Advanced hybrid systems and new integration challenges

O J Simmonds\* MEng MSc CEng CMarEng MIMarEST

*\* BMT, UK*

*\** Corresponding Author. Email: [ojsimmonds@gmail.com](mailto:ojsimmonds@gmail.com)

**Synopsis**

In recent years there has been a marked shift towards hybrid propulsion systems. Whilst the main reasons for adopting hybrid systems have been for efficiency and through-life fuel saving benefits, they also offer increased flexibility to the operators for varying mission profiles. New advanced hybrids combine a large main diesel engine with an active-front-end variable speed electric drive in combination with an induction motor, that can operate as both a motor (Power Take In – PTI) and a generator (Power Take Off – PTO), to drive a controllable pitch propeller through a gearbox. In these cases the systems used and the concepts of operation required need the correct integration to fully maximise the potential. This paper explores recent experience of this integration, using lessons learnt from the initial concept phase through to detailed design and equipment delivery on several new projects: the UK MARS Tankers and the Norwegian Logistics & Support Vessel. The paper addresses some of the challenges encountered and demonstrates how they can be mitigated focussing on a whole systems approach and the use of novel techniques.

Keywords: Hybrid; PTI; PTO; Propulsion; Integration; Marine systems

# Introduction: Moving away from mechanical propulsion

Since the mid-20th century the trend for Naval ship propulsion has moved away from a purely mechanical system towards an electric one. Historically both hybrid-electric and full-electric propulsion systems have been utilised, with some of the early hybrid systems acting as a ‘first-step’ away from mechanical propulsion. For example, the Type 23 ‘Duke’ Class Frigates, designed back during the 1980s, adopted a hybrid propulsion system, using electric drive for quiet anti-submarine operations, and gas-turbines for higher speeds (Simmonds, 2013).

In recent years larger ship projects have favoured Integrated Full Electric Propulsion (IFEP) where the same generators can provide power for both propulsion and ship’s services. This type of system allows the use of fewer prime movers for both propulsion and electrical loads. In addition, high levels of power can be made available (at low speeds) for a new generation of high power sensors, launchers and electric weapons. An electric propulsion system also allows for flexibility of layout and operation as the majority of equipment, especially the large prime movers with significant air inlet and exhaust requirements, can be positioned independently of the shaftline(s). These factors combined gave the operators flexibility for varying mission profiles whilst giving the Navy future flexibility to fit high-powered electric weapons and electromagnetic launchers.

The UK Royal Navy adopted IFEP for their latest frontline ships, namely the Type 45 Destroyer and the Queen Elizabeth Aircraft Carriers (Simmonds, 2013). In the case of the carriers, being able to move the location of the large gas turbines away from the shaftlines gave the Naval Architects increased space for the flight deck and hanger.

Whilst neither of these ships currently have any of the aforementioned high-power electric loads, one day they may be retrofitted as the technology maturity level of the equipment increases and threats evolve. As and when this occurs, the IFEP systems have the required power reserves to allow aircraft to be electromagnetically launched or directed energy weapons to target enemy threats.

1. **The hybrid option**

Despite the many well published benefits of IFEP, it has not always been the flavour of the month for smaller ships. IFEP comes at the cost of greater volume and weight compared to other types of more mechanical based propulsion, and it is often more expensive to purchase. For an auxiliary support ship there is currently little need for high power levels for next-generation weapons and sensors, instead through-life costs (TLC) and efficiency tend to be the main drivers. A hybrid mechanical and electric propulsion system is an excellent alternative choice to IFEP for such vessels (Dalton & McCoy, 2012).

The focus of this paper is on a COmbined Diesel eLectric Or Diesel (CODLOD) arrangement with the added flexibility that the electrical induction machine can operate as both a motor (Power Take In – PTI) and a generator (Power Take Off – PTO). A representative single line diagram (SLD) of this arrangement can be seen in Figure 1. At a simplistic level this hybrid system is shared by both the MARS Tankers and the Norwegian Logistics & Support Vessel (LSV).



Figure 1: CODLOD Hybrid Propulsion with PTI/PTO

Figure 1 shows a simplified view of the CODLOD hybrid system. On each of the two shafts, a main diesel engine (MDE) and a hybrid machine (HM) drive a controllable pitch propeller (CPP) via a reduction gearbox. As previously mentioned the HM can be run as either a motor (driving the shaft) or a generator (providing electric power for the ship), and it is connected to the main distribution network via a bi-directional power electronic converter. In addition, two diesel generators (DGs) can supply power for either electric propulsion or the ship’s service loads.

