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ICDCM 2021

Conceptualization of the MVDC Power System of Ultra-Deep Sea HyDrones

Johann W. Kolar, David Menzi, Jonas E. Huber

Swiss Federal Institute of Technology (ETH) Zurich
Power Electronic Systems Laboratory
www.pes.ee.ethz.ch

July 19, 2021

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… Enabling the "Race to the Bottom"

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Outline

- *Introduction*
- *Future E-HyDrone Concept*
- *DCX-Based DC Power Supply*
- *Multi-Objective Optimization*
- *System Dynamics*
- *Conclusions / Outlook*

Acknowledgement
P. Czyz
T. Guillod

ROV / HyDrone

Concept
Classification
Applications

Classification of Underwater Vehicles

- ROV — Remotely Operated Underwater Vehicle | Connected to Surface Vessel via Umbilical
- AUV — Autonomous Underwater Vehicle

Source: SCHMIDT OCEAN INSTITUTE

- Oceans Cover 71% of Earth´s Surface | 5% Explored
- Global Annual ROV Market — $3.5 Billion in 2020 / 11.5% CAGR in 2021...2026 RESEARCHANDMARKETS THE WORLD'S LARGEST MARKET RESEARCH STORE
- 74% Increase in AUV Demand in 2022

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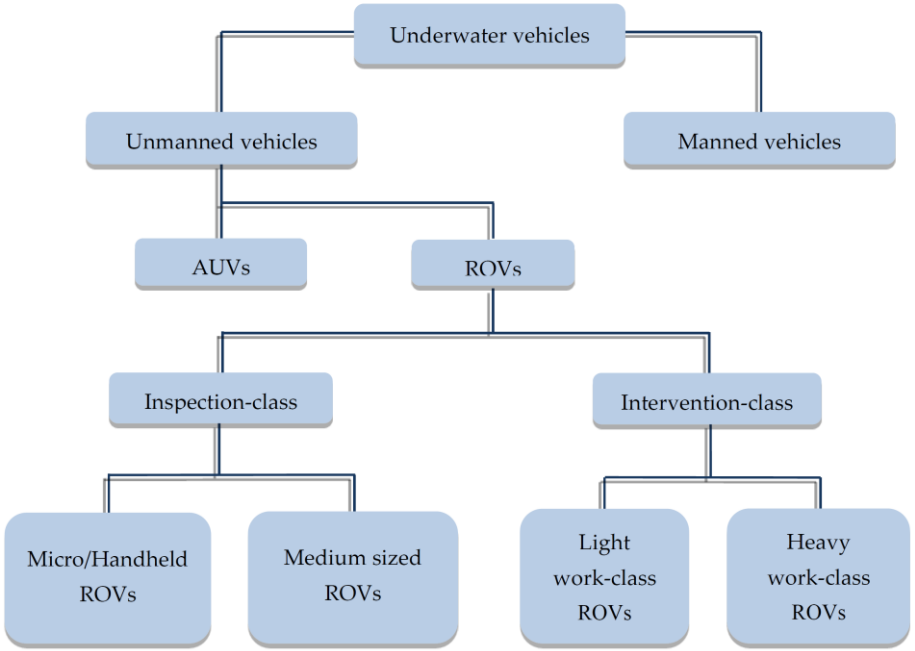

Source: Capocci, et al. / 2017 MDPI

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Work-Class ROV

- Thrusters / Manipulators / Instruments
- Lights / Video Camera

SPECIFICATIONS	
Depth rating	3000 msw (option to 6000 msw)
Length	2200 mm
Height	1500 mm
Width	1325 mm
Launch weight	2100 kg
Forward speed	> 3 knots
Thrust forward	325 kgf
Thrust lateral	290 kgf
Thrust vertical	225 kgf
Payload	225 kg
Through frame lift	1 Te
Tooling circuit	24 kW
Manipulator circuit	5 kW
Instrumentation power - 24 VDC	2 kW
Instrumentation power - 110 VAC, 50 Hz	2 kW
Depth accuracy & resolution	0.01% / 1 x 10^{-8}
Heading accuracy & resolution	±1° / 0.351°

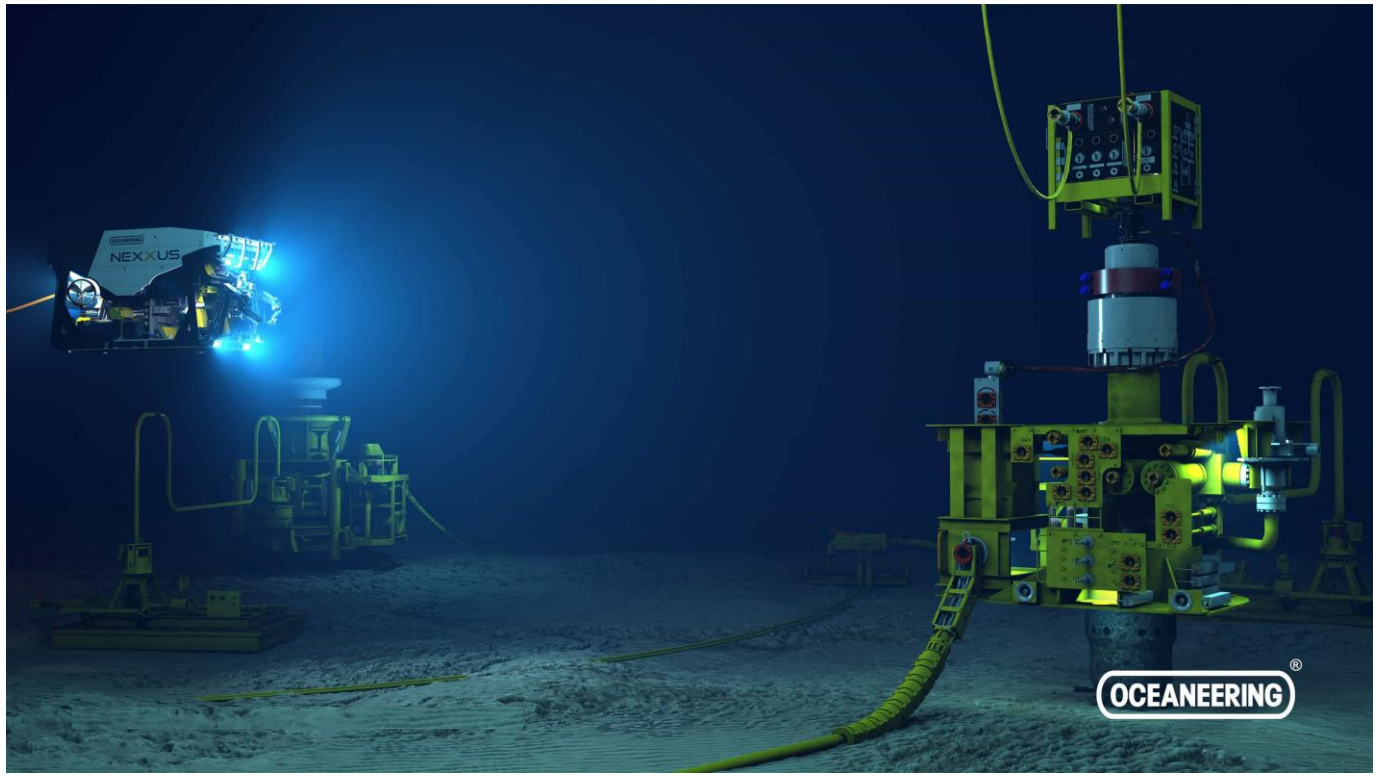
Source: SAAB

SYSTEM POWER REQUIREMENTS	
Input	3-phase 380-480 VAC, 50/60 Hz
ROV + Tooling	75 kVA
TMS	8 kVA
TMS propulsion (option)	28 kVA
LARS (typical)	150 kVA

- TMS — Tether Management System
- LARS — Launch and Recovery System

Subsea IMR — Inspection / Maintenance / Repair

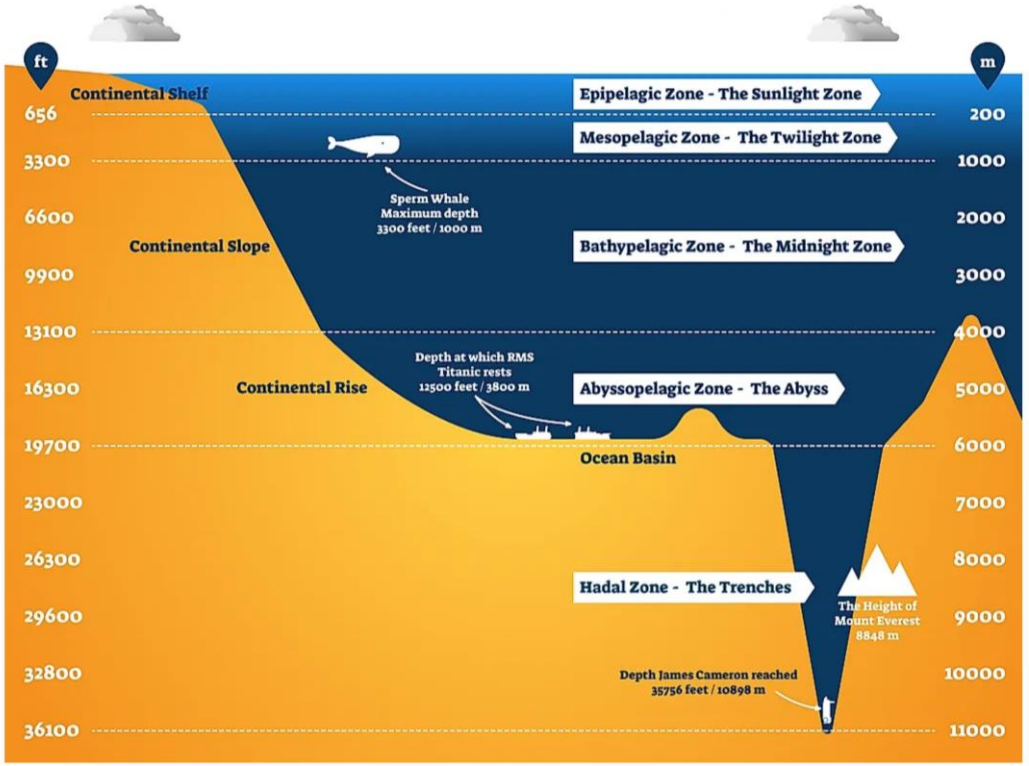
- Complex / Inaccessible Subsea Infrastructures → Inspections & Interventions
- Oil & Gas Industry → Well & Infrastructure Diagnostics | Remediaton of Damaged Wells etc.



