# Auxiliary drives for emissions reduction

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**Abstract**

Conventional propulsion systems are matched to meet power demand at designed operating points. Off-design conditions result in sub-optimal operation of prime movers since these are sized to cater for the peak power requirement. Hybridisation of power sources enables the advantages of separate sources to be exploited to best match actual operating conditions.

In this work, permanent magnet machines are considered as auxiliary drives, providing propulsion at low ship speeds, complementing their use as shaft generators. Various topologies of auxiliary drive layout were analysed, considering different machine torque and speed ratings according to installation choice. As part of this study, the examination of auxiliary electrical drives was performed on a RoRo and tug with a view to assess reductions in exhaust gas emissions and fuel consumption. The two vessels were considered under typical operating scenarios. By means of simulation, the emissions and fuel consumption under auxiliary propulsion were quantified and compared to the contribution from the main engine. Significant emission savings were observed for the RoRo case particularly due to the use of cleaner fuel as a source. In the tug case, emission reductions could not be observed for this particular setup since the auxiliary drive system only adds additional inefficiencies in the propulsion system. Capital costs are significant, and the use of diesel fuel represents an increased cost. Yet if emission reductions are incentivised, auxiliary drives using permanent magnet machines are an attractive solution.

*Keywords:* Emission reduction, Auxiliary drive, Permanent Magnet machine, Variable speed drive, Hybrid propulsion

## 1. Introduction

Reducing emissions is a worldwide high priority, and shipping is not an exception. Significant efforts are underway to drive down the emission of noxious gases and particles detrimental to climate change and human health. In the case of seagoing vessels, the periods spent in the vicinity of the coast and in ports represent a direct impact on the shore, hence addressing manoeuvring and in-harbour emissions has a very immediate impact on the quality of life in neighbouring regions.

Currently ships run their main engines until they are safely berthed in order to provide propulsion. These typically run on residual fuel oils, which when compared to the cleaner fuel supplying the auxiliary engines produce higher amounts of emissions. The aim of this paper is to examine the impact of electrical machines and power converters to provide an auxiliary drive capability such that manoeuvring and harbour transit can be performed by running only the auxiliary generator engines. An auxiliary drive can be understood to be an alternative mode of propulsion to the main engine, and in this context includes an electrical machine mounted along the shaftline.

The mode of operation of an electrical machine is determined by the direction of the power flow through the machine. Thus, if power flows from the mechanical shaft into the electrical network, the machine functions as a generator and feeds energy to the electric supply. Conversely, if electric power flows from the network to drive a mechanical load connected to the shaft, the machine is motoring and absorbs power from the electric supply. Crucially, the same machine can operate in both modes, depending on the way it is being used.

The fundamental operating mechanism of an electrical machine is based on the interaction between a current carrying conductor and a magnetic field, generating the machine's rotational torque. The direction of the resultant torque defines the mode of operation of the machine, i.e. whether it operates as a generator delivering electric power to the load, or whether it absorbs electric power from the supply as a motor. The efficiency with which this conversion is performed is very important in terms of emissions reduction.

Permanent magnet machines are especially attractive for low speed propulsion applications due to their low speed, high torque capabilities when compared to conventional synchronous and induction machines. They permit higher efficiencies due to reduced rotor losses and the elimination of unnecessary gearing stages. Disadvantages include higher costs due to the use of rare earth materials as well as a more constrained speed range compared to conventional machines. As part of this study, an examination of auxiliary electrical drives has been performed on a RoRo and tug with a view to assess reductions in exhaust gas emissions and fuel consumption.

The paper is organised as follows: section 2 outlines the permanent magnet machines being considered, while section 3 describes the power electronic drive system. The various installation topologies considered are outlined in section 4, while the strategies for sizing the system are given in section 5. Sections 6 and 7 describe the implementation of the chosen auxiliary drive on the study vessels, whose simulation results are tabulated in section 8 and subsequently discussed.