The arrangement gives three main operating modes, shown in Figure 2:

1. Full Speed: MDE fully driving propeller; HM off; DGs providing ship’s service electric loads
2. Diesel Cruise: MDE driving propeller and HM; HM in PTO (generator); DGs off (depending on load)
3. Electric Cruise: MDE off; HM driving propeller (PTI); DGs providing all electric loads



Figure 2: CODLOD Hybrid Power & Propulsion Operating Modes

The chosen operating mode primarily depends on a combination of the desired ship speed 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, and whilst this is not the subject of this paper, it is important to note some of the factors that influence this decision. Important factors include the total required propulsion power and the desired ‘efficient’ electric propulsion load, the potential maximum electrical load (including sufficient through life design margin), and the often critical factor: the availability of commercial off-the-shelf products that determine cost.

Note that an induction machine is used for the hybrid machine; this is because when coupled to a power electronic converter it can seamlessly serve as both a motor and a generator, it is inherently reliable, and it is well-proven technology. The converter is able to provide both excitation for the generation function, and accurate 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 results in a very high quality generated waveform suitable for direct connection to the main distribution network, without the need for isolation transformers.

# Benefits and additional flexibility of a hybrid system

There are several major benefits to be had from adopting a hybrid propulsion system similar to the type presented, many of which have been discussed before in published work (Buckingham, 2013 & 2014).

Modern Navies often do not have the luxury of multiple ships to carry out the roles required to meet today’s evolving needs, and instead are looking for multi-role platforms that can conduct a wide range of operations. This is especially true of non-frontline auxiliary and support ships. Typical uses can vary from stores and fuel replenishment, to humanitarian aid provision and medical/hospital support. This often means that an auxiliary ship can have a wide range of mission profiles ranging from fast transit and replenishment-at-sea (RAS), to harbour operation and even a ‘mother-ship’ role for other vessels in the fleet.

A hybrid system provides greater flexibility against a variable mission profile, compared to a conventional mechanical propulsion system, but with potentially lower initial costs (ultimate purchase cost – UPC) of equipment compared to an IFEP solution. This increased flexibility has been shown to directly impact the efficiency of the ships, saving fuel and offering a reduction in the TLC of the platform. Coupled to this increased operational flexibility is the design flexibility offered by a hybrid system and the ability to reduce the overall number of prime movers required. Once the decision has been made to go for a hybrid propulsion system additional flexibility can be incorporated.

## Shore supply frequency converter

With the addition of a suitable sized converter for the hybrid PTI/PTO system, an option exists to make use of this as a frequency changer for the shore supply to the ship. An example from a recent project is of a ship that uses a 50Hz power system on-board, however many of the ports the ship may visit use a more conventional 60Hz shore supply (as used by the majority of Naval ships). 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. A simplified indicative SLD of this solution can be seen in Figure 3. As well as allowing connection of a 50Hz ship to a 60Hz shore supply, this sort of arrangement would also allow a more conventional 60Hz ship to export power to the shore (50Hz) during disaster relief activities.



Figure 3: Hybrid Converter as SFC (Indicative)

## Shock-rated electric limp home mode

The advanced hybrid systems presented are also suitable for frontline Naval ships, which typically demand shock-rated equipment for their propulsion systems, however adding shock-rating to an entire shaftline 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 electrical machine and converter, along with another generator(s). This greatly reduces the cost and burden of a complete shock hardened propulsion system, whilst providing an electric ‘limp-home’ mode which can still be used following a significant shock event. A simplified indicative SLD from a recent project of this option can be seen in Figure 4.



Figure 4: Shock-rated Electric Limp-home mode configuration (Indicative)

# Overcoming the challenges

Whilst a hybrid power system offers many benefits, it does pose some significant challenges over a conventional mechanical propulsion system with standalone generators, and even some challenges not seen on an IFEP power and propulsion system.

## Selection of power electronic converter and management of voltage

The first challenge is dealing with the power electronic converter specification for a PTI-PTO hybrid generator application, since a number of factors need to be taken into account. The current capability of the drive, the maximum voltage it can sustain on the DC link and the impact this has on the lifetime of key components, the impedance of the network filter and the amount of reactive power (VArs) that need to be delivered all need to be considered.

