Naval Hybrid Power Take-Off and Power Take-In Solutions - Enabling Technologies and Intricacies of Power Systems Operations

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SYNOPSIS

Naval vessels have increasingly diverse operational profiles and governments face tightening of budgets and new environmental legislation. This leads to challenges for new vessel programmes to improve efficiency - both operational costs and energy consumption, deploying technologies that meet regulations whilst still enabling the naval mission to be carried out.

A variety of power and propulsion architectures have been used over the years. Each has its own benefits, but selection should consider what is most suited to the operational role and mission effects. Amongst propulsion systems available are several hybrid-electric applications, either in service or currently in build, such as the UK Type 26 City Class and the future Australian Hunter Class ASW Frigates.

Hybrid propulsion is not new; the latest hybrid solutions combine main diesels or a gas turbine engine with an active-front-end converter in combination with an induction motor, that can operate as both a motor (PTI) and a generator (PTO), to drive a controllable or fixed pitch propeller, either through a gearbox or direct. PTO/PTI can improve fuel efficiency by harnessing excess mechanical energy from a vessel's propulsion shaft.

The focus of this paper is to:

- Provide a hybrid propulsion concept overview, key electrical, mechanical qualities and issues leading to the shift towards such systems
- Describe different configurations and performances of hybrid propulsion from demonstrated and operational systems in the commercial and naval world
- Describe technologies used and systems modes of operation
- Cover lessons learnt in technologies and controls used of such systems
- Examine future architectures including energy storage and explore the benefits and flexibility these can bring to the hybrid propulsion sphere.

1. INTRODUCTION

The industrial revolution was driven by one of the greatest inventions of the 20th century: the combustion engine. For the majority of applications, it has been the power and propulsion behind almost the entire marine ecosystem. However, technology advances, coupled with a more challenging economic environment and the need to reduce carbon emissions, are now changing the way we can operate as an industry. While there is still a place for combustion engines, the marine ecosystem is more widely embracing electrification solutions, in a bid to become cleaner, smarter and more efficient.

Some key objectives for a design of a complex navy ship are to have versatility - the ability to have enough installed power *and* meet the trade-off between efficiency, adaptability of diverse operational profiles. Ship loads are increasing to the point where mission power requirements are close to that of the propulsion system. Therefore, a departure from the traditional mechanically driven propulsion with prime movers via a gearbox must be considered, such as integrated electric power and propulsion (IEP) or a hybrid electric system that may be better aligned to address such needs. Indeed, hybrid propulsion is not new to the navy world, it is being increasingly employed for frigates operating a low proportion of time at full speed and spending significant periods at low power, e.g. below 40-50% of their top speed.

2. SELECTION PRINCIPLES OF POWER AND PROPULSION SYSTEMS

The selection and design of a mechanical or an IEP[9] propulsion system follow a similar process and can be complex. The key points to consider are:

- Initial Concept of Operations (CONOPS)
- Propulsion power requirements, per shaft, per motor including torque/speed curves at rated and degraded parameters.
- Maximum and cruising speed powering requirements – link requirements to mission profile, systems and total ship mission effectiveness.
- Type and size of prime movers, e.g. gas turbine (GTG) or diesel generators (DG), allowing most economical fit to meet redundancy and powering requirements (total generation, overloads, ship services including end of life growth estimates).
- Environmental requirements especially relating to operation in higher temperatures and graceful degradation permitted. Both for cooling water (fresh/sea/chilled) and ambient air temperatures.

- Quality of power supply requirements.
- Power requirements and system fault level at high, medium and low voltage to determine most appropriate system voltage and equipment fault level capabilities.
- Redundancy groups, distributed system architectures, how the system will be split for resilience, i.e. graceful degradation after failure/damage.
- Simplified post shock event operational requirements.

The use of mechanically driven propulsion systems has its advantages where other loads of the ship are relatively low compared to the propulsion loads (less than 10%), but its main drawbacks are:

- Its power is dedicated 100% to use for propulsion
- Propulsion diesel or gas turbines must run at high speed for best efficiency, so a high ratio reduction gear is essential to obtain any economical propeller speed. Efficiencies of such engines are generally low at slow speed/power.
- Less flexibility to scale for future power and energy needs which are not defined to influence the 30-year ship acquisition plan.
- Complex shaft-line with large gearboxes

2.1 Integrated Electric Power and Propulsion

Many IEP navy platforms are now in service, with the Royal Navy, the US Navy and the French Navy, leading the way.

