The Expanding Role of Variable Frequency Drives in Naval Automation

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Synopsis

Variable Frequency Drives (VFDs) have provided improvements in the U.S. Navy across a myriad of shipboard applications through replacement of full voltage across-the-line contactors and modification of earlier hydraulic designs. The Collective Protective System (CPS) and Electronic-Standard Tensioned Replenishment Alongside Method (ESTREAM) are two examples. These applications offer a revealing list of long term benefits of maintenance savings, equipment performance gains, and overall operational efficiencies. In the case of the CPS, innovatively the engineers applied the power affinity laws and electrical power triangle principle to gain savings on the system's power consumption and alleviate motor wear and tear. For the ESTREAM, the VFD's torque limit feedback was applied to achieve more responsive tension and speed control of the underway replenishment (UNREP) process. Because extended equipment service life, increased reliability, and greater performance directly translate to a greater ability for the ship to accomplish its mission, such compelling reasons will generate further adoption of VFDs into other applications of the modern navies of today.

Keywords: VFDs; affinity laws; ESTREAM; CPS; Power Factor; UNREP

1. Introduction

The operating principles of a variable frequency drive are broadly understood across the industrial base and drives have been universally employed in all kinds of manufacturing plants throughout the world. Over 50 years ago, the first DC Drive was developed and from those humble beginnings the technology has evolved beyond those first drives due to advances in semiconductor innovations to create highly efficient, multi-megawatt AC Drives. Today's AC Drive consists primarily of three sections: a Converter, DC Bridge, and Inverter. Those components that are used for each section varies depending on the AC Drive's bespoke purpose and control methodology of voltage and current to the load. The end result of these designs is significant as engineers from all disciplines seek to gain the advantages of variable frequency drives such as to reduce wear and tear on their machinery, increase energy efficiency, gain greater control of output torque to the load, lower energy and electrical costs, improve performance and flexibility of their equipment, and replace other maintenance intensive, energy transferring media like hydraulics. Following suit with their industrial counterparts, marine engineers of both commercial and government entities continue to expand the use of variable frequency drives for shipboard applications in all modern navies.

1.1 The AC Motor

Numerous shipboard applications use AC motors as the mechanism of work output, thus it is important to start from the motor to understand why variable frequency drives are so beneficial. First, AC motors come in various categories: Induction Motor, Synchronous Motor, Wound Rotor Motor, and Permanent Magnet Motor to name a few. Second, the fundamental activity in the motor that produces work is the magnetic flux interaction between the rotor and stator. Third, a motor connected to a voltage source receives AC current to its stator; this AC current is apportioned into two parts that it produces which are the: Magnetizing flux, and Torque flux (Hughes and Drury, 2013).

The current used for magnetizing flux induces the voltage in the rotor winding which is necessary to develop rotor current and the rotor's flux field. The second part of this stator AC current interacts with this induced rotor flux field causing the rotor to move forward or reverse, depending on the variable or constant flux phasor angle of the two fluxes, and produces the motor's torque output hence it is called the torque flux.
Keep in mind that permanent magnet motors have this rotor flux excitation already within the rotor so they don't require the stator's AC current for that purpose. These factors influence the load(s) power factor and torque performance.

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1.2 Direct On Line (DOL) Motor Starting

When using a 3-phase FVNR (Full Voltage Non Reversing) contactor for across-the-line starting, the torque and power factor are not well controlled. When accelerating an AC motor to full speed using a full voltage connection, a large inrush current is required. DOL contactors lead to locked rotor starting AC current that is typically 6–10 times the motor's full load amps in order to create enough starting torque to overcome the load's stationary state. Additionally, the torque of the AC motor is mostly uncontrolled and can shock the connected equipment, potentially causing damage. Characteristics of this starting and stopping method include:

- Full voltage, current and torque are applied immediately
- Power is immediately removed when shut off
- High starting torque can cause damage to mechanical systems
- High current can cause problems in the electrical system and can also cause decreased system capacity
- It can be very disruptive to the electrical distribution system's voltage level
- Power factor is far less than unity

