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# How Modern Power Electronics can be used to Increase Payloads, Versatility, and Available Power for Subsea Power Deployment

## Abstract

A mantra for Unmanned Underwater Vehicles (UUV) and Remotely Operated Vehicles (ROV) might be as Scottie cried out on Star Trek, "I need more power!" The traditional method for deployment and conversion of power in deep sea autonomous vehicles often includes inefficient power conversions or bulky transformers. For battery powered Autonomous Underwater Vehicles (AUV), long umbilical cables for charging, transferring AC or DC power are hamstrung by low power delivery through their charging systems because there are few straightforward ways to provide high voltage to low voltage conversion subsea in a compact space. A key, perhaps *the* key, to solving this problem and having more powerful subsea systems is improving the efficiency and reducing the weight and volume of the power conversion system. Undersea power conversion using modern high performance wide band gap semiconductors can remove the inefficiency of hydraulic or 60hz transformer power conversion. For systems that use hydraulic power, the extra efficiency could result in aggregate power gain of more than 40%. For subsea medium voltage AC:DC conversion, this is uncharted territory, as it's typically only done at lower power levels because the size of traditional power converters becomes problematic.

The key to success involves reducing the size of the converter that powers the vehicle. Most "topside" transformers are far too large to go underwater, and subsea versions trade efficiency for size, adding cumbersome weight to the vehicle itself. The large size necessitates larger Launch and Recovery Systems (LARS) and reduces operational flexibility, resulting in increased deployment times. Alternatively, by removing these legacy methods of power conversion from the vehicle or docking platform and using subsea AC:DC or DC:DC power conversion at depth allows a reduced space claim and an electrically efficient system, enabling more power to be delivered to the mission with less effort needed to deploy.

## Introduction

This paper discusses a novel solution as an alternative to current topologies providing at-sea power conversion for autonomous systems. While focused on subsea systems, it may also be applied to autonomous surface vessels as the intent of the system is increased efficiency paired with reductions in space claim. Utilizing modern, commercial technology in a unique, stacked configuration provides both flexibility/scalability and system robustness.

## Current State and Limitations

The typical power flow path for a subsea tethered vehicle involves 480VAC or similar traditional low voltage sources from generators on the surface ship. Standard medium voltage 60hz transformers on-board the ship step this up to medium voltages, often in the range of 2-4kV. This is sent down an armored umbilical to a powered subsea cage, which serves to distribute power and provide a backup mechanical connection. Underwater vehicles then deploy from the cage on shorter, more flexible tethers where the high voltage electricity is traditionally converted to hydraulic power to perform mechanical work. Untethered battery powered AUVs with a resident charging center have a very similar main distribution umbilical—although they may run on DC instead of AC—and the topside power generation may be shore-based. They will typically charge a battery rather than operate on a tether.

The primary limit to the amount of available subsea power is the umbilical. These are typically 40mm or 42mm armored cables consisting of multiple conductors for AC or DC power, communications, and possibly fiber optic communication lines. These cables can be thousands of meters in length and are widely standardized in diameter such that changing out tooling for larger cables would be prohibitively expensive. This means a limited amount of current can be transferred without overheating (even in the depths of the sea). Although voltage will have limitations due to insulation dielectrics, usually it can be pushed much further than current. Typical maximum transmitted power may be in the range of 100-400kW.

Most existing systems use AC motors to operate hydraulic pumps, converting the electric power to fluid power. The hydraulic fluid power systems, commonly acknowledged for lower efficiency than electric power systems, have traditionally offered a much more compact way to make use of the power. In addition, hydraulics have a long history in the marine industry (including naval marine) and are well understood and time tested.

In practice, AC induction motors are typically used, and some basic control including soft starting can be handled top side. While this is simple system, it does not grant the ability to vary the speed of the motors as Variable Frequency Drives (VFDs) are typically not practical subsea, and it requires that all power is delivered at a fixed hydraulic pressure with no ability to divert the power to other assets.