- Operation Depths > 2500m

Scientific Exploration of Ocean Depths – 1/2

- Surveys of Submarine Volcanoes / Hydrothermal Vents / Subduction Zones
- Collection of Seabed Sediments / Microorganisms

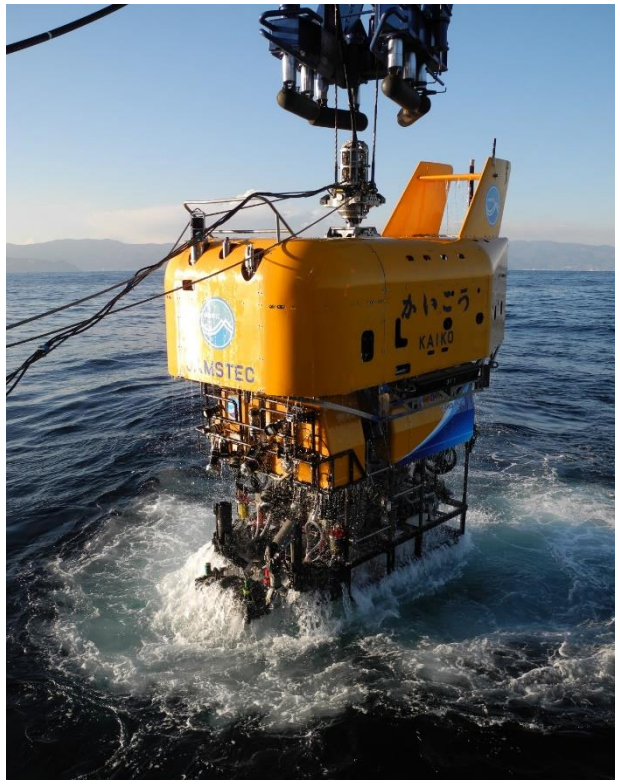


▼ Deep Ocean

Source: VectorMine/Shutterstock.com

- 5 Zones / Deepest Location → "The Challenger Deep" @ 11´034m (≈ 4°C) | 3´700m in Average

Scientific Exploration of Ocean Depths – 2/2



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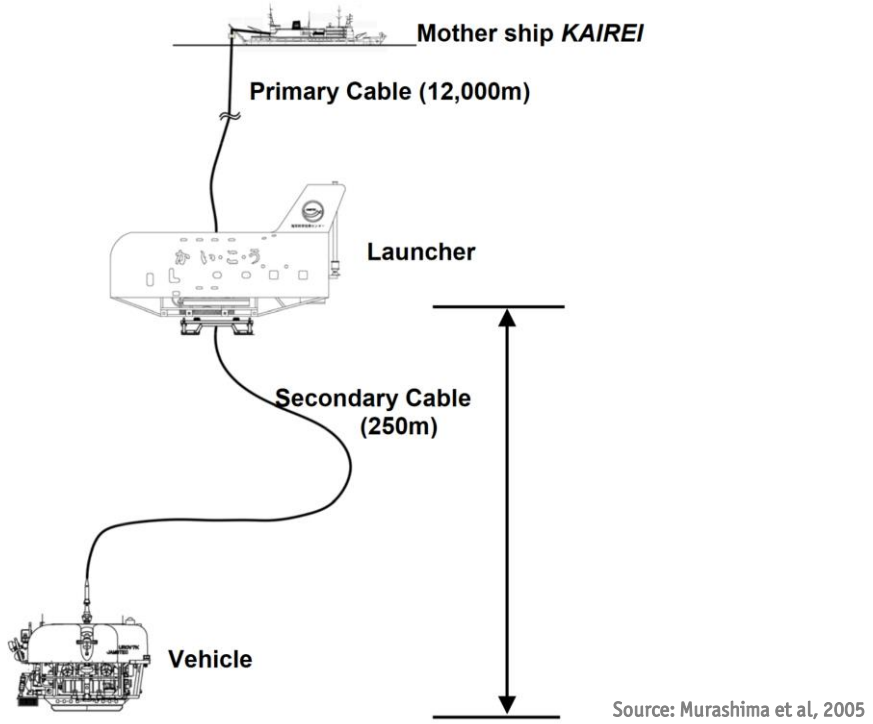
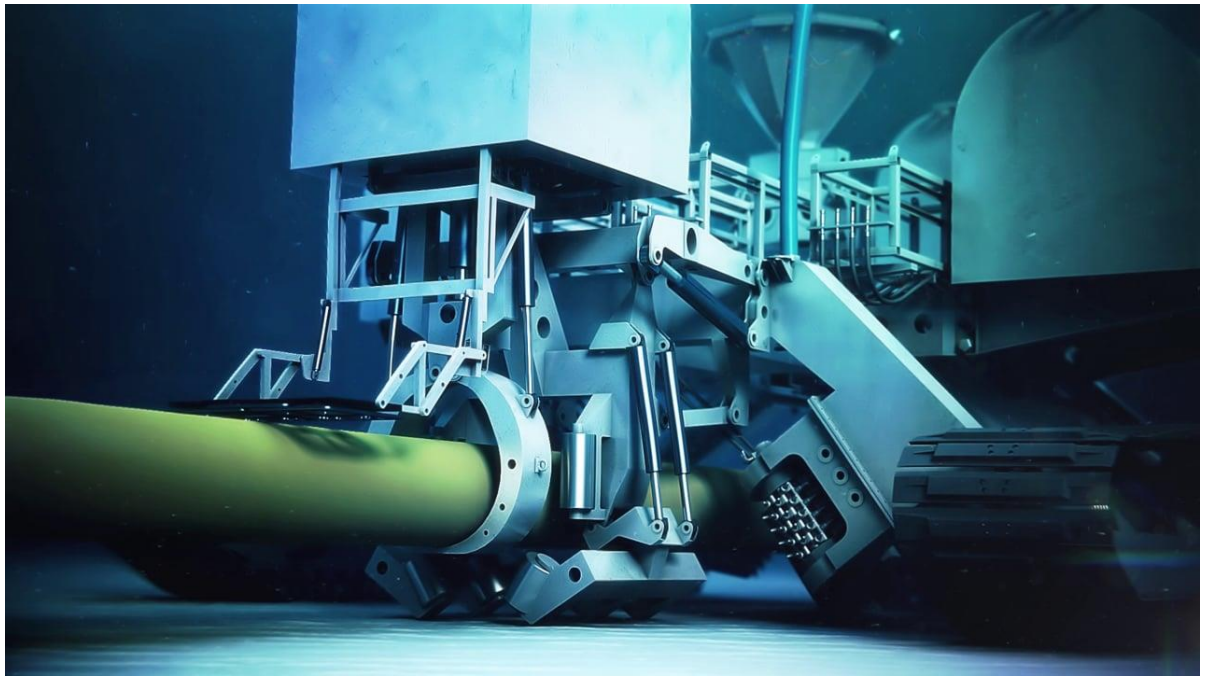


Source: Murashima et al, 2005

- Full Ocean Depth ROV Kaiko / JAMSTEC (Launcher & Vehicle) → 10´911m / Lost During a Typhoon
- New 11´000m-Class ROV (ABISMO — Automatic Bottom Inspection and Sampling Mobile)

Seabed Interventions – 1/2

- Burial of Subsea Pipelines and Cables
- Jet Trenching ROVs | Ploughs | Mechanical Trenchers — x 1000m Operation Depth



Source:
DEEPOCEAN

- World´s Most Powerful Trencher (T3200 / 2.4MW / DeepOcean)

Seabed Interventions – 2/2

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Source: DEEPOCEAN

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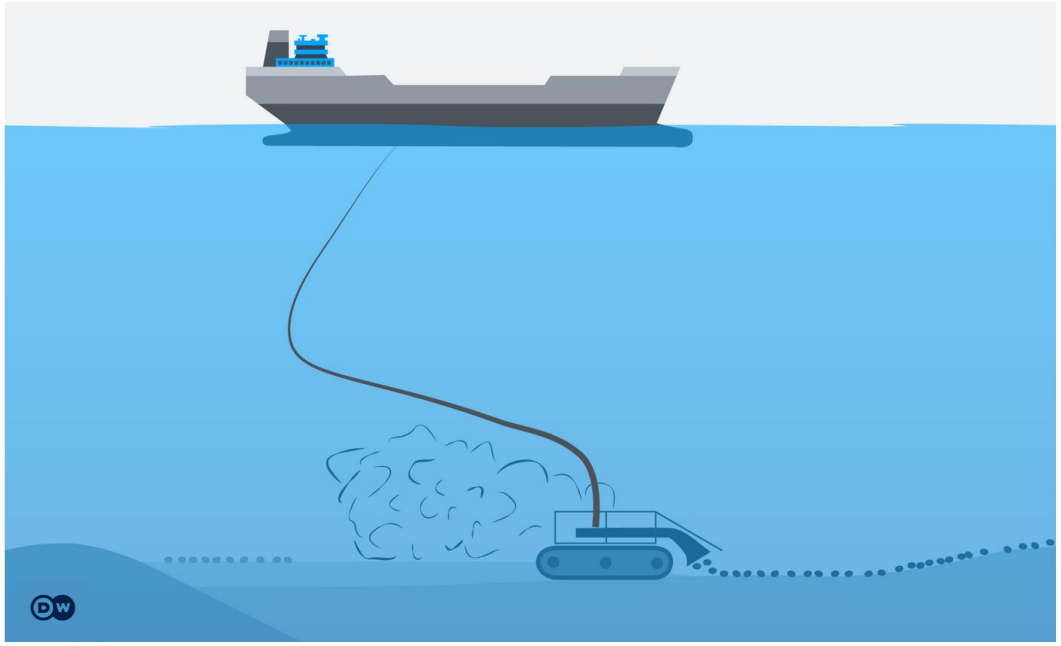
Deep-Sea Mining Vehicles – 1/2

- Suction of Polymetallic Nodules (Mn, Co, Cu, etc.) @ Seabed (4000...6000m)
- Subsea Crushers and Pumps for Transportation of the Minerals to Supporting Vessel



Source: www.hydrographica.org

- Potential Serious Threat to Global Oceans !