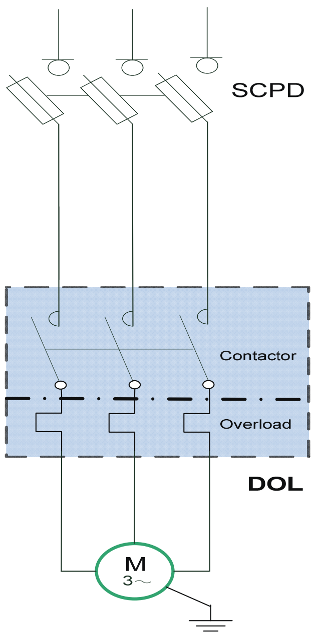

Figure 1 - DOL MOTOR STARTER

2. The AC Variable Frequency Drive

With the above review of an AC motor's operation, we come back to the variable frequency drive (VFD) to discuss its three main sections and how they help an AC motor perform more effectively for torque output and power factor. The first section that the line voltage source comes to is the VFD's converter; it is made of components such as Silicon Controlled Rectifiers (SCRs) or Insulated-Gate Bipolar Transistors (IGBTs). These SCRs and IGBTs are switch devices used to convert the 3-phase AC voltage into DC voltage by control algorithm modulation of opening and closing these gate switches at points along the AC voltage phase angle to transform the sinusoidal wave of each AC voltage phase into a DC voltage. The second section is the VFD's DC Bridge which consists of a DC bus in parallel with a capacitor and Inductor. The Capacitor and Inductor reduce voltage ripple to smooth out the resultant DC Voltage of the DC Bridge. The third main section is the Inverter which takes the DC voltage on the DC Bridge and inverts it into an approximate sinusoidal-like waveform voltage output with pulse width modulation (PWM) of similar semiconductors like the converter either IGBTs, MOSFETs, or SCRs (Hughes and Drury, 2013).

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The VFD's control algorithms within its logic circuits determine the optimum PWM of the gate switching for a duration and frequency based on the stages of motor operation of starting, stopping, and continuous operation with variable speed.

The resultant VFD output provides significant control of the earlier mentioned output voltage and frequency to the electric motor load and also has other improvements of field oriented control of the motor's stator winding field onto the motor's rotor field. Starting a motor with a VFD modulating the Voltage and Frequency ratio leads to near 100% torque at low speed requiring far lower starting current than the 3-phase contactor across-the-line start. Further, the power factor is near unity during the starting process. Both translate to less disturbance on the ship's electrical distribution system for voltage level and overall system's frequency stability. This certainly is important to the impact on other ship payloads using that electrical power from that same electrical distribution system.

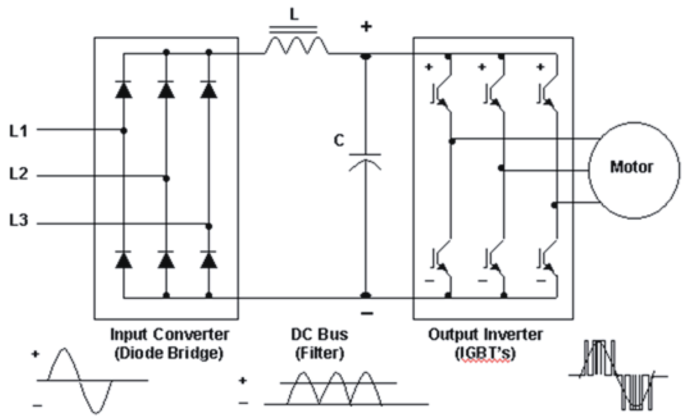

Figure 2 - TYPICAL VFD BLOCK DIAGRAM

3. The Opportunity for Energy Savings

As ships systems become ever more power hungry, the need to find energy savings becomes greater. A VFD allows operating a load at less than 100%, when the full load is not needed. This reduces the amount of energy consumed which translates into fuel savings for the ship. Centrifugal loads, such as pumps and fans, offer the greatest energy savings potential when less than 100% flow or pressure conditions are required.

