Operational Flexibility with Distributed Power Systems
Onboard DC Grid™
Daniel Ahern, VP Navy & Coast Guard Segment
Onboard DC Grid

... a paradigm shift ...

- Variable Speed
- Energy Storage
- Alternative Energy Sources
Onboard DC Grid

... the basic principles ...

Driving Factors

1. ~80% of consumers are frequency converters
2. Energy Storage is largely DC based
3. AC switch forces synchronisity
4. AC switch bases protection on availability of high currents
5. Valid up to ~20MW
Variable Speed Engines
Onboard DC Grid

Why variable Speed Engines
Onboard DC Grid

Why variable Speed Engines

Main benefits
- **Fuel Savings through improved SFOC characteristic**
- Reduced maintenance on engines
- Lower noise
- Higher exhaust temperatures giving better SCR performance and reduced urea consumption
- Can have medium speed reliability with high speed footprint and performance
Energy Storage Solutions
Energy Storage Solutions

Functionality

**Spinning Reserve**
Backup power to running generators.
Benefits include
- Improved safety
- Reduced fuel consumption and engine maintenance

**Peak Shaving**
Level power seen by engines and offset need to start new engines.
Benefits include
- Reduced fuel consumption and engine maintenance

**Enhanced Ride Through**
Short time backup power to running generators.
Benefits include
- Improved safety
- Reduced fuel consumption and engine maintenance

**Strategic Loading**
ESS used to charge or discharge with the aim of optimizing engine operating point.
Benefits include
- Reduced fuel consumption

**Enhanced Dynamic Perf.**
Instant power in support of running engines.
Benefits include
- Reduced fuel consumption
- Enabler for “slower” sources like LNG and fuel cells

**Zero Emission Operation**
Power system is fully powered by ESS.
Benefits include
- Quiet engine room
- Zero emission operation
# Battery integration in power systems

## Solutions overview

<table>
<thead>
<tr>
<th>System Connection Method</th>
<th>DC Direct Online</th>
<th>DC Converter</th>
<th>AC Converter</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Direct</td>
<td>DC/DC Conv choke</td>
<td>DC/AC conv filter Transformer</td>
</tr>
<tr>
<td>Response</td>
<td>Good</td>
<td>Instant</td>
<td>Good*</td>
</tr>
<tr>
<td>Autonomy</td>
<td>Partial</td>
<td>Full</td>
<td>Full</td>
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<tr>
<td>Functionality</td>
<td>Limited</td>
<td>Full</td>
<td>Full</td>
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<tr>
<td>Converter Size</td>
<td>None</td>
<td>$\propto$ Peak power</td>
<td>$\propto$ Peak power $\propto$ Peak SC &amp; Transients</td>
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<tr>
<td>Main selling point</td>
<td>Efficiency</td>
<td>Controllability</td>
<td>AC Power</td>
</tr>
</tbody>
</table>
## Control Integration

### Energy Storage vs. Engine

<table>
<thead>
<tr>
<th>Parameter</th>
<th>High Speed Engine</th>
<th>Example Energy Battery</th>
<th>Example Power Battery</th>
</tr>
</thead>
<tbody>
<tr>
<td>Battery Size</td>
<td>-</td>
<td>~2.4 MWh</td>
<td>~0.75 MWh</td>
</tr>
<tr>
<td>Continuous</td>
<td>2 MW</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>RMS Continuous Charging/discharging</td>
<td>-</td>
<td>~2.4 MW</td>
<td>~4.5MW</td>
</tr>
<tr>
<td>One discharge</td>
<td>-</td>
<td>~2.4 MW</td>
<td>~7.5MW</td>
</tr>
<tr>
<td>Pulse power for 10sec</td>
<td>~2.4MW</td>
<td>~2.4 MW</td>
<td>~11.2MW</td>
</tr>
</tbody>
</table>

