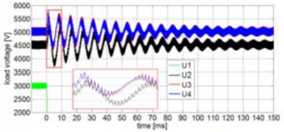


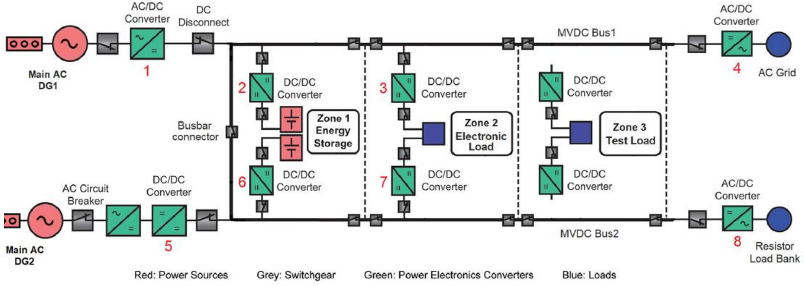
Figure 11. Load voltages transient in Case 3 (each Y-division is 500 V in zoomed graph).

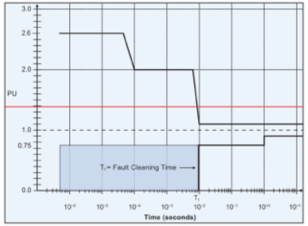
Last studies → Digital Twin of Zonal DC System (2/2)

IEEE TRANSACTIONS ON TRANSPORTATION ELECTRIFICATION, VOL. 9, NO. 3, SEPTEMBER 2023 4541

High-Performance Megawatt-Scale MVDC Zonal Electrical Distribution System Based on Power Electronics Open System Interfaces

Daniele Bosich, Senior Member, IEEE, Massimiliano Chiandone, Member, IEEE, Giorgio Sulligoi, Senior Member, IEEE, Andrea Alessia Tavagnutti, Member, IEEE, and Andrea Vicenzutti, Member, IEEE



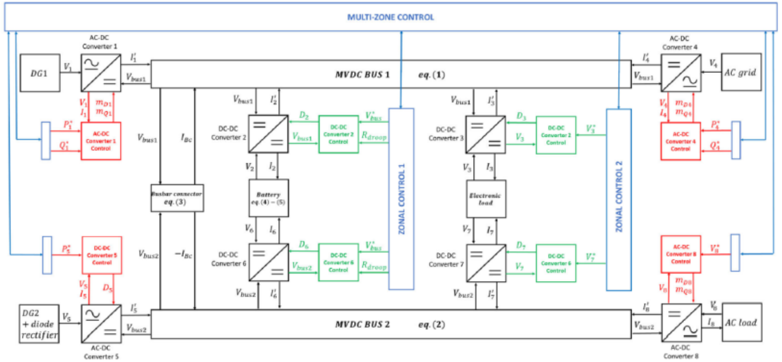


$$
\begin{cases}
pV_{\text{bus1}} = \dfrac{1}{C_{\text{bus1}}}\left[\displaystyle\sum_{k=1}^{4} I_k' + I_{Bc}\right], \\
C_{\text{bus1}} = \displaystyle\sum_{k=1}^{4} C_k \\
pV_{\text{bus2}} = \dfrac{1}{C_{\text{bus2}}}\left[\displaystyle\sum_{k=5}^{8} I_k' - I_{Bc}\right], \\
C_{\text{bus2}} = \displaystyle\sum_{k=5}^{8} C_k \\
pI_{\text{Bc}} = \dfrac{1}{L_{Bc}}[V_{\text{bus1}} - V_{\text{Bc}} - R_{\text{Bc}} I_{\text{Bc}}]
\end{cases}
$$

$$
\begin{cases}
pV_{\text{bus1}} = \dfrac{1}{C_{\text{bus1}}}[I_2(1-D_2) - I_3 D_3] \\
pI_2 = \dfrac{1}{L_2}[V_2 - (1-D_2)V_{\text{bus1}} - R_2 I_2] \\
D_2 = \left(K_{Pi2} + \dfrac{K_{Ii2}}{p}\right)[I_{2\text{ref}} - I_2] \\
I_{2\text{ref}} = \left(K_{Pv2} + \dfrac{K_{Iv2}}{p}\right)[V_{\text{bus}}^* - V_{\text{bus1}} - R_{\text{droop}} I_2] \\
pV_3 = \dfrac{1}{C_{\text{in3}}}\left[I_3 - \dfrac{V_3}{R_{L3}}\right] \\
pI_3 = \dfrac{1}{L_3}[V_{\text{bus1}} D_3 - V_3 - R_3 I_3] \\
D_3 = \left(K_{Pi3} + \dfrac{K_{Ii3}}{p}\right)[I_{3\text{ref}} - I_3] \\
I_{3\text{ref}} = \left(K_{Pv3} + \dfrac{K_{Iv3}}{p}\right)[V_3^* - V_3].
\end{cases}
$$