Energy consumption in centrifugal fan and pump applications follow the affinity laws: flow is proportional to speed, pressure is proportional to the square of speed, and horsepower is proportional to the cube of speed. So, if an application only needs 80 percent flow, the fan or pump will run at 80 percent of rated speed and only requires 50 percent of rated power.

Based on the Affinity Law, shown in Figure 3 the power of the electrical load is directly proportional to the cube of the load's speed by the ratio of new speed, n_2, to base speed, n_1.

$$P_2 = P_1 \left(\frac{n_2}{n_1}\right)^3$$

Figure 3 - AFFINITY LAW, SPEED VS POWER
where: P = electrical power and n = motor speed

Shown graphically in Figure 4, the Affinity Laws define the relationship between Speed, and Power. Simply stated, the power requirement varies by the cube of the change in speed. So, a 25% reduction in fan speed would reduce the power consumption of the fans by approximately 58%.

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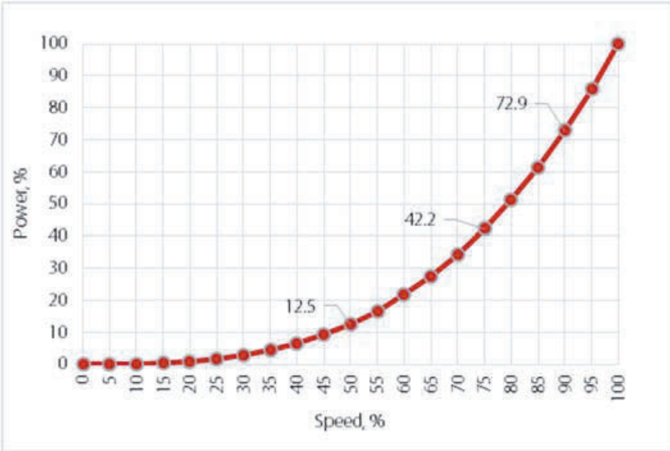
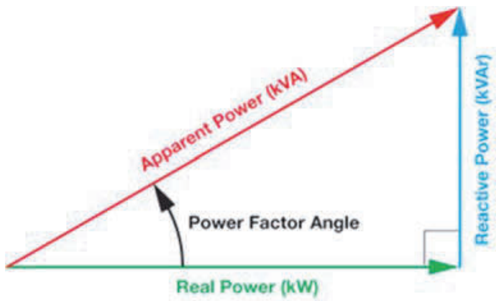


Figure 4 - Affinity Law, Speed vs Power

Another benefit of VFDs is they also effectively increase the Power Factor of an electrical circuit such as inductive loads; thus the electric power will be further reduced because a higher Power Factor means less electric supply current since the reactive power is reduced. This principle is the Electrical Power Triangle where the hypotenuse is Apparent Power and the other two sides of the triangle are Real Power and Reactive Power. The Power Factor is the cosine of the angle between the Apparent Power (kVA) and Real Power (kW). When the Reactive Power (kVAR) is decreased the cosine of that angle approaches one, i.e. the Power Factor is near unity. Thus, reducing the Reactive Power for the motor load reduces the total Apparent Power required.



4. Shipboard Applications

Over the course of the last 20 years, thousands of Variable Frequency Drives have entered into service in the U.S. Navy providing superior results across numerous deck-plate and engine room applications. When widely adopted in a vessel's electrical distribution system, the VFD's impact can be tremendous such as leading to reduced overall power requirements and thus less generating capacity requirements. Furthermore, electrical cable diameter size which is directly proportional to the conductor amp load rating will be reduced both from lower full load amp starting thresholds and from less reactive current within those conductors. This means smaller conduit runs throughout the ship's bulkheads and decks as well as upfront shipbuilding capital expenditure savings. In this paper, the two highlighted applications herein illustrate the potential savings, efficiencies, and many other benefits to be gained.