The motor is used to run a hydraulic pump, converting umbilical electrical power into hydraulic power. From there, hydraulic manifolds can distribute and control the flow to hydraulic thrusters and tooling to provide mechanical work. In practice, this entire process from medium voltage electric power to mechanical work is less than 60% efficient.

In addition to low efficiencies, hydraulics tend to be large and heavy and have high risk of leaks, leading to environmental challenges that are increasingly closely regulated.

Since the overall system limitation is the amount of current that can be carried by defined conductor sizes, the relatively low power factor of AC induction motors further decreases the total amount of available mechanical power—beyond the loss from system inefficiencies. 60hz passive power factor correction is bulky and imperfect, compared to an active high frequency power factor correction unit.

The principal difficulty in deploying fully electric high power subsea systems stems from interfacing to high voltage buses. For AC deployment systems, a 60hz transformer could be used, but for high power this is large and bulky relative to most autonomous craft sizes, negating some of the advantages. If a frequency conversion device is used on the topside, a higher frequency can be sent down the umbilical to reduce the size of the subsea transformer. However, since umbilical impedance cannot easily be altered, as frequency increases reactive power will also increase, effectively diminishing available subsea power.

## Increased Demands Require Lighter and More Efficient Systems

Because of the demands of deep sea operation, it can be reasonable to suggest that subsea systems have led the way in unmanned and autonomous systems. From mapping the ocean floor to carrying and deploying payloads in unrelenting pressure and complete darkness requires, for the most part, some semblance of autonomy. And, as with any working sea vessel, managing ever increasing payloads, faster ways to deploy, and greater reliability place higher demands on power. In order to have more usable power, lighter and more efficient systems are crucial.

Solid state power conversion can address the size issues of low frequency systems. By operating at high frequencies, small transformers and magnetics can be used at high efficiencies.

## Traditional Options

Although high voltage solid state switches such as Metal Oxide Semiconductor Field Effect Transistors (MOSFETs) and Insulated Gate Bipolar Transistors (IGBTs) exist and are becoming more commonplace, they are expensive and often have worse performance than their commercially produced lower voltage counterparts. Many of the high voltage devices are packaged in hermetically sealed pucks or modules that are not pressure tolerant, making deep sea use impossible. In addition, increased switching voltage leads to increased dv/dt, increased switching losses due to capacitive energy storage and linear region losses, as well as potentially longer switching times. Increased dv/dt in turn can also lead to increased Electromagnetic Interference (EMI) related issues. Very often, higher voltage converters run at lower frequencies to combat some of these effects, resulting in larger magnetics and increased system size. As a result, even the common availability of high voltage devices does not provide the optimal solution. Although lower voltage semiconductors can be series stacked, there are additional complications to balancing and control, and the high dv/dt and EMI will still be an issue.

One common solution to high voltage conversion is a multi-level converter. While these solve many of the above concerns, they typically use thousands of switches to approximate a 60hz or low frequency sine wave, still using traditional 60hz magnetics. They also consist of bulky balancing caps, as the caps must operate at 60hz as well. While these tend to be the preferred method at voltages ranging from 100kV to 1MV+ for DC grid conversion, their size makes them a poor choice at the medium voltages used for subsea power distribution.

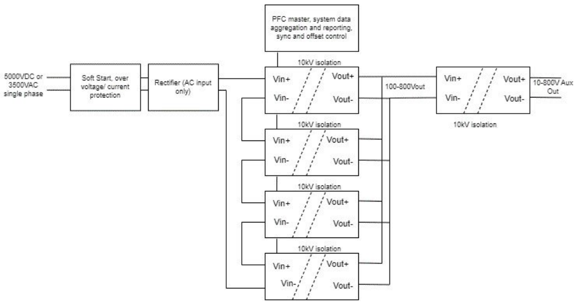
## A New Approach

Through a design of stacked low voltage isolated DC/DC power stages, a system is able to utilize commercial, pressure tolerant, lower voltage MOSFETs. Although IGBTs tend to become preferred at high power levels, the relatively low power output of any single stage can still be better optimized using MOSFETs. This, combined with proper circuit design, enables higher switching speeds which are not possible with IGBT's and eliminates the need for bulky and inefficient snubbers.

