NSRP MEETING, TALLAHASSEE, FL DECEMBER 2018

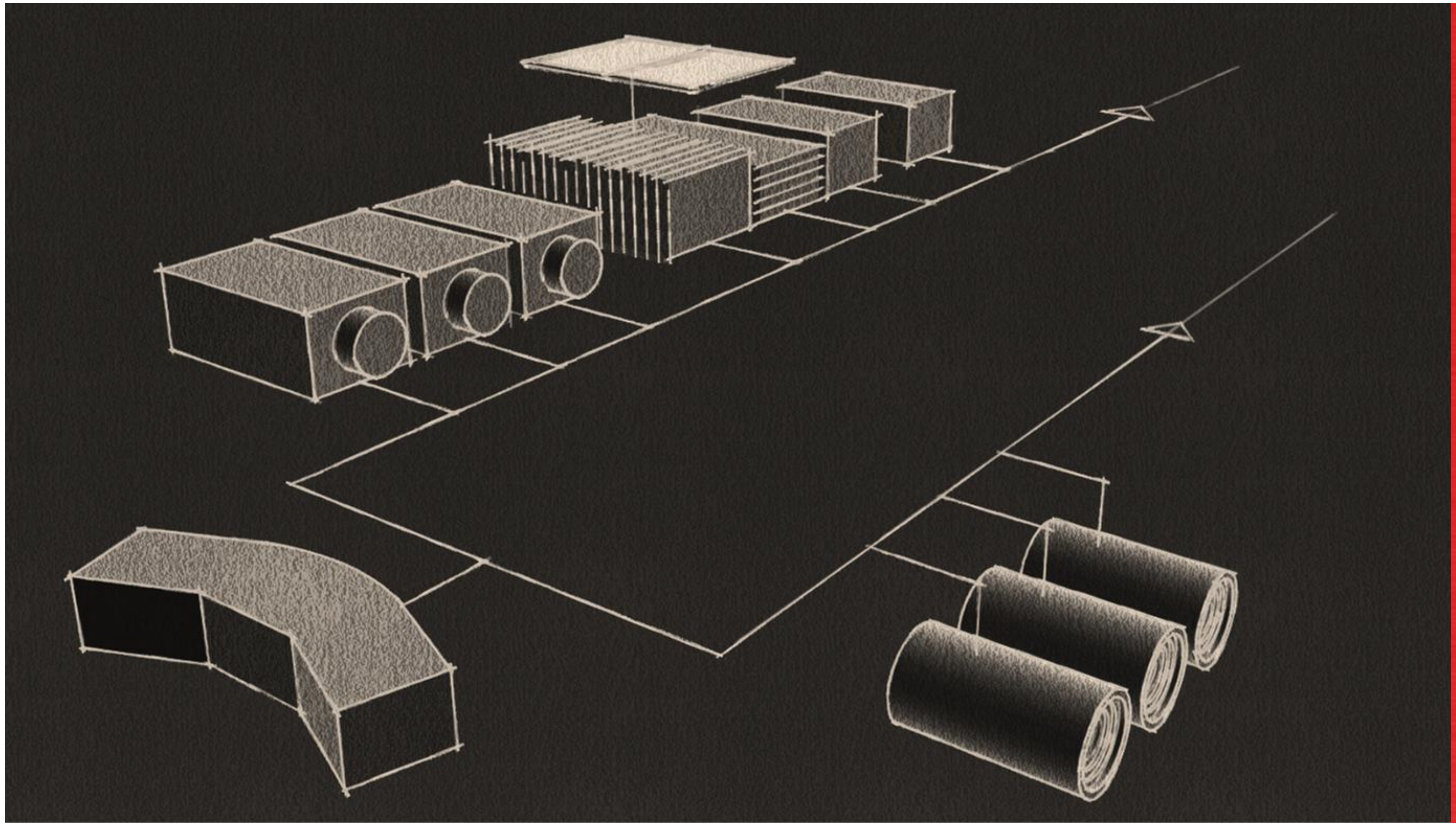
Operational Flexibility with Distributed Power Systems Onboard DC Grid™

Daniel Ahern, VP Navy & Coast Guard Segment

ABB

Onboard DC Grid

… a paradigm shift …



- ✓ Variable Speed
- ✓ Energy Storage
- ✓ Alternative Energy Sources

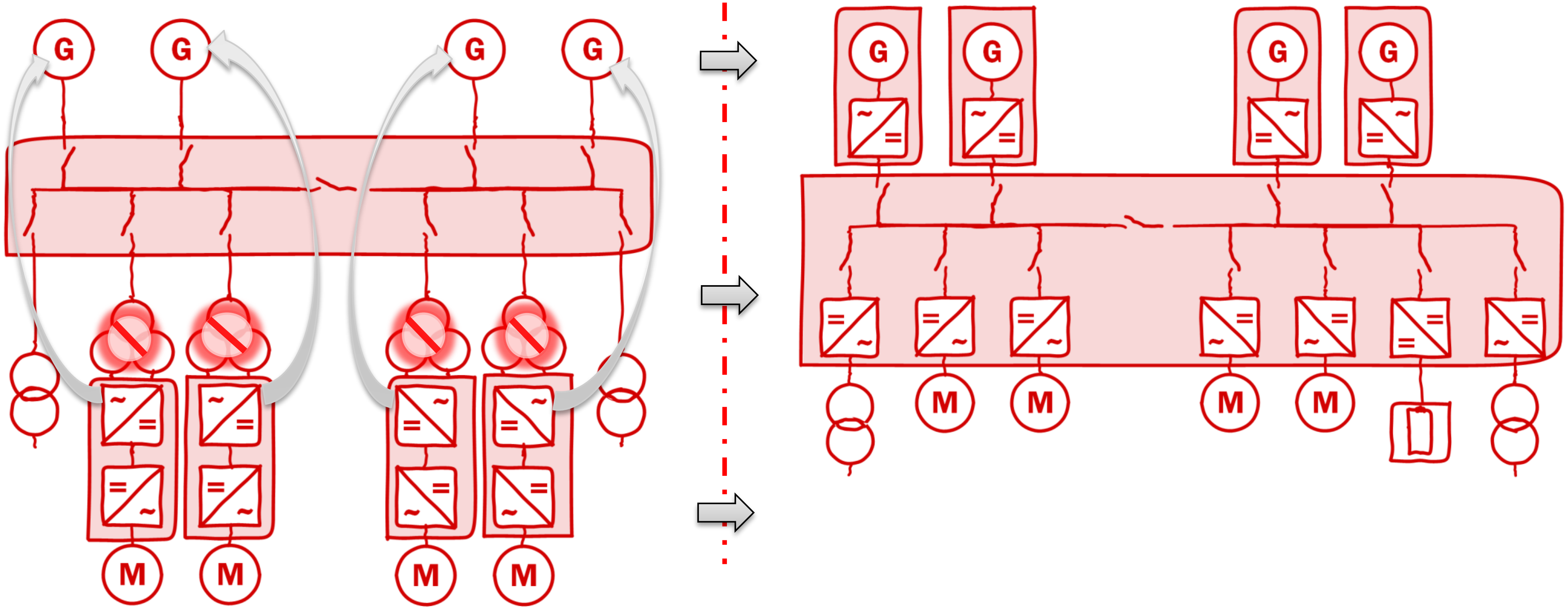
Onboard DC Grid

… the basic principles …

Driving Factors

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

Traditional AC System *Onboard DC Grid*



Variable Speed Engines

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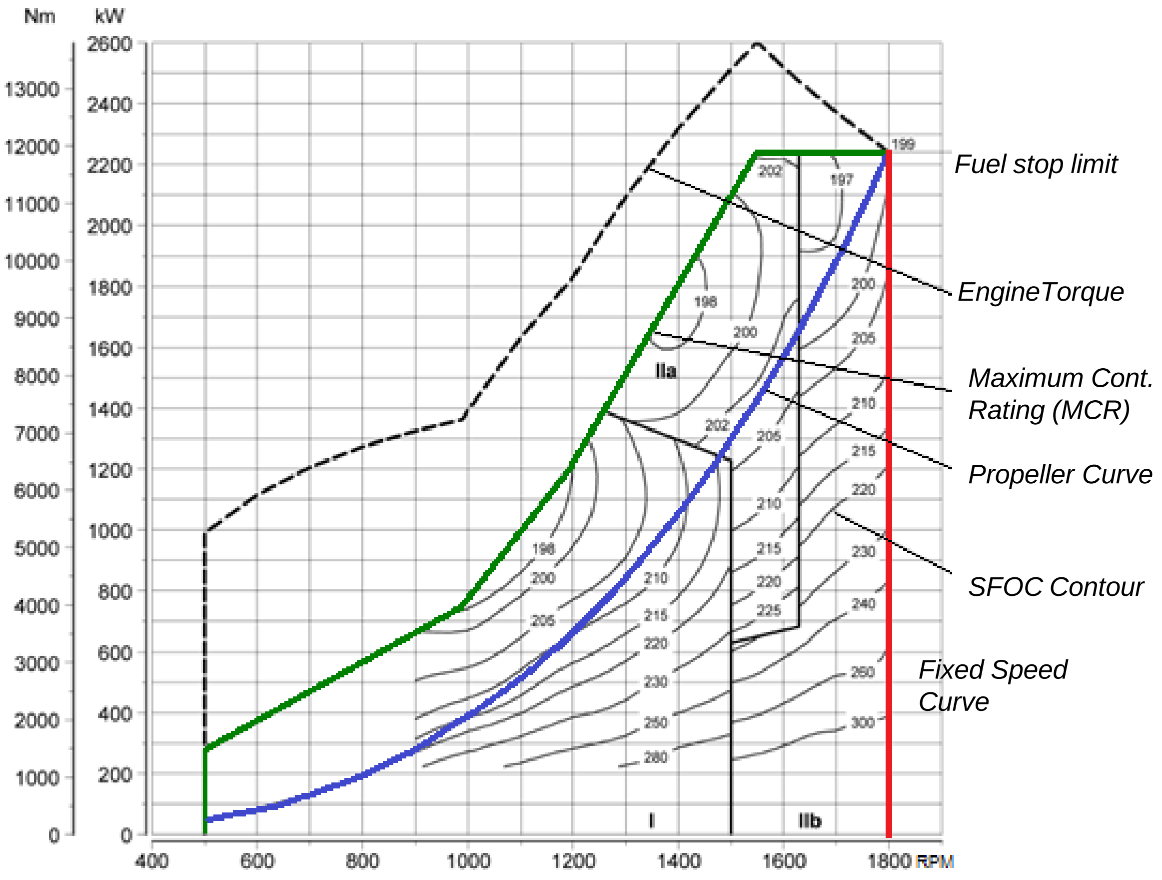
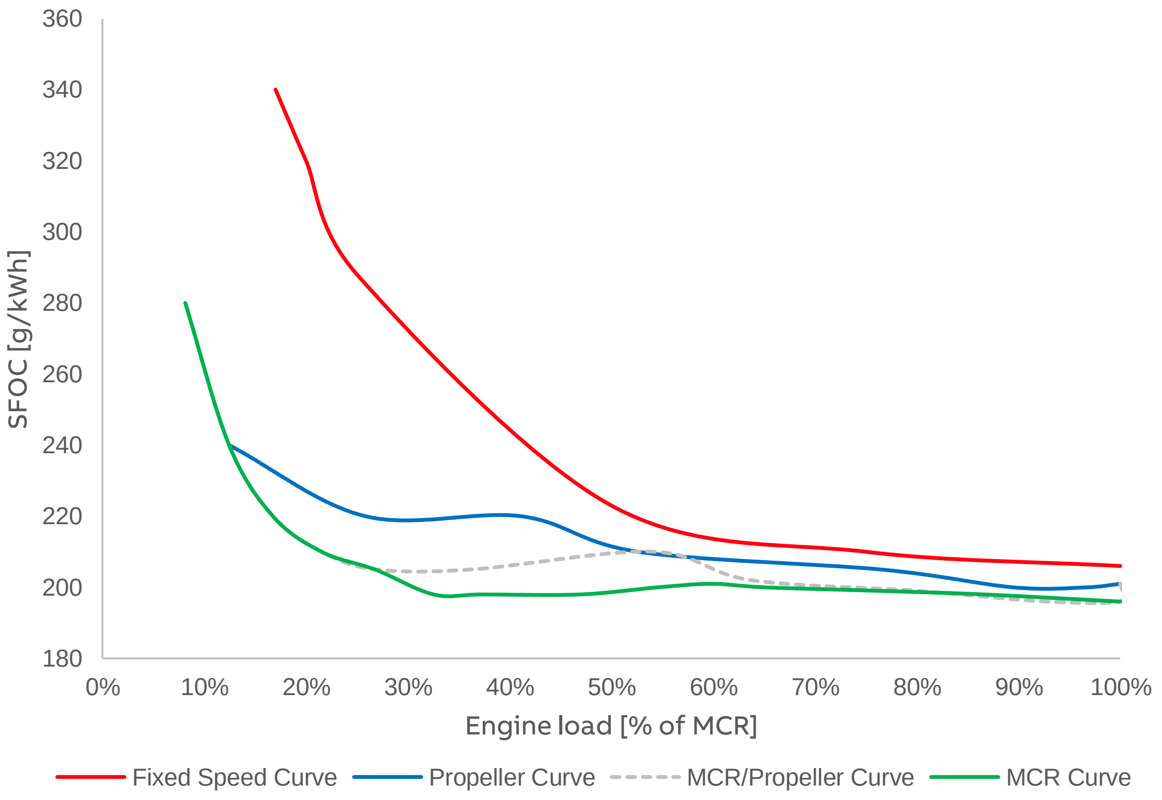
Onboard DC Grid

Why variable Speed Engines





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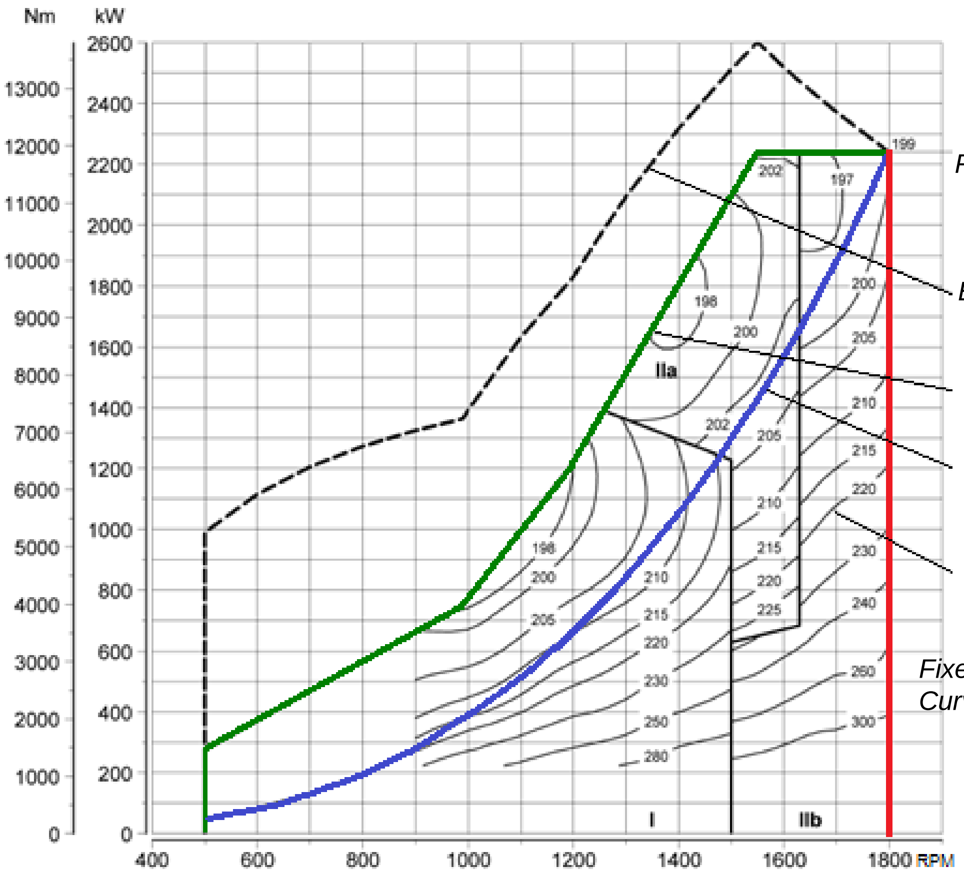
Why variable Speed Engines



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

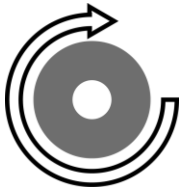
Energy Storage Solutions

...

