MOVING TO ALL-ELECTRIC

Washington State Ferries looks to the future

By Will Ayers, Stephen Gleaves, and Eben Phillips

The trend toward renewables and electrification of transportation are considered keys in fighting climate change. The shift is being seen in the maritime sector, especially with the advances in plug-in ferries in Scandinavia. Washington State Ferries (WSF), author Eben Phillips' employer, has ambitious plans to bring this movement to the United States, being committed to converting one of the world's largest ferry fleets and being positioned to lead the charge nationally.

The Pacific Northwest has depended on hydropower for decades. Seattle gets 84% of it power from this source with most of the rest coming from wind and nuclear. A recent study indicated that electrification could immediately reduce ferry carbon emissions by 95%, including the emissions of shore-side sources. WSF also enjoys some of the cheapest electricity in the nation: utility energy charges range from 5.7 to 7.1 cents/kWh and demand charges from $2.95 to $4.22/kW.

WSF has started this transition on two significant fronts. First, they will convert their largest ferries to hybrid-electric propulsion. The three Jumbo Mark II class ferries consume 26% of the fuel for the 21-vessel fleet. They also have obsolete propulsion control electronics from the 1990s, making it harder to reach WSF's typical 30-year, mid-life refit. Lifecycle analysis done in 2018 showed that converting the Seattle-Bainbridge route to plug-in operation could save up to 24%.

On its second front, the state decided to continue building its Olympic class vessels, but with a

Mock-up image showing a WSF vessel-mounted robotic charging arm. Image courtesy Siemens Energy.

completely different hybrid-electric propulsion system. The aging fleet has a serious need to continue new construction. Over half the vessels are older than 40 years, three are older than 50, and one is beyond 60. The new hybrid-electric Olympics (HEOs) will replace the oldest in the fleet with the ability to drastically reduce fuel consumption and emissions.

Jumbo Mark II conversions

Of the two efforts, the conversion of the Jumbo Mark II class presents additional challenges. This goes beyond the fact that it is a retrofit versus starting from a clean slate.

The existing propulsion systems were a standard Siemens product from 25 years ago. They are composed of an AC medium-voltage bus fed by up to four constant-speed 4160V, 900 RPM generators. The bus is split into two switchboards, each located in a separate engine room near a pair of diesel generators. Figure 1 shows a simplified one-line of the propulsion system before the conversion.

The AC bus feeds phase shifting transformers that feed cycloconverter drives. As the stern consumes approximately 90% of load in transit, the crossover ensures relatively balanced loads between each switchboard. It also ensures redundancy of propulsion at each end of the vessel. Most of the latest hybrid designs involve a DC grid. Due to the normal low voltage ranges of the lithium-ion battery banks combined with better control of associated fault currents, these

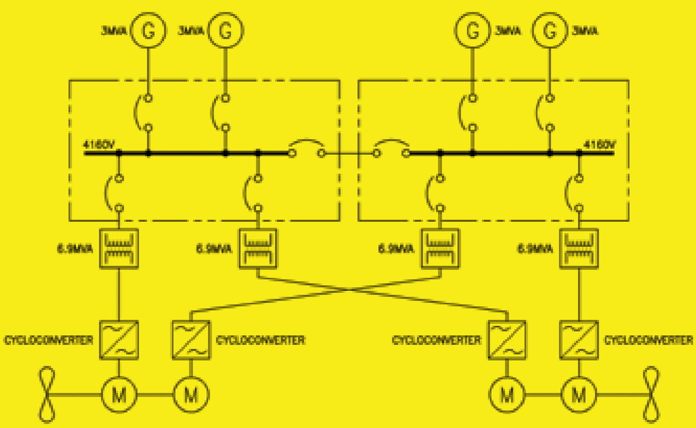


FIGURE 1: Existing propulsion one-line for a Jumbo Mark II.

