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The Cat® Advanced Variable Drive Marine Propulsion System

Igor Strashny (speaker/author), Caterpillar, USA

SYNOPSIS

Caterpillar has developed a proprietary advanced propulsion system for marine applications. The Cat® Marine Advanced Variable Drive™ (AVD™) is a patented system that leverages Caterpillar's extensive experience with heavy duty continuously variable transmission (CVT) technology, advanced controls and power system integration knowledge. Cat AVD represents a fully integrated marine propulsion solution from the bridge interface down to the propellers and is applicable to a wide range of vessel types and missions.

The paper will present a historical perspective on the evolution of various marine propulsion solutions, before outlining the AVD operating principle and its applicability for tugs. The paper will present a 2-3MW/shaft system case study, and detail operating modes and power flow for a typical tug or salvage vessel application, as well as the concept for scalability up to 20MW/shaft. Differentiated advantages offered by the Cat AVD for a wide array of vessel types will also be discussed.

INTRODUCTION

Attributes such as better controllability, higher operational efficiency, lower total cost of ownership (TCO), reduced greenhouse gas emissions, ease of serviceability and robustness are among the most common and important requirements for drive technology observed across multiple industry sectors. These requirements apply uniquely well to the tug and salvage industry. Superior controllability directly translates into safer operations, lower crew fatigue and better operational efficiency, while reduced emissions helps to lower the local and global environmental impact of vessel operations.

One key technology developed by Caterpillar, initially for land applications, has proven to be instrumental in satisfying the ambitious requirements cited above, as well as many other customer needs. Continuously variable transmission (CVT) machinery has been delivered over the years in various implementations and products, from purely diesel-electric D7E tractors to power-split hydro-mechanical 966XKE wheel loaders, to name just two.

Leveraging positive experience from these land products, the CVT principle has most recently been applied to the marine propulsion space. The resulting marine CVT configuration, the Advanced Variable Drive (AVD) is proving to be transformative in many ways, exceeding the challenging requirements of multiple types of vessels and applications.

HISTORICAL PERSPECTIVE ON THE EVOLUTION OF VARIOUS MARINE PROPULSION SOLUTIONS

Marine applications of CVT technology are not new, but date back to the beginning of the 20th century, during the first successful attempts to use diesel engines on marine vessels. While even the earliest forms of diesel engines offered significantly higher power density and efficiency compared to the steam power plants of the day, their power delivery was, and continues to be, limited to a relatively narrow speed range. Furthermore, early diesel engines (as well as most modern 4-cycle diesels) did not have a reversing capability. Steam engines, on the other hand, could be modulated to run in either direction from zero to maximum speed, allowing them to be either coupled directly or through a suitable fixed gear ratio to the propeller.

Power delivery within a limited speed range, and lack of reversibility in diesel engines created the need to develop marine transmissions or propeller thrust modulation technologies. Interestingly enough, the very first applications of the diesel engine to marine propulsion occurred almost concurrently in Russia and France in 1903, with the pioneering diesel-electric drive on the oil tanker ***Vandal*** and controllable pitch propeller on the canal vessel ***Petit-Pierre***.

The oil tanker ***Vandal*** had a LOA of 75m and beam of 9.7m with a deadweight of 800 tonnes *(see Figure 1* *and Figure 2)*. The propulsion system consisted of three 90kW diesels coupled to 500V DC generators, plus three DC motors coupled directly to the fixed pitch propellers.

Figure 1: Stern view of the oil tanker **Vandal***, showcasing triple propeller arrangement*

Figure 2: Model of the oil tanker **Vandal**

The speed of the propellers was modulated using the Ward-Leonard system, with control levers positioned directly on the bridge *(Figure 3)*. ***Vandal*** was built and operated by the Nobel Brothers' Oil Company to transport petroleum products from terminals on the Caspian Sea to St Petersburg via the Volga River and Volga-Baltic waterway system, with its associated multitude of locks. Negotiating this complex journey required superb vessel manoeuvrability, which was achieved by the diesel-electric propulsion. While the operational experience of ***Vandal*** was positive, though, 15 per cent losses associated with the electrical power conversion were noted.

When ***Vandal***'s sister ship, ***Sarmat***, was built two years later, it featured the first electro-mechanical hybrid propulsion system. This system was developed by the Italian engineer Cesido del Proposto and utilised two 134kW diesel engines directly coupled with a through-shaft to 125kW generators.

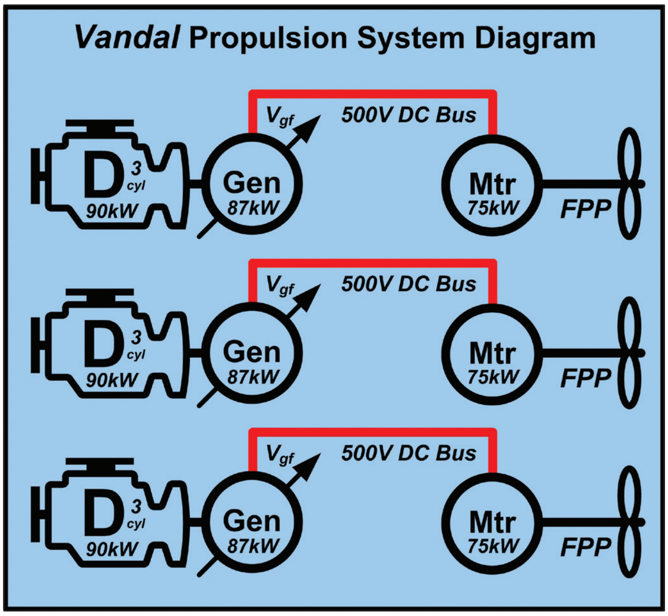

Figure 3: **Vandal** *propulsion system diagram*

The two through-shaft electric motors were connected to the fixed pitch propellers, and could also be clutched directly with the engine. Such a propulsion system arrangement enabled ***Sarmat*** to operate in either diesel-electric mode when manoeuvring ahead or astern, or in a direct-drive mechanical mode when cruising ahead *(Figure 4)*.

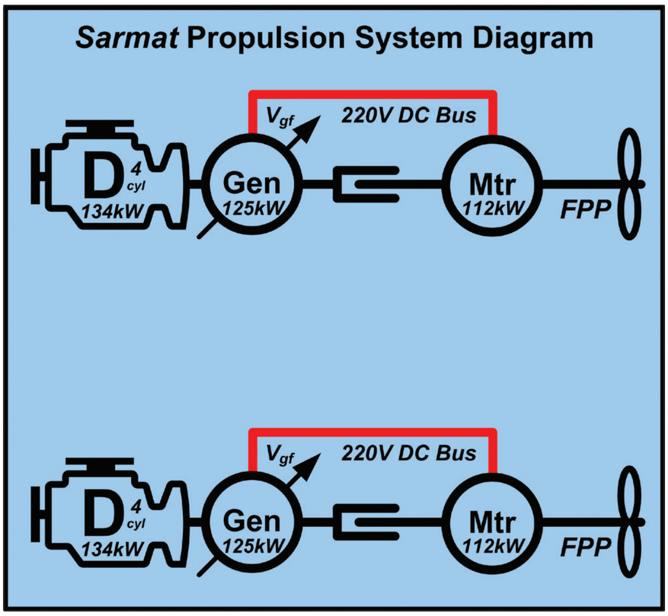

Figure 4: **Sarmat** *propulsion system diagram*

The utilisation of the more efficient Del Proposto system resulted in speed increases from 8-8.6 knots when unloaded and 7.4-8.1 knots loaded. It is worth noting that the currently popular electric generator/motor-PTO/PTI vessel hybridisation solutions are conceptually similar to the Del Proposto system, pioneered in 1904.

