THE GENEROSITY WITH THE REACTIVE ENERGY, AVOIDS POWER BLACKOUTS OF THE ELECTRICAL PLANTS ON BOARD

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Keywords

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Stability of the electrical Plants

Abstract

In ships, the generation of energy is carried out by generator sets and short distances with a direct connection between generation and consumption.

Traditionally, a power plant is designed with efficiency criteria and for resistive loads, being able to not adequately supply the current higher than the nominal one that demands, during a few seconds the direct start of an electrical motor. Traditionally Power Factor is 0,8, for a better stability with modern electrical loads, electrical motor and electronic converters, should be 0,4 or less.

The usual on-board synchronous alternators, generate significant voltage drops in the event of 200% overloads, due to their internal reactance. This reactance is much higher than that of a transformer of the same power, which is why the starting current of an electric motor with half the power of the alternator, generates a much larger voltage dip than when it is powered by a transformer in a network of infinite power.

Our terrestrial formation tends to assume the voltage stability, associated with the power supply, with transformers and to ignore the internal voltage drop of the generator, associated with the reactive energy demanded by inductive loads or rotating electrical machines.

The internal voltage drop of the alternator due to an overload can be compensated with the (AVR) system, which acts on the excitation of the alternator, increasing its electromotive force (e.m.f.). It has a reaction time of about 100 ms, which significantly reduces the motor's starting performance, lengthening its acceleration transient.

A more powerful alternator, with a lower internal reactance, is the best solution to reduce voltage dips. It does not significantly penalize friction because it has very high efficiency. Economically, this oversizing is cheaper than doing it on the Diesel.

This paper, based in the PhD works of Mr Antonio Herrero Sabat, entitled "Contributions to the Stability of Marine Power Generation Plants, with Flywheels ", pending defence in (FNB-UPC).

1 POWER TRANSFER TO NAVAL PROPELLER

1.1 Mechanical Transmission

The mechanical transmission shaft from the Diesel to the propeller provides the resistant torque that it demands. The engine torque varies depending on the speed of the Diesel engine and is defined by the manufacturer in its torque-speed brake curve.

This motor torque curve must cross at a point of balance with the one corresponding to the resistant torque demanded by the propeller, which is a parabola. The waves associated with bad weather make the resistant torque curve oscillate, turning it into a wide band of curves often far from the optimum operating points of the Diesel engine.

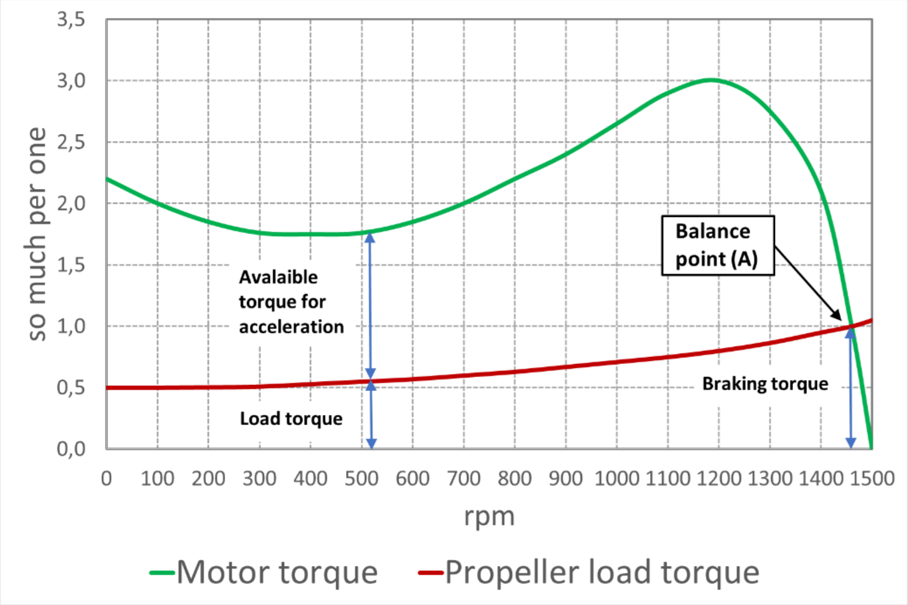


Fig. 1 Induction Motor: Diesel & Propeller load. Torque vs. Speed. Source: Own

The inertia of the Diesel engine and the shaft line assembly become important in torque transients, for example, when encountering a block of ice, which increases the resistant torque and causes the speed to drop as a function of inertia. This maximum torque must condition the size of the shaft to avoid breakage and must be generously higher than that corresponding to the nominal torque. This oversizing of the shaft is more expensive when it affects the gearboxes.

Icebreakers are usually Diesel-Electric, to electronically limit the torque exerted by the propeller on an obstacle, since current and torque are proportional.

This torque multiplied by the speed of rotation of the shaft, give the active mechanical power transmitted between the Diesel and the propeller.

$$P_{MECHANICS} = \Gamma * \omega$$

$P_{MECHANICS}$: Mechanical power transmitted (kW)

Γ: Torque (Nm)

ω: Rotational speed (rad/s)

The Diesel supplies the "cruising power" and its flywheel the torque peaks, to overcome specific obstacles.

1.2 Diesel-Electric Transmission with Direct Current (DC) Machines

The same philosophy of oversizing in torque or intensity must be respected when the transmission is electric. In Diesel-Electric boats, the maximum current to be supplied by the electric generator must be higher than the maximum current demanded by the engine that drives the propeller, to avoid power blackouts.

The electric transmission has more features than the simple mechanical transmission by shaft, as it can include the function of clutch and gear change among others, such as placing various propulsion assemblies in places on the hull that were unthinkable with a conventional shaft line.

