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Simulation-based efficiency evaluation of auxiliary drives for marine vessels

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Abstract

An auxiliary drive is an electric machine and power electronic converter mounted in parallel with the main ship propulsion system. With a bidirectional electric drive system, Power Take In and Power Take Off are both possible, enabling hybrid operational modes. This gives the opportunity for slow speed motoring periods with improved prime mover operation and potentially lower emissions. Permanent magnet and induction machines are the two likely electrical machine choices. This paper presents an evaluation of the relative efficiencies of the two machine types when implemented on a shipboard auxiliary drive system. Depending on the operational strategy and the adopted propulsion system, the auxiliary drive is required to operate at various points in its operating envelope. By using a detailed computer model of an auxiliary drive system, the efficiencies at various operating conditions are calculated, showing how knowledge of the ship's operational profile is essential in order to identify the configuration with the best efficiency.

1. Introduction

Hybrid vehicles combine two or more separate systems in order to meet a vehicle's operational aims by exploiting each individual subsystem's strengths to realise an improvement in the vehicle's overall condition. Automotive hybrids are commonplace, combining the environmental benefits of an electric vehicle with the range and performance of an internal combustion engine. In the marine industry, hybrids have not generally included energy storage systems, chiefly because of the larger energy levels associated with marine propulsion systems. However the use of multiple systems to provide the required propulsive power from separate sources is highly suited for marine applications, especially ones which exhibit a highly fluctuating power demand.

Especially in view of environmental regulations which are tightening emission levels, hybrid systems can help address periods when the main engine (typically running on Heavy Fuel Oil (HFO)) is operating at suboptimal conditions, such as during low speed transits. Alternative power can be sourced from the auxiliary power system which is generally supplied by auxiliary diesel generators running on cleaner diesel fuels (when compared to HFO).

The linking of the auxiliary power system with the main propulsion system is achieved with the use of auxiliary drives, which in the scope of this paper is understood to refer to an electrical machine and bidirectional power electronic converter capable of operating in motoring as well as generating mode. Conceptually, this arrangement is shown as Fig. 1, where the auxiliary drive is connected to the propeller shaft via the Main Reduction Gearbox (MRG), in this case showing a medium or high speed diesel engine. The electrical machine is connected to a Power Take-Off/Power Take-In (PTO/PTI), which is an additional geared shaft available for the connection of rotating equipment. This permits mechanical power to be delivered to the propulsion shaft from the auxiliary power system, or electrical power to be fed back to the onboard grid (Sciberras *et al.*, 2013).

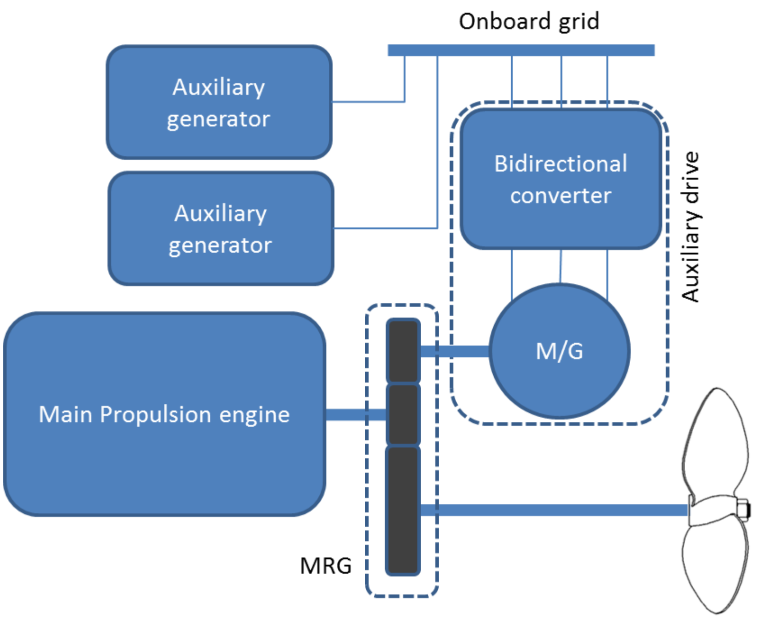

Fig. 1: Auxiliary drive topology.