A typical IEP system will comprise prime movers (gas turbine or diesel engines) driving generators to produce electric power.

Most generating systems employ more than one generator. Such generators may be of equal or different ratings and speeds. However, they all must work in parallel and share load proportionally. Droop characteristics of voltage and frequency are employed with the voltage regulator reference drooping pro-rata with reactive current and the governor speed reference drooping with applied shaft load. This facilitates load sharing of the parallel connected generators particularly when they are of unequal ratings or mixed engine types. Electrical design of generators must be co-ordinated with the switchgear to ensure fault levels and protection are achieved.

This electric power is then fed to switchboards which distribute the power to various ship consumers. IEP interfaces with the vessel's control and automation system.

The advantages of a central power plant configuration of an IEP are well documented for vessels ranging from auxiliary and support vessels through to surface combatants and even aircraft carriers e.g.:

Increased vessel safety: Redundancy in the power generation plant and propulsion drive trains enable the system to continue to supply power to the propellers even in the event of multiple failures. Electrical drive trains designed to be quiet and shock capable.

Higher flexibility: In addition to facilitating flexible machinery layouts, for example to contain fire and flood damage; the system allows the power plant to be electrically configured to suit the vessel's different operating profiles. Worth also noting that higher energy power demands for future sensors, radars and advanced weapon systems continue to be primarily electrical and such advanced features will only increase over time and may be called to operate simultaneously with propulsion systems.
Lower operating, through life costs: Achieved from savings in fuel and maintenance costs by running the minimum number of generator-sets at their optimum loads.
Electric drive train provides for a simplified shaft line and eliminates the need for costly complex gear boxes.
Enhanced availability, reliability and maintainability: Achieved by operating the inherently robust plant most efficiently and by permitting preventative maintenance work to be carried out during voyages. IEP systems can be reconfigured for efficiency and battle resilience, recovery and availability.

As in almost all industries, there is a push to achieve more with less for marine organisations. Some vessel operators are realising the value that electrical solutions bring in terms of increasing asset reliability and vessel longevity.

2.2 Hybrid Electric Power and Propulsion

Hybrid propulsion systems, introduced almost 40 years ago, take advantage of the best of both worlds of propulsion, conventional mechanical and full electric, to make a system better suited for some specific type of vessels, especially where the objective is to focus on efficient and where necessary quiet operation.

There are a wide range of hybrid configurations [5,7]; such as a high-speed motor to a gear box Figure 1a, or motors directly on the propeller shaft line, Figure 1b.

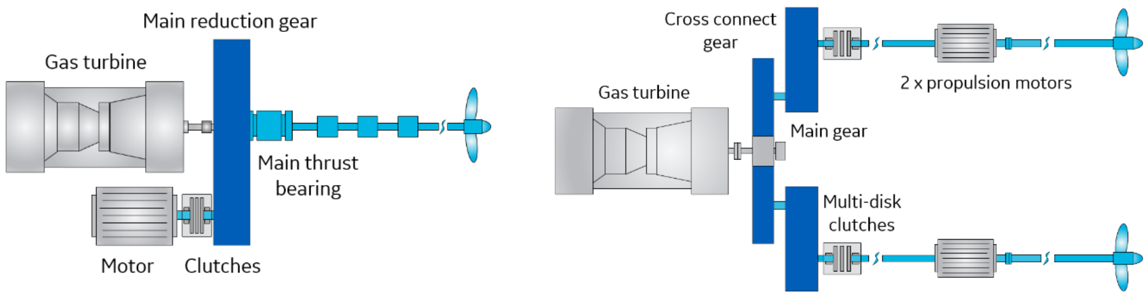

Figure 1: CODLAG Hybrid Propulsion Configuration – High and Slow Speed Electric Motor

The main benefits of hybrid electric propulsion are:

- Fuel savings by using the smaller electric motor for speeds up to 15-20 knots thereby reducing the need for large main engine operation.
- Reduced maintenance on the main engines due to reduced run time by using the hybrid electric motors (HEM).
- Main engines and hybrid electric motors can be operated independent of main gear.
- Enhanced fuel economy in all modes of operation, especially for vessels with fluctuating load demands and a mixture of transit and slow speed operation.

