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# Shymgen system: Optimizing the performance of shaft generator and drive train on fishing vessels

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*Abstract*— **This article outlines the impact of a variable speed generation system on a fishing vessel´s energy performance figures, analyzing electrical and hydrodynamic issues an presenting a practical case.**

**A very interesting energy saving approach for vessels with different operating profiles is the use of a variable speed generation system, so the synchronous generator can be run at variable speeds over a wide range of engine rpm.**

**This approach offers benefits by improving the energy efficiency of the propulsion train. On the one hand, it improves the performance when running at partial load; on the other hand, hydrodynamic performance of the propeller is also improved, increasing the open water efficiency by running on a higher pitch and advance ratio, and at the same time reducing cavitation, vibrations and noise.**

**The main technical consideration on this type of installation has to do with the new operational envelope of the diesel engine together with the hydrodynamic performance and possible redesign of the propeller blades.**

**When it comes to the electrical installation of the ship, a key task is to evaluate the electrical loads and space required, especially for retrofitting projects, which are becoming very common for existing vessels due to the increase in fuel prices.**

***Keywords: energy saving, fisheries performance, fuel saving, generation power plant,***

## I. INTRODUCTION

Energy efficiency is probably one of the most important technological topics of this decade in fishing, shipping and shipbuilding industries. Fishing industry is suffering the high cost of energy, companies are making efforts on reducing the fuel bill by making investments on new and existing ships; but it must be taken into account that the implementation of any technological solution needs a previous analysis of the system performance for a successful application and guaranteed savings.

Energy audits are one of the most effective ways to identify and analyze how energy is transformed and used onboard a ship, in order to be able to judge the existing potential for improvements leading to a reduction on the energy consumption on board. The energy audit must be the very first step on an energy efficiency management plan. A well planned energy audit guarantees that the best return on investment can be obtained for every euro invested in the ship.

An energy audit provides the ship owner with very useful information, allowing him to make the right decisions. The key advantages of an energy audit are:

-Immediate fuel savings are derived from the knowledge of the consumption profile, detecting inefficient work conditions and avoiding malpractice.

-Detailed identification of potential engine problems or malfunction (excessive consumption, poor combustion, etc.)

-Hydrodynamic characterization of the entire ship (main energy consumer)

-Study of the potential improvements with their technical and economic impact including guidelines for implementation.

-The energy audit supports and opens the door to future requests from the administration regarding emission reductions such as the EEOI (Energy Efficiency Operational Index) or for sailing on controlled areas for reduced emissions (ECA's).

-The implementation of the proposed improvements typically has a low payback time and enhanced profitability from day one.

## II. PERFORMANCE ON PROPULSION AND GENERATION SYSTEM

Propulsion configuration and operational profile are one of the main parameters affecting the energy efficiency of a fishing vessel.

### *A. Diesel engine.*

Diesel engines are normally optimized to achieve its optimal efficiency at 85% of the maximum continuous power or MCR.

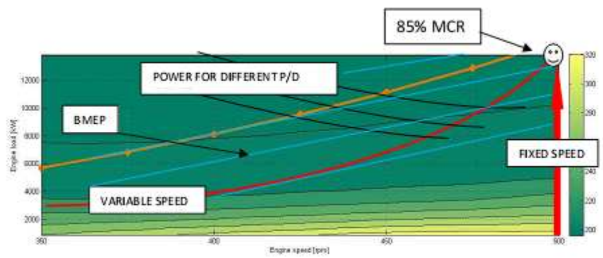


Figure 1. Diesel engine envelope [Source: VICUSdt]

Diesel engines operating at constant speed are normally used for diesel generators or on controllable pitch propeller installations. Their efficiency at variable load and constant speed diminishes significantly when the load is reduced,

Diesel engines operate more efficiently at variable speed.

### *B. Propeller*

The control of thrust on fixed pitch propellers (FPP) is done by changing its rotational speed, absorbing more torque and therefore power.

Thrust control on controllable pitch propellers (CPP) is done by changing the blade pitch angle and the shaft speed. CPP are widely used because the flexibility of operation, although the higher complexity and lower efficiency.

Combining variable speed and CPP installations, in the so called "combinator mode", the vessel takes advantage of an improved and more flexible propulsive train.