The use of an electrical machine rated at higher speeds (as an auxiliary drive) results in smaller and lighter units compared to equivalently rated (in terms of power) slow-speed electric machines. This is a result of the reduced torque requirement which translates to a lower current rating and hence smaller required conductor area. Two types of electrical machines are compared in this work by means of computer simulations, namely a Permanent Magnet Synchronous Machine (PMSM) and an Induction Machine (IM). Fig. 2 shows a simplified cross-section through the two machines, showing the main differences on the rotor, namely the surface mounted permanent magnets compared to the solid bars on the induction machine’s rotor.

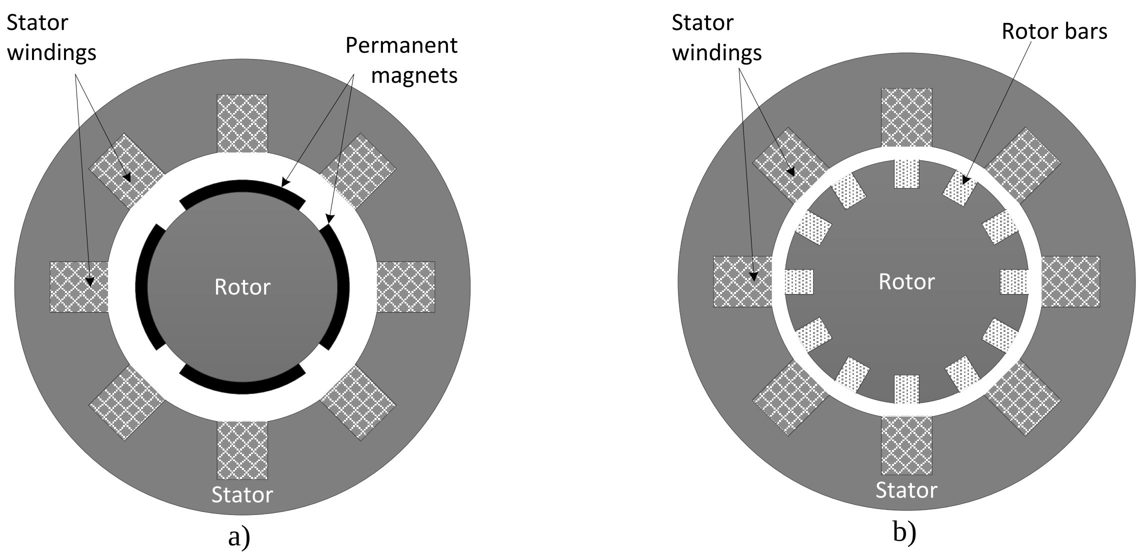

Fig. 2: Cross-sectional comparison of a) Permanent magnet and b) Induction machines.

A permanent magnet synchronous machine uses permanent magnets mounted (typically) on the rotor to generate a magnetic field. When rotated, flux linkage with the stationary windings induces a voltage in the conductors and a current to flow. The benefit of PMSMs is that the magnetic field is set up without the need to supply any external energy, resulting in a higher level of efficiency of the machine. This permits higher torque densities to be achieved and PMSMs are generally more compact and lightweight than their equivalent conventional machines. However magnetic materials are expensive, raising significantly the cost of these machines. Furthermore, the magnets make the machine less robust, both in terms of thermal withstand capability as well as physical robustness (especially at assembly and maintenance stages) (Gieras, 2009).

Induction machines can be considered analogous to a rotating transformer. A rotating magnetic field is set up in the stator which induces currents to flow in the short-circuited rotor bars. These currents set up a magnetic field in opposition to the stator field, whose cross-coupling results in the development of an electro-magnetic torque, causing the rotor to rotate. Since some relative motion is always required to induce the currents in the rotor, the rotor does not rotate at the speed of the stator field, but lags behind by a small fraction known as the slip (Chapman, 2012). By their construction, induction machines are simple, robust and cheap. However their efficiency (compared to PMSMs) can be somewhat lower (Zhu and Howe, 2007).

In this study, a permanent magnet machine is compared to an induction machine to examine their relative efficiencies when used as part of a ship's bidirectional auxiliary drive. Permanent magnet machines are inherently more efficient in their operation than induction machines, but for applications which require operation across a wide speed range, the choice of permanent magnet machines might result in higher system losses. In this analysis, the two machine types are compared for the same operating scenario based on a typical journey made by a RoRo vessel using computer models of the power electronic components and electrical machines that make up the auxiliary drive system.

2. Auxiliary drive operating envelopes

Modern power electronics and microprocessor-based control have facilitated fast and precise control of AC machines such that performance and characteristics similar to a separately excited DC machine are easily achieved. Fast microprocessor-control permits the action of the mechanical commutator on DC machines to be performed electronically, enabling the operational envelope of an AC machine to be maximised to encompass a broad power/speed region.

