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Leveraging Technology to Deliver Performance Objectives SESSION

Mesh Networks and “Halo” Machines, A Marine Technology Power System Reset?

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Abstract

With the continuous drive for Reliability, Redundancy and Resilience as well as Efficiency, Reduced Crewing, simplicity and autonomy it may be a time for a rethink of how power systems are arranged, connected and operated. The challenges of single prime mover operation, single bus protection, short circuit testing, higher and higher fault levels, harmonics, switching losses, drives with more and more levels and bridges are becoming more and more complex challenges to existing power system architectures. The paper proposes that a complete reset and simplification could be possible and is currently being proposed and tested. The ships on board grid could be revolutionized, simplified and reduced in size, cost with a step change in resilience. This architecture transcends traditional DC and AC and current power electronic approaches. Using Halo machines and mesh networks, separate variable speed drives and switchboards can be removed, and a much more resilient power network could be realized. Lower Losses, Lower footprint, Less cabling, self-healing and higher availability. The Author will introduce how such a system could apply to a DP3 ship and the potential benefits it could bring. This is a power system as you have never seen it before, solid state, switchboard free, variable speed drive free efficient and resilient operation with only a handful of moving parts and a self-healing mesh network.

Abbreviation / Definition

AC	Alternating Current
DC	Direct Current
MV	Medium Voltage
LV	Low Voltage
QPS	Quality of Power Supply
ASM/G	Active Stator Motor/Generator
DP	Dynamic Positioning
IP	Ingress Protection
CACW	Closed Air Closed Water
LRU	Line Replaceable Unit
PWM	Pulse Width Modulation (Converter Drive Technology)
HALO	Not an Abbreviation, an Architecture that uses Machine Rings

Introduction

Electrical systems are inherently flexible, and configurable compared to mechanical systems, but they can have size and weight challenges, and also whether they are AC or DC they have relied on redundancy, additional switchboards, cabling to give them enough resilience. The author proposes that there is hidden redundancy within electrical machines and convertors that could greatly add to the resilience of power systems if it could be liberated.

Reimagining the Integrated Power System

What if we reinvented the HV electrical power system completely, looking at it from both the shipyard and customer perspective? Using lessons learned from decades of design and operational experience across a fleet of hundreds of vessels has resulted in the following considerations and objectives.

Challenge

Aims:

- Reduced size and weight, cabling, moving parts, ***acquisition*** and through-life cost.
- Increased resilience and graceful degradation
- Don’t redesign everything, so the maturity is lost
- No reliance on exotic and expensive materials e.g. cryogenic cooling, superconducting etc, just copper and steel.

Leading to framing the challenge, what if there was a power system architecture that:

- Removed all power and propulsion (P&P) switchboards and separate convertors
- Enabled enhanced connectivity and resilience.
- Significantly reduced cabling terminations
- Had no moving parts in distribution system
- Was inherently quieter and more efficient than current solutions
- More resilient that current HV electrical power systems by releasing untapped resilience within machines and drives
- Removed single point failure star points

This has led us to consider an architecture for the future, that is being developed and tested today at MW scale.

The Active Stator Machine

The first element to underpin the new architecture is an electrical machine with an active stator, as opposed to a passive stator, which is just copper and steel. An active stator has switching elements within the stator windings.

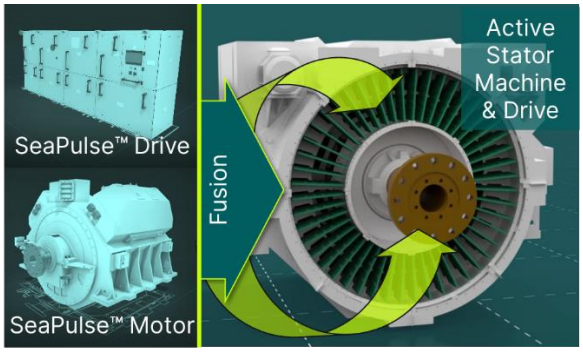


Figure 1 The GE Vernova Active Stator Machine

This 3MW second-generation machine, Figure 1, has been on test for the last 12 months, and is now commencing land-based integration testing. It combines the drive's power electronics into the machine, not just physically, but electrically, so individual phases are operated by separate power electronics. There is no such thing as 3, 6 or 9 phase anymore. This machine has 48x2 "phases", or "torque producing elements" connected to two pairs of DC endrings.

This is a true DC machine, with a permanent magnet rotor. There are no AC sine waveforms, there is no PWM (pulse width modulation) switching required to synthesize a sine wave. The machine, therefore, has no PWM high frequency noise or switching losses or dV/dT insulation stress. With 48 phases that can be operated independently, it has a huge amount of redundancy and resilience inherently within the machine. Also, with improved winding factors and enhanced torque-producing wave shape, it is inherently smaller than equivalent AC permanent magnet machines.

The 96 phases add no complexity to the stator windings; the windings, corepack and permanent magnet rotor construction are the same as a standard machine, just copper and iron with no exotic materials or cooling media. In fact, due to no PWM waveforms, the insulation is reduced, and due to the removal of the three phase end rings, it has significantly fewer brazed electrical connections than a standard AC machine. The changes to the machine are in the endwinding area, where the endwindings now connection to power electronics called "Coil Drivers" and these connect to DC rings which replace the AC rings. The machine cooling is standard CACW (Closed Air, Closed Water) with a water- to-air heat exchanger on the machine, with the power electronics being cooled directly by water on the end of the machine.

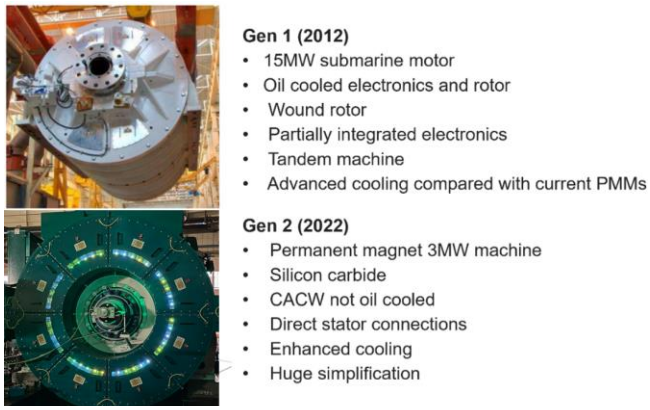


Figure 2- Active Stator Generations

This machine has its origins in the generation 1 active stator machine shown in Figure 2 which was built in 2012. It was remarkably compact, but due to limitations of available power electronics and the cost of permanent magnets at the time, led to a complex machine, mechanically and from a cooling perspective.

The new generation machine is physically and mechanically much simpler. Generation 2 active stator machine takes advantage of greater permanent magnet availability and industry-standard silicon carbide, switching devices to produce a dramatically mechanically simpler and more compact machine with standard water-cooling techniques. The machine is not only compact and contains the power electronics but offers significant advantages over the AC permanent magnet machines in the market today. The physics in this technology is inherently low loss and quiet, removing some of the major noise-producing elements in current machines.

The number of stator slots and copper bars, and indeed power electronic devices has not increased, they are simply the same windings within the machine, applied better, both electrically and physically, to produce enhanced torque and resilience. It uses a standard permanent magnet rotor and the well-proven standard classical stator corepack, but with reduced insulation stress, releasing the true polyphase machine smoothness and redundancy that has always been hiding inside current 3/6 phase machines.

Liberating Hidden Redundancy

Now let's consider how we might use this remarkable machine.