4.1 Collective Protective System (CPS)

A ship's collective protective system (CPS) is used to protect critical, vital areas of the vessel against chemical, biological, and radiological attacks by providing clean fresh air at a higher pressure, i.e. overpressure, than the surrounding ship spaces' ambient pressure or atmospheric pressure, thus ensuring that no airborne chemicals or other containments enter that CPS area. Shown in Figure 5, this activity is accomplished through the CPS filtration modules and supply fans providing air to those designated areas. Initial designs of surface combatants in the 1980s had single speed operation with across-the-line starters of these supply fans. By original design the CPS fans operated continuously at their maximum speed under all conditions. The application of VFDs have proven to significantly save energy for those pumps and fans with variable flow requirements.

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NSWC Dahlgren/NSWC Carderock SSES took the initiative to explore variable speed operation and application of VFDs for those CPS supply fans; and in 2013 the first CPS VFD based system was installed, tested, and measured on a surface combatant. This CPS VFD system used Commercial-Off-The-Shelf (COTS) technology of PLC control and VFDs. The various facets of improvements and benefits were astonishingly good.

First, the base speed of the CPS supply fans could be reduced while still giving sufficient overpressure to those CPS areas. Each supply fan is controlled by a new variable frequency drive modulating its speed to a set point defined by inputs of dynamic pressure and pitot pressure sensors to ensure that the CPS space was always above atmospheric levels. The reduction in electric motor speed meant power savings. The actual result for this surface combatant that was achieved was an Apparent Power reduction of 45% (Snodgrass, Clark, Snyder, Dupuis, 2015).

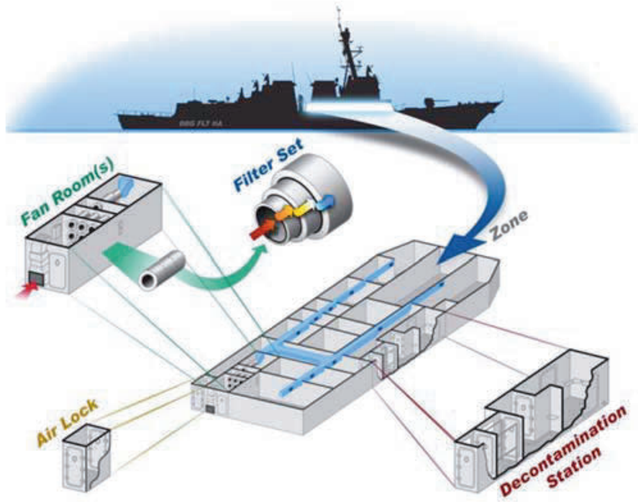

Figure 5 - CPS System Overview (Gallimore, 2017)

Second, installing a VFD effectively increased the Power Factor of the electrical circuit to near unity; in this case the Power Factor improved by 10% from its original level. That meant the electric power was further reduced because less electric supply current was required to generate the magnetic flux for the motor's stator field.

Third, the CPS VFD control system is considered virtually maintenance free thus reducing the manpower labor hours of the crew on the ship to support it and giving them more time to focus on other priorities. Corollary benefits from VFD use on this CPS system include overall Total Ownership Cost savings to operate the CPS system like:

- Increased service life of each motor
- Reduced energy consumption of the HVAC system to heat and cool the CPS air supply, and
- Less wear and tear on the motor's bearings and mechanical parts during the cycles to start or change speed

Measured Energy Savings were validated by shipboard power measurements taken multiple times before and after the system's installation. Following a year of evaluation, it was observed that both the fan speed and CPS air flow rates were reduced significantly by 25%. Shown in Table 1, it was confirmed that the CPS fans actually consumed 59.3% less power compared to the original control system (Snodgrass, Clark, Snyder, Dupuis, 2015).

	Before	After	Reduction
Fan Power	65.4 kW	38.8 kW	59.3%

Table 1 - Measured Supply Fan Power

Considering that the CPS ties into the ship's HVAC system, it was predicted that reducing the system air flow by the use of VFDs would also reduce the energy required to heat and cool that air to meet habitability and crew comfort requirements. This was true and the data in Table 2 shows that operational energy consumptions for Heating and Cooling were reduced from 32.5kW to 8.3kW resulting in an overall 74% reduction (Snodgrass, Clark, Snyder, Dupuis, 2015).

