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ENERGY EFFICIENCY AUDITS ON SHIPS: IMPACT OF A VARIABLE SPEED SHAFT GENERATION SYSTEM ON SHIP FUEL CONSUMPTION AND PROPELLER HYDRODYNAMICS

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ABSTRACT

This article outlines the impact of a variable speed generation system on a ship's energy performance figures, analyzing electrical and hydrodynamic issues.

Energy efficiency audit is the first step for evaluating the energy efficiency of a ship; it is fundamental for identifying the key areas where more fuel can be saved with the best return on investment. The audit must include a thoughtful analysis of the ship's operational profile and machinery together with an evaluation of the different choices for fuel saving.

One of the most interesting solutions for vessels with different operating profiles and fitted with controllable pitch propeller with shaft generator, 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, hydrodynamics of the propeller are also improved, increasing the open water efficiency by running on a higher pitch and advance ratio, and at the same time reducing the problems associated with cavitation 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. Redesigning the propeller blades for the new condition can be advantageous since an additional gain can be achieved.

When it comes to the electrical installation of the ship, the main work 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.

INTRODUCTION

Energy efficiency is probably one of the most important technological topics of this decade in shipping and shipbuilding industries. Almost every shipping company is making efforts on reducing the fuel bill, by making investments on new and existing ships. The implementation of any technological solution needs a previous analysis of the system performance for a successful application and guaranteed savings.

1. ENERGY AUDIT

1.1. Objective of the audit

The goal of energy audits is 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 is 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.

1.2. Methodology

Due to the complexity of this type of analysis, the methodology should be capable of different tools and knowledges from different disciplines like: hydrodynamics, electrical engineering, sensors, measurements, machinery, etc.

The normal procedure can be outlined on the five stages below:

- Compilation of technical information: at this first stage, all the relevant technical information is compiled, while all the work is planned and scheduled together with the technical personnel of the shipping company and crew. In some cases, the available technical information is scarce, and therefore it should be gathered from different sources like shipyards, suppliers, etc.

- Onboard measurements: measuring real operational data on board the ship is one of the most relevant source of information. This step includes recording shaft power, fuel consumption and electrical power measurements among other parameters.

- Hydrodynamic analysis: since propulsion is the most important consumer on a ship, the hydrodynamic performance of the hull and propulsion system must be addressed. This procedure includes CFD computation of the current situation and possible improvements, like, for instance, the use of energy saving devices, new propeller design, etc.

- Machinery analysis: based on numerical models and measurements previously carried out; engines, auxiliary systems and consumers must be thoroughly analyzed.

- Results, reports and recommendations: results and recommendations must be included into a final report. This should comprise an economical assessment of the proposed energy saving measures, including returns on investment. This report should state the base for a ship energy efficiency management plan, including objectives, milestones and process review.

1.3. Results and benefits

An energy audit provides the ship owner with useful information allowing him to make the right decisions:

- Immediate fuel savings derived from the knowledge of the consumption profile together with detecting inefficient work conditions and avoiding malpractice.
- Identification of potential engine problems (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 have a low payback time and enhanced profitability from day one.

2. SHYMGEN SYSTEM

2.1. The power generation link

After an energy audit, one of the most common problem 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 described below.

2.2. Power generation. Constant and variable generator speed

Power generation onboard is normally carried out by diesel engines driving constant speed synchronous generators (as shaft generators) or auxiliary diesel generators. In this example we are going to focus on a shaft generator fitted with a CP propeller.

In a CPP configuration, main engine normally runs at constant speed driving a shaft generator; there is also an option to run the propulsion train at variable speed on the so called “combinator mode”. In this case, hydrodynamics of the propeller are improved, but the shaft generator cannot be driven, which is limiting the power generation options [1].
At constant rpm and partial load the efficiency of the diesel engine is poor due to the shape of the iso-consumption curves at loads below 80%. 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 engine efficiency. In the combinator mode, when load is variable, diesel engines operate more efficiently at variable speed.

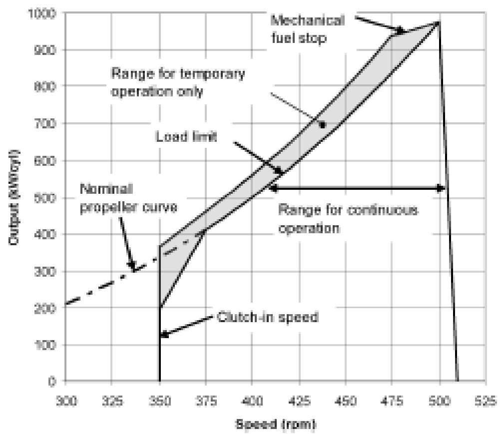

Fig. 1: *Diesel engine envelope* [Source: Wärtsilä]

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 description leads to the development of the SHYMGEN system. This system was jointly developed by VICUSdt, INGETEAM Technology and EMENASA. The technology behind this system is briefly described below.