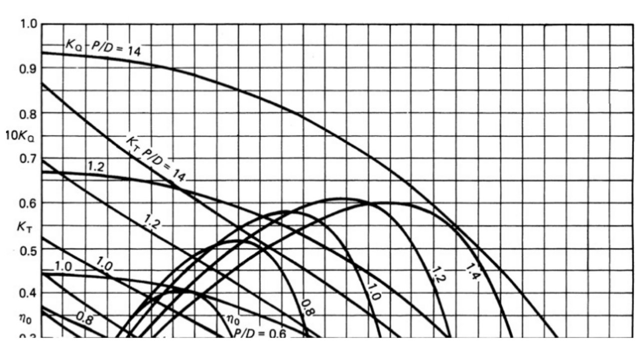


Figure 2. Example of propeller open water curves

As it can be seen from the open water propeller curves, for a given point, varying rpms changes J (advance ratio, a coefficient that takes into account the water inflow), and so better efficiency points can be achieved for every pitch.

### *C. Configuration of propulsion and power plant*

Power generation onboard is normally carried out by diesel engines driving constant speed synchronous generators as shaft generators or auxiliary diesel generators. The power generation depends on the configuration of the propulsion.

Here two of most the common configurations on fishing vessels are presented and studied.

#### *1) FP drive train with auxiliary diesel engine generator/s*

In this configuration, propeller is driven by main engine at variable rotating speed, depending on ship speed.

Because of variable speed on drive train, electrical generator machine cannot be directly fitted on a power take off (PTO), linked to the propulsion. An option which is implemented in some vessels is a hydraulic transmission set, where a hydraulic pump is fitted on a PTO, this pump is connected to the hydraulic circuit feeding a hydraulic motor, driving a synchronous generator at constant speed. Unfortunately, the efficiency of this solution is very low, leading to a higher fuel consumption, therefore the gain obtained driving a generator from the main engine is lost on the transmission.

#### *2) CPP drive train with shaft generator/s*

In this configuration, normally one main engine drives CPP and one or two shaft generators main engine normally runs at constant speed driving a shaft generator.

In this configuration, one of the most common problems has to do with the optimization of the electrical generation and propulsion systems. Both systems are frequently linked by means of a shaft generator. When it comes to the shaft generator, keeping constant frequency forces to maintain a fixed shaft speed on the propulsion drive train, resulting on non-optimal performance of the propulsion engine and propeller as has been previously described.

Furthermore, the performance of the CP propeller is also affected since the partial load operation at constant speed means a significant reduction in pitch, thus leading to less efficiency and more cavitation.

Working in different speed points can provide not only better propeller efficiency but also increased engine efficiency as described above.

There are vessels which are fitted with "combinator mode" implemented on their control. In this case, shaft generator cannot be driven in the whole operation time, which is limiting the power generation options [1].

## III. SHYMGEN SYSTEM

A system which is able to adapt a variable voltage-frequency electrical power source to a constant reference level on the ship's network would allow a more efficient performance of the power plant on board, by running the shaft generator at variable rotational speed.

The above need lead to the development of the SHYMGEN system. This system was jointly developed by VICUSdt, INGETEAM Technology and EMENASA, in cooperation with the fishing vessel owner association of Vigo (ARVI). The technology behind this system is briefly described below.

### *A. Working principles*

In order to adjust the voltage level and frequency value, the SHYMGEN system is installed between a generator running at variable speed and ship's main switchboard.

When SHYMGEN system is operating, the 3-phase AC current at variable voltage and frequency from a shaft generator is received by a rectifier, where it is converted to DC current. Then, an inverter converts this power to 3-phase AC current at constant voltage and frequency.

SHYMGEN system can be synchronized with the operating network (working in parallel with the other power supplies) or it can create its own network.

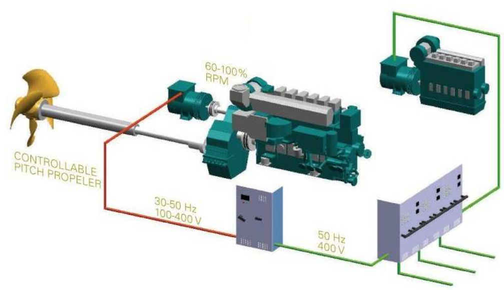


Figure 3. System scheme

### *B. Technology*

The system basically consists of a Power Voltage-Frequency Converter (PVFC) together with other auxiliary systems.

The PVFC is based on the Insulated Gate Bipolar Technology (IGBT) semiconductor technology, where rectifier and inverter are from the Active Front End (AFE) topology. These power stacks are bidirectional on power.

Power conversions are accomplished by the Power Width Modulate (PWM) technique on a 6-pulse mode.

Dumper resistances are installed on the DC bus.