A key difference between sizing a converter for duty as a PTI motor drive and sizing it for use as a PTO generator 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.

The exact modelling of this and the actual sizing is a commercially sensitive subject and needs to be carefully considered; however for the purposes of this paper the result is that for a PTO generator application a larger converter is in fact required in order to provide both the real and reactive power requirements.

## PTO generator protection schemes

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. Converters are rated by how much current they can provide to a load in normal operation, and to avoid high levels of thermal loading on the power electronic devices are typically very limited in terms of overload rating. A conventional diesel powered alternator, which has significant inertia and a high thermal mass (due to the nature of its construction from copper and iron), is capable of transiently providing up to three times full load current (FLC) under a short circuit. 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.

An easy, although extreme, solution would just be to simply install a (current) rating of converter three times larger than is actually required. However this would not be practical nor would it make the hybrid option competitive in terms of space, weight and cost to do this in order to meet the required overload. Instead a more refined solution is needed that requires a thorough understanding of the issues. As previously discussed, it is usually necessary to install a slightly larger converter for a PTO application compared to what could be used if it was only for PTI. This assists in allowing the converter in providing fault current, due to the fact that some additional converter (current) margin is already installed. The result is that whilst the PTO transient overload is still not as high as a conventional alternator, it is greater than the baseline overload due to the extra installed capacity.

With careful design of the protection co-ordination scheme, the resultant overload margin is sufficient to provide the required discrimination for most loads. The challenge continues however when large ship service transformers are installed. As can be seen in Figure 5, a simplified version of the MARS Tanker SLD only showing one shaftline, the FLC of the two large 3800kVA transformers is 3179Amps. This is much larger than the nominal current that a single hybrid will provide in PTO mode which is approximately 2510Amps. There could easily exist a case when running in Diesel Cruise mode with only the PTO generators operating and sufficient load on the transformers where the PTO generators become fully loaded. In the case where the load continues to increase (before the power management system has started additional generators) the protection relays for the PTO incomers in the switchboard would see this overload as a fault and trip the breakers, potentially blacking out the ship as these are the only source of generation.



Figure 5: Simplified MARS Tanker Single-Line-Diagram

The proposed solution for this is to program two sets of protection curves into the transformer feeder relays: one curve for the FLC rating, and one for a reduced current rating. A switchboard controller monitors the power system configuration and when only the PTO generators are online as the sole generators, the controller sends a signal to the protection relays switching the protection curves. This effectively de-rates the transformers when fed by the PTO generators so the transformer breakers will trip first in an ‘overload’ situation. As a backup, the protection relays could also be configured with a voltage restrained overcurrent setting (ANSI 51V). If a fault occurs the system voltage will drop and the 51V relays will sense this and ultimately trip the relevant breakers.

One key requirement of a PTO generator fed power system is that it is essential for the transformers to be fitted with pre-charge units to provide magnetisation of the main transformer in a controlled manner. This is due to the fact that the converter would not be able to cope with the transient inrush current that can be a factor of approximately seven to ten times the nominal full load current rating of the transformer. As an example, Table 1 gives the design data values of the ship-service transformers fitted to the Norwegian LSV.

Table 1: Design Data for Transformers fitted to the Norwegian LSV

|  |  |  |  |
| --- | --- | --- | --- |
| Transformer | Primary 690V  Nominal Current | Inrush Current | Factor |
| 1000kVA  LC1 & LC2 | 836.7 Amps | 9.23 kA | 11.0x |
| 2500kVA  LC3 & LC4 | 2091.9 Amps | 14.20 kA | 6.8x |

## Total harmonic distortion

Power quality is a recurring challenge on islanded power systems, and it can be affected with the addition of power electronic converters. Ship specifications often incorporate STANAG 1008 for the LV distribution (up to 440V) and whilst this doesn’t apply to the high power LV generation system (690V), the level of Total Harmonic Distortion (THD) should be minimised at the source to aid meeting the requirement downstream. STANAG 1008 requires that the THD on the distribution system in any configuration must be less than 5% with a single frequency maximum of 3%.

The use of AFE converters for the PTO generator, with a carefully designed network filter, results in the production of a very high quality waveform. This results in an inherently low THD being produced, which allows a very high quality of power supply at the LV distribution level. However the addition of 3rd party converters, which may be six-pulse or AFE with a different switching frequency and filter design, needs careful consideration to avoid interference and/or resonance which could in fact lead to increased harmonics.