- Lower noise signature for Anti-Submarine Warfare (ASW) operations.
- Additional installed power for future power availability, accomplished by powering the ship using the main mechanical engine and using the hybrid electric machine system to slow down the ship enabling the hybrid motor to act as a generator power take off (PTO) that can feed pulsed power applications. This power take-off capability is not used on all ships.

3. HYBRID PROPULSION SYSTEMS CONCEPT CONFIGURATIONS

The focus of this paper is on a **CO**mbined **D**iesel e**L**ectric **A**nd **G**as (CODLAG) configuration, as represented in the single line diagram (SLD) at Figure 2. This hybrid system with one gas turbine via a reduction gearbox with two shafts, each with a hybrid electrical motor (HEM), drive a controllable pitch propeller (CPP) and could be a simplistic representation of an Anti-Submarine Warfare Frigate (ASW) or the Global Surface Combatant currently on order by the Royal Navies of UK, Australia and Canada.

The paper does not give any descriptions of the systems' operations for such frigates or details of equipment but covers concepts or possible concepts of operations and beneficial additions of typical CODLAG systems.

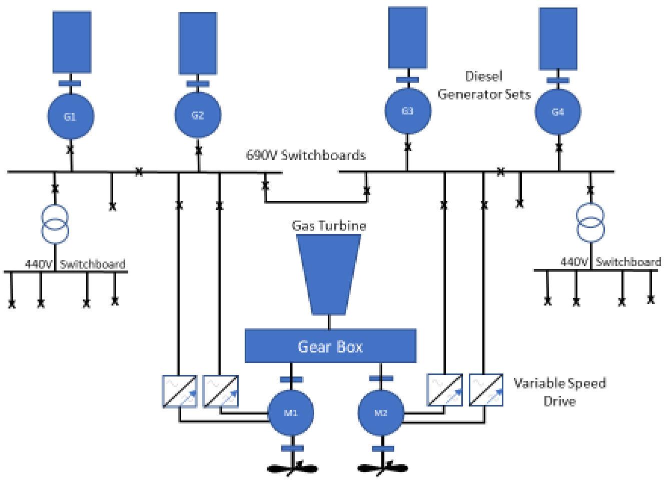

Figure 2: CODLAG Hybrid Propulsion

The propulsion and the electrical power systems have multiple operating configurations. The chosen operating mode primarily depends on a combination of the desired ship speed, ship mission and its effectiveness and the total electrical load demand on the system. The actual design of the system and the ratings of the prime movers requires careful consideration, such as total required propulsion power, desired 'efficient and quiet' electric propulsion load, maximum electrical load (including sufficient through life design margin), and often availability of products to meet most requirements at affordable cost.

The HEM is of induction machine design, with multiple phases and each group of three phases has its own dedicated pulse width modulated power variable frequency drive (VFD) to vary its frequency and therefore speed. The compact induction motor has been selected as it is inherently simple, has fewer components, has robust, reliable, well-proven technology and is successfully used on many navy platforms (destroyers and aircraft carriers).

The VFD is able to provide accurate and smooth control of both the voltage and the frequency of the waveform across a wide range of motor speeds. The use of an active-front-end (AFE) converter i.e. bidirectional, results in a very high-quality generated waveform suitable for quiet mode operation of the HEM and direct connection to the main distribution network, without the need for isolation transformers.

Both HEM and VFD as a drive train and within the full-scale electrical system have been through extensive proving testing to demonstrate the ultra-quiet function at various speeds and loads and have been barge shock tested. On some arrangements the electrical motor has the added flexibility to operate as both a motor (Power Take In – PTI) and a generator (Power Take Off – PTO) with the excitation from the VFD, providing additional electric power for the ship, and it is connected to the main distribution network via a bi-directional power electronic converter. This, in addition to diesel generators sets (DGs), can supply power for either electric propulsion or the ship's service loads. Note that the PTO mode is not selected to ASW platforms currently in build.

3.1 Full and Top Speed:

The arrangements below give possible hybrid systems configurations and operating modes:

Figure 3a. GT fully driving both propellers; HEM off; DGs providing ship's service electric loads

Figure 3b. GT can be boosted by HEMs driving both propellers for maximum speed; DGs providing ship's service electric loads.

