**Microgrid Maritime**

Josep M. Guerrero 陈乔
Professor in Microgrids, IEEE Fellow,
Department of Energy Technology
Aalborg University, Denmark
joz@et.aau.dk
www.microgrids.et.aau.dk
State-of-the-art of SPS

Mortality from Ship Emissions


Case 2b Mortality Cardiopulmonary
- 1 - 10
- 11 - 50
- 51 - 100
- 101 - 200
- 201 - 300
- 301 - 600

2% ... of global CO₂ emissions
15% ... of global nitrogen oxide (NOx) emissions**
6% ... of global sulfur oxide (SOx) emissions** ... are generated by ships
Several methods for improving fuel efficiency

- LNG
- Waste Heat recovery
- Hull optimisation
- ECO upgrades
- Port-to-ship Shore connection

Source: Schneider Electric
State-of-the-art of SPS

Shipping’s CO2 Reduction Goals

Source: ICS
# State-of-the-art of SPS

## Comparison of CO₂ emissions between modes of transport

<table>
<thead>
<tr>
<th>Grams per tonne/km</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.0</td>
<td>Very large container vessel (18,000 teu)*</td>
</tr>
<tr>
<td>5.9</td>
<td>Oil tanker (80,000 – 119,999 dwt)</td>
</tr>
<tr>
<td>7.9</td>
<td>Bulk carrier (10,000 – 34,999 dwt)</td>
</tr>
<tr>
<td>80</td>
<td>Truck (&gt; 40 tonnes)</td>
</tr>
<tr>
<td>Air freight (747, capacity 113 tonnes)</td>
<td>435</td>
</tr>
</tbody>
</table>

*teu = twenty-foot equivalent unit  
dwt = deadweight tonnage  

Source: Second IMO GHG Study (*AP Møller-Maersk, 2014)
Containers: now +20 million shipping containers are plying the world’s oceans
The MV Emma Mærsk officially carries 11,000 TEU (14 tons gross each)
State-of-the-art of SPS

Emma Maersk, the world's currently largest container ship in Aarhus 5-9-2006

www.microgrids.et.aau.dk
State-of-the-art of SPS

The biggest in the world:
- 2,000 metric-ton fully-electric
- 70.5m long, 13.9m wide, 4.5m deep, 3.3m draft design
- Launched late 2017 in Guangzhou
- Guangzhou Shipyard International Company Ltd.
- 70.5-meter cargo boat
- Lithium battery
- Cruise for 80 kilometers
- 2h charge @ 2.4 MWh
- Top speed is 12.8 km/h
The electric propulsion solutions applied for some of the main vessel types. Based on the difference requirement of the ship mission.
**State-of-the-art of SPS**

**Conventional Ship**

- **Switchboard**
- **Service Loads**
- **Propulsion**

**Integrated Power System (AC)**

- **Switchboard**
- **Prime Mover**
- **G**
- **Service Loads**

**Shaft Generation Solution**

- **Switchboard**
- **Prime Mover**
- **G**
- **Reduction Gearbox**
- **Propulsion**

**Game changer: Growing demand of electricity**

**Integrated Power System (DC)**

- **Prime Mover**
- **G**
- **Service Loads**
- **Electric Propulsion**
- **Battery**

**(Parallel) Hybrid Propulsion Solution**

- **Prime Mover**
- **G**
- **Reduction Gearbox**
- **Propulsion**
- **Battery**

**Game changer: Energy storage**

---

**Growing demand of electricity**

**Energy storage**
State-of-the-art of SPS

1. Electric Motor
2. Inverter
3. Engine-generator
4. Switchgear
5. Central Control Desk
6. Battery Converter
7. Battery Storage

Source: Typhoon HIL
Terrestrial Microgrids V.S. Shipboard Microgrids:

Terrestrial Microgrids

- Intermittent Renewables
- Regular Loads

Shipboard Microgrids

- Economical Generation
- Dynamic Loads

Control of Energy Storage Systems

- Intermittency Compensation
- Mismatch in Generation & Consumption
- Instant Power Support

Key Point
Higher levels design:

**Distribution Level**
- Voltage Restoration Level
  - Nominal Voltage Restoration Function
  - QoS Management

**Optimization Level**
- Fuel Consumption Optimization Function
- Joint SoC-Generation Scheduling

**Power sharing Level**
- Inverse-droop based voltage deviation calculation
- Master/slave based voltage & current control

**Physical Level of Microgrid**

---

*Graph showing the state-of-the-art of SPS*
Queen Elizabeth II – cruise ship

Integrated electric propulsion configuration

- Diesel Generator Set 1
- Diesel Generator Set 2
- Diesel Generator Set 9

- 16-cylinder Wärtsilä 16V46CR EnviroEngine marine diesel engines, providing 67,200 kW (90,100 hp)@514 rpm
- 2 General Electric LM2500+ gas turbines, total provide 50,000 kW (67,000 hp)
Radial AC distribution system

The 2 busses:
- port side bus
- starboard side bus

are linked with bus-tie switches.

These switches can be opened to disconnect the faulty bus from the healthy bus in the event of a fault and thus potential blackouts can be prevented.


Modern electric ships tend to use zonal electrical distribution system (ZEDS) architecture based IPSs over radial architecture:

It is a real **multi-microgrid cluster**
State-of-the-art of SPS

Multi-microgrids electrical propulsion ships
Multi-microgrids electrical propulsion ships
**Isochronous Control**

- Measure the power difference between generators and adjust in transient the speed
- Some companies use CAN bus / ex. Kongsberg
- No steady-state frequency errors

**Isochronous speed controller**

**Droop Control**

- Use the inherent droop mechanism of two synchronous generators connected in parallel
- No intercommunications are needed
- Large steady-state frequency deviations

**Speed droop**

**Voltage droop**
State-of-the-art of SPS

Power Management System / PMS

Functions:

• **Energy saving:**
  - reduction in specific fuel oil consumption (SFOC)
  - reduction in propulsion fuel consumption
  - reduction in overall vessel fuel consumption.

• **Automatic start/stop/standby of auxiliary generators**

• **Automatic load sharing**

• **Load shedding**

• **Automatic synchronizing and system restoration**

• **Monitoring and load analysis illustration**

• **Load transfer:** can control and monitor the load transfer from shaft to auxiliary and vice versa in hybrid electric ships, and shore power to auxiliary in cold ironing.
State-of-the-art of SPS

AC Shipboard Power System

Onboard DC grid – Multidrive power system scheme

BlueDrive PlusC from SIEMENS

<20MW
State-of-the-art of SPS

Onboard DC grid – Multidrive power system scheme

Source: SIEMENS
Onboard DC grid – Distributed power system scheme

ABB Concept
State-of-the-art of SPS

Onboard DC Grid
Vessel layout example – Onboard DC Grid

<20MW

Source: ABB

www.microgrids.et.aau.dk
State-of-the-art of SPS

AC SMG

DC SMG

Schematic diagram of fuel efficiency characteristic for diesel generation (in fixed speed)
State-of-the-art of SPS

Dynamic AC concept – DAC by ABB

Variable frequency 48~60Hz

Source: ABB
Dynamic AC concept – DAC by ABB

Benefits of Dynamic AC- Up to 6 % annual fuel savings for large cruise vessel (+20MW)

Source: ABB
Operating modes (PTO/PTI) of a shaft generator/motor system with VFD-

We may switch-off a DG!
State-of-the-art of SPS

Platform support vessel (PSV)
State-of-the-art of SPS

Platform support vessel (PSV)

AC

DC

AC Architecture

DC Architecture

www.microgrids.et.aau.dk
Benefits of using a DC ship power system

- Improvement of prime mover efficiency and reduction of fuel costs,
- Weight and space savings,
- Generators operating with a unity power factor,
- Lower transmission losses,
- Faster and simpler parallel connection of generators,
- Simpler implementation of energy storage.

Offshore Supply Vessel: Viking Lady

- Norway
- 2.2m long x 21m wide
- Gross tonnage 6,100t
- Dead weight 5,900t
- 25 people
- deck area 945m²
- deck load of 3,450t
- water ballast capacity of 3,518m³
- Capacity 993m³ of fresh water
- 167m³ of methanol.