## 2. Permanent magnet machines

Electrical machine designs and technologies are varied, with each configuration having evolved towards best meeting a particular type of application. As design objectives therefore, an onboard auxiliary drive should be efficient, rugged, cost effective and compact. Such requirements are not much different from those of other shore-based applications, and hence do not represent a need for new technologies, but rather the identification and matching of technologies employed in other applications.

Permanent Magnet (PM) machines address these aims very well. In conventional synchronous machines, an electric current contribution is required to build up the magnetic field. By having the magnetic field established by permanent magnets, power losses are intrinsically reduced, implying a higher efficiency. Furthermore, the field established by modern rare earth materials such as Neodymium Iron-Boron (NdFeB) permits higher flux densities than would be practically possible with wound coils. This increased airgap magnetic flux density permits a higher torque density for the same volume compared to a conventional machine.

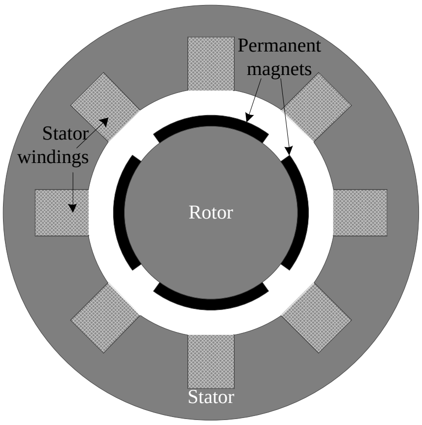
The construction of a PM machine generally locates the magnets on the rotor, avoiding the need for brushed contacts to conduct electric current to the rotor, greatly reducing maintenance requirements. Two basic machine topologies are commercially available which take advantage of permanent magnets; radial flux machines and axial flux machines.

### *2.1. Radial flux machines*

In the configuration which mirrors conventional machines most closely, magnets are placed on the surface of a cylindrical rotor in order to establish a magnetic flux in the machine's radial direction. An example of a machine with radially mounted magnets is illustrated in Figure 1. Such machines are now available as high efficiency options directly replacing conventional machines with standard frame sizes.

*2.2. Axial flux machines*

In an axial flux machine, the magnets are mounted in such a way so as to establish flux along the machine's axial direction. In this topology, the rotor is of a disc shape, with magnets mounted on the disc faces. This configuration gives very axially compact machines with the added advantage that a number of rotor/stator disc pairs can be stacked in order to increase the torque rating (Caricchi *et al.*, 1999). At high torque values however, a difficulty exists in the mounting of the rotor discs onto shaft as the small interface between the two must handle a significant amount of torque (Jacek F Gieras *et al.*, 2008). Hence axial flux machines are especially suited for higher speed applications as well as direct drive wind turbines when they can be made very structurally robust.



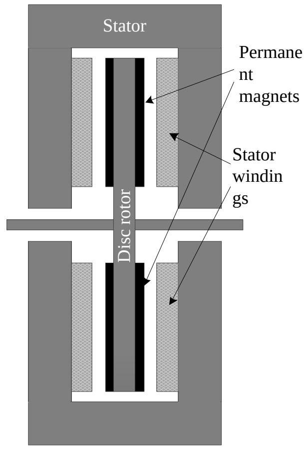




**Figure 1 Radial flux machine with surface mounted permanent magnets (left) and axial flux machine.**

## 3. Auxiliary drives

In a conventional propulsion arrangement, a shaft generator is typically installed on the propeller shaft in order to provide electrical power from the main engine, thus representing a link between electric and mechanical propulsion systems. The motivation for a shaft generator is to provide electric power from the cheapest fuel source, off which the main engine runs. On systems employing Controllable Pitch Propellers (CPPs) the shaft generator can be used across a wide vessel operating range due to the maintenance of a quasi-constant shaft speed. This is different in the case of Fixed Pitch Propellers (FPPs), where the shaft generator is only engaged at rated speed, since the alternator speed determines the electrical frequency (Woud and Stapersma, 2008).

