Subsea Uninterruptible Power Supplies (UPS) for Local Holdup of Magnetic Levitating Bearings in Subsea Production Hardware

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Abstract

The use of batteries subsea has historically been limited to powering autonomous instrumentation for oceanographic applications with power capacities typically limited to less than a few hundred watt-hours. Over the past decade, engineering design and technology advances in subsea applications have led to an increased focus on battery technology, including increased capacity. In particular, the growth of the autonomous underwater vehicle (AUV) market in the early 2000’s lead to regular use of batteries subsea with capacities of up to tens of kilowatt-hours (kWhr).

In order to enhance production and maximize reliability of offshore fields, focus has increased on placing traditional terrestrial equipment subsea and incorporating electrically powered process equipment. Some of these applications have led to the deployment of large battery and UPS modules for subsea deployment. Notable applications include the recent development of 165kWhr battery modules for the Marine Well Containment Company (MWCC) to allow subsea pumping of dispersant from bladder fields to an uncontrolled hydrocarbon leak, and uninterruptible power supplies that have been marinized for holdup of critical equipment on compressors being qualified now for installation on the Ormen Lange oilfield.

This paper focuses on a concept system being developed and qualified for military applications, similar to the MWCC battery system. The focus is on a marinized pressure compensated battery module of 150kWhr, which can be daisy-chained or arranged in a hub configuration for up to 1.5MWhr of holdup capacity. This paper details original analysis on the application of these battery power modules to provide a UPS for dedicated use with magnetic levitating bearings common on subsea compressors and motors on subsea production systems. By providing a localized UPS system to the magnetic levitating bearing controllers, it is possible to provide a redundant power source, mitigating risk from failure of the primary subsea power supply. Coast down times for the magnetic bearings typically take just a few minutes and fit well within the voltage, current, and power supply levels of the UPS design described in this paper. The distributed UPS system design discussed herein utilizes a modular design. The modules discussed can be configured to allow for expansion and enhanced redundancy to be integrated subsea without the need for a unique qualification program.

This paper discusses potential applications of the UPS within subsea production equipment, including interface points, recovery, discharging, charging, and monitoring.

Background

Subsea Application.

As oil and gas companies explore deeper and more distant offshore natural resources, conventional resource extraction methods become prohibitively expensive and innovative subsea extraction solutions must be developed. Ormen Lange, a major oilfield, is currently in the process of building and qualifying subsea gas compression systems. These systems enhance resource recovery by reducing backpressure on the reservoir due to tieback distance and water depth.
The global trend of increased tieback distances and the increased start-up costs associated with deepwater wells have increased the fiscal incentives to optimize resource recovery, making subsea enhanced production equipment more attractive. Enhanced production equipment may include subsea separators, electric submersible pumps (ESP) or seafloor located pumps for oil extraction, and/or seafloor located compressors for gas extraction. The pump and compressor systems are driven by electric motors powered by a terrestrial substation, with subsea power controlled by switch gear and Variable Frequency Drives (VFD). The pump and compressor outlets are connected to pipelines, which traverse the seafloor to a processing station.

For gas systems, compressors operate at high rotational speeds to compress extracted gas to the pressures required to reach the processing stations. At these speeds, conventional bearings wear out quickly and require regular maintenance. Oil and gas companies require the highest possible uptime and reliability, and most manufactures utilize magnetic levitating bearings in their compressor systems.

**Magnetic Levitating Bearings.**

Magnetic levitating bearings (Figure 1) provide the same functionality as conventional bearings. The fundamental difference is that magnetic levitating bearings use strong electromagnets to levitate the through shaft, resulting in near frictionless conditions. Since there is minimal friction during operation, magnetic levitating bearings can operate extremely reliably at high rotational speeds, requiring no planned maintenance over extended periods of time.

During normal bearing and compressor operation, the electrical power that magnetic levitating bearings require is sourced from a DC voltage system. In the event of a power failure, magnetic levitating bearings lose the ability to levitate the compressor shaft and will fail onto auxiliary conventional bearings. These auxiliary bearings are able to withstand a minimal number of power failures. In order to increase reliability and reduce the usage of the auxiliary bearings during power failure, a backup power supply must be connected to the bearing controller. This power supply ensures that the magnetic levitating bearings are powered while the rotational inertia of the compressor runs down. Once the compressor completely stops, the magnetic bearings are able to follow their power-down sequence.

**Uninterruptable Power Supply.**

A UPS is a backup power system used to mitigate critical equipment failure or loss of function during power loss. If the UPS contains rechargeable batteries, it will have three main components: a battery bank, charging module, and controller. The battery bank is comprised of appropriately sized batteries with the ability to provide sufficient power for critical equipment holdup. Since batteries dissipate energy over long storage periods, the charging module ensures that they are at full capacity in the event of a power failure. The controller decides whether power should be sunk or sourced from the battery bank.