It is understood as electric transmission, that the Diesel drives an electric generator that, through cables and electronic controls, feeds the electric motor coupled to the propeller.

In electricity, everything goes a few thousand times faster than in mechanics and requires measuring instruments that allow visualizing how magnitudes such as voltage and current evolve every millisecond.

This response speed over time makes it advisable to abandon the concept of power as the first parameter in the design, to first analyze its components: Voltage (V) and Current (I), which correspond to speed (ω) and torque (Γ), respectively.

If the Diesel drives a permanent magnet direct current generator (DC PM) generator, these two mechanical magnitudes (Speed ω and Torque Γ) correspond linearly to the electrical ones of Voltage and Current respectively.

$$V = K_E * \omega$$

$$I = K_T * \Gamma$$

V: Voltage (Volts)

I: Current (Ampers)

K_E: Constant voltage

K_T: Constant torque

This electrical power could move the propeller coupled to an electric motor, also a direct current permanent magnet motor (DC PM).

If the shaft of a small motor (DC PM) is held by hand, and current is injected progressively, the correlation between current (A) and torque (Γ) is verified, even at zero speed.

This simple experiment should not be missing in academic laboratories.

The same modeling engine can work as a generator (DC PM), if it is rotated by hand or with a household drill at low speed. The voltage generated is proportional to that speed of rotation.

If it rotates as a no-load generator, the resistant torque is small, but if we short-circuit the generator with the ammeter, the resistant torque increases considerably and proportionally to the current flowing, even at very low speeds. The same is true of large and small electrical machines.

1.3 Diesel-Electric Transmission with Alternate Current (AC) Machines

In alternating machines, these same relationships hold. They must be analyzed with complex numbers, which allow the analysis of the usual phase shifts between Voltage (V) and Current (I), where ϕ is the angle. The torque of the machine represents the real part and is affected by the power factor $\Gamma = I * \cos \phi$, multiplied by the voltage at the terminals, would give the active electrical power that is transmitted.

The imaginary part of the current $I * \sin \phi$, multiplied by the voltage, would be the reactive power. It is used to magnetize the squirrel-cage rotor, which does not have a specific magnetic field excitation winding.

This phase shift ϕ between (V) and (I), allows having very simple constructional "induction" electric motors, which are very robust and economical. However, they consume considerable reactive power, even if they work at rated speed, without resistant torque on the shaft (no load).

The mechanical power of the drive must be the electrical active power transmitted, multiplied by the efficiency. This energy enters the transmission system in the form of resistant torque in the shaft of the alternator driven by the Diesel engine of the plant, multiplied by the speed of rotation or synchronism,

$$\mathbf{P_{MECHANICS} = P_{ACTIVE\ ELECTRICAL} * \eta = \omega * \Gamma}$$

$$\mathbf{P_{ACTIVE\ ELECTRIC} = \sqrt{3} * V * I * \cos \phi}$$

$P_{ACTIVE\ ELECTRIC}$: Active electrical power transmitted (kW)

Ƞ: Efficiency

ϕ: Voltage & Current, angle

The maximum electrical current also conditions the electrical system, since it must be able to circulate, even for fractions of a second, without causing significant voltage drops. These brief currents cause a transitory resistant torque in the alternator, which is usually overcome by the inertia of the alternator and the Diesel that drives it (instantaneous power).

The internal impedances limit the maximum current, which in alternators takes the name of short-circuit current (I_{CC}) and in motors, starting current (I_S). They should be able to generally hold for a second, without triggering electrical protections.

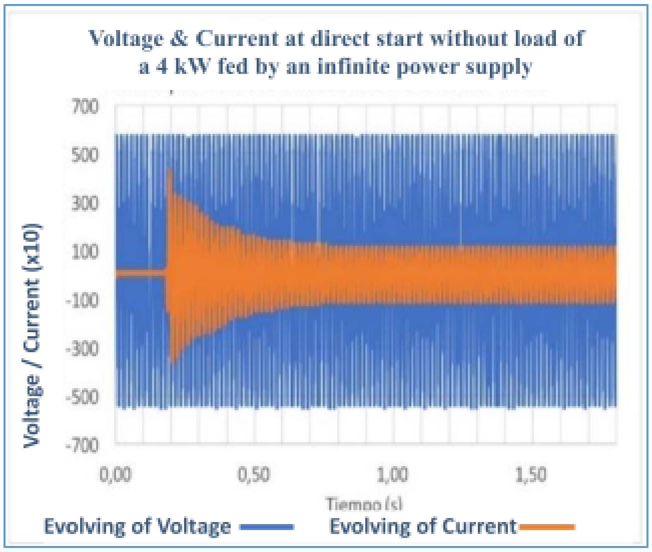


Fig. SEQ Fig. * ARABIC 2 Direct Start without load of a 4-kW induction motor fed by an Infinite Power supply.
Source: Own

Terrestrial systems powered by electromagnetic transformers, with $I_{CC} = 20 * I_N$, are more stable, since the voltage varies little with the starting currents (I_S) of the powered motors.

The reactive power transmitted from the generator to the rest of the loads does not generate significant resistant torque on the alternator shaft.

$$\mathbf{Q_{\text{REACTIVE ELECTRICAL}} = \sqrt{3} * V * I * \sin \phi}$$

$P_{\text{REACTIVE POWER}}$: Reactive electrical power (kVAr)

The reactive is the power that feeds the magnetic fields (inductances) and electric fields (capacitors), of the loads fed at a given alternating voltage. It is controlled by the current flowing through the excitation winding of the alternator, which is usually equipped with an automatic voltage regulator (AVR).

These self-powered (AVR) alternators lose current performance in the short-circuit zone.