Deep-Sea Mining Vehicles – 2/2

- Suction of Polymetallic Nodules (Mn, Co, Cu, etc.) @ Seabed (4000...6000m)
- Subsea Crushers and Pumps for Transportation of the Minerals to Supporting Vessel

Source: GSR

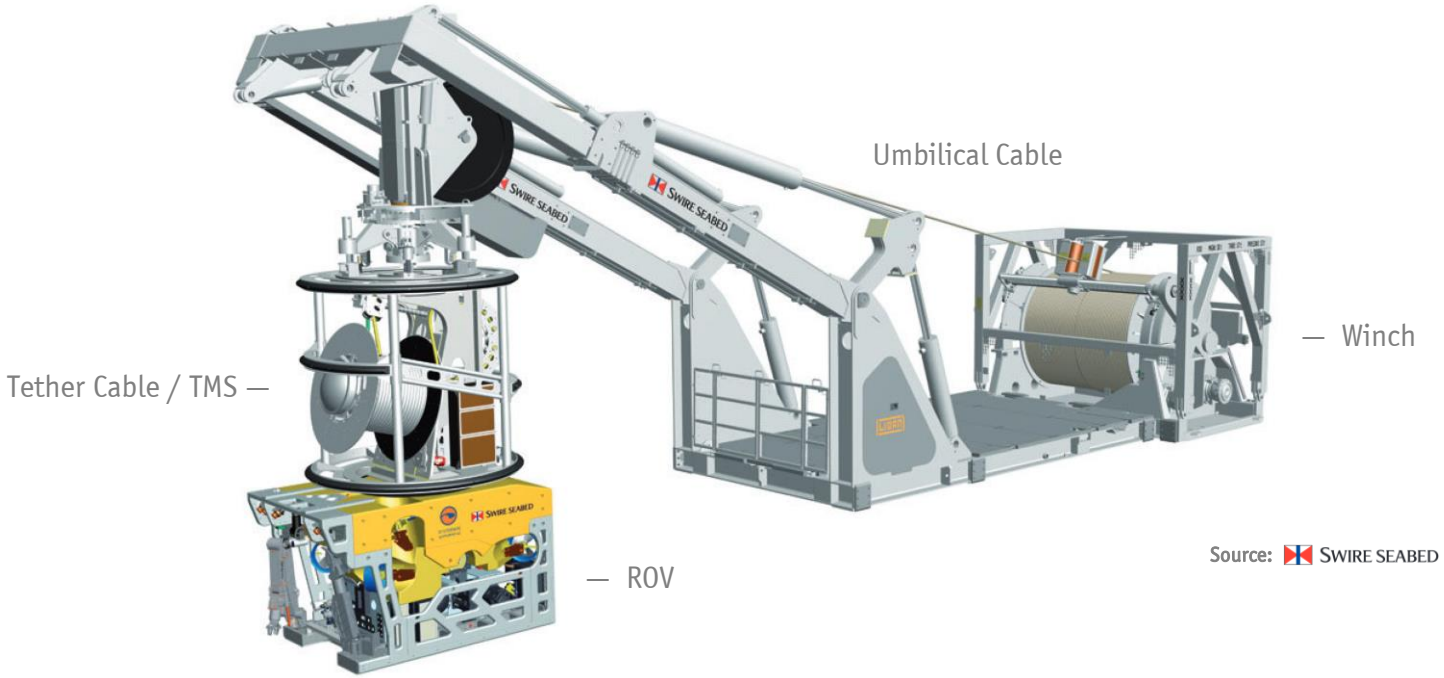
- Patania II 25t Robot "Nodule Collector" (tested @ 4500m)

ROV Power Supply System

Architectures
AC vs. DC Supply
Thermal Load on Umbilical
E-HyDrones

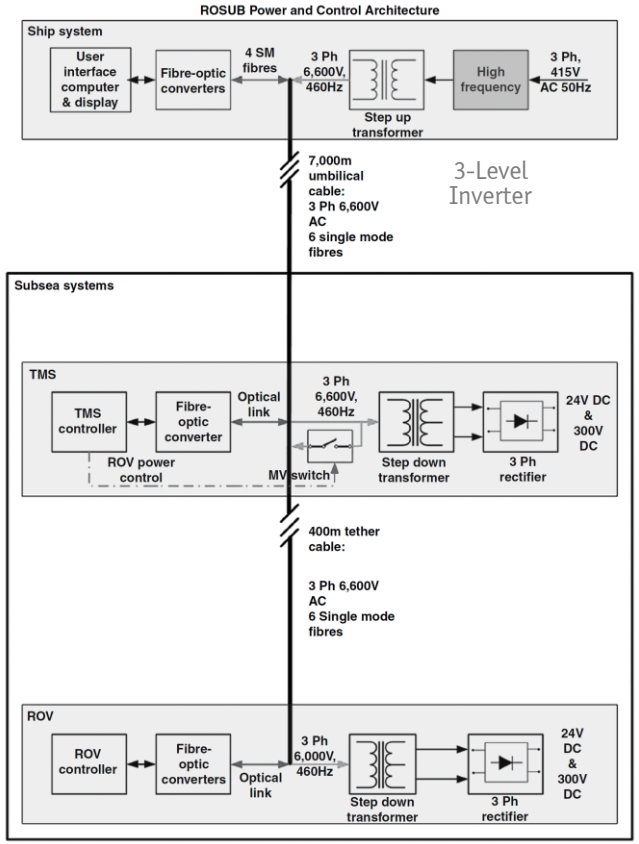
ROV Deployment

- Launch and Recovery System (LARS) & Tether Management System (TMS)
- Heavy Duty Electro-Optical Umbilical / Soft Neutrally Buoyant Tether



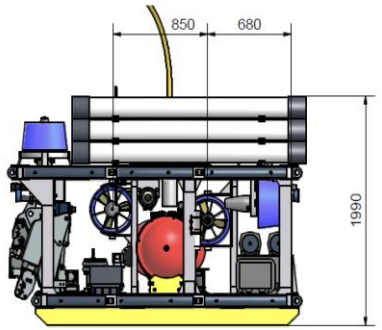
- Winch — Driven by Hydraulic or Electric Power (Active Heave Compensation)
- TMS — Decouples Lightweight Tether from Heavy Duty Lifting Cable / Umbilical

Work-Class ROV AC Power Supply System - #1



Source: Raju et al. www.sut.org

- 3-Φ 415V / 50Hz → 3-Φ 6.6kV / 460Hz
- 6´000m Umbilical / 400m Tether

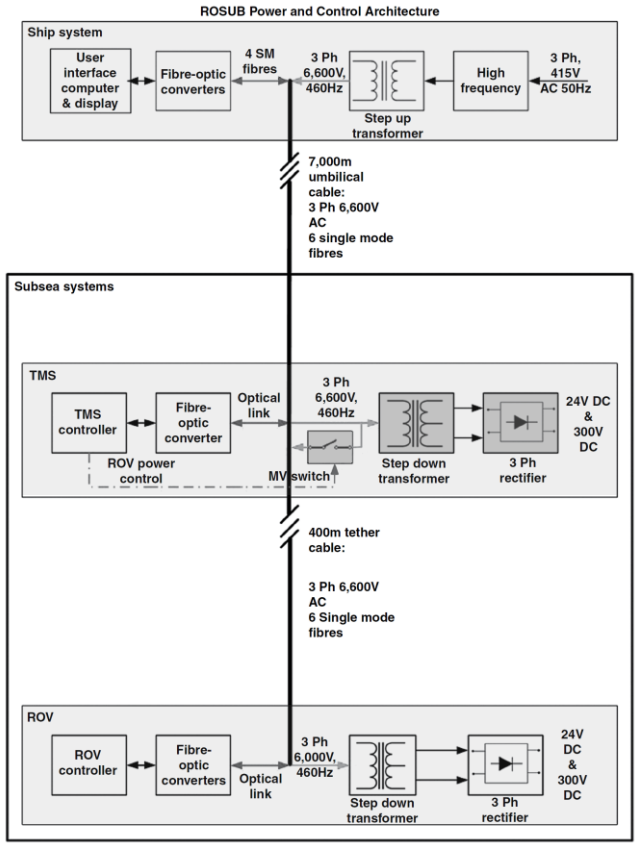


20kW @ TMS
70kW @ Vehicle

- ROV Isolated by MV Switchgear in TMS
- 7 BLDC Motor Thrusters / DC 300V Inverter Supply
- DC 24V Auxiliary Supply

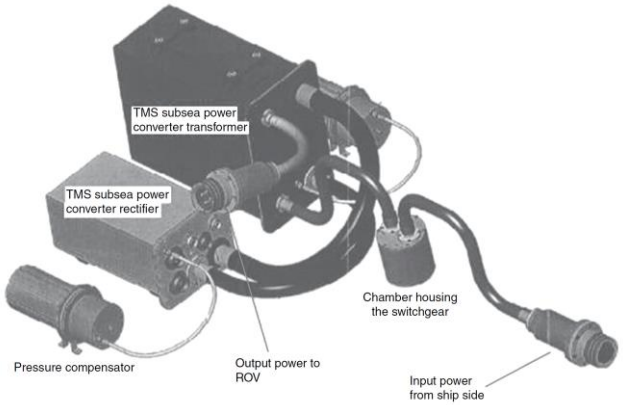
- ROSUB 6000 Electric & Control System Architecture

Work-Class ROV AC Power Supply System - #1



Source: Raju et al. www.sut.org

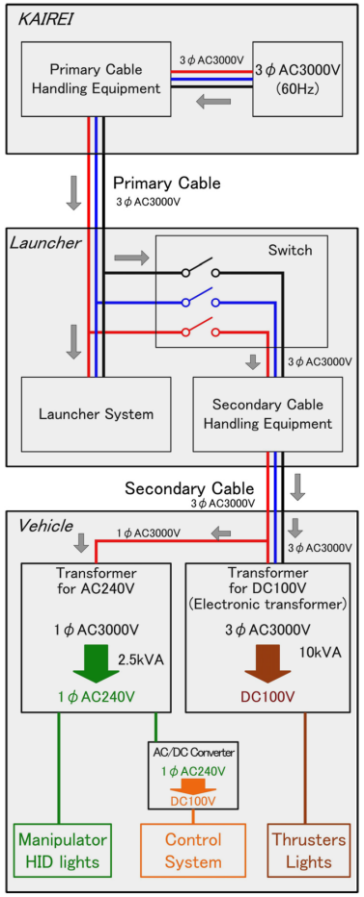
- 3-Φ 415V / 50Hz Ship Power System
- 6´000m Umbilical / 400m Tether
- 3-Φ 6.6kV / 460Hz



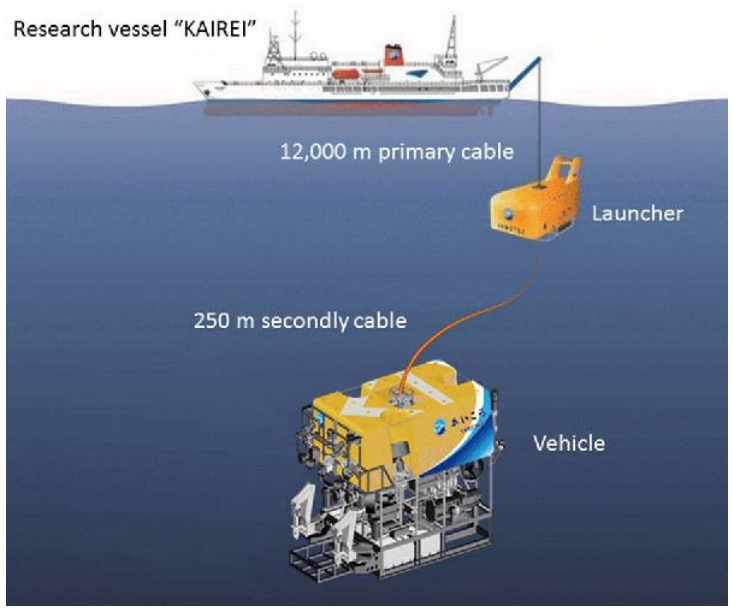
- 600bar @ 6000m → Hydraulic Pressure Compensation
- Int. Pressure Slightly > Ext. Hydrostatic Pressure
- No Thick-Walled Enclosures