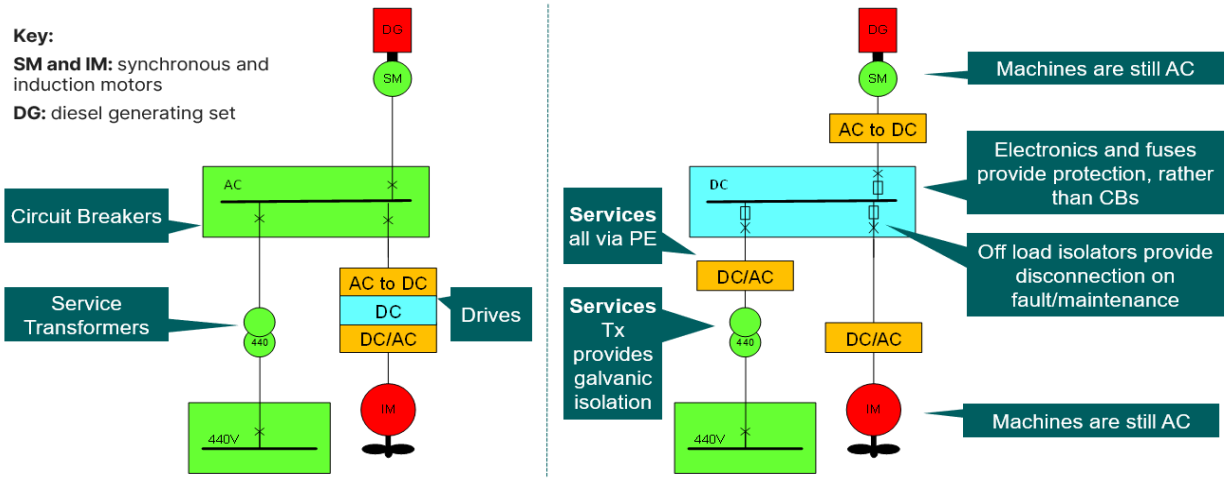


Figure 3 shows the current standard building blocks of AC and DC marine architectures full electric systems, from

Figure 3 - Basic building blocks of a) AC and b) DC marine power system architectures

engine to propulsion motor. AC systems have switchboards and circuit breakers and electronics packaged within discrete drives, as well as transformers for services. Modern DC systems often remove the circuit breaker, moving electronics from the drives and brings them into the DC switchboard, acting as both control and protection. AC normally packages all the power electronics in a single, separate drive between the switchboard and Motor. DC splits up this drive and puts one bridge on the generator and the other on the motor, but physically often houses both bridges within the DC switchboard.

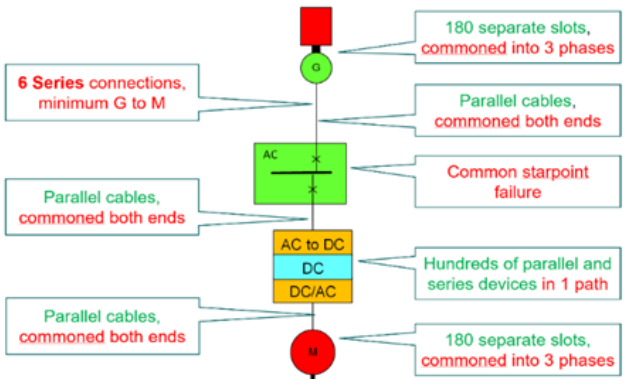


Figure 4- Opportunities for redundancy (Green) but lost in existing systems (Red)

Both solutions require plant between the generator and motor. Whilst all are still actually using AC machines at the top and the bottom. All this intermediate plant takes up space and requires cabling and cooling.
Let's also consider the resilience and redundancy and the lost opportunities in almost all current systems (Figure 4)

The motor and generators have many separate slots and windings within the machine, but we braze them together into a single set of three AC endrings. This ensures that any single fault anywhere takes down the complete machine. We

run cables, often with parallel cores, but then common-up both ends, ensuing any one failure takes down all the individual cables.

We have a switchboard that is a star-point failure for all the connected equipment, so if there is a bus fault, often 50 per cent of the ship's equipment is lost. Finally, we put all the electronics in a drive, (or in the switchboard sometimes for DC), we make this 3 phase, despite hundreds of IGBTs in the circuit at drive, module and device level, with the result a single point failure takes out the whole drive or bridge.

We clearly do not maximize the inherent redundancy already available within the existing parts. Of course, we add parallel generators, switchboards, drive channels, motors, and can dual-wind machines, but there must be a better way to release the inherent redundancy in the system. That's what we will consider here.

First, let's consider how the active stator machine repurposes the machine endrings that already exist within all AC machines. The photograph on the left of Figure 5 shows the endrings of a "Dual Wound" 6 phase machine; this is typical of a machine with 50/50 redundancy.

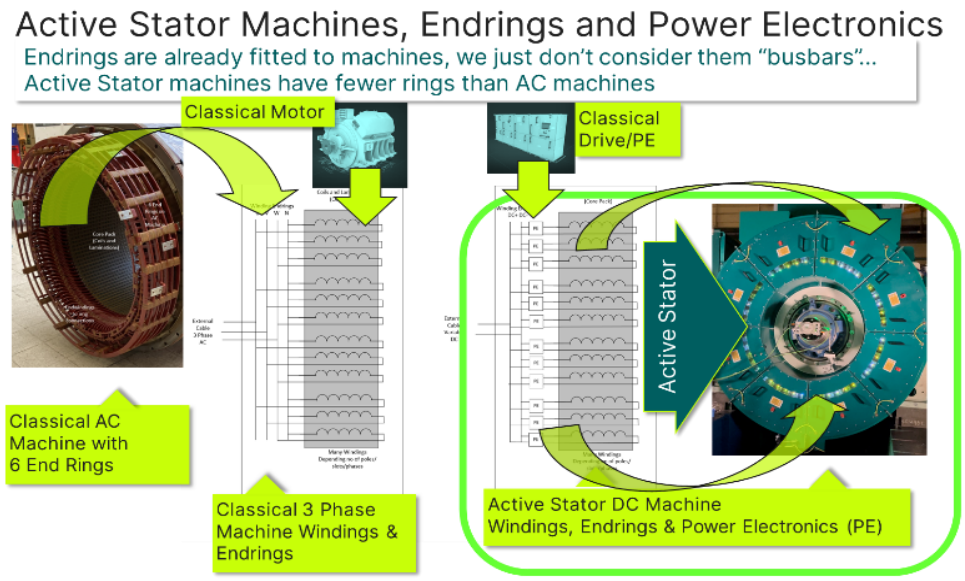


Figure 5- Making better use of machine end rings and windings

The diagram on the left in Figure 5 shows a simplification of a 3-phase machine with four end rings, 3 phase and neutral, where all the windings are brazed to the end rings, and any single point failure results in loss of the machine.

The diagram on the right shows the active stator arrangement, with the endrings now being DC, with electronic switches between them and the windings. Each of the 96 elements can be switched in or switched out for efficiency or if there is a failure. Rather than not tolerating more than one winding or Device failure, this machine could in theory up to 95 failures before stopping.

How do we fully use this new redundancy that has always been there and is being liberated, It commands an equally ground-breaking approach to the architecture.

The Active Stator "Fusion" Machine in a Full System - The "Halo" Architecture

Figure 6 shows a Halo machine in the centre, with a classical system on the left and a Halo system on the right.

