Enabling Pressure Tolerant Power Electronics - PTPE for Deep Water Applications

Findings and interim conclusions from 10 years of research at SINTEF Energy Research

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Two Research projects at SINTEF Energy Research on Pressure Tolerant Power Electronics

- 2006-2012: “Feasible power electronics for demanding subsea applications”
  - Financed by The Research Council of Norway and 7 industry partner
- 2012-2016: "Pressure Tolerant Power Electronics for Subsea Oil and Gas Exploitation – PressPack"
  - Financed by The Research Council of Norway and 9 industry partner
- Main objective for both projects:
  - Provide fundamental material and packaging knowledge for supporting realisation of reliable pressure tolerant power electronic components and circuits
  - Reliable operation up to 500 bar ambient pressure, corresponding to 5000m sea depth
This Presentation

- Examples of subsea converter applications and power circuits
- Converter circuitry and components
- Potential advantages by PTPE
- PT packaging challenges
- Strategy for the research
- Test objects, test facilities and test programs
- Interim findings and conclusions
Some subsea electric power converter applications

- Power supplies for control and monitoring
- Valve actuators
- Emergency power (UPS)
- Energy storage conversion
- Variable speed motor drives
- Pipeline heating systems (DEH)
A general 3-phase AC/DC converter

- Bidirectional active power flow
- Bidirectional reactive power flow
- Very fast transition

DC-link capacitor bank
Switching devices
Filter reactors
**IGBT - Insulated Gate Bipolar Transistor**

- Today the most common switching device
- Various encapsulations

- A 750A/6500V IGBT module from Infineon
- 1000A/4500V StakPak press-pack IGBT from ABB
- A 1800A/4500V hockey puck type press-pack IGBT from Westcode
Converter topologies for higher voltage levels

Due to voltage limitation of single power semiconductors, high voltage converters need more complex topologies and/or series connection of IGBTs.
Potential advantages by pressure balanced solutions

- Reduced weight and volume
  - Reduced container wall thickness
  - Full freedom for shape of container, e.g. flat constructions
  - Less filler material (liquid)
- Reliability and cost
  - Natural cooling possible
  - No moving parts (pumps, fans)
  - Reduced number of pressure penetrations
  - Reduced risk for leakage

*Pressure balanced construction with direct conductive heating through walls of vessel*
Pressurized converter power circuit

- One bar compartment for converter central control
- Pressure barrier
- 1-300 bar liquid environment
- Converter driver and sensor interface
- Aux. power
- IGBT drivers with electric or optic interface
- Sensors V, I, T, P, H
- Dr.
Focusing the assumed most critical power components

• Identify the most critical components of a power electronic converter
  ✓ Power semiconductors, DC-link capacitors, IGBT gate drivers
  ✓ Auxiliary power supplies, I,V,P,T sensors etc. assumed to be located in pressure compartment

• Provide roadmap for the experimental work
  ✓ Involving component and material manufactures
  ✓ Provide custom made test objects
  ✓ Provide the required special equipment for the experimental work

• Component material experiments
  ✓ Electric insulation properties
  ✓ Chemical compatibility

• Single components experiments
  ✓ Passive tests and live tests

• Converter power modules
  ✓ Live operation up to rated power for the components
  ✓ With the most critical power components
  ✓ Insulation tests, Pulse testing and Continuous operation
Summary of pressure tolerant packaging challenges

• Mechanical stress to encapsulations caused by the high pressure environment, and also possibly due to vacuuming processes in connection with filling.
  – Dedicated experiments in pressure vessel with high pressure slew rates

• Possible change of functionality and characteristics of semiconductors due to pressure
  – Such as changes in switching performance due to impact on driver electronics and/or directly on IGBT parameters.
  – Live experiments with high voltage converter modules in pressure vessels
  – Including IGBTs, driver electronics auxiliary supply, sensors etc.

• Impact from the pressurized environment on the "self-healing" performances of PP-film capacitors.
  – Live testing of components according to established procedures for industrial applications

• Possible reduced performance of the electric insulating materials.
  – Such as existing IGBT silicon gel facing various external insulation liquids.
  – Systematical studies on silicon gel in contact with insulation liquid candidates.

• Impact from humidity on the power semiconductor insulation
  – Giving requirements to the surrounding filling liquid, or to barriers between the most critical locations and external less critical filling liquid.
Options for enabling PT planar/bonded IGBT modules

Requirements:

• Provide 100% filling of solids or liquids
• Electrical insulation properties as good as or better than existing/replacement materials
• The required long term chemical compatibility between the new materials and with the existing component interface materials (e.g. with existing gel of IGBT modules, or with chip surface if gel is not used).
• Sealing properties (particles, ions, humidity) as good as or better than existing/replacement materials.
Investigering the most critical locations of the semiconductor chips

- Dedicated insulation material experiments
  - On IGBT & diode chips
  - On substrates
  - Complete modules
  - Long term insulation stress
  - Controlled humidity
  - Material compatibility

- Live experiments with converter modules
  - Alternative insulation schemes
  - In switch mode operation
  - Up to rated component voltage of 6.5 kV