- ROSUB 6000 Electric & Control System Architecture

Work-Class ROV AC Power Supply System - #2



Source: Murashima et al, 2005

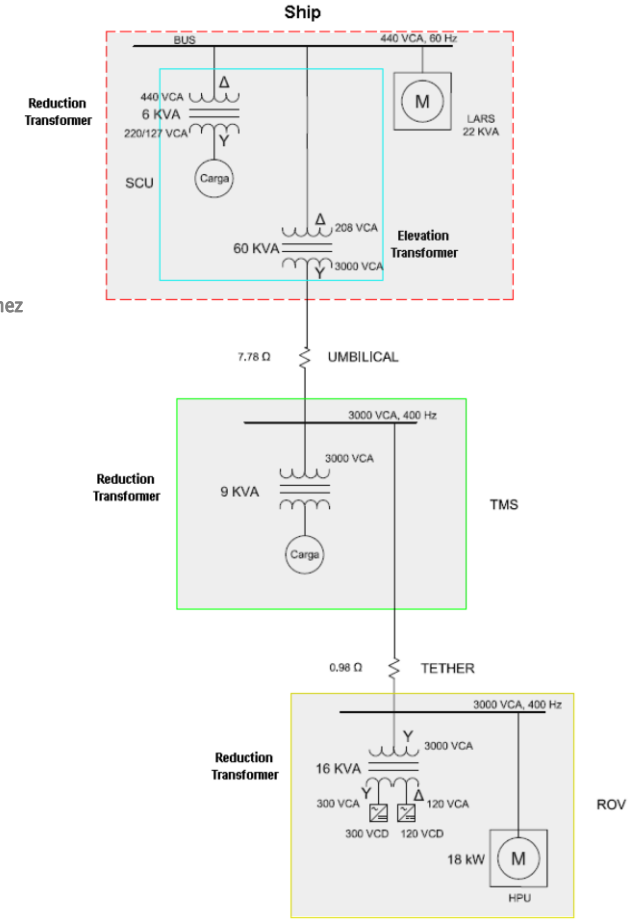


Source: Nakajoh et al, 2016

- KAIKO 7000 Electric Power System

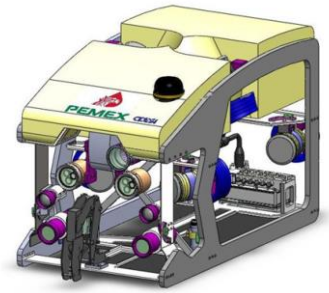
- 3-Φ AC 3000V / 60Hz Primary & Secondary Cable
- 1-Φ AC 240V / 2.5kVA & DC 100V @ Vehicle
- Passive XFRM & 30kg Electronic XFRM
- Vehicle Disconnect Switch

Work-Class ROV AC Power Supply System - #3



Source: Salgado-Jimenez CIDESI /Mexico, 2010

- AC 3-Φ 440V / 60Hz @ Ship
- AC 3-Φ 3kV / 400Hz / 60kVA Overall @ TMS & ROV

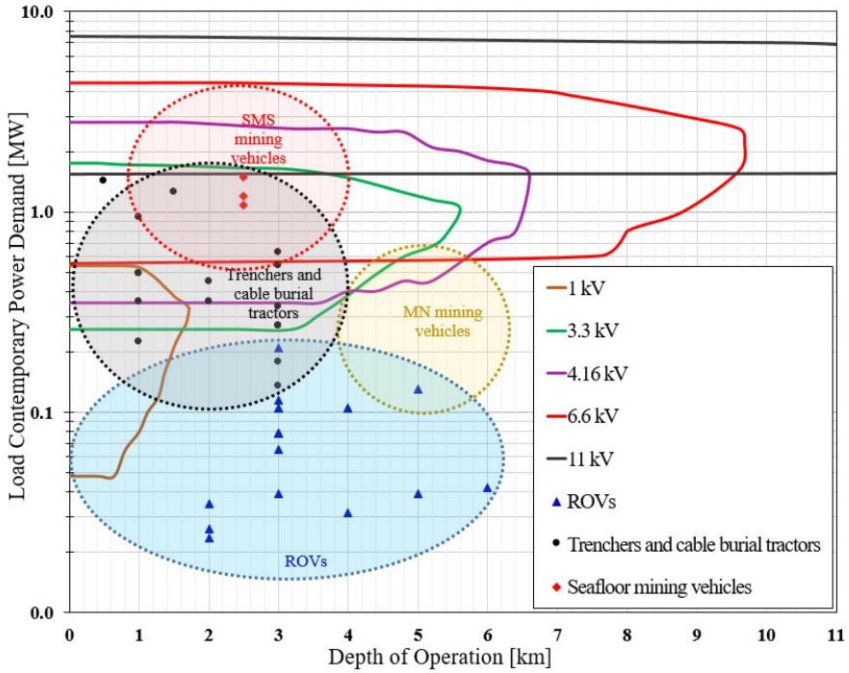


- Reduction XFRM AC 3kV → AC 300V & DC 300V /120V
- 18kW HPU (Hydraulic Power Unit)
- Control Electronics in Pod (30mm Wall)

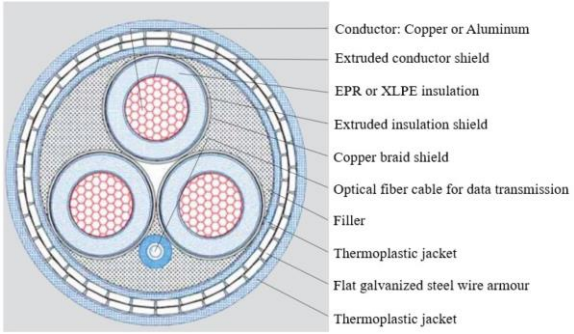
- Concept Study for Mexican Oil Industry / 1.4m x 1.2m x 0.9 m / < 2000m

AC Power Supply Voltage Levels

- Consideration of Voltage Drop / Power Loss / Capacitive Reactive Current / Costs / Mech. Tension
- ROVs | MN — Mn Nodule Collectors | Seafloor Trenchers | SMS — Seafloor Massive Sulfide Mining Machines
- 4000...6000m Water Depths



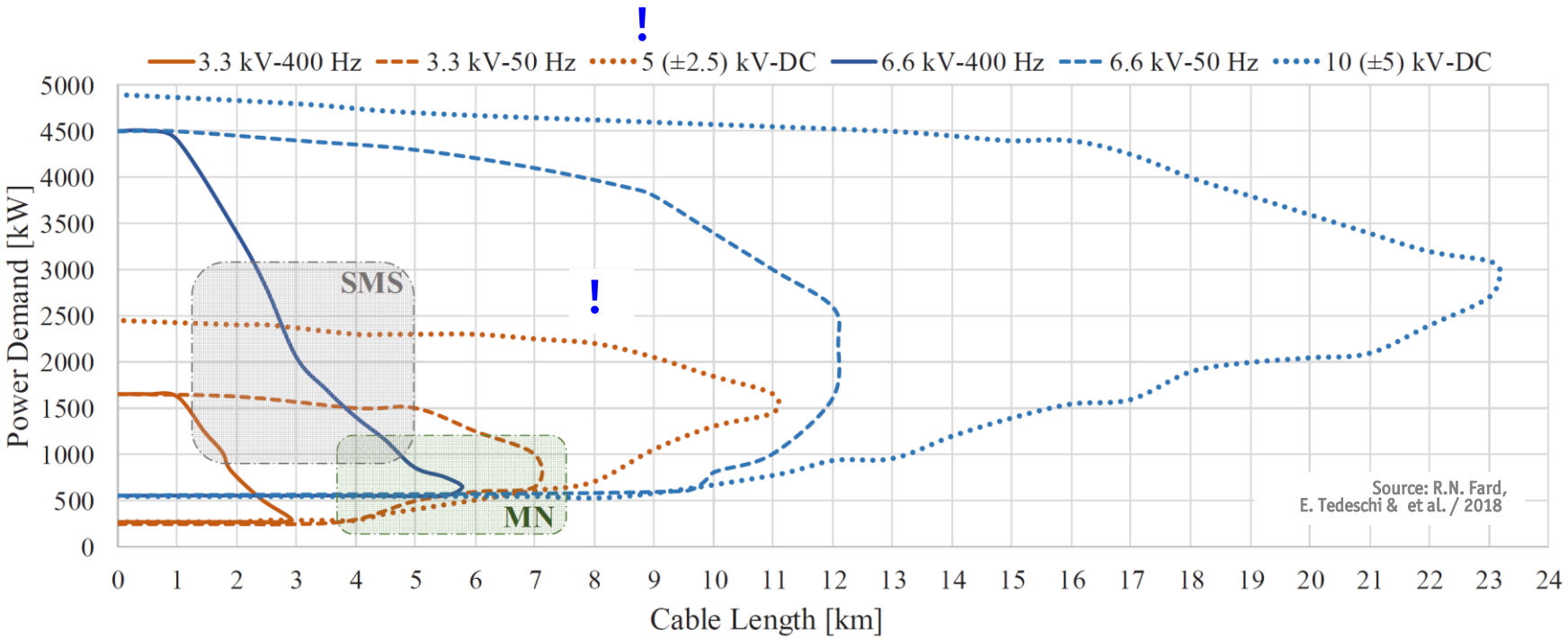
Source: R.N. Fard, E. Tedeschi & et al. / 2018



- 50Hz AC / 10% Max. Voltage Drop
- 1kV @ 10...240mm² | 3.3kV @ 25...240mm² | 6.6kV @ 25...400mm² | 70...400mm² @ 11kV

AC vs. DC Power Supply

- AC @ 50Hz / 60Hz or Medium-Frequency (MFAC) vs. DC
- MFAC → Lower Transformer Volume & Weight / Larger Voltage Drop / Shorter Distances
- DC → High Efficiency / Low Voltage Drop / Small & Light Cable



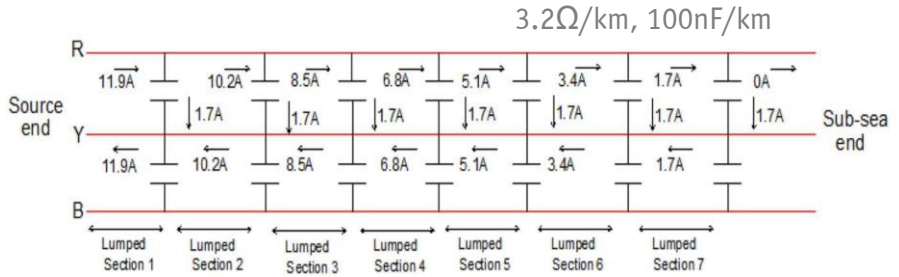
- 3.3kV & 6.6kV @ 25...240mm²
- 10% Max. Voltage Drop | 50% Min. / 80% Max. Cable Load

Thermal Analysis of Winch–Wound Umbilical – 1/2

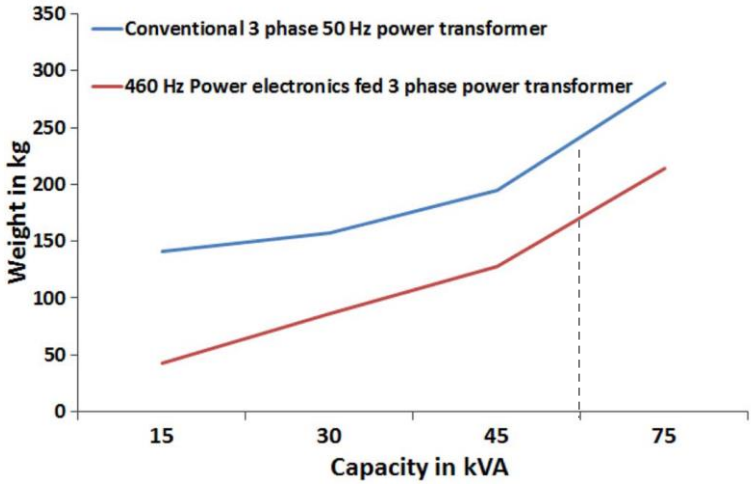
- ROSUB 6000 — 7000m / 37.5mm Diameter Armored Electro-Optical Umbilical (EOU)
- Multi-Layered Arrangement of EOU on Winch Impairs Heat Transfer
- ROV Operation in Depths < EOU Length
- Unwound Portion → Ampacity Derating