Energy Storage Solutions

Functionality

Spinning Reserve



Backup power to running generators.

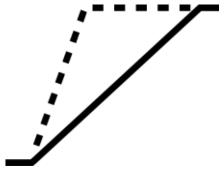
Benefits include
- Improved safety
- Reduced fuel consumption and engine maintenance

Peak Shaving

Level power seen by engines and offset need to start new engines.

Benefits include
- Reduced fuel consumption and engine maintenance

Enhanced Dynamic Perf.



Instant power in support of running engines.

Benefits include
- Reduced fuel consumption
- Enabler for “slower” sources like LNG and fuel cells

Enhanced Ride Through

Short time backup power to running generators.

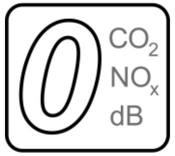
Benefits include
- Improved safety
- Reduced fuel consumption and engine maintenance

Strategic Loading

ESS used to charge or discharge with the aim of optimizing engine operating point.

Benefits include
- Reduced fuel consumption

Zero Emission Operation



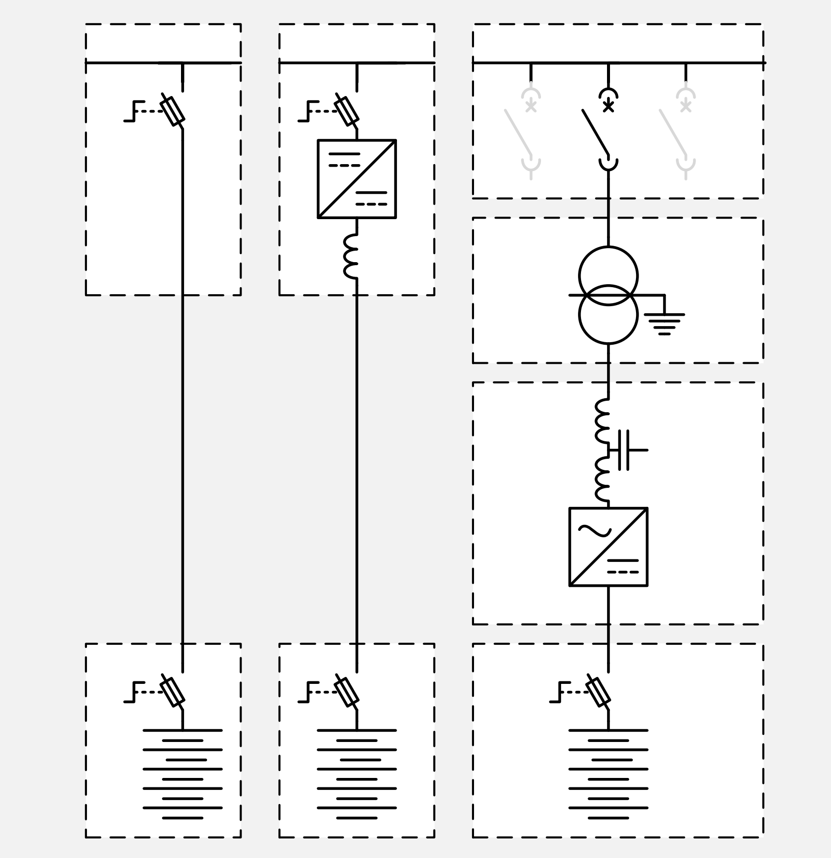
Power system is fully powered by ESS.

Benefits include
- Quiet engine room
- Zero emission operation

Battery integration in power systems

Solutions overview

	DC Direct Online	DC Converter	AC Converter
System Connection Method	Direct	DC/DC Conv choke	DC/AC conv filter Transformer
Response	Good	Instant	Good*
Autonomy	Partial	Full	Full
Functionality	Limited	Full	Full
Converter Size	None	∝ Peak power	∝Peak power ∝Peak SC & Transients
Main selling point	Efficiency	Controllability	AC Power



Control Integration

Energy Storage vs. Engine

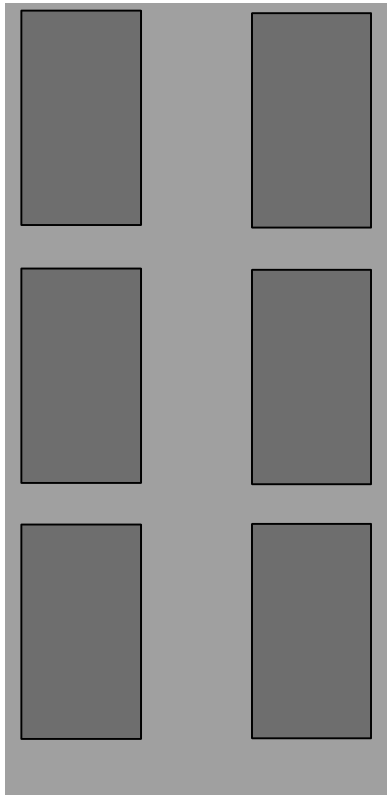
Parameter	High Speed Engine	Example Energy Battery	Example Power Battery
Battery Size	-	~2.4 MWh	~0.75 MWh
Continuous	2 MW	-	-
RMS Continuous Charging/discharging	-	~2.4 MW	~4.5MW
One discharge	-	~2.4 MW	~7.5MW
Pulse power for 10sec	~2.4MW	~2.4 MW	~11.2MW

Note:

- Converter, fuel tank, exhaust systems not included in comparison
- Typicall <80% of battery size is available for use

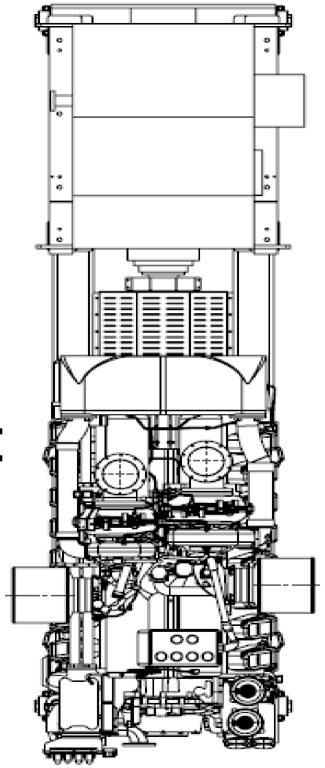
20" Container

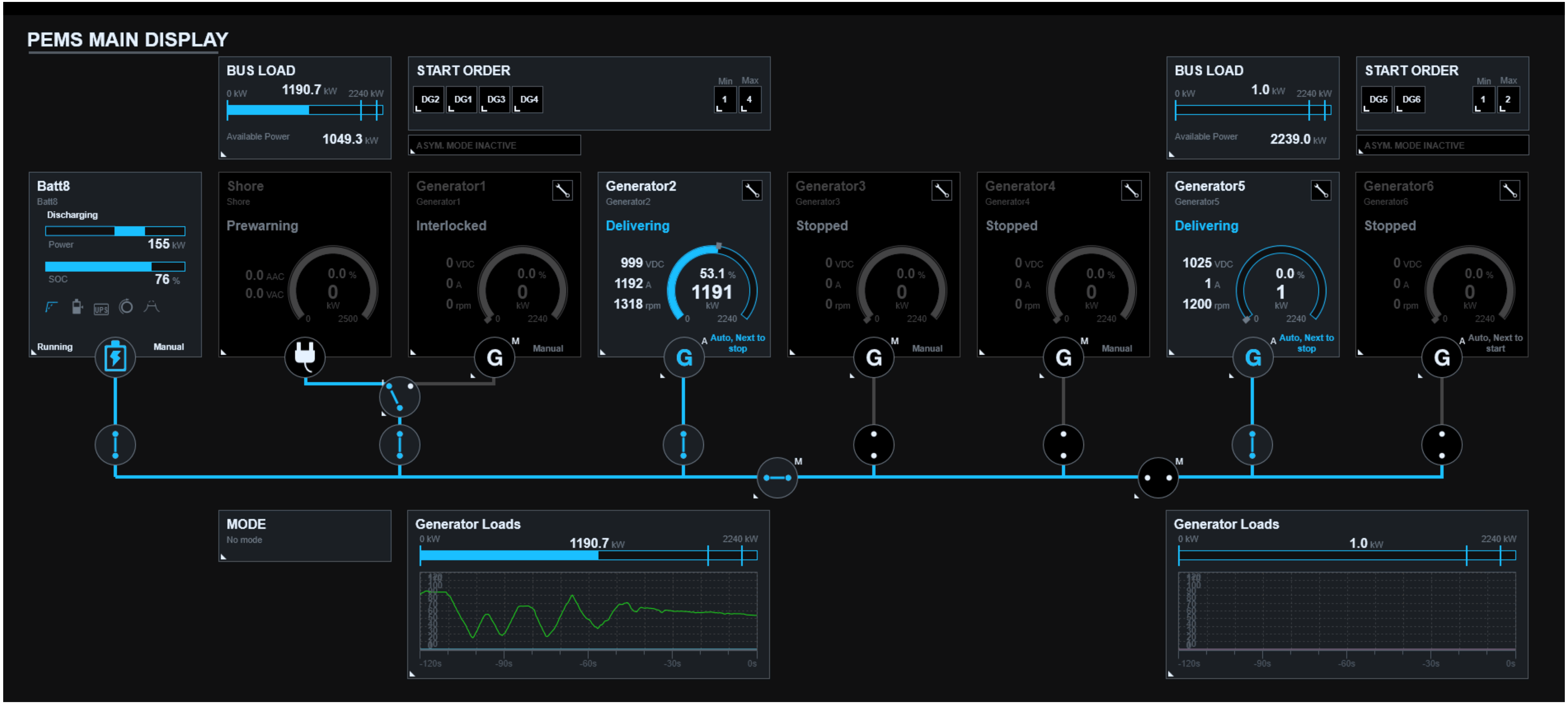
Appr. 2.44 x 6.1m



2MW HS Genset

Appr. 2.2 x 6m




PEMS MAIN DISPLAY
BUS LOAD
0 kW
1190.7 kW
2240 kW
Available Power
1049.3 kW
START ORDER
DG2 DG1 DG3 DG4
Min Max
1 4
ASYM. MODE INACTIVE
BUS LOAD
0 kW
1.0 kW
2240 kW
Available Power
2239.0 kW
START ORDER
DG5 DG6
Min Max
1 2
ASYM. MODE INACTIVE
Batt8
Batt8
Discharging
Power 155 kW
SOC 76 %
Running
Manual
Shore
Shore
Prewarning
0.0 AAC
0.0 VAC
0.0 %
0 kW
2500
Generator1
Generator1
Interlocked
0 VDC
0 A
0 rpm
0.0 %
0 kW
2240
Manual
Generator2
Generator2
Delivering
999 VDC
1192 A
1318 rpm
53.1 %
1191 kW
2240
Auto, Next to stop
Generator3
Generator3
Stopped
0 VDC
0 A
0 rpm
0.0 %
0 kW
2240
Manual
Generator4
Generator4
Stopped
0 VDC
0 A
0 rpm
0.0 %
0 kW
2240
Manual
Generator5
Generator5
Delivering
1025 VDC
1 A
1200 rpm
0.0 %
1 kW
2240
Auto, Next to stop
Generator6
Generator6
Stopped
0 VDC
0 A
0 rpm
0.0 %
0 kW
2240
Auto, Next to start
MODE
No mode
Generator Loads
0 kW
1190.7 kW
2240 kW
-120s -90s -60s -30s 0s
Generator Loads
0 kW
1.0 kW
2240 kW
-120s -90s -60s -30s 0s