In both cases, the shaft mounted machine typically consists of a conventional synchronous generator, wound with a pole number to give rated electrical frequency at the rated propeller speed. No provision is made for bidirectional control of the machine, such that it operates solely in generating mode. In order to provide both motoring and generating control, a drive system with a power conversion stage is required, where electrical power can be fed from the onboard auxiliary generators to provide electric propulsion. Several challenges emerge from such a seemingly simple statement.

The provision of variable speed control entails the use of power electronic converters to modulate the voltage and current as required, and furthermore the need to permit both generation and motoring requires the drive to be bidirectional. This greatly increases the costs of the drive since an active front end is required rather than a simple rectifier, as illustrated schematically in Figure 2.

With the use of PM machines, the power electronic converter is in use all the time hence an additional efficiency drop is present compared to a conventional shaft generator. The suitability of such a drive is therefore dependent on whether the advantages of having bidirectional capability outweigh the additional losses and costs of the system.

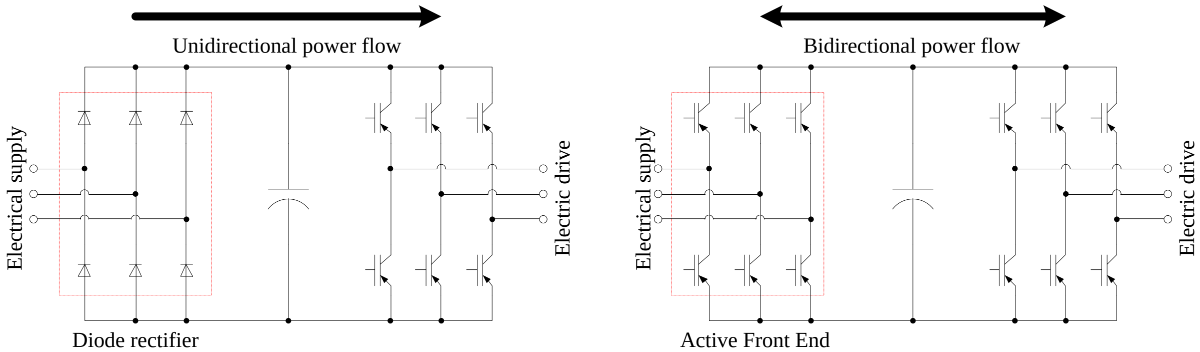



**Figure 2 Comparison between passive rectifier (left) and active front ends in power electronic converters.**

## 4. Choice of topology

The layout of the drivetrain gives several installation possibilities of the electric machine along the propulsion line. Each placement offers different base speeds and hence different torque ratings. Three possible topologies are considered for a generic propulsion train in the following subsections.

### *4.1. Low speed direct drive (Topology 1)*

In the topology shown in Figure 3, the electrical machine is installed directly on the propeller shaft (showing an installation with a low speed engine). This avoids the use of gearboxes, hence increasing overall efficiency and reducing any maintenance needs. However, the use of low speed machines implies a penalty in terms of weight and cost, since a higher torque is required for the same power. This increases the current rating of the machine, entailing thicker conductors and increased copper losses.

### *4.2. Geared low speed drive (Topology 2)*

Similar to the previous topology, the electric machine is installed on the propeller shaft, but with the provision of an intermediary gearbox. This permits a higher speed machine to be installed with corresponding lower torque at the expense of an additional mechanical component (gearbox).