**UPS Applications for Subsea Power Distribution.**

Subsea UPS solutions can be configured in two arrangements. The first is a global solution which utilizes a large UPS system with switchgear capable of supplying all low voltage loads within the field. The second is a local solution which utilizes a separate UPS solution for each piece of equipment that requires holdup.

Both solutions, local and global, have merit and need to be assessed based on the application in question.
**Functional Architecture**

There are two fundamental UPS architectures: online and offline. Online systems are placed between the main power supply and the load, whereas offline systems are run parallel to the main power supply, only providing power in the event of power loss. Typically, online systems are not used in magnetic levitating bearing UPS applications, as recovering the UPS requires de-energizing the system, and thus will not be discussed in this paper.

Offline functional architecture is most frequently employed in magnetic levitating bearing UPS applications. Since offline UPS configurations run in parallel with the source power, they can be recovered without completely de-energizing the magnetic levitating bearing system.

The UPS functional design discussed here incorporates a configuration of up to four separate modules designed to maximize flexibility in architecture and utilize a building block development that minimizes the need to re-qualify a system for alternate applications.

Figure 2 shows a UPS system with an input interface module, UPS interface module, UPS module, and output Power Conversion Module. Figure 3 is a depiction of a UPS module (UPSM) with three independent 50kWh battery strings.
**Input Interface Module.**
Enclosed in the input interface module are two optional components: voltage conversion and media conversion. Voltage conversion provides the ability to adjust customer voltage levels to match UPS native battery voltage. Depending on source voltage specifications, this component may not be required. Media conversion is only required if source media specifications differ from UPS media requirements.

**UPS Interface Module.**
The UPS interface module contains OR-ing blocks and a fuse isolator. The OR-ing blocks sum the UPS module power outputs, as well as their media outputs. The UPS interface module takes inputs from the input interface module if power and media conversion are required, otherwise the UPS interfaces directly to the customer source.

**UPS Module.**
The UPS module is the central module of the UPS system. It provides core UPS functionality, and contains the majority of the system complexity. The UPS module contains the UPS electronics, medium voltage (MV) circuit breaker, control computer, ethernet switch, and battery bank. The ethernet switch and control computer are responsible for monitoring and controlling the MV breaker, UPS electronics, and battery bank. The battery bank can be configured to contain up to three separate 50kWh strings, providing a maximum capacity of 150kWh. When UPS power is requested, the UPS electronics and MV breaker allow requested power levels to flow from the battery bank to the load. One unique feature of this design is the ability to utilize the connection of multiple battery strings within a UPSM to allow for scaling and redundancy, depending on the application, without the need to create a new system design.

**Power Conversion Module (PCM).**
The PCM is an optional component. If the customer load requires a voltage which differs from the native battery bank voltage or requires a constant output voltage over the entire state of charge range, a PCM is required. This module contains three major components: the ethernet switch, control computer, and output voltage converter. The ethernet switch and control computer are responsible for monitoring and controlling the output voltage converter ensuring precise, steady output.

**Batteries**
One of the major considerations requiring attention with subsea equipment is the high external pressure that components must withstand. One methodology to address this is to place the entire subsea UPS system in a single one-atmosphere housing to simulate operation in a terrestrial application and to minimize the changes to the UPS system from proven terrestrial solutions as required by the marinization process. However, the approach described here separates components into functional blocks and leverages the ability of certain components to tolerate the ambient pressure at depth. One major component of a subsea UPS system that can be specified as pressure tolerant is the batteries.

Multiple battery chemistries are available and some can be pressure compensated, the battery chemistry utilized in the testing was absorbent glass mat (AGM). Submersing AGM batteries in a pressure balanced oil filled (PBOF) environment allows them to handle the required subsea pressures. AGM batteries were selected for a number of reasons, including safety in handling, lack of restrictions in transport and storage, costs, proven performance in deepwater applications, and their suitability to the load profiles and discharge cycles expected for this application. The batteries were tested against the two load profiles defined below. Charging characteristics have also been analyzed against charging batteries from state of charge (SOC) levels associated with three rundown.

Substantial qualification testing with AGM batteries in a PBOF environment has been completed for UPS applications for other loads [1].

AGM battery performance is heavily dependant on ambient temperature and age. As ambient temperature decreases, AGM battery capacity significantly decreases. Since subsea temperatures reach as low as 4°C, battery capacity can be reduced by as much as 30 percent. AGM battery capacity will also decrease with age. Over a five-year lifespan, AGM battery capacities are expected to decline by 25 percent. Based on this information, worst case limits of 45 percent SOC (relative to a new battery at room temperature) will be considered the lowest possible SOC before charging is required.