Source: Vedachalam et al. www.sut.org

EOU Lumped Cap. Model —



50Hz vs. 460Hz Transformer



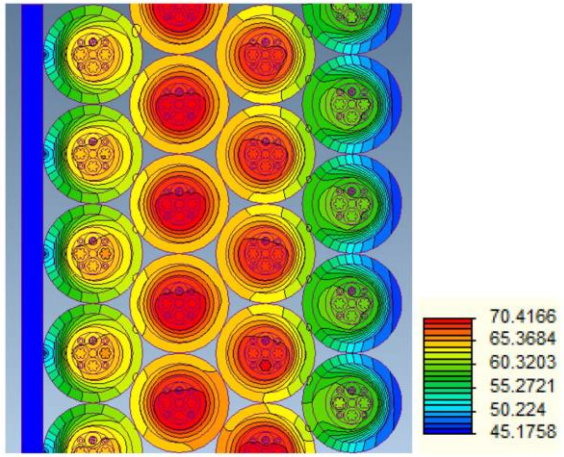
3m Inner Drum Diameter

Source: DECKWIN MARINE CO.

- Higher Frequency AC Operation → Reduced XFRM Volume BUT Higher Cable Cap. Charging Current (!)

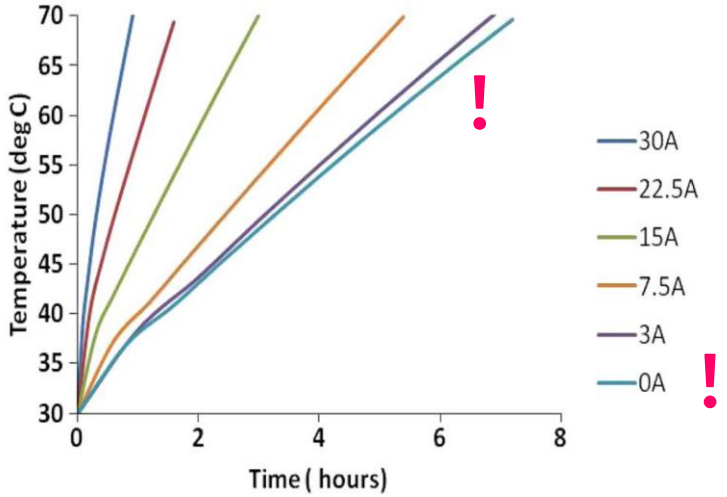
Thermal Analysis of Winch–Wound Umbilical – 2/2

- EOU Designed for 30°C Ambient / 70°C Max. Conductor Insulation Temperature
- 182h of Cooldown Time (70°C → 40°C) of 32-Layered Winch-Wound EOU
- Non-Uniform Current Distribution / Heat-Transfer / Heating
- Remaining Winch Layers Determine Operation Window



Temperature Rise in °C for
4-Layer Configuration (T_{amb}=30°C)

Source: Vedachalam et al.
www.sut.org



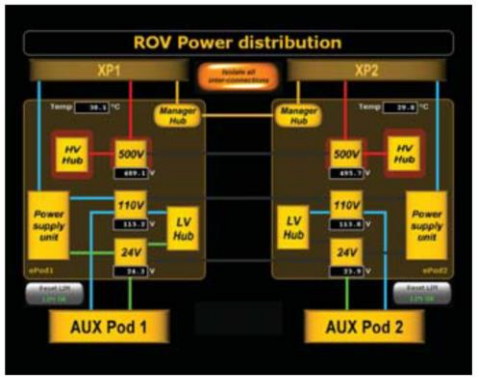
23 Layer EOU Temperature Dependent on
Loading Condition @ AC 6.6kV / 460Hz

- 3 h Operation at Full Ampacity (30A) / Max. 8 h Operation Under No-Load Condition

Full-Electric HyDrones

Electric ROVs

- Hydraulic Manipulators / Thrusters → Electric Systems
- 50% Fewer Moving Parts Compared to Hydraulic Systems → Lower Maintenance $$$
- 20% More Compact / 20% Lower Weight → Smaller Diameter Umbilical / Smaller Vessel
- Higher Efficiency → 20% More Thrust



Source: SAAB

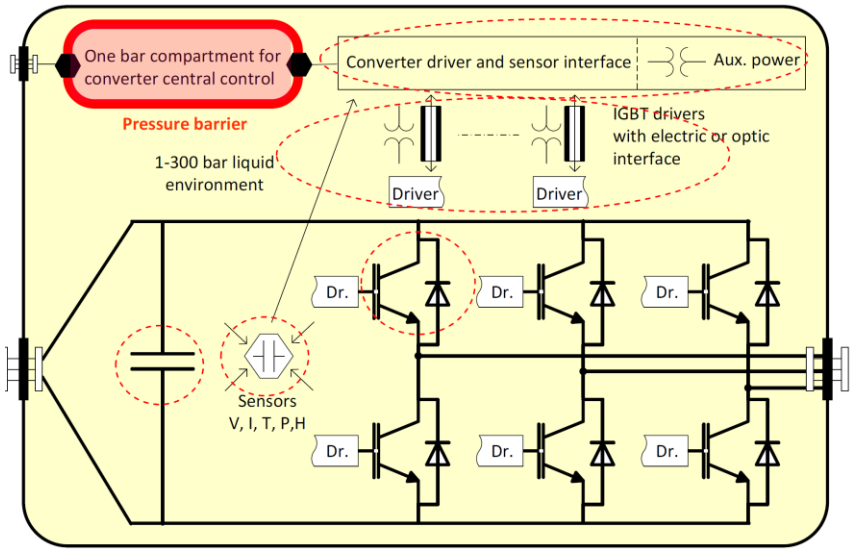
Additional Hydraulic Power Unit
for Hydraulic Tools (50l/min @ 210bar)

- Example – SAAB Seaeye Jaguar — Fully Redundant Throughout the Vehicle
- 2 Separated Power Distribution Systems / 2 Electronics Pods
- 4 Horizontal / 4 Vertical DC 500V BLDC Thrusters (Thrust Vectoring)
- AC 3kV / 800Hz Single-Phase Supply → 2 XFRM @ ROV → AC 110V / 50Hz | DC 500V | DC 24V

Remark Pressure Housings

- Air or Gas Filled Components → Would Implode in Large Depths (e.g. 6000m → 600bar)
- One-Atmosphere Housings → Maintain Constant Inside Pressure / Cylindrical or Spherical Shape
- Pressure Balanced Housings → Int. ≈ Ext. Pressure / Oil Filled – No Voids / Not Shape (Cooling) Restricted !

Source: M. Hernes SINTEF



Source: SAAB

Electronics Compartment of Seaeye Jaguar

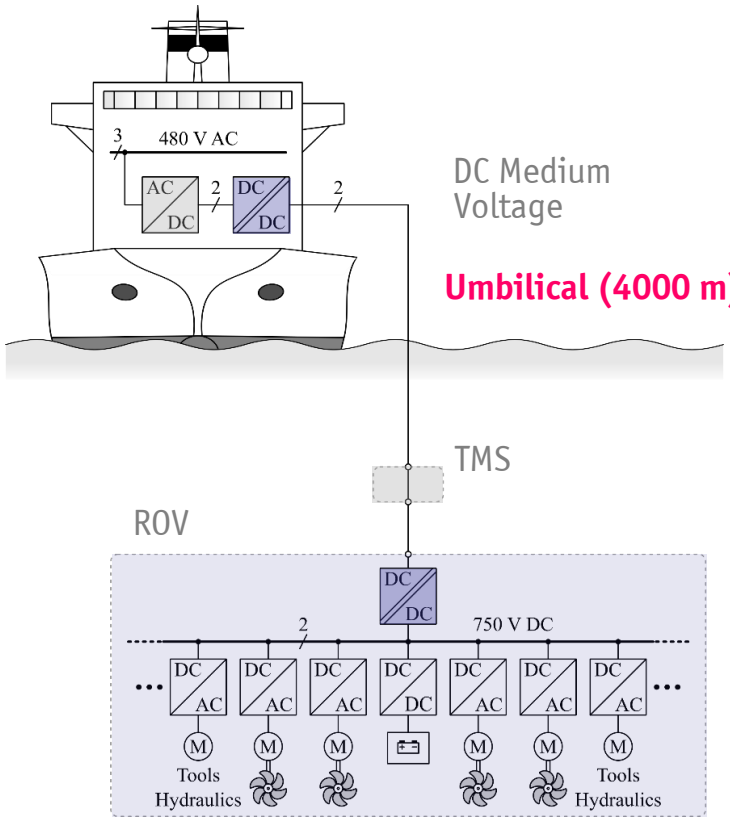
- Research on Pressure-Tolerant Power Electronic Components (300 bar) @ SINTEF
- IGBTs → Sw. Behavior Unaffected / Chip Interface Needs to be Protected from Surrounding Liquid
- Pressure Affects BH of Magnetic Cores & Impairs Self-Healing of PP Film Cap. → Voltage Derating

Analysis of E-HyDrone DC Power Supply System

DC Power Supply Architecture
DC-Transformer Concept
System Optimization

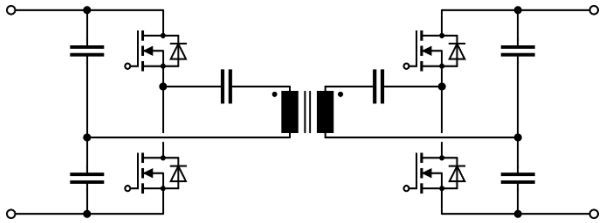
Medium-Voltage DC ROV Power Supply

- Concept Study for 50kW ROV | Shipboard 3-Φ PFC Rectifier AC 480V / 60Hz → DC 800V
- DCX DC 800V → DC Medium Voltage | 4000m Umbilical | DCX DC Medium Voltage → DC 800V



- DCX (Shipboard & ROV)