A technique known as vector control achieves these requirements, mathematically transforming the three-phase rotating quantities (which are complex to control), to equivalent DC figures which take on meaningful and directly relatable quantities. Fundamentally, two orthogonal transformed currents are obtained, namely the direct current i_d, and the quadrature current i_q. Their significance comes about since under decoupled conditions, the direct current i_d is termed the *field forcing current*, while the quadrature component i_q is termed the *torque producing current*. This permits easy and straightforward control of an electric machine in all its operational quadrants.

The operating envelope of an electric machine under vector control is illustrated in Fig. 3, showing the torque and power characteristics as functions of shaft speed. Up to rated speed, the machine is able to develop power proportional to the shaft speed (with a corresponding flat torque characteristic) up to its rated power at the nominal design point. Beyond rated speed, operation is possible using a technique known as field weakening. This corresponds to a constant power region up to the machine's maximum shaft speed, with a decreasing level of torque available from the machine. Simplistically, field weakening can be described as an intentional weakening of the magnetic field within the machine in order to reduce the back-EMF (Electro-Motive Force) which increases with shaft speed. This permits control over the machine to be maintained as otherwise, a limit is reached in terms of the drive's capacity to control the current in the machine since it cannot impose sufficient voltage onto the stator.

Fig. 4 illustrates the auxiliary drive envelope superimposed on a theoretical propeller curve. At low ship speeds, the auxiliary drive is required to operate in motoring mode and provide the required propulsion power. This avoids having to run the main engine at low loading factors, which adversely affects engine life, emission characteristics and fuel consumption rates. At higher ship speeds, the auxiliary drive would be operating in generating mode. This avoids the need to run the onboard generators, and provides the onboard auxiliary power from the cheapest available source (main engine) (Castles *et al.*, 2009; Buckingham, 2012). These two distinct operating points as highlighted in Fig. 4 imply a requirement to size the drive to operate at (or close to) its rated condition (speed and power) when motoring, while then generating under field weakening at the higher speed point.

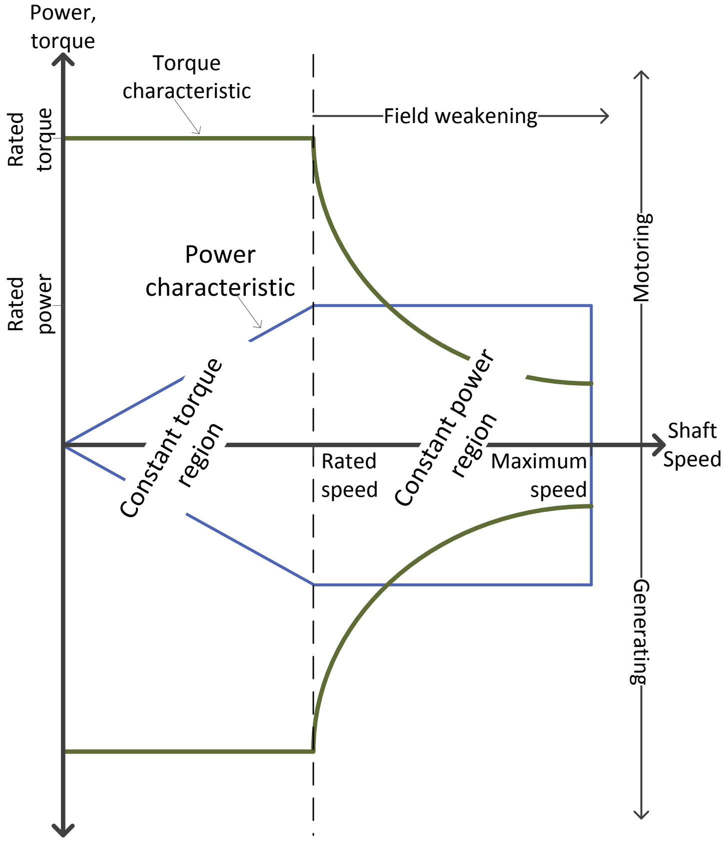

Fig. 3: Electrical machine operating envelopes.