Connecting or disconnecting a load requires that the (AVR) gives the orders to act on the excitation current I_{exc}, to maintain the voltage at the alternator terminals, not only to compensate for the Joule losses of its internal resistance (R), but also to provide the internal reactive power (Q) of the alternator and necessary to the system.

It is not easy to feed the (AVR) during transients, when the current requested by the load is close to that of the alternator short-circuit, since its terminal voltage drops to zero and the (AVR) cannot correctly execute its orders, feeding the excitation of the alternator. Another electrical source must be found, to inject the necessary excitation current, according to the control of the (AVR). Often an auxiliary pilot exciter driven on the same shaft as the alternator.

2 THE PROBLEM OF STARTING LARGE INDUCTION MOTORS

The transverse bow thruster is usually a large induction motor. In the first instants of the starting transient, when the speed of rotation of the impeller is still zero, it demands a higher than nominal current to accelerate its rotor and strongly inductive to establish the magnetic field between rotor and stator. [1]

2.1 Currents Absorbed by The Induction Motor

2.1.1 Previous Considerations

When starting any electric motor, it seems to be a short circuit for the source that feeds it, since the stopped rotor does not generate back electromotive force (emf).

The induction motors of the bow transverse propellers, in their direct start, consume a high current, of the order of $I_S=7 * I_N$ with a power factor of 0,4 or even lower.

Although the bow motor starts at reduced voltage (method star-triangle), it is not exempt from this problem, since in some cases, at the moment of commutation star-triangle, high direct starting currents may appear, which generate the problem studied.

2.1.2 Torque-Speed and Power-Speed Factor Curves of an Induction Motor

These curves are defined at the rated voltage of the induction motor.

If we reduce the voltage, for example, in the event of a 30% voltage dip, the motor loses performance and the torque-speed curve shifts down the ordinate axis. [2]

The engine has lost performance in torque, due to an effect that it has probably caused. [3]

If it is the frequency that drops, the synchronous speed decreases. The frequency drops in synchronous generators are usually due to the fact that the resistant torque of the alternator cannot be assumed by the Diesel that drags it and decreases its speed, until the Diesel is capable of assuming the resistant torque of the alternator.

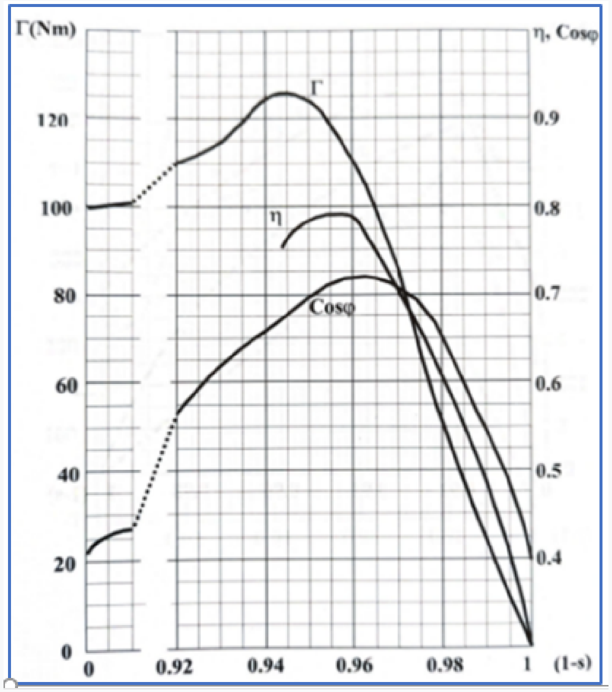


Fig. 3 Characteristic curve, Torque, Efficiency & Power factor vs. Slip of an Induction Motor. Source: Tecnología Eléctrica ed. Ceysa Ref [3]

The rest of the installation's motors also reduce their synchronism speed associated with the frequency, contributing their kinetic energy in the form of electricity, working temporarily as generators.

This phenomenon will be used in this work, for the design of the kinetic accumulator of electrical energy (ACEE), electronically controlling the feeding frequency of a 9 kW auxiliary induction motor, with a flywheel coupled to the motor.

No load on the shaft, no-load motor, it uses all its torque in the starting process to accelerate the rotor.

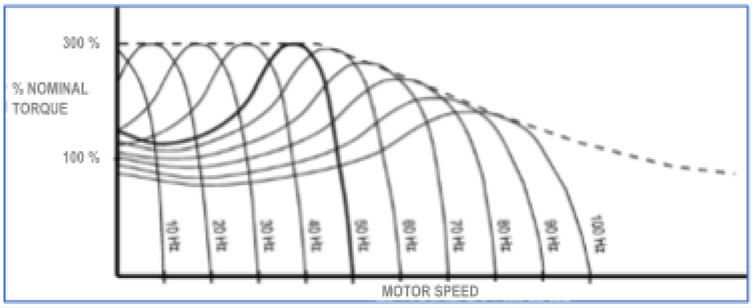


Fig. 4 Curve Torque -Speed at different frequencies. Source; Teoria general de máquinas eléctricas. [1]

2.1.3 Starting Process of an Induction Motor

The (Γ-ω) curves of the propeller are used to see how the available motor torque is distributed at each speed, as the speed increases during starting, between the resistant torque of the load and the inertia associated with the rotor.

In the graph below, expressed with ordinates in so much per one, the curves of torque and intensity of the start of an induction motor are observed, with infinite power supply (continuous line) and generator set (discontinuous line), activating a propeller type load in stable navigation regime.

As shown in Fig. 1, the positive difference between the motor torque curve (green curve) and the load curve (red curve), corresponds to the acceleration torque of the load, which happens until both curves intersect at point (A), called the motor torque-resistant torque balance point.