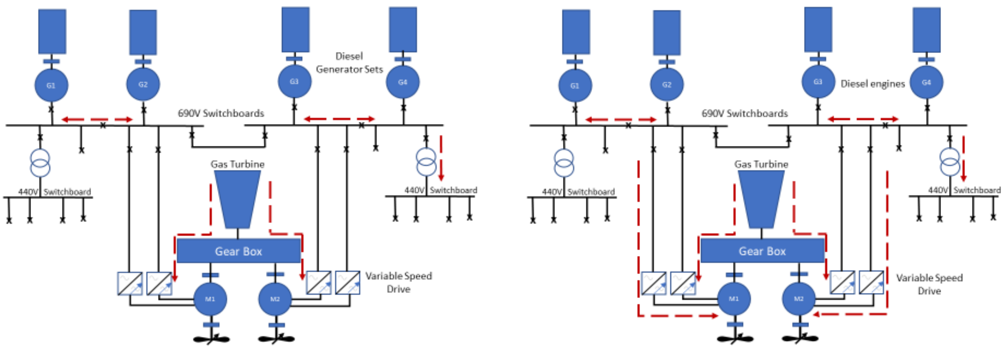

Figure 3: (a & b) CODLAG Propulsion by GT and topped up by HEM

3.2 Quiet Mode:

Figure 4 HEM driving propellers in PTI (mode); DGs providing propulsion and ship's service electric loads. GT / gear box not running

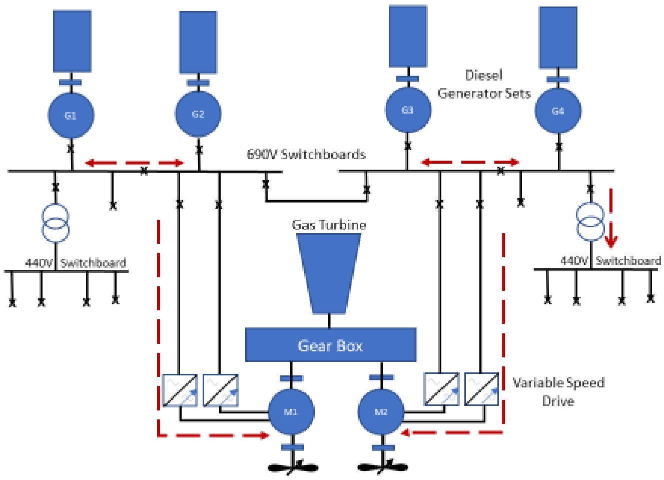

Figure 4: CODLAG Propulsion by HEM

Naval vessel design can be driven by ASW requirements, with a need for low noise and vibration (N & V) signature and very quiet operations at slow to medium speeds: "Detect the enemy before they detect you". Electric propulsion systems can meet highly demanding acoustic signature specifications, in part because gearboxes and their auxiliaries are not required. This allows naval vessels to operate with lower risk of detection.

Advances in electrical machines and their associated converter drives in electromagnetic design, waveform smoothing, anti-vibration technology along with shock proof motors achieve a much quieter operation than can easily be obtained by traditional mechanical systems.

The ability of the system to operate without a gearbox improves its maintenance regime, the efficiency of the drive train and the noise signature (highly relevant to ASW frigates).

3.3 Electrical System Complemented by Energy Storage

As stated above, arrangements below do not form current topologies of ASW electric hybrid systems but could easily be envisaged in the future. However, such configurations need to consider type and size of prime movers, ship services' power requirements, system architectures, how the system will be split for resilience and space …etc.

Energy Storage System (ESS) [11, 14] can provide multiple additional benefits [12] such as:

- Running lower numbers of generators online at higher load due to reducing limits for spinning reserve. ESS acts as online backup or additional power reserve instead of generator power reserve, providing available power in case of a generator's failure for a predetermined duration.
- Improves system stability to accommodate response time of engines to load changes.
- Enables reducing load ramp limits at thrusters and quickly available thrust force. This enables fast responsiveness to environmental forces, enhances the manoeuvring capabilities of the vessel, thus increasing safety against collision and grounding.