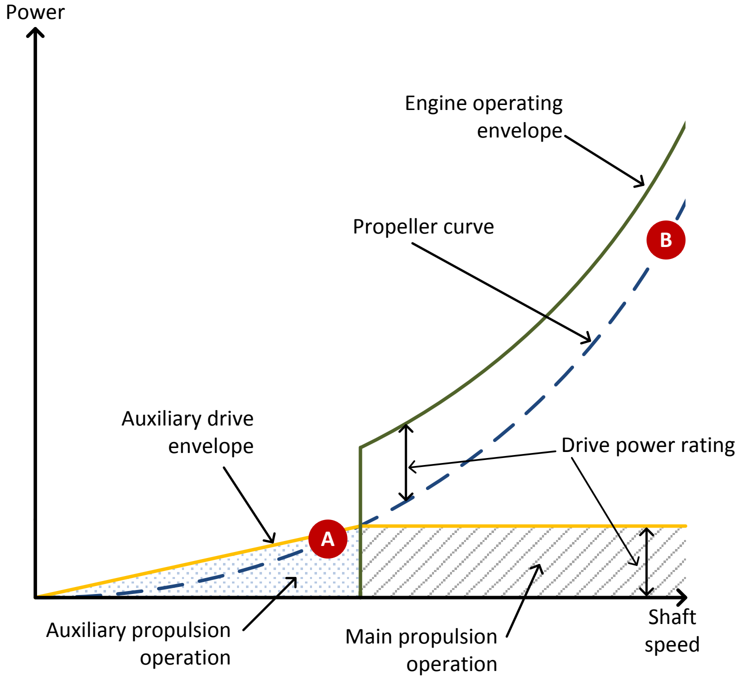

Fig. 4: Operating envelopes of auxiliary drive, main engine and propeller curve. Operating point A corresponds to low speed propulsion, while operating point B is sailing at rated speed.

In a PMSM, the magnetic field is set up inherently by the rotor. Once the magnets have been assembled, no direct control of the magnetic field is possible. Under normal operation therefore, the field forcing current (i_d) is maintained at 0A for minimum copper losses. This is known as the maximal torque per Amp condition, as all available current is used for torque generation. For operation beyond rated speed, the magnetic field set up by the magnets must be decreased. This is achieved by injecting a negative value of i_d such that a stator field opposing that set up by the magnets is created (de Doncker *et al.*, 2011b). Care must be taken since irreversible demagnetisation can occur on the magnets if these are exposed to high levels of opposing flux. Machine designs such as those using interior mounting of the permanent magnets helps to avoid the risk of damage to the magnets (Zhu and Howe, 2007). Furthermore, additional current (since previously i_d was zero) needs to be injected into the machine, increasing Ohmic losses.

In an induction machine, the magnetic field must be set up using an external power source, leading to a non-zero value of i_d. Up to rated speed, the field forcing current is set to maintain rated flux levels in the machine. Beyond rated speed, in order to reduce the flux in the machine (in a simple implementation of field weakening), i_d is simply reduced proportionally (de Doncker *et al.*, 2011a). Hence at higher speeds, less current is potentially required by an IM than a PMSM. A comparison of the two must therefore be performed in order analyse the trade-offs between a potentially higher overall efficiency due to the different operating modes.

3. Computer Modelling

For the case vessel being considered, two similarly rated machines (one IM and one PMSM) were selected from industrially available devices. Detailed models of the drives were built to be able to give quantitative comparisons between the two setups. Within the Matlab environment, Simulink provides a graphical simulation tool which greatly facilitates the setting up of complex models. SimPowerSystems is a toolbox which provides models for electrical components. This permits models of electro-mechanical systems to be built using building blocks of pre-assembled elements (MathWorks, 2014). Two complete drive system models were set up, modelling the power electronic converter and electrical machine. The schematic of the simulation setup is shown as Fig. 5, illustrating the various modules which make up the simulation. The two external inputs are the speed and torque setpoints. These define the operating point of the drive, with the direction of the external torque determining whether the machine is generating or motoring.