The Halo system is all DC, *including the machines*, with the bus sections and bus-couplers now housed within the machine itself, so we have no need of switchboards (replaced by the machine DC rings), and with all the motor and generator power electronics housed within the machines, we have no need of separate drives either (replaced by the coil drivers). It would be foolish to take 96 phases and all that individual resilience and connect them to one set of

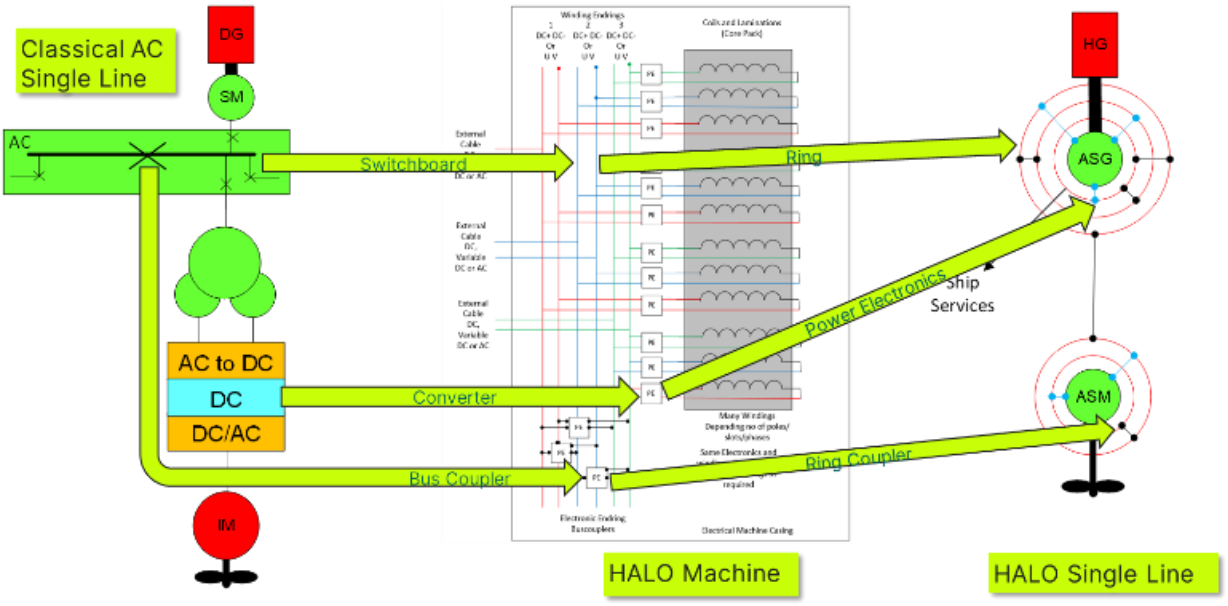


Figure 6 – Replacing classical system elements with Halo equivalents

busbars, so they are connected here to three sets of DC busbars. There is also a simple ring coupler switch between end rings to 'common' them if required. (replacing switchboard bus couplers). The stator windings, rotor and corepack are all identical to the classical machines. The machine endrings have always been there. The only new element are the integrated electronics on the endwindings.

How do you draw a single line power diagram when there are no switchboards and no drives? It requires a different approach.

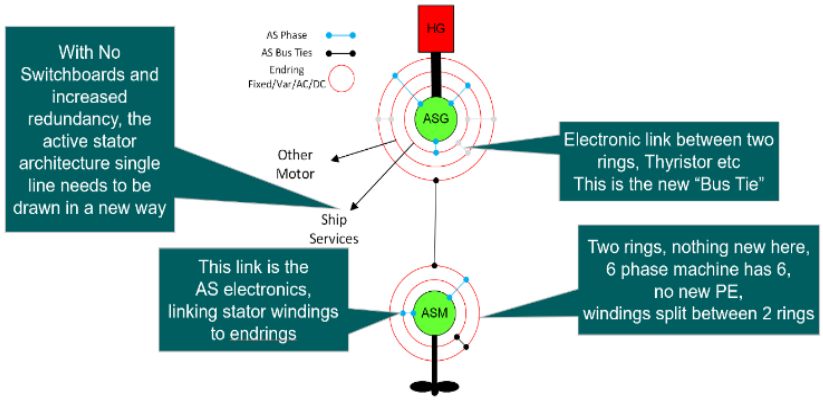


Figure 7 Building blocks of the active stator Halo architecture

Figure 7 shows the new building blocks of the active stator "Halo" architecture, with one generator and one motor.

The internal endrings (which have always been hidden within machines) are shown as red rings around the machine, the blue links are the Active Stator power electronics, The motor is drawn here with two DC rings, each depicting a DC pair, and a black bus coupler so that they can be operated together or separately. In essence the 96 phases or "individual motors" are split 48 on each DC bus connected via the blue power electronics with a black bus coupler between the rings. On the generator we have three rings, so the 96 phases are split between three sets of DC bus rings, still with two bus couplers

.

What is now possible here is to allocate rings to either propulsion or services and reconfigure via software and power electronics as required. Within a single generator, for example, we have the ability to run three split buses, one to services, two to propulsion, all electrically separated, with each bus having 16 mini generating elements. Remember, there are no more endrings than a normal machine, also the stator corepack, windings and the rotor are all standard, so the active stator liberates a great deal of redundancy that has been within the machine but never exploited.

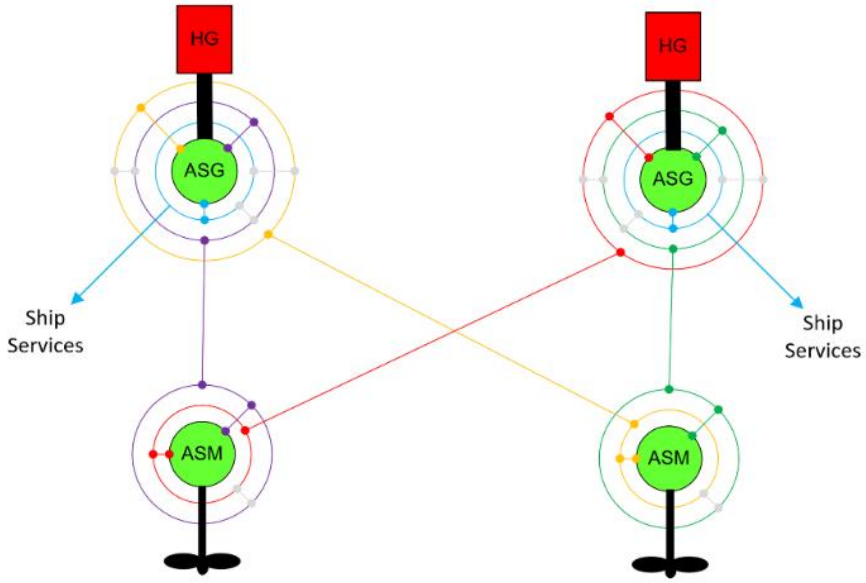


Figure 8- Halo System with four machines - Six Electrically Separate Islands

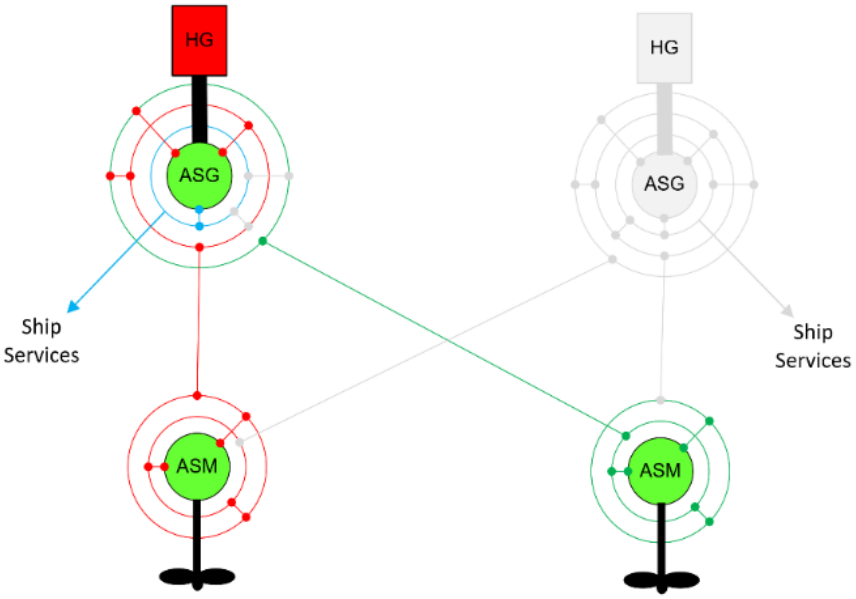


Figure 9 - 3 Halo System Island Split bus operation with a single prime mover

Instead of a single point generator failure, there are now 96 elements that can fail and be isolated, split into three buses, all within a single unit. The electronics are fitted in the space of the endwindings of both generator and motor and they provide protection for the system, just like a DC system at present. Additional compact electrical or mechanical air gap isolation is fitted in the cable boxes if required.