- ESS can reduce the power system vulnerability to faults in externally supported systems, provide power to essential auxiliary systems, offer additional benefits if self-supported and not dependent on external systems, especially during possible power system blackout.
- Reduces operating costs due to enhanced fuel consumption and lowers maintenance costs when engine(s) cyclically loaded.
- Reduces the risks of blackout by operating ESS as 'Uninterruptable' Power Supply (UPS), and in case of blackout enables quick power system recovery, faster than when emergency generators are used.
- Depending on the operating load profile, ESS can reduce the number of generator start/stops and make power available during start-up of stand-by generator(s).

In addition to above advantages, ESS could power HEM providing an even quieter mode of operation in naval applications without any GT or DGs running.

In light of new, up-coming regulation, emission free modes, taking power from ESS, cannot be ignored when the vessel operates in Emission Control Areas (ECAs), close to harbour, or entering/leaving harbour or during short stays in harbour where shore supply is not available.

The ESS duration of support could typically vary from just a few minutes in vessel manoeuvring, up to 20-30 minutes in transit, and could be extended up to one or two hours if the battery can be recharged at shore.

With the flexibility of electrical systems, ESS could be connected to a main switchboard through a power electronic rectifier or to the propulsion VFD DC link or through another optional DC/DC rectifier.

Configurations with ESS are shown at Figure 5.

