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Potential of hybrid systems with permanent magnet motors for propulsion improvement on surface longliners

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Abstract— **The raise in fuel cost have increased the interest on reducing the fuel consumption on fishing vessels. Several research and development projects have been promoted all over the world, many of them with the objective of identifying the energy consumption profile of the different types of fishing vessels as a first step for future optimization.**

The propulsion systems employed by most of the fishing vessels are based on conventional fixed or controllable pitch propellers driven by diesel engines, but recent developments on electrical rotating machines, power electronics and electrical energy storage technology suggest that combined mechanical / electrical propulsion can be a very suitable alternative for improving the energy efficiency of these ships.

The results of a preliminary project for assessing the potential of hybrid propulsion systems for surface longliners are presented. The Spanish surface longliner fishing fleet is composed of nearly 300 ships, featuring a very specific and fluctuating power demand. First, the power demand and operating profile of a typical surface longliner is analysed based on the results from several research and development projects and energy efficiency audits carried out on the Spanish fishing fleet. A tentative architecture of the power plant is proposed and described; it is based on a variable speed synchronous permanent magnet motor / generator connected to a double AC / DC bus linked to an electrical energy storage system. Each component of the hybrid power plant is briefly described, carrying out a preliminary calculation of a custom design permanent magnet machine for propulsion and generation, in two alternatives, direct drive and geared

Keywords: longliner; energy audit; hybrid propulsion; permanet magnet motor

I. STATE OF THE ART

Main propulsion drive fitted onboard of almost every fishing vessel typically consist of a diesel engine driving a propeller through a reduction gear. In most of the cases, the response of these engines is not optimised for the ship operating profile since most of the fisheries and fishing techniques require the ship to carry out frequent manoeuvres being the propulsion power demand highly variable during the different stages of the fishing operation.

The improvements in electrical machines and power electronics have opened the door to more innovative solutions for increasing the energy efficiency of the fishing fleet.

Different alternatives of electric propulsion currently exist on the market. The common feature is the use of electrical energy for propulsion by means of one or several electric motors.

A conventional diesel-electric propulsion system typically comprise several diesel driven generators, powering one or several electric motors which drive one or several propellers through the corresponding tail shaft. This solution is expensive and requires a significant space in the engine room, being difficult to apply on fishing vessels (It is practically impossible as a retrofitting solution for existing ships)

These solutions have not been very successful on the few implementations carried out on fishing vessels, mainly longliners, stern trawlers and some tuna purse seiners. Among these pioneers we may cite a pair of diesel-electric longliners built in Vigo (Spain) in the late eighties; these ships featured a DC power plant with a 550 kW electric motor and 4 x 300 kVA generators. At least one of them, called "CEIBE DOUS", is still in service with the Spanish shipowner Ibérica de congelados S.A.

HJ Barreras in Vigo, Spain, in 1996 delivered to the French company Saupiquet, a couple of diesel-electric tuna purse seiners, "Via Libeccio" and "Via Gwalarn". The high power demand of the fish freezing and processing plant justified this type of installation. The ships were fitted with a 6200 kW electric motor for propulsion, driving a fixed pitch propeller through a reduction gear. The electrical power plant was composed of 7 diesel generators, 6 x 1280 kW plus 1 x 630 kW.

Figure 1. Diesel-electric tuna seiner Via Gwalarn

Marin Teknikk AS of Norway designed a diesel-electric bottom longliner which was delivered by Solstrand AS to Ervik Havfiske AS in 2001. The ship, called “Froyanes Senior”, is fitted with diesel – electric propulsion with two electric motors (600 + 800 kW) driving a controllable pitch propeller through a reduction gear. The power generation plant consists of three diesel generators (2 x 1140 kVA and 1 x 450 kVA). The operation profile of the bottom longliners, with very prolonged period of line hauling at very low and fluctuating speeds, makes the diesel-electric approach very interesting.

Figure 2. Diesel-electric bottom longliner Froyanes

A more innovative solution is the one installed in the purse seiner / pelagic trawler “Teigenes”. It consists on a hybrid propulsion without electrical energy storage system. The total propulsion power of 5800 kW is delivered to a double input reduction gear by a 2000 kW asynchronous electric motor and a 3800 kW diesel engine. A novel characteristic is the fact that the main diesel engine is able to drive a generator through its forward power take off, giving the ship a higher flexibility.

In Japan, the trawler Shinei Maru Nº66 features an innovative hybrid propulsion system, but no details about this solution are available.