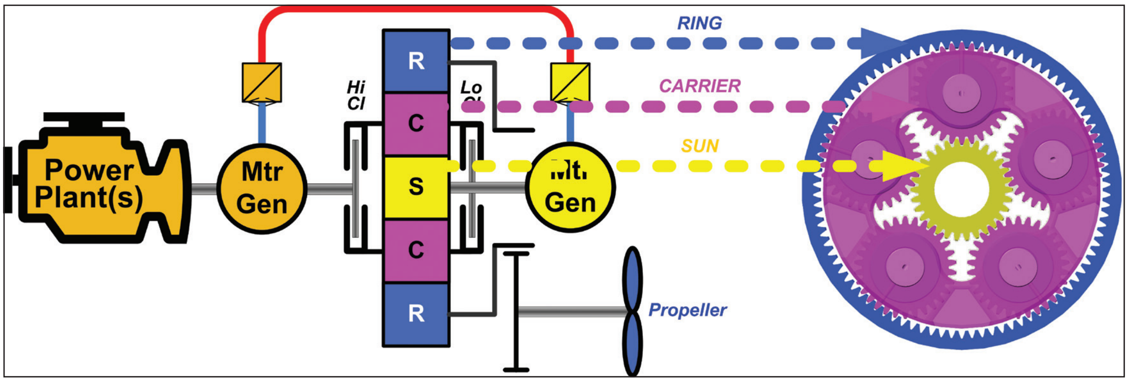

Figure 5: AVD propulsion system diagram

Concurrently with the successful utilisation experiences of ***Petit Pierre***, ***Vandal*** and ***Sarmat***, various companies around the world developed reversing diesel power plants, as well as reversing and non-reversing mechanical transmissions, which enabled worldwide proliferation of the marine diesel as the power plant of choice. While initially these mechanical propulsion solutions complemented the full diesel-electric Del Proposto and controllable-pitch propeller (CPP) propulsion system solutions, eventually they fully eclipsed them (in terms of numbers, at least).

The most widespread marine propulsion system configuration to have emerged over the past 100 years has been a diesel engine combined with a reversing mechanical transmission and a fixed pitch propeller. While this type of propulsion system does not offer the same degree of vessel manoeuvrability as diesel-electric propulsion, it offers the highest degree of power density, robustness and reliability at the lowest possible cost. Nevertheless, the CVT advantages associated with diesel-electric propulsion systems continue to be present in mostly higher value vessels, which can accommodate significantly larger and heavier electric drive packages and absorb increased propulsion system costs. Similarly, the variable thrust advantages associated with CPPs have been mostly utilised by higher value vessels that are able to accommodate the higher cost of this technology, as well as the more complex periodic maintenance procedures associated with the use of this technology (periodic dry-docking to inspect and replace CPP seals).

There are two important points that can be summarised by looking at the history and evolution of marine propulsions systems:

1. Continuous propeller thrust modulation enabled either by CVT or CPP technologies deliver highly desirable features that due to unfavourable cost, packaging, maintenance and cruising efficiency considerations, historically have only been applied to high value and/or highly specialised vessels.

2. Mechanical gearboxes (reversing and non-reversing) in combination with fixed pitch propellers dominate the marine propulsion space across vessel types and missions. This is due to the favourable cost, robustness, reliability, packaging, maintenance procedures and cruising efficiency associated with these technologies, despite having a limited range of propeller thrust modulation capability, and having only one point of optimal propulsion system efficiency (generally, cruising speed).

It would be a significant step forward if it were possible to combine all the benefits of the robust mechanical power transmission and a fixed pitch propeller with the ability to fully modulate propeller speed independently of engine speed, while minimising propulsion system losses. The resulting propulsion system would allow a wider range of vessels to benefit from the intrinsic efficiency and robustness benefits of mechanical propulsion while also taking advantage of the superior operational efficiency benefits that have been associated with CVT technology (historically, provided by full electric propulsion or CPP technologies).

It was with these ideas in mind that the AVD system was conceived and developed.

THE AVD OPERATING PRINCIPLE – AN INNOVATIVE APPROACH TO MARINE PROPULSION

We shall examine various elements that comprise a typical AVD marine propulsion system, that will allow a -60 to +100 per cent propeller speed modulation capability *(see Figure 5)*. Please note that with a relatively minor modification, AVD can be implemented to allow a -100 to +100 per cent propeller modulation capability (such a fully reversing AVD system of electro-mechanical type is exemplified in the analytical model schematic in *Figure 13, below*).

AVD has two paths to transmit power from the vessel power plant(s), which are most typically comprised of diesel engines, but can also be natural gas or turbine power plants.

The first power transmission path is purely mechanical, and is comprised of an epicyclic gear-set and two clutches: Lo and Hi. Lo clutch is intended to selectively interconnect any two members of the epicyclic gear-set to effectively lock the planetary and cause all members to operate at the same speed. In *Figure 5, above*, Lo clutch is shown to selectively interconnect the Sun and Carrier members of the planetary gear. Hi clutch selectively interconnects the

Carrier with the vessel power-plant(s). The gearing of the mechanical path is sized to be able to transmit full vessel MCR power requirements for a given shaft-line.

The second power transmission path goes through a variator arrangement, comprised of a four quadrant energy conversion device. In the diagram above, the variator is depicted as an electric power conversion system that, as pointed out previously, only needs to be sized to be able to transmit at most 20 per cent of MCR power. The generator part of the variator is connected directly to the vessel's main engine, while the motor part of the variator is connected to the Sun gear of the epicyclic gear-set.

The Ring gear member of the epicyclic gear-set is connected through a suitable final reduction ratio to the vessel propulsor, which AVD enables in most cases to be a fixed pitch propeller (FPP).

In order to clearly illustrate the details of AVD operation, the relative speeds and powers of all key elements of the system are depicted on the AVD speed-power diagram below *(Figure 6)*.

The y-axis of the yellow, magenta and blue lines represents, respectively, speeds of the Sun, Carrier and Ring members of the epicyclic gear-set. It is worth noting that the spacing between these lines represents the gear ratio relationship within the epicyclic gear-set.

Since the Sun gear is permanently connected to the variator, the relationship between the speed of the Sun gear and power transmitted through the variator is depicted on the leftmost part of the AVD speed-power diagram. Since the Ring gear is permanently connected to the propeller, the relationship between the speed of the Ring gear and power absorbed by the propeller is depicted on the rightmost part of the diagram. The top portion of the diagram depicts how the power-plant(s), variator, propeller and planetary members are interfaced, and also shows the direction of power flow across the variator.

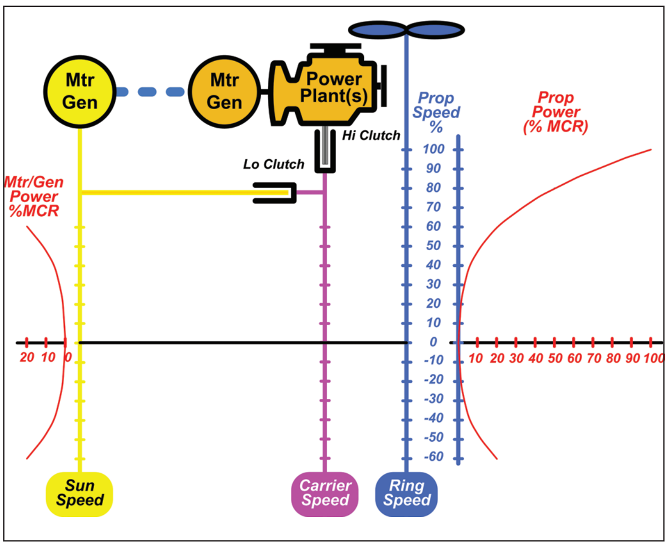

Figure 6: Graphical representation of the AVD speed-power relationships

We will first examine the Variator propulsion mode. In this mode of operation, as depicted in the diagram below *(Figure 7)*, the Lo clutch is locked and the Hi clutch is open. With the Lo clutch locked, all members of the planetary gear-set will be forced to rotate at the same speed. The propeller speed in this mode can be seamlessly modulated in forward or reverse directions by controlling the output speed of the variator. In this mode, the propeller is allowed to reach up to [-60..0..+60 per cent] of its maximum speed, at which point it will absorb about 20 per cent of the shaft-line MCR power. Power from either the main or appropriately sized auxiliary vessel power plants can be utilised to propel the vessel in this mode, while the respective power plant(s) can be optimised for efficiency, thereby fully offsetting the relatively small power conversion losses that occur in the variator at these low power levels.