## Earth faults

There are two main issues that are commonly experienced concerning earth faults in a hybrid power system: firstly the resultant current flowing during an earth fault, and secondly detecting the location of the earth fault. For an auxiliary support ship with tanker notation, the relevant regulations must be adhered to: SOLAS regulations require the earth fault current for single earth fault to be limited to less than 5A. To meet this requirement the capacitance to ground in any part of the system should be managed. Depending on the number of power electronic converters this might result in requiring changes to the filter design, which will cause an impact on the resultant THD. A careful trade-off must be used requiring in-depth understanding of the system interaction.

When an earth fault occurs, the main task is to identify where on the power system it is so it can be quickly and easily isolated to clear the fault from the rest of the system. Supporters of unearthed systems maintain that a system should be able to run with a single earth fault, whilst this is credible for a 440V LV distribution system, it is impractical for a high power 690V system and in practice should be avoided and the fault cleared as soon as possible. The longer a single fault is left, the more likely the chance a second fault will occur resulting in significantly higher current, with more damaging consequences (Meggs, 2013). The initial solution to this is to fit core balance current transformers to the switchboard and an earth fault detection system, which allows the fault location to be identified and the relevant feeder isolated. A complication arises if the fault occurs within a converter, as detecting and isolating an earth fault here requires specialist knowledge to ensure only the faulty drive is isolated and avoid any other nuisance tripping (Benatmane, 2016).

## Blackstart recovery

Another challenge is using the PTO generators for blackstart 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 blackstart recovery. An induction machine 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.

The required restart module comprises of a small rectifier fed from the emergency switchboard connected directly to the DC link of the hybrid converter. Figure 6 shows traces, with the main points marked, from actual testing of the system at GE’s Marine Power Test Facility at Whetstone. The restart module initially energises the DC link (Point A to Point B) so the machine bridge of the drive can provide sufficient volts to energise the induction machine (the corresponding magnetisation current is shown at Point C). The hybrid machine will have been driven by the main diesel engine (MDE) up to speed (the MDE fuel pumps are battery backup fed), and by use of an encoder the machine bridge can synchronise its output to the rotating machine. Once this occurs active power can be taken from the PTO generator and the machine bridge can boost the DC link to rated volts (Point D), which allows the machine flux to be increased up to its nominal value (Point E to Point F). The process to get the DC link and machine side up to rated volts takes approximately twelve seconds. Then all that is left is for the network bridge of the drive to control the pre-charging of the network filter (Not Shown). Once these steps are completed the main breaker is allowed to be closed, thus energising the distribution network and completing the blackstart operation. This restart module has been successfully installed in both the MARS Tankers and Norwegian LSV.



Figure 6: Trace of Black-Start Recovery Testing

## Avoiding hybrid converter trips

There is a history of converters protecting themselves from a faulty distribution network by tripping, however this philosophy cannot be followed when the converter is acting as the power source (i.e. the PTO generator). For example, there may exist a significant fault that causes a potential fault current greater than the hybrid converter’s maximum overload capability. Conventionally in this situation the converter would trip and shutdown requiring an operator to reset the controller and bring it back online – a potentially lengthy event, and one that depending on the current operational scenario might have a major impact on the situation. A solution to this has been developed using a technology transfer from the wind renewables application. The power system network operator (the National Grid in the UK) set restrictions on when a converter for a wind-turbine is allowed to trip – that is they have identified a range of grid faults through which the system must remain connected, known as grid fault ride-through. To meet these requirements a process of current management has been applied in the controller software code and this has now also been applied to the hybrid PTO marine application.

The exact methods of current management used are commercially sensitive; however as a high-level summary the process works as follows: at all times the controller in the hybrid converter is monitoring the current being produced. If a significant current is detected due to a short circuit or arcing event, the controller interrupts the path of current, and prevents any further current rise. During this time, the fault can be cleared by the relevant breaker opening using the normal protection scheme (the system will see some overcurrent and so the protection devices will be able to respond). Once the relevant breaker has cleared the fault, the hybrid converter can quickly resume providing power and normal system operation will be restored.

