Design Challenges of a SiC-based MVDC Power Supply for Deep-Sea applications

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***Abstract*—Design challenges of medium-voltage DC/DC converter for deep-sea applications using silicon carbide (SiC) power MOSFET modules are reviewed. Challenges of high-pressure conditions at deep-sea operation are presented and the pressure tolerance of power electronic components is investigated based on existing literature. Several topologies for high-power DC/DC conversion are reviewed. Power loss estimations are performed on a dual active bridge using SiC discrete devices and power modules with data provided by the manufacturers. The simulations are performed in PLECS/Simulink.**

***Index Terms*—Medium-voltage DC/DC converter, Wide-bandgap semiconductor devices, Pressure-tolerant power electronics, dual active bridge.**

I. INTRODUCTION

This paper presents major challenges regarding the design of high-power, high-efficiency and reliable medium-voltage direct current (MVDC) power supply for remotely operated vehicles (ROVs). ROVs are currently used in multiple subsea and offshore activities. They are needed in the oil and gas sector (for intervention, trenching, umbilical and power cable laying, repair and maintenance tasks), as well as, other niche applications requiring subsea operations (e.g. military and forensics). Considering the steep increase in offshore wind farm installations, the use of ROVs is expected to increase in the ocean renewable sector, where extensive cable-based collection grids are required. The focus of this paper is on work-class ROVs (WROVs) with power ratings exceeding 200 kVA and operation at water depths of 3000 m, and as deep as 11000 m [1], [2]. Today, the state-of-the-art WROVs use hydraulic systems on board in order to meet the high power demands of their manipulators and propulsion systems. However, a trend towards modernizing WROVs by designing them as fully electric in terms of power transmission, supply, control and propulsion is clearly observed [3]. Such fully electric systems will enable higher reliability, reduced weight, improved efficiency and controllability, while environmental risks associated with possible leakages form the hydraulic circuits will be eliminated. To enable fully electric WROVs, the design, analysis and experimental verification of high-efficiency, power dense DC power supply based on medium-voltage DC technology should be a focused research area. Such power supply will enable higher reliability, reduced weight, improved efficiency and controllability, while the environmental risks associated with possible leakages from the hydraulic circuits will be eliminated.

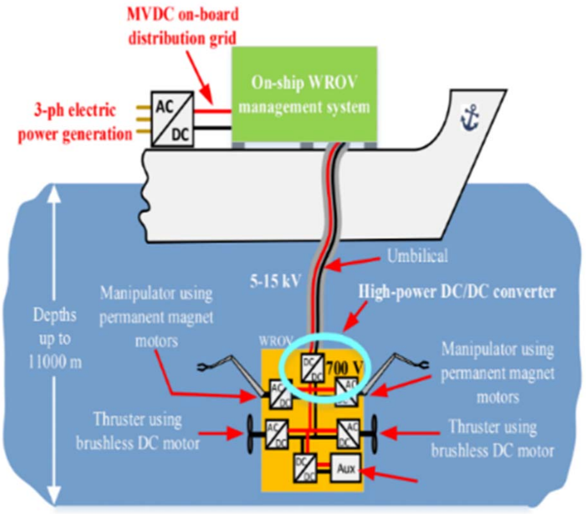


Fig. 1: System overview: the DC/DC converter is marked with blue circle.

This paper is to address and review the major challenges of designing the DC/DC converter for high-pressure operating environments and possible solutions based on existing literature. The goal is to design and optimize high-power, galvanically-isolated DC/DC converters suitable to perform electrical energy conversion from MVDC (e.g. 3-15 kV) to low voltage DC (e.g. 700 V) for the future fully electric WROVs. A graphical illustration of the system configuration is shown in Fig. *1*. The WROV is powered via a MVDC umbilical from an on-board/on-shore power distribution station. The medium voltage is converted through the evaluated DC/DC converter to a suitable voltage level for electrifying load connected on the low voltage DC-bus on WROV, such as motor drives and auxiliary systems.

This paper is organized as follows. Firstly, the challenges and reviewed research on the pressure tolerance of power electronic components is presented. Then, a design and performance evaluation of converter topologies suitable for high-power DC/DC conversion system and associated design aspects is presented, and lastly conclusions are given.

II. PRESSURE TOLERANT POWER ELECTRONICS

The ROVs are required to operate at immense depths leading to exposure at high pressures. Two approaches are commonly followed when designing pressure-tolerant power electronic systems:

A. *Atmospheric-pressure vessels*

The power electronics are assembled in approximately 1 bar pressure vessels [4], [5]. As the power electronic components, converter rating and design depth increase, the pressure chamber become increasingly bulky, inconvenient and often extremely heavy due to the high wall thickness required for the pressure difference between the sea-water and inside of the vessel.