A cheaper, but also very effective, solution consists on using a diesel engine as main propulsion and installing an auxiliary electric motor driving a power take in (PTI) on the reduction gear. Several Spanish longliners have installed this type of system, among them we can cite two bottom longliners “Illa de Rua” delivered in 1998 and “Anchousa”, delivered in 2008, these ships are equipped with a fixed pitch propeller, the electrical machine operates only as an auxiliary electric motor (electrical power delivered by auxiliary diesel generators). Another alternative is the one installed on the surface longliner “Ana Barral”, this configuration allows the electrical machine to operate either as an auxiliary motor or shaft generator, for this purpose a controllable pitch propeller is fitted, running at constant rotational speed.

All of the aforesaid configurations used conventional electrical machines (motors or generators), which are of the wounded rotor type. In recent years, the development of new materials, drive solutions and control strategies has promoted the advance and optimization of novel electrical machine topologies. These topologies feature higher power densities and better efficiencies. Concerning low speed high torque applications, the most common electrical drive configuration (low torque induction motor attached to a gear box) is being replaced by direct drive multi pole Permanent Magnet Synchronous Machines (PMSM), which has resulted to be a very promising alternative.

The main factor spreading the use of PMSMs in industry is drives’ price reduction. Moreover, machines built with permanent magnets have many advantages such as: no rotor losses, no need of external source to create rotor magnetic field, high torque per volume unit, and no need of maintenance for the rotor. All these reasons lead to the use of PMSM in different applications as: wind turbines, ship propulsion, elevators, paper mills, direct drive actuators, railway traction, automotive applications, electrical hybrid vehicles, and so on.

Regarding the electrical energy storage, the use of batteries onboard ships has been traditionally limited to emergency back-up services with a very small power. The available technology allowed only a very limited use of batteries for other services because of the low energy and power densities; recent research efforts on the electronics and automotive industry lead to dramatic improvements on these ratios, opening the door to high power / energy demanding applications, like ship propulsion and electrical power supply for reasonable periods of time.

The traditional solutions based on lead-acid, have been substituted by Li – Ion technology, allowing much better energy and power density ratios (both in terms of weight and volume), furthermore, current research on fields like the automotive industry is expected to bring dramatic improvements on the performance of electrical energy storage systems.

Power electronics is broadly used on land based industries for driving many different types of electrical machinery, however, its use on board ships is scarce and almost inexistent in the fishing vessel case.

The potential of variable speed electrical drives for improving the energy efficiency of ships is very significant, and its integration on a hybrid ship can provide further improvements if we take advantage of an available DC bus, avoiding double power conversion.

This type of mid-size fishing vessels has a very limited automation and control systems. The most common systems found are engine room alarm systems and freezing hold monitoring. Existing alarm and control systems are normally not interconnected and available performance data is not shared among systems or with the user.

Concerning load sharing, since all the electrical power supply is expected to be provided by a single AC generator, no load sharing means are installed (except on large trawlers and tuna seiners).

II. CURRENT RESEARCH AND DEVELOPMENT PROJECTS ANALYSING SURFACE LONGLINERS

Below, three R&D projects aimed at improving the energy efficiency of the Spanish fishing fleet are briefly described, as an introduction to the R&D efforts done by several fisheries associations in Spain for improving the energy efficiency of different types of ships.

A. Iniciativa ahorro

Iniciativa ahorro ("Saving initiative") was one of the first set of projects promoted by the Spanish Fishing Confederation CEPESCA, in cooperation with some other fishermen organizations like ARVI, the ship-owner association from Vigo. The first two projects within this initiative aimed at obtaining real operational data from six different types of fishing vessels, including two surface longliners. This highly valuable data includes real torque and speed measured on the propeller shaft, electrical power, engine fuel consumption, ship speed, etc… The sensor data has been recorded by means of a custom designed data acquisition system and sensors. These first two projects have been partly funded by the Spanish Ministry of Rural and Marine Environment and the Innovation Council from the Galician Government.

Figure 3. Surface longliner

B. CENIT BAIP 2020

It is a large cooperative project started in 2006 and due to finish in December 2010. It aims to develop innovative technologies for fishing vessels. The project covers almost every technology on board fishing vessels, including hydrodynamics, propulsion, machinery, fishing gear, accommodation, automation, navigation, etc. The role of Vicus Desarrollos Tecnológicos S.L. (VICUSdt) within the project, has been focused on improving the propulsion performance of a 42 m length surface longliner, this work included development a new hull form, a high efficiency propeller and rudder, analysing different propulsion-generation combinations and developing a direct drive propulsion system. Some of the results obtained so far have been used for writing this article and are highly encouraging despite not all the planned simulation and model testing has been finished yet. This project has been partly funded by the Centre for the Development of Industrial Technology CDTI, belonging to the Ministry of Science and Innovation.