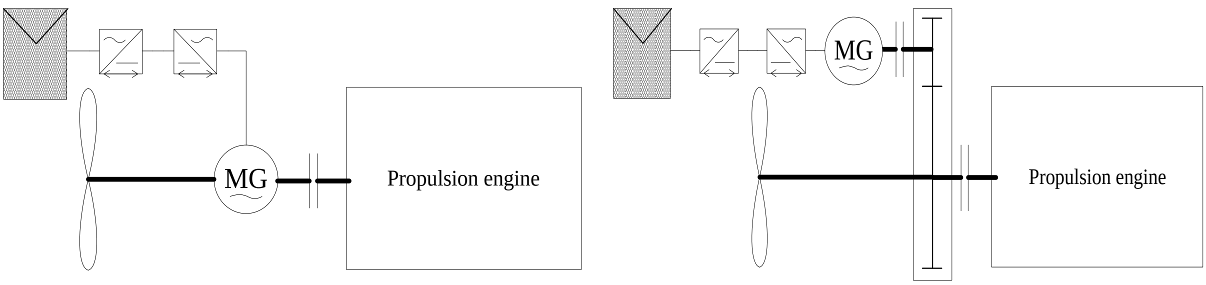



**Figure 3 Topology 1 – Direct low speed drive machine (left) and Topology 2 – Geared low speed machine.**

### *4.3. Engine side drive (Topology 3)*

In case of a high or medium speed prime mover, a Main Reduction Gearbox (MRG) is used to step down the engine shaft speed to that required by the propeller shaft. Most MRGs provide the provision of a Power Take Off/Power Take In (PTO/PTI) to mechanically power auxiliary equipment via an additional shaft. This can provide an additional gear stage in addition to the MRG ratio, hence permitting higher speed machines to be used.  Alternately the machine can be mounted on the high speed shaft for a single reduction stage.  In this case the MRG is a necessary component and hence this topology does not entail the use of additional components.

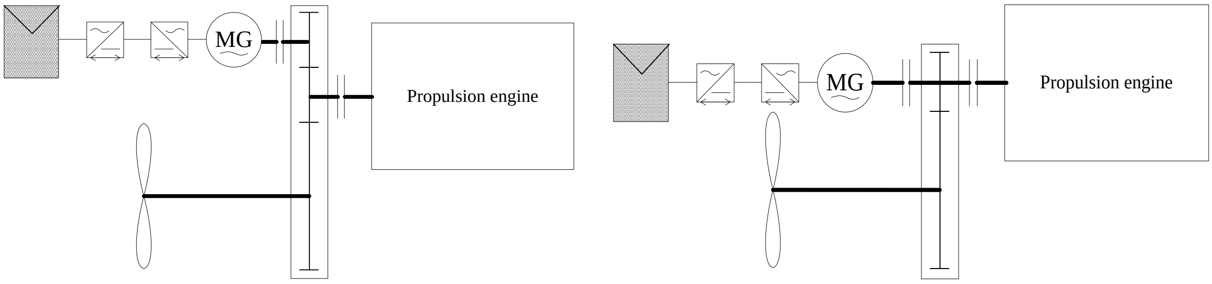



**Figure 4 Topology 3 – High speed installation geared to PTO (left) and directly on high speed shaft (right).**

The three topologies are compared in Table 1 which gives an overview of the benefits and drawbacks associated with each installation.  Apart from the inclusion/omission of a transmission gearbox and the losses associated with each stage, a further consideration is the ease with which the auxiliary drive can be mechanically decoupled and turned off.  With a direct shaft mounted installation, the permanent magnets will be turning whenever the propeller shaft is moving, generating a voltage in the stator at all times and additional no load losses.  For geared installations it is relatively straightforward to provide a declutching mechanism.  This is complex in case of a direct shaft mounted machine.  It precludes any maintenance work or operator intervention while at sea.  One must note that in case of a conventional shaft alternator using a synchronous machine, the absence of permanent magnets avoids this issue.

**Table 1 Comparison of different installation topologies.**

| Topology 1 | Topology 2 | Topology 3 |
|---|---|---|
| No gearbox needed | Gearbox is an additional component | Gearbox is a necessary (not additional) propulsion component |
| No gearbox needed | Gearbox rated to auxiliary drive mechanical power | Fully rated MRG |
| Low speed electric machine | Higher speed electric machine | Higher speed electric machine |
| Mechanical decoupling is complex | Mechanical decoupling possible | Mechanical decoupling possible |
| No transmission inefficiency | Single stage transmission inefficiency | Two stage transmission inefficiency |
| No additional maintenance | Additional maintenance | No additional maintenance |

## 5. Sizing of the auxiliary drive

The sizing of the auxiliary drive entails the selection of the power rating of the system which has a direct influence on the reduction of emissions and fuel consumption.  In turn, the topology choice affects the speed (and hence torque) ratings of the machine.  Various operating strategies can be chosen to rate the system based on the power profile of the scenario vessel.