The required wall thickness of a pressure vessel assuming a cylindrical shell is given in TABLE I with accompanying geometrical parameter values. The assumed material is carbon steel alloy plates SA-515-70, widely used for pressure vessels. The calculations [6] assume a maximum operating pressure of 150 bars (Approx. 1500 m depth) and a temperature of $T = 37.8\,°C\ (100\,°F)$. It can be seen that the weight of such pressure vessel quickly becomes very high.

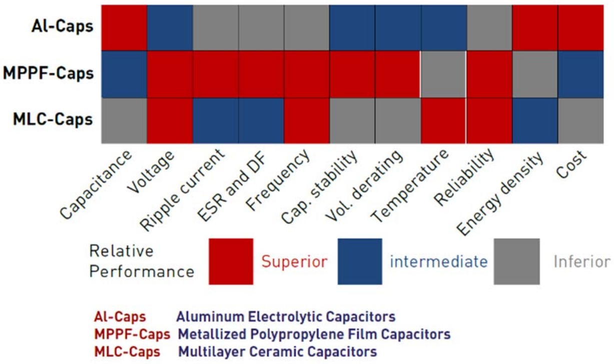
TABLE I

GEOMETRICAL PARAMETERS FOR P=150 BAR

Geometrical Parameter	**Value**
Shell Length	$L = 254\ [cm]$
Shell Diameter	$D_o = 127\ [cm]$
Wall Thickness	$t = 6.35\ [cm]$
Shell Material	SA-515-70 (Carbon Steel)
Material Density	$\rho = 27680\ \left[\frac{kg}{m^3}\right]$
Shell Volume	$V_{shell} = 0.676\ [m^3]$
Shell Weight	$m_{shell} = \rho \cdot V_{shell} = 18712\ [kg]$

B. *Pressure-balanced vessels*

The power electronics are exposed to full ambient pressure by packaging them in thin-walled housing filled with a dielectric fluid. Pressure compensation is used to balance the pressure, a technique where the enclosures internal fluid pressure is maintained in equilibrium with the external sea-water pressure with the use of pressure compensators [7]. The compensation fluid which fills the enclosure is balanced or equalized to all variations of ambient sea water or atmospheric pressure, reducing the differential pressure to approximately zero. Thus, the enclosure thickness can be made independent of the water depth, although a minimum thickness has to be ensured for structural integrity.



	Capacitance	Voltage	Ripple current	ESR and DF	Frequency	Cap. stability	Vol. derating	Temperature	Reliability	Energy density	Cost
Al-Caps	🟥	🟦	⬜	⬜	⬜	🟦	🟦	🟦	⬜	🟥	🟥
MPPF-Caps	🟦	🟥	🟥	🟥	🟥	🟥	🟥	⬜	🟥	⬜	🟦
MLC-Caps	⬜	🟥	🟦	🟦	🟥	⬜	⬜	🟥	🟥	🟦	⬜

Relative Performance 🟥 Superior 🟦 intermediate ⬜ Inferior

Al-Caps Aluminum Electrolytic Capacitors
MPPF-Caps Metallized Polypropylene Film Capacitors
MLC-Caps Multilayer Ceramic Capacitors

Fig. 2: Performance comparisons of the 3 types of capacitors [13].

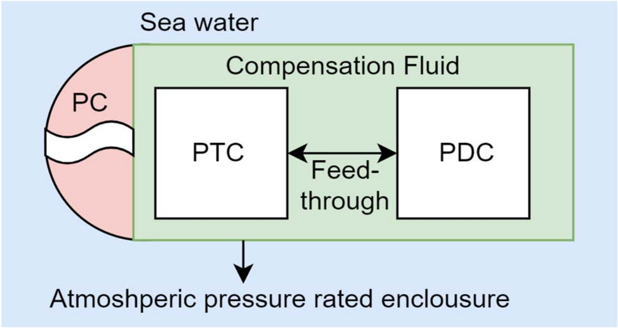


Fig. 3: Conceptual illustration of pressure-tolerant system. PC: Pressure compensator, PTC: pressure-tolerant components, PDC: pressure-dependent components.

Pressure compensation can be performed using several different methods, e.g. using bag/bladder compensator, bellows or convoluted tube, elastomeric tube, diaphragms, spring-loaded piston, flexible membrane, pneumatic actuator or self-pressurizing reservoir [8].