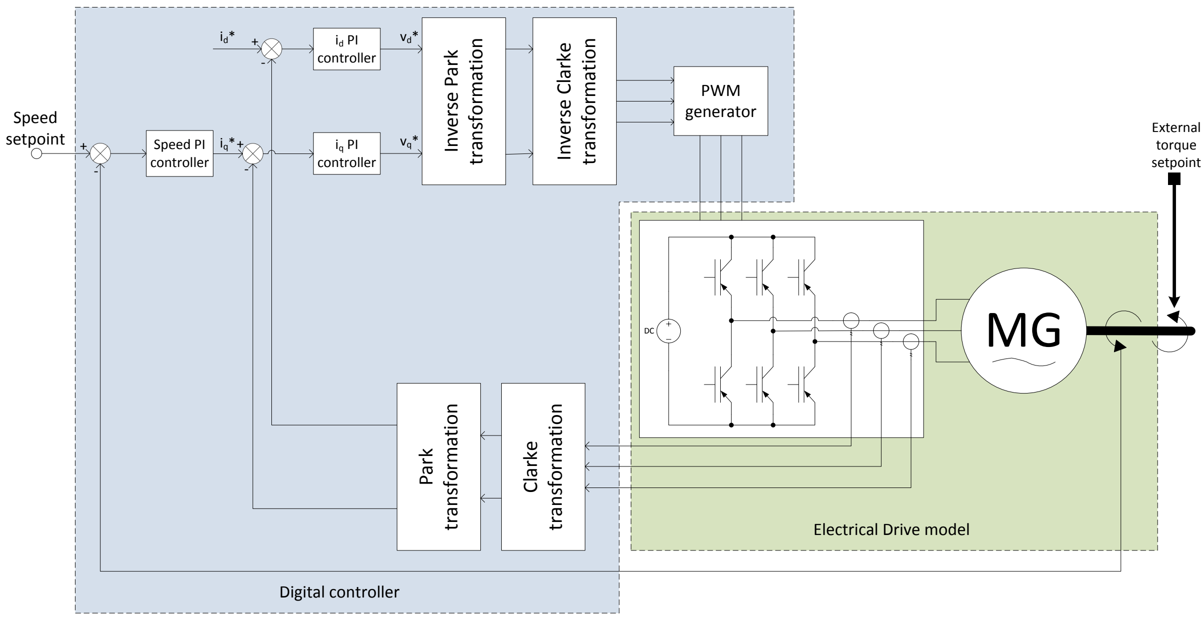

Fig. 5: Auxiliary drive model overview.

The electrical drive model is composed of SimPowerSystems components, facilitating modelling of the electrical machine as well as power electronic inverter, in this case implemented using Insulated Gate Bipolar Transistors (IGBTs). The electrical machine model is replaced by the PMSM or IM model as required. The control algorithm and mathematical transformations are performed by a digital controller implemented as C-code. This emulates the microprocessor control of the auxiliary drive. The desired value of i_d is determined by the digital controller according to the machine's operating region, while i_q is the output of a Proportional + Integral (PI) controller which adjusts the speed of the drive.

3.1. Operational data

This comparison was performed using data available for a RoRo vessel which typically operates with the operating profile of Table I. Within these conditions, propulsion is to be provided by the auxiliary drive for the manoeuvring periods, while the drive is to provide power to the onboard grid by operating as a shaft generator during the At Sea period. The whole propulsion system is considered to be shut down while the vessel is berthed. Some salient characteristics of the RoRo vessel are provided in Table II.

Table I. Typical operating profile of vessel.

Operating condition	*Percentage of time*
At sea	75%
Berthed	20%
Manoeuvring	5%

Table II. RoRo characteristics.

Propulsion arrangement	CPP with medium speed diesel engine
Engine speed at nominal operation	500rpm
Engine speed for manoeuvring condition	350rpm
Averaged propulsion power demand during manoeuvring	580kW

Two separate machines were selected from manufacturer catalogues, fitted to a PTO/PTI on the MRG (as in Fig. 1), with an additional PTO gear ratio of 2.3. This gives electrical machine speeds of 800rpm and 1142rpm for the motoring and generation periods respectively. The parameters for the PMSM and IM are given as Table III and Table IV. These were used to simulate the auxiliary drives as outlined in the previous section, with the Simulink model for the PMSM drive shown as Fig. 6. This shows the SimPowerSystems implementation of the model described in Fig. 5 with the corresponding modules highlighted accordingly. The simulation was run until steady state was reached and the resultant efficiency determined at each operating point of interest.

Table III. Specifications of selected Permanent Magnet Synchronous Machine.

Rated speed	800rpm
Rated power	1005kW
Rated torque	12kNm
Efficiency at rated condition	97.3%

Table IV. Specifications of selected Induction Machine.

Rated speed	744rpm
Rated power	970kW
Rated torque	12.5kNm
Efficiency at rated condition	95.4%

Table V. Operating points specification.