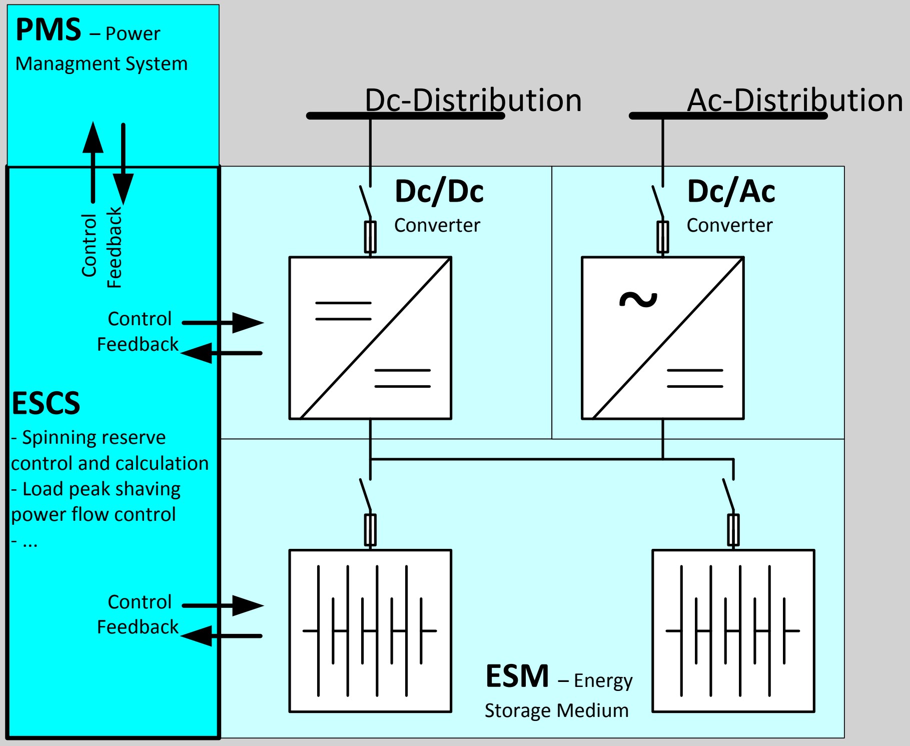
Energy Storage Integration

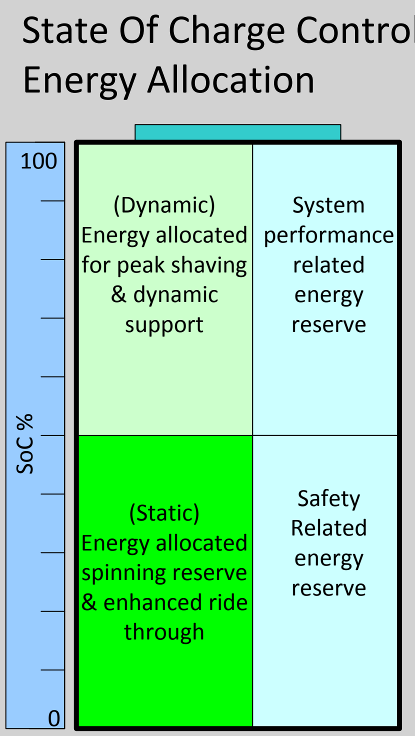
Integration into Power System

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

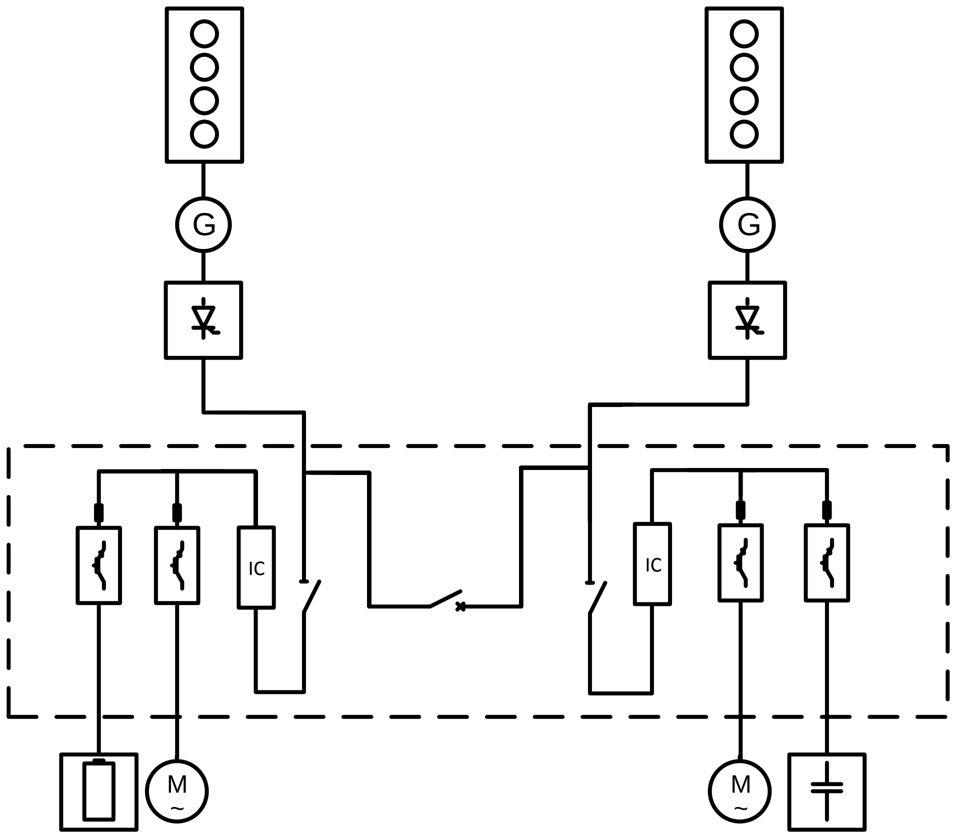


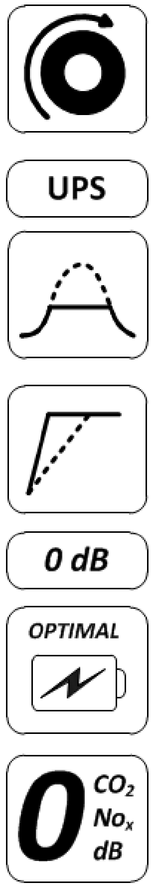


Onboard DC Grid

Marintek Laboratory

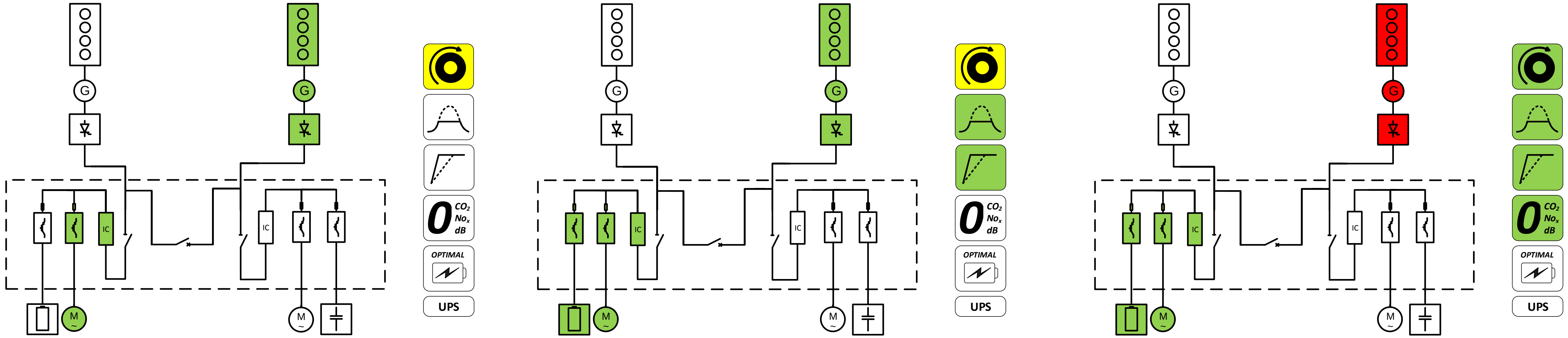
Start of Testing:	March 2014
Voltage Level:	540Vdc
Speed range:	900-1800rpm
Engines:	1 x Perkins GCD325A 1 x Perkins 2506C-E15TAG1
Generation:	1 x 400kVA UNIREC 1 x 230kVA UNIREC
Loads:	2 x 160kW ACS800
Energy Storage:	1 x 55kWh Battery 1 x 1MWs Super Capacitor





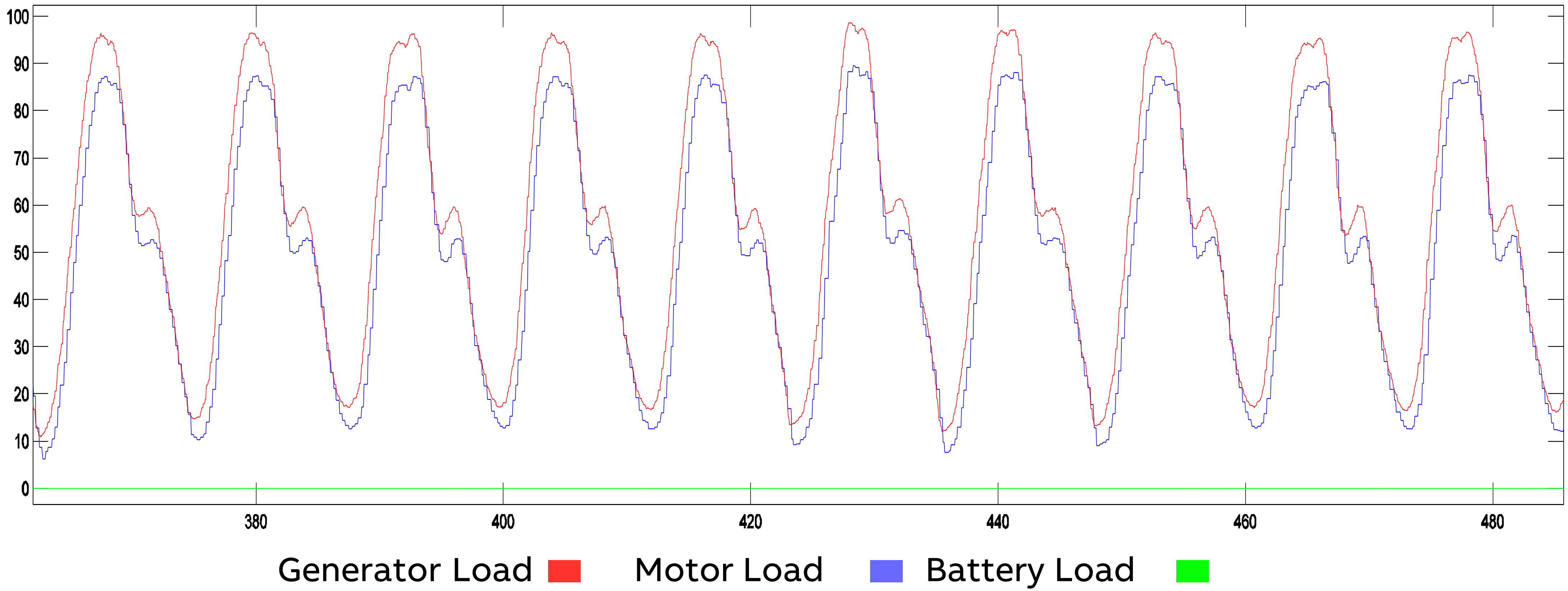
Onboard DC Grid

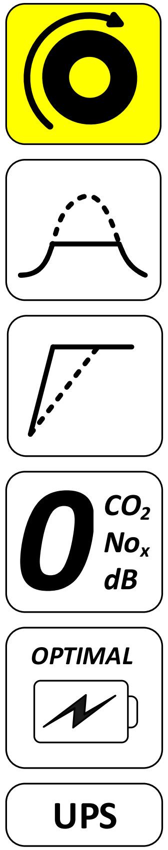
Three Tests – Energy Storage Works



Onboard DC Grid

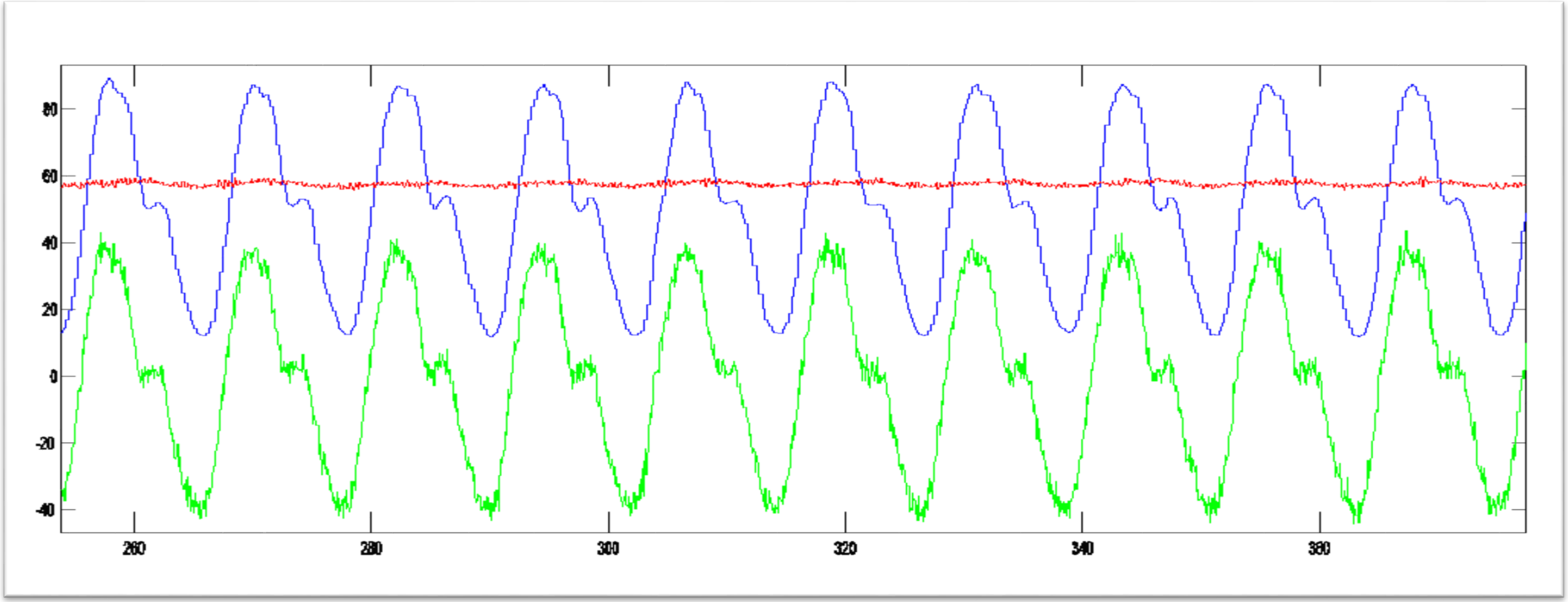
Laboratory Results – Only Generator



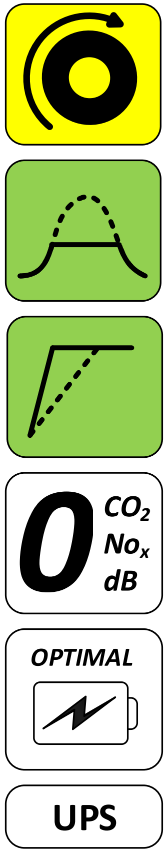


Onboard DC Grid

Laboratory Results – Only Generator



Generator Load   Motor Load   Battery Load



Onboard DC Grid

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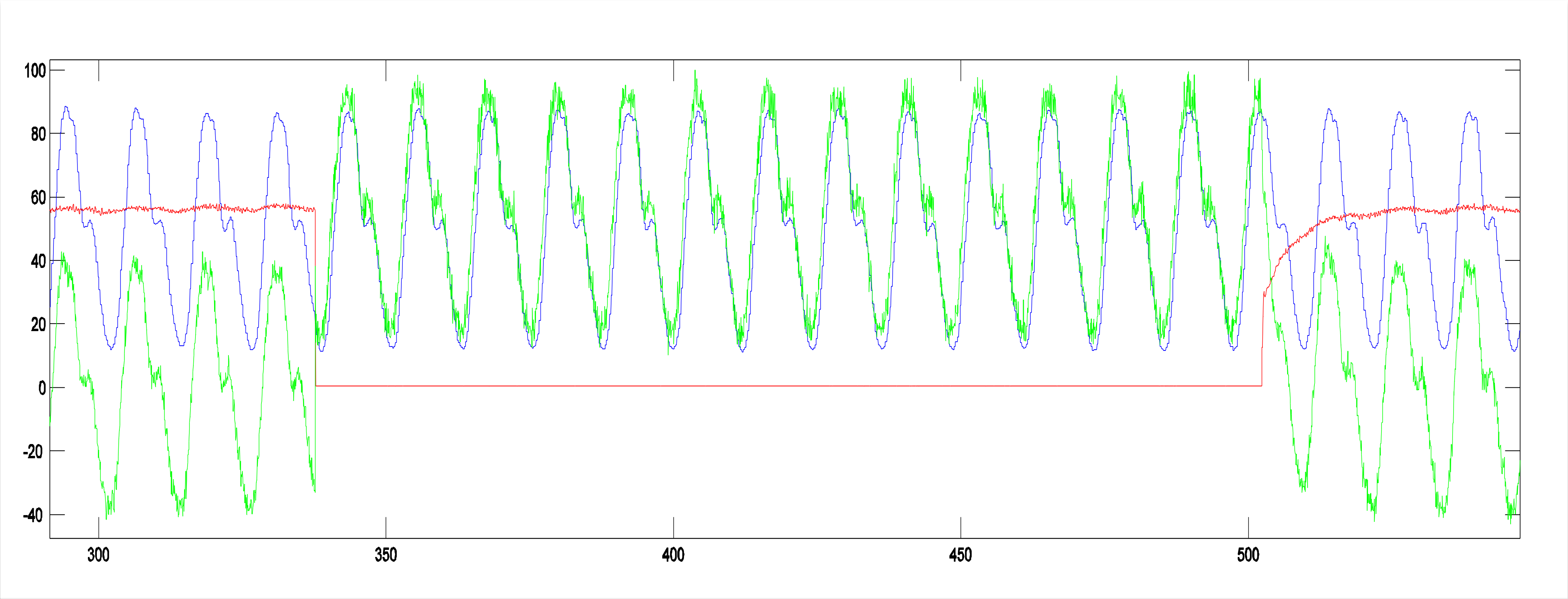
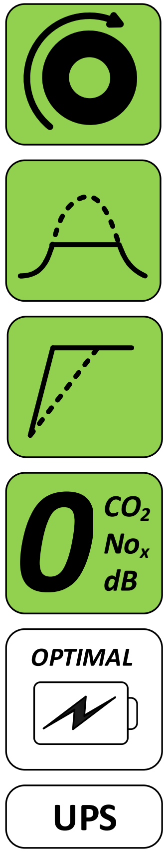