Guard rings for controlling E-field

1200V, 400µm
Some PP-film capacitor challenges

Assumed interior weak points of metallized film capacitor

Risk for unsuccessful self-healing under high pressure
Power semiconductor test objects

- Planar bonded IGBT modules
  - Highest voltage available (6.5kV)

- Press-pack IGBT
  - Highest voltage available (4.5kV)

- Need 100% filling of dielectric liquid
  - Good electric insulator
  - Free from contaminants
IGBT driver electronics test object
Capacitor test objects

- PP-film capacitor elements for live testing

- PP-films 4µm, 5.8µm, 8.5µm, 9.8µm
  - for self-healing experiments
  - for liquid compatibility experiments

- Ceramic capacitor test samples for live testing
Test cell for experiments with live converter module in liquid pressurized environment

**Major HSE concerns:**
- High voltage
- High current
- High pressure

**Solved by:**
- Custom test circuits
- Certified pressure vessels
- Multiple safety barriers
Test circuit for experiments with live converter modules in liquid pressurized environment 0-300 bar

Solving HSE concerns:
• Separate voltage supplies for continuous operation and insulation testing
  ➢ High impedance line supply
  ➢ Very high impedance insulation tester
• Circulating power
• Limiting external DC buffer capacitor
• Limiting capacitor test object in pressure vessel
• Pressure vessel certified to 500 bar
• 100% liquid filling
• Multiple safety barriers

• Pulse testing
• Continuous switching
• Voltage withstand ability testing
Live experiments of capacitors in pressurized environment

Solving HSE concerns:
- Separate voltage and current control
- High impedance voltage source
- Resonant mode current control
- Pressure vessel certified to 500 bar
- 100% liquid filling
- Multiple safety barriers

- Characterization: IEC 61071:2007
- Voltage: Up to 1.5x rated DC
- Current: Up to rated AC
- Test liquid: Midel@7131
- Pressure: 0-300 bar
Insulation material experiments

**Materials – Liquids**
1. Midel – Synthetic ester
2. FR3 – Organic ester
3. Fluorinert FC-77(3M)
4. Perfluoropolyether – Galden (Solvay)
5. Monobenzyltoluene - Jarylec

**Test objects**
- Custom made PCB
- 6.5 kV DBC substrate
- 4.5 kV diode chips
- 6.5kV IGBT modules

**Conditions**
- Influence of water
- Influence of temperature

**Materials – surface cover**
1. Parylene
2. Silicone Gels
3. Polyimide
Chip termination area is vulnerable for particles

4.5kV diode
Test object

Microscopy analysis after insulation breakdown
Findings from live experiment with converter module 0-300bar

"Double pulsing" waveforms
Some findings from live experiments of PP film capacitors

- 0-300 bar in synthetic ester Midel 7131
- Failures have been experienced
  - When subject to 1.5 times rated DC voltage
  - Own post investigations and by the manufacturers gives reason to suspect unsuccessful "self-healing"
Interim conclusions capacitors

- **PP-film capacitors and ceramic capacitors**
  - All electrical characteristics, such as capacitance and $\tan \delta$ are well maintained in high pressure liquid environment up to 300 bar.
  - The mechanical durability such as the film interconnection to the termination layers is maintained.

- **PP-film capacitors**
  - Even though traces from the surrounding liquid are found inside the film roll, there are no indications of deterioration of the film metallization like erosion.
  - The major concern is that the important self-healing mechanism of the metalized PP-film seems to be negatively affected by the high pressure.
  - Continuing experiments applying reduced DC-voltage has been in operation for a significant longer period compared to those resulting in failure.
  - This is taken as an indication that high pressure operability of PP-film capacitors could be feasible provided significant derating of operating voltage.
Interim conclusions IGBT and IGBT driver packaging

• All electrical characteristics as well as mechanical ruggedness are maintained at least up to 300 bar
  – IGBT voltage and current waveforms close to unaffected by pressure
  – Indicating that IGBT and IGBT driver electrical functionality have the sufficient pressure ruggedness

• Chip termination area is vulnerable for fibers and other particles.
  – The chip and substrate interface need to be protected from direct contact with liquids by a material with the sufficient mechanical and electrical properties.
  – One option is to maintain the generally used silicon gel, however the long-term compatibility with adjacent liquids need to be further investigated
  – Experiments with 30-50µm Parylene covering the silicon die surface look promising
  – Long-term compatibility between liquids and adjacent IGBT materials to be further investigated

• Humidity control is important
  – By time humidity will penetrate the complete converter environment, including critical locations
  – Then either hermetically sealed components encapsulations are required
  – Otherwise the complete converter filling liquid need to have humidity control
Interim conclusions other components in 0-300 bar

• Magnetic core materials
  – Iron wound cores, Amorphous wound cores, Ferrite cores, Nanoperm, Arnold powder cores
  – Mapping coercive force, saturation flux density, relative permeability
  – More or less affected by pressure
  – All test objects seem to be possible candidates, provided proper design considerations

• Temperature and humidity sensors
  – All have maintained their specified functionalities

• Current transducers
  – Close to no influence from pressure on functionality, accuracy, characteristics
Thank you for your attention!