PHASE 1 FINAL PRESENTATION: 12121-6302-01:
Subsea High Voltage Direct Current Connectors for
Environmentally Safe and Reliable Powering of
UDW Subsea Processing

Project 12121-6302-01
Qin Chen
GE Global Research Center

RPSEA Ultra-Deepwater Subsea Systems TAC Meeting
Tuesday, June 10, 2015
Greater Fort Bend Economic Development Council Boardroom, Sugar Land, TX

rpsea.org
Acknowledgement

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The project team would like to thank all the Working Project Group members and the subject matter experts attending the workshops for their support and guidance
## Project Overview

### ProjectCostSummary

<table>
<thead>
<tr>
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<th>Period of Performance</th>
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</thead>
<tbody>
<tr>
<td>Project budget</td>
<td>$2,928,013</td>
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<tr>
<td>Project start date</td>
<td>06/20/2014</td>
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<tr>
<td>Spend to date</td>
<td>$740,468</td>
</tr>
<tr>
<td>Project end date</td>
<td>09/30/2016</td>
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</tbody>
</table>

- **Objective:** develop electrical prototype mock-up of subsea DC cable connectors

Subsea cable connector examples

- Wet-mate AC 36kV/500A, 3-phase
- Dry-mate AC 36kV/700A

Subsea DC system example
Project Team

**Performance Team**

- **GE Global Research**
  - Role: Design, materials development, testing, project management
  - PI: Qin Chen

- **GE Oil & Gas**
  - Role: Prototype vendor & consulting
  - Project lead: Albert Ericsson

**Working Project Group**

(Champion: Dr. Xiaolei Yin, Exxon Mobil)

- **University of Connecticut**
  - Role: Specialized materials testing
  - Project lead: Prof. Yang Cao
Project cost

Project Costs

Invoiced Technology Transfer Costs

- Planned
- Actual

Project month

Cummulative costs ($K)

Project cost ($K)
Project status

○ Phase I accomplishments (06/14 – 04/15)
  ✓ Technical requirements, 1st industrial workshop (Nov 19, 2014)
  ✓ Technical gap analysis, 2nd industrial workshop (Mar 2015)
  ✓ Preliminary design (Mar 2015)
  ✓ Preliminary materials study (Mar 2015)
  ✓ Prepare for prototyping (Apr 2015)

○ Phase 2 plan (05/15 – 09/16)
  □ Connector design optimization
  □ Prototype construction
  □ Electrical test under dry condition
  □ Electrical test with simulated subsea condition
Overview of subsea power system

- Top side AC
- Subsea AC 50/60Hz
- Subsea AC Low frequency
- Subsea DC

Higher Power rating

Depth: up to several km

Longer step out

Deployed
Pilot-tested, not deployed
New system, similar concept
New concept
DC for long distance and high power

\[ S \xrightarrow{I_S} I = I_S - I_c \xrightarrow{L} I_c = wCU_0 \]

- Cable too long -> most of the AC current needs to charge/discharge cable capacitor

Example of AC Power transfer capability vs Distance

<table>
<thead>
<tr>
<th>Length of the cable (mile)</th>
<th>Power [MW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>70</td>
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<tr>
<td>10</td>
<td>60</td>
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<tr>
<td>20</td>
<td>50</td>
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<td>30</td>
<td>40</td>
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<td>40</td>
<td>30</td>
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<td>50</td>
<td>20</td>
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<tr>
<td>60</td>
<td>10</td>
</tr>
<tr>
<td>70</td>
<td>0</td>
</tr>
</tbody>
</table>

Voltage limit

*Two ways to reduce/eliminate transmission loss are:

- Additional compensation for reactive power
- Make \( \omega \rightarrow 0 \): LF AC or DC
Example of subsea DC system

HVDC connectors are critical components
Technical requirements for subsea DC connector

- Operational conditions (depth, temperature, etc)
- **Electrical ratings (focus on DC)**
- Mechanical ratings
- General requirements (life, maintenance-free, etc)
- Specific requirements for wet/dry mate connectors and penetrators
- **Test requirements (to be finalized in Phase II)**

Focus on defining requirements related to DC electrical operation
Technical requirements - Approach

General requirements
• Distance
• Power
• Depth, etc.