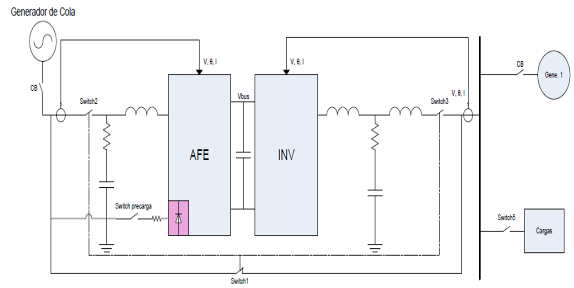


Figure 4. System diagram

Input and output filters are set to guarantee low THD levels on the power plant. These filters are designed through the simulations of the power plant taking standard levels of active and reactive power. The input filter is LC and output filter is LCL.

Most of classification societies advice the THD level to be under 8% [2], which is accomplished with this configuration.

The installation has to be fitted with a 3-pole shielded cable.

Moreover, the system disposes of a manual bypass consisting on 3 switchers to operate at constant speed without conversion losses.

### *C. Aspects at the power plant*

In order to implement a voltage - frequency converter system like this on board, we can face two situations: the first one is a new ship, which is an easier case because everything can be tailored to fit the system; another option is retrofitting an existing ship. Additionally to a general energy audit, some specific trials have to be conducted in order to analyze and design this system.

The implementation requires some critical aspects to be considered at the power plant:

- Grounding scheme of network
- Generator bearings
- Current peaks on consumers starters
- Generator cooling
- Voltage drop

Utilization of PVFC's based on the Power Width Modulation (PWM) can generate Common Mode Voltage (CMV). CMV generates high frequency eddy currents that are confined on the ground of the vessel. Therefore every device of power plant has to comply the requirements to achieve an ensure network. An optimal grounding scheme is needed in order to guarantee a proper performance of the vessel network.

Isolated bearings are proposed to improve the protection against the CMV of generator machine.

Another issue also should be taken into account: the main consumers starting type. Transitory phenomena is produced on a power plant when an electric motor (pumps, compressors,…) is started. There are different types of starting modes; most common on vessel installations are given below:

- Direct on-line
- Star-Delta
- Soft Starters
- Frequency converters

Demanded current by the electric motor during the start depends on the type of starting system, and it could be very high during the first milliseconds. This phenomenon is known as "peak current", and it can induce an unwanted voltage drop at power plant.

The level of peak current on electric motors is measured with respect to the Rated Current (RC). Typical values of peak current starting modes are as follows:

- Direct on-line 8-10 RC
- Star-Delta 4-6 RC
- Soft Starters 1,5 RC
- Frequency converters 1 RC

Since semiconductor devices are designed based on the current level, an accurate calculation of the current balance taking into account the different starters present on the power plant should be carried out. An implementation of novel starting modes (soft starter, frequency converter…) minimizes the size of the voltage - frequency converter system and it is an optimal solution for new buildings.

Most of the generators on vessels are auto cooled synchronous generators with a fan installed on shaft. This type of cooling is known as IC01, according to the IEC standards [3]. This fan turns at same speed as the rotor of the machine, so a reduction of cooling is produced when rotor speed is decreased in SHYMGEN operation. Due to this, temperature control of generator is necessary, and additional cooling system must be implemented in some cases.

Finally, the voltage drop of the generator due to the speed change must be considered; this voltage drop can be very significant and implies an increase on current drawn to keep the same power on the network. A detailed analysis of the generator and adjustment of the AVR (automatic voltage regulator) is mandatory in order to the successfully cope with these changes.

## IV. CASE STUDY: PUNTA VIXÍA

Practical example of an existing fishing vessel conversion project from a constant speed shaft generator to the variable speed generator by means of the voltage frequency converter unit like SHYMGEN is presented here. This example expounds, with some calculations, the performance improvement results that can be achieved for a given operational profile of this ship.

Then, the implementation on board was carried out. Particularities are presented here.

### *A. Approach, ship particulars and operational profile*

The fishing vessel is a stern trawler with the following main particulars:

- Length: 36 m
- Beam: 8,2 m
- Draft: 3,5 m
- Installed power: 930 bkW
- Shaft generator: 144 kWe (180 kVA)
- Freq. network: 50 Hz
- Voltage level: 380 V

The real operational profile of the ship showed a diverse range of speeds, with only a limited amount of time operating at free run speed, as can be seen in the table below.

The total number of working hours per year is taken as 7.180 hrs, while load is variable depending on the operation.