C. Energy audit and proposal for improvements on the surface longline fleet

Another more recent project within the saving initiative has been promoted by CEPESCA, and aims to carry out energy audits on a large number of ships (27 surface longliners) and to propose cost-effective energy efficiency improvements which can be implemented on existing ships. This project has been totally funded by the Spanish Ministry of Rural and Marine Environment.

III. POWER DEMAND PROFILE OF A TYPICAL SURFACE LONGLINE FISHING VESSEL

Surface longline, figure 9, is a fishing method based on a longline floating near the surface; it is typically used for catching pelagic fish like swordfish and tuna. Spanish fishing fleet is composed by almost 300 vessels fishing mainly on the Atlantic, Pacific and Indian oceans. The long distance fleet consists of 180 ships with length between perpendiculars ranging between 23 and 40 m, and a gross tonnage between 200 and 850 GT. Swordfish is the main catch.

Figure 4. Longliner at sea

The operating profile of a typical surface longliner, combines periods of high speed line setting and hauling with waiting times when power demand is low. Line setting usually takes about 6 hours a day and is usually carried out at speed about 8-10 kn. Hauling the line is also carried out at quite high speed but includes frequent and sudden stopping manoeuvres when a fish appears hooked on the line, this operation implies a sudden backing manoeuvre and sometimes a hard turn in order to ease the hauling procedure and avoid loosing the catch. Once the catch is onboard, the ship accelerates again very hard in order to reach the hauling speed as soon as possible. It must be taken into account that it probably has to run 60 miles to recover the whole gear.

The same scheme is repeated everyday, alternating periods of line searching, hauling, line setting and even waiting stopped.

Data from a 40 m longliner can be seen on figure 5.

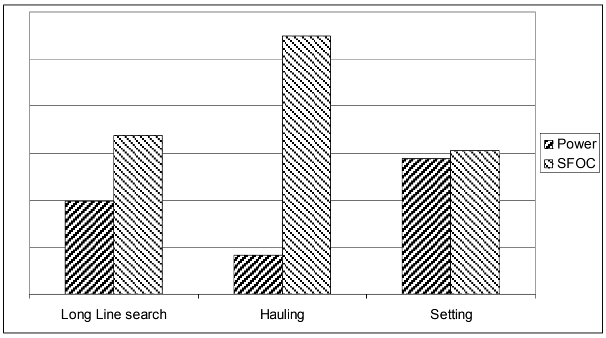

Figure 5. Diagram showing average power by condition

This first bar diagram shows a comparison between power and specific fuel oil consumption (SFOC) on each condition according to the data recorded with the sensors installed during the "saving initiative" projects. We note that there is an important difference on the average power demand among the different conditions and there is a significant increase in specific fuel consumption during the hauling manoeuvres, due to the large fluctuations on power demand during this stage of the fishing operation. The differences on specific fuel oil consumption between line search and line setting are not significant. The procedure used for data recording did not allow obtaining a detailed profile of the ship's power demand, but the data is still very useful for obtaining a first picture of the fleet profile.

The Figure 6 shows the time spent on each condition. This figure reveals the importance of improving the performance at the line hauling operation, which takes most of the time; in addition, it is the most inefficient of all the operating conditions.

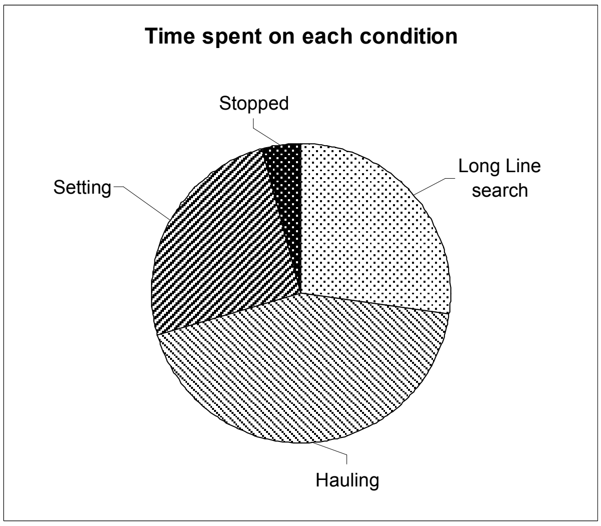

Figure 6. Time per condition

The number of manoeuvres carried out per day in the analysed ship ranges between 150 and 350, depending on the day. The figure 7 includes a significant percentage of backing manoeuvres, when the propeller start turning backwards. Most of these manoeuvres are concentrated at the line hauling condition.