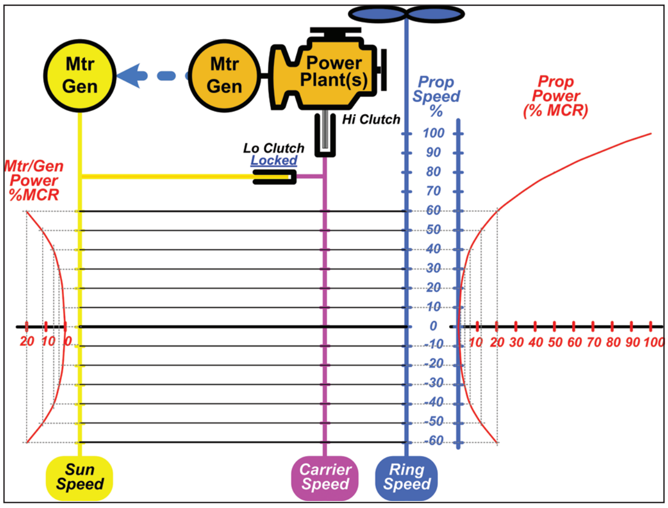

Figure 7: The AVD Variator mode of operation

The direction of power flow in the Variator mode is from the power plant(s) through the variator and to the vessel propeller. It is clearly evident from the AVD speed-power diagram *(Figure 7)*, that at most 20 per cent of the shaft-line MCR power is transmitted through the variator and absorbed by the propeller. At +60 per cent of maximum propeller speed, the speed ratio across the variator is 1:1. In other words, the power plant, generator and motor will rotate at the same speed when the propeller is operated at the 60 per cent point.

We can now examine the transition from the Variator to the Variator-Mechanical operating mode *(Figure 8, opposite)*. As propeller speed in the Variator mode reaches +60 per cent of the maximum propeller speed, the speed differential across the Hi clutch, which is still unlocked, will be zero. At this point, a nearly instantaneous synchronous shift between the modes can be accomplished by engaging Hi clutch and disengaging Lo clutch. As this transition occurs, the propeller speed and power transmitted to the propeller remains unchanged. However, the split of power transmitted through the variator drops from 20 per cent to 8 per cent, while the remaining 12 per cent is now transmitted mechanically. It is important to note that in addition to the reduction in the power transmitted through the variator, the direction of power flow through the variator changes as well.

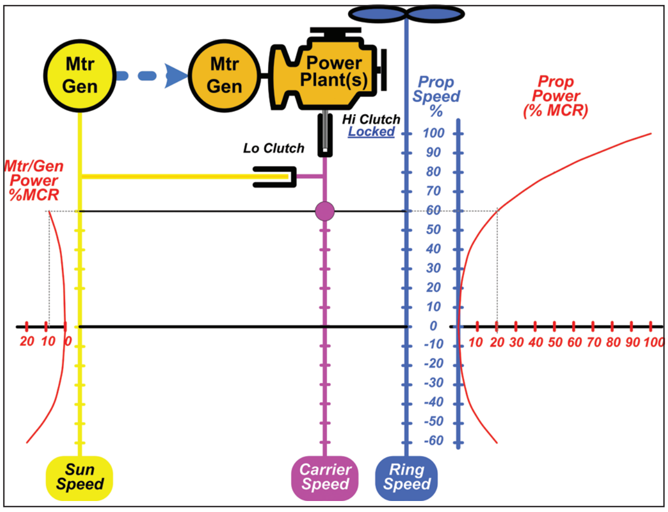

Figure 8: The AVD Variator mode to Variator-Mechanical mode shift

Next, we will review AVD operation in the regenerative part of the Variator-Mechanical mode *(Figure 9)*. As the transition from the Variator to Variator-Mechanical mode is accomplished, the power plant engages with the carrier of the epicyclic gear-set, and the speed governor of the power-plant will automatically accommodate the regenerative power it receives from the variator, while resisting speed changes imposed by the overall system loads transmitted to it. Consequently, as the variator ratio is commanded to decrease, the epicyclic gear-set speed solution line will articulate around the power-plant speed set point. More specifically, as the speed of the Sun gear coupled to the variator is commanded to decrease, the speed of the propeller will increase, while the speed of the engine powering the system will remain the same. The power absorbed by the propeller will also continue to increase as a function of the respective propeller polynomial coefficient. However, the power conversion through the variator will start to progressively diminish.

For example, assuming a free-running vessel condition, as the variator ratio is commanded to be 0.16, the propeller speed reaches 73 per cent of maximum, while the power transmitted to the propeller will be in the order of 40 per cent of MCR power, and the power transmitted through the variator will be less than 3 per cent of MCR power. Depending on the specific application of the vessel in this mode, and a multitude of other conditions, the specific propeller polynomial loading coefficient might vary considerably. As a result, the propeller might require significantly higher power to be delivered to it in this speed range.

Nevertheless, in the regenerative portion of the Variator-Mechanical range *(Figure 9)*, over 90 per cent of this power will still be transmitted mechanically, and no more than 10 per cent of the required propeller power will undergo power conversion. Furthermore, as the variator ratio is commanded to zero, all power to the propeller will be transmitted mechanically, eliminating any power conversion losses. This operating point can be matched to correspond to the vessel's efficient cruising speed requirements, while still preserving the capability to independently vary the speeds of the propeller and of the vessel power-plant(s) to reach the optimum overall propulsion system efficiency.

The remaining part of the AVD operation envelope *(see Figure 10)* is the additive portion of the Variator-Mechanical mode, which covers 80 to 100 per cent of the propeller speed range. In this part of the operating envelope, the Sun gear direction of rotation is reversed by commanding the variator to operate in the [0..-1] ratio range. The epicyclic gear-set speed solution line will continue to articulate around the power plant speed set point, and propeller speed will continue to increase. Over 80 per cent of the propeller power will still be transmitted mechanically, and the power transmitted through the variator will now be added to meet the propeller demand. *Figure 10* represents this region on AVD operation.

For clarity, the above explanation of the AVD operating principle assumed constant power plant input speed. It demonstrates that for a given input speed, there is a wide range of propeller speeds that can be achieved. In some applications, it might be