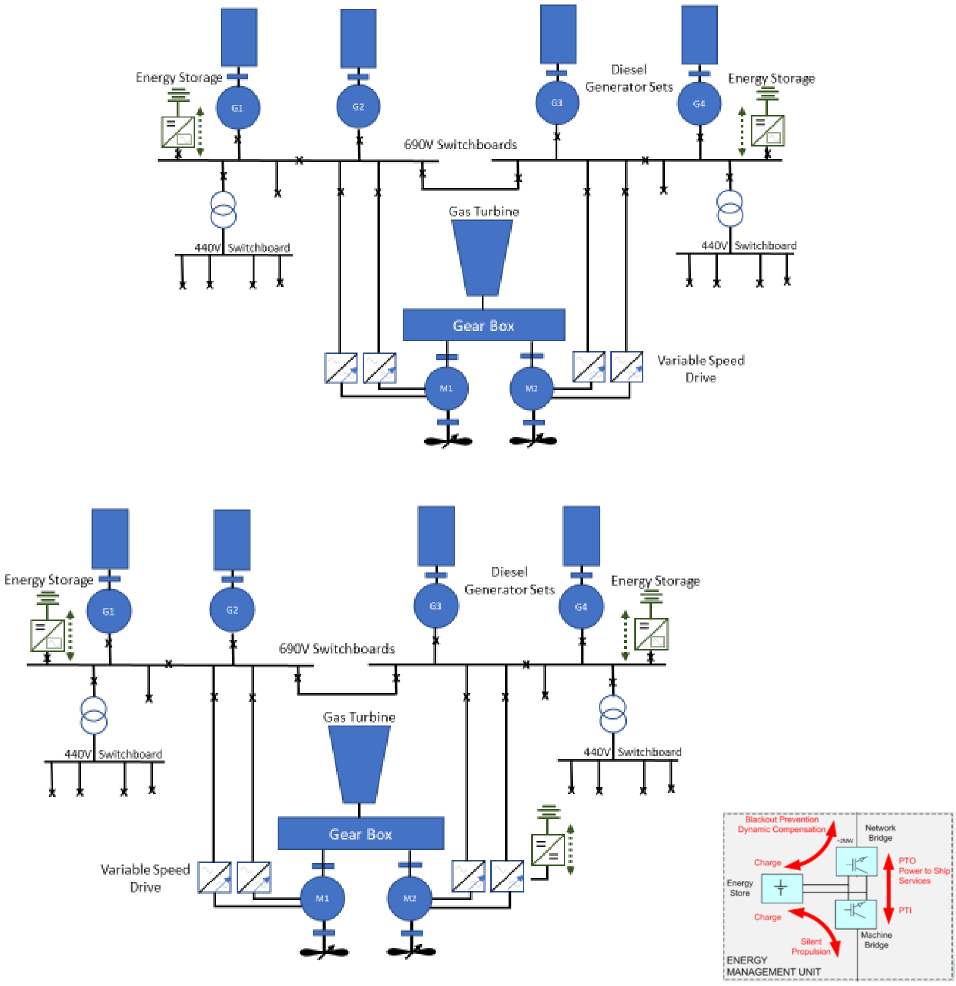

Figure 5: Electrical system complemented by energy storage

3.4 Power Take Off Generator (PTO) – Figure 6:

GT driving both propellers; HEM on as PTO; reduced number of running DGs providing ship's service electric loads. This mode normally used in transit sailing harnesses the excess mechanical energy from the vessel's propulsion shaft. The GT not only powers ship propulsion but could supply electric power for the ship's domestic consumers. This mode will lead to high loading of the GT with low specific fuel oil consumption, minimal emissions and impact on the maintenance period of the DGs as they can be switched off when not needed.

Additionally, with a suitable bi-directional converter sized converter for the hybrid PTI/PTO , an option exists to make use of this as a frequency changer for the shore supply to the ship of different grid frequency The hybrid converter in this case can be used as a static frequency converter (SFC) on board allowing the seamless import of power from shore, or export from ship; helpful functionality can be in a disaster relief situation.

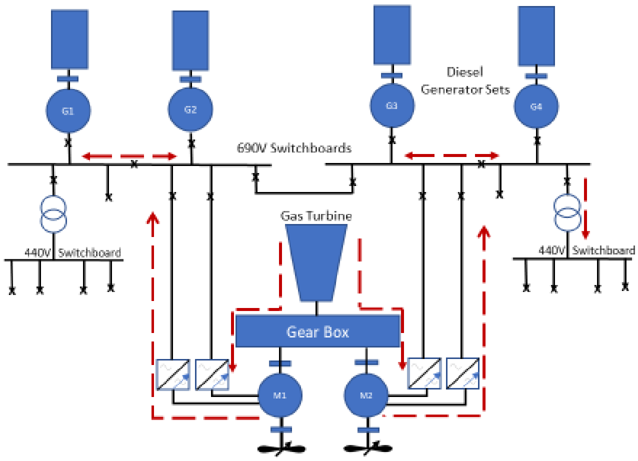

Figure 6: Power Take Off Generator (PTO)

4. OVERVIEW OF ADVANTAGES AND THEIR APPLICATION

There are several hybrid applications that have either recently been brought into service or are currently in build and these illustrate the range of potential benefits that a hybrid system can bring. No single application makes use of all those features, but each selects the range of benefits that is most suited to their operational role. A summary of benefits and the vessel types are illustrated in Table 1**Error! Reference source not found.**:

	Direct Drive Frigate Anti-Submarine Warfare (ASW)	**Direct Drive Commercial**	**Geared Auxiliary Vessel**	**Geared Light Frigate**	**Geared Assault Ship LHD/LHA**
Reduced Engine Count		✓	✓		
No Gearbox	(✓)	✓			
Efficiency	✓	✓	✓	✓	✓
Reduced N&V	✓			(✓)	
Electrical Energy	(✓)	✓	✓	✓	✓
Survivability	✓			✓	✓
Shore Supply / Disaster Relief				✓	

Table 1: Example Recent Hybrid Systems

4.1 Shock-Rated Electric Limp Home Mode

Frontline Naval ships typically demand shock-rated equipment for their propulsion systems; however, adding shock-rating to an entire shaft line is an expensive option. This would be especially true for a hybrid system if both the electrical and mechanical propulsion systems required shock hardening.

An alternative option is to only shock harden the HEM drive train, along with another generator(s). This greatly reduces the cost and burden of a complete shock hardened overall propulsion system, whilst providing an electric 'limp-home' mode which can still be used following a significant shock event.

5. FUNCTIONALITY CHALLENGES AND ADVANTAGES

5.1 Propulsion Control System

The complexity of different modes of operation of a CODLAG system requires a propulsion controller able to:

- Perform several dedicated functions to safely manage the various propulsive modes of the vessel.
- Consider the different propulsion modes and their changeover, and in different quadrants in the case of PTI/PTO, as illustrated in this paper.
- Represent the dynamic behaviour of the machinery performance and manoeuvrability of the vessel.
- Select the proper matching between prime movers and propellers loads, take advantage of the simultaneous use of GT and HEM with the ship navigation and manoeuvring conditions in mind.