MVDC

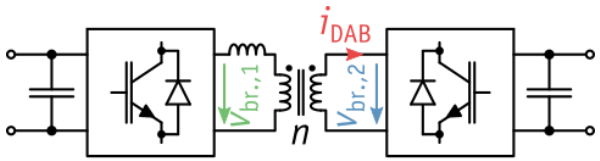


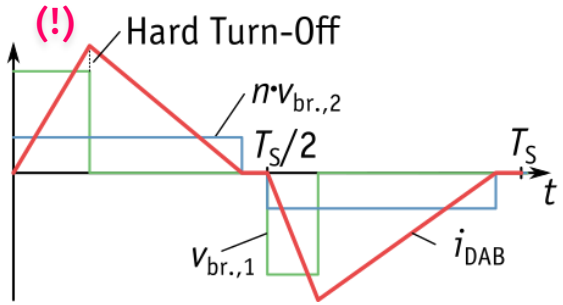
800 V DC

- Multi-Objective Optimization — Umbilical | DCX | System

Realization Options for DC-DC Converters

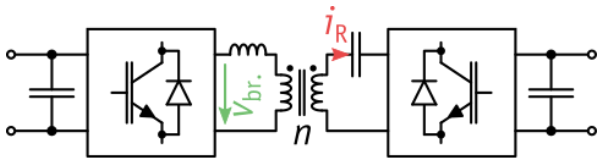
- Dual Active Bridge
- Control-Defined Power Flow
- Can (Must!) Be Controlled

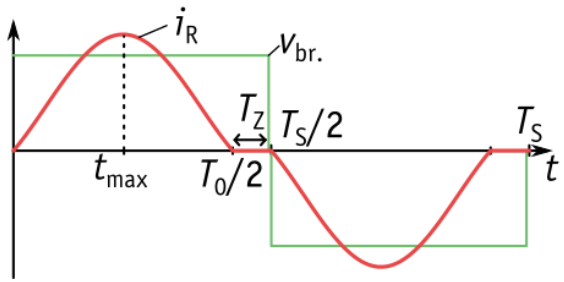




- Triangular Current Mode
- MV-Side ZCS

- DC Transformer ("DCX")
- Series Res. Conv. Operated @ Res. Frequency
- Must Not (Cannot!) Be Controlled

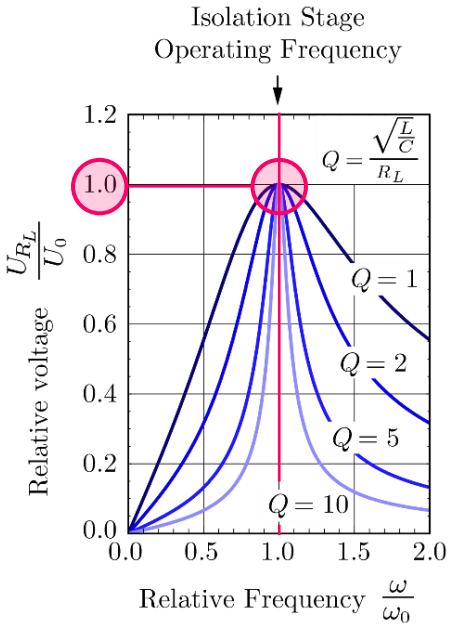


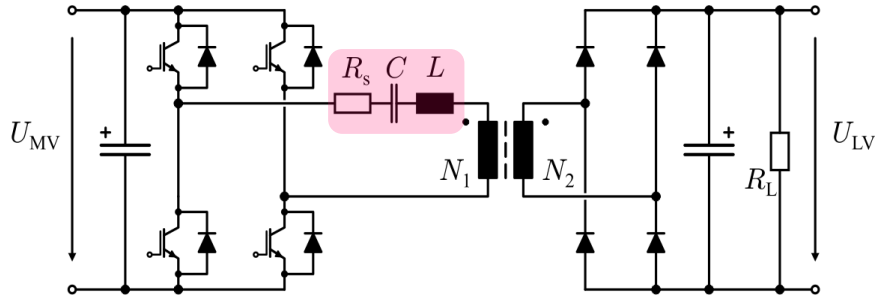


- Reduces Complexity in Multi-Cell Converters
- ISOP Autom. MV-Side Voltage Balancing
- Soft Switching

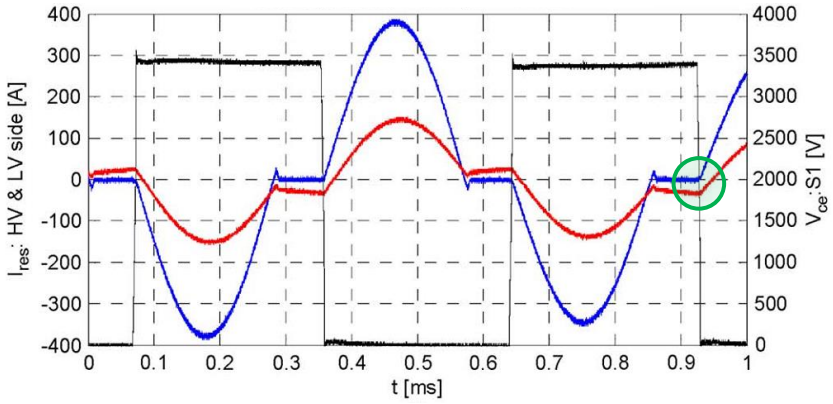
DCX Operating Principle

- **Resonance Frequency ≈ Switching Frequency → "Unity Gain" / Fixed Voltage Transfer Ratio**
- **U_{LV} : U_{MV} Independent of Transferred Power (!)**





Source: Ch. Zhao, 2014/ABB

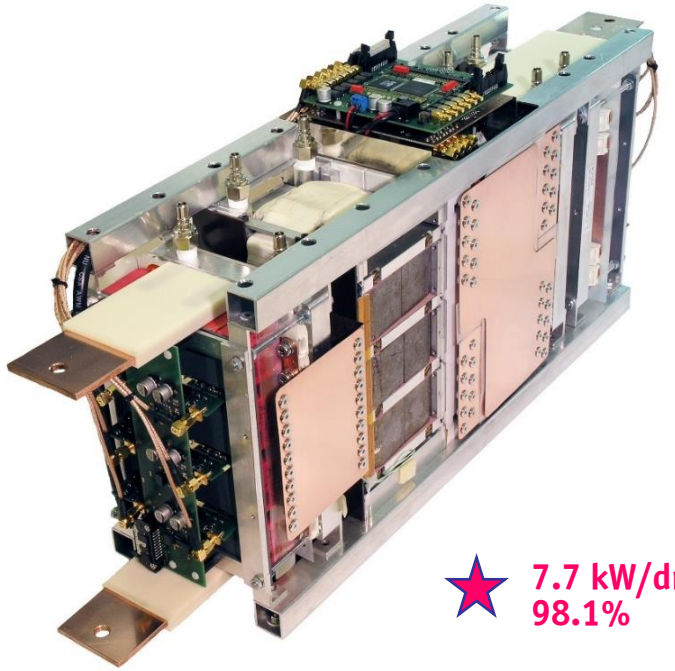


ZCS/ZVS

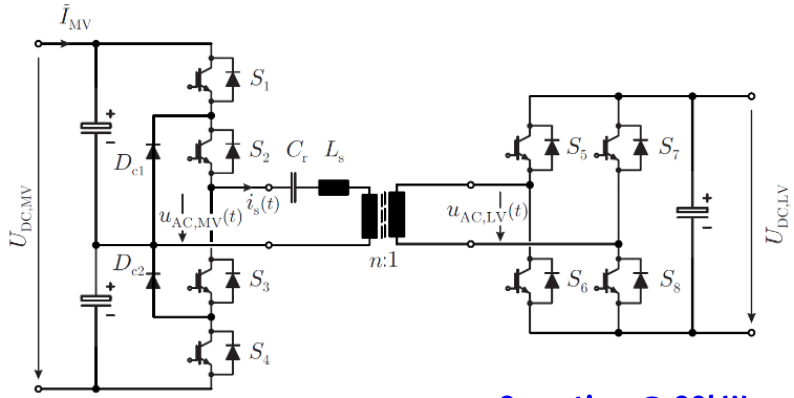
- **ZCS of All Devices**
- **Load-Independent ZVS Using Mag. Current →**

166kW / 20kHz Si IGBT DCX

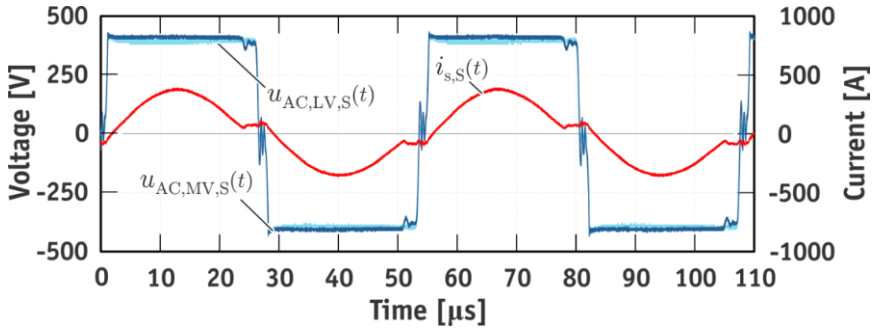
- Half-Cycle DCM Series Resonant DC-DC Converter
- Medium-Voltage Side 2kV
- Low-Voltage Side 400V



7.7 kW/dm³
98.1%

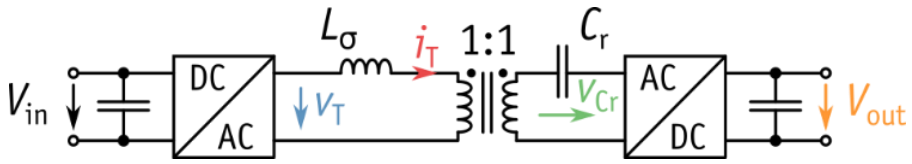


Operation @ 80kW

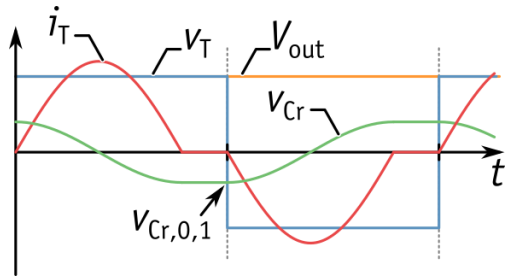


DCX "DC Transformer" Property

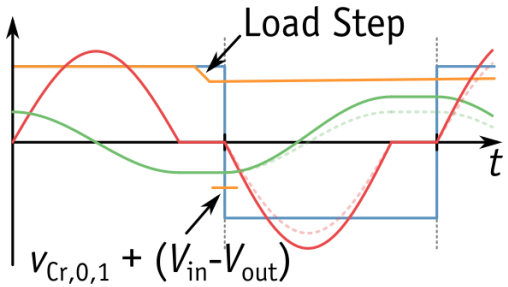
- Analysis of a Load Step
- Source Bridge → Actively Switched
- Sink Bridge → Passive Operation (Diodes)