Now you have this measure of redundancy and flexibility, it really comes into its own when your start to build a system with it.

Any combination of generators and motors can be fitted into the system. Figure 8 shows a two generator, two motor example.

The different "islands", or independent circuits, are shown in different colours, so with just two generators and two motors we can have four separate distribution buses.

Immediately a huge amount of flexibility is released, including modes that are not possible on current systems. For example, in figure 9 we have single prime mover mode, split bus, with three separate buses, two for propulsion and one for services.

Comparing Halo with Classical Redundancy

Let's compare Halo redundancy in Figure 10 with the classic system that was shown in figure 4.

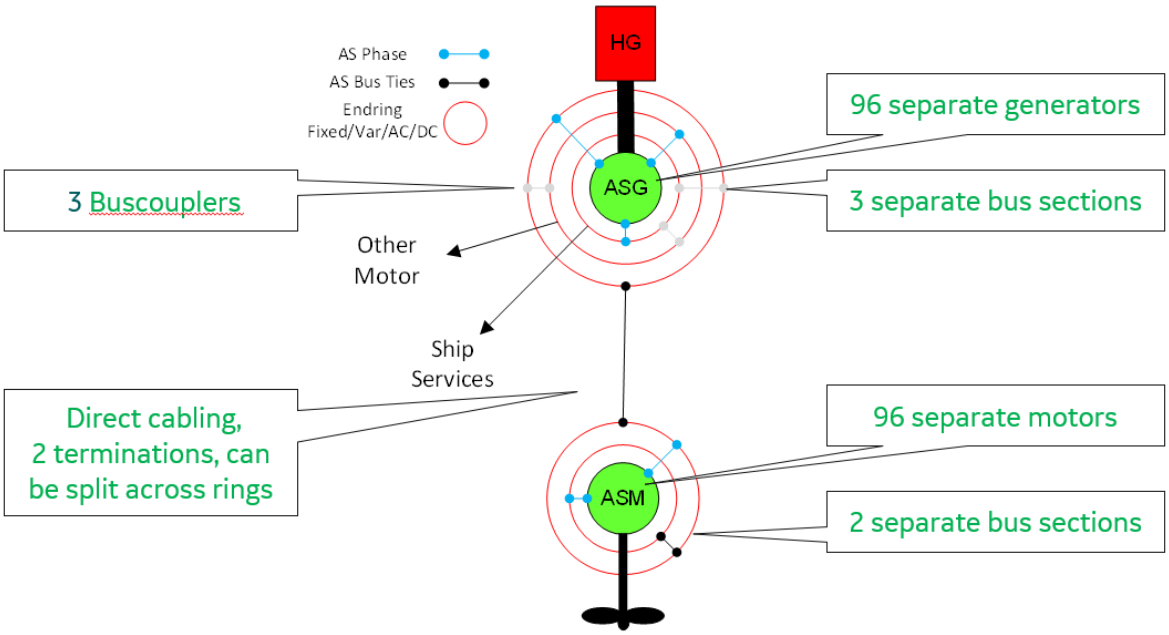
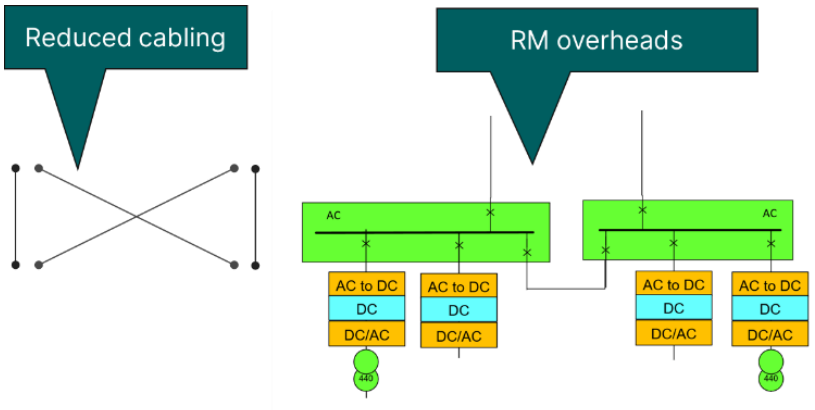


Figure 10- Halo Redundancy Comparison

The switchboard star-points are removed, each rotating machine has 96 individual elements, with either two or three sets of DC end rings, and associated bus couplers, so in two machines there are five bus sections, 192 separate winding elements and real mesh connection opportunity with other machines, remember this is with no *more end rings, and no more coils than a standard machine*, and a standard rotor. Also, the *power electronics are now distributed and smaller, rather than centralized and larger in a drive*.

With this much graceful degradation there is a real argument to not replace any units if they happen to fail until return to harbor. This could be significant, not only for lean-crew operation, but also for autonomous vessels.

Cost Savings for Shipyards & Liberating Space



Let's look at the balance of plant removed, when we consider the new system against the old. If we remove motors and gensets from both systems, what are we left for the shipyard to integrate?

Figure 11 shows that it's just the cable for Halo, whereas there is much more additional equipment for the classical system, including switchboards, drives, transformers and their associated rooms, cabling and cooling (right).

Figure 11 - Besides gensets, what is left for the shipyard to integrate, Halo vs Classical

Figure 12 shows the IP (ingress protection) ratings and cable terminations between equipment in a classical vs Halo system. Rotating machines can also be rated at IP56/67, much higher than switchboards or drives, so they can be sprayed with mist or fire hoses directly on HV, which is all within the box.

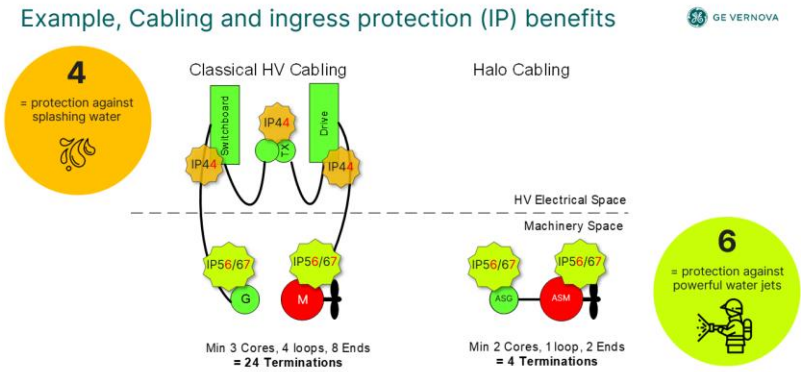


Figure 12- Cabling and IP firefighting benefits

Apart from the rotating machines, the shipyard only has to integrate the cables, the number of which is potentially greatly reduced as shown in Figure 12, which shows how in a classical system, power is connected, generator to switchboard to transformer to drive to motor, with up to eight series terminations. With Halo, there are only two, saving a large number of terminations (cable lugs) for the same power whilst actually increasing resilience.

Fault levels are much lower, not only because the system naturally has smaller elements, but unlike PWM systems there are no capacitors on the system adding to the fault level. Also, as the system is naturally split, even when running off a single prime mover, then there is potentially no need for single bus routine short circuit testing as it doesn't have a single bus or need to split busses during a fault.

The line-replaceable unit (LRU) is common between motors and generators and on the prototype is less than 8kg. But in fact, with 96 points of graceful degradation within each machine, it is expected not to require repair only during maintenance periods as only a few percentage points are lost on each machine if there is a fault in one of the LRUs. This makes it potentially attractive to uncrewed vessels too, as it's highly resilient, self healing and degradable.

It is still possible to connect static systems like energy storage to the halo system, as well as incorporate heavy static loads and new prime movers.

There is no such thing as fixed voltage anymore, there is no need to match the systems to switchgear voltages of 4.16kV, 6.6kV, it can truly be optimized for the machines, as the voltage only exists between them and not on other equipment.

Services can be a modern DC distribution system directly from the Halo rings, or this can be converted to legacy 440VAC at the points of consumption with a suitable inverter.