- Kongsberg K-Pos 2 dynamic positioning (DP) system.
- 4 x 2,010kW Wartsila 6R32DF engines
- 4 x 1,950kW main generators Alconza NIR 6391 A-10LWs, each producing of power.
- 2 x Rolls Royce AZP 100FP propeller systems

Source: Wartsila
System integration

Source: Wartsila
- Dual-fuel liquefied natural gas (LNG)/diesel-electric power plant
- Fuel cell operates at 650°C and generates 320kW
Due to the combined use of the fuel cell and a gas engine, vessel can reduce: sulphur oxide by 100%, nitrogen oxide by 85% and carbon dioxide by 20%.

Source: Wartsila
Lithium battery technology available: a 11.5 kWh on Greenline 33, 23 kWh on Greenline 40 and 46 kWh on Greenline 46 (battery pack with a permissible discharge of 100%).

www.greenlinehybrid.si
Hybrid Yachts
Hybrid Yachts: Operation Modes

At the dock

In electric drive mode

In diesel drive mode

At anchor
Hybrid Ferries

Scandlines

1. Prinsesse Benedikte, built in 1997, hybrid since August 2013
2. Capacity: 364 cars or 124/30 cars and lorries
3. The world’s largest hybrid ferry - 1.9 MWh battery bank
4. The system equals approx. 400 hybrid cars
5. Reduce CO2 emissions by 15%
Hybrid Ferries

How you convert a ferry to hybrid

A. 85 ton motor taken out

B. 50 ton batteries installed

C. ESS control system installed

D. Integration into operations
Hybrid Ferries

Worlds largest hybrid ferry fleet

Puttgarden - Rødby

Rostock - Gedser

Source: Scandlines
Ampere Ferry from Norled (Norway)

Norled AS, MF Ampere Ferry powered by Corvus Energy ESSs on both vessel and shore charging stations.

Source: Norled
World's First All-electric Car Ferry

- Designed by Siemens AS and Corvus Energy
- Onshore Corvus Energy 410kWh
- ESS comprised of 63 AT6500 Liquid-Cooled modules installed on both sides of the route, each providing near instantaneous transfer of power to the vessel ESS.

Source: Norled
Outline

- State-of-the-art and trends in SPS
- AC-DC grids in SPS
- ESS integration
- Power Quality Issues in SPS
- Cold-Ironing
Outline

- State-of-the-art and trends in SPS
- AC-DC grids in SPS
- ESS integration
- Power Quality Issues in SPS
- Cold-Ironing
State-of-the-art of SPS

Fully electric ship with AC and DC grid

Source: Vacon Power / Danfoss
HyELEF project 2017

Hybrid Electrical Ferry including Batteries

AALBORG UNIVERSITY
DENMARK

VISEDO
Electricity in Motion.

SOIC
Ship and Ocean Industries R&D Center

www.microgrids.et.aau.dk
Asia’s First Hybrid Electric Ferry

Ferry in Kaohsiung

Ferry retrofitting
Asia’s First Hybrid Electric Ferry

Gushan Ferry Pier Station
(Point A)

Cijin Ferry Station
(Point B)

5 min
every 15 min

Cruise Terminal

Diesel Engine (Prime Mover)
and Synchronous Generator
2 x 64 kW

440 V
AC BUS

440/220 V
Transformer

AC/DC Bi-directional Converter

SHORE TO SHIP
POWER (COLD
IRONING)

DC/DC Bi-
directional Converter

BATTERY
100 kW, 160 Ah

DC BUS

750 V

HOTEL LOAD PEAK 3.0 MW

750 V

HOTEL LOAD PEAK 3.0 MW

DCAC
Converter

2 x 1.12 kW

PROPELION LOADS

www.microgrids.et.aau.dk
Asia’s First Hybrid Electric Ferry

- Original gear box, main shaft, and propeller.
- Original throttle system.
- Same driving characteristic.
- Low cost.