Generator Load Motor Load Battery Load



Safety and Performance

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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

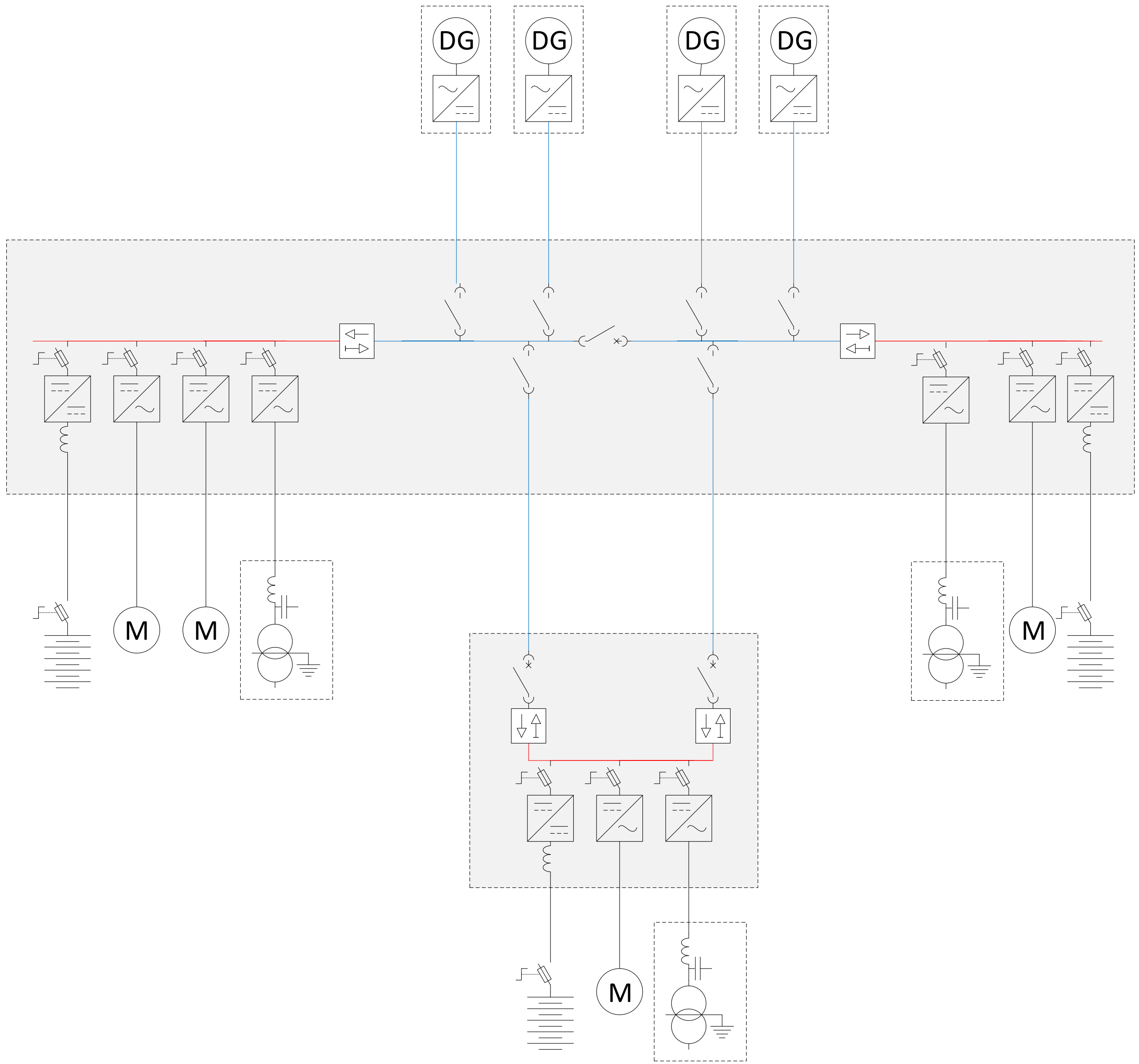
DC Distribution (Grid Side)

- 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.



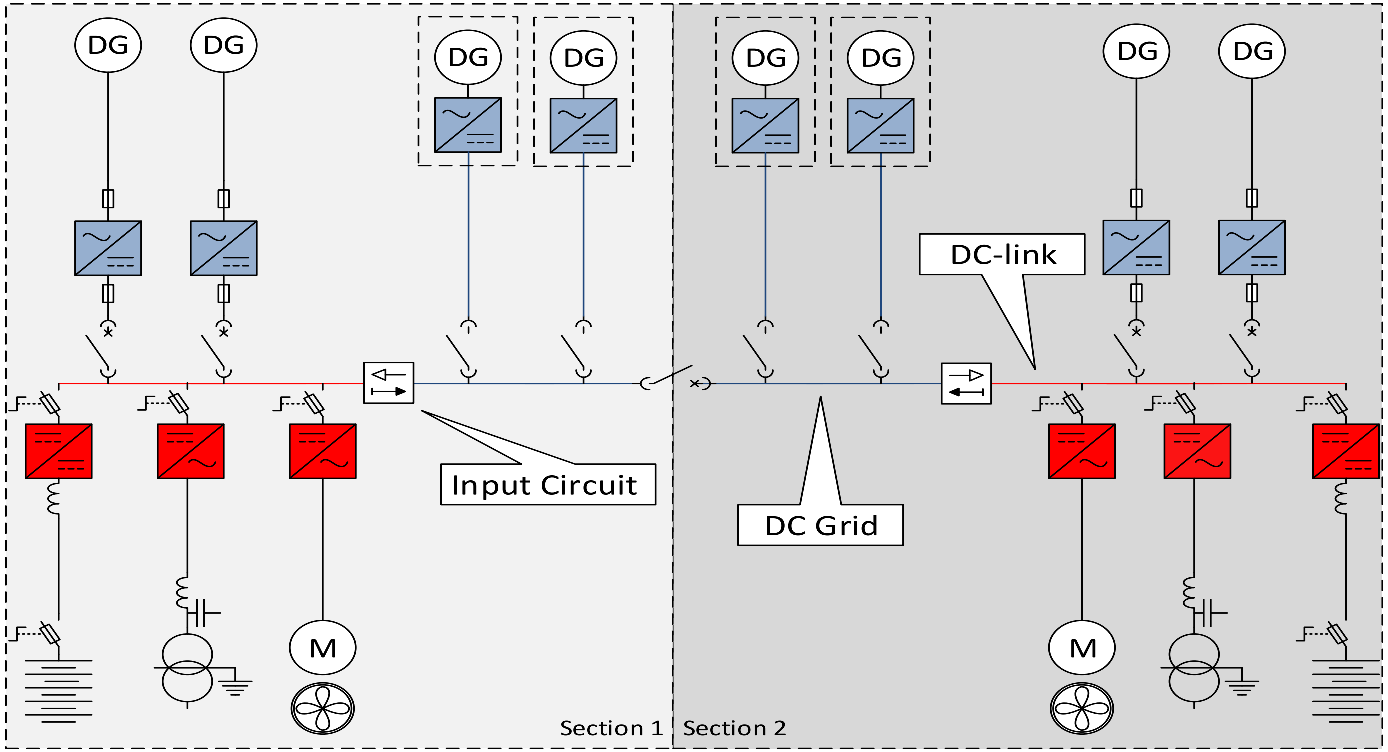
What is Onboard DC Grid

Onboard DC Grid

Protection Philosophy

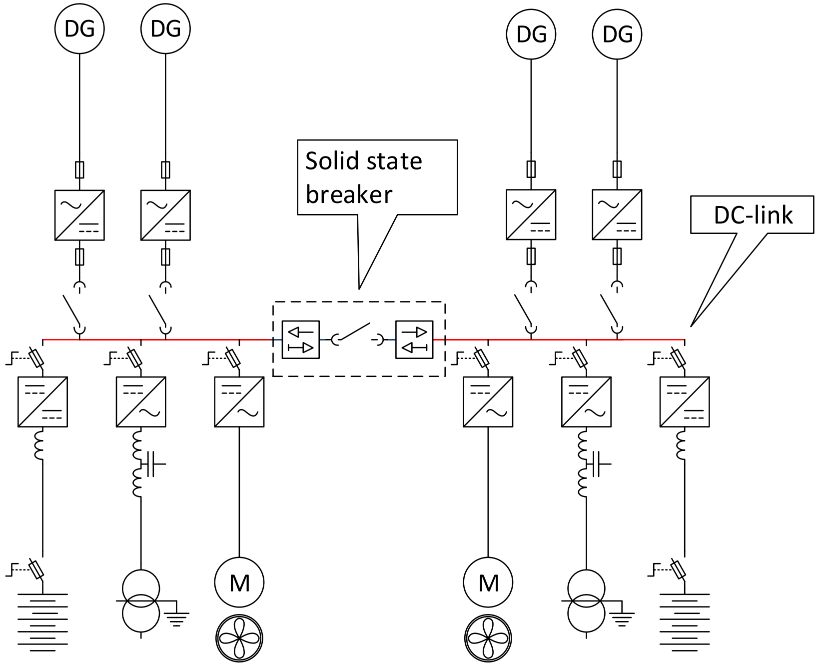
Grid Side
- Slower Time Constants
- No capacitors
- All Sources can block current during faults
- Patented protection philosophy

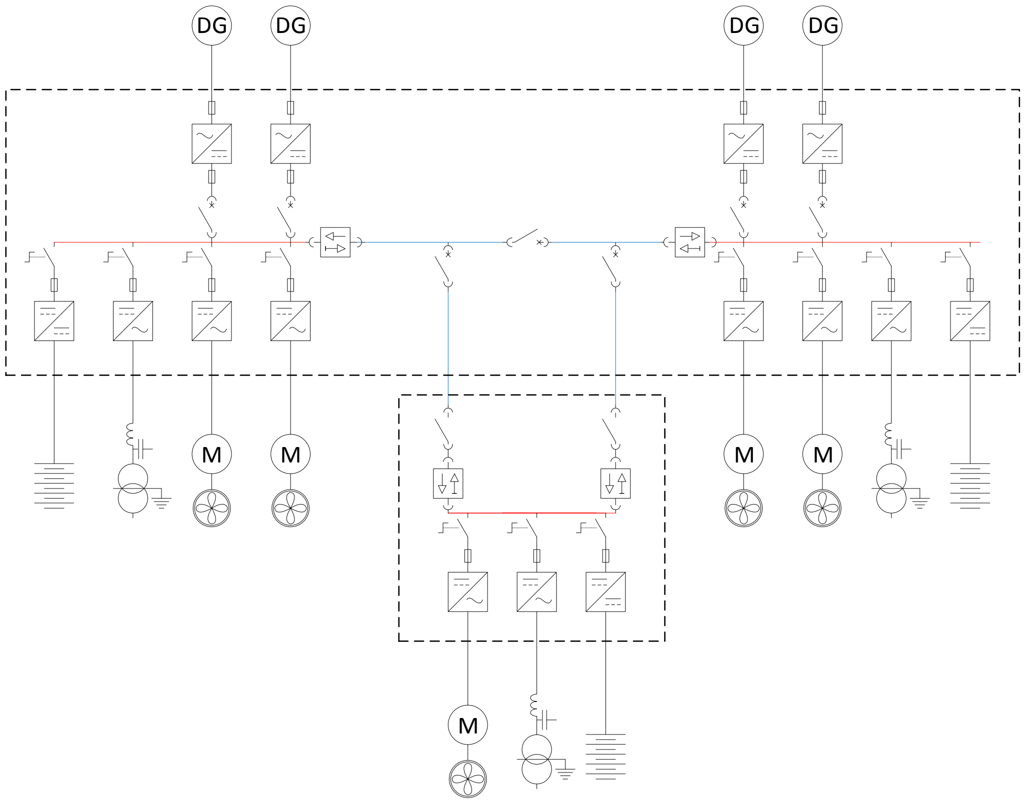
DC Link Side
- Very short Time constant
- Sources cannot block current during faults on DC link.
- Fused Protection