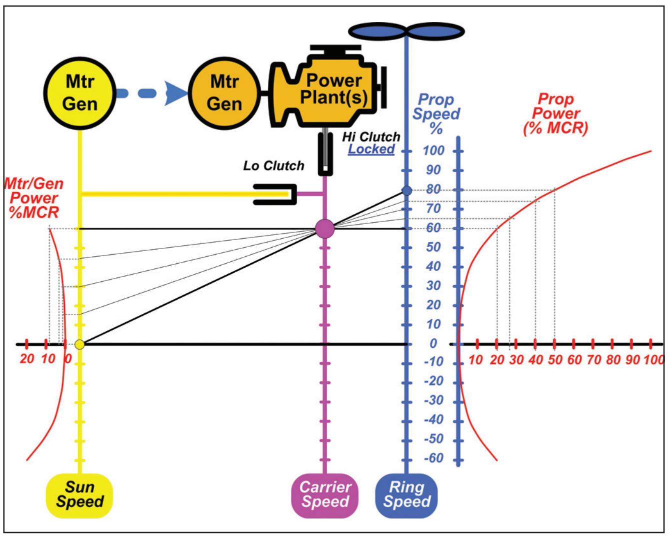

Figure 9: Regenerative portion of the AVD Variator-Mechanical mode

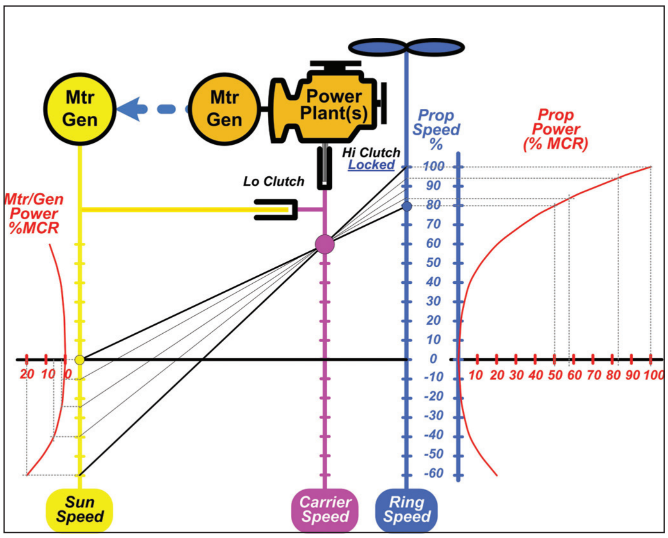

Figure 10: The additive portion of the AVD Variator-Mechanical mode

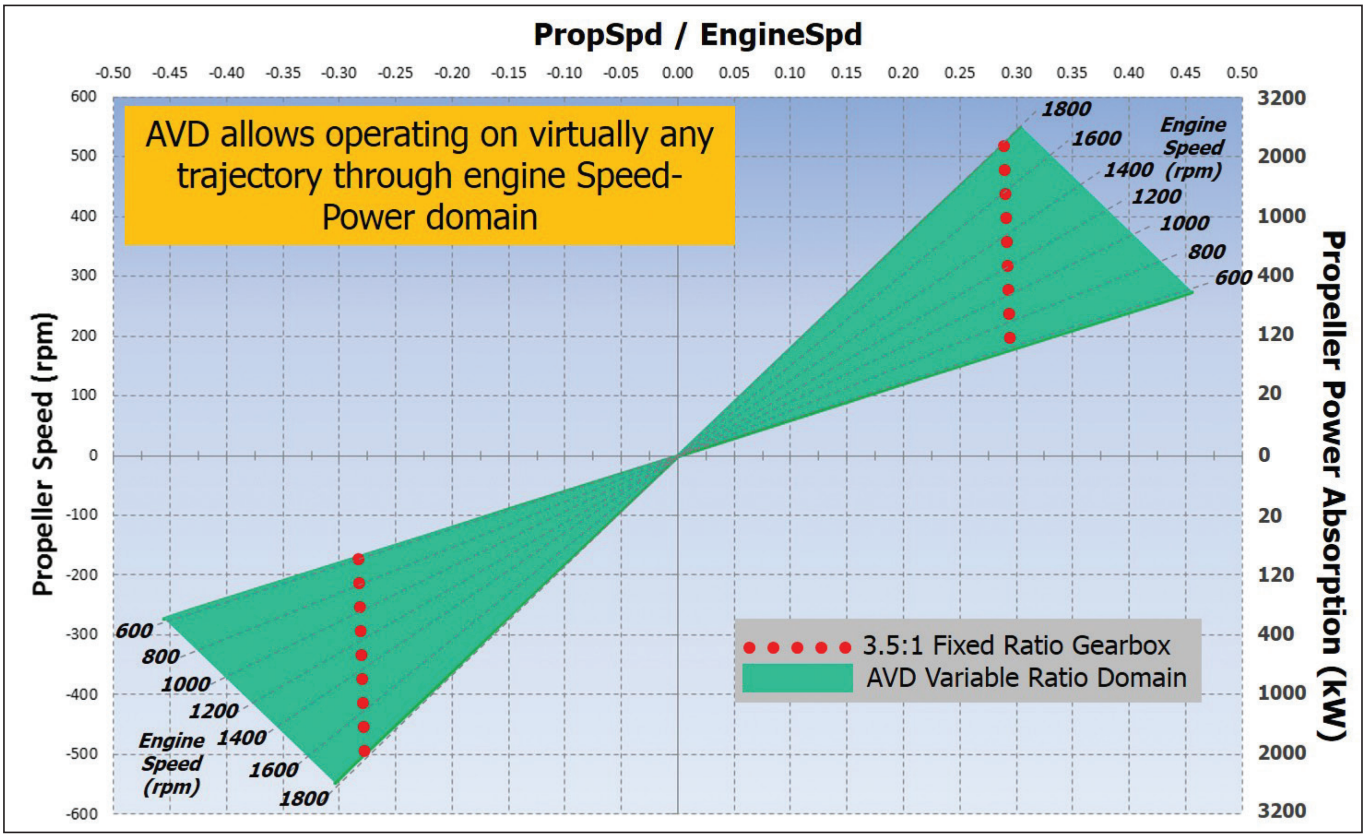

Figure 11: Ratio range domain of a fully reversing 2.5MW AVD propulsion system with fixed ratio gearbox reference

advantageous to operate vessel power-plant(s) at a constant speed (for example, in cases where natural gas or gas turbine prime movers are utilised). In most cases, however, it would be highly advantageous to operate vessel power-plant(s) in accordance with the speed-power trajectory that provides the best possible specific fuel consumption (SFC), and independently from propeller speed demand. The ratio range capability of the practical concept of a fully reversing AVD propulsion system versus a conventional reversing fixed ratio gearbox is exemplified in *Figure 11*.

Another way of looking at the flexibility that AVD enables in optimising propulsion engine efficiency is represented in *Figure 12*. This shows a few possible trajectories the engine can be operated on. It is worth noting that due to the inherently fast ratio change response of the AVD propulsion system, the engines can be loaded all the way up to the maximum torque at a given engine speed without concerns of stalling. This method of operating can result in the highest levels of fuel efficiency across the full propeller speed range.

Having covered the basic operating principles of the AVD propulsion system, we can review a more detailed example of a practical concept for a 2.5MW, fully reversing, electro-mechanical AVD. The concept configuration can be studied in the top-level analytical model snapshot presented in *Figure 13*. This underlying high fidelity analytical AVD model has been implemented using a Caterpillar proprietary modelling tool called Dynasty. This tool has a library of physics-based models of various Caterpillar components and subsystems, such as engines, electrical machines, gears, clutches, etc. This allows expedient development and assessment of various AVD concept variations, and zeroing-in on the optimal solution.

One of the model runs, representing a slow, full ahead, propeller speed sweep from zero to 100 per cent speed is presented in *Figure 14*. This time history allows us to observe how all key parameters of the AVD

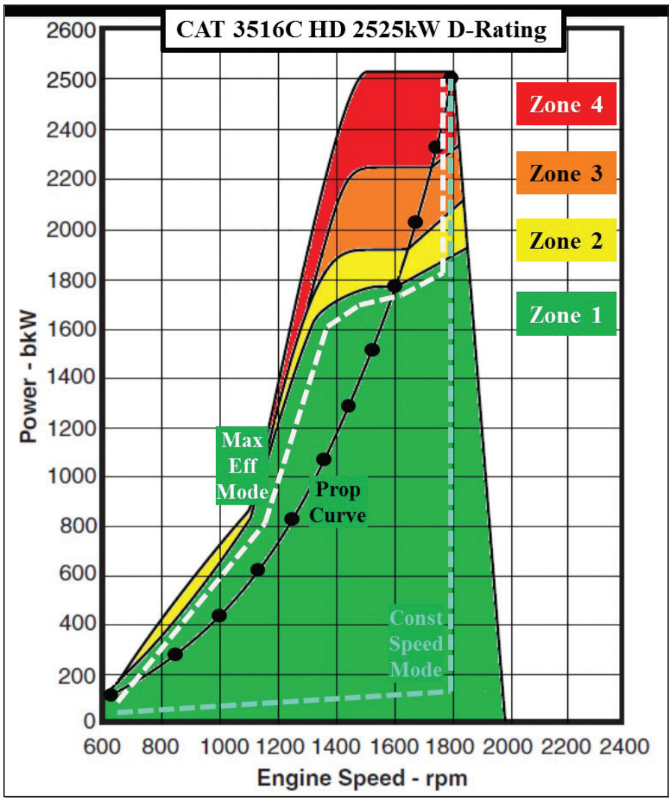

Figure 12: Examples of AVD operating trajectories plotted on an engine speed-power envelope