The thinner walled housing significantly reduce the weight and increase reliability and simplicity of the converter cooling system as the heat is more easily conducted through the vessel walls instead of by separate heat exchangers [4], [7]. This allows for higher power-density design, as the volume of heat sinks may be significantly reduced. Furthermore, as the flooding fluid is an insulating, dielectric fluid, clearances between potential differences (such as bus-bars) may be reduced compared with nitrogen-filled enclosures commonly used with 1-bar vessels [7], further promoting a higher power-density design. In power electronic systems, the most critical components for pressurization is found to be the semiconductors, gate drivers and DC-link capacitor banks [4].

For WROV applications, where weight reduction is critical, pressure-balanced vessels will pose advantages over atmospheric-pressure vessels. Pressure tolerant power electronic (PTE) systems are, thus, necessary to eliminate the need for heavy and unpractical atmospheric-pressure chambers to house the power electronics and other pressure sensitive components. As the components are exposed to high pressures (possibly exceeding 1000 bars), it becomes highly important to assure proper working and reliability of the components. Complete, pressure tolerant power electronic conversion systems are not much investigated in scientific literature, although pressure tolerance of single components has been done to some extent [9], [10]. SINTEF Energy Research has done research on the pressure tolerance of different IGBTs with accompanying gate drivers up to 300 bars of pressure with different insulation materials and experimental test set-ups [4], [11]–[13]. Superior cooling options with pressure-balanced systems, as dielectric insulation materials such as MIDEL®7131 has better thermal conductivity compared to nitrogen or air, further promotes pressure-balanced solutions.

C. Passive components

Passive components have been research for their pressure tolerance[4], [9], [14]. It should be emphasized that electronic components not tested and rated for use in high-pressure environments by their manufacturers, experiments have to be done in order to identify components which can operate reliably at high pressure. *Resistors* are usually of solid construction and stand up well under pressure, although carbon composition resistors is found to exhibits a 1-5 percent pressure dependency on the resistance value per 1000 feet due to the compression of carbon particles [9]. *Capacitors* sensitivity to pressure depends highly on materials used. Under high pressure, aluminum electrolytic capacitors will only work if filled with compensation fluid or tar due to their wound construction including small internal air spaces causing them to deform under high pressure [9]. It has been found that DC-link film capacitors are suitable for operation under high hydrostatic pressure [4]. They further identified ceramic capacitors as immune to pressure, thus either film or ceramic capacitors should be focused upon during further developments. There are significant performance differences between the types of capacitors (see Fig. *2*. [14]) hence a trade-off between volume, cost and reliability while maintaining satisfactory electrical and thermal characteristics is needed.

Magnetic components may have somewhat variable parameter values when exposed to high pressure. Some exhibits hysteresis of inductance with pressure, while others change their inductance differently with each exposure to pressure [9]. Air-core inductors may change characteristics at high pressure when submerged in fluid rather than air. Laminated cores is found to be fairly stable, while other types, such as ferrite cores, tend to be less predictable. Magnetic, wounded components contains intrinsic voids due to their design (round cross section wires). High external pressure may cause damage to the insulation if these voids are sealed by varnish or potting material, as this could expose the insulation to mechanical stress [12].

D. Active components

Active components with accompanying gate driving and auxiliary electronics, must carefully be tested for high-pressure operation. To the knowledge of the authors, only high-pressure testing of high-power semiconductors on press-pack and bonded silicon-based insulated gate bipolar transistors (IGBTs) has been done by SINTEF Energy Research in Norway [4], [11]–[13]. Packaging is especially susceptible to high pressure and the chip and bond-wire coating gel needs to be compatible with the submerging fluid. Thus, these component structures need to be investigated for the specific semiconductor module used in the converter. Variations of pressure tolerance of similar-rated devices from same and different manufacturers should further be expected. High-switching-frequency-enabling semiconductor materials (e.g. Silicon Carbide (SiC)), a possible solution for the DC/DC converter for this application, has little known literature discussing their pressure-tolerance. Therefore, SiC power semiconductors must be subjected to rigorous testing in order to verify their high-pressure performance and ensure high reliability.

III. CONVERTER TOPOLOGIES AND CONSIDERATIONS

A major design factor of the WROVs is the light-weight structure. This challenge is strongly associated with increased power densities of the electric power supply system. In particular, using MVDC supply through the umbilical, bulky low-frequency transformers (e.g. 50 Hz) are not required, while the umbilical is lighter due to the elimination of the third conductor used in 3-phase supply. However, high-performance DC/DC power electronic converters with voltage isolation must be considered along with wide-bandgap (WBG) power devices (e.g. SiC) to enable higher compactness.