$$V_k = V_{\text{OC}k}(\text{SOC}_k) - R_{bk} I_k$$

$$p\text{SOC}_k = -\frac{1}{k_b C_{bk}} I_k.$$



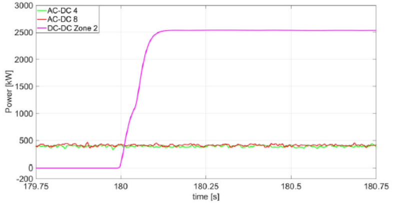


Fig. 17. Power transients of load converters and magnification (exp.).

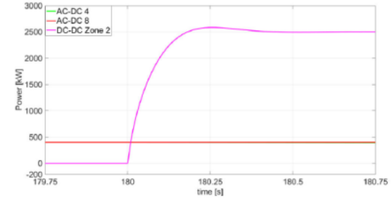


Fig. 12. Power transients of load converters and magnification (sim.).

Conclusions (1/3)

- **Microgrids** are the **future** for electrical distribution → **system energy optimization!**
- Not only AC microgrids, **DC technology** opens new scenarios
- In the **shipboard context**, the new Medium Voltage DC distribution represents an opportunity to re-design the IPS **(higher power density, enhanced quality of service, optimization of distribution size)**
- **Radial VS Zonal** distribution
- Widespread use of **filtered power converters → possible CPL instability!**
- **Instability = blackout → not good!**
- The **voltage actuator approach** is a reliable possibility **to compensate for the destabilizing effect**

Conclusions (2/3)

- **Several control techniques** are tested on a single converter case
- A shipboard **multiconverter MVDC** power system as case of study for the **voltage control design**
- **The voltage control must compensate for the CPL system instability**
- Different tests have demonstrated the **AD-LSF capability** is solving the **system instability**
- **Global AD + Local LSF** is suggested in case of **few CPLs**, where the **LSF (load side)** is exploitable to locally solve the instability of a **high CPLs** (→ thrusters in future MVDC cruise liners)
- Conversely, **Global LSF** (generator side) is recommended to guarantee global stability in presence of a **large amount of CPLs** (→ future MVDC naval vessels with high performance radars)

Conclusions (3/3)

- What about **parameters uncertainty?** → **insufficient** (instability) **OR extreme** (saturation) → DILEMMA
- The **model parameters estimation** based on **SS** represents a valuable approach for **calibrating the control parameters in case of mismatching**
- In such a way, a **proper linearization** is guaranteed by means the well-estimated LSF, while **avoiding the over-linearization strategy**
- **Is the CPL model realistic?** → very conservative scenario when the load is nonlinear
- **First order control** has been finally proposed for modeling **high-bandwidth controlled converters**
- **Weighted Bandwidth Method + Digital Twin**

Author Papers on DC Microgrids Modeling and Control

- G. Sulligoi, D. Bosich and G. Giadrossi, "Linearizing voltage control of MVDC power systems feeding constant power loads: Stability analysis under saturation," *2013 IEEE Power & Energy Society General Meeting (PESGM)*, Vancouver, BC, 2013, pp. 1-5.

- G. Sulligoi, D. Bosich, V. Arcidiacono and G. Giadrossi, "Considerations on the design of voltage control for multi-machine MVDC power systems on large ships," *2013 IEEE Electric Ship Technologies Symposium (ESTS)*, Arlington, VA, USA, April 22-24, 2013.

- D. Bosich, G. Giadrossi and G. Sulligoi, "Voltage control solutions to face the CPL instability in MVDC shipboard power systems," *2014 AEIT Annual Conference (AEIT)*, Trieste, Italy, Sept. 18-19, 2014.

- D. Bosich, A. Vicenzutti, R. Pelaschiar, R. Menis and G. Sulligoi, "Toward the future: The MVDC large ship research program," *2015 AEIT International Annual Conference (AEIT)*, Naples, Italy, October 14-16, 2015.