TABLE I. OPERATIONAL SPEED PROFILE

| Condition | At Sea | Setting | Trawling | Hauling |
|---|---|---|---|---|
| **Av. Sp.[kn]** | 11 | 5 | 3,3 | 1,9 |
| **Time (%)** | 18 | 2 | 78,8 | 1,2 |
| **Time (hr)** | 1.305 | 143 | 5.649 | 83 |

Since the optimal propeller speed is lower during trawling condition and power demand at lower speeds is smaller, the shaft speed could be reduced for better performance in a substantial percentage of time.

This ship is fitted with a single shaft line composed of one main diesel engine driving a controllable pitch propeller; this propeller is rotating at constant speed due to the need of keeping the shaft generator frequency.

The main propeller characteristics are as follows:

- Diameter: 2,5 m
- Number of blades: 4

- Blade area ratio: 0,498
- Design pitch ratio: 1,09
- Rotational speed: 181,6 RPM

### *B. Performance calculations*

Once the operational profile of the ship is know, two different sets of calculations are carried out: a set of calculations is done for the real operational profile, with the current propulsion and generation arrangement, i.e. constant shaft speed; the second set of calculations is done for an optimized scenario where the speed of the shaft is varied according to the optimal speed for each condition. This normally implies to reduce the speed of the shaft for the trawling.

As it can be seen, in the case of trawlers there are two optimal propeller speeds, one for trawling and one for free sailing.

For the speed of 11 knots, the shaft speed is not altered, but for the lower speeds, the shaft rotation is decreased by 10,2%, which leads to an improvement of the hydrodynamics of the propeller. The specific fuel consumption of the main engine is also slightly improved at partial load and reduced speed (between 1-3 %).

Calculated shaft speeds, power and energy savings are summarized in the table below:

TABLE II. THEORETICAL CALCULATION RESULTS

| **Cond.** | **At Sea** | **Trawling** | **Setting** | **Hauling** | |
|---|---|---|---|---|---|
| **Av. Speed** | 11,0 | 3,3 | 5,0 | 1,9 | kn |
| **%** | 0,2 | 0,8 | 0,0 | 0,0 | |
| **h** | 1.305,6 | 5.657,8 | 143,6 | 86,2 | |
| | | | | | |
| **N1** | 181,6 | 181,6 | 181,6 | 181,6 | rpm |
| **Av. Power** | 500,0 | 450,0 | 325,0 | 180,0 | kW |
| **Energy** | 652,8 | 2.546,0 | 46,7 | 15,5 | MWh |
| | | | | | |
| **N2** | 181,6 | 163,0 | 163,0 | 163,0 | rpm |
| **Av. Power** | 500,0 | 395,0 | 301,0 | 150,0 | kW |
| **Energy** | 652,8 | 2.234,8 | 43,2 | 12,9 | MWh |
| | | | | | |
| **Shaft Speed** | 0,0% | -10,2% | -10,2% | -10,2% | |
| **Power Reduction** | 0,0% | -12,2% | -7,4% | -16,7% | |
| **EN Saved (Prop.)** | 0,0 | 311,2 | 3,4 | 2,6 | MWh |
| **BSFC** | 0,0% | 3,0% | 3,0% | 3,0% | |
| **EN Saved (Total)** | 0,0 | 320,5 | 3,5 | 2,7 | MWh |
| **k$ Saved** | 0,0 | 60.558,8 | 670,7 | 503,0 | € |
| | | | | | |
| **Total Saved** | 61.732,5 | € | | | |

The total number of sailing hours per year is taken as 7.180 hrs, while 18 % are at project speed, and the rest are at partial load due to the operation of fishing.

N1 represents the main engine speed at the original scenario; the power demand has been calculated combining CFD calculations [4] for the hull and propeller with the NavCad [5] software from HydroComp. The off design computations of the CP propeller performance were done by CFD computations.

It can be seen that the more off design the condition is, the higher the savings from the variable speed generation system (like for instance at trawling or manoeuvring, which is at low speed vessel); this is due to the poor performance of a propeller turning at high speed with low load, because the pitch is too small and the pitch distribution is very inefficient (tip unloading).

### *C. Implementation*

A prototype of SHYMGEN system was implemented on the real vessel to evaluate the performance and validate theoretical calculations.