Motoring condition	
Drive speed	800rpm
Power demand (mechanical)	580kW
Generating condition	
Drive speed	1143rpm
Auxiliary power demand (electrical)	400kW
Auxiliary load power factor	0.8 lagging

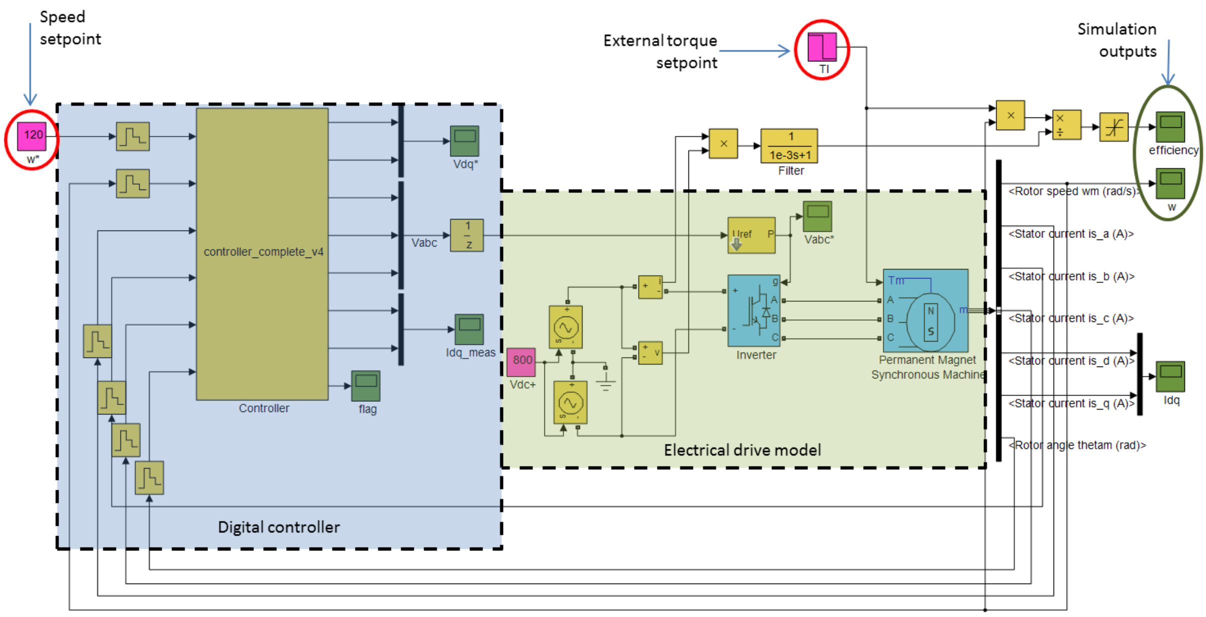

Fig. 6: Drive model set up in Simulink.

4. Results

An example of the simulation output is shown as Fig. 7 which shows the step response of the auxiliary drive with a PMSM when motoring as defined in Table V. The direct axis current is maintained at 0A for minimum copper losses, while the quadrature current is clamped to rated value for maximum torque during acceleration. Once the desired speed has been reached, the current reduces to its steady state value.

Fig. 8 shows the corresponding characteristic when in generating mode. The motor is accelerated to the desired speed (under no load), with the direct current observed to take on a negative (non-zero) value in order to permit over speeding of the machine. The quadrature current is decreased as a function of the maximum permissible current in the stator in order to prevent overloading. A negative torque (mechanical power fed from the shaft) is applied at 1s, with the quadrature current then settling to a negative steady state value, indicating real power being fed back to the electric supply. Characteristics for the induction machine drive are similar, except that the direct current takes on a non-zero value and is decreased accordingly during field weakening.