Figure 7 shows traces from actual testing of this concept at GE’s Marine Power Test Facility at Whetstone. During this test a fault was created on the main bus to demonstrate the ride-through capability of the converter. The traces shown compare the converter response with and without current management. On the left trace, the standard configuration, when the fault is applied the main voltage rapidly collapses (Point 1) as the currents spike to very high levels (Point 2). With current management applied, the right-hand trace, the main voltage drops to zero (Point 3), and there is some current rise but it is managed (Point 4). During this time the breakers are able to clear the fault, and then the volts can be quickly restored, all within approximately 250ms.

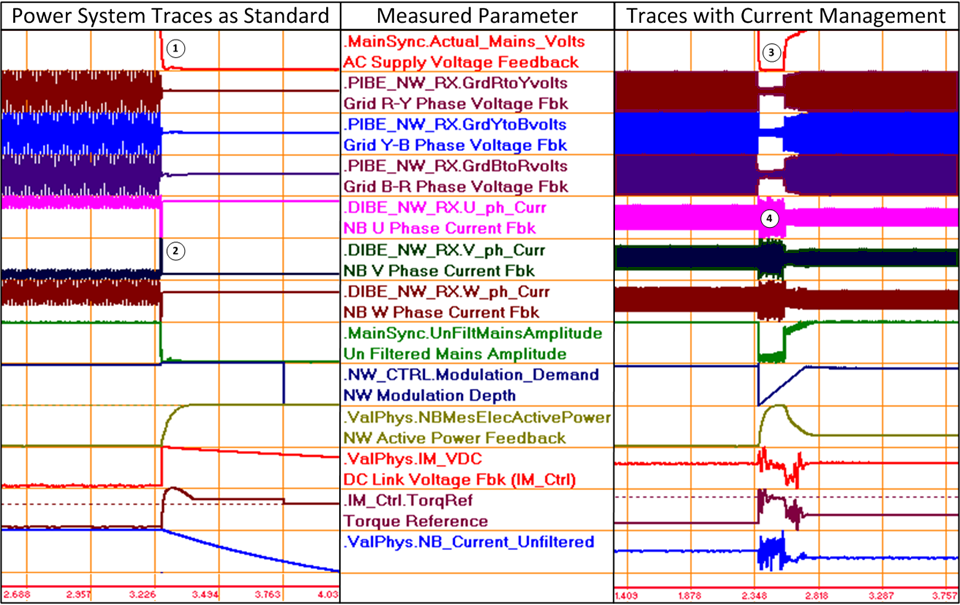


Figure 7: Trace of Current Management Testing

## Commercial integration

A final challenge that is often overlooked during the concept phases of a project is the commercial integration. It is mentioned here in order to highlight how some of the hybrid systems discussed can have more complicated commercial interfaces. This can be shown best through the use of a diagram.



Figure 8: Split of Commercial Responsibilities for the Norwegian LSV Project

Figure 8 shows the split of the commercial responsibilities for the Norwegian LSV hybrid system, with each organisation’s scope shaded differently and the communication paths shown as arrows. As depicted, no one organisation has control of or responsibility for the end-to-end system (whether in PTI or PTO), and some of the control and monitoring signals for key components, such as the hybrid converter, are from two different sources. In practice this can result in significant integration challenges during the detailed design phase. In the case of Norwegian LSV it has been ultimately up to the shipyard to both lead the integration of an unfamiliar new hybrid power and propulsion system, and enforce the correct commercial behaviour to successfully integrate the project. For future projects, a dedicated (and ideally independent) integrator with complete system oversight may offer some benefit.

# Conclusions

In the last half-century there has been a marked shift away from purely mechanical propulsion towards some form of electric propulsion system for reasons of performance, efficiency and flexibility. Historically hybrid propulsion has offered a first-step away from mechanical propulsion, however now a new range of advanced hybrids are available, offering greater benefits and flexibility without the space, weight and cost implication of IFEP.

In order to get the most out of a hybrid propulsion system the system needs to be tailored at the design stage to meet the owner’s requirements and what is actually needed from the ship. Whilst these new advanced hybrid systems are very flexible, the main benefits come when the complete system is fully optimised and integrated to the platform. With the benefits come many challenges to the successful integration of the hybrid system. The challenges found during the successful integration of recent projects have been presented, and some of the lessons learnt discussed. The real-world examples cited demonstrate that the challenges are varied and complex, often requiring careful trade-offs to optimise the solution.

Hybrid propulsion must be designed as a complete system combining the needs of propulsion, ship’s service power supply and equipment type. Integration of the hybrid system as a whole is essential, and the experience, skill and knowledge required to do this should not be underestimated.

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