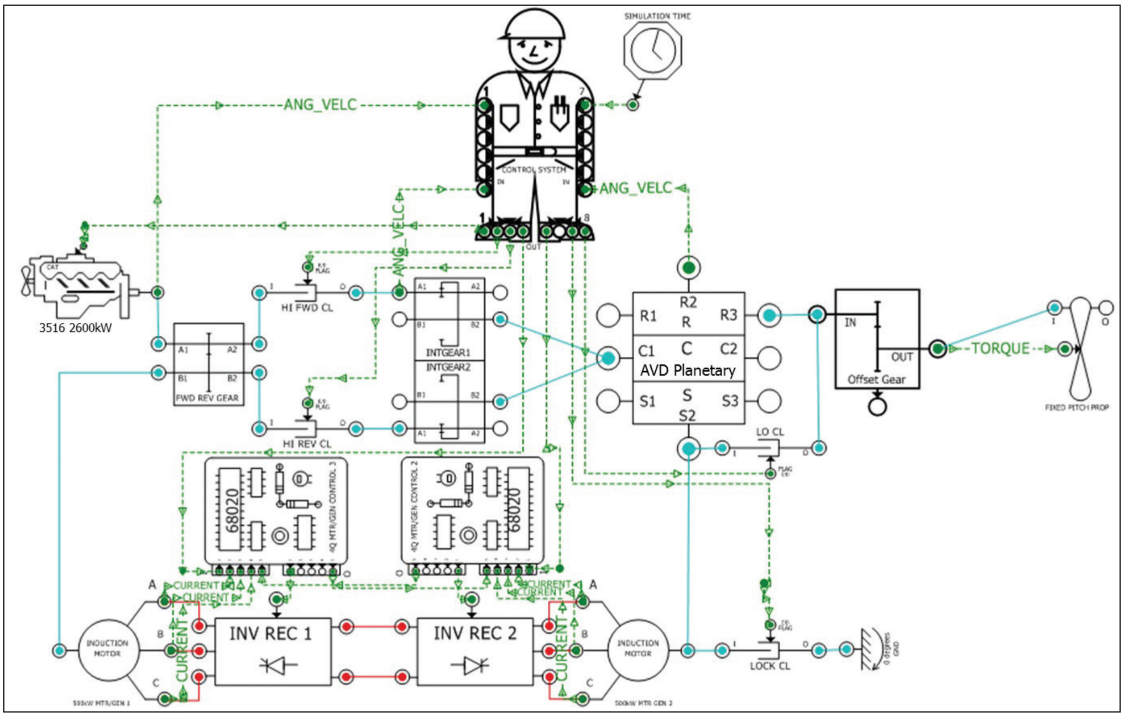

Figure 13: Analytical model of a 2.5MW, fully reversible electro-mechanical AVD propulsion system

system change in response to progressive loading by the propeller, parameterised to follow a free-running power absorption curve.

In addition to the normal AVD operating modes, this propulsion system has an inherent triple propulsion redundancy capability that can be of great importance for some vessel types. These redundancy modes are enabled by the parallel path nature of the propulsion system.

The first redundancy mode is functionally the same as the Variator propulsion mode. It can be invoked in cases of (an unlikely) upstream mechanical failure within the AVD gearbox or the main engine. It can be accomplished by using variator motor, and requires the Lo clutch to be engaged (in accordance with class rules, the clutch can be engaged manually if needed). The power for the variator motor can be supplied from the auxiliary engine, and the propeller can reach up to 60 per cent of its maximum speed, limited only by the power associated with the source used for this redundancy mode.

The second redundancy mode is fully mechanical, and can be invoked in case of a variator system failure. This mode is accomplished by allowing the variator motor to free-wheel, and engaging both Lo and Hi clutches. In the second redundancy mode, the propeller speed can then be modulated by controlling the main engine speed between low and high idle set points, corresponding to 20-60 per cent propeller speed modulation capability.

The third redundancy mode is also fully mechanical, and it too can be invoked in case of variator system

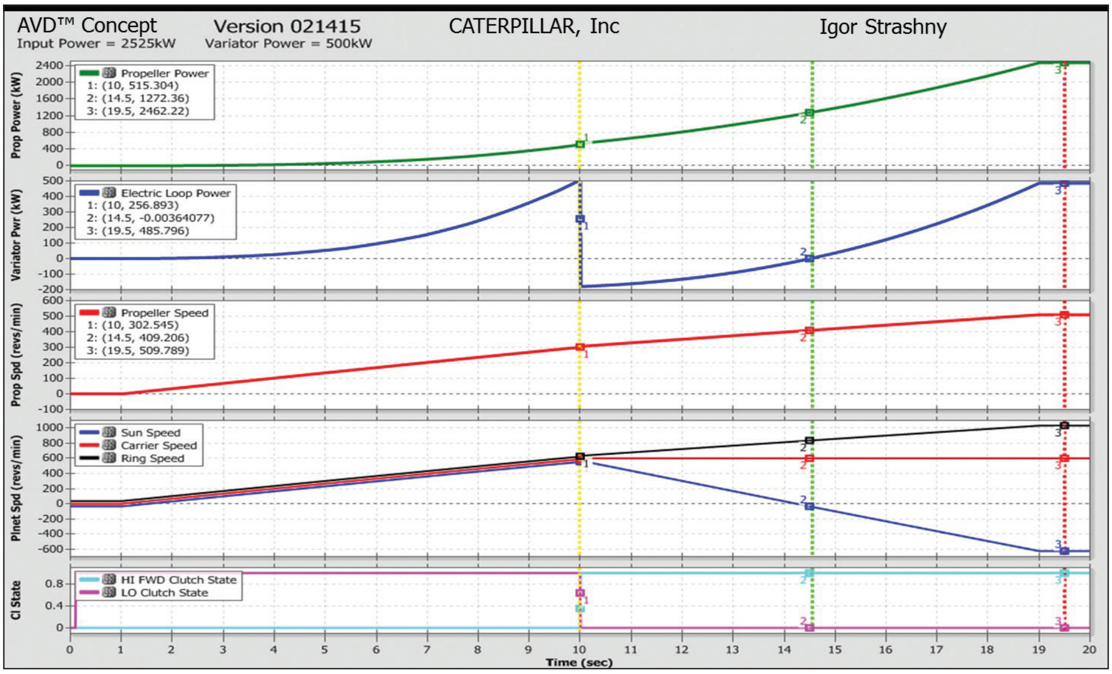

Figure 14: Propeller speed sweep (full ahead) vs time for the 2.5MW electro-mechanical AVD propulsion system

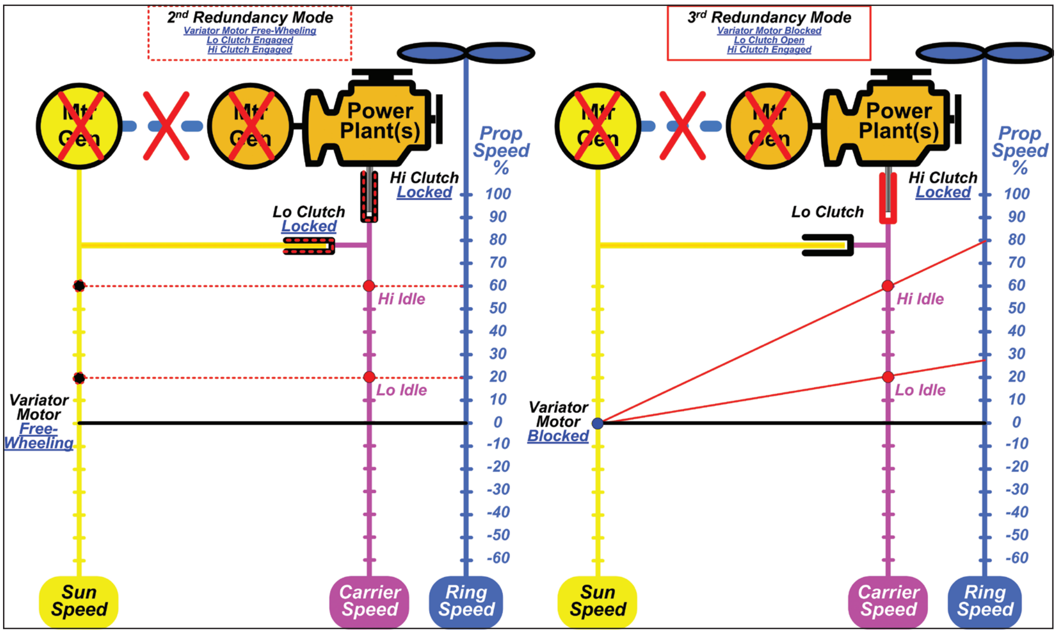

Figure 15: AVD mechanical redundancy modes

failure. This is accomplished by blocking the variator motor and engaging the Hi clutch. In the third redundancy mode, the propeller speed can then be modulated by controlling the main engine speed between low and high idle set points, corresponding to 28-80 per cent propeller speed modulation capability. The second and third mechanical redundancy modes are graphically depicted in *Figure 15*. Any one of the three available redundancy modes should allow more than adequate capability for safe limp-home operation.

AVD APPLICABILITY FOR TUGS – A 2-3MW/SHAFT SYSTEM CASE STUDY

Tugs represent some of the more power dense and cost competitive vessels, making them uniquely challenging platforms in which to adopt hybridisation technologies. The engine room space and acceptable centre of gravity envelope is fairly limited, generally precluding adaptations of full diesel-electric propulsion and integrating large capacity battery packs.The most popular propulsion system configuration, one that has evolved over many years of tug development, employs two main engines, coupled through either slipping or non-slipping clutches with two ducted azimuth thrusters with FPPs. The systems are arranged in either pusher or tractor configuration, and the main engines are sized to provide enough power to reach target bollard pull requirements. Additionally, there is often a fire-fighting pump connected either via a clutch to one of the main engines or to a dedicated power plant.