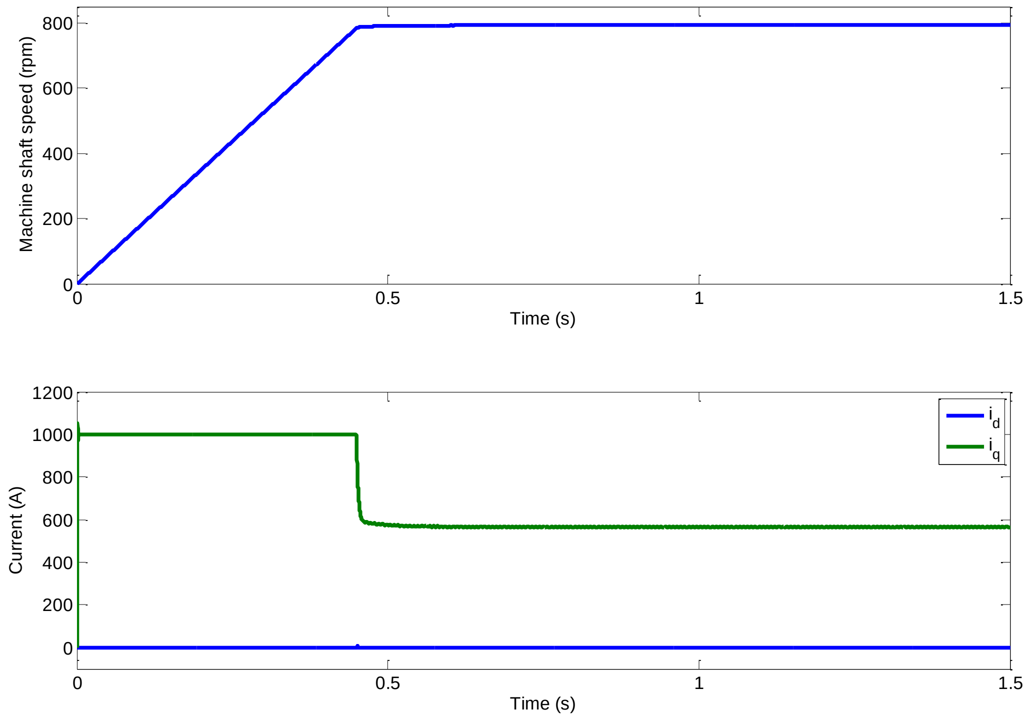

Fig. 7: Step response of PMSM drive when motoring.

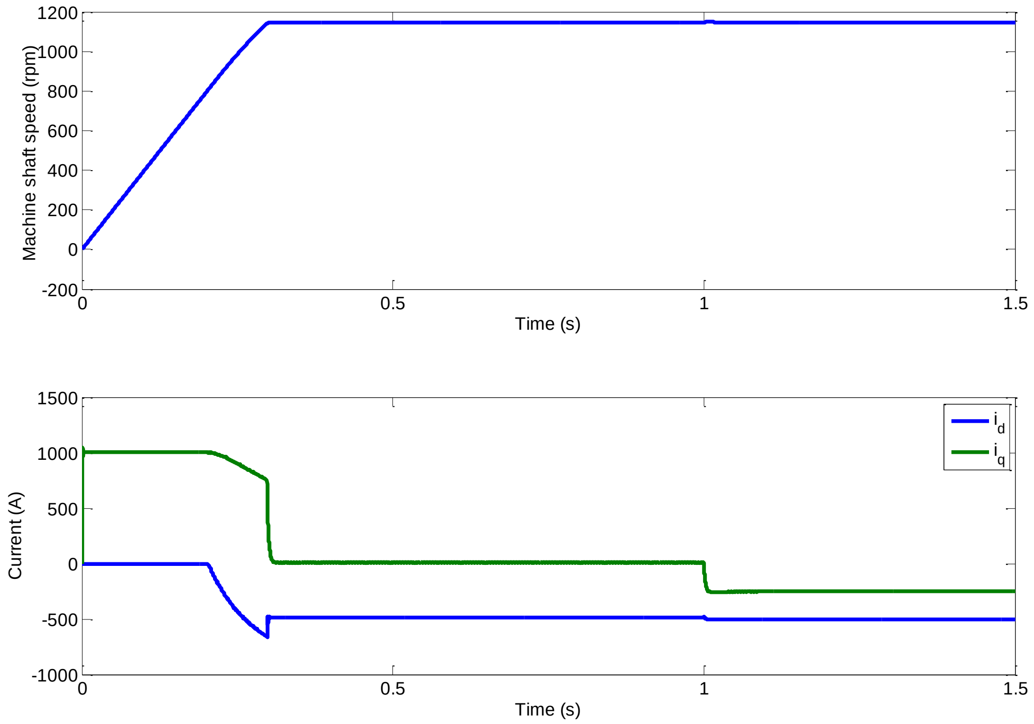

Fig. 8: Step response of PMSM drive in generating mode.

The comparison of the steady-state results of the two drives are listed in Table VI and Table VII highlighting the current values together with overall drive efficiency. The salient point from these tables is the fact that while the PMSM drive shows a higher efficiency during motoring condition, the efficiency during the generating period is marginally lower than the IM drive. This comes about since a larger current magnitude is now injected into the drive to force field weakening, leading to higher losses.

Table VI: Steady-state characteristics of PMSM drive.

	Motoring mode	*Generating mode*
i_d *(A)*	0	−500
i_q *(A)*	565	−250
Stator current (A)	565	559
Efficiency (%)	**97**	**92**

Table VII: Steady-state characteristics of IM drive.