First step is dimensioning the converter unit in function of the electrical power needs of the vessel. The ship's shaft generator has the following features:

- Model: Leroy Somer L46.2
- Rated power: 180 KVA
- Rated speed: 1.500 rpm
- Frequency: 50Hz
- Voltage level: 380 V

Electrical power consumption was measured on real operation, the results obtained per condition were:

TABLE III. ELECTRIC POWER DEMAND

| **Condition** | **Time (%)** | **Av. Power (kWe)** |
|---|---|---|
| **Trawling** | 78,8 | 94,1 |
| **Hauling** | 1,2 | 79,2 |
| **Setting** | 2 | 87,7 |
| **At Sea** | 18 | 92,4 |

This means that the average electric power used in the power plant is around 93 kWe. This power supply has to be guaranteed on the whole operation time.

To get this power, an extra cooling system was implemented in the shaft generator, because of temperature increase when turning speed decrease.

Bearings of shaft generator were changed for isolated bearings.

Soft starters were fitted on two hydraulic pumps of hydraulic system (2x18,5 kW)

180 kVA unit power converter was fitted on board. The unit was connected between shaft generator and network by shielded tripolar cable.

During the implementation on board, some test were done adjusting the system control. A control of current was programmed, controlling current value and time of peak ($I^2t$).

Sea trials were done to check the performance and to measure the savings of the use of SHYMGEN system implemented on Punta Vixia.

Two real fishing trawls were done where speed of propeller was decreased in some steps. Drive train power and fuel consumption were measured.

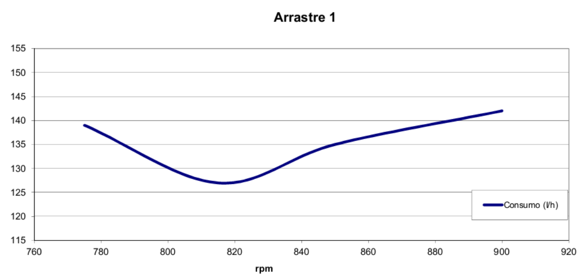


Figure 5. Fuel consumption vs. RPM. (Case 1)

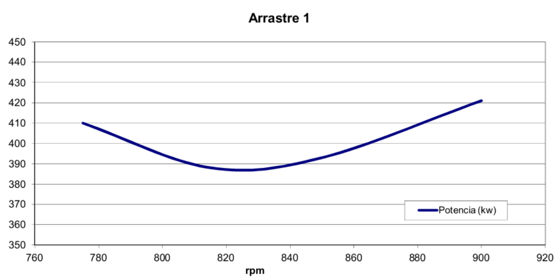


Figure 6. PStotal vs. RPM. (Case 1)

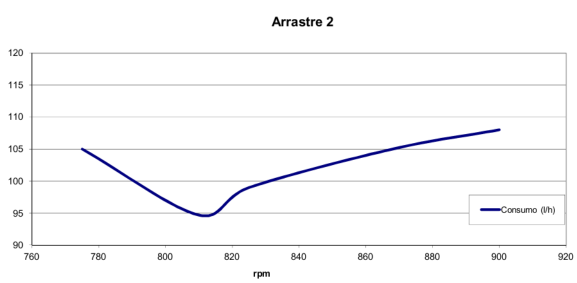


Figure 7. Fuel consumption vs. RPM. (Case 2)

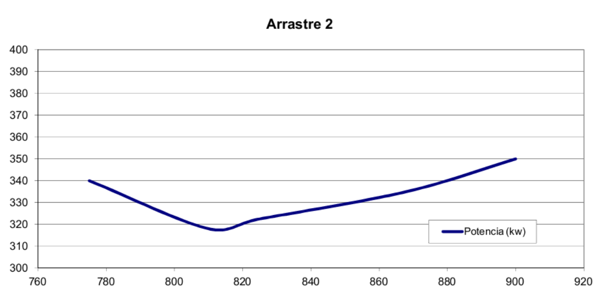


Figure 8. PStotal vs. RPM. (Case 2)

Taking into account these values, low speed operation was programmed at 810 rpm in the engine, this results on 163,5 rpm on the propeller, a 10% of speed reduction.

## V. RESULTS

The SHYMGEN system was successfully installed on board the Punta Vixía, the system has been fully operational for one year. The system was used with 9,4% of speed reduction because of operational considerations.

The savings achieved were around 9,1% resulting on 53.150 € per year.

The calculations were carried out considering a fuel oil price of 730 €/t and a base specific fuel consumption of 220 gr/kWh.

Since the price of this type of retrofitting operation has been around 65.000€, it can be estimated a payback period 1,2 years.

## VI. CONCLUSSIONS

The use of a variable speed power generation system on the shaft generator of a fishing vessel can lead to very significant savings on the normal ship operational profile. This type of solutions can be applied to the new ships and also to the retrofitting existing vessels. Investments required are affordable due to the interesting payback period achieved.

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