The conventional Dual Active Bridge (CDAB) topology [15] (Fig. *4a*), is a promising concept as the DC/DC converter for electrifying the WROV. Adding a resonance circuit, either in series or in parallel to the isolation transformer (termed DAB Series Resonance Converter (SRC) or DAB Parallel Resonance Converter (PRC)) (Fig. *4b*)) is reported to provide higher efficiency over a wider load range because of the extended zero-voltage switching (ZVS) and zero-current switching (ZCS) range [16]–[19]. The improved efficiency can lead to less complex thermal management systems and possibly higher power densities.

However, the additional passive components add both additional failure points, as well as, increased weight and volume, and, thus is not necessarily a better

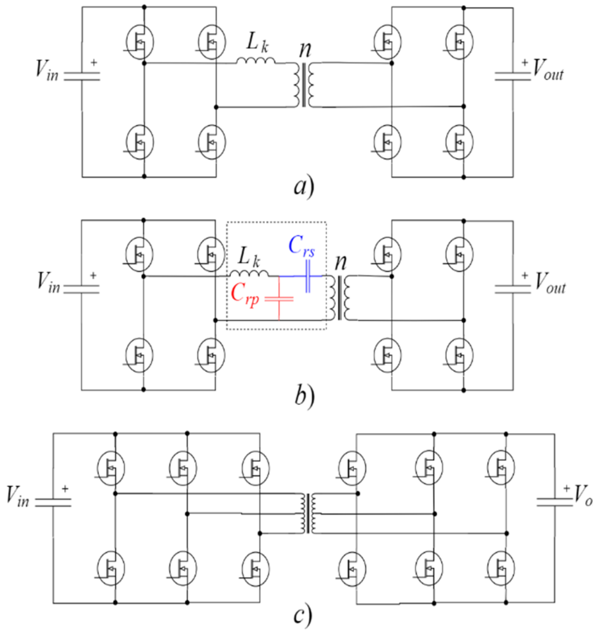


Fig. 4: (a) Single-phase conventional dual active bridge (CDAB), (b) Blue capacitor: single-phase series-resonant converter (SRC), red capacitor: parallel resonant converter (PRC), (c) 3-phase CDAB.

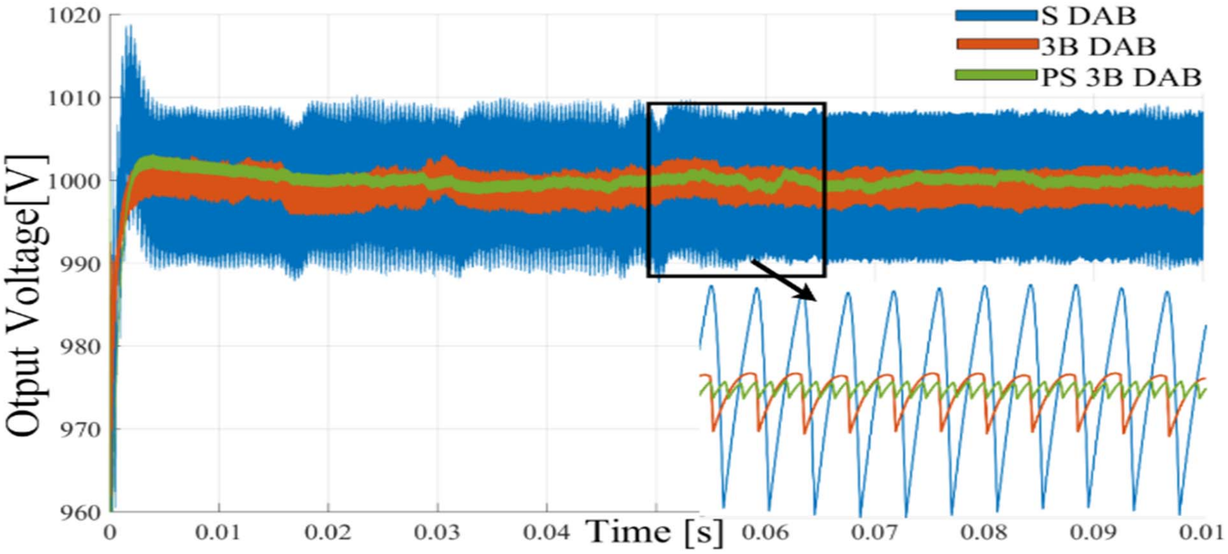


Fig. 5: Simulation results using Simulink/PLECS showing the output voltage ripple for the same filter capacitance and switching frequency, using *S DAB*: Single bridge DAB, *3B DAB*: 3Bridge DAB, *PS 3B DAB*: Phase Shifted 3 Bridge DAB.