This dominant propulsion system configuration has proven to be safe and successful. However, there are a number of opportunities for further optimisation.

For example, examining a typical tug power histogram *(Figure 16)*, we can see that the majority of operating time is spent at very low power levels. More specifically, about 50 per cent of operating time is spent at or below 10 per cent of MCR power, and about 78 per cent of operating time is spent at or below 20 per cent of MCR power. This type of operation is inefficient, results in high SFCs, and greater than needed emissions. Furthermore, maintenance requirements for the main engines depend on the number of operating hours, not so much on load history, significantly impacting service costs over what they could be if the main engines were only operated when the higher power levels were required.

The dedicated fire-fighting engine most often present in harbour tugs is utilised less than 1 per cent of the operating time, mostly to periodically verify the fire-fighting system's functionality. This represents a significant underutilisation of this power-plant. Alternatively, tugs that use the main engine to power fire-fighting equipment compromise the propulsion system functionality during this operation. Finally, tug propellers are generally pitched to absorb full MCR power at the bollard pull condition, making them lightly loaded at the maximum engine speed and in free running applications.

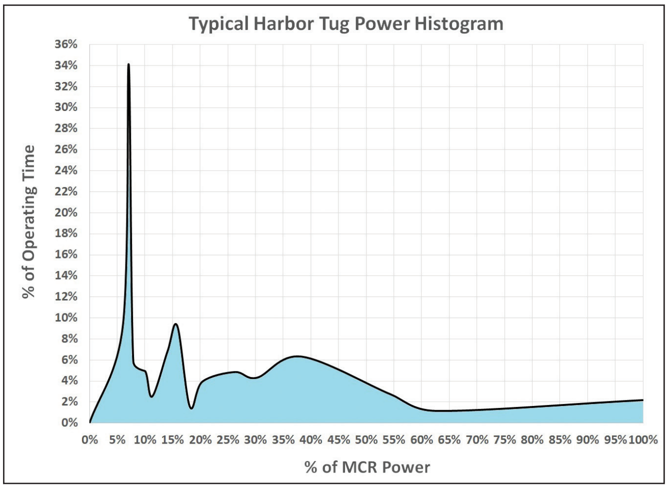

Figure 16: A typical harbour tug power histogram

The improvement opportunities identified above, and other benefits, make a solid case for employing AVD propulsion systems in tugs. A potential configuration is presented in *Figure 17, opposite*.

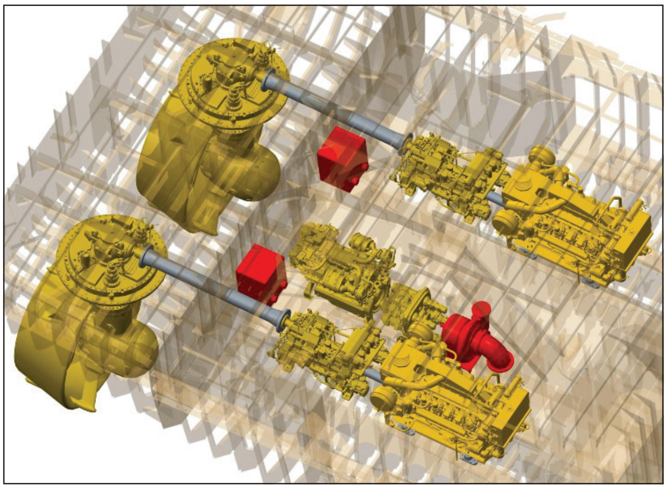

Figure 17: An AVD propulsion system installation in a harbour tug

The port and starboard AVD gearboxes are positioned behind the downsized main engines. Conventional shaft lines interconnect the outputs of the AVD gearboxes with Kort nozzle azimuth thrusters, equipped with fixed pitch propellers. The fire-fighting engine, positioned in the centre of the engine room, is also powering a power distribution gearbox that provides auxiliary power input to both port and starboard AVD systems. The installation is relatively light and compact, and fits very well within the existing structure of a typical tug vessel.

Tugs equipped with an integrated AVD propulsion system are intended to have several operating modes and associated power flow scenarios *(Figure 18)*.

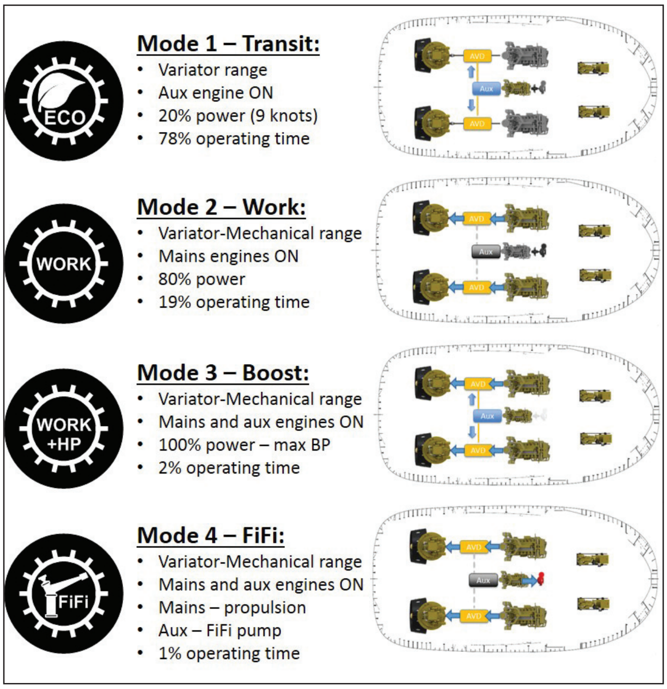

Figure 18: AVD harbour tug operating modes and power flow scenarios

1. In the *Transit Mode*, the main engines are off, and only the auxiliary engine is on, providing up to 20 per cent of maximum power to both port and starboard AVD gearboxes. This enables the respective propellers to continuously modulate their rotational velocity from [-60..0..+60 per cent] of their maximum speed range. While in transit mode, the AVDs are being operated in the variator range *(as shown in Figure 7)*. Due to the CVT nature of the AVD gearboxes, the speed of the auxiliary engine can be optimised independently from the desired propeller speeds, allowing this engine to operate at its most optimum SFC point. These SFC benefits fully offset the power conversion losses associated with the variator range. As discussed previously, the tugs tend to spend up to 78 per cent of their operating time at these propeller speeds/power levels. Utilising a better size for these power levels, the auxiliary engine, results not just in significant fuel efficiency improvements, but also in significant reductions of maintenance costs for the main engines: the hour accumulation on the main engines is projected to be reduced by as much as 80 per cent. From an operational efficiency standpoint, the continuous modulation of the propeller speed in both forward and reverse directions offers superior positioning capability for the tug captain while avoiding unnecessary propeller churning losses.

2. In the *Work Mode*, the main engines are on and the auxiliary engine is off, providing up to 80 per cent of maximum power to both port and starboard AVD gearboxes. This enables the respective propellers to continuously modulate their rotational velocity from -60 to +100 per cent of their maximum speed range. The maximum propeller speed in this mode will vary as a function of a specific propeller loading and the main engine power limit. This mode offers very low system losses, as AVD will be accomplishing continuous propeller speed modulation predominantly in the low power conversion regions of the variator mechanical range *(see Figure 9 and Figure 10, page 5)*. Due to the CVT nature of the AVD gearboxes, the speed of the main engines can be optimised independently from the desired propeller speeds, allowing the engines to operate at their optimum SFC points. A majority of the tug's working manoeuvres are expected to be accommodated, and it is projected that a vessel will spend about 19 per cent of its operating time in this mode.

3. In the *Boost Mode*, the main engines and the auxiliary engine are on, providing up to 100 per cent of maximum available power to both port and starboard AVD gearboxes. The power of the main and auxiliary engines is combined to deliver the maximum specified bollard pull performance. The propeller speeds can still be continuously modulated across their full speed range, -60 to +100 per cent, and the maximum propeller speed will be defined as a function of the propeller loading and combined main and auxiliary engine power limits. This mode offers low system losses, and AVD will be accomplishing continuous propeller speed modulation predominantly in the additive region of the variator mechanical range *(Figure 10)*. Due to the CVT nature of the AVD gearboxes, the speeds of all engines can be optimised independently from the desired propeller speeds, allowing engines to operate at their optimum SFC points. This mode enables the tug's

maximum performance manoeuvres, and it is projected that a vessel will spend about 2 per cent of its operating time in this mode.