### *5.1. Sized for generation*

The power rating of the drive can be chosen such that it directly replaces the shaft generator and supplies the required auxiliary electrical power.  The possible ship speed under auxiliary propulsion is therefore a consequence of this power value and hence represents an emergency ‘take-home’ capability.

### *5.2. Sized for propulsion*

In this approach, a desired ship speed when operating under auxiliary propulsion is chosen, the power demand calculated (along with the necessary sea margin) and the system sized accordingly. Though this will provide the electrical power when generating, it must be borne in mind that auxiliary generating plant must also be available to supply this necessary power when in motoring mode.

*5.3. Constant revolutions mode*

With a CPP, the propulsion system usually operates in Constant Revolutions (CR) mode where a fixed engine speed is maintained and ship speed variation is obtained by adjusting the propeller pitch. If the auxiliary drive is simply considered as an alternate propulsion source, then the system is a simple fixed speed motor. However this does not take full advantage of the power electronic converter, and also presents a comparatively high power demand at lower speeds (see Table 4 in Section 6).

*5.4. Variable revolutions mode*

In case of an FPP, the ship speed is proportionally related to the shaft speed, with the engine required to operate across the whole speed range. Thus the auxiliary drive must provide variable shaft speeds in order to provide speed variation, while providing generating power when underway. Commercial variable speed drives provide a suitable solution, however permanent magnet machines present some challenges when operating over a wide speed range. This comes about because operation above the machine's base speed requires the injection of a field weakening current. In case of a magnetic field established by PMs, the weakening effect can permanently demagnetise the rotor if a critical value is exceeded. Hence a more limited speed range is recommended for PM machines, with figures from 1.2 to 2 times rated speed being feasible (Zhu and Howe, 2007). The speed-power characteristic of the propeller follows a cubic approximation with considerably lower power at lower speeds.

*5.5. Combinator mode*

In case of a CPP system, the advantages of a variable pitch system and a variable revolutions installation can be exploited in a combinator mode of operation. When underway, the vessel speed is controlled by pitch adjustment with the main engine running at fixed speed. At low vessel speeds however (such as manoeuvring), when the auxiliary drive takes over the propulsion, the operating point can be adjusted by varying both the pitch and the shaft speed in the so-called combinator mode. The lower shaft speed reduces the power demand while the pitch adjustment allows the propeller to operate at higher efficiencies. This will be considered in the case of the RoRo ship since it exploits the pitch controllability of the existing driveline as well as the speed control of power electronic converters, making for the most feasible solution.

## 6. Scenario vessels

In the study being undertaken in this project, a reference RoRo ship and tug boat were considered as the case vessels, whose main particulars are listed in Table 2 and Table 3.

**Table 2 RoRo ship particulars**

| | |
|---|---|
| Vessel length: | 138.5m |
| Gross tonnage: | 18,979T |
| Main engine: | Wärtsilä 16V46A; 14480kW |
| Service speed: | 20.2kn |

**Table 3 Tug ship particulars**

| | |
|---|---|
| Vessel length: | 25.36m |
| Bollard pull: | 53T |
| Main engine: | 2x Caterpillar 3512C; 2x1469kW |

The scenario considers the RoRo ship on a voyage between the ports of St. Nazaire (France) and Vigo (Spain), with the study focussing on the manoeuvring conditions. During these periods the main engine is generally running at low loadings with associated higher specific emission rates. Although manoeuvring accounts for a small percentage of the total time, it occurs in port areas and hence emission reduction while manoeuvring has an immediate impact on the local environment.

Similarly, the tug is considered when providing manoeuvring assistance. This involves periods idling (standby), in transit, and providing assistance. The auxiliary drive is examined as providing propulsion both in idling and transit periods.

The study considers the provision of electric power from onboard auxiliary generators. A number of commercially available PM machines were considered according to the speed/power rating required depending on the chosen installation topology. The RoRo main engine runs at a nominal speed of 500rpm, geared down to 150rpm at the propeller. With a minimum engine speed of 350rpm (105rpm propeller speed) and the pitch adjusted for optimum efficiency, the power characteristic is tabulated as Table 4 for adjusted pitch conditions in combinator mode.