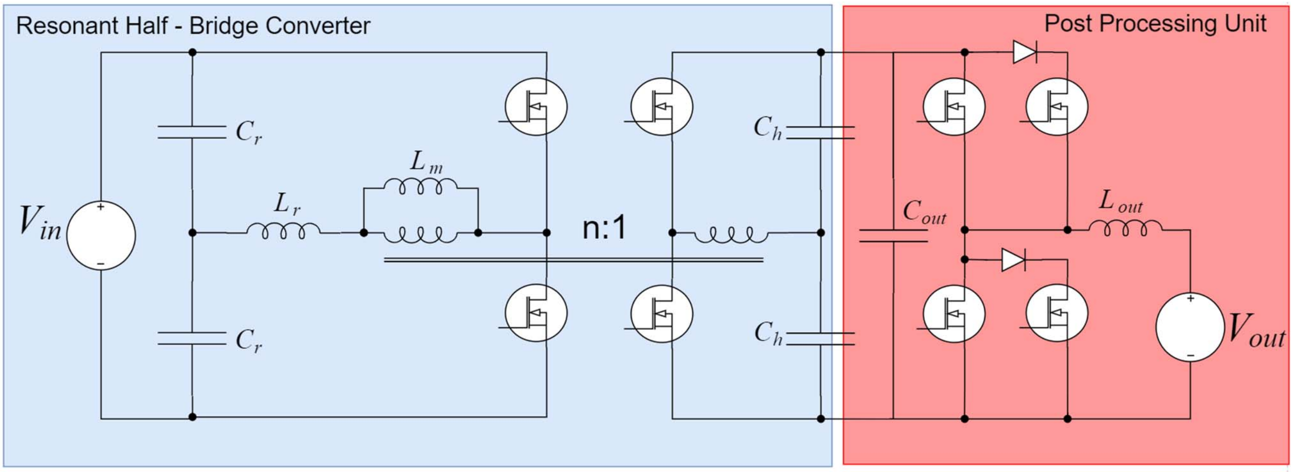


Fig. 6 – Resonant half-bridge converter with non-isolated, post-processing converter unit [20].

choice than a CDAB topology. Furthermore, odd-phased DAB topologies are reported to lead to reduced capacitor RMS current and dc-voltage ripple because of their higher apparent frequency, with the effect increasing with increasing number of odd phases [17], [18]. Nonetheless, increasing the phases increase complexity, cost, weight and volume. Increasing the number of phases above 3 can be an interesting alternative in high-current applications where conduction losses are critical, or when reduction in the DC-link capacitor is required [17].

Another option is to cascade the DAB with a post-processing, non-isolated DC/DC converter, as seen in .Fig. 6. This is a configuration, which may allow a lower transformer voltage gain, where the rest of the voltage gain is made in the post-processing converter. As the winding ratio (voltage gain) has a direct impact on the transformer design, changing the winding ratio could potentially increase the transformer compactness, hence lead to a more optimized, overall converter design, even though the post-processing converter adds complexity and weight in added switches and passive components. A similar idea is investigated in [20] for a dual active resonant half-bridge converter topology, with minimally poorer performance compared with a conventional DAB topology.

The modular multi-level DC/DC converter (M2DC) has been investigated and compared to a full-bridge DAB for very high powers (15 MW-1.6 GW) and voltage levels (±5 kV - ± 30 kV). It has been revealed that the M2DC is not suitable for high voltage ratios because the circulating current becomes high, resulting in significantly poorer efficiency compared to DAB, while the DAB features high efficiency up to 99% independent of the voltage transformation ratio. In general, the M2DC equires a much higher number of semiconductors, increasing the investment cost for the M2DC converter up to 3 times the investment cost of DAB converter systems, and seems as an unfeasible solution for this application [21].

Considering high power ratings, the single phase DAB must be modified to accommodate high voltage and current stress of the power switches. For the MVDC level required for this application, either a modular series-input topology or series-connection of switches are required. Series connection of switches contains several challenges, either related to the design of the gate drive circuits or to the parameters spread of the semiconductor devices [22]. Timing shifts in the gate driver circuits, as well as, variations in stray inductances between the series-connected switches and unavoidable physical differences in the structure of the device can induce uneven distribution of the overall voltage across series-connected devices [22], [23]. Increased difficulties arise with increased switching speeds, thus with the use of high-speed SiC devices, special care must be taken when designing the topology, gate drive and auxiliary circuits.