### Note:
- Converter, fuel tank, exhaust systems not included in comparison
- Typically <80% of battery size is available for use
Energy Storage Integration
Integration into Power System

Energy Storage Control System

Functions
- Interface to Battery BMS
- Interface to PMS
- Energy and power control
  - Spinning Reserve
  - Peak Shaving
  - Enhanced Dynamic Support
  - Strategic Loading
  - Enhanced Ride Through
  - State Of Charge Control
  - Battery Condition Test
  - Energy Storage Maintenance Mode
- Protection of energy storage system

PMS – Power Management System
ESCS – Spinning reserve control and calculation
Load peak shaving power flow control

ESM – Energy Storage Medium
Dc/Dc Converter
Dc-Distribution
Ac-Distribution

State Of Charge Control
Energy Allocation

(Static) Energy allocated
spinning reserve & enhanced ride
through

(Dynamic) Energy allocated
for peak shaving & dynamic
support

System performance
related energy reserve

Safety Related
energy reserve
Onboard DC Grid

Marintek Laboratory

Start of Testing: March 2014

Voltage Level: 540Vdc

Speed range: 900-1800rpm

Engines: 1 x Perkins GCD325A
1 x Perkins 2506C-E15TAG1

Generation: 1 x 400kVA UNIREC
1 x 230kVA UNIREC

Loads: 2 x 160kW ACS800

Energy Storage: 1 x 55kWh Battery
1 x 1MWs Super Capacitor
Onboard DC Grid

Three Tests – Energy Storage Works
Onboard DC Grid

Laboratory Results – Only Generator
Onboard DC Grid

Laboratory Results – Only Generator
Onboard DC Grid

Laboratory Results – Only Generator
Safety and Performance

...
Onboard DC Grid
Safety and Performance

Safety

*Blackout restart*
- First Generator Online: 12s
- All Generators Online: 13s

*FMEA*
- No findings during DP2 FMEA
- Governor Failure – only takes out affected engine
- AVR / Sensor Failure only takes out affected generator
- Approved DP2 operations with closed bus-tie

Performance and Functionality

*Main Propulsion Ramps*
- More dynamic than AC system with same engines @ 1800rpm
- 0-70% Power: 7sec (without energy storage)
- Ramp is adjusted as a function of no.engines online
- The main cabling equipment is fed directly from DC swbd and braking is fed back into the power system
- Fault tolerant system that inspires confidence for operator resulting in more efficient operation
Arc Flash & Personell Safety

Zone characteristics

**DC Distribution (Grid Side)**
- Slower Time Constants (similar to AC)
- No capacitors and low (relative) fault currents depending on connected sources
- All Sources can block current during faults (10us – 100ms depending on source)

**Internal DC Bus (DC Link Side)**
- Very short time constants and high prospective fault currents due to capacitors
- Cabinet designed to vent overpressure through explosion vents in the roof

*Arc detection can be installed and configured to trigger relevant protection functions.*
What is Onboard DC Grid
Onboard DC Grid
Protection Philosophy

**Grid Side**
- Slower Time Constants
- No capacitors
- All Sources can block current during faults
- Patented protection philosophy

**DC Link Side**
- Very short Time constant
- Sources cannot block current during faults on DC link.
- Fused Protection
Onboard DC Grid

System Configurations

Solid state breaker

DC-link
Onboard DC Grid

System Configurations
Onboard DC Grid
System Configurations
Onboard DC Grid
System Configurations
Onboard DC Grid

System Configurations || Centralized -> Highly Distributed

Centralized solution with AC (red) in and AC out of a centralized swbd

Distributed system where main consumers are connected to a distributed DC bus-system (blue).
This can also be realized using cables

A 3-split highly redundant variant of the distributed system showing double-fed thrusters allround
This can also be realized using cables

A 4-split highly redundant variant of the distributed system.
This can also be realized using cables.
Onboard DC Grid