This illustrates the significant reduction in power demand by adjusting both pitch and speed and hence permits a more feasible machine size. With such a combinator mode of operation, the power demand is reduced, permitting propulsion just below 7kn with an auxiliary drive rated at 1MVA. The average electrical power demand of the ship while at sea is of 600kVA (at 0.8 power factor) which can easily be met by the auxiliary drive operating in generating mode.

**Table 4 Propeller power demands at different speeds with adjusted pitch.**

| Ship speed (kn) | Propeller power at 500rpm (kW) | Propeller power at 350rpm (kW) |
|---|---|---|
| 0 | 2190 | 751 |
| 7 | 2700 | 1085 |
| 10 | 2980 | 1676 |

The tug on the other hand has an FPP system with the propulsive characteristic of Figure 5. This shows quite a wide speed range as expected with VR mode of operation, but the power values are much lower than those of the RoRo ship. For this vessel, the electric power demand is very low at 20kW; hence sizing for generation is not realistic as this would not give any appreciable tug speed.

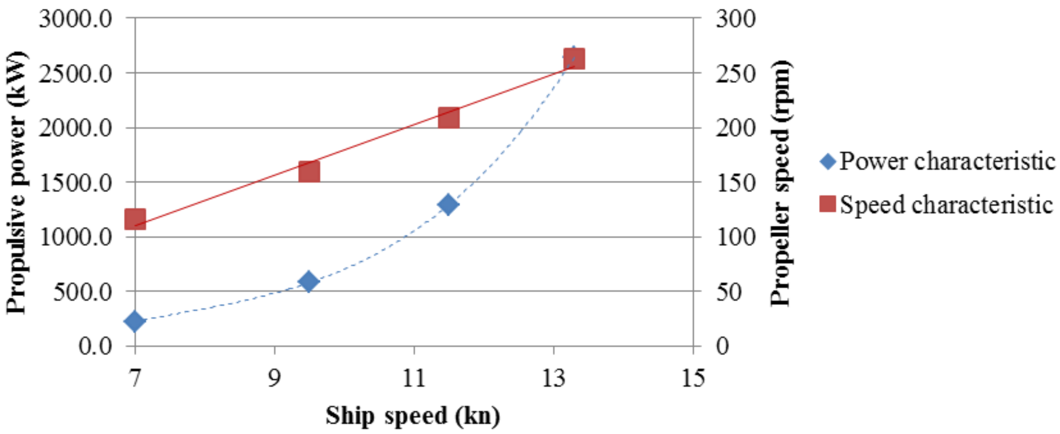



**Figure 5 Tug propulsive characteristics**

## 7. Drive configuration arrangements

*7.1. RoRo ship*

Based on the previous considerations, a number of commercially available PM machines were considered, summarised in Table 5 for the RoRo ship. It is apparent how the topology choice affects the size, weight and cost of the machines. The machines exhibit very similar (high) efficiencies, which makes any savings more dependent on the operating range as well as transmission inefficiencies. The low speed machine will have less transmission losses due to the omission of the gearbox, while the higher speed machines in the geared systems will have an approximate 2% power loss at each gearing stage. For the geared topologies the existing reduction gear is used, hence minimising installation costs.

**Table 5 Selection of electrical machines for for roro auxiliary drives**

| | Machine A | Machine B | Machine C |
|---|---|---|---|
| Installation topology | 1 | 3(b) | 3(a) |
| Rated power (kW) | 893 | 875 | 746 |
| Rated speed (rpm) | 173 | 400 | 3600 |
| Rated torque (Nm) | 49296 | 20900 | 1980 |
| Mass (kg) | 12470 | 4680 | 340 |
| Gears | Direct | MRG | MRG+PTO |
| Machine type | Radial flux | Radial flux | Axial flux |
| Torque p.u. mass (Nm/kg) | 3.95 | 4.47 | 5.82 |
| Torque p.u. volume (kNm/$m^3$) | 32.4 | 24.3 | 15.7 |
| Efficiency at rated (%) | 96.4 | 96.5 | 96 |
| Cost (€) | 271,226 | 155,760 | - |

*7.2. Tug*

In the case of the tug, the machine selection is given in Table 6, considering the two cases of providing propulsion during standby (idling) and during transit periods. Only one installation topology is possible since the existing driveline involves an azimuthing thruster with an integrated step down gearbox. Thus the auxiliary machines will be directly installed on the (high speed) engine side shaft.