The use of modularized topology avoids these issues. Several topology configurations (e.g. Input-Series-Output-Parallel (ISOP), Input-Parallel-Output-Series (IPOS) or combinations) exist [24]–[26], and are suitable for a wide range of high-power and voltage applications. Series connection of the input ports and parallel connection of the output ports enable higher input voltage and output current [24], a suitable configuration for this application. The modules make it possible to increase or decrease voltage and power ratings after specific application-oriented needs, and increase the reliability of the complete system as the converter can be made to operate at reduced ratings with malfunctioning modules. The output parallelization yields lower output voltage ripple amplitude and by phase shifting the bridges, the final output current ripple frequency can be further increased, reducing filtering capacitance needs for equal switching frequency, as shown in Fig. *5*. Modular topologies makes it possible to increase or decrease voltage and power ratings based on system requirements, and increase the reliability of the complete system by operating at reduced ratings with malfunctioning modules. The input can further be parallelized, yielding the topology shown in Fig. *7* to accommodate maximum current ratings of the semiconductors, which might be necessary for this application. Thus, modularized converter design may increase converter performance, power density and reduce and ease manufacturing cost with the ISOP configuration being the most promising candidate for MV to LV conversion [27].

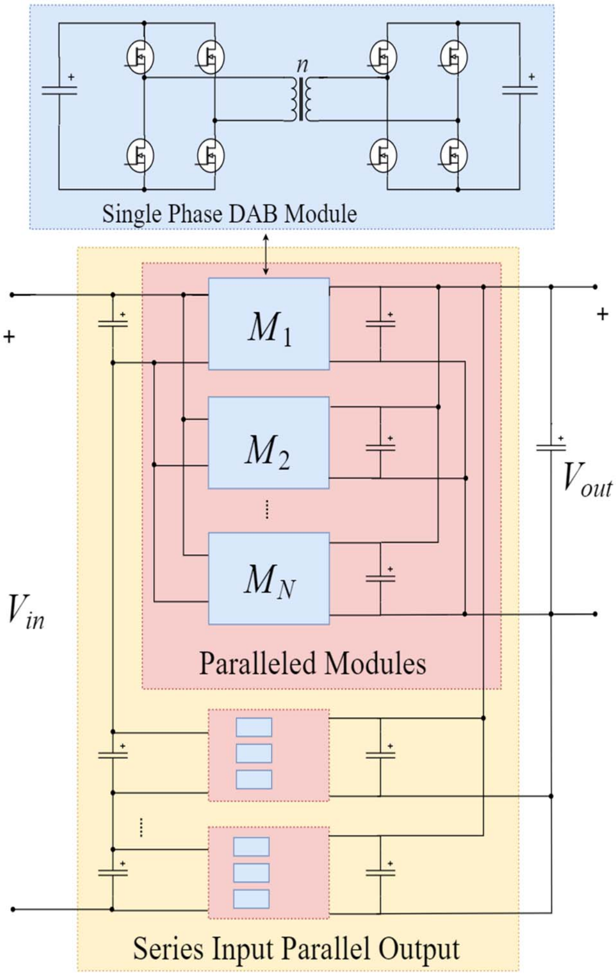


Fig. 7 - Possible converter configuration. Serial-Input-Parallel-Input-Parallel Output (SIPIPO).

TABLE II

Power density with various semiconductor materials. (*Water cooled. **Air cooled. *** Half - Bridge (HB) topology. **** 3-phase)

Topology	**Power Range [kW]**				
	≤1	1-5	5-10	10-100	100-1000
Conventional DAB	SiC 3.96 kW/l [16] SiC 4.3 kW/l*** [16]	SiC 1.132 kW/kg [31] Si 0.75 kW/kg [31] Si 7.1 kW/l [32]	-	SiC 1.9 kW/l, 1.39 kW/kg [33]	-
Resonant DAB	SiC 3.66 kW/l [16] SiC 5.5 kW/l*** [16]	SiC 1.1 kW/l [34]	GaN 10.5 kW/l, 9.6 kW/kg [35] Si 3.7 kW/l, 1.5 kW/kg [35]	Si 11.13 kW/l*, 6.6 kW/l**[29]	SiC >16.1 kW/kg[28] Si 1 kW/l, 2.5 kW/l****[36]