Onboard DC Grid

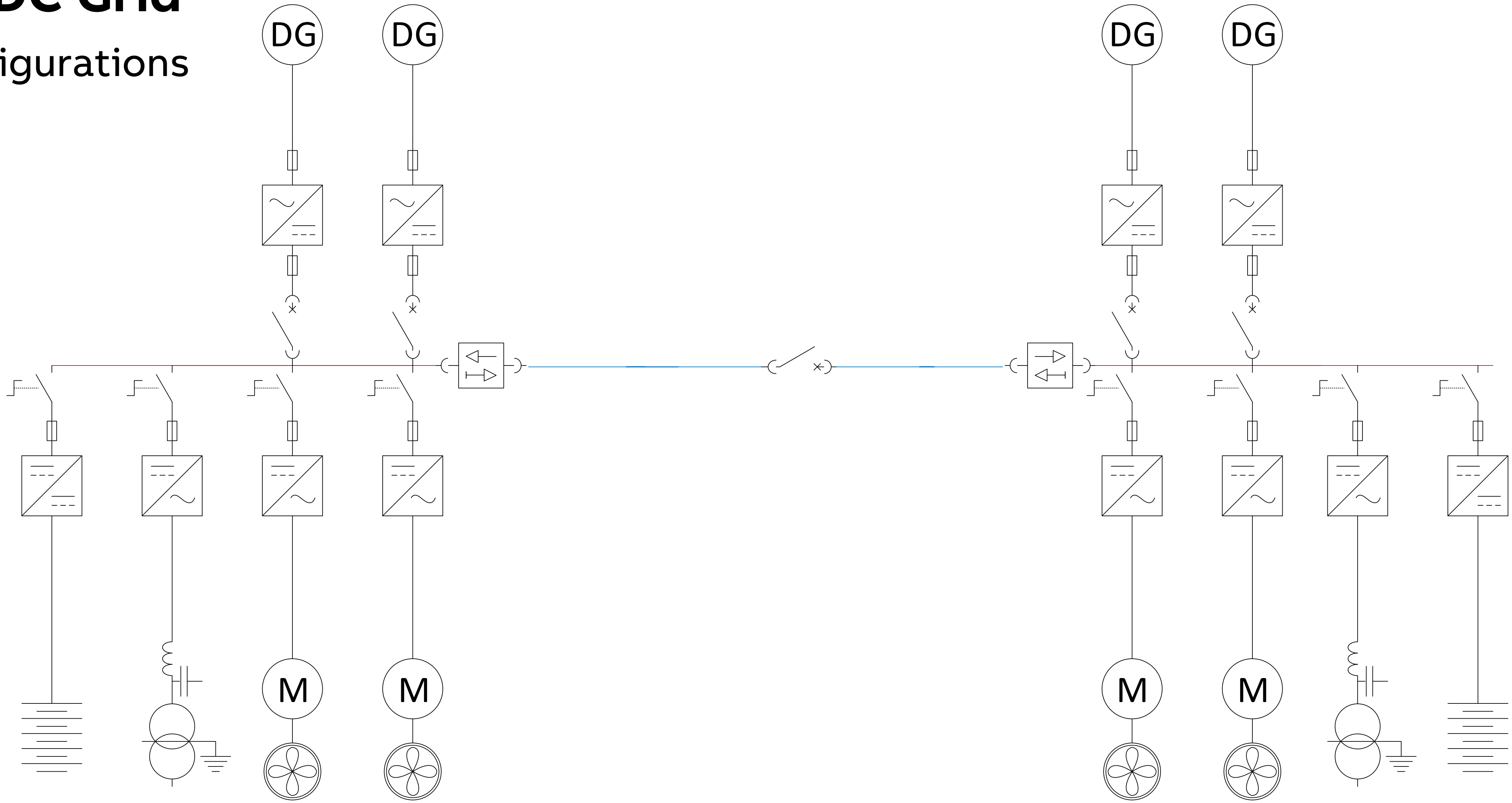
System Configurations





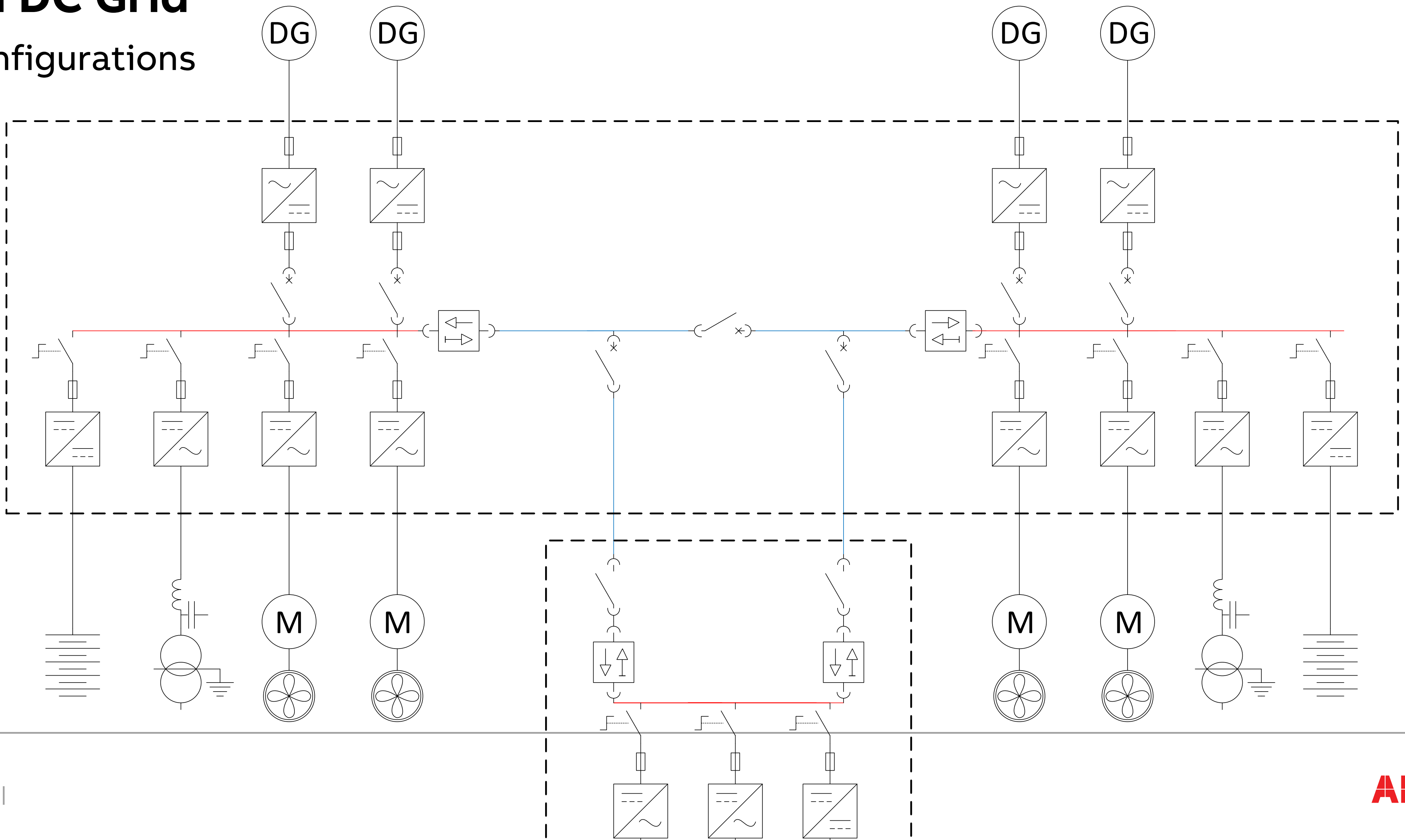
Onboard DC Grid

System Configurations



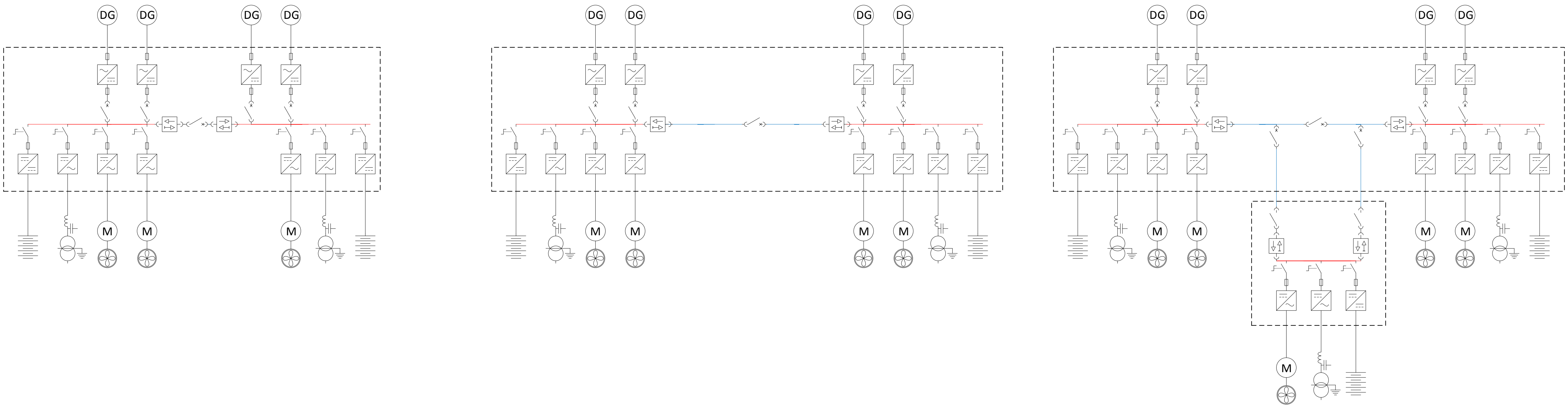
Onboard DC Grid

System Configurations



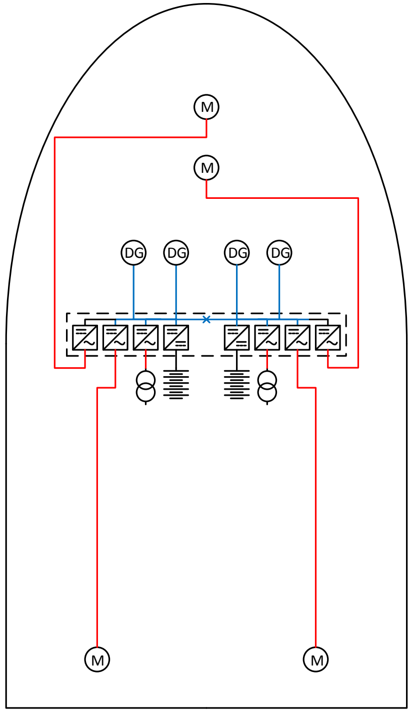
Onboard DC Grid

System Configurations

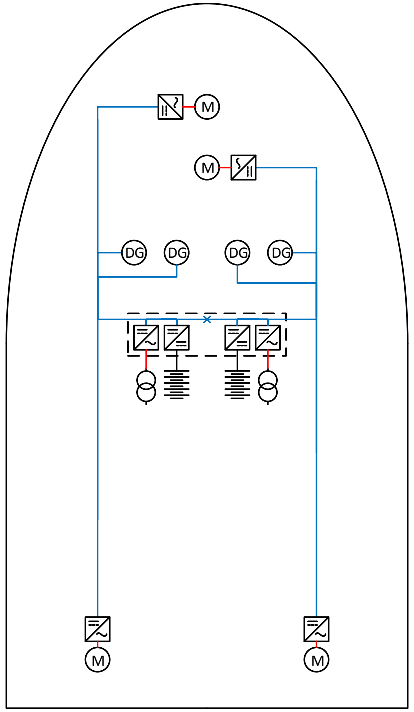


Onboard DC Grid

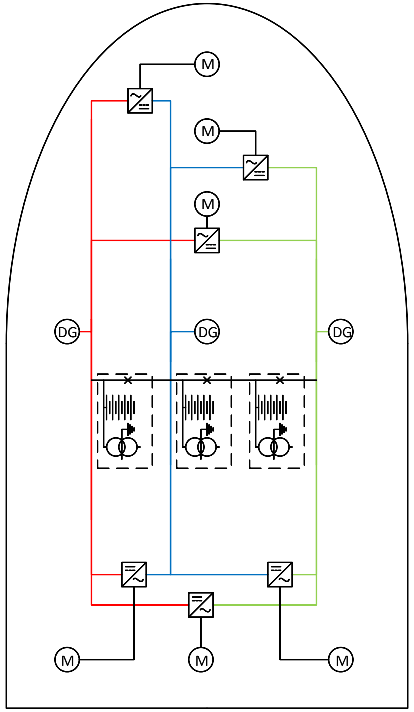
System Configurations || Centralized -> Highly Distributed



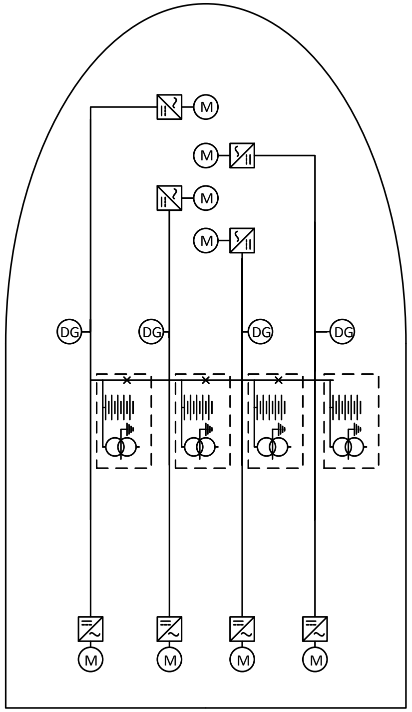
Centralized solution with AC (red) inn and AC out of a centralized swbd



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



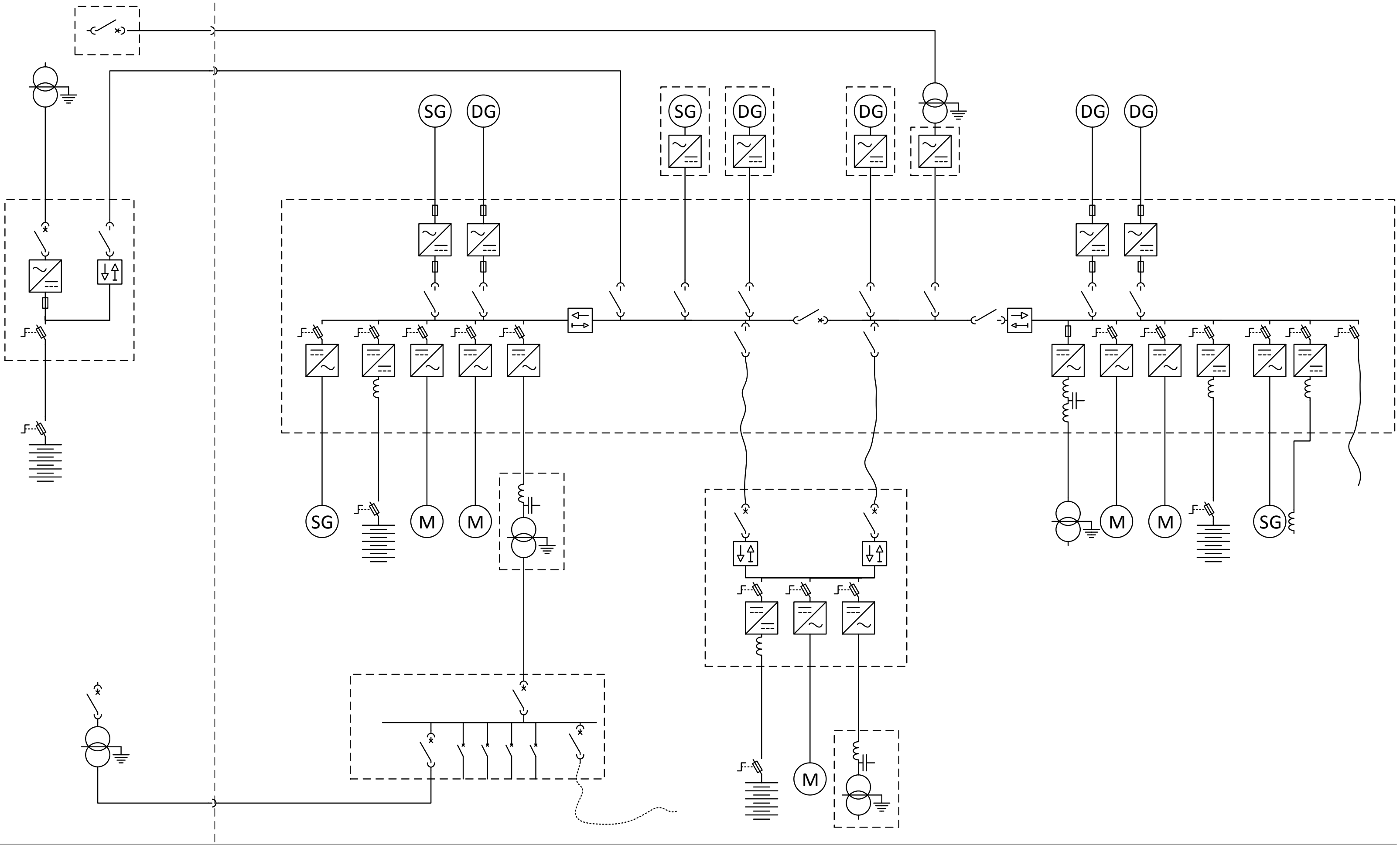
A 4-split highly redundant variant of the distributed system.
This can also be realized using cables.