- V. Bucci, U. La Monaca, D. Bosich, G. Sulligoi, A. Pietra, "Integrated ship design and CSI modeling: A new methodology for comparing onboard electrical distributions in the early-stage design*", International Conference on Ship and Shipping Research*, NAV 2018, Trieste, Italy, 20-22 June 2018.

Author Papers on DC Microgrids Modeling and Control

- G. Sulligoi, D. Bosich, G. Giadrossi, L. Zhu, M. Cupelli and A. Monti, "Multiconverter Medium Voltage DC Power Systems on Ships: Constant-Power Loads Instability Solution Using Linearization via State Feedback Control," in *IEEE Transactions on Smart Grid*, vol. 5, no. 5, pp. 2543-2552, Sept. 2014.

- D. Bosich, G. Sulligoi, E. Mocanu and M. Gibescu, "Medium Voltage DC Power Systems on Ships: An Offline Parameter Estimation for Tuning the Controllers' Linearizing Function," in *IEEE Transactions on Energy Conversion*, vol. 32, no. 2, pp. 748-758, June 2017.

- D. Bosich, M. Gibescu and G. Sulligoi, "Large-signal stability analysis of two power converters solutions for DC shipboard microgrid," *2017 IEEE Second International Conference on DC Microgrids (ICDCM)*, Nuremburg, 2017, pp. 125-132.

- D. Bosich, A. Vicenzutti and G. Sulligoi, "Robust voltage control in large multi-converter MVDC power systems on ships using thyristor interface converters," *2017 IEEE Electric Ship Technologies Symposium (ESTS)*, Arlington, VA, 2017, pp. 267-273.

- S. Pastore, D. Bosich and G. Sulligoi, "Analysis of small-signal voltage stability for a reduced-order cascade-connected MVDC power system," *IECON 2017 - 43rd Annual Conference of the IEEE Industrial Electronics Society*, Beijing, 2017, pp. 6771-6776.

- D. Bosich and G. Sulligoi, "Stability-Oriented Filter Design optimization in Cascade-Connected MVDC Shipboard Power System," *2020 IEEE Power & Energy Society General Meeting (PESGM)*, Montreal, QC, Canada, 2020, pp. 1-5.

Author Papers on DC Microgrids Modeling and Control

- G. Sulligoi, D. Bosich, A. Vicenzutti and Y. Khersonsky, "Design of Zonal Electrical Distribution Systems for Ships and Oil Platforms: Control Systems and Protections," in *IEEE Transactions on Industry Applications*, vol. 56, no. 5, pp. 5656-5669, Sept.-Oct. 2020.

- D. Bosich, G. Giadrossi, S. Pastore, and G. Sulligoi, “Weighted Bandwidth Method for Stability Assessment of Complex DC Power Systems on Ships,” *Energies*, vol. 15, no. 1, p. 258, Dec. 2021.

- A. A. Tavagnutti, D. Bosich and G. Sulligoi, "A Multi-Model Methodology for Stability Assessment of Complex DC Microgrids," *2021 IEEE Fourth International Conference on DC Microgrids (ICDCM)*, Arlington, VA, USA, 2021, pp. 1-7.

- A. A. Tavagnutti, D. Bosich and G. Sulligoi, "Active Damping Poles Repositioning for DC Shipboard Microgrids Control," *2021 IEEE Electric Ship Technologies Symposium (ESTS)*, Arlington, VA, USA, 2021, pp. 1-8.

- A. A. Tavagnutti, D. Bosich and G. Sulligoi, "Strategies for Preserving the Battery SOC in DC Shipboard Power systems," *2021 IEEE Electric Ship Technologies Symposium (ESTS)*, Arlington, VA, USA, 2021, pp. 1-6.

- A. A. Tavagnutti, T. Coletto, D. Bosich and G. Sulligoi, "HIL Virtual Prototyping of a DC Shipboard Microgrid," *2021 AEIT International Annual Conference (AEIT)*, Milan, Italy, 2021, pp. 1-6.

Author Papers on DC Microgrids Modeling and Control

- M. A. Hassan et al., "DC Shipboard Microgrids With Constant Power Loads: A Review of Advanced Nonlinear Control Strategies and Stabilization Techniques," in *IEEE Transactions on Smart Grid*, vol. 13, no. 5, pp. 3422-3438, Sept. 2022.

- M. Chiandone, A. Vicenzutti, D. Bosich, A. A. Tavagnutti, N. Barbini and G. Sulligoi, "Open Source Hardware in the Loop Real-time Simulation of Zonal DC systems," *2022 Open Source Modelling and Simulation of Energy Systems (OSMSES)*, Aachen, Germany, 2022, pp. 1-6.