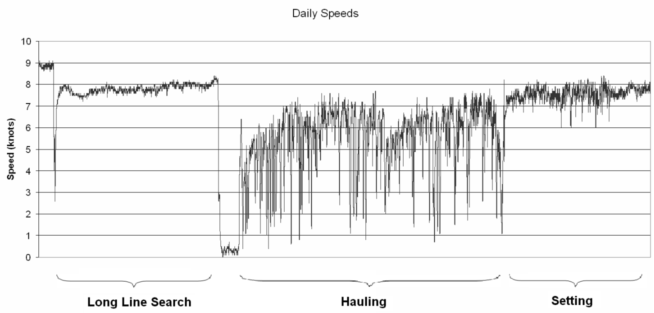

Figure 7. Average velocities and number of manoeuvres

A similar profile will be probably repeated all over the fleet, this issue will be further investigated at the last project promoted by CEPESCA, which includes energy efficiency audits on 27 ships, including real power and fuel consumption measurements on 12 of them.

Concerning the electrical power plant demand, it shows a quite steady power demand; in smaller ships, high load fluctuations take place due to the start of the electrical refrigeration compressors, which are by far the most important consumer. As can be deduced from Figure 8, any measure taken to improve the performance of the power plant can lead to significant reductions on total energy consumption. The use of frequency controlled drives for refrigeration compressors are scarce on the fishing fleet, despite have became a quite common solution on land based installations, featuring proven benefits in terms of energy efficiency.

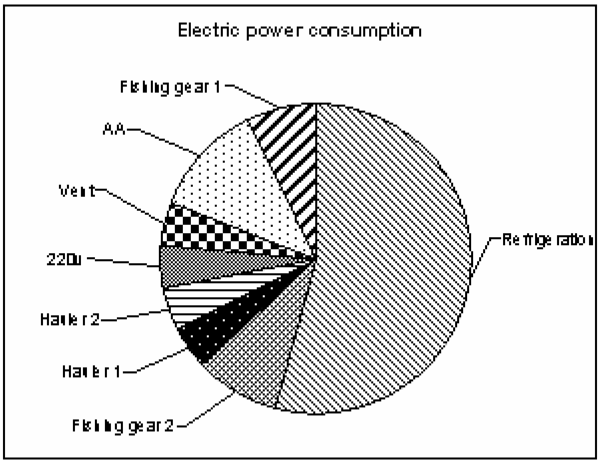

Figure 8. Electric power consumption

Air conditioning units are another important consumer together with the hydraulic power packs needed for running the line setter and haulers. The use of electrical direct drive system on the line haulers would probably improve the efficiency. Frequency controlled drives for AC unit compressors and hydraulic pumps would improve the energy efficiency with a reduced investment.

Figure 9. Surface longliner at sea

Defining the most suitable propulsion / power generation system for a fishing vessel, needs a thorough work evaluating its operating profile in order to identify power / energy demand. At the project stage, there is typically very little information about the real ship operating profile and the little information provided usually overestimates the power needs, i.e. much higher speeds and powers than what afterwards will really be used. This results in propellers oversized in terms of blade area ratio, CP propellers with high design pitch, engines and generators permanently operating at partial load , hydraulic power packs circulating pressure oil back to the oil tank (and therefore wasting the energy in terms of flow x pressure). The results obtained from the energy audit process carried out so far, have shown this as a common problem on most of the ships.

IV. DESCRIPTION OF POSSIBLE ALTERNATIVES OF ELECTRICAL / HYBRID SYSTEMS

After analyzing the energy demand profile of this type of ships, it can be noticed that in terms of energy efficiency, would be desirable to take advantage of the benefits of the conventional diesel drive for steady loads and an electric drive for fluctuating loads. Furthermore, a combination of both would be very advantageous in many types of ships, becoming a hybrid propulsion system for fishing vessels.

Some of the possible alternatives have been studied during the project BAIP 2020, where each proposal has been weighted with a figure of merit in terms of energy efficiency. Due to the limitations of the project, other aspects, such as the installation cost, maintenance costs, production of harmful exhaust gases or space needed were not taken into account in calculating, despite comments have been made sideways. However, it can provide an overview of the available alternatives in a simple way and applicable to other types of vessels operating according to their specific profile.

Different types of propellers (CPP, FPP) and their drives, either mechanical or electrical, were taken into account. The results showed out much of the energy was lost in the conversion process for a pure electrical configuration, but it offers the possibility to easily drive propellers in tandem, that have been proved most efficient, and the advantages of having an engine within optimum working condition.