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

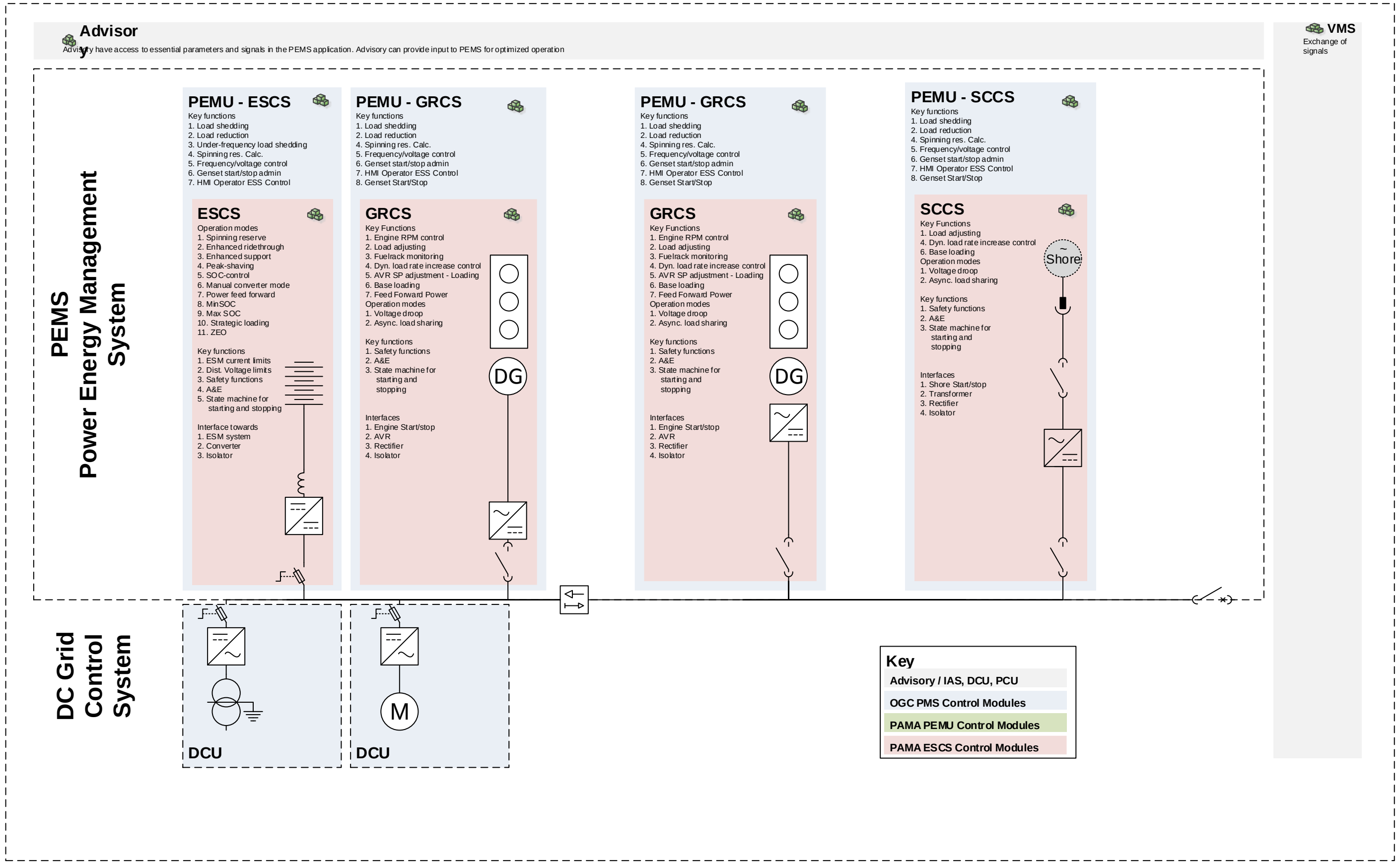


Onboard DC Grid

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



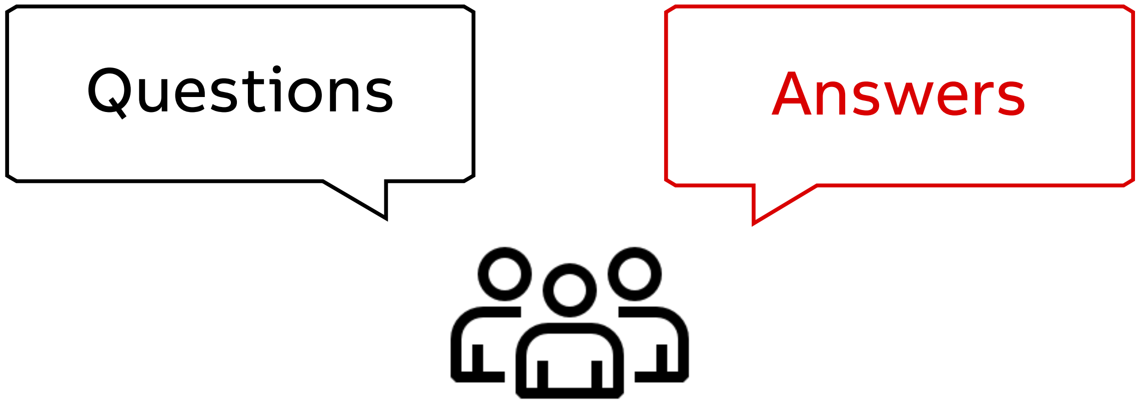
Conclusion: Power System Requirement Drivers – Navy & Coast Guard

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

AC	DC	Extension
red	green	▪ Operational Profile – Flank vs Loiter
yellow	green	▪ Environmental Requirements
		▪ Emissions
		▪ Noise
yellow	green	▪ Shore Power
red	green	▪ Fuel Efficiency
red	green	▪ Alternative Energy Production
red	green	▪ Human Factors – Noise & Vibration

ABB

Q&A



Some references – Reference Material

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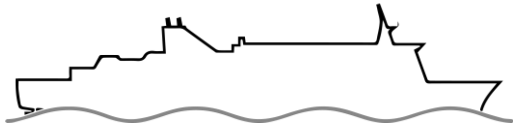
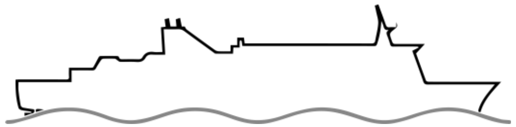
Onboard DC Grid

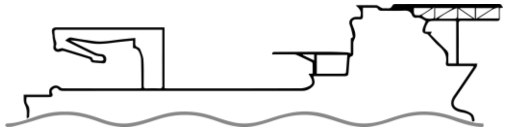
Reference overview – March 2017



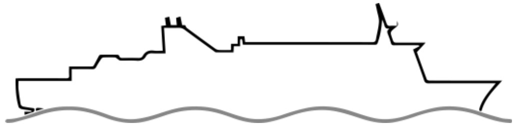
2x RoPax & RoRo



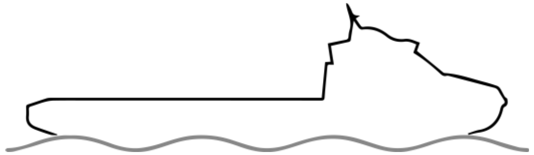
2x Yacht



5x OSV & OCV



5x Car/Road Ferry



2x Icebreakers & Icegoing OSV

2x Shuttle Tanker

Onboard DC Grid

19x

Of these

14x

have Energy Storage

and

2x

have shaft-generators

Reference List

NKT Victoria
First feedback trickling inn…


SHIP OF THE YEAR
BY SKIPSREVYEN
NKT VICTORIA
NKT VICTORIA

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 achieveing greater efficiency and precision.

The vessel is custom built according to NKT's specifications and will measure approx. 140m-long and 30m wide, have capcacity for a crew of 100 and up to 9500 tons of cargo. It will enhance the capacity of NKT's subsea cable operations while delivering optimum efficiency and accuracy.

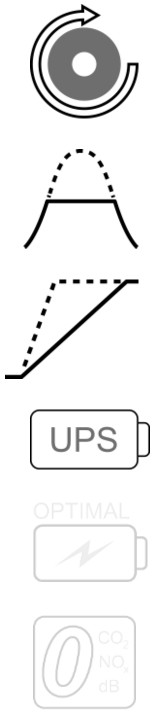
ABB

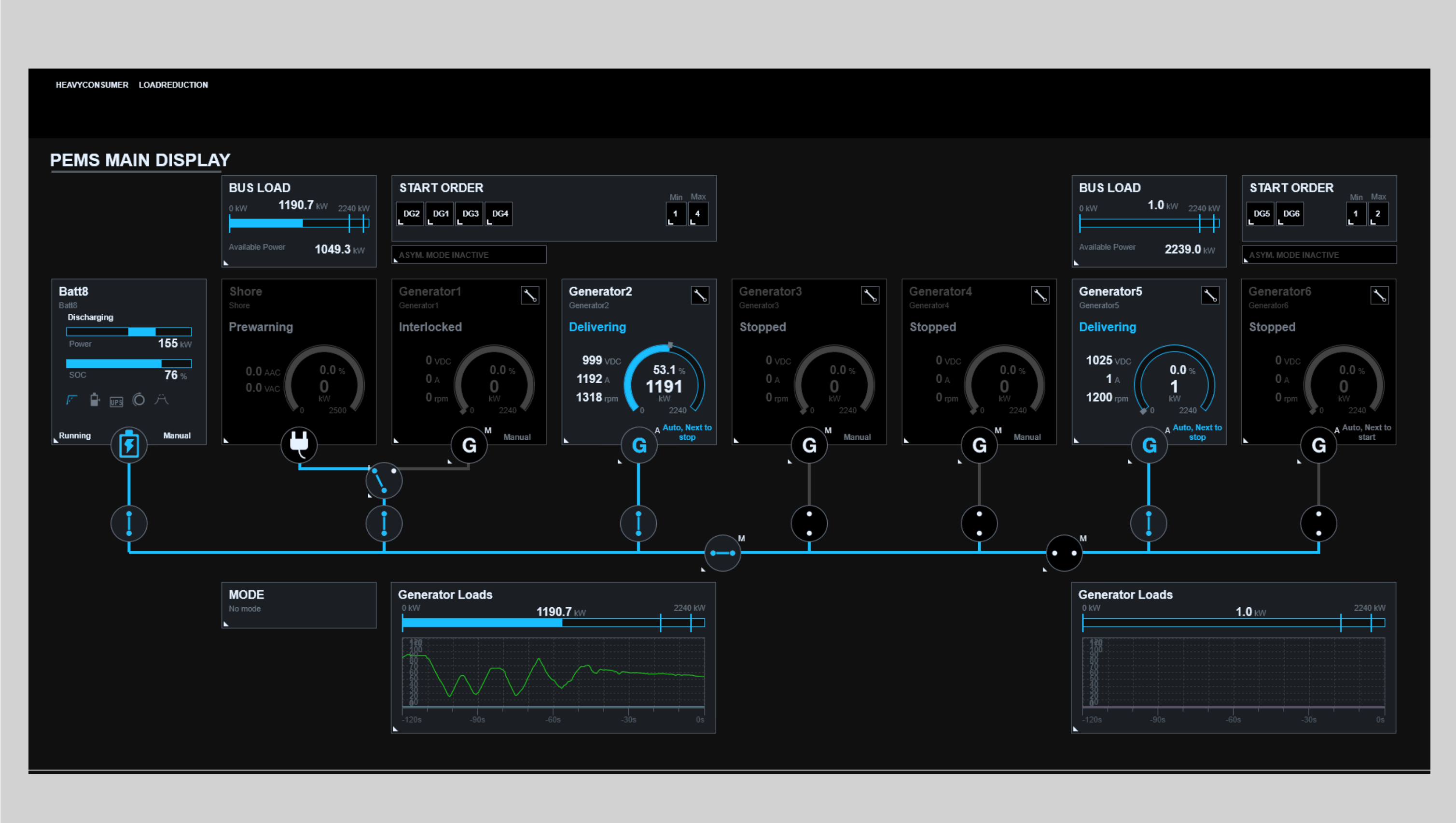
Onboard DC Grid

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

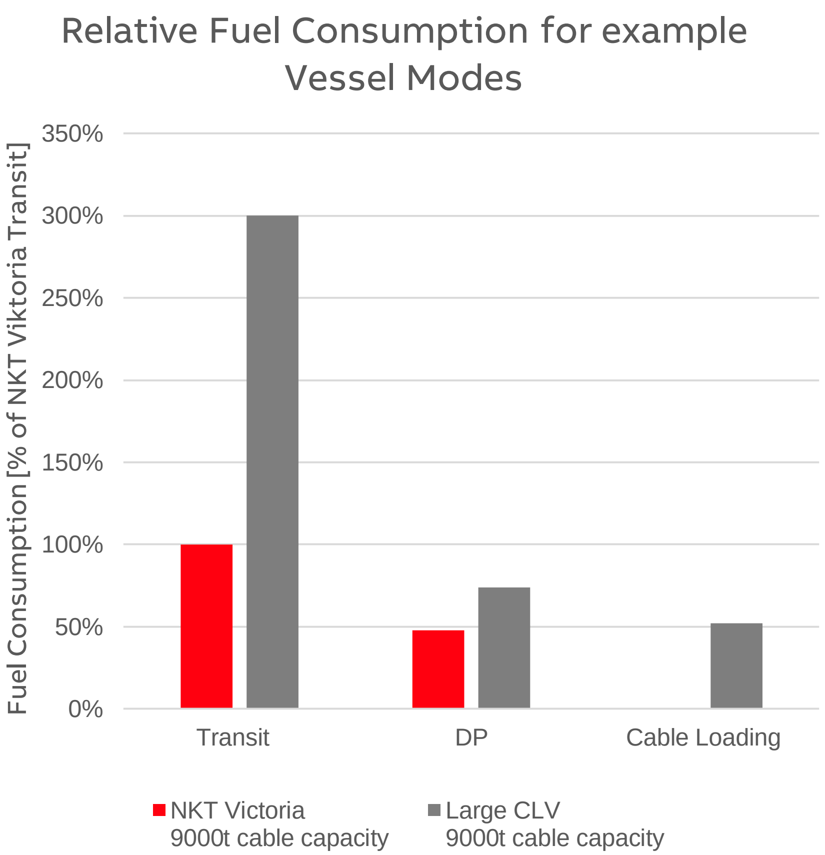
NKT Victoria – Reduction of Fuel Consumption relative to other CLV’s