	Before	After	Reduction
Heating & Cooling Power	32.5 kW	8.3 kW	74.5%

Table 2 – Heating & Cooling Power

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4.2 Replenishment At Sea/Fueling At Sea (RAS/FAS)

For extended operations at sea or on station, ships require replenishment of their used resources such as stores, food, ammunition, oil, and fuel. That undertaking would mean either transiting back to a port to receive new goods or performing an underway replenishment (UNREP) from the Delivery Ship to the Receiving Ship. The U.S. Navy has performed UNREP operations for many years and the transfer of cargo between two ships has significantly evolved in response to operational necessity. The first UNREP requirement was for coal to fuel battleships during the Spanish-American War, followed by fuel oil for destroyers to transit to Europe in World War I, then replenishing air launched ammo to carriers in World War II.

Since the ability of ships to remain on-station is necessary for power projection ashore and around-the-clock sea operations; UNREP systems have become an essential activity of modern navies. UNREP has two processes that were developed over 40 years ago to handle both Solid Cargo and Liquid Cargo transfers. Navies across the globe refer to these processes as the **S**tandard **T**ensioned **R**eplenishment **A**longside **M**ethod (STREAM) which incorporate the use of unique equipment components.

Those principle components for either type of transfer are the Ram Tensioner, Electric Hydraulic Winch, and the Sliding Padeye. The ram tensioner maintains the proper tension on the line, in concert with its Anti-Slack Device (ASD), to ensure either the hoses or solid cargo lines will not hit the ocean water. Its mode of control used hydraulic and pneumatics to adjust the ram tensioner's output tension on the spanwire or highline to compensate for most changes in ship separation and each ship's motion (Hadley, 2015).

Figure 6 - Carrier and Cruiser replenishing from T-AOE supply ship (McLachlan, 2014)

The Electric Hydraulic Winch is comprised of an electric motor and a hydraulic transmission to offer smooth variable speed control of the transfer lines such as the highline, outhaul, inhaul, spanwire, and saddle whip. It too uses hydrostatic fluid and pneumatics as the work media to control the speed and tension of each cable.

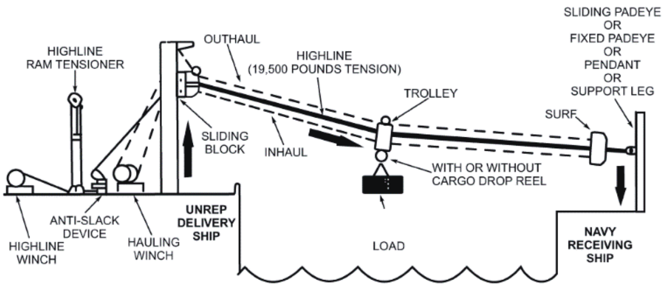

Figure 7 - RAS, MAJOR COMPONENTS (NSTM 571, 2009)

The Sliding Padeye has a drive screw controlled by a two speed electric motor to rotate the drive screw causing the padeye to slide up, when needed to clear the cargo over the deck, and slide down, when needed to lower the cargo onto the deck.

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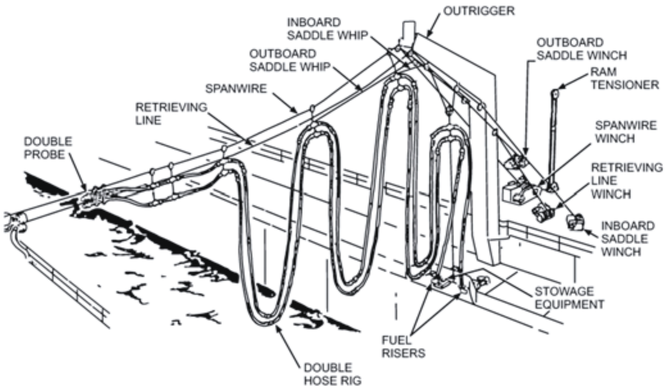