- A. A. Tavagnutti, S. Bertagna, D. Bosich, V. Bucci and G. Sulligoi, "Coordinated Power Control for Flexible and Sustainable Operation of DC microgrids in Yacht Marinas," *2022 International Symposium on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM)*, Sorrento, Italy, 2022, pp. 689-694.

- A. A. Tavagnutti, D. Bosich, S. Pastore and G. Sulligoi, "A Template Model to Assess the DC Stability of Green Charging Microgrids," *2022 IEEE 21st Mediterranean Electrotechnical Conference (MELECON)*, Palermo, Italy, 2022, pp. 878-883.

- A. A. Tavagnutti, D. Bosich and G. Sulligoi, "The WBM Reconfiguration to Prevent the Instability on DC Shipboard Microgrids," *2022 International Conference on Smart Energy Systems and Technologies (SEST)*, Eindhoven, Netherlands, 2022, pp. 1-6.

Author Papers on DC Microgrids Modeling and Control

- A. Vicenzutti, D. Bosich, A. A. Tavagnutti and G. Sulligoi, "System Stability and Short Circuit Contribution as Discordant Targets in Cascade Connected DC Microgrids: a Design Procedure," *2022 International Conference on Smart Energy Systems and Technologies (SEST)*, Eindhoven, Netherlands, 2022, pp. 1-6.

- A. A. Tavagnutti, D. Bosich and G. Sulligoi, "Stability-Oriented Analysis of a DC Shipboard Zonal Distribution System," *2022 IEEE Power & Energy Society General Meeting (PESGM)*, Denver, CO, USA, 2022, pp. 1-5.

- D. Bosich, M. Chiandone, G. Sulligoi, A. A. Tavagnutti and A. Vicenzutti, "High-Performance Megawatt-Scale MVDC Zonal Electrical Distribution System Based on Power Electronics Open System Interfaces," in *IEEE Transactions on Transportation Electrification*, vol. 9, no. 3, pp. 4541-4551, Sept. 2023.

- A. A. Tavagnutti, D. Bosich, S. Pastore and G. Sulligoi, "A Reduced Order Model for the Stable LC-Filter Design on Shipboard DC Microgrids," *2023 IEEE International Conference on Electrical Systems for Aircraft, Railway, Ship Propulsion and Road Vehicles & International Transportation Electrification Conference (ESARS-ITEC)*, Venice, Italy, 2023, pp. 1-6.

- A. A. Tavagnutti, A. Cecon, D. Bosich and G. Sulligoi, "Renewable Power Routing from a DC Microgrid to an Industrial Cluster," *2023 IEEE International Conference on Environment and Electrical Engineering and 2023 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe)*, Madrid, Spain, 2023, pp. 1-5.

Author Papers on DC Microgrids Modeling and Control

- M. A. Hassan et al., "DC Shipboard Microgrids with Constant Power Loads: A Review of Advanced Nonlinear Control Strategies and Stabilization Techniques," *2023 IEEE Power & Energy Society General Meeting (PESGM)*, Orlando, FL, USA, 2023, pp. 1-1.

- A. A. Tavagnutti, D. Bosich and G. Sulligoi, "Optimized Tuning for Flexible and Resilient Control of Zonal DC Microgrids on Ships," *2023 IEEE Power & Energy Society General Meeting (PESGM)*, Orlando, FL, USA, 2023, pp. 1-5.

- A. A. Tavagnutti, M. Chiandone, D. Bosich and G. Sulligoi, "A Stability-Aimed PMS for Shipboard Zonal DC Microgrids: The C-HIL Tests on Real-Time Platform," *2023 IEEE Electric Ship Technologies Symposium (ESTS)*, Alexandria, VA, USA, 2023, pp. 453-457.

- A. A. Tavagnutti, D. Bosich, A. Vicenzutti, V. Pediroda and G. Sulligoi, "A Multi-objective Optimization for the Power Management of Shipboard Zonal DC Microgrids," *2023 IEEE Electric Ship Technologies Symposium (ESTS)*, Alexandria, VA, USA, 2023, pp. 484-489.

UNIVERSITÀ DEGLI STUDI DI TRIESTE

detef
Digital Energy Transformation & Electrification Facility

Thank you for your attention!

Dr. Daniele Bosich, PhD

Università degli Studi di Trieste
Dipartimento di Ingegneria e Architettura

dbosich@units.it

dia dipartimento di ingegneria e architettura

dia.units.it