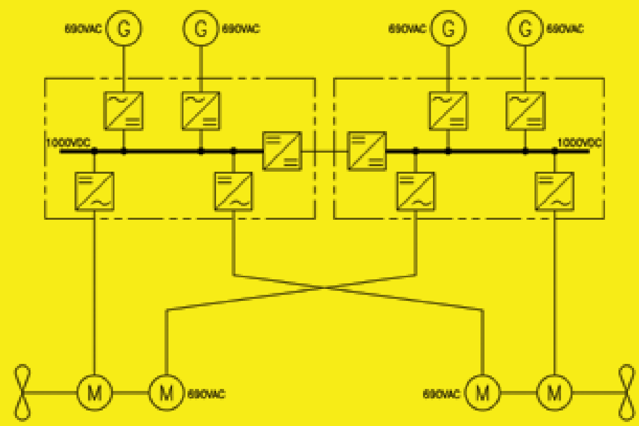


FIGURE 2: Typical hybrid DC propulsion one-line.

DC grids typically involve a roughly 1,000 VDC bus and 690 VAC electrical machinery. See figure 2.

However, along with the current 4,160V generators, the existing propulsion motors are rated at 1,850V. The medium-voltage switchgear would also have required replacement. Therefore, it would have been a significant cost to replace such medium-voltage equipment simply to conform to the latest hybrid designs. A solution was sought that could reduce the impact on the system and still achieve zero emission crossings.

The new hybrid-electric Olympics (HEOs) will replace the oldest in the fleet with the ability to drastically reduce fuel consumption and emissions.

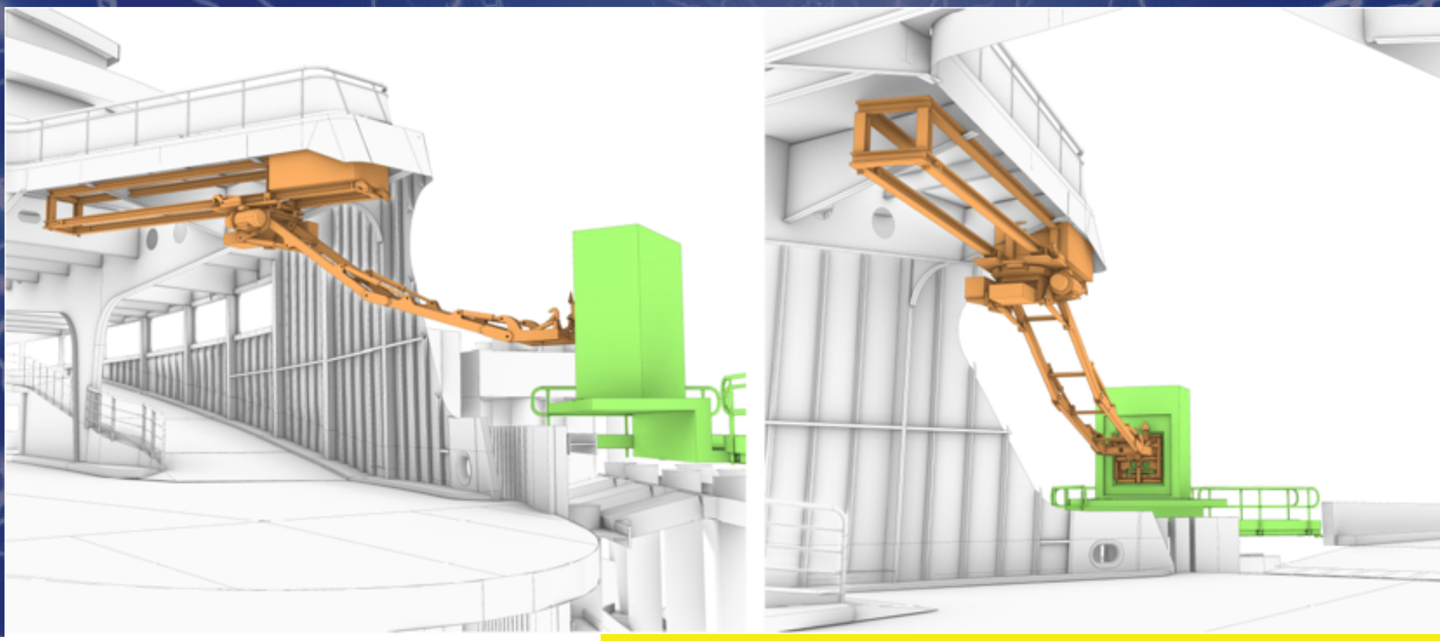
Fortunately, the largest hybrid fleet in the world, operating between Germany and Denmark, served as a template. Scandlines had converted its six exceptionally large passenger vessels to hybrids starting with the 364-car *Prinsesse Benedikte* in 2015. These vessels also had medium-voltage power fed by constant-speed generators. In addition, Siemens had performed these conversions. They removed one propulsion diesel and replaced it with lithium-ion batteries, an inverter and step-up transformers to synchronize the 1,000V battery packs with the 6.6 kV, 60 Hz bus. The Jumbo Mark II hybridizations would similarly connect 1,000V batteries to a 4.16 kV, 60 Hz bus. Having supplied the original Jumbo Mark II systems, Siemens was uniquely qualified to upgrade their aging controls.