Considerations for Dynamic Positioning Vessels

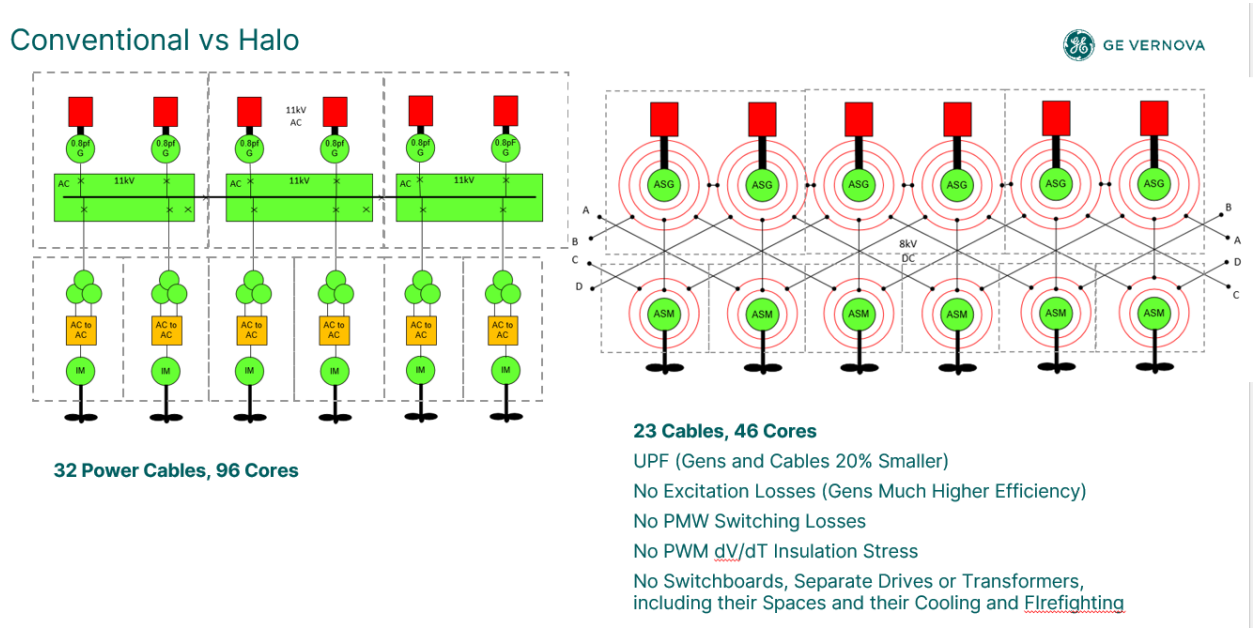


Figure 13 - Conventional System vs Halo Comparison for a DP3 Ship (HV Only)

Figure 13 shows a generic DP3 Vessel with three redundancy groups on the left, with the equivalent Halo mesh system on the right. Low voltage and auxiliaries are ignored for this example, it is assumed that they would both be classical 440V or similar fed by transformers, so they are not shown, here we are comparing the HV systems. Six thrusters, Six Engines, Three Switchboards and three redundancy groups for DP3 are considered.

The Halo equivalent is also divided into the same three generator spaces, it can be noted that although it is a mesh network, with three connections per thruster, there are less than half the cable cores in the halo system, there are no excitation losses from the generator or motor and no PWM switching losses. Additionally, none of the system is subject to PWM inverter insulation stress due to dV/dT requiring filters, additional insulation or special inverter cables.

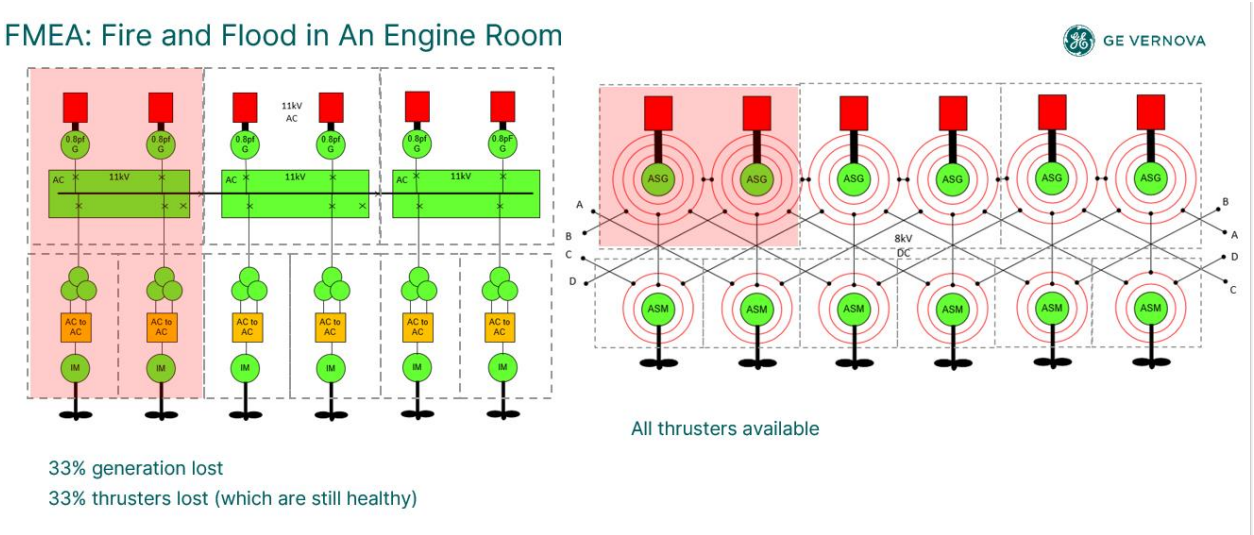


Figure 14 - Impacts of Fire or Flood in an Engine Room

Figure 14 considers a fire and flood in one of the engine spaces, with the classical system, two engines and the switchboard in the affected compartment/area are lost representing 33% of the vessels generation and 33% of the ships healthy thrusters. With the Halo system, of course the engines are still lost, but as there is no switchboard, the matrix preserves the operation of all of the thrusters, so no connections to healthy thrusters are lost.

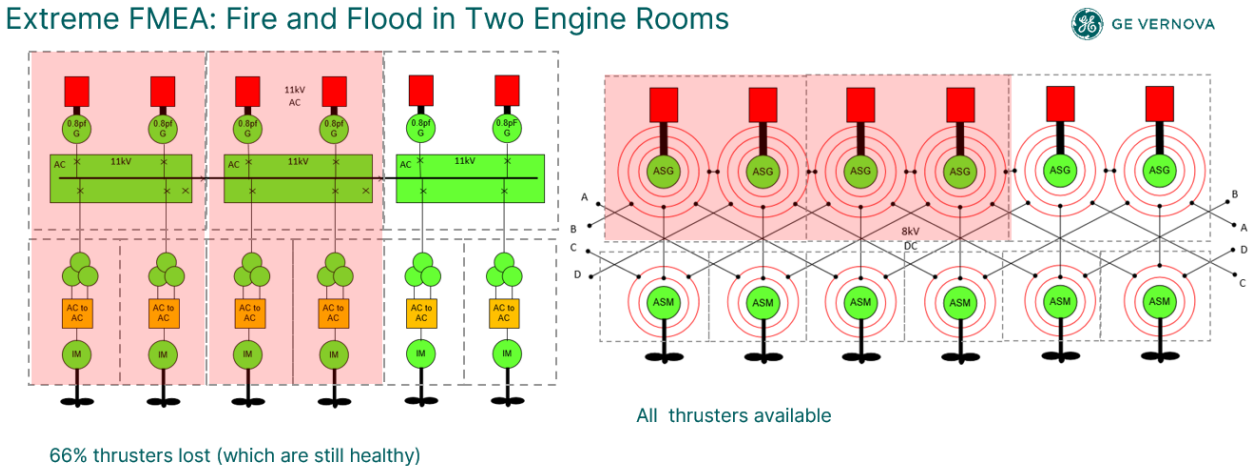


Figure 15 - Impact of Fire and Flood in 2 Engine Rooms

Figure 15 shows an even more extreme case, not usually considered for DP3, which is the loss of two engine rooms, this would leave the classical system with four engines down and four healthy thrusters down. Of course it would be possible to move the classical switchboards into their own compartments or add changeover cabling to the classical system by adding cost, It is also recognized that loss of generators of course in both cases would leave the ship short of electrical power.