If the nominal working speed is exceeded, the available torque balance is negative, since there is more resistant torque from the propeller than motor torque and the rotor slows down to equilibrium speed, stabilizing its current and rotational speed.

This point must coincide with the nominal torque and current of the motor, if the drive is well dimensioned for that motor. In this case, it corresponds to a speed of 1460 rpm and a slip S=2.6%.

At no load, all the torque is used to accelerate the rotor. It is the fastest phenomenon, compared to load starts, where there is less torque available to accelerate masses.

Blue: Current

Red: Propeller Load

Green: Motor Torque

Continous Line: Infinite Power Supply

Dotted Line: Genset

Balance Points:

A: Normal load

A": Underload

A': Overload

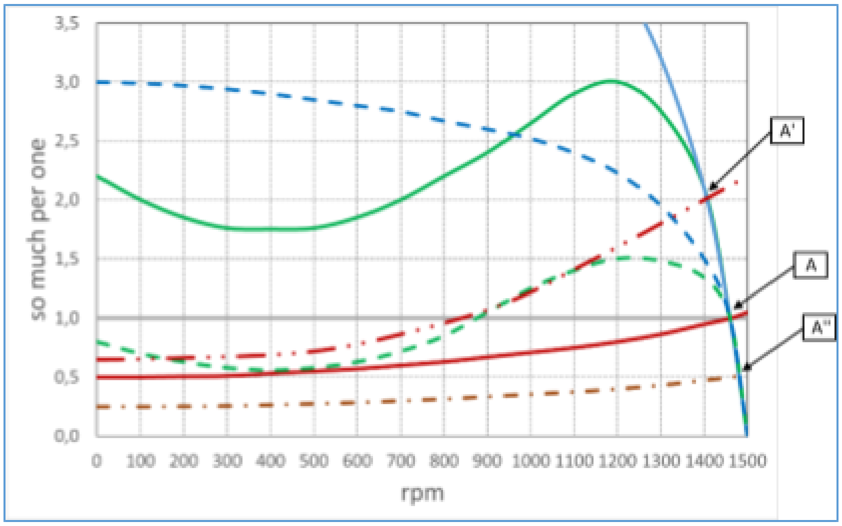


Fig. SEQ Fig. * ARABIC 5 Balance points at synchronous speed facing waves. Source: Own

The relative depth variations of the propeller associated with the waves, significantly affect its resistant torque curve and the balance points. Its electronic control associated with the challenge of sailing with waves is feasible, although not easy: kinetic accumulator of electrical energy (ACEE).

2.2 Supply Currents from The Alternator

2.2.1 Alternator and Reactive Inertia

The rolling inertia of the Diesel engine and the alternator are capable of supplying the brief instantaneous surge associated with the active acceleration power of the bow engine, even though the Diesel fuel control is slow, as long as the voltage remains stable at its nominal value.

It is imperative that the alternator is capable of supplying its rated power at power factors of 0,4 or less. Its regulation system (AVR) [4]which controls the excitation current of the alternator, must be able both to rapidly supply the reactive energy necessary for the magnetization prior to the bow thruster starting, and to reduce the nominal one once the propeller is at rated speed, where the consumption of active and reactive energy, due to acceleration, has ceased.

2.2.2 Alternator Drivers for Reactive Control (AVR) and (Q)

Reactive power transients cannot be fed by generator inertia.

They require a fast and well-regulated (AVR) [5], which gives the opportune commands to control the excitation current I_{exc}.

In order to have an independent source of electricity for the (AVR), another generating machine with permanent magnets called a pilot exciter is mounted on the same alternator shaft, exclusively to feed the (AVR) and the excitation intensity I_{exc}.

It is a more expensive solution, but recommended if large electric motors have to be started, especially if they are electronically controlled.

The short-circuit current does not exceed three times its nominal current ($3*I_N$), in the best alternators on the market, duly regulated. Transformers easily feed short-circuit currents of twenty times the nominal ($20*I_N$), because they do not have an air gap between the primary and secondary. Alternators need an air gap so that the rotor can rotate and this severely penalizes their transient response.

It is the big difference between terrestrial power grids, powered by transformers, and on board powered by synchronous alternators.

An alternator is incapable of correctly starting an induction motor of the same power, even when it is without load, that is, without resistant torque on the shaft.

2.3 Voltage Dips

A drop-in voltage at the terminals or "voltage gap" will always be detectable, associated with a starting current such as that of the bow thruster, although the frequency controllers f- P active power, (Diesel fuel) and the excitation of the alternator (AVR), voltage V-reactive Q, are adequate. This voltage dip is characterized by its depth in percentage with respect to the nominal voltage of the alternator and by its duration in seconds. The measurement of this depth and duration is recommended in all boats and for the higher power motors of the electrical installation.

The traditional design, focused only on active energy, results in an alternator incapable of supplying reactive energy with a power factor of less than 0,5 at its nominal current, which is insufficient to feed the correct starting of large electric motors.[6]

Fig. SEQ Fig. * ARABIC 6 Serious Accident 2017, formally reported by "CIAIM" as a Power Blackout. Source: M. Fomento 05/2018

This lack of margin to supply reactive power can cause serious accidents, due to the power blackout of the plant[7]. The reactive evolves 1000 times faster than the active one and requires that the excitation current of the alternator follow these evolutions to be stable, faster than the Diesel fuel control, responsible for the active power.