Source: SOIC
Asia’s First Hybrid Electric Ferry

- Reconstruct storage room.
- Away from genset heat zone.
- Easy access for maintenance.

Source: SOIC
Asia’s First Hybrid Electric Ferry

- DC/DC, DC/AC, LCL, Inductor.
- Extreme compact size.
- Very low heat generate.

Source: SOIC
Asia’s First Hybrid Electric Ferry

e-ferry battery load profile

(100kWh@20%~80%SOC ÷ 57.5kWh Useage)

- 5knot Pure Electric
- 5knot range extend

Pure electric mode consumes 57.5kWh energy in 60min interval

- Charge from 20% SOC
- Charge reach 80%SOC switch into pure electric mode
- After 1hour, the ferry either go to 50kW charge station or continue (repeating) running by range extend mode

> Every one hour running, the boat can either continue by range extend or stop and doing shore 50kW one hour charging.

Source: SOIC
Asia’s First Hybrid Electric Ferry

Goal:
1. Output same power as original diesel engine
2. Maximize system efficiency

Source: SOIC
Asia’s First Hybrid Electric Ferry

Cruising

- DE 1
- Battery operated

Berthing

- Battery
- DE 2
- Propulsion
- Hotel load
- OPS

Discharge if:
20 ≤ SOC ≤ 80

Charge if:
SOC ≤ 20

DE – Diesel Engine
OPS – Offshore Power Supply

www.microgrids.et.aau.dk
Technical challenges:
- Original old generators are not stable which costs much extra work and budget.
- DC microgrid stability adjustment requires lot of experience and tests.
- Signal interfere within different equipment is a trial and error uncertain process.
- Battery life care strategy.

Non-technical challenges:
- Crew and client have stereotype that motor and battery has no power.
- Hybrid system operation is unfamiliar to crew especially with electric equipment.
- Investment payback time regarding battery life.
- Silence cruise makes crew feel unconfident.
State-of-the-art and trends in SPS
AC-DC grids in SPS
ESS integration
Power Quality Issues in SPS
Cold-Ironing
- State-of-the-art and trends in SPS
- AC-DC grids in SPS
- ESS integration
- Power Quality Issues in SPS
- Cold-Ironing
EFFICIENSEA project 2014-2018

Off-shore Application of the Flywheel Energy Storage System

AALBORG UNIVERSITY
DENMARK

Den Danske Maritime Fond

MAERSK DRILLING

WattsUp Power

www.microgrids.et.aau.dk
EFFICIENSEA Project

- WattsUp Power IVS, Martin Speiermann
- Maersk Drilling A/S, Helene Aagaard
- Aalborg University – Department of Energy Technology, Josep Guerrero

**Budget:** DKK 16 million

**Innovation Fund Denmark investment:** DKK 8 million

**Duration:** 3 years
Dynamic Positioning (DP) is a computer-controlled system that automatically maintains a vessel’s position and heading.

Forces and motions

- Heave
- Yaw
- Roll
- Surge
- Pitch
- Sway

DP Control

- Yaw
- Waves
- Sway
- Surge
- Current
- Azimuth Thruster
- Man Propeller and Rudder
- Tunnel Thruster
- Existing engine control
Dynamic Positioning (DP)

GPS
Gyrocompass
Laser Positioning
Hydroacoustic Positioning

DP Control System
Symmetry’s DP System (Brazil)

Voith Schneider Propeller
Azimuth Thruster
CP Propellers
Rudder
Dynamic Positioning (DP)

Example of configuration for Dynamic Positioning system

WEST VENTURE
Type: Semi-submersible
Location: Norway
Availability: Available
Maximum depth: 2,600 feet

Semi submersible drilling rig with four podded azimuthing thrusters

Full-scale data from West Venture

Vessel position.