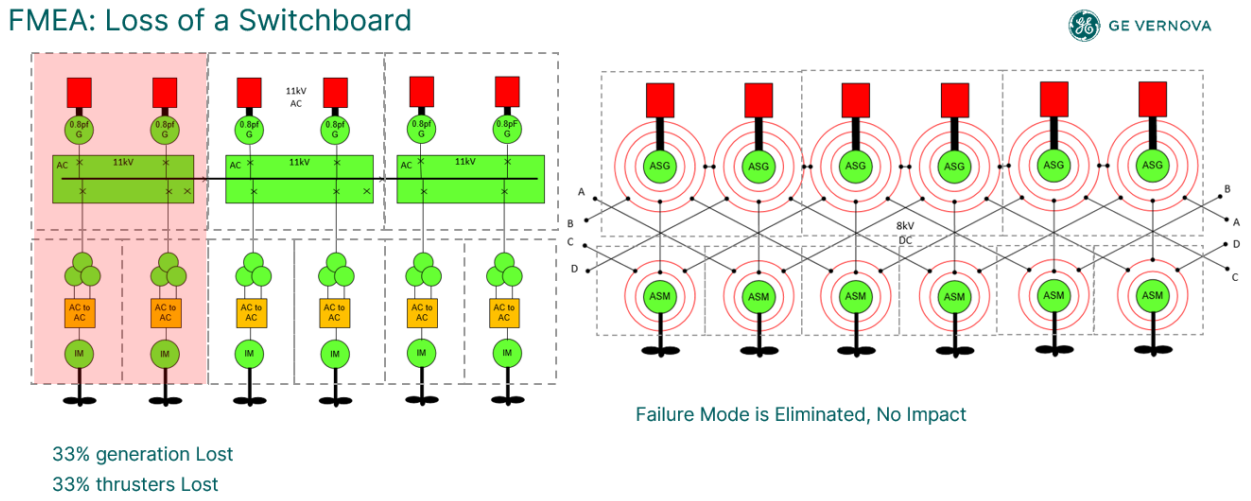


Figure 16 - Impact of Loss of a Switchboard

Figure 16 shows the effect of losing a switchboard, due perhaps to a major busbar fault, or a fire or water damage. In the classical system, anything connected to the switchboard would be lost, generators and thrusters even if they were perfectly healthy. 33% of the ships generators and thrusters would be lost. There are no separate switchboards in the Halo system, so this failure mode is eliminated. If we consider attempt to consider ring failures to be equivalent, remember the classical system also has these rings within the machins that are not normally shown, Ring failures of course only affect at worst the single machine concerned as well.

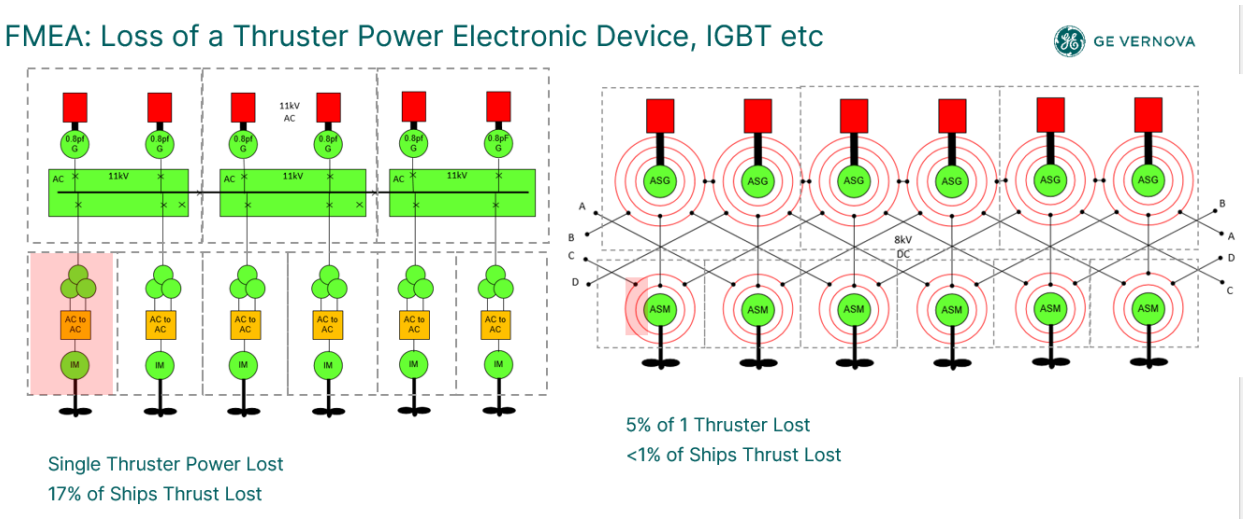


Figure 17- Impact of Loss of a Thruster Power Electronic Device

Now let's consider some less extreme and more likely failure scenarios, figure 17 shows the effect of a loss of a power electronics device or module. In the classical case, this would lead to the loss of a single thruster, or 17% of the ships thruster capability. In the Halo case remembering that a single coil driver loss is self-healing and results in less than 5% of one machine power loss (1% on the prototype) then this means the thruster continues to operate with a minor derating, and less than 1% of the ships thrust is lost. In fact, multiple failures on the same or multiple thrusters could be tolerated. This gives the crew not only the capability to not have to react quickly, but it allows them to plan any replacement or repair days, weeks or month into the future, when convenient.

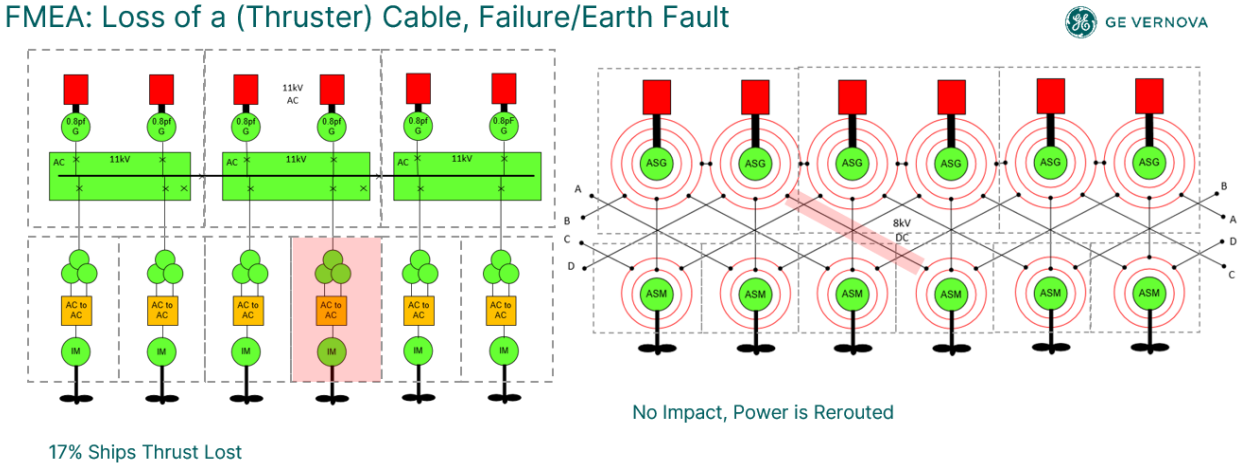


Figure 18- Impact of Loss of a Thruster Cable

Figure 18 shows the effect of a cable failure on one of the thrusters four cables, resulting in a thruster loss on the classical system, but on the Halo system the same cable loss has no impact, as despite having half the cable cores of the classical system, no cable core is unique, and power can always be rerouted through the mesh to avoid any impact or loss of thrust.