4. In the *Fire-fighting Mode*, the main engines and the auxiliary engine are on. The propulsion power will be provided by the main engines, enabling identical performance to the Work Mode. The power of the auxiliary engine will be dedicated to the operation of the fire-fighting pump. In this case, the tug's propulsion performance is not compromised in any way by the operation of the fire-fighting equipment. It is projected that a typical tug will spend at most 1 per cent of its operating time in this mode.

In conclusion, an AVD propulsion system can offer meaningful improvement in the tug's intrinsic and operational efficiencies, as well as significant reductions in its operating costs. Intrinsic fuel efficiency is estimated to be improved by at least 16.5 per cent. The operational efficiency benefits are harder to predict. However, making use of the knowledge that Caterpillar has gained on other CVT applications, it can be estimated to be in the order of an additional 8-10 per cent.

AVD SCALABILITY UP TO AND BEYOND 20MW/SHAFT PROPULSION POWER LEVELS

At this point, the feasibility and performance of the 3MW/shaft AVD system has been fully developed and validated, and understanding the scalability potential of this technology has been judged as a valuable exercise. With this mission in mind, a study has been conducted by Caterpillar to develop a 20MW/shaft electro-mechanical AVD concept in application to a small surface combatant vessel. Brief highlights from this study are presented below.

Small surface combatant vessels are typically powered by a combination of diesel and gas turbine power plants, and often feature dual shaft-lines, full electric propulsion and fixed pitch propellers.

One of the latest representative vessels of this type is the Type 45 destroyer of the Royal Navy, which was selected as a reference craft for this study. The Type 45 uses a propulsion system called Integrated Electric Propulsion (IEP). The system consists of two 22.5MW at 3,600 rev/min gas turbines coupled with full-scale AC alternators and two 2MW diesel gen sets, providing AC power for the port and starboard 20MW 15-phase propulsion motors and hotel loads.

The propulsion motors are coupled via shafts to the 4.85m-diameter, five-blade fixed-pitch propellers. IEP employs a medium voltage electric system, operating at 4.16kV. The total installed power-plant power on this vessel is about 49MW, while the propulsion power rating is about 40MW. A simplified diagram of this propulsion system is provided in *Figure 19*.

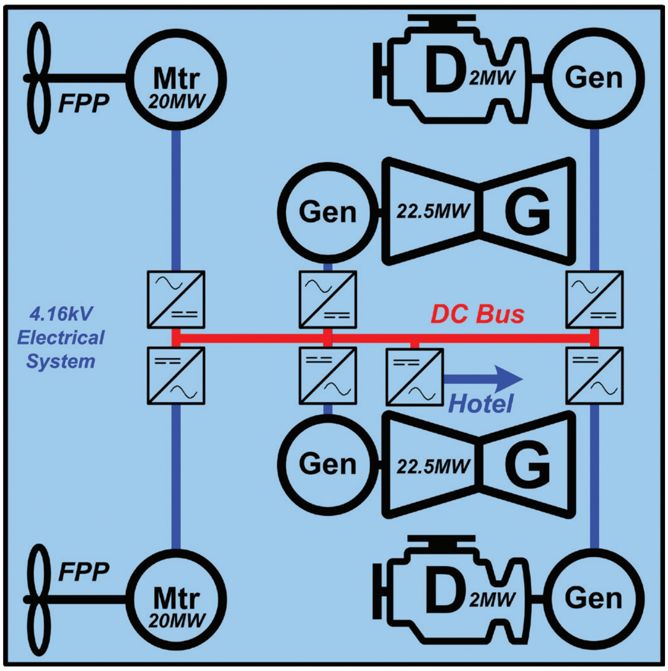

Figure 19: Simplified Type 45 destroyer integrated electric propulsion diagram

As a part of the above mentioned scalability study, an AVD concept for a small surface combatant vessel of similar characteristics to the Type 45 destroyer has been developed. A simplified diagram of this concept is presented in *Figure 20*.

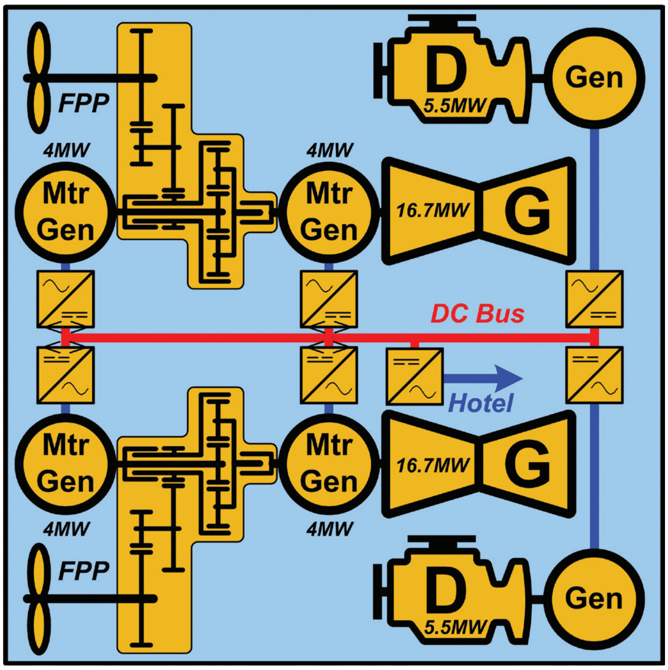

Figure 20: Simplified AVD propulsion system diagram for a small surface combatant vessel

At first glance, it is evident that the AVD propulsion system diagram *(Figure 20)* appears to have more components than the baseline IEP propulsion system *(Figure 19)* – namely, six electrical machines and a mechanical AVD transmission. It is important to note that these six electrical machines are of significantly more conventional type than the ones used as a part of IEP. More specifically, AVD technology enables these

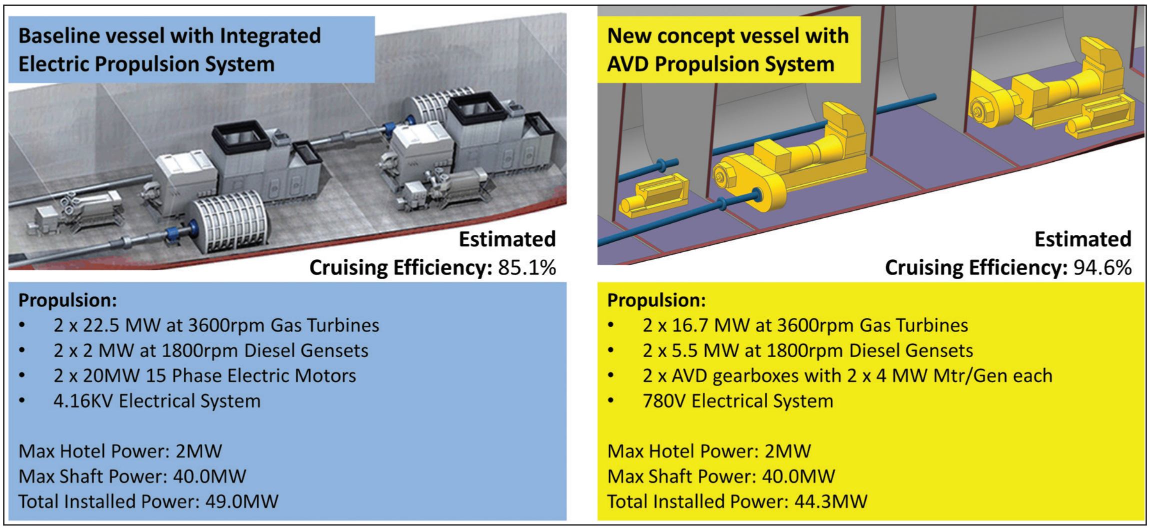

Figure 21: Packaging comparison between IEP and AVD

electrical machines to be of a low voltage type, and to have four poles with a total combined power rating of 27MW. The utilisation of a low voltage system is possible as the power rating of each individual electrical machine does not exceed 5.5MW, the upper limit of a practical low voltage system. The utilisation of the four-pole electrical machines is possible since all of the electrical machines within the AVD system are required to operate at relatively high speeds and low torques.