In the case of hybrid configurations, the use of variable speed shaft generators have been found to be a good option to limit the use of batteries and improve the behaviour of the system in all navigating conditions.

A. System architecture

The chosen solution for the system architecture is based on a hybrid system. The main feature of this configuration is a very flexible system able to provide the advantages of the electric or diesel drive when necessary, combined with a large electrical energy storage system able to supply electrical power at every condition, even when the diesel engines have been turned off.

The architecture of the system is shown in Figure 10 and it consists mainly of a fixed or controllable pitch propulsion system 5, driven by a medium or high speed diesel engine 3 through a reduction gear 4. A low power electric motor - generator is coupled to the propulsion train either as a direct drive low speed machine 1, installed on the tail shaft or as a high speed machine installed between diesel engine and reduction gear 2; resulting on a much smaller and lighter machine than a conventional one, as will be shown later on. There exist a main power conversion unit 6, transforming the voltage and frequency of the electrical current between generators / motors and the main DC switchboard.

One diesel generator set 14 provides electrical power for long periods at harbour or as emergency propulsion.

The power control system allows the diesel generators to run at variable speed improving the efficiency at low load operation.

A central control unit 15, supervise and manage the whole system, based on the data received either from the main components and also from other systems and sensors onboard the ship like the ship's speed 18, rudder angle 19, pitch – rpm lever command 20,etc…adjusting the power flow to the most energy efficient configuration on each operating condition and particular situation.

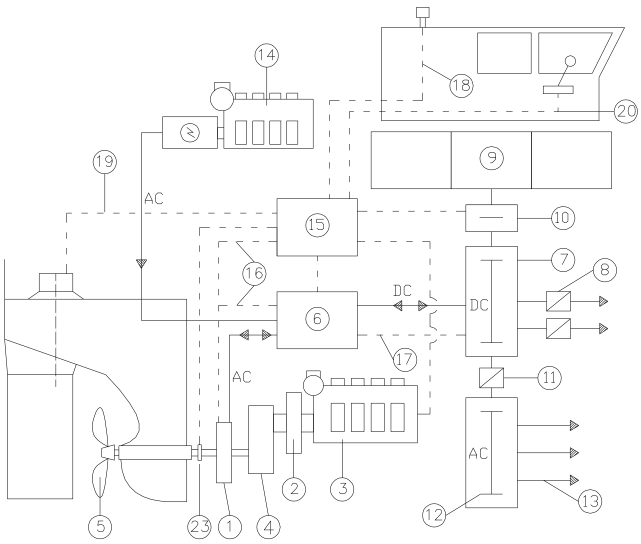

Figure 10. Diagram of the system configuration

B. Electrical power system

Although the concept of electric propulsion is not new, the possibility to control electric motors/generators with variable speed in a large power range with compact, reliable and cost-competitive solutions has emerged in new application areas during the last two decades. This new electric ship approach is enabled by the rapid advancements in solid state semiconductor technology that have been applied to power semiconductor devices. These new power semiconductor devices have enabled the development of new power electronic converter topologies.

In order to integrate electric propulsion and energy generation in combination with other ship electric systems, the complete ship design has to be taken into consideration. For example, the location of components, their weight, dimensions, impact on cooling and on other auxiliaries, influence on personnel safety, speed and maneuvering restrictions play an important role.

To connect all type of power sources and consumers the zonal distribution should be AC and DC. Connection from DC grid to AC grid or vice-versa is typically accomplished by means of a Voltage Source Converter VSC. The use of a VSC allows bidirectional power flow and the implementation of a more sophisticated protection and control system. This means that in the all electric ship application, the power electronic converter combines the energy transfer control and component protection function, (e.g. separate generator unit automation and protection equipment in separated switchboards are not necessary). The minimum external protection acts for faults in the power electronic module, because in normal operation mode the power electronic unit limits the over-current to a desired and adjustable level. This approach reduces the size and weight of the total electrical distribution system compared with usual solutions. Connection from DC grid to DC grid can also be accomplished by means of a DC-DC converter, (buck/boost). It is possible to use bidirectional DC-DC converters allowing bidirectional power flow.

When it comes to the electrical power conversion on the proposed system architecture, the chosen solution features a single main DC switchboard (DCS) 7 connected to the previously described power conversion unit 6. The main DCS is also linked to the electrical energy storage unit 9 by means of a VSC 10. The DCS powers the main electrical consumers of the ship 8, like refrigerating compressors, air conditioning units and main hydraulic power packs by means of inverters, this way each electrical machine can be driven at its optimal speed. Minor AC consumers 13 are fed from a secondary AC switchboard 12, powered from the DCS via a single inverter 11, providing constant voltage and frequency.