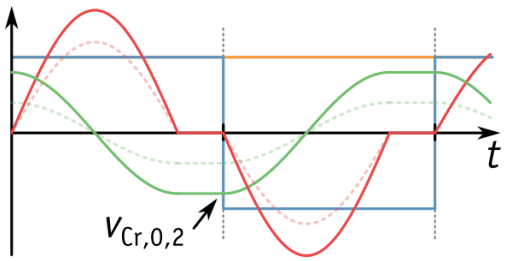
$$\hat{\imath}_{T,1} = \frac{\hat{v}_{Cr,0,1}}{Z_0} \qquad V_{out} = V_{in}$$



$$V_{out} \neq V_{in}$$



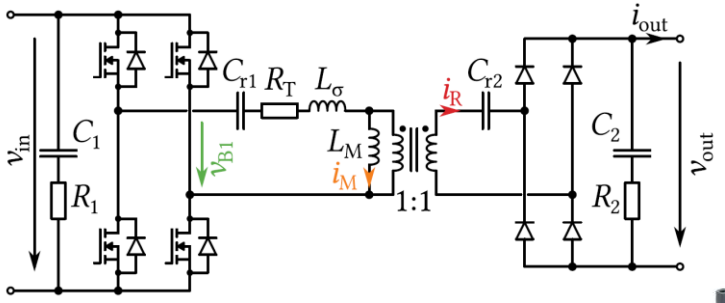
$$\hat{\imath}_{T,2} = \frac{\hat{v}_{Cr,0,2}}{Z_0} \qquad V_{out} = V_{in}$$



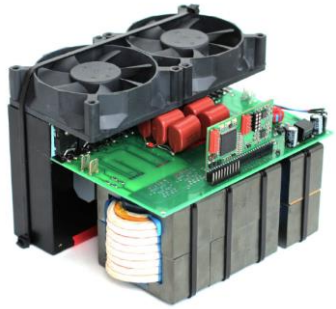
- Load Step → Red. Output Voltage → Larger Res. Circuit Excitation → Larger Res. Current / Power Transfer
- *Converter Acts as "DC Transformer" (DCX) with Certain Dynamics*

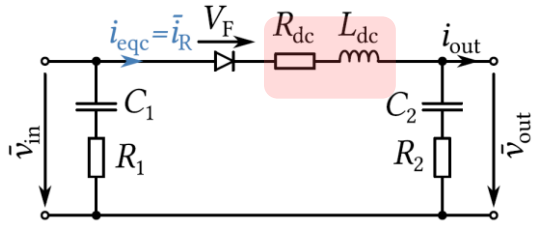
DCX Dynamic Behavior

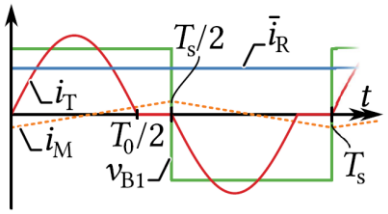
- Dynamically Equivalent LC-Circuit with Equal Local Avg. Power Transfer
- Equal Energy Storage Related to Res. Current Peak Value
- Equal Ohmic Losses

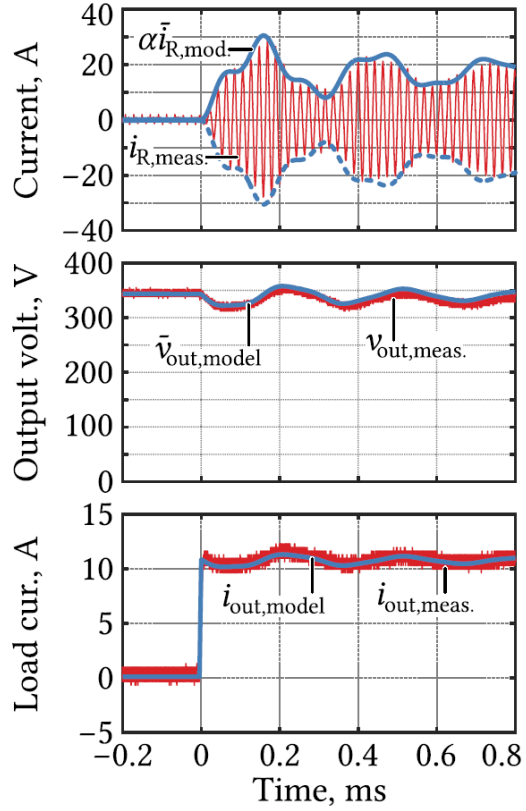


U_{in} = 350V
U_{out} = 350V
10 kW @ 50 kHz





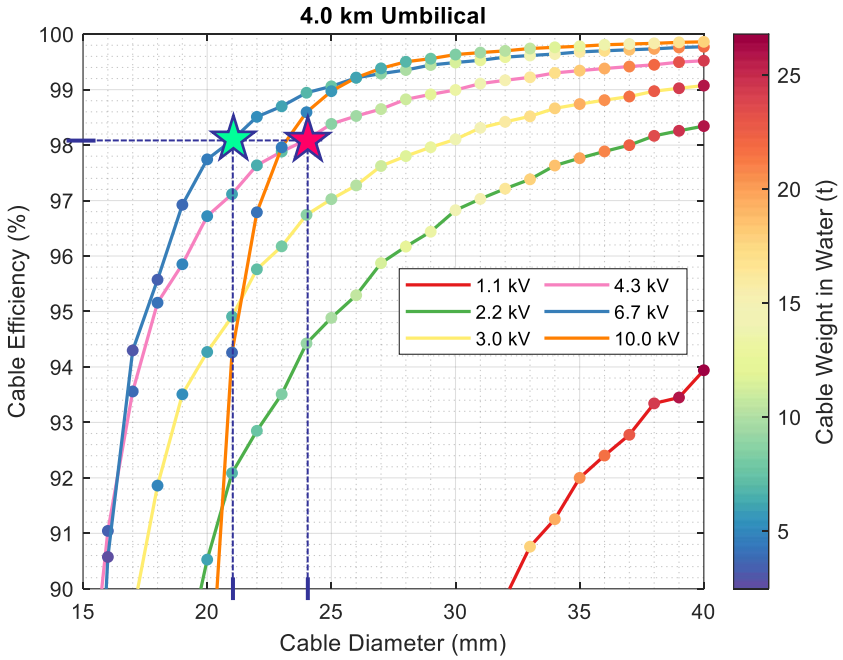


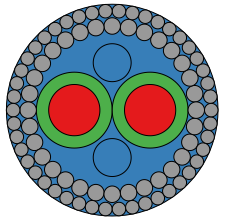


Multi-Objective Optimization of DCX-Based Medium-Voltage DC ROV Power Supply

MVDC Umbilical Optimization

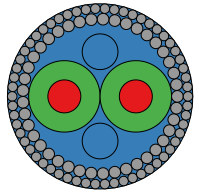
- 4000 m / 50 kW / Stranded Copper Conductor / PP Isolation
- Two-Layer Steel Wire Armor Dimensioned incl. TMS (Eff. Mass 1000 kg)





★ 4.3 kV

Diameter	24 mm
Weight in Water	6.4 t
Armor Strength	300 kN
Efficiency	98.1 %
Voltage Drop	1 %



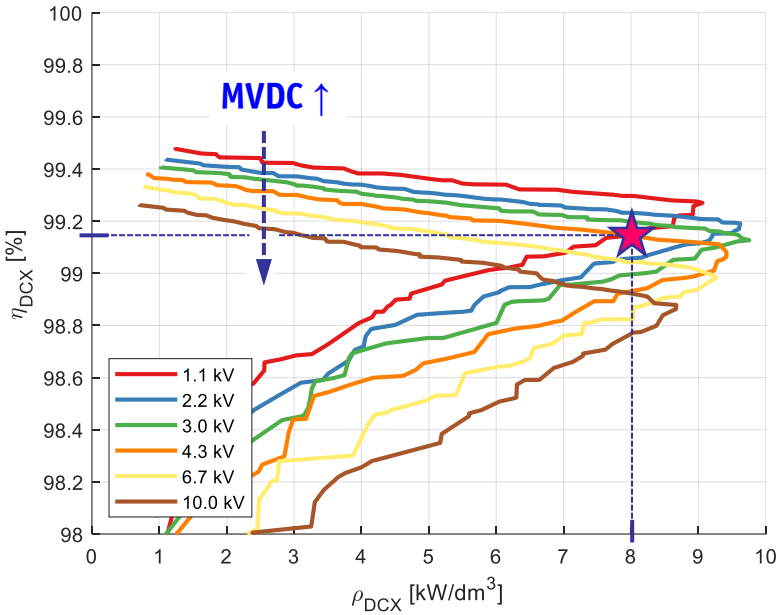
★ 6.7 kV

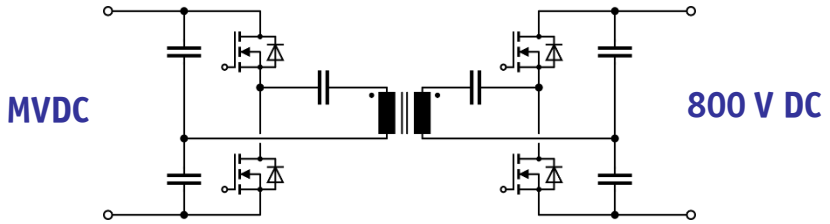
Diameter	21 mm
Weight in Water	3.7 t
Armor Strength	190 kN
Efficiency	98.1 %
Voltage Drop	1 %

- Trade-Off → Efficiency / Cable Diameter & Weight
- Given Diameter → Weight Reduces w/ Increasing Voltage (Lower Spec. Weight of Insulation Comp. to Cu)

DCX Optimization

- 50 kW / MVDC → 800 V / Bidirectional
- SiC Power Semiconductors — 1.2 kV, 3.3 kV, 4.5 kV, 6.5 kV, 10 kV | 2/3 Blocking Volt. Utilization
- Switching Frequency Range — 20...70 kHz / Chip Area Optimization
- Dry-Type Medium XFRM / N87 Ferrite Cores / Litz Wire Wdg. / 10kV Isolation