Electrical system
• System topology
• Fault analysis

Connector requirements
• Electrical requirements
• Non-electrical requirements

First open industrial workshop (Nov 19, 2014)
Generic system models and fault scenarios

Focus on transmission-side faults
1. Cable ground fault
2. DC voltage short circuit fault
3. Ground fault between the stacked modules
4. Fault within the individual modules

System parameters:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC voltage</td>
<td>150kV (+/- 75kV)</td>
</tr>
<tr>
<td>Load power rating</td>
<td>60MW</td>
</tr>
<tr>
<td>Step out distance</td>
<td>180km</td>
</tr>
</tbody>
</table>
Example of case study (VSC, ground fault of the cable)

Generic model

Current path under fault

Source

Load

Wet mate DC connector current (1.4X)

Wet mate DC connector voltage (~2.1X)

*Note: fault response depends on cable impedance

IRE

VC1

Charge the capacitor

Discharge the capacitor

Time: sec

Current: kA

Time: sec

Voltage: kV

Overvoltage due to ground fault

Wet mate DC connector voltage (~2.1X)
## Summary – key connector electrical ratings

<table>
<thead>
<tr>
<th>Parameter</th>
<th>RPSEA prototype (tentative)</th>
<th>Future need</th>
<th>Governing factors</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Rated voltage</strong> (U_0)</td>
<td>± 50 kV</td>
<td>± 50 to ± 150 kV</td>
<td>System power, distance</td>
</tr>
<tr>
<td><strong>Rated current</strong> (I_0)</td>
<td>500 A</td>
<td>200 – 1000 A</td>
<td>System power, distance</td>
</tr>
<tr>
<td><strong>Overvoltage</strong></td>
<td>(2.5 \times U_0)</td>
<td>(2.5 \times U_0)</td>
<td>Cable ground fault, with high impedance grounding</td>
</tr>
<tr>
<td><strong>Rated thermal short-time current</strong></td>
<td>(15 \times I_0) (0.5 sec)</td>
<td>(15 \times I_0) (0.5 sec)</td>
<td>Cable ground fault, DC system short circuit, Protection mechanism</td>
</tr>
<tr>
<td><strong>Rated dynamic current</strong></td>
<td>(5 \times I_0) (&lt; 1 msec rise time)</td>
<td>(5 \times I_0) (&lt; 1 msec rise time)</td>
<td>System ground fault</td>
</tr>
<tr>
<td><strong>Polarity reversal</strong></td>
<td>Full reversal in 1 msec</td>
<td>Full reversal in 1 msec</td>
<td>System ground fault</td>
</tr>
</tbody>
</table>

Depth: up to 3000 m
Ambient temperature: -5 °C to 20 °C
State-of-the-art: subsea AC connectors

- **Rating:**
  - DM: 145 kV, 700 A
  - WM: 36kV, 900 A
- **Vendors:**
  - GE Oil and Gas
  - TE Connectivity (DEUTSCH)
  - Hydro Group
  - MacArtney
  - POWERSEA
  - RMSpumptools
  - SEA CON Group
  - Siemens
  - Teledyne ODI

<table>
<thead>
<tr>
<th></th>
<th>MECON DM-III (145kV/700A, single phase)</th>
<th>MECON WM-II (36kV/500A, 3 phase)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight (kg)</td>
<td>190</td>
<td>380 (male) 410 (female)</td>
</tr>
<tr>
<td>Length (mm)</td>
<td>900</td>
<td>2000</td>
</tr>
<tr>
<td>Diameter (mm)</td>
<td>370</td>
<td>400</td>
</tr>
</tbody>
</table>

No DC connectors (>10kV) commercially available
Technical gap analysis - Approach

State-of-the-art
- Subsea AC connectors
- Land-based HVDC
- No DC connectors (> 10kV)

Requirement & challenges
- DC electrical
- Subsea operation
- DC + subsea

Closing of technical gap
- Develop 50kV DC prototype in RPSEA project
- Further engineering development & qualification

Second open industrial workshop (March 25, 2015)
Why is DC different? – steady states

- Challenge with field control in wet-mate chamber
- Beyond field control – challenges of contamination, surface discharge, ...
Why is DC different? – sensitivity to materials

- Reason of variation – conductivity change (*not happen in AC*)
- Change of thermal gradient can “shift” DC field distribution

- Variation of materials property can significantly alter DC field distribution
- Real situation could be more complicated (e.g., change of property is not uniform in the same material)

Epoxy becomes 10x less conductive

Epoxy becomes 10x more conductive

Equipment lines (denser -> higher field)
Why is DC different? – transient voltages

**Superimposed impulse**
- Time = 0
- Contour: Electric potential (V)
- Rise/fall = 250 µsec/2500 µsec; time in seconds

**Polarity reversal**
- Time = 0
- Contour: Electric potential (V)
- Full reversal in 1 sec; time in seconds

- Basically AC + DC
- Very complicated, no simple approximation
Experimental study

Seawater uptake experiment

- Clear Lid
- Recordable Thermometer
- Thermocouple
- Al Mesh for support
- Seawater
- Seawater bath lid
- Epoxy Pieces
- DI Water
- Water Bath (controller)

Resistivity measurement

Dielectric breakdown measurement
Impact of seawater – change of DC electrical properties