Scope of Solutions – Power System

Current Solutions

• Power Sources
• Shore Power Solutions
• Energy Storage Solutions
• Double Feed Solutions
• Link Cable Solutions
• Off Grid Converter w/ Filter
• Off Grid Converter w/o filter
• Shaft Generators
• Grid Cable Solutions
• Solutions for P>15MW
Onboard DC Grid
Scope of Solutions - PEMS

Current Solutions

- PEMS
- Generator Rectifier Control System (DSU and UNIREC)
- Energy Storage Control System
- Shore Connection Control System
- PEMS
  - Advanced Power Control
  - Advanced Load Sharing
  - «Software» Interfaces
  - Shaft Generator Control System
  - Fuel Cell Control System
# Conclusion: Power System Requirement Drivers – Navy & Coast Guard

## Core
- Survivability
- Re-Configuration
- Redundancy
- Highly Responsive Propulsion
- Ship Service Power Reliability
- Weapons Systems Power Quality
- Stochastic Load Support
  - Sensors
  - Directed Energy
- Energy Storage
- Charging for UAV, UUV, other
- Comprehensive Energy Management

## AC
- Operational Profile – Flank vs Loiter
- Environmental Requirements
  - Emissions
  - Noise
- Shore Power
- Fuel Efficiency
- Alternative Energy Production
- Human Factors – Noise & Vibration

## DC
Some references – Reference Material
Onboard DC Grid
Reference overview – March 2017

<table>
<thead>
<tr>
<th>2x</th>
<th>RoPax &amp; RoRo</th>
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<tbody>
<tr>
<td>2x</td>
<td>Yacht</td>
</tr>
<tr>
<td>5x</td>
<td>OSV &amp; OCV</td>
</tr>
<tr>
<td>5x</td>
<td>Car/Road Ferry</td>
</tr>
<tr>
<td>2x</td>
<td>Icebreakers &amp; Icegoing OSV</td>
</tr>
<tr>
<td>2x</td>
<td>Shuttle Tanker</td>
</tr>
</tbody>
</table>

19

Of these
14
have Energy Storage and
2
have shaft-generators
NKT Victoria
First feedback trickling inn...
Onboard DC Grid
NKT Victoria – Cable Layer

Vessel information
- Vessel name: NKT VICTORIA
- Vessel Type: Cable Layer
- Design: SALT 306 CLV
- Yard: Kleven Yard BN 372
- Year: 2017
- Class: DNV AUTRO (DP3)
- Owner: NKT

Solution and scope: Onboard DC Grid
- Generators: 6 x 2240kWe 1200-1800rpm
- Energy Storage: 1 x 156kWh
- Propulsion: 3 x 1.9MW Azipod® propulsion units
- Thrusters: 3 x 1900kW ACS800 Tunnel
- Automation: PEMS with integrated VMS
- Advisory: RDS, EMMA, CM

Other information
State-of-the-art cable ship including the newest ABB technology achieving greater efficiency and precision.

The vessel is custom built according to NKT’s specifications and will measure approx. 140m-long and 30m wide, have capacity for a crew of 100 and up to 9500 tonnes of cargo. It will enhance the capacity of NKT’s subsea cable operations while delivering optimum efficiency and accuracy.
Onboard DC Grid
NKT Victoria – Cable Layer

Power System

- Generators: 6 x 2240kWe
- Speed Range: 1200-1800rpm
- Energy Storage: 156 kWh (nom.)
  - Power peak (1min): 800 kWe
  - Power rms: 300 kWe
  - Design Life: ~10yrs
- Propulsion: 3 x 1.9MW
  - Azipod C
- Thrusters: 3 x 1900KW
  - Brunvoll TT w/ ABB motors
Onboard DC Grid

NKT Victoria – Reduction of Fuel Consumption relative to other CLV’s

NKT VICTORIA – 9000t cable capacity

Other NKT Cable Layer Vessel with 9000t cable capacity
Onboard DC Grid

NKT Victoria – Reduction of Fuel Consumption relative to other CLV’s

Relative Fuel Consumption for example Vessel Modes

Relative Total Fuel Consumption for example Campaign

In total

59% w/o Harbour

42%
Onboard DC Grid
NKT Victoria – Reduction of Emissions

Reductions of CO₂

55%
NKT Victoria vs. Large CLV
(9000t cable cap.)