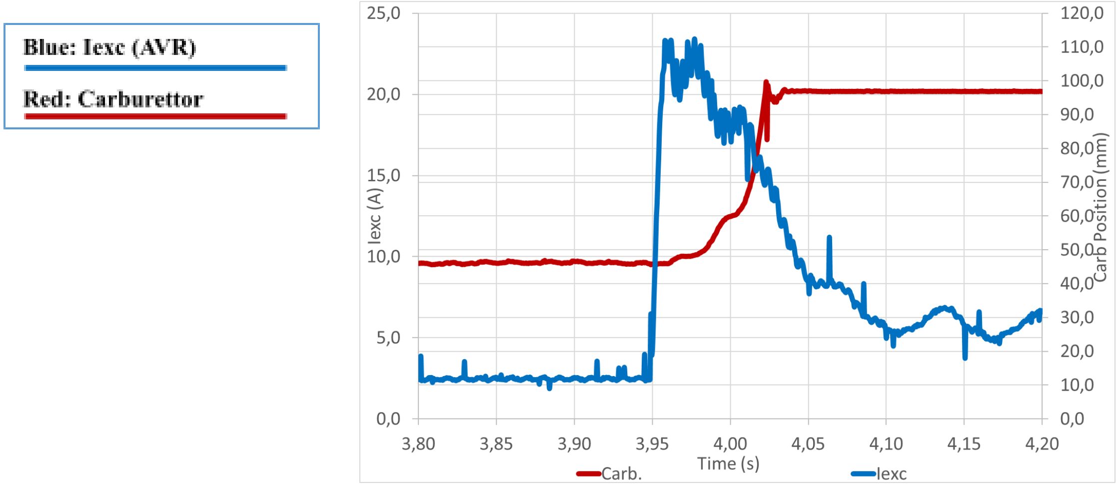


Fig. 7 Evolution of the Carburettor & (AVR) response vs. time, during the experimental reproduction of the electrical system, in front of the direct start of the 4-kW induction motor. Source: Own

3 EXPERIMENTAL DEVELOPMENT

3.1 Awareness

On-board power blackout occurs more often than it might seem. Although not all cases are reported, many appear in the national public reports that the commission for the Investigation of maritime accidents and Incidents (CIAIM), publishes with the result of "Power Blackout", as well as in international reports. Special incidence is evidenced in the activation of the Bow propellers, during the docking maneuvers.

3.2 Experimental Analysis

3.2.1 Industrial Solution with Kinetic Accumulators of Electric Energy

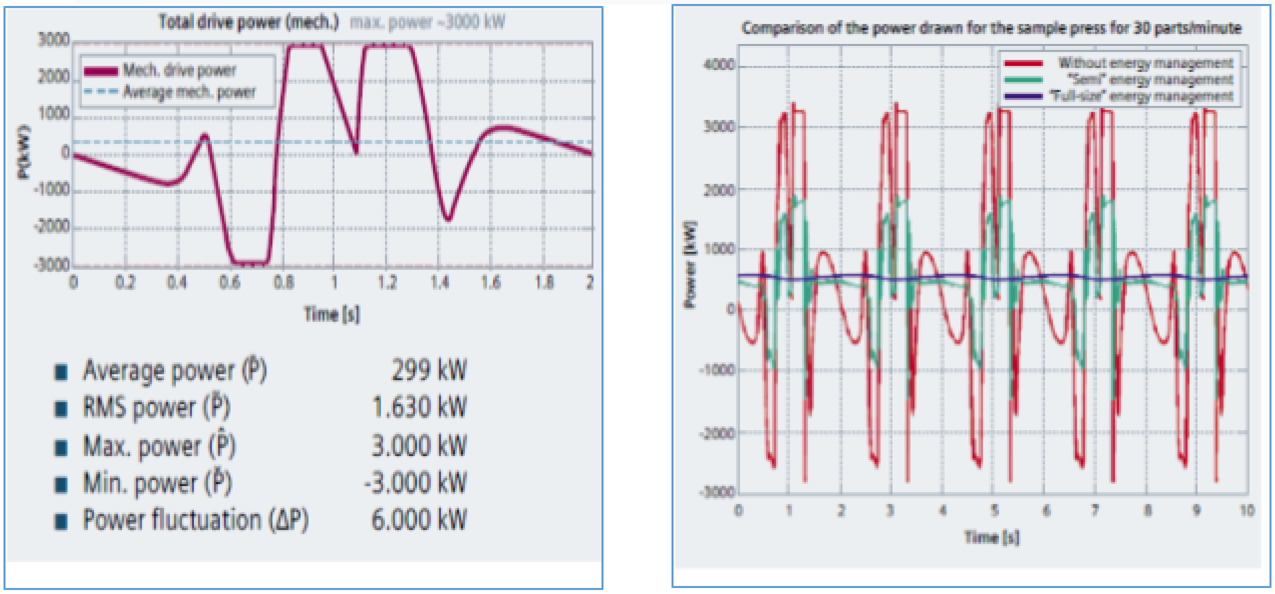
We had the opportunity to participate as a supplier company in the development and industrialization project of the first large servo press in the world (2016-2017) 100% electric, for the automotive sector, by the Japanese group "Nidec Corp.", (Kyoto, Japan) and specifically developed in its Spanish company ARISA (La Rioja).

The electrical power supply system for the press drive was complemented with a kinetic energy accumulation system, high inertia motors (Flywheel motors), these allow managing active energy and its controls, with capacitor banks, which allow managing reactive energy.

Applying this technology to the naval world is the hypothesis of this work, to improve the stability and operational safety of on-board electrical power generation plants.