While a good template, the Scandlines vessels do not have any plug-in capability. Their battery banks achieve fuel savings by operating as back-up power. The Jumbo Mark II battery packs had to increase in size significantly to achieve the WSF desired goal of all-electric operation. However, this allowed for two propulsion diesels to be removed versus just one, freeing up space for the added equipment. To achieve required redundancies, two completely independent battery banks with separate inverter banks would feed into different existing switchboards. To enable charging the system without expanding the number of main circuit breakers in the current switchgear, three-winding transformers were used. See figure 3.

Everything feeding out of the propulsion switchgear remains untouched. The removal of the two generators frees up two circuit breakers that can receive power from either the battery inverters or from shore power while docked. Each three-winding transformer allows the batteries to charge while pushing the dock and supplying hotel loads. Back-up power is often set at the level of one diesel for perhaps two to five minutes. However, a 35-minute crossing with the output of at least two diesels makes proper battery sizing more critical. Route analysis was done both during feasibility studies and as part of Siemens' efforts. Figure 4 shows an example one-way trip measured with the accurate onboard datalogging systems.

The datalogging shows the per-unit power of the #1 generator. Three generators were online at the time. The peak on this crossing hits approximately 7.2 MW. Because the online cycloconverters operate at about 0.8 power factor at such load, both inverter banks and both

WSF is working with partners Siemens and Stemmann-Technik to provide a rapid charging system for the Jumbo Mark II project. Shown here is the arm extending during charging operations. Image courtesy Siemens Energy.



three-winding transformers would have to be at least 9 MVA in size to accommodate.

However, variation in the crossing energy and power also needed determination. Figure 5 shows a worst-case example of variations in both. Feasibility studies estimated that the average transit energy for battery sizing was approximately 2.2 MWh, but that the shore charging system would need to handle peaks of 2.4 MWh. With a charging time of 17 minutes, that would equal a charge rate of 9.6 MW. Periodic diesel usage to handle higher worst-case operation was estimated at 1.67% of current annual fuel consumption and included in consumption and emissions estimates.

A Jumbo Mark II operating on the Seattle-Bainbridge route would incur approximately 7,200 charge/discharge cycles per year on the lithium-ion batteries. The design had to balance space constraints with up-front and subsequent battery replacement costs. Feasibility studies concluded that a 4-year replacement cycle with lithium-ion batteries of a nickel manganese cobalt chemistry discharged 35% at the beginning of service could supply the 28,800 total cycles. This translated to a roughly 6 MWh battery system.

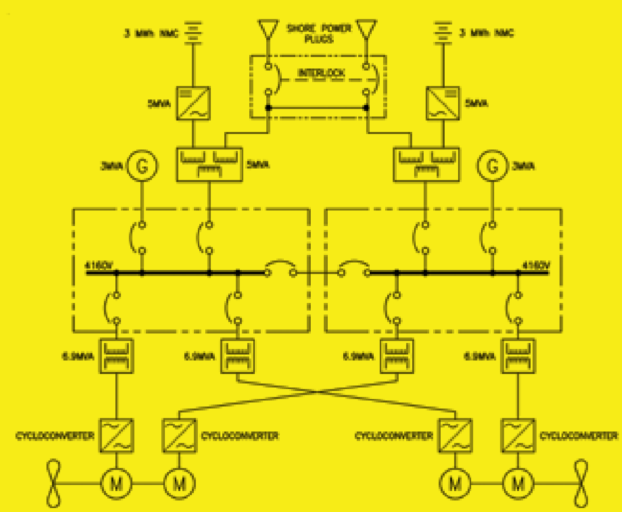


FIGURE 3: New hybrid one-line for a Jumbo Mark II.