2.2. Working principles

In order to adjust the voltage level and frequency value, the SHYMGEN system is located between generator and distribution switchboard.
When SHYMGEN system is on, the 3-phase AC current at variable frequency - voltage from 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 frequency - voltage levels.
SHYMGEN system can be synchronized with the operating network (working in parallel with the other power supplies) or it can create its own network.

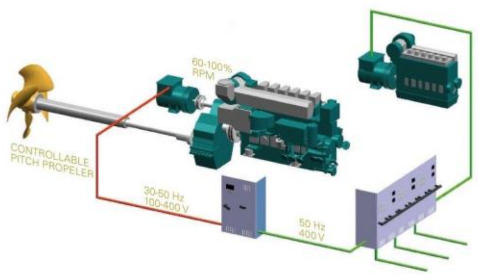

Fig. 2: *System scheme*

2.3. 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.

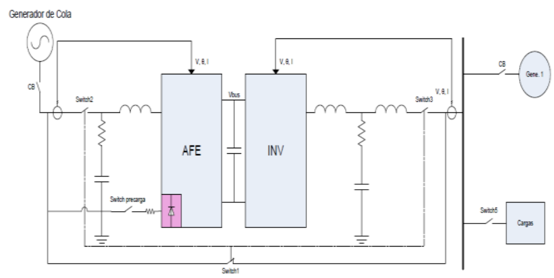

Fig. 3: *System diagram*

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.

2.4. Implementation on board

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 towards this solution; another 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.
This implementation requires some critical aspects to be considered at the power plant:

- Grounding scheme (IT-grid)
- 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), therefore every element of power plant has to comply the requirements to achieve an IT-grid. 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.

3. APPLICATION OF A VARIABLE SPEED GENERATION SYSTEM TO A MERCHANT VESSEL

3.1. Approach, ship particulars and operational profile

Practical example of an existing RoRo 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.
The RoRo vessel has the following main particulars:

- Length: 150 m
- Beam: 20 m
- Draft: 10 m
- Installed power: 15000 BkW
- Shaft generator: 500 kWe

The real operational profile of the ship showed a diverse range of speeds, with only a limited amount of time operating at "nominal" or "projected" speed, which can be seen in the table below.

Condition	A	B	C	D	E
Av. Sp.[kn]	20	18	16	8	4
Time (%)	45%	29%	19%	5%	3%
Time (hr)	2768	1784	1169	308	185

Table 1: *Operational profile*

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

3.2. Propeller

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: 4.8m
- Number of blades: 4
- Blade area ratio: 0.7
- Design pitch: 1.1
- Rotational speed: 150.7 RPM

3.3. 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 load. This normally implies to reduce the speed of the shaft for part of the sailing period.
For the speed of 20 knots, the shaft speed is not altered, but for the lower speeds, the shaft rotation is decreased, 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:

Cond.	A	B	C	D	E	
Av. Sp.	20	18	16	8	4	kn
%	45%	28%	19%	5%	3%	
h	2768	1722	1169	308	185	
N1	500	500	500	500	500	rpm
Av. Pow.	15000	10935	7680	2000	1800	kW
Energy	41513	18830	8974	615	332	MWh
N2	500	450	425	400	400	rpm
Av. Pow.	15000	10450	7000	1000	650	kW
Energy	41513	17995	8180	308	120	MWh
Shaft sp.	0%	-10%	-15%	-20%	-20%	
Saving	0	-4,4%	-8,9%	-50,0%	-63,9%	
EN Saved	0	835	795	308	212	MWh
BSFC	0	1%	2%	2,5%	3%	
EN Saved	0	1015	958	315	216	MWh
K$ saved	0	139,9	132,0	43,4	29,7	$
Tot. Sav.	345	K$				

Table 2. *Calculation results*

The total number of sailing hours per year is taken as 6150 hrs, while 45% are at project speed, and the rest are at partial load due to the schedule restrictions in a fixed route.
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 with the panel code PPB.
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 port approach and low speed); 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).

3.4. Savings and return on investments

As can be seen in the table above, the use of a variable speed drive train can lead to savings around 345.000 $ per year. The calculations were carried out considering a fuel oil price of 680 $ /t and a base specific fuel consumption of 200 gr/kWh.
Since the price of this type of retrofitting operation could be around 260.000 $, it can be estimated a payback period well below one year.

CONCLUSIONS

The use of a variable speed power generation system on the shaft generator of a cargo 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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