15%
NKT Victoria vs. Small CLV
(4000t cable cap.)

Reductions of NOₓ

15-80%
Depending on NOₓ reduction technology installed
NKT Victoria – where does the 59% fuel consumption reduction come from?

Source of fuel consumption and CO₂ reductions

- Non ABB technology
  - Hull design specific to cable laying operations
  - Operation awareness
- ABB technology
  - Onboard DC Grid power generation and distribution system
  - Shore connection
  - Energy Storage
  - Azipod® Propulsion

Preliminary results
Onboard DC Grid

NKT Victoria – where does the 59% fuel consumption reduction come from?

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How can we prove savings provided by ABB technology?

- By collecting all relevant operational data onboard
- By transferring data in real time to onshore organization
- By analyzing performance and status of equipment
- By visualizing it online to customer and ABB product designers

We can do it because ship is highly digitalized and connected!
Case Study
Submarine Rescue Vessel Case
Assumptions and input data

The following assumptions and input data has been used:

- SFOC curves from CAT3516C engine as on slide 6.
- Vessel operational profile from Volstad Surveyor operating as a rescue vessel in end 2014.
- Vessel Electrical load analyses from similar vessel in North Sea.
- ABBs experience and logging from similar vessels.
PSV Operational data from North Sea

System loads

<table>
<thead>
<tr>
<th>Operational Modes</th>
<th>DP High</th>
<th>DP</th>
<th>Transit 16kn</th>
<th>Transit ECO</th>
<th>Maneuvering</th>
<th>Moored</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main Propeller 1</td>
<td>300</td>
<td>100</td>
<td>2200</td>
<td>850</td>
<td>400</td>
<td>0</td>
</tr>
<tr>
<td>Main Propeller 2</td>
<td>300</td>
<td>100</td>
<td>2200</td>
<td>850</td>
<td>400</td>
<td>0</td>
</tr>
<tr>
<td>Tunnel 1</td>
<td>200</td>
<td>100</td>
<td>0</td>
<td>0</td>
<td>100</td>
<td>0</td>
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<tr>
<td>Tunnel 2</td>
<td>200</td>
<td>100</td>
<td>0</td>
<td>0</td>
<td>100</td>
<td>0</td>
</tr>
<tr>
<td>Fwd Az 2</td>
<td>200</td>
<td>100</td>
<td>0</td>
<td>0</td>
<td>100</td>
<td>0</td>
</tr>
<tr>
<td>Sum Thruster Load</td>
<td>1200</td>
<td>500</td>
<td>4400</td>
<td>1700</td>
<td>1100</td>
<td>0</td>
</tr>
<tr>
<td>Other loads</td>
<td>300</td>
<td>300</td>
<td>300</td>
<td>300</td>
<td>300</td>
<td>200</td>
</tr>
<tr>
<td>Total Load</td>
<td>1500</td>
<td>800</td>
<td>4700</td>
<td>2000</td>
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Notes:
- The following loads has been used in the different operational profiles in the study.
- The average propulsion load in DP modes has been assumed based on actual measurements from PSV.
- We assume a 30kW auxiliary machinery load per engine.
## Volstad Surveyor Analysis

### Operational modes

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<tbody>
<tr>
<td>Time [%]</td>
<td>9,0 %</td>
<td>38,0 %</td>
<td>3,0 %</td>
<td>16,0 %</td>
<td>16,0 %</td>
<td>18,0 %</td>
</tr>
<tr>
<td>Time [hours]</td>
<td>788</td>
<td>3329</td>
<td>263</td>
<td>1402</td>
<td>1402</td>
<td>1577</td>
</tr>
</tbody>
</table>