Rapid charging systems

For a short-haul ferry, the biggest obstacle in achieving zero emissions is in making a safe and timely shore power connection. High-rate connections have been around for years for both navy and commercial applications. Yet, the process usually requires a small crew manually operating equipment for at least 10-15 minutes before power can flow. Of course, the time at the dock for a typical ferry is limited. The nature of operations requires a rapid connection and disconnection, ideally no longer than a minute for each. With the crossing usually of longer duration than the time at dock, the charge rate typically exceeds the propulsion power by a significant margin. Medium voltage is needed to avoid plugs rated for thousands of amps. Making quick connections safely at medium voltage many times a day requires a rapid charging system (RCS) that eliminates direct human intervention. Various levels of autonomy have been developed in recent years.

The breakthrough project for plug-in ferries was in 2015 with MF *Ampere*. Given the challenges with an RCS, two were installed. A Cavotec "hook" paid out a plug from an overhead reel to slot into an upward facing receptacle. A Stemmann-Technik pantograph extended rows of carbon brushes horizontally to press against vessel-mounted bus bars. Both systems had roll-up or retractable doors to keep the connection components protected from the elements when not in use. However, both systems depended on a securing pin at the bow and a vacuum pad positive restraint system at the beam of the ferry to minimize any movement. The systems had no ability to automatically adjust for vessel motions.

Subsequent RCS, however, have become much more adaptive. Robotic arms with laser-guided electric eyes target the vessel-mounted receptacle. ABB mounted its industrial IRB 760 robot in a windowed glass tower on a side dock on a crossing between Sweden and Denmark. It employed a 3D laser scanner, a machine vision camera and gyroscopic sensors to zero in on the vessel-mounted receptacle. It used autonomous 4-axis motion: left-right, up-down, in-out, and swivel at its outermost point.

Stemmann-Technik also developed an autonomous robotic arm in a tall tower for side dock locations.

This photo shows WSF typical dolphins, wingwalls, transfer span, and passenger overhead.

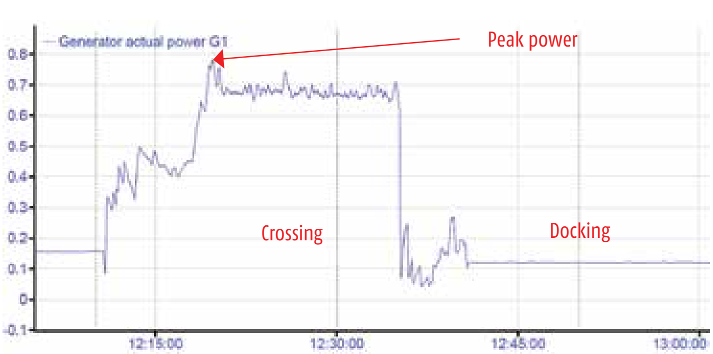


FIGURE 4: A typical Jumbo Mark II one-way trip.

Tall but narrow doors opened toward the ferry with an elevator-like carriage inside moving up and down to accommodate tidal fluctuations and vessel motions. It also had an extending motion combined with a limited lateral one, however still dependent on positive restraint. These systems became the most employed to date with a large number of installations throughout Norway.

Charging power also increased with subsequent systems. The *Ampere* system had been able to achieve a 1.5 MW throughput at a low voltage of 690 VAC. However, the ABB systems made a big leap achieving 10 MW at 11 kV. No system since has equaled such a power level though some have used 11kV. There are at least five other routes now in the range of 4.0 – 6.2 MW.

In this progression of robotic arms, there also emerged options to charge at the bow of the vessel rather than at the beam. The large dock at the side of the ferry represents a considerable capital investment as well as a delay in project schedules and greater impact to the environment. Most ferry operators load at the bow with significant existing structure there that might be used by the RCS. The advance here occurred with *Ellen*, serving Ærø Island in Denmark. This EU-funded project was heavy on pushing the technology. The 30-car ferry had a carbon fiber hull and not a single diesel engine onboard, yet made an 11-mile round trip before charging. Mobimar developed a multi-axis robotic charging arm with a narrow enough footprint to be mounted on the vehicle ramp right next to vehicle and foot traffic.

The Mobimar system has now operated successfully for more than a year. This system did benefit from a vacuum pad positive restraint system. Yet, the same system without positive restraint is now undergoing long-term testing for the Swedish Ministry of Transportation at Ljusterö.