Higher switching frequency allows the design of smaller and lighter passive components. For this application, there are two key components that should particularly be focused on for designing the converter with as high power density as possible; the isolation transformer and capacitors. Both component weight and volume may significantly be reduced by increasing the switching frequency. Furthermore, one of the most vulnerable converter components under high pressure are the capacitors [4], since only certain materials are suitable for high-pressure environments. Reduced capacitance should be a design goal, and may be achieved by increasing the switching frequency and by selecting the proper converter topology. SiC power switches enables higher switching frequencies than existing high-power silicon IGBTs. However, higher switching frequency leads to increased switching losses and reduced efficiency, increasing the complexity of cooling system. Odd-phased DAB topologies, with a 3-phase CDAB depicted in Fig. *1* c) are reported to reduce the current ripple, thus reducing the required filtering capacitance. Optimal design of the isolation transformer is reported to significantly increase the converter power density, where in [28] a SRC DAB using air-core transformer achieves a gravimetric power density of 21 kW/kg compared to 8 kW/kg using ferrite core material. With the use of dielectric fluid as core material, with a higher relative permittivity and breakdown strength than air, the power density may further be increased, as insulation material may be reduced. An optimal solution should be investigated using multi-objective optimization. High power density should be emphasized during design to accommodate lightweight structures. A summary of reported gravimetric and volumetric power densities based on topology and power level is given in Table I. The use of WBG semiconductor materials (i.e. GaN and SiC) can increase the power density when similar topologies are compared. Higher power densities are reached using WBG devices, although high power densities are also reached using silicon IGBTs [29], [30]. It can further be noted that power density is sparsely reported in literature regarding DC/DC converters design, although having high importance in especially electro-mobility applications like electric vehicles, aerospace, and railway.

IV. CONFIGURATION EFFICIENCY SIMULATION

To evaluate efficiency performance of different configuration options, loss estimations are performed on the input-side full-bridge using PLECS and Simulink. The simulated system is a 200 kW rated DAB converter operating at a switching frequency of $f_{sw} = 100$ kHz where the switches on the input bridge use MOSFET simulation models and the output bridge use ideal switches. The switches on the input bridge are modelled using test-data on turn-on and-off energy for different drain currents and blocking voltages, $R_{ds(on)}$ temperature variations, gate driver and temperature conditions, as well as thermal impedances provided by the manufacturer. Using thermal and electrical simulations in PLECS/Simulink, switching and conduction losses are extracted. PLECS thermal simulation is highly advantageous as the RMS-current through the device in DAB-converters using single-phase shift modulation is complex. Furthermore, the $R_{ds(on)}$ and turn-on/off energies depend on device voltage and current, gate driver and thermal conditions. Both conduction and switching losses are thus complex values depending on several factors, hence thermal simulation provides both accurate and accelerated results. How the bridges and devices are configured is shown in Fig. 8. 4 configurations have been tested with the result given in TABLE III and Fig. *9*. The modules parameters are given in TABLE IV. Module 1 is a discrete SiC MOSFET. Modules 2, 3, and 4 is SiC MOSFET power modules.

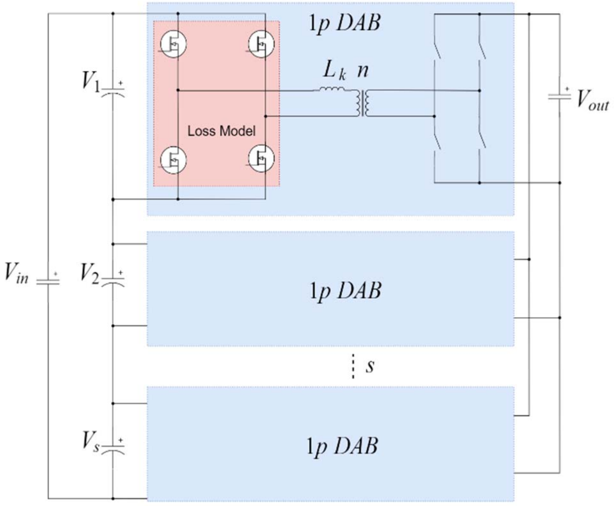


Fig. 8 - System configuration. The number of series connected 1-phased DAB ($1p$ DAB) is s. $P = 200\ kW$ with $f_{sw} = 100\ kHz$.

TABLE III

SIMULATION RESULTS WITH THE DIFFERENT POWER LOSSES IN KW

P_{sw} = Switching Loss [kW], P_{cond} =Conduction Loss [kW],
P_D = Diode Loss [kW], P_{tot} = Total Input Bridge Loss [kW],
M=Module Number.