The term of power of the electric power transformer station is reduced between 50% and 70% approximately. [8]

The maximum peak power of the press is ± 3 MW. Using the kinetic accumulators of electrical energy and a Plc software designed for this application, the power is smoothed to 650 kW rms, always positive, saving costs and electromechanical fatigue of the affected elements. [9] See the power consumed by the press, during the work cycle, with and without the electrical energy kinetic accumulator system and its control system:



■ Average power ($\bar{P}$)	299 kW
■ RMS power ($\tilde{P}$)	1.630 kW
■ Max. power ($\hat{P}$)	3.000 kW
■ Min. power ($\check{P}$)	-3.000 kW
■ Power fluctuation (ΔP)	6.000 kW

Fig. SEQ Fig. * ARABIC 8 Energy profile during a cycle (left), same during 5 cycles (right) with and without Flywheel system of an Electrical Press. Source: [4]

Hours of operation of the press of 7000 h/a, a monthly cost for supply of €10/kW and a cost for consumption of 12 ct/kWh are considered, and without paying the energy returned to the network, savings are achieved of 41.6%, drastically reducing the "Pay Back".[10]

3.2.2 Reproduction of the Problem in the Laboratory

The main elements of a naval power plant have been reproduced on a scale of around 6,5 kVA cos ϕ= 1.

The no-load direct start-up of a 4-kW induction motor has been considered the most severe electromechanical transient, which brings down the electrical plants on board. Commercial materials have been used with series controllers, which are not usually modeled in detail due to their economy.

In this case, it is a faster and more reliable measurement methodology than computer simulation of poorly characterized materials.

The polytechnic university of Catalonia (UPC), department of electrical engineering, teaches at the faculty of nautical sciences of Barcelona (FNB), and at the higher technical school of industrial engineering of Barcelona (ETSEIB). It has made the (ETSEIB) electrical engineering laboratory available.

Appropriate digital instrumentation has been used to record the evidence.

The no-load start of the induction motor has been done from the infinite power network and from various generator sets:

Propellant “Novat”

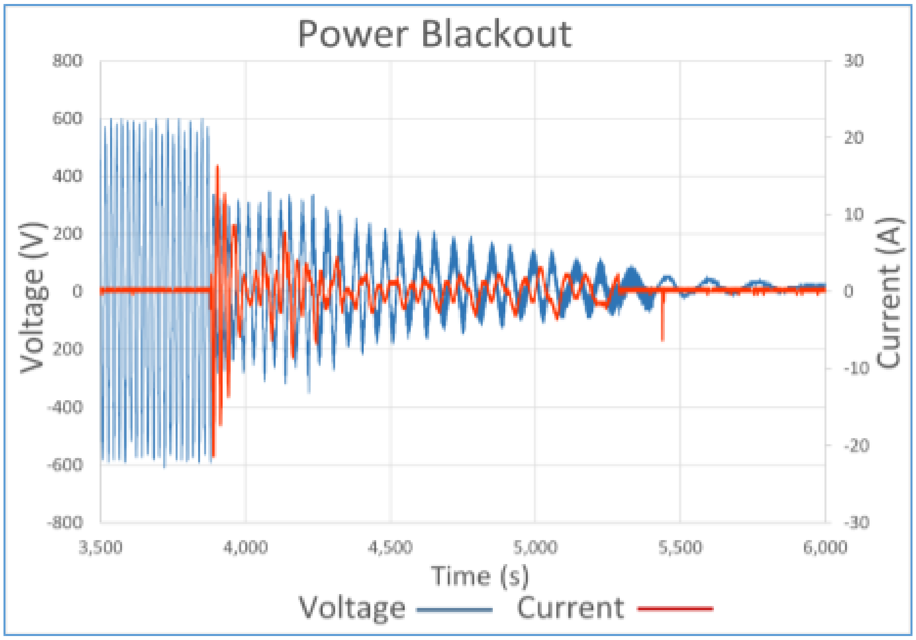
Table SEQ Table * ARABIC 1 Main performances of the Genset HONDA 6,4 kW- 6,5 kVA cos ϕ 1. Source: Own

GE HONDA ECMT 6500 (commercial)	**Thermal Machine GX 390**	**Alternator HONDA**
Nominal Power	6,4 Kw	6,5 kVA
rpm	3000	3000
Frequency		50 Hz
I_N Nominal		10 A
I_{CC} short circuit		30 A
cos ϕ	1	
Torque	26,5 Nm at 2500 rpm	
Weight	31,7 kg	
Inertia Genset	0,002951 kgm^2 calculated	

Plate features:

- Manufacturer: “Novat”
- Size: 112M
- Rated voltage: 400V
- Rated current :8.5 A
- Rated power: 4 kW
- RPM: 1420
- Frequency: 50 Hz
- I without load: 5,1 A
- I start: 70 A

The power blackout can be seen in the graph below and it occurred during the idle start of the engine, in two out of every ten starts:



The alternator's (AVR) system, which injects the excitation current to increase the rotor's magnetic field and thus generate the electromotive force E, has not been able to keep the voltage sufficiently stable.

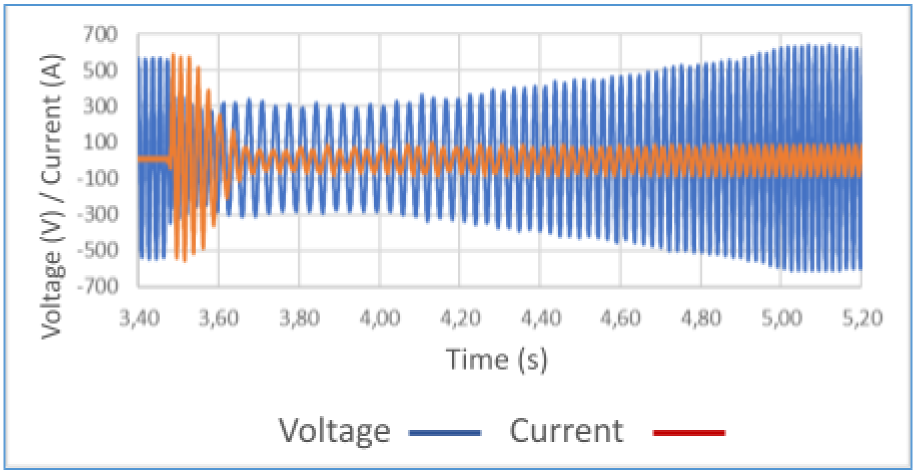


Fig. SEQ Fig. * ARABIC 10 Voltage dip by direct start of a 4 kW induction motor fed by a Genset HONDA 6,4 kW 6,5 kVA cos ϕ 1. Source: Own

In eight out of ten starts, there is a deep and long-lasting voltage dip of 68% voltage drop and 1530 ms. duration, caused by the no-load start of the 4 kW motor.