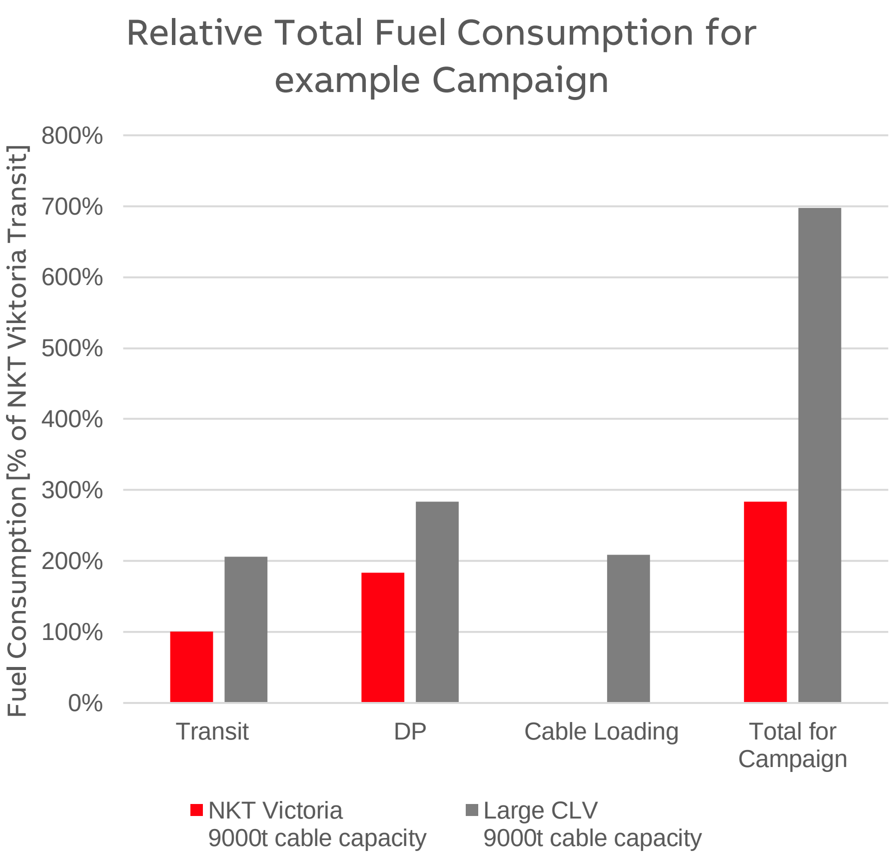
NKT VICTORIA – 9000t cable capacity

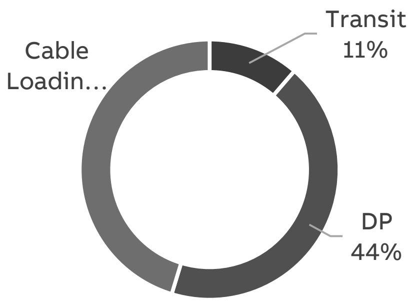
Other NKT Cable Layer Vessel with 9000t cable capacity

Onboard DC Grid

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







In total

59%

w/o Harbour

42%

Onboard DC Grid

NKT Victoria – Reduction of Emissions

Reductions of CO_2

55%

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

15%

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

Reductions of NO_X

15-80%

Depending on NOx
reduction technology
installed

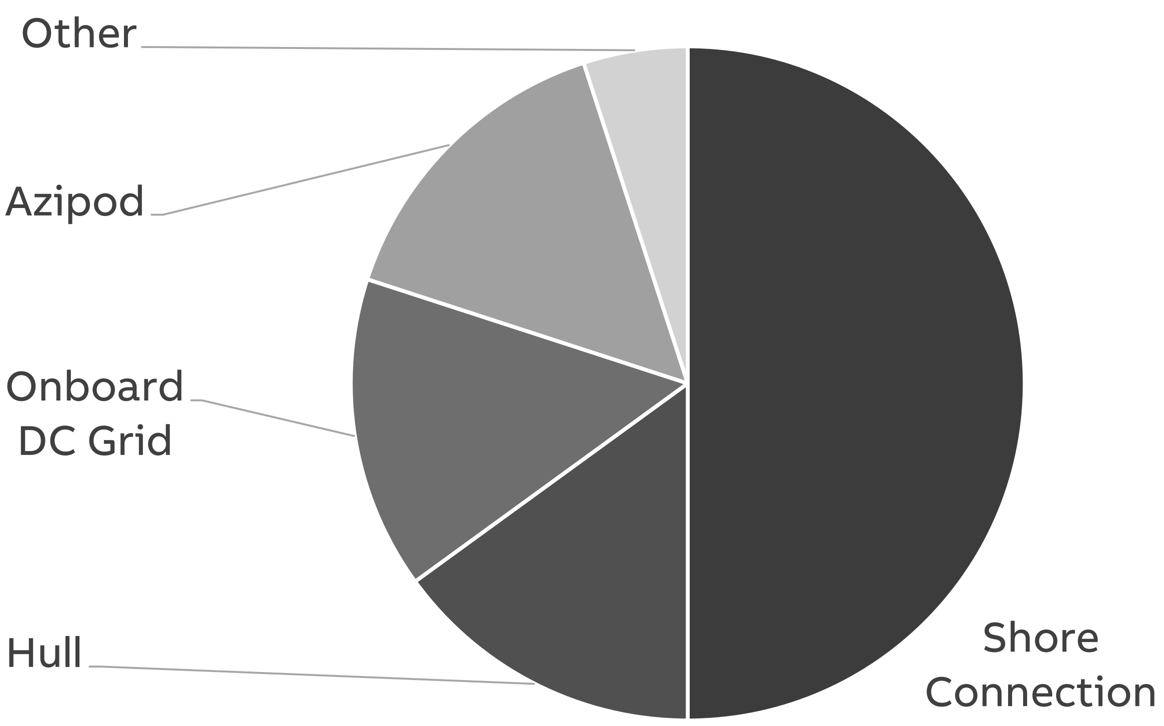
Onboard DC Grid

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

Source of fuel consumption and CO_2 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?

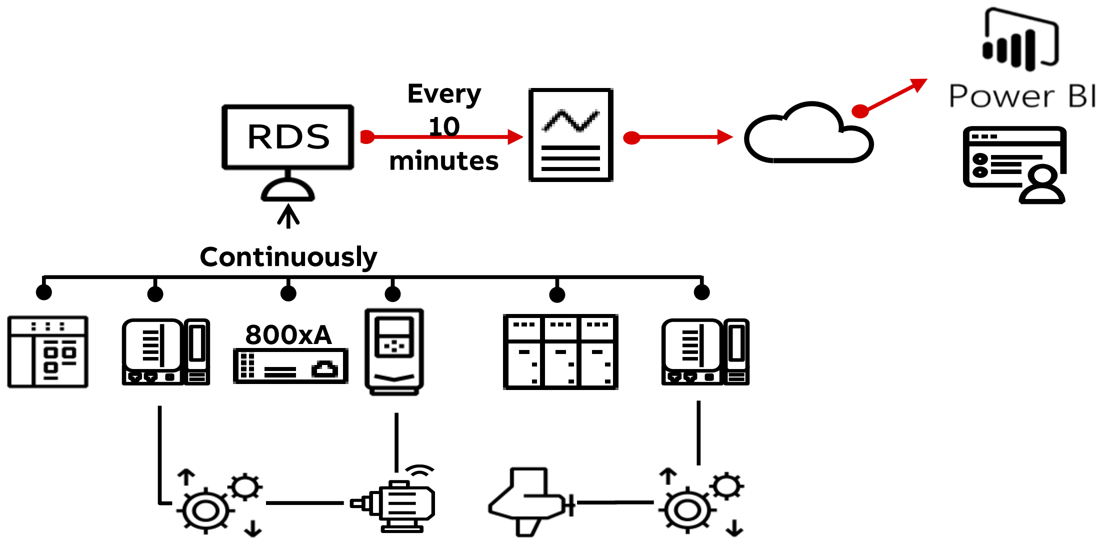
Source of fuel consumption and CO_2 reductions

- 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

We can do it because ship is highly digitalized and connected!

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

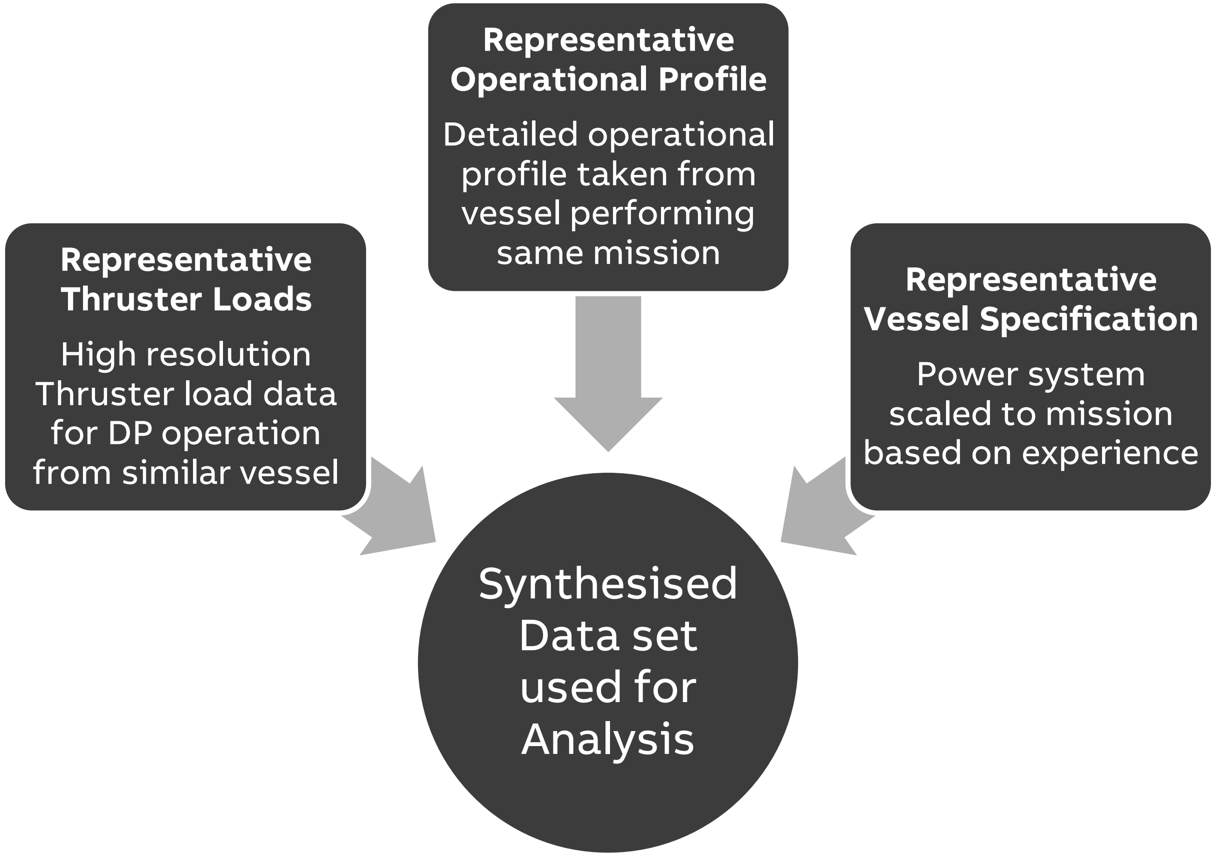


Case Study
Submarine Rescue Vessel Case

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

Operational Modes	DP High	DP	Transit 16kn	Transit ECO	Maneuvering	Moored
Main Propeller 1	300	100	2200	850	400	0
Main Propeller 2	300	100	2200	850	400	0
Tunnel 1	200	100	0	0	100	
Tunnel 2	200	100	0	0	100	
Fwd Az 2	200	100	0	0	100	
Sum Thruster Load	**1200**	**500**	**4400**	**1700**	**1100**	**0**
Other loads	300	300	300	300	300	200
Total Load	**1500**	**800**	**4700**	**2000**	**1400**	**200**

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.

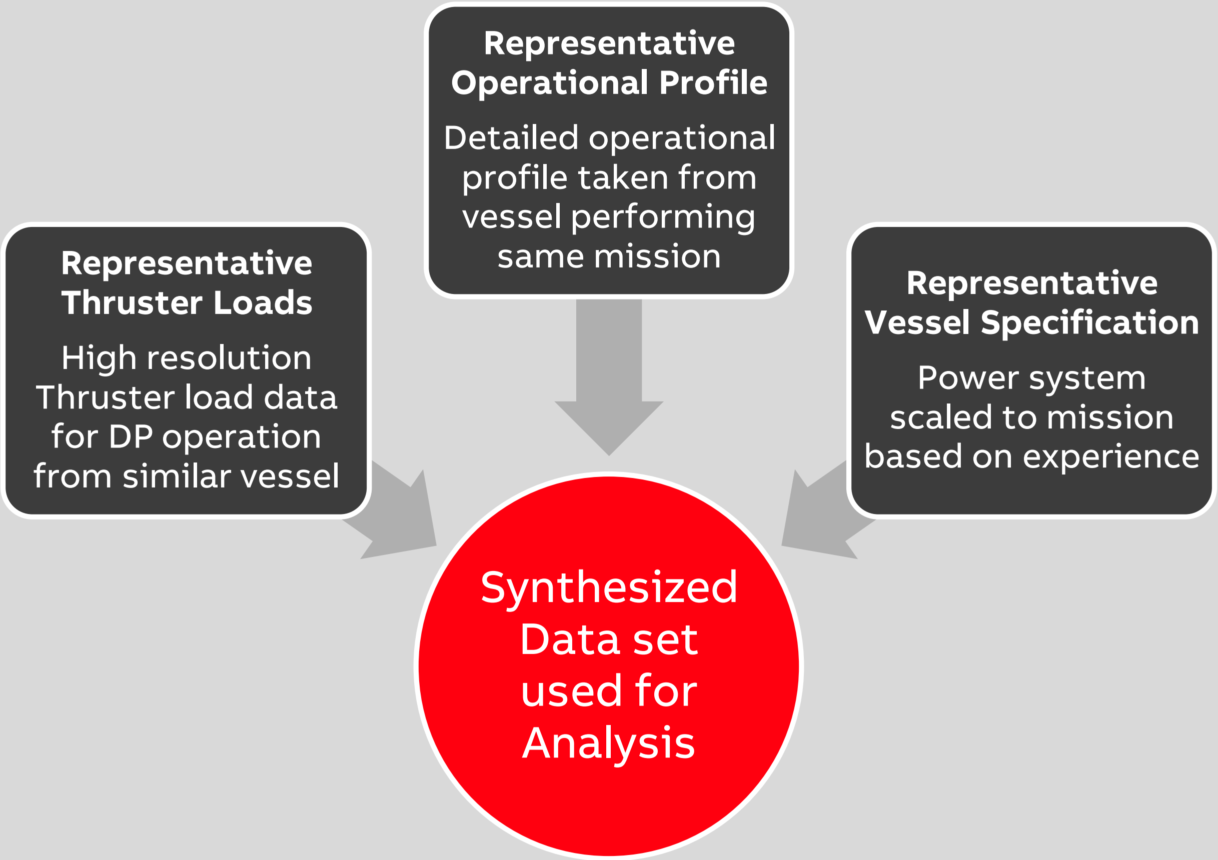
Volstad Surveyor Analysis

Operational modes

Operational Modes	DP High	DP	Transit 16kn	Transit ECO	Maneuveri ng	Moored
Time [%]	9,0 %	38,0 %	3,0 %	16,0 %	16,0 %	18,0 %
Time [hours]	788	3329	263	1402	1402	1577