By utilizing wide-bandgap semiconductors such as silicon carbide and phase shifting the multiple stages, effective output switching speeds in excess of 1Mhz are possible, even when operating at voltages of 5kV+ and power levels of 200kW. This enables small magnetics and high power densities.

The modular approach also provides significant advantages to reliability and serviceability as systems can be built with N+1 modules. This design allows any single module or any piece of any module to fail during operation without negatively impacting system performance due to the hot redundancy. Systems for varied voltages and power ratings can be assembled without expensive NRE due to the modular nature of the design. Also, the system can easily have a single module serviced or replaced in the event of a failure.

Operating power stages in a stacked method requires innovative control schemes capable of maintaining stage balance while dealing with changes in output power. A fully digital system control scheme enables high quality monitoring and tight stage balancing.



*Design Topology*

## AC vs DC Input

A traditional AC to DC switched-mode power converter consists of two stages, a non-isolated boost power factor correction stage (PFC), and an isolated DC-DC stage, often a dual active bridge or phase shifted full bridge. The PFC creates a rectified, semi-regulated DC bus. For a three phase input, this PFC configuration is often a Vienna or modified Vienna Rectifier, possibly configured as a three-level converter.

This two-stage solution provides excellent impedance conversion. The AC system can see high power factors typically greater than 99.5% and the DC output can see excellent regulation and step response with no 60hz ripple and control loop speeds around 1-20khz. There are some downsides however. The addition of the intermediate DC capacitor bus and second switched magnetic stage results in double the volume and increased converter losses when compared to a single stage solution. High end two stage converters may operate at 94-96% peak efficiency with >90% typical. Also, the Vienna Rectifier will face many of the same difficulties of scaling up to higher voltage. While five or more level converters can be used in place of the traditional three-level converter to reduce dv/dt, it is much more difficult to eliminate the need for high voltage switches.

A distinctive approach is to run a single stage that combines the PFC, rectifier, and full bridge isolation. The isolation enables the use of three single-stage PFCs in a delta configuration, and the full bridge input enables the use of stacked DC stages to utilize lower voltage switches and all the advantages they provide. The delta configuration provides inherent support of single phase operation during fault conditions. The resulting converter can see efficiencies of up to 98% with >95% typical, in addition to doubling the power density.

Although buck PFCs such as the considered solution using a full bridge first stage typically operate at lower power factors, a novel architecture based on the stacked modules enables reaching >99% power factor at higher loads.

The main drawbacks of a single-stage system is that the output capacitor must carry the 60hz ripple necessary to maintain good power factor, and the step response must be on the order of 10hz to provide low harmonic distortion in the AC system. For a three-phase input, this is typically less than 3% voltage ripple during normal operation, but can be as much as 20% voltage sag during a large step change due to the intentionally slow response. While this is unacceptable for some applications, most high power devices including thrusters, pump motors, and actuators all transduce electrical power to the mechanical domain, and very few of these systems can respond at greater than 60hz. Furthermore, intelligent motor controllers can utilize control algorithms with voltage feed-forward, enabling constant power delivery even during transient conditions.

The ability to deliver lower voltage DC in the range of 350-800V as system voltage rather than medium voltage AC enables smaller point-of-load motor drives that are capable of being integrated with the thrusters or pumps, further reducing system size.

## Conclusion

For DC power systems (autonomous/battery powered systems), high frequency power supplies can reduce overall system volume and enable increased efficiencies through the use of higher voltage. For AC systems, a solid state AC-DC converter can enable direct electric vehicle power from a medium voltage umbilical, without the need for bulky and heavy transformers. A new generation of power conversion devices combined with flexible, modular topology enables efficient operation across a multitude of input voltages and powers.

This paper outlines a converter that uses a unique topology and modern high-bandwidth semiconductors to achieve modular conversion of both AC and DC inputs at medium voltages with high efficiency, high power density, high reliability, and easy configuration to different voltages and power levels. Such a converter enables the use of commercially available DC motor drives and can result in greater mechanical power transmitted to subsea assets using existing tether infrastructure.

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