	Motoring mode	*Generating mode*
i_d *(A)*	247	170
i_q *(A)*	695	−450
Stator current (A)	737	481
Efficiency (%)	**95**	**93**

A typical journey of the RoRo in question (berth to berth) lasts around 28hrs, and combining the averaged powers of Table V and the operational profile of Table I with the results obtained leads to the summarised losses of Table VIII. Clearly, though the PMSM drive shows a lower efficiency while generating at sea, when motoring an increased efficiency of around 31% can be realised. However, the greater proportion of time spent at sea implies that the energy lost will be greater.

Table VIII. Comparison of losses between drive types.

	Losses during manoeuvring period	*Losses at sea*
PMSM drive	39.26kWh	851.35kWh
IM drive	56.98kWh	790.32kWh
PMSM vs IM	−31%	7.7%

Fundamentally, all energy on board a ship translates to an equivalent fuel cost. The losses at sea (when generating) are supplied by the main engine, while those during the manoeuvring period are supplied by the auxiliary generators. Based on the typical Specific Fuel Consumption (sfc) figures for these engine types (Cooper, 2002), the fuel consumed to supply these losses, and the bunker cost (Bunkerworld, 2014) is shown in Table IX. This illustrates how due to the lower cost of HFO used by the main engine, the economic savings due to the higher (generating) efficiency of the IM drive are much smaller since they are offset by the higher cost of the fuel used in the auxiliary generators, but when considering the total losses due to the operating profile, an overall improvement is seen with the IM drive. The resultant losses/savings will therefore be determined based on the particular operating profile, highlighting the importance of considering the actual design conditions for which the system is to be designed (Buckingham, 2012; Sciberras and Norman, 2012).

Table IX. Economic comparison of losses due to different auxiliary drives.

	Equivalent fuel loss during manoeuvring (MGO)	*Equivalent fuel loss during at sea period (HFO)*	*Total equivalent cost of fuel to supply losses*
PMSM drive	8.52kg	181.34kg	€79.75
IM drive	12.36kg	168.34kg	€76.76
PMSM vs IM	**−31%**	**+7.7%**	**+3.8%**

5. Conclusions

Auxiliary drives give the potential for improvement of prime mover operation by providing low speed propulsion power via the auxiliary power system. While the vessel is sailing, the auxiliary drive is able to operate as a shaft generator when coupled to a bidirectional power converter, providing the onboard auxiliary power demand from the most economical source available. Two possible electric machines for application as an auxiliary drive are an induction machine or a permanent magnet machine.

In this work, a detailed drive model of the two machines was built in order to analyse their operation at the various operating points, taking the operation of a particular RoRo vessel as an example. Based on the characteristics of the vessel, a wide operating speed range is required of the auxiliary drive, requiring field weakening control of the electrical machines. This leads to different efficiencies for the machines at the various operating points such that the resultant improvement in overall operation must be considered according to the operational profile.

It was seen how an auxiliary drive using an induction machine shows a lower efficiency while motoring when compared to one with a permanent magnet machine. Conversely, when generating in this particular set up, the induction machine shows an overall higher efficiency. This must be considered in conjunction with the cost of fuel since each operating mode sources power from a different system, and the resultant costs will be determined by the amount of time spent in each condition. For this particular scenario, an auxiliary drive with an induction machine will realise (slightly) higher economic savings, mainly due to the length of time spent sailing at rated, when compared to the brief period in manoeuvring. When considering the capital costs of the machines involved, this weighs heavily in favour of the cheaper induction machine system.

The design of hybridised systems must therefore be carefully analysed based on the vessel's operational profile since the resultant operating points will determine the overall effectiveness of the system. Thus a vessel with a larger proportion of time in manoeuvring condition will benefit more by having higher efficiency while motoring. Similarly, vessels with a significant portion of time spent in off-design conditions will benefit from hybrid drives since overall operating costs can be improved. This also reflects in emission reductions by operation of the auxiliary system rather than the main propulsion engine at low loadings.

The availability of computer-based simulation models permits quick and easy evaluation of different technologies and components. With a detailed model such as the one used in this paper taking into account the switching behaviour of the power electronics, as well as the dynamic response of the electrical machine, a realistic estimate of the total losses in the drive can be obtained at the various operating conditions. This availability of detailed simulations permits complex electro-mechanical systems to be easily simulated at the design stage such that optimal configurations can be identified.

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