**Table 6 Machine selection options for tug.**

| | Machine A | Machine B |
|---|---|---|
| Tug operation (under auxiliary propulsion) | Idling | Transit |
| Rated power (kW) | 160 | 628 |
| Rated speed (rpm) | 600 | 800 |
| Rated torque (Nm) | 2546 | 7500 |
| Mass (kg) | 1125 | 3040 |
| Size (mm) | 508x588 | 750x1365 |
| Volume ($m^3$) | 0.119 | 0.603 |
| Machine type | Radial flux | Radial flux |
| Torque p.u. mass (Nm/kg) | 2.26 | 2.47 |
| Torque p.u. volume (kNm/$m^3$) | 21.4 | 12.44 |
| Efficiency at rated (%) | 95.5 | 97.2 |
| Cost (€) | | |

For both vessels, a simulation model was built in Simulink. This involved the use of Look Up Tables (LUTs) to simulate the energy losses associated with the auxiliary drive as well as the losses associated with the various topologies (number of gear stages). Figures for emission factors based on a previous study (Cooper, 2002) were used for the generator emissions in order to quantify the emissions produced and fuel consumed over the manoeuvring scenario. The power profile was obtained from onboard measurements performed as part of the project study, as well as the accompanying emission measurements and is illustrated for the RoRo and tug in Figure 6. The highlighted periods in both cases will be addressed by auxiliary propulsion and the comparative emission figures reflect solely these periods.

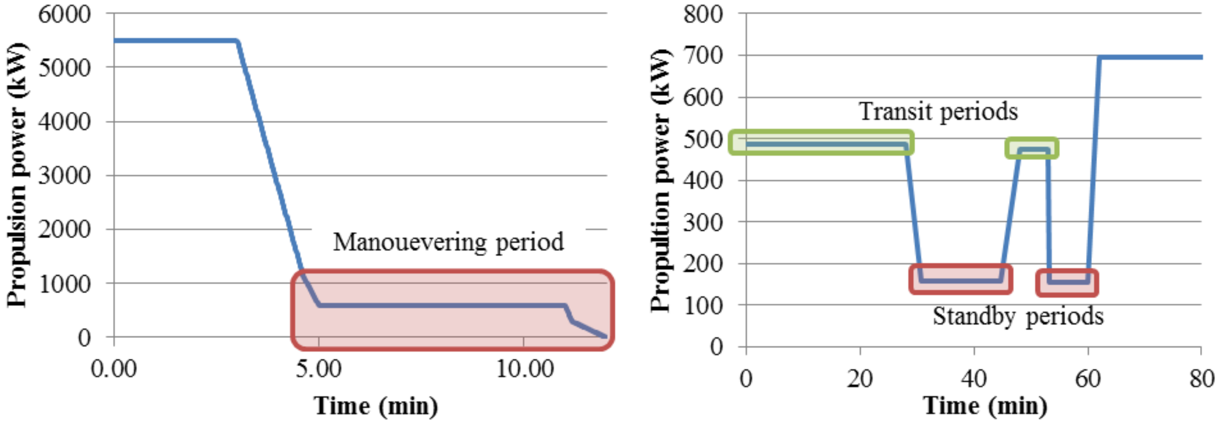



**Figure 6 Scenario profiles for RoRo (left) and tug (right)**

## 8. Results

The simulated emissions for the RoRo manoeuvring in the port of Vigo are given in Table 7, while the corresponding figures for standby and transit scenarios of the tug case are given in Table 8.