- Water Saturation: Resistivity drops 4 orders magnitude
- The change is reversible (fully recovered after drying in oven)
- Partial recovery after “flushing”
Learnings from Subsea AC connectors

- Up to 3000 m water depth
- Subsea connection in presence of sand and silt
- Operating temperature range: -5 to 20 ºC
- Storage temperature -25 to 60 ºC
- 25 years design life – no maintenance

- Partial Discharge
- Hyperbaric
- Thermal cycling
- Thermal shock
- Vibration
- Impact

- Same (significant) challenges for DC connectors
- Mechanical design not under electrical stresses – leverage from AC connector technology
Learnings from land-based HVDC (examples)

**HVDC cables**

- Key is to develop solid insulation with high dielectric strength and low loss

**HVDC transformers**

- Key is to handle stress in oil/solid hybrid insulation

Work by GE supported by ARPA-E Award No. DE-AR0000224 & DE-AR0000231
## Subsea DC connector vs. existing technology

<table>
<thead>
<tr>
<th>Subsea AC connector</th>
<th>Submarine cable joint</th>
<th>Cable terminations</th>
<th>Outdoor insulation</th>
<th>Converter Xformers</th>
<th>Subsea DC connector</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC or DC</td>
<td>AC</td>
<td>DC</td>
<td>DC</td>
<td>DC</td>
<td>DC</td>
</tr>
<tr>
<td>Voltage (kV)</td>
<td>36 (WM) 145 (DM)</td>
<td>500</td>
<td>500</td>
<td>800</td>
<td>800</td>
</tr>
<tr>
<td>Function</td>
<td>Cable terminating &amp; connecting</td>
<td>Cable joining</td>
<td>Cable terminating</td>
<td>Insulating bare conductors</td>
<td>Winding insulation</td>
</tr>
<tr>
<td>Insulation system</td>
<td>solid + oil</td>
<td>All solid</td>
<td>Solid + oil</td>
<td>Solid + air</td>
<td>Solid + oil</td>
</tr>
<tr>
<td>Operating environment</td>
<td>Submarine</td>
<td>Underground or submarine</td>
<td>Above ground</td>
<td>Above ground</td>
<td>Above ground</td>
</tr>
<tr>
<td>Contamination</td>
<td>Exposure to seawater during mating (WM)</td>
<td>Clean</td>
<td>Clean</td>
<td>Dirty (outdoor termination)</td>
<td>Clean</td>
</tr>
</tbody>
</table>

### Key challenges:

1. DC electrical insulation within subsea packaging

: Challenges related to subsea DC connectors
Engineering challenges: 50 kV vs. 100 kV

50 kV design
Length: 1450 mm
Insulator O.D.: 190 mm
Weight: ~ 200 lb

100 kV design
Length ~ 1900 mm
Insulator O.D.: 370 mm
Weight: ~ 360 lb

Current (500 A) is the same for both design

Similar DC field distributions achieved for both ratings

- 50 kV DC
- 100 kV DC

Contour: equipotential lines
Color: electric field

- 50 kV design fits in most existing mechanical “shell”
- 100 kV design may require new mechanical shell
Phase 2 – Overview of approach

<table>
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<tr>
<th></th>
<th>05/15</th>
<th>08/15</th>
<th>11/15</th>
<th>04/16</th>
<th>09/16</th>
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<tr>
<td><strong>Design</strong></td>
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<td>Design simulation &amp;</td>
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<td>materials test</td>
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<td><strong>Construction</strong></td>
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<td>Prototype No. 1</td>
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<td>Prototype No. 2</td>
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<td>Subsea conditioning</td>
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<tr>
<td><strong>Prototype testing</strong></td>
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<td>(50kV)</td>
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<tr>
<td>Testing,</td>
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<tr>
<td>$U_0=50$ kV</td>
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<tr>
<td>“Dry” test</td>
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<tr>
<td>$U_0=50$ kV</td>
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<tr>
<td>“Wet” test</td>
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<tr>
<td>$U_0=50$ kV</td>
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<td><strong>Simplified</strong></td>
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<td>geometry test</td>
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<tr>
<td>(50–150 kV)</td>
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<td>Design support</td>
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<tr>
<td>Additional exploration</td>
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</tbody>
</table>

50kV prototype: critical DC electrical risk retirement on prototype level; avoid excessive engineering risks

Simplified geometry tests provide knowledge for higher voltages
Summary

- Phase 1 successfully finished
  - Technical requirements defined
  - Technical gap identified
  - Gap-closing strategy determined

- Phase 2 outlook
  - Design optimization and materials testing
  - Prototype construction and testing @ 50kV level
  - Simplified geometry tests @ 50-150 kV level
Contacts

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