It is also observed how the load current after about 7 periods decreases because the rotor already rotates at its rated speed.

The current absorbed by the motor is lower than the no-load current at nominal voltage, because the voltage has drop by 68%, affecting the performance of the motor and its no-load consumption. When the voltage recovers after the dip, the no-load consumption returns to its normal value.

4 WORKING HYPOTHESES TO SOLVE THE PROBLEM

4.1 Oversizing of the alternator

It is necessary to size the alternator generously with respect to the thermal engine, so that the whole can work with the power factors of 0,4, which the induction motor demands during its start, even without load.

It is an experimental evidence to stall the heat engine of the 6,4 kW reference generator set with a 6,5 kVA alternator cos ϕ= 1, compared to the direct no-load start-up of a 4 kW induction motor, which is taken from reference to show that it is not a problem of active power, but of reactive power of the alternator. To demonstrate the hypothesis that it was not an active power problem, the power of the heat engine has been reduced to 4,6 kW, and associated with an oversized alternator resulting in the special generator set being called "RAS". [11]

GE HONDA “RAS” (especial)		**Thermal Machine GX 270**	**Alternator Tekel TT 8,5**
Nominal Power		4,6 Kw	8,5 kVA
rpm		3000	3000
Frequency			50 Hz
I_N Nominal			12,3 A
I_{CC} Short Circuit			37 A
cos ϕ		0,5	
Torque		19,1 Nm at 2500 rpm	
Weight		25,8 kg	
Inertia Genset		0,003497 kgm^2 calculated	

Table SEQ Table * ARABIC 2 Main performances of the Genset RAS 4,6 kW-8,5 kVA cos ϕ= 0,5. Source: Own

This Genset RAS 4,6 kW, 8,5 kVA, cos ϕ= 0,5 generator set allows the safe start of the same 4 kW induction motor in more than 100 starts, without plant failure.

The voltage gap caused is shallower and shorter.

The voltage drop is 46% compared to 68% in the case of the reference Genset HONDA cos ϕ= 1, with a recovery of 840 ms. compared to 1530 ms. for same genset.

Blue: Evolving of Voltage

Red: Evolving of Current

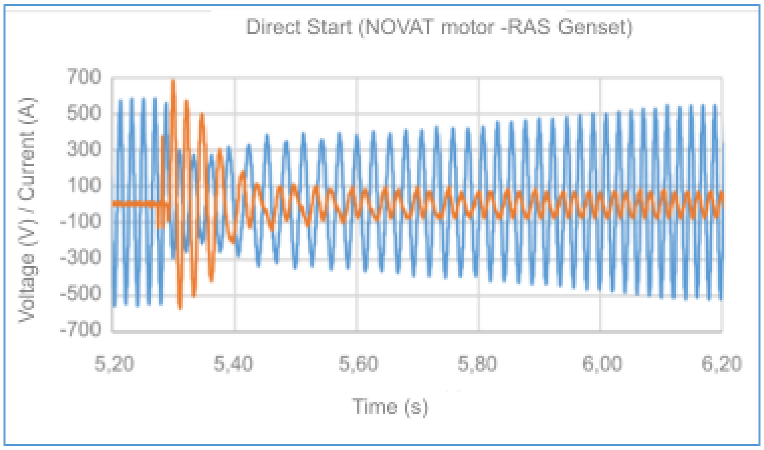


Fig. SEQ Fig. * ARABIC 11 Direct start without load of a 4 kW Novat induction motor fed by RAS Genset 4,2 kW-8,5 kVA cos ϕ= 0,5. Source: Own

This shallower gap allows the rotor to accelerate faster by 4 periods, as evidenced by the current equaling no-load.

4.2 Kinetic accumulator of electrical energy (ACEE)

4.2.1 Components

It is an alternative solution, for when it is difficult to change the alternator to work at lower cos ϕ.

It is proposed to use the energy stored in an electric motor with a flywheel (blue), to avoid the voltage drop of the alternator. It is about cushioning the voltage dip, caused by the start of an induction motor.

This system is called Kinetic Accumulator of Electric Energy, (ACEE).

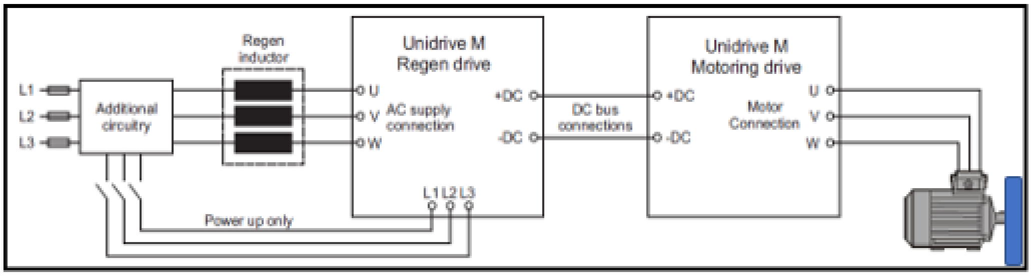


Fig. 12 Blog Diagram of a Regenerative system (ACEE) reproduced in the lab. Source: Control Techniques and Own

It is a controlled regenerative or active front end (AFE) system, made up of two frequency converters (VSD), linked by the direct current regenerative voltage, (DC Bus).