## Notes:

- ...
Analysis of Synthesized Data Set

...
### Submarine Rescue Vessel Case Study

**System loads**

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<td>300</td>
<td>200</td>
</tr>
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<td>1500</td>
<td>800</td>
<td>4700</td>
<td>2000</td>
<td>1400</td>
<td>200</td>
</tr>
<tr>
<td>#Genset Non Hybrid</td>
<td>4</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>#Genset Hybrid</td>
<td>2</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

**Notes:**
- The following loads has been used in the different operational profiles in the study.
- Scaled to Volstad Surveyor
- The average propulsion load in DP modes has been assumed based on actual measurements from PSV.
- We assume a 30kW auxiliary machinery load per engine.
Submarine Rescue Vessel Case Study

Fuel Consumption and CO2 emissions

Summary:
- The yearly consumption for the AC: 2570 Tons
- DC: 2250 Tons (-12%)
- DC + Battery: 2060 Tons (-20%)
- The major reduction is in DP mode, Maneuvering and slow steaming (partial loading)
- The yearly CO2 reduction is estimated to 1614 tons
- The yearly SO2 reduction is estimated to 589 kg
**Summary:**

- The accumulated yearly engine running hours
  - AC: 17,800 hrs
  - DC: 12,460 hrs (-30%)
  - DC + Battery: 7,816 hrs (-56%)

*Equivalent running hours*
## Submarine Rescue Vessel Case Study

### Summary

<table>
<thead>
<tr>
<th></th>
<th>DC</th>
<th>DC + Battery</th>
<th>Link to xl file</th>
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</thead>
<tbody>
<tr>
<td>Reduction in Fuel Consumption</td>
<td>317</td>
<td>509</td>
<td></td>
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<tr>
<td>MDO Cost [USD/Ton]</td>
<td>560</td>
<td>560</td>
<td></td>
</tr>
<tr>
<td>Fuel Spend Savings [USD]</td>
<td>177 779</td>
<td>285 111</td>
<td></td>
</tr>
<tr>
<td>Reduction in Running Hours</td>
<td>5 320</td>
<td>9 966</td>
<td></td>
</tr>
<tr>
<td>Maintenance Cost [USD/Hr]</td>
<td>17</td>
<td>17</td>
<td></td>
</tr>
<tr>
<td>Maintenance Savings [USD/Yr]</td>
<td>90 446</td>
<td>169 429</td>
<td></td>
</tr>
<tr>
<td>Total Savings [USD/Yr]</td>
<td>268 225</td>
<td>454 540</td>
<td></td>
</tr>
</tbody>
</table>
Case Study
Frigate CODOE System Design
1. System components have been distributed to improve system fault tolerance against fire, flooding and explosions.
2. Distributed and double-fed shaft generator system for reduced cabling and improved fault tolerance
3. Double-fed system design allows load sharing between FWD and AFT without closing of main bus-tie.
4. Energy storage connected to AC supply swbd shielding AC consumers from system disturbances.
5. Bow thruster motor fed from FWD AC supply swbd for compact footprint.
6. Power swbds are prepared with spare DC feeder for future load bank or battery extension
Overview – Equipment

1. Variable Speed generators for prolonged engine maintenance intervals and reduced fuel consumption.
2. DC switchboard based on new generation ACS880 modules and cabinets.
3. Main power switchboard is of air-cooled type to improve fault tolerance and reduce dependence on water cooling circuits.
4. Battery package 2 x 400kWh with peak power of 2MW each for 30sec for spinning reserve with combined peak power. DC/DC converters are used for optimal control and fault tolerance.
5. Distribution transformers with integrated LCL filters for a compact overall design.
6. Asynchronous shaft generators for more robust design relative to synchronous generators.