C. Electric propulsion and generation

Below, the preliminary design of the rotating electrical machinery using the permanent magnet machine technology is presented. Two machines will be designed, one tailored for each location (1, on the propeller shaft and 2 between diesel engine and reduction gear) as mentioned before. Both of them are preliminary designs because of the space limitations and the multidisciplinary nature of this technical article, a much more comprehensive study will be needed for a detailed design.

1) Motor/generator concepts

A custom design of electrical machines proposed, given the particular characteristics of the application and the benefits that can be obtained from a tailor designed machine. The machines will be of the multi pole synchronous permanent magnet type, and can be used either as motor or generator depending on the propulsion and power generation needs on the vessel. As has been already mentioned, this double operation is possible by using bidirectional variable speed drives, regenerating the energy produced when the machine work as generator.

Permanent magnet machines allow operating throughout its speed range, either as motor or generator with a great efficiency. When it works as a motor it gives the 100% of rated torque throughout its speed range and operating as generator, it is only needed to adjust the voltage generated to the nominal voltage of the grid we are feeding, which is done through the use of power electronics and a proper control of the machine.

2) Motor concept design and optimization

The first step when designing an electrical rotating machine is the definition of some fixed design parameters, depending on the application, machine location and constraints. For this project, where the machine will be used as generator and auxiliary propulsion machine for a surface longliner, the initial design data concerning the required power, rated speed, space available, structural constraints, and weight, are presented on Table I:

TABLE I. INITIAL DESIGN DATA

Location	After reduction gear (A)	Before reduction gear (B)
Rated power (kW)	250	
Rated speed (rpm)	150	1000
Maximum external stator diameter (mm)	1000	
Minimum interior rotor diameter (mm)	150	
Maximum length (mm)	1000	200
Maximum weight (kg)	1500	
Geometrical constraints to guarantee the structural rigidity of the machine		

These particulars have been defined based on real constraints derived from steel and engine room drawings of an existing ship.

The design takes place in two stages, as explained below:

a) 1st stage: Preliminary electromagnetic design

For the development of this first stage, analytical design software developed by VICUSdt has been used. This code allows carrying out many variations in the electromagnetic design parameters of the machine with each combination. Thanks to the results obtained, the different alternatives can be analyzed and compared, choosing the best one in order to optimize the goal parameters.

The design parameters and theirs ranges during the iterative process are:

- Number of pole pairs, between 20 and 40
- Width of the magnet, between 60 and 90% of the pole pitch
- Current density, between 3 and 10 A/mm2
- Line current density, between 20 and 50 kA / m
- Thickness of the air gap, between 1 and 8 mm
- Slot opening.

The goal parameters which have been analyzed to obtain the analytical optimized machine are the following:

- Efficiency: performance and power factor
- Mechanical rigidity and electromagnetic operation.
- Weight

From the analysis of the results of all combinations optimal machine designed is obtained for each location (high and low torque, after and before reduction gear).

b) 2nd stage: Simulation

From the geometric and electrical parameters calculated previously, the models of the machines are implemented in commercial software. Several finite element simulations were carried out in order to verifying the results obtained in the 1st stage. In this step, parameters not covered in the 1st stage can be optimised, analyzing the electromagnetic operation of the machine.

3) Performance analysis, motor / generator.

From the two previous design phases, the following results at rated speed of the machines are obtained operating as a motor (Table II) and as generator with power factor load 1; because of using bidirectional variable speed drives (Table III):

TABLE II. CHARACTERISTICS AS MOTOR

Location	Stage	Weight (kg)	Efficiency (%)	Power factor
A	Algorithm	1035	96.21	0.958
	Simulation		98	0.953
	Error (%)		1.82	0.52
B	Algorithm	177	97.39	0.943
	Simulation		98.9	0.952
	Error (%)		1.52	0.94

TABLE III. CHARACTERISTICS AS GENERATOR

Location	Stage	Weight (kg)	Efficiency (%)
A	Algorithm	1035	96,8
	Simulation		97
	Error (%)		0.2
B	Algorithm	177	97.5
	Simulation		98
	Error (%)		0.5

Both machines are adjusted to an external stator diameter of 1 meter, being the length of the machine located after the reduction gear of about 0.7 meters while the machine before the reduction gear has a length of 0.097 meters. The machine frame is not including on these dimensions, but according to previous research work, it will involve a very small increase in size.

For comparison, a typical marine 300 kVA generator, 1500 rpm has a weight of around 1200 kg, being much longer than the proposed machines.