**Table 7 Simulated emissions for roro in Vigo manoeuvring scenario.**

| | Current estimate | Machine A | | Machine B | | Machine C | |
|---|---|---|---|---|---|---|---|
| Fuel consumption (kg) | 28.15 | 15.12 | -46.29% | 15.15 | -46.18% | 15.33 | -45.54% |
| Fuel cost (€) | 14.41 | 10.90 | -24.37% | 10.92 | -24.23% | 11.05 | -23.33% |
| $CO_2$ emission (kg) | 89.63 | 48.07 | -46.37% | 48.18 | -46.25% | 48.73 | -45.63% |
| $NO_x$ emission (g) | 1.35 | 0.76 | -43.62% | 0.76 | -43.50% | 0.77 | -42.85% |
| $SO_x$ emission (kg) | 1.53 | 0.08 | -94.98% | 0.08 | -94.97% | 0.08 | -94.92% |

**Table 8 Simulated emissions for tug in Vigo harbour operation**

| | Standby operation | | | Transit operation | | |
|---|---|---|---|---|---|---|
| | Machine A | Current estimate | Difference | Machine B | Current estimate | Difference |
| Fuel consumption (kg) | 37.34 | 36.66 | 1.85% | 177.04 | 175.24 | 1.03% |
| Fuel cost (€) | 26.92 | 26.43 | 1.85% | 127.65 | 126.35 | 1.03% |
| $CO_2$ emissions (kg) | 118.76 | 116.70 | 1.77% | 563.00 | 558.00 | 0.90% |
| NOx emissions (kg) | 1.88 | 1.58 | 18.88% | 8.89 | 7.54 | 17.90% |
| SOx emissions (kg) | 0.19 | 0.18 | 4.71% | 0.90 | 0.86 | 3.82% |

The comparative results are given for the same periods of operation, either by main engine propulsion or by auxiliary propulsion from auxiliary generator sets in combinator mode. On the RoRo, the main engine runs on heavy fuel oil while the auxiliary generators run on diesel fuel. In the case of the RoRo, it is very apparent how the change from main engine to auxiliary engines has resulted in drastic decreases in emissions across the board. Also noteworthy of mention is the significant drop in emissions according to the permitted Sulphur content in fuel. However, with the use of this cleaner fuel the fuel cost savings are much less due to its higher cost. Across the three topologies, the direct drive machine has shown the greatest overall efficiency as expected, while the geared installations do exhibit marginally higher emissions. It must be emphasised however that these savings are only measured for the in-harbour manoeuvring periods with a duration of six minutes. This is a very short duration hence overall savings and return on investment would be increased for vessels with longer manoeuvring times. When considered as part of the complete voyage, the overall emission savings in this case would be very small.

In the case of the tug, the use of an auxiliary drive has not shown improvements over the use of the main engine, both in standby or in transit modes. This is because both main and auxiliary engines already use clean (compared to HFO) fuel, and the use of an electric auxiliary drive further introduces additional conversion losses without reducing power demands. In this case, the specific fuel consumption (SFC) of the main engine at low load is higher than the auxiliary engines' SFC, hence reducing the potential for improvements. This situation would be changed if onboard energy storage were to be used, since no emissions would then be produced during standby or transit.

## 9. Conclusions

The use of PM machines as auxiliary drives is a feasible possibility for low speed propulsion. Based on a selection of commercially available machines, a study was performed to examine the resultant emissions on a representative RoRo and tug vessels, considering various installation topologies. In the case of the RoRo ship, a significant reduction in emissions was demonstrated, especially due to the change from residual fuel oil and power reduction by the use of variable propeller speed. The use of a low speed direct drive machine permits the highest savings to be achieved, albeit at a higher initial cost. In the case of the tug, the electrical drive presents additional losses, and no improvement in fuel use. Hence savings were not realised by running on auxiliary engines.

Economically, the installation of an auxiliary drive represents significant additional cost which is countered by the reduction in emissions. Hence the prime motivation for the use of electrical auxiliary drives would stem from incentives to reduce emissions and reward low emitting vessels.

## 10. Acknowledgements

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