By contrast, due to the high power conversion requirements and torques needed to be transmitted to the propellers, the baseline IEP propulsion scheme employs a medium voltage electrical system and 12-pole propulsion motors. The total combined power rating of the electrical machines used within the IEP system is 80MW. Consequently, the weight, cost, complexity and maintenance requirements of the AVD electrical system will be significantly more favourable than that of the IEP electrical system currently used on the Type 45 destroyer and other similar vessels. The mechanical portion of the AVD propulsion system consists of gear, shaft and clutch elements that possess the highest power transmission density, represent mature and robust technology, have superior durability and have conventional service requirements. The conceptual packaging comparison between IEP and AVD propulsion systems within the constraints of the Type 45 destroyer hull is presented in *Figure 21*.

As previously noted, an AVD propulsion system provides high levels of redundancy. In the earlier part of this paper, the redundancy modes have been described in standalone fashion, as applied to a single AVD powered by a single power plant. The presence of multiple power-plants, electrical machines and electric bus interconnections (not pictured on the simplified diagram in *Figure 20*) yields superior redundancy, fault tolerance and survivability potential. The expanded range of the redundancy modes results in 17 possible normal operating modes and 76 possible emergency operating modes *(Figure 22)*.

Projected vessel performance characteristics in the normal modes of operation, plotted over a typical destroyer speed histogram, are in *Figure 23, overleaf*.

In summary, an AVD propulsion system applied to small surface combatant vessels promises to outperform the existing state-of-the-art IEP systems in a number of respects, such as more favourable total cost of ownership, weight, efficiency and redundancy, just to

		Operational Power Plant Combinations				Normal and Emergency Propulsion Operating Submodes												Number of Propulsion submodes for a given Power Plant Mode
						Electric			Electro-Mechanical			Mechanical Low			Mechanical High			
Mode #	Mode Name	Diesel Port	Diesel Stbd	Gas Port	Gas Stbd	Port Stbd	Port	Stbd	Port Stbd	Port	Stbd	Port Stbd	Port	Stbd	Port Stbd	Port	Stbd	
1	DP					±47%	±60%	±60%										3
2	DS					±47%	±60%	±60%										3
3	DPDS					±60%	±60%	±60%										3
4	GP					±60%	±60%	±60%		+90%			+60%			+90%		6
5	GS					±60%	±60%	±60%			+90%			+60%			+90%	6
6	DPGP					±60%	±60%	±60%		+96%			+60%			+90%		6
7	DPGS					±60%	±60%	±60%			+96%			+60%			+90%	6
8	DSGP					±60%	±60%	±60%		+96%			+60%			+90%		6
9	DSGS					±60%	±60%	±60%			+96%			+60%			+90%	6
10	GPGS					±60%	±60%	±60%	+90%	+90%	+90%	+60%	+60%	+60%	+90%	+90%	+90%	12
11	DPGPGS					±60%	±60%	±60%	+96%	+96%	+96%	+60%	+60%	+60%	+90%	+90%	+90%	12
12	DSGPGS					±60%	±60%	±60%	+96%	+96%	+96%	+60%	+60%	+60%	+90%	+90%	+90%	12
13	DPDSGPGS					±60%	±60%	±60%	+100%	+100%	+100%	+60%	+60%	+60%	+90%	+90%	+90%	12
																	Total Number of Propulsion Modes:	93

Note: *Number in the cell represents maximum attainable propeller speed for a given submode*

Figure 22: AVD propulsion redundancy modes

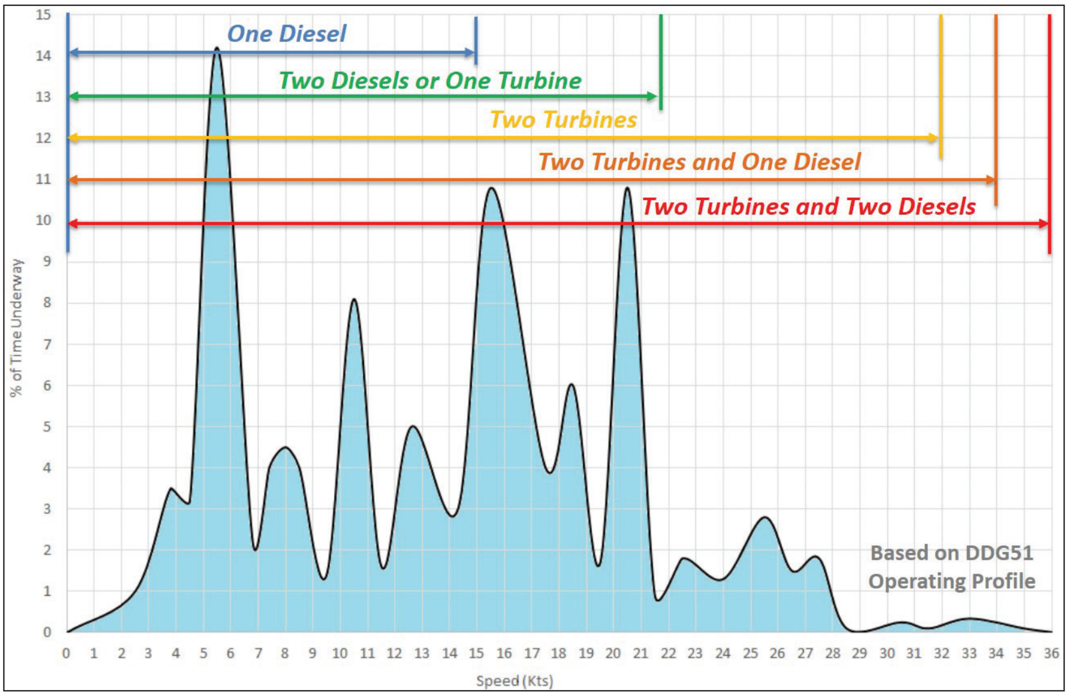

Figure 23: AVD-equipped small surface combatant vessel performance in normal propulsion modes

name a few. Some of these benefits versus IEP have been quantified in *Figure 24*.

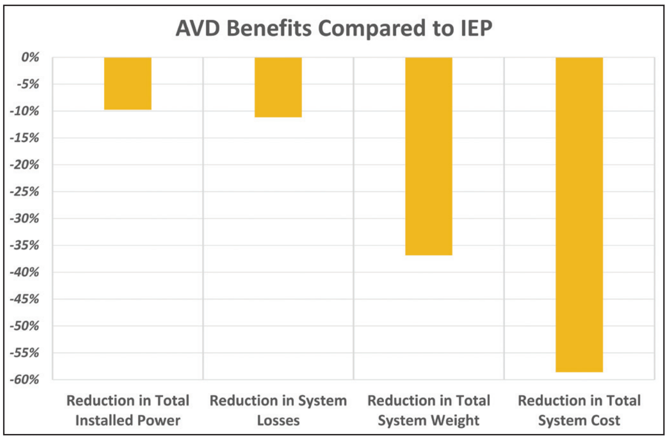

Figure 24: AVD vs IEP propulsion system benefits

CONCLUSION

The key feature of the AVD marine propulsion system is that during vessel operation the majority of the propulsion power (more than 80 per cent) is transmitted mechanically and only a small fraction of the propulsion power (up to 20 per cent) is undergoing power conversion. The power conversion path can be implemented hydrostatically, electrically or mechanically, depending on the power rating of the propulsion system and vessel-specific integration considerations.

Transmitting more than 80 per cent of propeller power mechanically results in superior propulsion efficiency, and seamless and responsive propeller speed modulation, while also enabling triple propulsion redundancy capability for each shaft-line. AVD enables the speed of the vessel's engines to be modulated and optimised independently from the speed of the fixed pitch propellers. The speed of the propellers can be varied continuously throughout their full speed range. In addition, the power of the main and auxiliary engines can be channelled independently or jointly to propel the vessel. This results in superior vessel performance and manoeuvrability, while facilitating significant improvements in fuel and operational efficiency.

AVD technology is a cost effective and fully integrated hybrid propulsion solution that reduces maintenance costs and has conventional service requirements. The system is scalable to meet the requirements of a wide range of vessel types, applications, and power levels, and enables effective downsizing of engines without loss of performance.

FURTHER READING

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ACKNOWLEDGEMENT

The photo of a model of the tanker ***Vandal*** was taken by Pavel Emelyanov at the Museum of History of Samara, Russia. Photo used with permission of the author.