On the other hand, there is a standard efficiency for three-phase cage induction motors with three efficiency classes. The designed machine is more efficient than the high efficiency machine (IE3 "PREMIUM efficiency level") for this power.

This analysis of the design machines shows the potential of this type of configurations for hybrid propulsion and even retrofitting, due to the reduced size and weight and optimal performance of this type of machines.

D. Electric energy storage

Use of advanced battery technology based on innovative chemistries will provide a brilliant future for electrical energy storage systems on ships. Nevertheless, there exist technology today which can immediately be installed on a hybrid ship with very favorable power and capacity ratios.

1) Main characteristics of current battery technologies.

As an example of the potential of the battery technology to help improving the energy efficiency of ships, Table IV below, shows the main characteristics of different battery technologies. Please note that these values are indicative of each technology but can vary strongly depending on the maker and technical characteristics and details of each battery.

TABLE IV. MAIN CHARACTERISTICS OF DIFFERENT BATTERY TECHNOLOGIES

Technology	**Energy density**			**Power density**
	Wh/Kg	**MJ/Kg**	**Wh/l**	**W/Kg**
Lead acid	35	0,126	100	100
NiMh	95	0,342	300	300
Li Ion	180	0,648	230	230
Future	300	1,08	250	250

According to the above, in the near future would be feasible to provide 300 kW of electrical power during 10 minutes with a battery pack below 200 Kg. Therefore, installing large battery packs (5000 - 10000 Kg) on existing ships seems very affordable if it is taken into account that a 40 m longliner has a displacement of about 600 t.

2) Battery concepts

Below an outline list of some important battery magnitudes is shown:

- Capacity [Ah]: (Current [A] x Time [h])
- C-rate [A]: Charge or discharge current, numerically identical to the rated capacity of the battery
- Power [W]: (Current [A] x Voltage [V])
- Energy [Wh]: (Power [W] x Time [h])
- Capacity efficiency [%]: Ah(out) / Ah (in) ; ~ 99,5 % for Li-Ion
- Energy efficiency [%]: Wh (out) / Wh (in) ; ~ 95 % for Li-Ion

3) Power demand

According to the operating profile of the ship, the condition with the most demanding electrical propulsion power requirements will be the time spent hauling the longline each day, this takes approximately ten hours, carrying out an average of 200 manoeuvres. It might be estimated an average power need of 150 kW during each of these manoeuvres, the power needed for the acceleration should not be higher than that.

On the other hand, there exists a period of approximately one hour each day when the ship wait before starting to haul the line, for this period, would be desirable to turn off the main and auxiliary engines running the electrical power plant and auxiliary propulsion for sailing at low speed, by means of the electrical energy storage system.

4) Required capacity

Considering the use of conventional Li-Ion technology and according to the power demand stated above, it has been identified two ways of working. The first one defines a battery with high capacity, which is charged during the line launching and free sailing condition, since this is the best operational point of the diesel engine, the other option includes a battery with much lower capacity but with high C rates (charging and discharging), this system would be charged during every condition, for instance during constant speed sailing between each hauling maneuver, a very fast charging and discharging rate is needed.

5) Requirements and constrains

There are several aspects to be taken into account when defining a battery system. One of the most important, apart from capacity, is the charge-discharge ratios. High power cells are capable of large currents but do not store a lot of energy, a battery discharging at 18C delivers a specific energy of 100 Wh/Kg, while a battery discharging at 100C, delivers a specific energy of 70 Wh/Kg. On the other hand, there exists high energy cells maximising the energy rates, but which are not capable of high discharge rates; for instance a battery discharging at 2C, has an energy rate of 180 Wh/Kg.

Temperature is another important issue. Cell impedance increases at low temperature leading to low voltage under load. Special electrolytes make discharge possible even at low temperatures. Not all the rated capacity is available at low temperature. Despite these limitations, temperatures onboard the ship should not fall below 0-5ºC, even inside the double bottom below freezing hold, so no significant problems are expected. Li-Ion batteries are better stored at low temperatures, but on the other hand, these types of batteries are better charged at high temperature. Desired operational range lies between 20ºC and 60 ºC, which in principle seems suitable for inboard spaces next to the engine room (for instance substituting the space occupied by the engine room lateral fuel tanks).

The type of load applied also affects the response of the battery, heavier load (greater current or power) result in lower voltage, lower than nominal capacity and higher heat output.

Seems that a large battery unit is needed in order to have enough capacity margins and for operating at low charging rates in order to keep battery performance. Maybe a solution based on two different technologies, each tailored for a specific purpose might be advantageous.