$V_{in} = 5\ kV$		$P_{in} = 200\ kW$		$f_{sw} = 100\ kHz$	
M	s	P_{sw}	P_{cond}	P_D	P_{tot}
1	9	1.035	2.79	0.855	4.68
2	8	3.1	0.32	0.14	3.56
3	5	4.0	0.37	0.1	4.47
4	3	12.3	0.15	0.06	12.51

TABLE IV

MODULE PARAMETERS

M	Blocking Voltage	Bridge Voltage	$R_{ds,on}$
1	$V_{DS} = 900\ V$	$V_s = 555\ V$	$30\ m\Omega$
2	$V_{DS} = 1200\ V$	$V_s = 625\ V$	$4.2\ m\Omega$
3	$V_{DS} = 1700\ V$	$V_s = 1000\ V$	$8\ m\Omega$
4	$V_{DS} = 3300\ V$	$V_s = 1667\ V$	$2.35\ m\Omega$

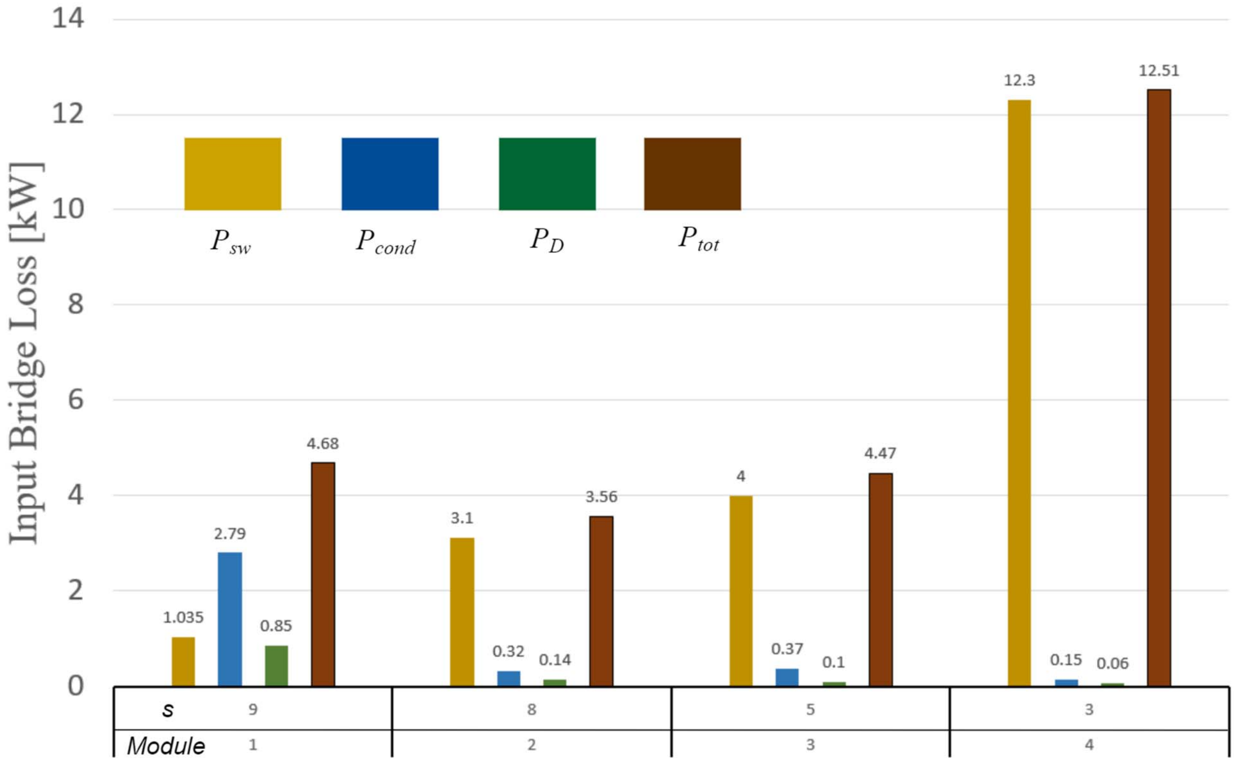


Fig. 9 - Input bridge losses. The number of series connected bridges are *s*.

V. CONCLUSIONS

The major design challenges of power electronic systems for deep-sea WROVs supplied by a MVDC grid are presented, focusing on pressure-tolerant power electronics and design of lightweight DC/DC converters. The power electronic systems need to be placed in high-pressure insulation fluid to allow feasible weight and volume of the ROV. Based on the reviewed literature, it is clear that open source research on pressure-tolerant power electronics is sparse, and further effort should be put on PTE research to develop reliable power electronic systems for high-pressure environments. For high-power MV DC/DC conversion, both resonant and hard-switching topologies are commonly used. Either series-connection of switches or an ISOP-type configuration should be used for the specified input voltage level, with the ISOP topology favored due to the challenges of series-connected switches.

From the electrical and thermal simulations, it is observed that module 2 produce the overall lowest losses. The power modules features significant lower conduction losses due to the lower $R_{ds(on)}$ than the discrete device, with the governing loss mechanism being the switching energy. As the device blocking voltage increase, the switching energy increase, resulting in higher switching losses, having large impact on the total losses at high switching frequencies.

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