**Performance**
Based on information provided from two different subsea engineering, procurement, and construction (EPC) providers, two load profiles have been analyzed against a 144AH AGM battery.
LOAD PROFILE ONE – Local UPS supply: The first profile is for a single compressor in the 10 to 15MW range, with the UPS system providing power holdup only to the magnetic levitating bearing system on the compressor and motor, to provide full operation of the magnetic bearings until the compressor can be safely released onto the auxiliary bearing sets.

LOAD PROFILE TWO – Global UPS Supply: The second profile corresponds to the use of the UPS to hold up all low-voltage power requirements within a concept field, including the magnetic levitation bearings on two 12MW compressors, high voltage switchgear monitoring equipment, and the subsea production communication and instrumentation loads.

The test setup for this paper consisted of a single 12V 144AH battery connected to a load bank for discharging, and a power supply for charging. The load bank was programmed with the current profiles associated with load profile one and load profile two, to accurately simulate system performance. Charging was completed at 20A, the maximum current rating of the power supply. In order to output the required power for a magnetic levitating bearing application, multiple batteries can be placed in series, which will not affect the current output or SOC levels. Figure 4 shows a one line diagram of the test setup used.

![Diagram of test setup](image)

Discharging.

It was assumed that the UPS system should be able to provide enough energy for three consecutive rundown cycles at the end of life. Load profile testing has been completed against this requirement. Tables 1 and 2 show both rundown load profiles analyzed.

<table>
<thead>
<tr>
<th>Load Profile One</th>
<th>Load Profile Two</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Duration (min)</strong></td>
<td><strong>Power (kW)</strong></td>
</tr>
<tr>
<td>10</td>
<td>9.0</td>
</tr>
<tr>
<td>3</td>
<td>50.0</td>
</tr>
<tr>
<td>10</td>
<td>10.0</td>
</tr>
<tr>
<td>15</td>
<td>3.0</td>
</tr>
</tbody>
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Load profile one requires a total of 1.5kWh of energy for a complete magnetic levitating bearing system rundown. Based on the load test results, one complete magnetic levitating bearing rundown profile requires 13.6 percent UPS SOC (Figure 4 and Table 3). After three complete magnetic bearing rundown profiles, 25.0 percent UPS SOC was consumed (Figure 5 and Table 4). These results show that the proposed UPS capacity is able to provide over double the required number of rundown.
Load profile two requires a total of 4.9kWh of energy for a complete system rundown. Based on the load test results, 18.6 percent of total UPS system energy was consumed during a single rundown (Figure 6 and Table 5). Three consecutive rundown resulted in a 32.9 percent consumption of total UPS system energy (Figure 7 and Table 6). These results show that the UPS capacity nearly doubles the requirement of three consecutive rundown.

Table 5: Load Profile Two; Single Rundown Results

<table>
<thead>
<tr>
<th>Voltage (V)</th>
<th>Difference (V)</th>
<th>SOC</th>
<th>SOC Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start:</td>
<td>13.16</td>
<td>96.5%</td>
<td></td>
</tr>
<tr>
<td>End:</td>
<td>12.88</td>
<td>77.8%</td>
<td>18.6%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
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<th>SOC</th>
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</thead>
<tbody>
<tr>
<td>Start 1:</td>
<td>13.16</td>
<td>96.5%</td>
<td></td>
</tr>
<tr>
<td>End:</td>
<td>12.88</td>
<td>77.8%</td>
<td>18.6%</td>
</tr>
<tr>
<td>Final:</td>
<td>12.64</td>
<td>63.6%</td>
<td>6.8%</td>
</tr>
<tr>
<td>Capacity Used:</td>
<td>18.6%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Charging.
The UPS design is capable of handling a maximum charging current of 25.0A at a charging voltage of 14.4V/battery, equating to a maximum charging power of 360W/battery. If a UPS with a required native voltage of 300V is specified, the maximum charging power is calculated as follows:

\[
\frac{360\ W}{\text{Battery}} \times \frac{300\ V}{12\ V_{\text{Battery}}} = 9.0\ kW
\]

The UPS is completely charged when its system voltage is 14.4V/battery (360V for a 300V system) and charge current is less than 2.9A. Figures 9 and 10 show charging voltage and current results from a 20A charge current on a 144AH battery, for rundown profiles one and two, respectively. These charge profiles reflect battery SOC levels corresponding to three complete run downs; at a 20A max charge current, load profile one requires 112 minutes to charge completely, whereas the load profile two requires 180 minutes to charge completely.

Physical Architecture

UPS Layout.
As described in the functional architecture, there are four separate components to the UPS design: an input interface module, a UPS interface module, a UPS module, and a power conversion module (dependant on application). Subsea magnetic levitating bearing UPS applications are considered for depths of over 3,000 meters resulting in extreme pressures; careful consideration must be taken with physical architecture.