Figure 8 - FAS, MAJOR COMPONENTS (NSTM 571, 2009)

Since these technologies were over four decades old, many components and individual parts were either obsolete or difficult to fabricate. Thus, a new technological approach was needed to alleviate this problem whereby commercial off-the-shelf VFDs were employed into the new design which became known as E-STREAM (**E**lectronic-**S**tandard **T**ensioned **RE**plenishment **A**longside **M**ethod). One of the most notable differences E-STREAM has from the STREAM standard system is the removal of hydrostatic transmissions on the highline, spanwire, and hauling winches through the control fidelity afforded by use of VFDs (Hadley, 2015). While the UNREP's procedural steps remained little changed, VFDs generated exceptional performance improvements and maintenance savings for the overall process. A stated principle for the new design was to eliminate labor intensive components of the original system and reduce maintenance. This was achieved in three ways:
One, the double drum, hauling winch of the Standard STREAM was a complex system of transmission, air clutches, and pneumatic controls. That winch was replaced in the E-STREAM by two relatively simple all-electric single drum winches with VFD controls, thereby eliminating all the earlier wear components of air clutches and pneumatics mentioned above. Maintainability of the system was dramatically improved with reduced labor hours per UNREP due to fewer parts replacement as well as significant savings for repairs and replacement parts because the costliest maintenance items were the air clutch friction shoes and aluminum bronze friction drums of the double drum hauling winch. Two, like with all hydraulic machines, the original STREAM hauling winches' hydraulic fluids would leak and cause frequent repair hours by ships force in order to prevent both the safety risks of slipping and falling as well as the environmental hazards to the ocean. Those maintenance hours were eliminated entirely. Three, the VFD control system provides enhanced alarms and error information to the crew which reduces troubleshooting efforts and time to fix a problem (Hadley, 2015).

Regarding performance, the original hauling function of the hauling winch is now split between two hauling winches which achieve twice the speed of the earlier design, approximately from 900 fpm to 2,000 fpm, while also compensating for sea state 5 conditions (Hadley, 2015). The VFD control system removes the earlier need for an operator's hand-eye coordination because the VFD's control algorithms calculate trolley position enabling rapid transfer and automated slowing and docking at each terminus. The operator has proportional velocity control and automatic docking features with E-STREAM; i.e. the trolley will automatically slow down as it approaches the Receiving Ship and it stops at the terminus if the operator does not slow the trolley down manually (Hadley, 2015). This feature greatly enhanced load control and increased UNREP throughput.

With the Heavy version of E-STREAM, the superior torque load control performance of VFD control algorithms for the hauling winch, ASD, and ram tensioner was exploited to gain an advantage of increased weight capacity of Solid Cargo transfers. The HEAVY E-STREAM system consists mainly of the same components as the Navy Standard STREAM though with higher capacity components that include: the hauling winch VFD with an electric motor directly couple to a gearbox, a larger ram tensioner, larger diameter cable, and the Anti-Slack Device (ASD) with VFD to control the highline slack at a higher torque limit. The result: cargo transfer weight is up to 12,000 lb. loads as compared with the earlier STREAM design of 5,700 lb. and the transfer rate is increased to 50 loads per hour from approximately 25 (Hadley, 2015). All of this improved performance is accomplished through the VFD's high accuracy, closed loop switching control of its inverter IGBTs to adjust the output voltage modulated to the motor and then compare that output with the actual voltage and current at the motor leads.

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Figure 9 - Heavy E-STREAM trolley transferring 12,000lb test load during at sea qualification trials (McLachlan, 2014)

Finally, the VFD's Active Front End design at the Converter creates near unity Power Factor by which any excessive Reactive Power, KVAR per the Electrical Power Triangle principle, that these motors' stator field properties induce is dramatically reduced; hence the ship's main bus power consumption is reduced and energy efficiency is greater. The Active Front End VFD also provides the optional ability, when configured appropriately, to resupply any excess power and/or generated energy from the motors' electromotive force back into the ship's electrical main bus which would save on ship's power usage and consequently fuel consumption. Clearly, employing the variable frequency drive on this shipboard application produced numerous benefits.