A lot of research work is still needed in order to define the most suitable locations, since there are different positions for batteries, requirements in terms of cabling, ventilation and maintenance. An important issue is the weight, but since most of the fishing vessels are fitted with fixed ballast, it should not be a problem adjusting it for the installation of the considerable weight of the batteries.

A correct definition of a battery system for this ship, will need a much detailed study, including a thoroughly assessment of the loads, currents, charging procedures and system constraints, exceeding by far the extent of this article.

E. Control strategy

The most important aspect of a hybrid system is probably the control system, since is responsible of the right operation of the different systems in combination and it should be adjusted the response of the system in order to obtain the best efficiency and response.

A possible control unit (as item 15 shown on the diagram in Figure 10) would receive control signals from the wheelhouse like power lever and steering wheel / tiller, indicating what the user want to do and also gps and other navigation and sensor signals.

Physical signals from the machinery like torque, rpm, turbocharger pressure and scavenge air temperature, are also critical for assessing the operating point of the combustion engines.

Electrical power signals from the machinery like generator power, main consumers, are fundamental for the right tuning and load sharing of the power plant.

Figure 11. Surface longliner “Glacial”

The optimal control system would include intelligent control algorithms able to adapt to a changing situation and able to learn the operator reactions environment and profile.

Since the ship typical operation profile distinguish a few different operations (like route, line setting, line search, hauling, waiting, maneuvering,…), seems feasible the development of a simplified control system where the skipper indicates to the central system the control strategy to be followed by means of a selector or touch screen display. This solution would be suitable in the first stages of the development of the system since require less development effort and allows the implementation and testing of a hybrid system with shorter development times, allowing at the same time longer periods for developing and adjusting the definitive control algorithms.

V. COMPARISON BETWEEN THE CONVENTIONAL PROPULSION AND THE HYBRID SYSTEM CHOSEN

The most important aspect for selecting a hybrid propulsion solution for a given ship would be of course the energy efficiency comparison (and therefore exploitation costs). Previous studies carried out by VICUSdt have shown that an improvement of at least 15% can be achieved if this solution is compared against a conventional drive.

Another important issue for this type of fishing vessels is the maneuvering response, since longer maneuvering time means longer periods for hauling the line (which can last from 8 to 10 hours).

Several other aspects are improved as outlined below:

- Better maintenance. More time available for maintenance carried out by the crew at sea due to the use of electrical propulsion for some periods.
- Reduced maintenance costs. Less wear of the machinery due to steadier load on the different devices.
- Reduced downtime. Because of a better monitoring, better maintenance and reduced wear.

Concerning initial investment, a key aspect is whether it is addressing a completely new installation or a retrofitting, since despite the machinery cost might be similar, the installation cost will be very different. Due to the current situation of the fleet, a reasonably young fleet facing low prices for the catch and low profit, the retrofitting scenario is the more likely one.

This type of solution will dramatically improve the safety of the ship since it provides a take home device for emergency propulsion.

VI. CONCLUSIONS AND FUTURE WORK

There is still a huge research and development work to be done on innovative electrical / hybrid propulsion systems for fishing vessels, but it should not be forgotten that there are already a base knowledge from other sectors that have been studying this solutions for many years, increasing dramatically the R&D effort in the recent years (like on the military and automotive industry), and naval industry should take advantage of this knowledge and technology.

The oil prices expected for the following years just remind the fishing industry which path that must be followed for a sustainable and profitable fishing.

The solutions proposed in this article must be combined with suitable cost-effective improvements in the field of hydrodynamics (like for instance wake adapted propellers and rudders, better hulls, appendages, …) and renewable energies and fuels, in order to achieve major gains in efficiency and transform longline fishing in a very profitable and sustainable activity even in a scenario with oil prices over 200 $ per barrel.

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REFERENCES

[1] F. Libert, “Design, Optimization and Comparison of Permanent Magnet Motors for a Low-Speed Direct -Driven Mixer” Doctoral thesis, Royal Institute of Technology Department of Electrical Engineering Electrical Machines and Power Electronics, Stockolm 2004

[2] T. Heikkilä, “Permanent Magnet Synchronous Motor for Industrial Inverter Applications-Analysis and Design” Acta Universitatis Lazppeenrantaenis 134, Stockholm, March 2010.

[3] A. Grauers, “Design of direct-driven permanent-magnet generators for wind turbines” Doctoral thesis, Chalmers Univesity of Technology, Götebirg, Sweeden, 1996.

[4] J.F.Gieras, M.Wing, Permanent Magnet Motor Technology. Marcel Dekker, 2002.