Dotted lines: when available power on the busses are reduced to 0.3 MW
Solid line: the total thruster power on each bus
Dynamic Positioning (DP)

DP Basic Control Loop

- **WANTED POSITION**
- **WIND SENSOR FEED FORWARD**
- **POSITION REFERENCE FEEDBACK**

1. **Controller**
2. **Wind Model**
3. **Thruster Transform**
4. **Thrusters**
5. **Vessel**
6. **Position & Heading Measurement**
Dynamic Positioning (DP)

Source: Pirie & Smith, Ltd, UK
Offshore support vessel OSV example

Typical Operation Profile

<table>
<thead>
<tr>
<th>Mode</th>
<th>Time [%]</th>
<th>Power Demand [kW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>DP</td>
<td>37</td>
<td>2128</td>
</tr>
<tr>
<td>In port</td>
<td>23</td>
<td>168</td>
</tr>
<tr>
<td>Steaming 11kn</td>
<td>20</td>
<td>1836</td>
</tr>
<tr>
<td>Stand-by High</td>
<td>8</td>
<td>1000</td>
</tr>
<tr>
<td>Stand-by Low</td>
<td>8</td>
<td>755</td>
</tr>
<tr>
<td>Out of Service</td>
<td>2</td>
<td>4260</td>
</tr>
<tr>
<td>Steaming 15kn</td>
<td>2</td>
<td>0</td>
</tr>
</tbody>
</table>
Phase II: Optimal Operation Management

Source: www.flywheel.et.aau.dk
EFFICIENSEA Project

Phase III: HIL Test and Validation

Source: www.flywheel.et.aau.dk
New release: 30 kWh Flywheel

Source: WattsUpPower
Outline

- State-of-the-art and trends in SPS
- AC-DC grids in SPS
- ESS integration
- Power Quality Issues in SPS
- Cold-Ironing
Outline

- State-of-the-art and trends in SPS
- AC-DC grids in SPS
- ESS integration
- Power Quality Issues in SPS
- Cold-Ironing
AC Maritime Microgrid Systems

PQ issues
(steady/ transient)

Harmonic/Inter-harmonic
Unbalanced Waveforms
Frequency Variation
Power oscillations
Flickers, Notching
and Fluctuation
Power flow/Power sharing
Protection
12-pulse Voltage Source Inverter (VSI)
a) Medium voltage single drive for thrusters

b) Low voltage drilling multidrive

## PERMITTED LEVELS OF VOLTAGE AND FREQUENCY DEVIATIONS FOR SHIP POWER SUPPLY SYSTEMS

<table>
<thead>
<tr>
<th>Standards</th>
<th>Range of the Standard</th>
<th>Voltage</th>
<th>Frequency</th>
<th>Total Harmonic Distortion</th>
<th>Individual Harmonic Distortion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polish Register IEC60092-101</td>
<td>Electrical Installations in ships. Definitions and general requirements</td>
<td>+6% to -10%</td>
<td>±5% ±10%(5s)</td>
<td>5%(40th)</td>
<td>3%</td>
</tr>
<tr>
<td>Lloyd's Register</td>
<td>Selection and Use of Standards for Naval Ship</td>
<td>+6% to -10%</td>
<td>±5% ±10%(5s)</td>
<td>8%(50th)</td>
<td>1.5%</td>
</tr>
<tr>
<td>STANAG1008</td>
<td>Characteristics of Shipboard Electrical Power Systems in Warships of the North Atlantic Treaty Navies, NATO, Edition 9, 2004</td>
<td>±5% ±16%(2s)</td>
<td>±3% ±4%(2s)</td>
<td>5%(40th)</td>
<td>3%</td>
</tr>
<tr>
<td>American Bureau of shipping 2008</td>
<td>Rules of International Ship Classification Societies, e.g PRS/25/P/2006</td>
<td>+6% to -10%</td>
<td>±5% ±10%(5s)</td>
<td>5%(40th)</td>
<td>3%</td>
</tr>
<tr>
<td>IEEE Std. 45-2002</td>
<td>IEEE Recommended Practice for Electrical Installations in ships</td>
<td>±5% ±16%(2s)</td>
<td>±3% ±4%(2s)</td>
<td>5%(40th)</td>
<td>3%</td>
</tr>
</tbody>
</table>
Harmonic mitigation solutions

While variable speed drives help optimize production, save energy and extend equipment lifetime, they also introduce harmonic currents to the on-board grid. Many applications in the industry require a low level of harmonic distortion. Regulations have been imposed by marine certification bodies which state that harmonics must be kept to 5% or 8% of the total harmonic voltage distortion (THDV) on the main bus bar.