Cavotec also has developed a ramp-located charging arm. It has been initially deployed for the Nesodden ferries operated by Norled out of Oslo and will soon be used on other ferry routes in Norway. It also operates without need for positive restraint.

Additional considerations

WSF had little interest in pursuing any technologies that required a side dock for a charging tower and positive restraint. Along with the cost, the organization also has significant environmental and tribal responsibilities to consider. The region is subject to additional environmental impact assessments regarding eelgrass, a marine plant that provides habitat to juvenile salmon, herring, crab, and other species. It must also abide by tribal treaties that require negotiations with local tribes over any expansion of terminal structures.

FIGURE 5: Worst-case example of crossing variations.

The WSF vehicle ramps are an exceptionally large structure. They include a long adjustable transfer span to accommodate the high tidal flux of up to 22 ft. This is also a system with 20 terminals. Careful consideration is required of changes that would ultimately impact all of them.

It is with the perspective of these evolving technologies and the added challenges at WSF that one can appreciate their approach to the RCS. The organization is pursuing a robotic arm mounted onboard each end of the vessel with the receptacle on the dock's wingwall. They have teamed with their partners Siemens and Stemmann-Technik to provide such a system for the Jumbo Mark II project.

WSF ferries have what is termed a pickle fork. This is a raised passenger deck space that extends forward of the pilothouse both port and starboard on top of a wrapping side shell extending down to the car deck. When at the dock, the pickle fork wraps about halfway along the wingwall located at either side of the transfer span. The telescoping RCS will be mounted underneath the pickle fork at one side with the receptacle mounted on top of the opposing wingwall nearer the transfer span.

High-speed telemetry will communicate between the vessel and the shore-side component. Just before coming in for a landing, the robotic arm will unfold from its stored location and position itself in advance for the anticipated tidal height. Once the ferry is pushing against the wingwall, the connection can be made quickly.

To better align with utility distribution voltages in the region and lower the required amperage, the charging voltage will be 12.47 kV. The onboard RCS currently in the detailed design phase will enable a transfer of approximately 15 MW. In this way, the RCS will become a common platform for routes at WSF.

Olympics and future efforts

With lessons learned and WSF having a better handle on hybridization, it then looked at how to apply the technology to the Olympic class vessels. It was decided that a DC grid would be best employed, as shown in figure 2, but with the addition of step-down transformers and shore power inverters to convert the same 12.47kV to the 1,000 VDC propulsion bus.

The Seattle-Bainbridge route is an average one. Yet, the next logical locations for an HEO ferry would be either at Mukilteo-Clinton or Seattle-Bremerton. For routes with significant passenger volume, these represent the extremes at WSF. The first is a short 14-minute sailing followed by 16 minutes at the dock. The crossing energies therefore are in the range of 0.5 to 1 MWh. However, the schedule would require 12,000 cycles per year.

At the other end of the spectrum, Seattle-Bremerton is a 55-minute transit. Only about 4,700 cycles per year would be needed. But each crossing would consume anywhere from 3.5 to 4.5 MWh. The Bremerton route still has roughly the same time to charge as a Jumbo Mark II, possibly pushing the charge rate up to 15 MW.

To balance such variation in routes, cycle counts, and crossing energies, as well as to achieve fleet interchangeability, an HEO with a common propulsion system was desired for either route. This led to a battery system approaching 10 MWh in size. On the other hand, designing to the longest crossing boosted interoperability. On some of the shorter routes, it allows for charging at only one side, reducing terminal infrastructure costs.

Finally, the ferry organization took a hard look at what this transition would mean for the rest of the system years into the future. A new-design 144-car vessel class is expected to fill out other locations at Edmonds-Kingston and the San Juan Islands. Four new 124-car ferries would serve the Vashon Island triangle route. The three 64-car Kwa-di Tabil ferries would be converted to hybrid operation on two shorter routes. It is projected that, by 2040, most all of the vessels will leverage shore power and net a more than 70% reduction of CO_2 emissions as legislated by Washington state law.

The course that WSF has set will not be without challenges. While much of the technology has been explored in Northern Europe, there are further learning curves to be overcome. Solutions must meet the unique needs of the state and its Puget Sound waters. But success will enable the ferry system to transition to local, green, and low-cost electricity as its main fuel source. **MT**

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