4.3 Other Naval VFD Applications

Various other applications across all U.S. Navy surface combatants have employed the benefits of VFD technology. For the new FORD Class aircraft carrier, the VFD has made its impact on some critical subsystems of the aircraft launching system. The carrier's Jet Blast Deflection (JBD) which move steel panels up to block the jet blast from the aircraft's engines have VFDs and electric motors to actuate their motion up and down with greater speed than the earlier design of hydraulic transmission. This resulted in eliminating the hydraulic fluids for that system too which reduced maintenance hours and its environmental hazards just like the benefits to the E-STREAM.

The FORD-Class carrier has VFD technology for the aircraft EMALS system which, using electro-magnetic principles, has replaced the longstanding steam transmission source to launch aircraft. This VFD transition eliminates all the maintenance intensive equipment and labor to upkeep the boilers and auxiliary equipment of the steam system itself. Significant savings were gained in those operational costs necessary to create that steam supply as well. Moreover, the EMALS' performance is superior to the old steam design in that the electro-magnetic launching offers far more accurate launch energy matching to the aircraft's weight, thereby reducing excessive energy and lowering the structural wear and tear on the aircraft's landing gear. For the carrier's Deck Edge Doors, VFDs also provide more precise control of door position and speed than the standard single speed across-the-line starter.

Other surface combatants have also benefited from VFDs used in their pertinent applications. Their Weapons Elevators improved with greater speed control and less mechanical stress on the elevator's AC motors than with DOL starting. The same factors can be said of the NIMITZ Class aircraft carrier's Vertical Packaging Conveyers, and the ship's Anchor Windlass has more effective speed and torque control through VFDs for lowering and hoisting the anchor and anchor chain than with the legacy two-speed motor and across-the-line starter.

These are a small segment of the many applications on US Navy ships and there are many others with parallel principles that could benefit just the same with a VFD. Questions to consider for a potential application include ("When to use a Soft Starter or an AC Variable Frequency Drive", 2014):

1. Does the application need full torque at zero speed?
2. Does the application need speed control once the motor is at operating speed?
3. Does the application need constant torque?
4. Does the application need precise starting and stopping times?

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5. With any actuator-based system using hydrostatic fluid or pneumatic air, could a design change that utilizes an electric motor accomplish the same function?

The latest surface combatants today have new designs incorporating an all-electric propulsion plant and power management system supplied from diesel engines. As such, it becomes more and more compelling to effectively and efficiently reduce voltage and/or current disturbances to the various electrical buses of the ship's electric distribution system. VFDs controlling the ship's motors and other electrical loads make such results possible and can improve a ship's overall electrical margin. It is now a matter of engineers to continue their evaluation of VFD technology during an exciting era in flexible ship design, and it is certain that the list of new applications with VFD technology will expand.

5. Conclusion

Variable Frequency Drive (VFD) advances in Naval Automation are evident for the future because of the many advantages gained for shipboard applications. The Collective Protection System (CPS) and the UNREP's E-STREAM are two notable applications where the technology proved its robustness and capability to enhance the ship's performance for accomplishing its mission. Other benefits of VFDs include maintenance labor hours saved for the crew, electric power reductions and stability, and lower environmental impact by eliminating the HAZMAT issues of hydraulic fluids. In applications like the CPS for air flow, such as HVAC, energy savings could be as significant as 45%.

Speed control and torque control improvements found in the E-STREAM design doubled its load from 5,700 lb. to 12,000 lb. and speed performance went from 900 fpm to approximately 2,000 fpm. Successful implementations of VFDs into other applications like cranes and elevators have translated to smooth speed acceleration and deceleration as well as torque capabilities which lowered the mechanical forces induced on their motors thus extending that component's service life.

Lastly, installing VFDs on ships with hybrid or all-electric propulsion plants could realize broad energy and fuel consumption savings. Thus, it is provocative then to forge ahead with future VFD designs for shipboard machinery systems and engineering plants.

6. Acknowledgements

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