The final failure mode considered in Figure 19 is the loss of a thruster transformer winding, which once again loses the complete thruster on the classical but isn't a failure mode for Halo as there are no transformers on the thrusters.

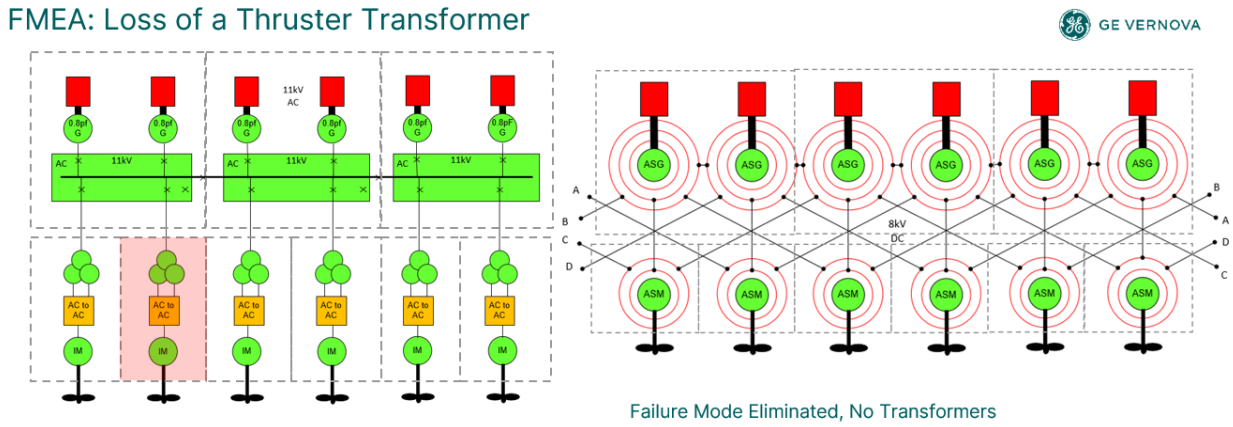


Figure 19 - Impact pf loss of a Thruster Transformer

Clearly the halo system offers some potentially valuable savings on space, volume and weight, but also on resilience, failure modes such as loss of transformers and switchboards (with their star point failures) are completely eliminated, but more mundane and likely failures such as cables and drive IGBTs loss are either reduced to no impact in the case of a cable or minimal impact in the case of a loss of an IGBT or similar in the thruster drive.

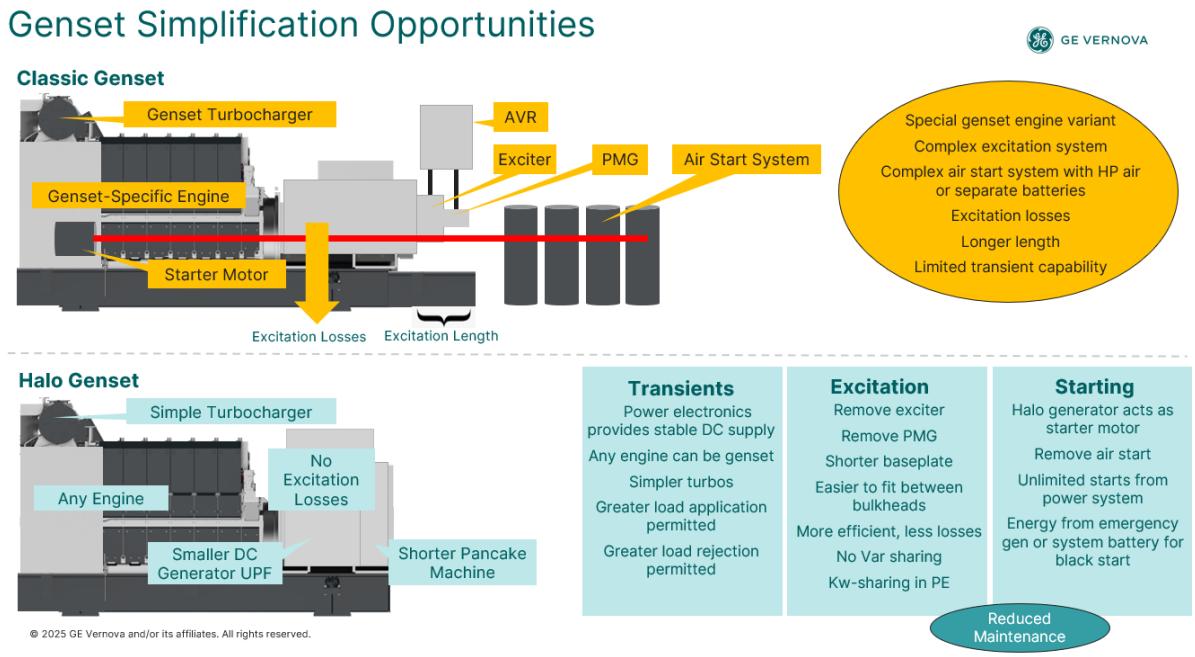


Figure 20 - Comparison of Classical and Halo Gensets

There are many further simplifications possible, such as on the gensets shown in future 20. It is expected the Halo system can operate with any Engine, not just dedicated genset engines as frequency and dynamic response are less important and can be ironed out with the power electronics. Also, the Halo generator does not require an exciter, PMG or AVR, simplifying the genset, and it does not even need the engine to have its own air start or electric start system as the main generator can also act as the starter motor, provided there is electrical power somewhere on the network, or some centralized energy storage. This allows potentially many more engine start attempts than existing systems.

Maturity a nd Testing of the Halo System

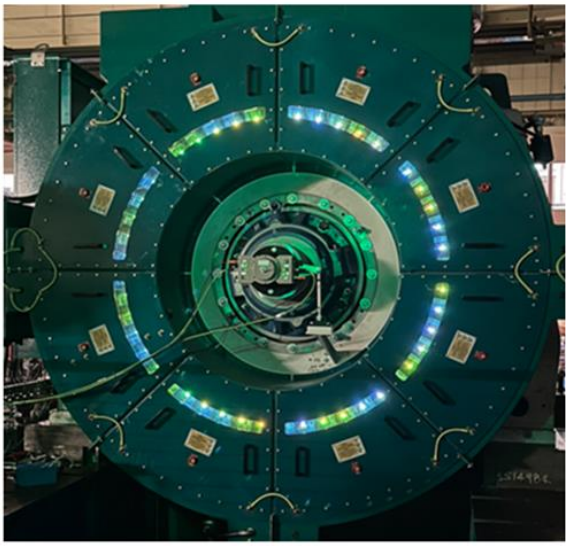


Figure 21- Direct Drive Active Stator Machine on Test

90% of the machine, including the stator core pack, rotor and endrings is standard. The electronics normally centralized in the DC switchboard bridges or AC drive bridges are now simply distributed in the active stator to considerable redundancy advantage. The power electronics system protection is similar to modern DC switchboard protection.

The first 3MW low speed Halo Active Stator propulsion motor has been completed and has been on test since the summer of 2024. Figure 22 shows the ring of lights from the coil drivers with the factory lights dimmed. These lights are a crucial element of the system, as they allow for the first time the maintainer *to physically 'see' torque in the machine* (blue lights) and if there is a problem with a winding or a coil driver there is a red light at the physical location, so both operation and diagnosis of any problem is visual.

The motor with its electronics and cable connections has completed its uncoupled and coupled running, including its heat run where, despite its small size, was well below its permissible temperature.