Danfoss Drives’ wide range of mitigation solutions which can help restore weak networks, increase network capacity, meet compact retrofit demands or secure sensitive environments includes:

- VLT® Advanced Active Filter AAF 006
- VLT® Advanced Harmonic Filter AHF 005/AHF 010
- VACON® NXP AFE

Source: Danfoss
Poland – Denmark Cooperation PhD Project 2017

Unbalance and Harmonic Analysis in Shipboard Microgrids
Fig. 1 The industrial AC MMGs based on Horizon II ship
Comparison: Balanced SPS
Slightly Unbalance SPS (UF=1.5%)
State-of-the-art and trends in SPS
AC-DC grids in SPS
ESS integration
Power Quality Issues in SPS
Cold-Ironing
State-of-the-art and trends in SPS

AC-DC grids in SPS

ESS integration

Power Quality Issues in SPS

Cold-Ironing
• Change grid frequency from 50Hz to 60Hz and synchronize with ships grid.
• Reduced local emissions, noise and vibrations
• Increased lifetime for ships engines
• Allow maintenance on the ships engines during the harbour stay
• Bi-directional: Generator load test power can be fed back to the shore grid – complying to local grid code

Source: Vacon Power / Danfoss
Cold Ironing

Generic cold ironing standard requirement

Shoreside
- Main utility grid
- Transformer
- Frequency converter
- Switchboard

S2SP connection cable

Shipside
- Transformer
- Switchboard
- Onboard generator sets

www.microgrids.et.aau.dk
• **Used one frequency converter as a central and double busbar to allowed the ship berthing either 50Hz or 60Hz.**

• **Directly extend the system by replicates the complete regime of each berth with frequency converter and transformer.**
• Excellent flexibility and redundancy
• High costing
DC distribution configuration

- By extending of two previous configuration with introducing DC bus.
- Easier to integrate with any energy storage device
- Able to use in small quay area

Synchronization
If Ship tries to synchronize bulky DG with the shore, huge inrush currents appear due to inertia

SP2S case
Phase currents of the synchronous generator during synchronization with low voltage AC grid

Source: Ship-to-Shore vs. Shore-to-Ship Synchronization Strategy, R. Smolenski, et al., IEEE TEC, 2018
Port Cranes

Diesel ICE GenSet

Hoist  Trolley

Spreader

Steering  Gantry

www.microgrids.et.aau.dk
Source: Nan Zhao, Nigel Schofield, and Wangqiang Niu
Energy Storage System for a Port Crane Hybrid Power-Train
IEEE TRANSACTIONS ON TRANSPORTATION ELECTRIFICATION, VOL. 2, NO. 4, DECEMBER 2016
Port Cranes

- +45% Energy recovery
- Possibly DC microgrid config.
- Coordination between FW
- Savings and...
- Power peak reduction


20. A Flexible Power Control Strategy for Hybrid AC/DC Zones of Shipboard Power System with Distributed Energy Storages / Li He; Yong Li; Zhikang Shuai; Josep M. Guerrero; Yijia Cao; Ming Wen; Weiyu Wang; Jingrong Shi. IEEE Transactions on Industrial Informatics. Year: 2018.

Ongoing PhD maritime projects

- Integration of Microgrid Technologies In Future Seaports - Nor Baizura Binti Ahamad
- Energy Management System in Shiphoard Microgrids - Muzaidi Bin Othman
- Maritime DC Microgrid Based On-Board Power System - Zheming Jin
- Power Electronics and Power Quality in Maritime Microgrids Systems - Wenzhao Liu
- Improving the Power Quality Issues of Shipboard Power Systems - Yacine Terriche
We Chat: JG2037

For contact/cooperation:
Josep M. Guerrero  joz@et.aau.dk

Thank you!

www.maritime.et.aau.dk

www.microgrids.et.aau.dk