The input interface module and power conversion module are both housed within one atmosphere pressure vessels. The UPS module is split into two separate modules: the UPS interface module and UPS battery module. The UPS interface module is housed in a one atmosphere pressure vessel, while the UPS battery module is housed in a PBOF environment.

The UPS components are contained within a standard ISO container footprint (e.g., Figures 11 and 12), allowing for easy transportation, deployment, and recovery. All component interconnections are dry-mate, and therefore must be connected on the surface before deployment. UPS input and output connectors are wet-mate, allowing subsea connection for magnetic levitating bearing power and source power. The wet-mated connectors can be operated by a remote operated vehicle (ROV).
Deployment & Recovery.
One of the primary benefits of utilizing a dedicated UPS system for the magnetic levitating bearings used on subsea compressors is the ability to deploy and recover the system easily, as the UPS physical architecture is modular in design. The small size of the UPS module (20' x 8’ x 4.25’) allows for recovery with a standard offshore service vessel. The inherent redundant nature of the system also allows for notification of failure and planned maintenance. Given the small physical size of the unit spares can be kept on shore for rapid deployment. Utilizing a single module design that can be stacked and run in parallel ensures that a basic UPS building block can be used in multiple fields and applications, increasing design flexibility.

Scalability

The UPS system described in this paper is one variation of many available systems. Depending on power input specifications and output requirements a UPS system can be reconfigured for various applications. Different arrangements and combinations of components allow for scalability in voltage, current, and capacity.

Voltage Scaling.
Magnetic levitating bearing voltage requirements vary between manufacturers. The UPS design is voltage scalable through two methods: voltage conversion or scaling the native UPS voltage.

Voltage conversion requires an extra power conversion module, which interfaces directly with the UPS module. A power conversion module provides the ability to easily scale output voltage to any requirement via software. Voltage levels remain constant through the entire UPS state of charge (SOC) range, producing a steady voltage spectrum. The advantage of this design is that a single UPS battery voltage can be standardized and qualified for multiple applications reducing costs related to expensive qualification. However, voltage conversion significantly increases system complexity.

Scaling the native UPS voltage requires modifying the number of batteries within the UPS battery bank. This method is simpler and more cost effective (no need for power conversion module), though it has potential drawbacks. Since there is no power conversion module, the output voltage cannot be regulated and will decrease as the UPS SOC depletes. If voltage tolerance is outside the system tolerance, power conversion must be used. As well, it is necessary to qualify the UPS battery bank design for each output voltage, resulting in increased schedule and non-recurring expenses.

Current Scaling.
Current is limited in a UPS system design by the current capacity of the connector ports. Care must be taken at the time of initial design to ensure that these components are selected with sufficient capacity to meet present and future needs. The UPS system described herein has a local limit to its available current based on the selection of connectors and wiring. The architectural arrangement described can allow multiple systems to be incorporated in parallel to provide the required current capacity.

Capacity Scaling.
UPS capacity is heavily dependent on discharge rates. One UPS unit is capable of 150kWh of energy, however if greater UPS system capacity is required, additional UPS modules can be connected in parallel. Similar to current scaling, the UPS design allows additional UPS modules to be connected together, providing a simple and effective method of capacity scaling (Figure 12).
Redundancy

Reliable long term deployment is critical in a magnetic bearing subsea UPS application. The UPS system contains components which can be run in parallel with a redundant set of components, increasing system reliability. Some of these components may include, but are not limited to, the UPS electronics, ethernet switch, and control computer.

Battery bank redundancy is another critical issue. The UPS design discussed can be configured to include n+1 redundancy: (n) components, with the addition of one independent backup component (+1). This n+1 redundancy ensures that system availability will not be affected if one battery bank module fails. In the event of a battery bank module failure, the failed module can be removed and replaced subsea, without system down time and improved system reliability.

Conclusion

Advancements in subsea technology have motivated oil and gas companies to place equipment directly on the seafloor near the well head at greater water depth and increased tieback distance. This trend will likely continue to grow as the potential fiscal benefits of extending or increasing production levels with power loads subsea increase.

UPS technology for magnetic levitating bearing holdup on subsea process equipment is critical to ensure system integrity in the event of a failure to the mains power supply. The described UPS design offers a novel option to mitigate the risks associated with power failure.

Subsea processing system designs must focus on the modularity, recovery, and interface designs to minimize the need to develop and qualify a unique solution for each application, minimizing costs and minimizing schedule for deployment.

The flexibility inherent in the architecture discussed allows for qualification to be performed on a number of discrete components that can then be organized in multiple configurations to meet the power and current requirements of various subsea process loads. The architecture also provides the ability to deploy scalable systems that can be augmented based on field needs in the future.

The test and qualification performed to date shows that UPS systems, using a pressure compensated batteries and a modular design, can accommodate a variety of subsea load scenarios envisioned for fields today and in the future.

References