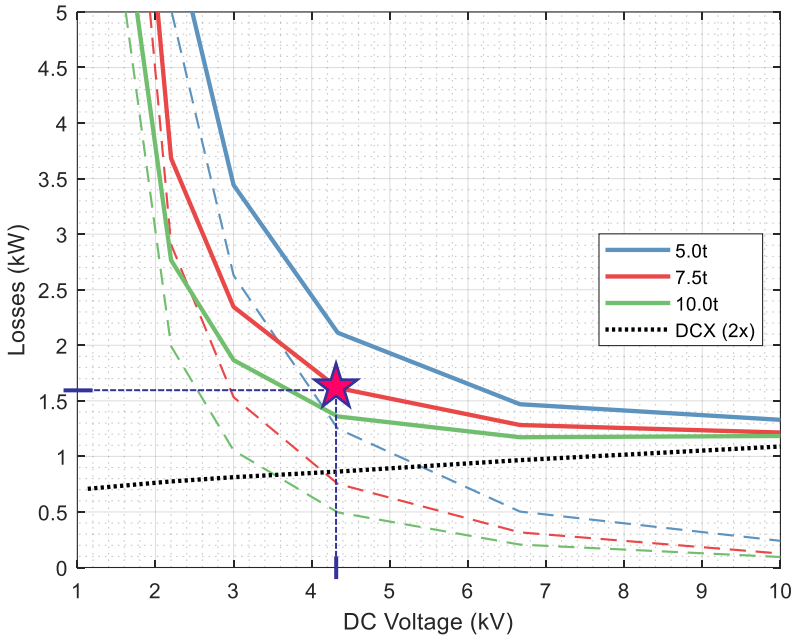


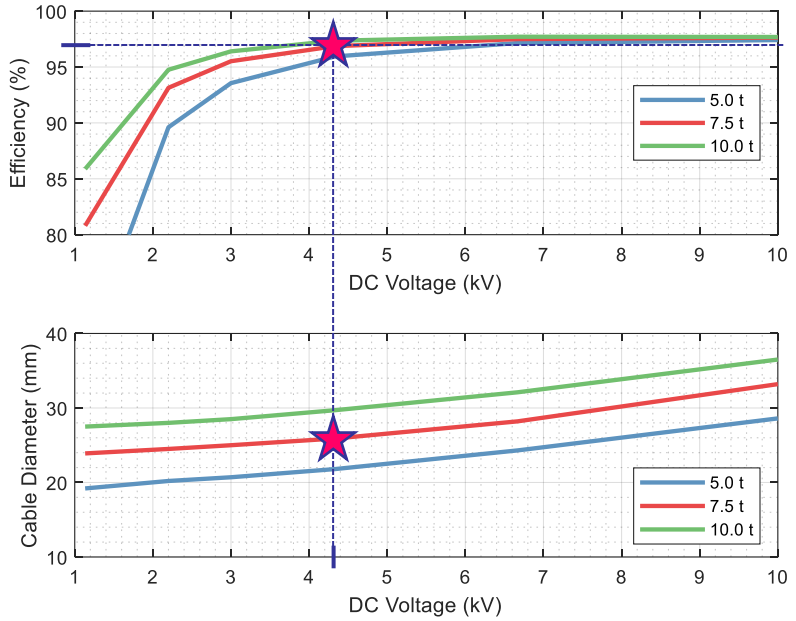


- Decreasing Semiconductor FOM for Increasing MV-Side Blocking Voltage
- 99.15 % Efficiency @ 8 kW/dm^3 for MVDC = 4.3 kV / 6.5kV SiC Power MOSFETs & f_s = 70 kHz

System Optimization (DCX — Umbilical — DCX)

- 50 kW | 2x DCX @ 8 kW/dm³ & 4000 m Umbilical @ 5.0/7.5/10.0 t
- Higher DC Voltage → Higher DCX Losses BUT Lower Transmission Losses



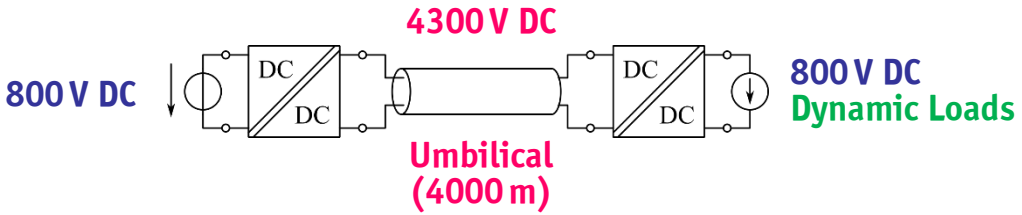


96.5%

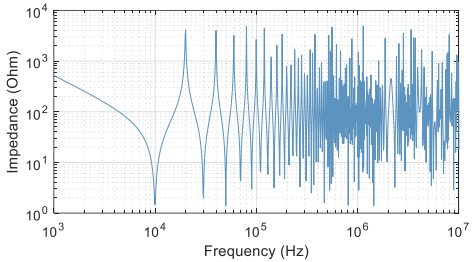
- 4.3 kV DC → 96.5% System-Level Eff. / 6.5 kV SiC @ f_s = 70 kHz
- Umbilical Mass = 7.5 t @ 26 mm Diameter | Minor Efficiency Improvement for 7.5 t → 10 t

System Dynamics (DCX — Umbilical — DCX)

- Uncontrolled DCX | 4000 m Transmission Line | Uncontrolled DCX | Switched Resistive Load
- 70 uF LV DC Capacitance / 500 nF MV DC Capacitance

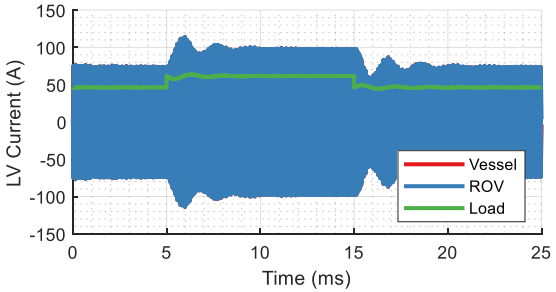


Umbilical Impedance

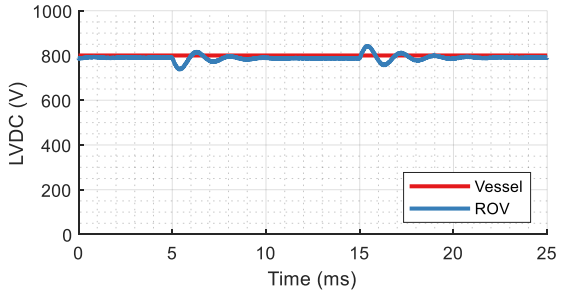


C′ = 76 pF/m
L′ = 517 nH/m
R′ = 0.69 mΩ/m

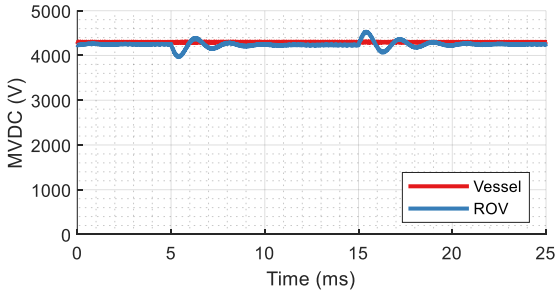
Load Current 75% → 100% → 75%



LV-Side / 5% Overshoot



MV-Side / 5% Overshoot

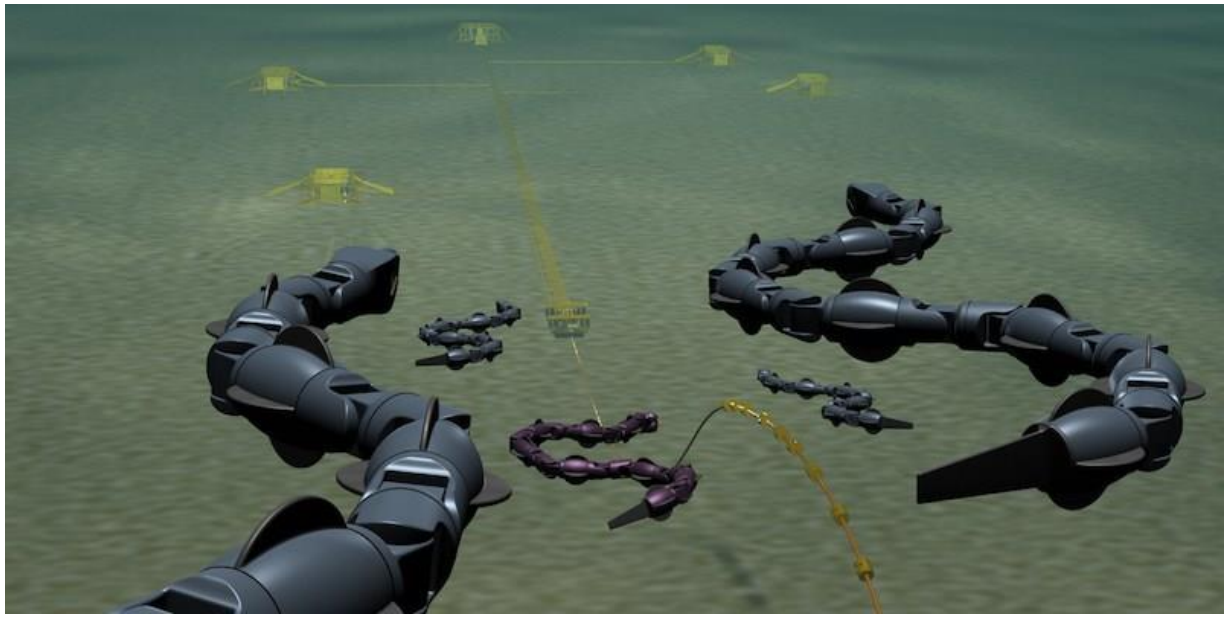


- Active Damping → ROV DC/AC Converters or ROV DC/DC Battery Converter &/or Shipboard AC/DC Stage

Outlook

Resident Underwater Drones

- Snake Like Robots w/o Umbilical Connection to Support Vessel
- Subsea Docking Station for Battery Charging / Data Transfer / Assignments

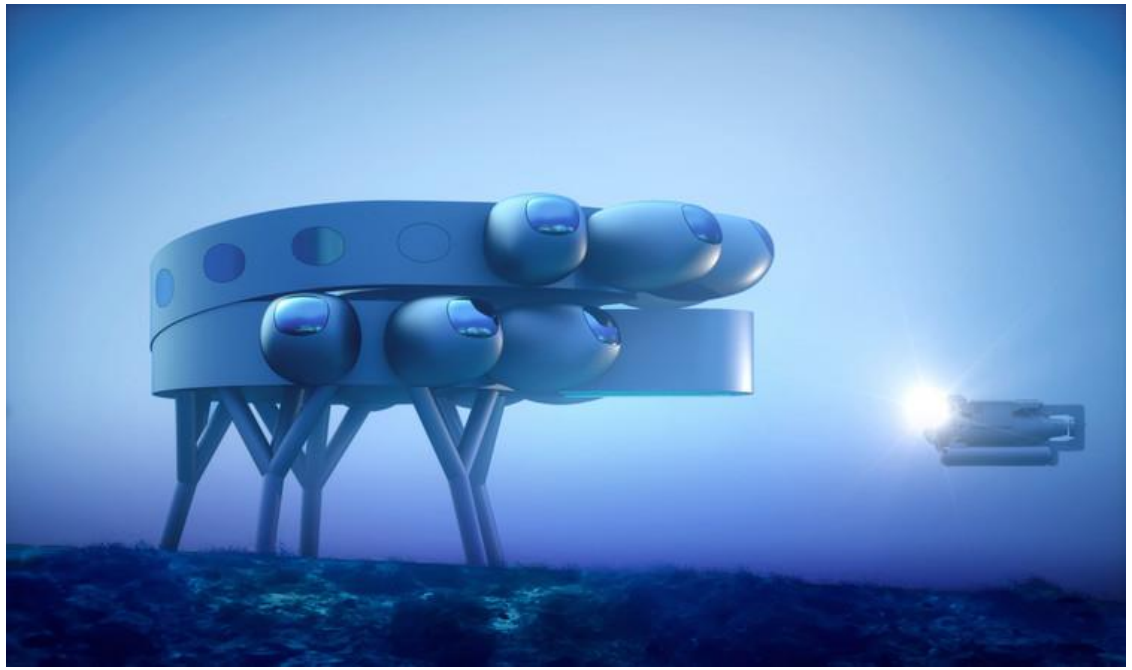


Source: Eelume

- Eelume – Equinor / Kongsberg Maritim / NTNU

Future Underwater Stations

- Underwater Version of the International Space Station
- Discovery of New Species of Marine Life / Aquacultures / Understanding Climate Change Effects



Source: ArchDaily / Protheus

- PROTEUS – First in a Network of Underwater Habitats

Thank you!