Notes:

- …



Analysis of Synthesized Data Set

…

Submarine Rescue Vessel Case Study

System loads

Operational Modes	DP High	DP	Transit 16kn	Transit ECO	Maneuvering	Moored
Time [%]	9,0 %	38,0 %	3,0 %	16,0 %	16,0 %	18,0 %
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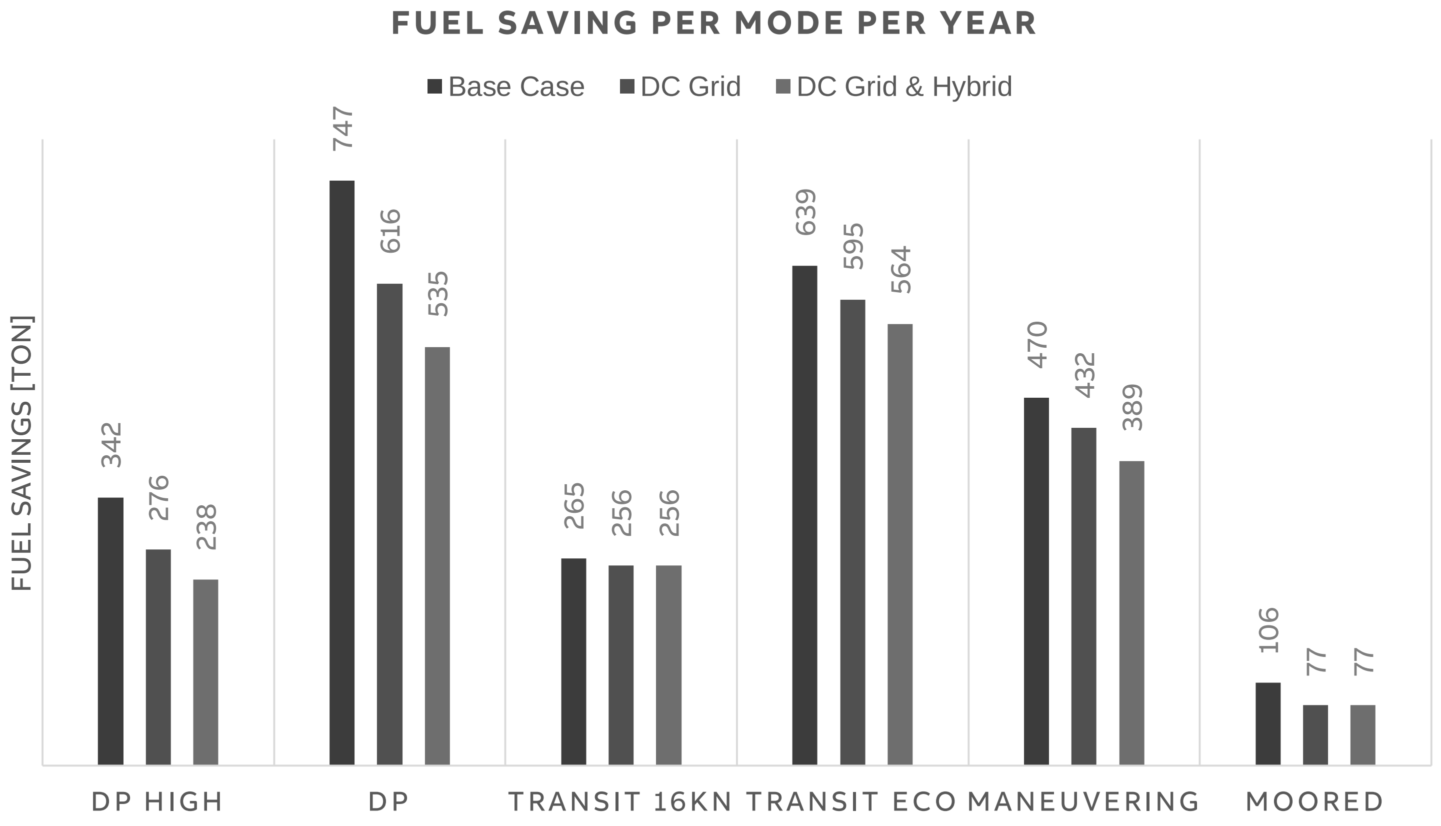
Sum Thruster Load	**1200**	**500**	**4400**	**1700**	**1100**	**0**
Other loads	300	300	300	300	300	200
Total Load	**1500**	**800**	**4700**	**2000**	**1400**	**200**
#Genset Non Hybrid	*4*	*2*	*3*	*2*	*2*	*1*
#Genset Hybrid	*2*	*1*	*3*	*1*	*1*	*1*

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

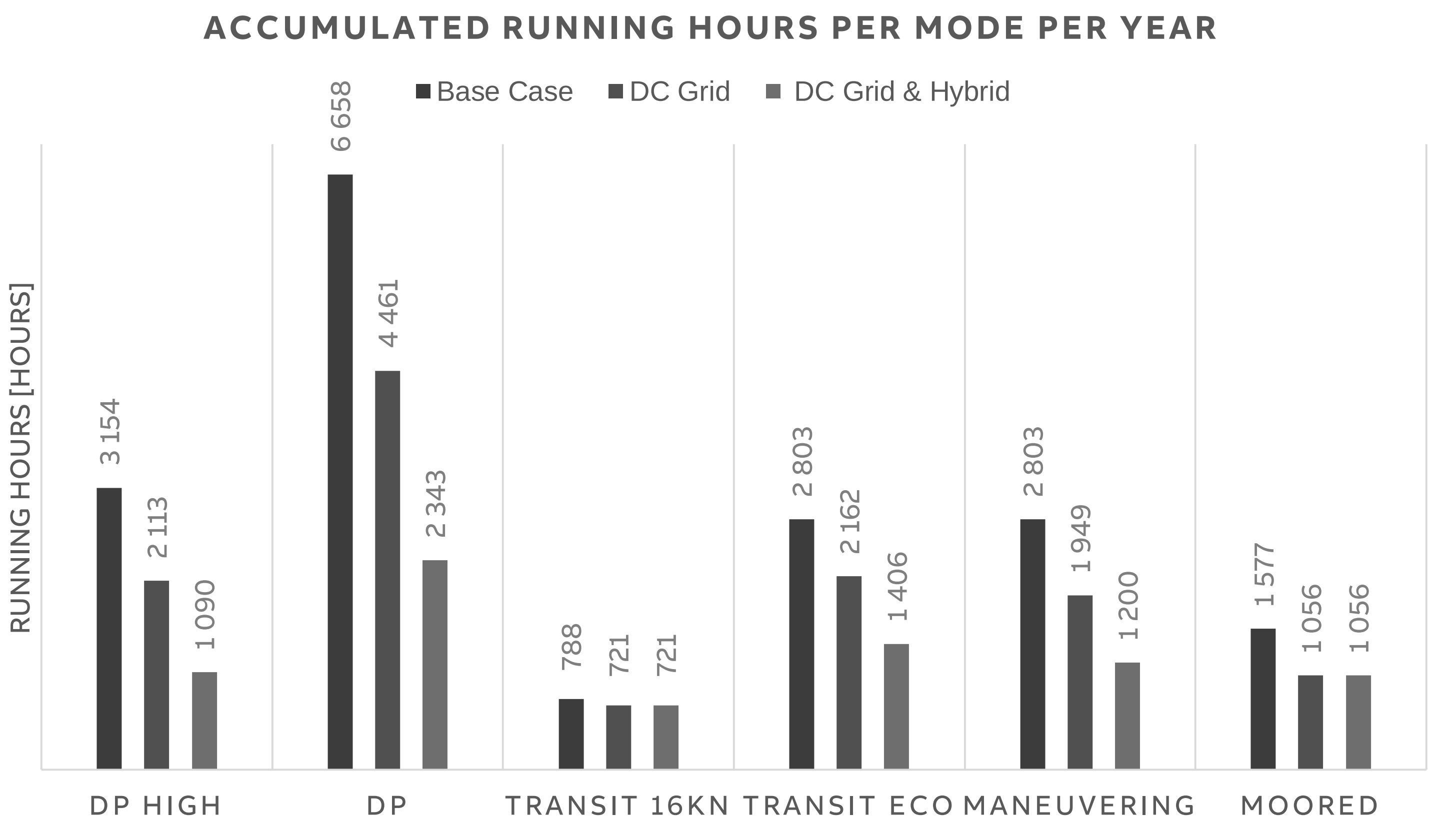


Summary:

- 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 CO_2 reduction is estimated to 1614tons
- The yearly SO_2 reduction is estimated to 589kg

Submarine Rescue Vessel Case Study

Engine running hours



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

	DC	DC + Battery
Reduction in Fuel Consumption	317	509
MDO Cost [USD/Ton]	560	560
Fuel Spend Savings [USD]	**177 779**	**285 111**
Reduction in Running Hours	5 320	9 966
Maintenance Cost [USD/Hr]	17	17
Maintenance Savings [USD/Yr]	**90 446**	**169 429**
Total Savings [USD/Yr]	**268 225**	**454 540**

Link to xl file

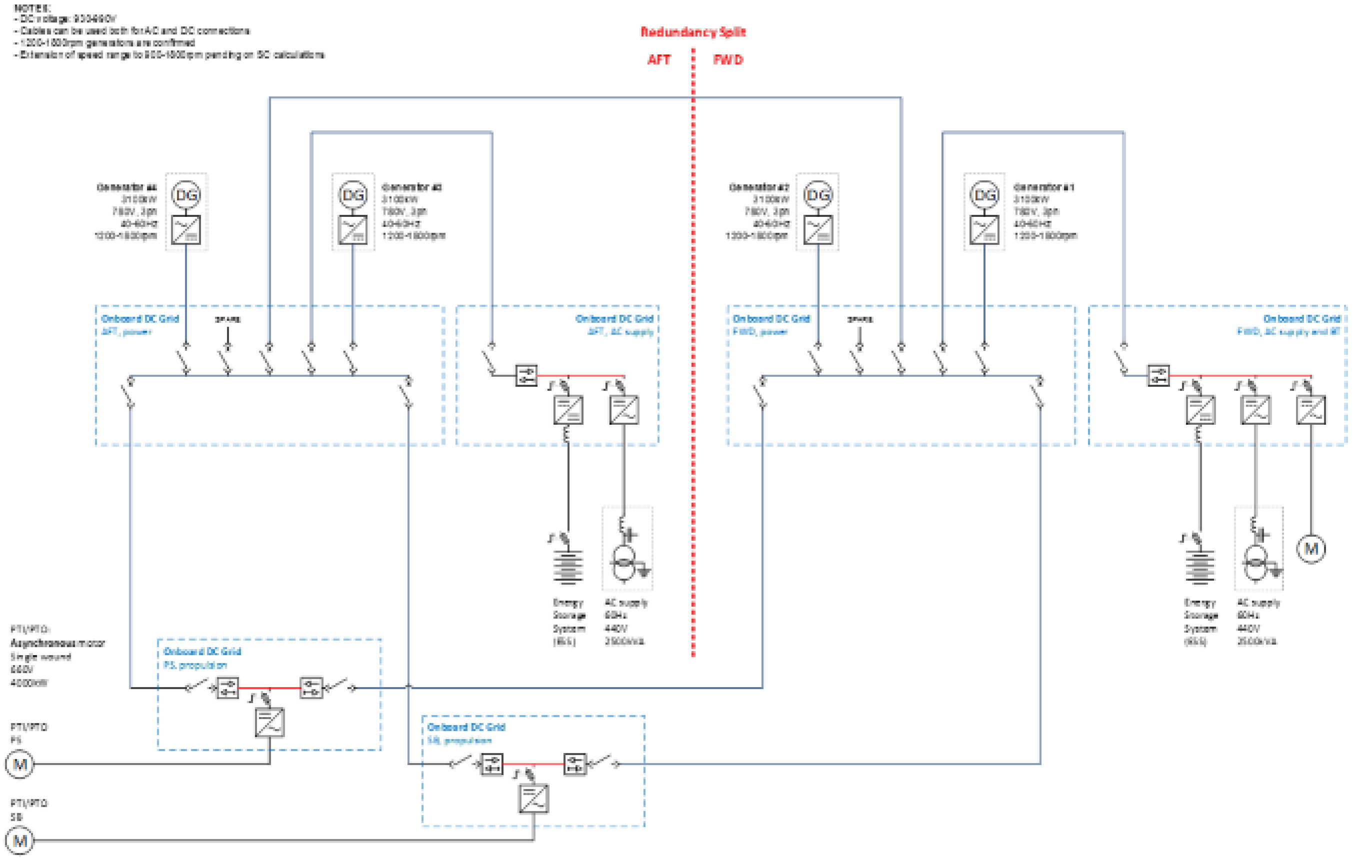
Case Study
Frigate CODOE System Design

Onboard DC Grid

Frigate CODOE Example – Single line Diagram

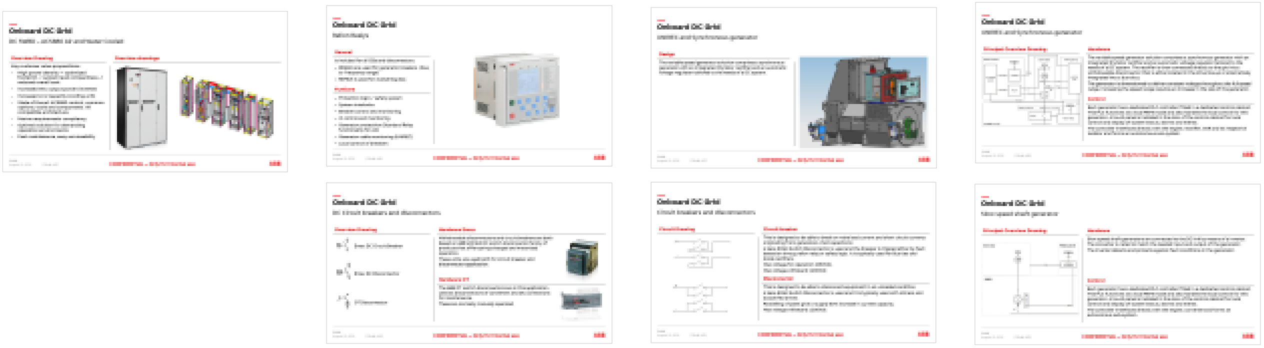
Overview – System Topology

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 <u>without</u> 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



Onboard DC Grid

Frigate CODOE Example – Single line Diagram



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