One of the most remarkable tests was operating the motor uncoupled from a battery. This proved the negligible excitation losses and no PWM losses. *The motor not only turned but started when connected to four 1.5V AA batteries as the only DC power source to the machine.*

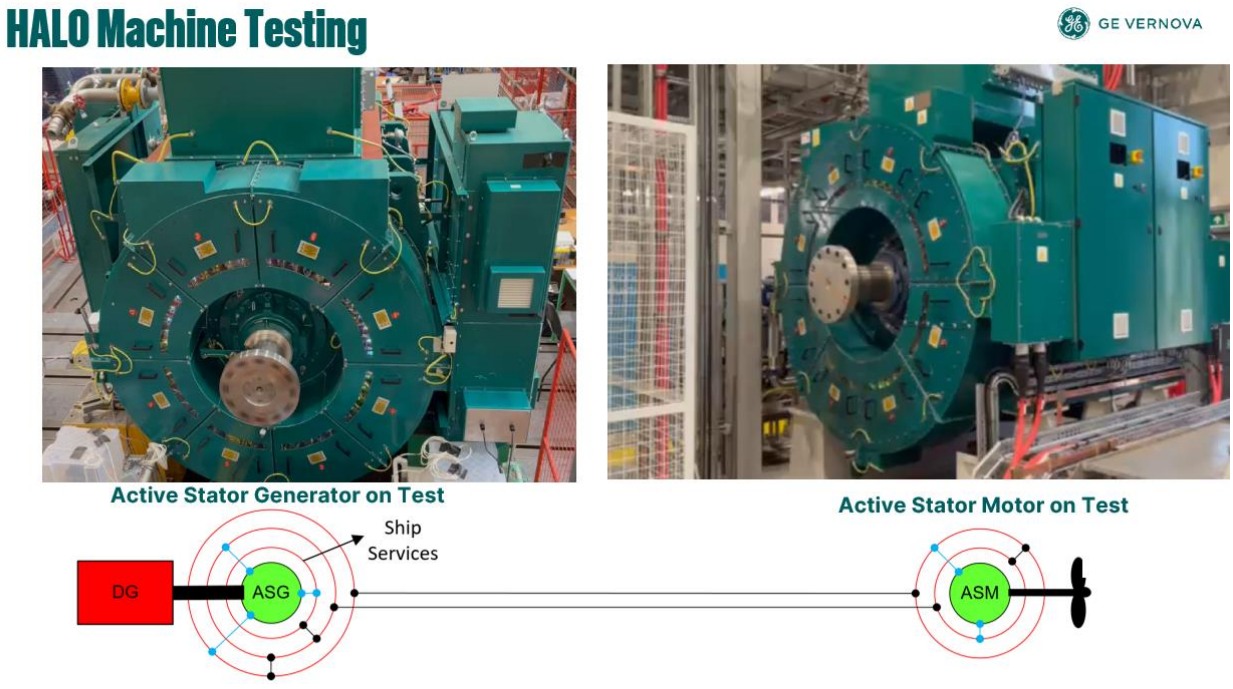


Figure 22 - Halo Active Stator Generator and Motors on Test

The motor was installed at GE Vernova's Marine Power Test Facility (MPTF) early in 2025 after extensive testing in the factory (22) and the generator was installed mid 2025 after passing its factory acceptance testing. The two machines are being tested at MPTF both separately, and also as a "Halo Pair" with only the interconnecting cable between the rings.

Benefits Summary

Specific DP Vessel Benefits

Redundancy

- The machines themselves are self-healing and tolerate of a winding or power electronic failure whilst losing less than 5% of a machine rating, thus preserving motors and generators on the network, less reliance on redundancy only at the full machine level.
- Cable failures do not result in loss of drives, power can be automatically rerouted around the mesh.

Resilience

- The system is inherently split for both propulsion and services within each machine, so does not need a debate about open or closed bus
- The equivalent of a split bus with a single prime mover is possible, or variations thereof.
- The single point failure of a centralized switchboard is removed.
- Electrical Faults on the propulsion network are always galvanically isolated from the services and drilling networks, even when the same generator is in operation.

Reliability

- The system does not rely on closed bus with rapid acting electromagnetic protection like a switchboard.
- The system potentially removes the requirement for routine single bus short circuit testing on board.
- The system being current source has a significantly lower fault level than current AC or DC voltage source systems
- The system is inherently solid state, with all live devices continually in operation in circuit so hidden failures are reduced.
- Insulation stress on motor and generator windings is reduced due to lack of PWM waveforms.

In the Areas of Space, Weight, and Cost Saving, the system:

- Is much more compact than current equivalent systems, leaving significantly more space for other systems, or as an enabler for smaller vessels.
- Has no switchboards and no drive cubicles associated switch room spaces and cooling.
- Is fully compatible with DC and its associated cable size reductions.
- Is inherently transformer-less, even at higher powers.
- Reduces cable terminations whilst improving resilience and no cable cannot be bypassed on the mesh.
- True DC Propulsion motor and generator have a smaller diameter and active core length than existing permanent magnet motors can achieve today for the same rating.
- Motor windings are all made from copper and steel, no exotic electrical conductor materials, or cryogenic cooling.
- Offers a significant overall weight reduction compared to current systems.
- The generators have no Exciter, Excitation PMG or AVR saving size, complexity and losses.

In the Areas of Resilience, Recoverability, Reconfigurability, the system:

- Is, compact, solid state and remotely controllable and configurable.
- Has improved ingress protection, where the lowest IP rating could be as high as IP56/67 to allow seawater firefighting, even on MV, with direct fire hose or water mist.
- Has 4-5x more graceful degradation inherently within the equipment than current systems.
- Achieves true split bus operation with only one prime mover running.

- The generator can be used to start the engines, potentially removing the need for air or electric start dedicated systems. The starting power can be taken from main power system or a shared battery on the system rather than local units. Offers unlimited start attempts with no recharge delays if the ship is live.
- Allows rotating machine damage/winding failures to be isolated on fault individually, instantly, remotely, while the machine remains running.

In the Areas of Efficiency and Noise the system:

- Offers the opportunity to be potentially significantly quieter than existing permanent magnet or other machines available today.
- Has no PWM carrier frequency/losses, and there are therefore improvements in efficiency at all power levels and noise attenuation of carrier frequency is not required.
- Only uses the required number of individual machine windings, selected, by software, remotely, to improve efficiency.
- Due to their permanent magnet nature, the generators have no excitation losses in the field, exciter or remainder of excitation system.

In the Areas of Operations and Lifecycle, the system:

- Fully scalable, but the higher the power and voltage the greater the benefits.
- With no PWM switching reduces insulation requirements and extends machine life even at higher voltages, removing the need for filtering.
- Has potentially capital and operating expenditure benefits, flexibility and efficiency, lower size and weight, reduction in equipment, cabling and terminations.
- Uses less raw material and energy to produce, as well as less fuel to move its own mass through life.

In the Areas of Maintainability and Crew Reduction

- Electrical failures do not need to be addressed until reaching port.
- Apart from the motor and generator rotors there are no significant moving parts and no gearboxes.
- Has a single, common, electronic spare part, easily handled by one person, which a maintainer can learn to fit easily.
- System reconfigurability is software controlled, locally, remotely, or off ship, if required.

Conclusion

The Halo system offers a true, next-generation networked environment for energy, using a smarter application of today's components, to offer highly simplified, highly resilient, highly efficient, highly compact system.
With reduced components, volume and weight Halo offers the opportunity for either smaller vessels or liberating compartment spaces for other uses. For Dynamic positioning ships it also offers new opportunities for significance resilience benefits, by removing complete failure modes such as HV switchboards and thruster transformers but is also allows the opportunity to reroute power around things such as cable failures.

Due to the graceful degradation of its distributed coil drivers, it also the opportunity for its rotating machines to self-heal on a devices or coil loss; It maintains almost full capability on such failures, sacrificing less than 1% of the ship's propulsion capability. The system is inherently simple, with fewer components, fault diagnosis by a ring of light, self-healing and significant graceful degradation. Combine this with its increased efficiency due to no excitation or PWM switching losses in either the motor or the generators and it offers potential benefits that existing system cannot match. Perhaps providing the opportunity of taking systems to the next levels of Redundancy, Reliability and System Resilience.

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