5.2 Shaft Load Dynamics

Significant torsional load changes[3] on a propulsion shaft line are typically gradual with the changes taking place over a number of seconds. However, torsional load on a *generator* shaft line can change very suddenly with a large load application or rejection on the electrical distribution system. For this reason, engines that are designed to operate as the prime mover of a generator have demanding performance standards, applied by the class societies, that are not normally applied to propulsion engines and it may be expensive to do so.

5.3 System Component Selection

A key difference between sizing a converter for duty as a PTI motor drive and sizing it for use as a PTO generator [1,2] is that a PTI drive has its input voltage sustained by the distribution network, but a PTO generator must sustain the voltage downstream of its network filter. This means that the power electronics must counteract the effect of volt drop in that filter. A key factor that gives rise to volt drop is the amount of reactive current that must be supplied by the converter i.e. the power factor of the system. An AFE drive has the luxury of always being able to draw its power at near unity power factor but a PTO converter must supply its power at the power factor dictated by the distribution network and the connected loads.

5.3.1 Protection Implications of PTO

There are a number of system related issues that arise when integrating PTO with a vessel. A common certification class requirement is that for the PTO generators to be classed as primary generators and included in the ship's load list they have to provide full discrimination for protection. If they were not primary generators then their supply of power to the system could not be counted when looking at electrical loading for given operational scenarios, which would result in extra DGs being required. In order, for a PTO generator to provide discrimination it needs to be able to provide sufficient short circuit current in the event of a fault.

Some of these issues arise out the fact that PTO is tying one system, the propulsion system, to another, the electrical distribution system. Others relate to the fact that a new technology is being used as a source of energy (i.e. based on solid state silicon) that has different underlying behaviours from the conventional technology (based on rotating copper and iron). Comparatively a power electronic converter has very limited overload capability since its thermal mass is much less, and beyond the limit the controller will normally trip the converter to protect the devices. [1,2]).

5.3.2 Avoiding Hybrid Converter Trips

VFDs are important assets and protect themselves from a faulty distribution network often by tripping and shutdown requiring an operator to reset the controller and bring it back online, e.g. a significant fault that causes a potential fault current greater than maximum overload capability. Such an event can be lengthy, and, depending on the operational scenario, might have a major impact. This philosophy cannot be followed when the VFD is acting as the power source (i.e. the PTO generator), a process of current management with the controller software code needs to be applied to maintain the converter connected.

5.3.3 Current Management for Selectivity

A conventional generator has the natural property of delivering a significantly higher current than its maximum load current when a short circuit is applied. Sensing-circuit and protection relays deduce that there is a downstream fault and open associated circuit breakers to isolate this fault. A converter, however, does not have this natural property. It is normally sized to deliver its load current with only a small overload capability. Where the protection settings can be integrated with the electrical power system configuration this can be managed with a simple current clipping feature in the converter [1,2]. However, where a simple, conventional protection scheme is used the converter must be designed to deliver the correct fault current in the event of a fault. This is illustrated in Figure 7. This shows current and voltage traces during a fault event.

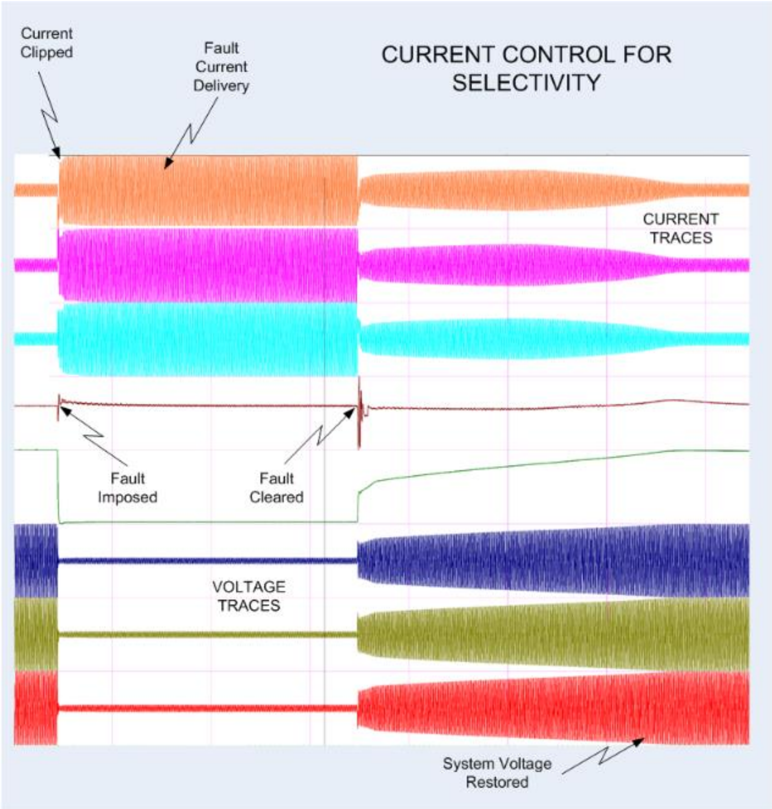

Figure 7: Current Control for Selectivity

5.4 Harmonics

A converter imposes time harmonics on the network to which it is connected. On a three-phase system where a converter has a Diode Front End (DFE) network bridge then those harmonics occur at $F_0(6N\pm1)$, where F_0 is the fundamental frequency and N is an integer. For a modern PTO system with an Active Front End drive (AFE) the network bridge uses transistor switching and the harmonics are dominated by the Pulse Width Modulation (PWM) switching frequency and its multiples, of 10 to 50 times F_0 or more. However, the AFE will incorporate a network filter which will reduce the PWM element to a small percentage of the waveform. This is typically a few percent and is therefore normally within the class society voltage Total Harmonic Distortion (THD) limits.

The electrical system load, however, may include DFE converters and these are typically unfiltered. Where a system is generator fed, the sub-transient reactance of the generator will tend to reduce the impact of these harmonic currents on the system voltage. This is not the case for a PTO system and the PTO filter is unlikely to be targeting the DFE harmonics. This means that for a PTO fed system the total amount of distorting load on the system must be carefully managed to ensure the system stays within limits in the worst-case configuration of the power system.

5.5 Black-start Recovery

Another challenge is using the PTO generators for black-start recovery operation, whereby the entire ship has lost power and the hybrid system is used to restore power. This could be the case operationally if the DGs are unavailable. If an induction machine is used for the hybrid it causes a challenge when it comes to black-start recovery, as it requires excitation voltage to be applied for magnetising before it can produce power. Normally when the hybrids become PTO generators this voltage can be simply provided by the converter which is connected to a live distribution network (fed by the DGs). In a blackout situation this is not possible and so a restart module is needed to connect to the hybrid converter. ESS is the ultimate solution.

5.6 Load Sharing

In a traditional ship's supply system, the frequency is controlled by a relatively low bandwidth engine governor and the voltage by a generator automatic voltage regulator (AVR) acting through the (relatively slow response) of the generator field windings. For a PTO system, the control bandwidth and precision are vastly superior to the traditional generator. Exact, high response control of frequency, voltage, active and reactive power are possible. In this context it is possible to shape the response of the PTO system depending on whether it is sharing with a generator and what the overall state of the system is.

When this capability is combined with a converter energy store that is independent of the dynamic limitations of the mechanical system then further system capability benefits can be released.

5.7 Propulsion Converter as Energy Management Unit

The listed benefits of energy storage come at a price in terms of volume and vessel infrastructure and its energy is not stored in convenient 60Hz units that can match a normal AC distribution bus. Therefore, all energy stores need some form of power electronics to interface to the DC or AC distribution bus. Such power electronics add cost, take up volume, need auxiliary services and are typically connected to the distribution bus via a dedicated protective device, such as a circuit breaker. All these factors need to be considered.

6. CONCLUSION

Recently completed projects with modern hybrid propulsion have demonstrated advantages as well as some challenges encountered during system design, testing and operation. Electric hybrid propulsion systems need to be tailored at the design stage to meet the operator's requirements and what is needed from the ship.

Whilst the new advanced hybrid systems are very flexible, the main benefits come when the complete system combining the needs of propulsion, ship's service power supply and equipment type are fully optimised and integrated to the platform. Integration of the hybrid system as a whole is essential.

The hybrid concept continues to evolve to give greater benefits and flexibility, and the use of its major components, particularly the hybrid propulsion converter, is emerging as the heart of the energy management system of vessels of the future.

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