The "Motoring" drive (right), is responsible for the management of the motor that carries the flywheel, its acceleration and its braking, returning the energy transformed from kinetic to electrical in the braking process, which implies that the value of the (DC Bus) exceeds 630V.

The frequency converter (VSD) (left) "Regen", is responsible for synchronizing with the network and returning the electrical energy that has been generated in the braking of the flywheel.

The system includes inductances for the sinusoidal ripple, in the form of the voltage and current waves, which we deliver to the network. Also, capacitors to have reactive power and filtering capacity. The two frequency converters (VSD) have a memory space in their main microprocessor "Plc on Board" to program in "Ladder" the functions that you want the system to execute.

4.2.2 Experimental Measurements on the Reproduction in the Laboratory of the Power Plant, with the (ACEE) System Built

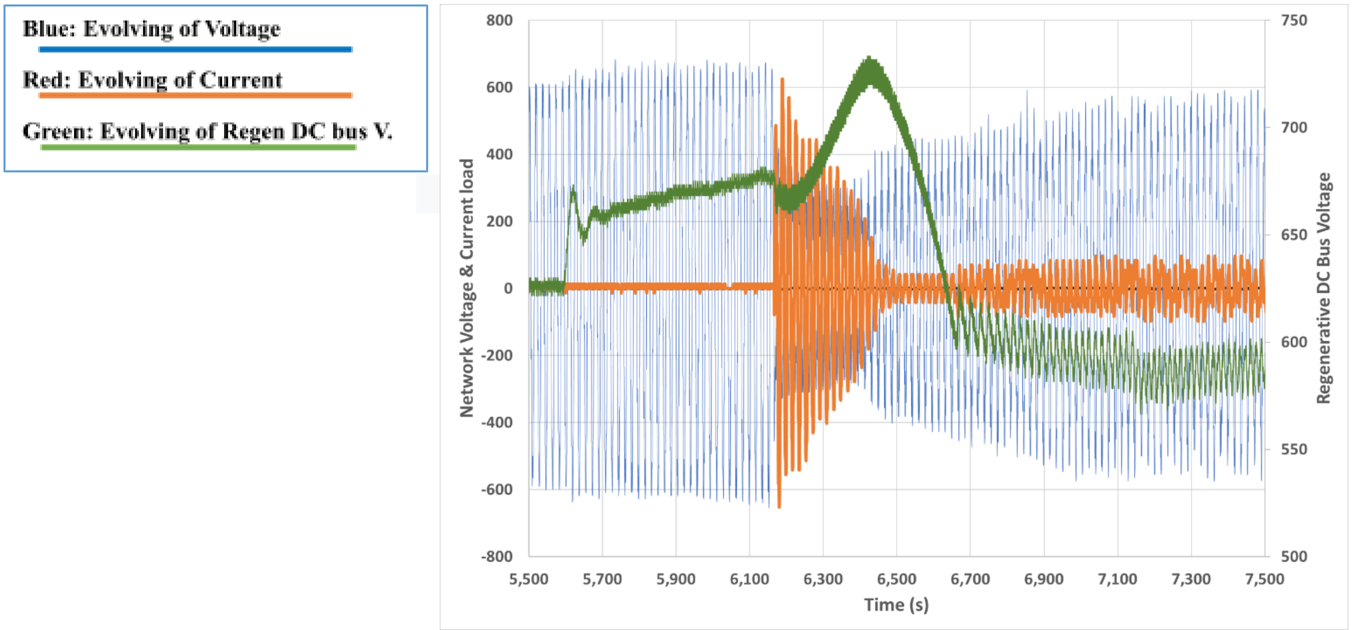


Fig. 13 Direct start without load of 4-kW induction motor fed by RAS Genset 4,6 kW-8,5 kVA cos ϕ= 0,5, with anticipatory discharge (600 ms.) of the kinetic accumulator of electrical energy (ACEE). Source: Own

See in fig. 13 above a record of the direct startup of the Novat induction motor without load, with anticipatory discharge (600 ms.) of energy from the (ACEE) system, fed by special RAS generator.

In blue, the envelope of the peak-to-peak values of the alternator voltage, in red that of the intensity values at startup of the Novat motor, and in green the curve of the DC Bus, which corresponds to the energy discharge of an (ACEE) system. Built for the thesis on which this work is based with 9 kW of motor power and 7,4 kJ of energy stored in the flywheel. A current peak provided by the (ACEE) system of 68 A is observed.

The system is fully configurable. Anticipatory discharge tests have been carried out, delaying 600 ms. the engine start order, to relatively advance the discharge of the (ACEE) and thus make the maximum of the DC Bus (green) coincide with the largest voltage dip of the alternator, and thus optimize the efficiency of the (ACEE) accumulator system.

The improvements that have been obtained using this flywheel system are shown below:

Direct Start without load, with (ACEE) system **Induction motor 4-kW** **Genset RAS 4,6kW-8,5kVA, cosϕ= 0,5**	**Time improvement of the Voltage recuperation vs. Direct Start**	**Voltage dip improvement vs. Direct Start**
By Bus DC rise	**23%**	**34%**
By Current rise	**53%**	**38%**
Anticipatory 60 ms.	**60%**	**43%**

Table 3 Table of improvements values obtained with the installation of a kinetic accumulator of electrical energy (ACEE). Source: Own

The grid connection diagram for this (ACEE) system is shown below:

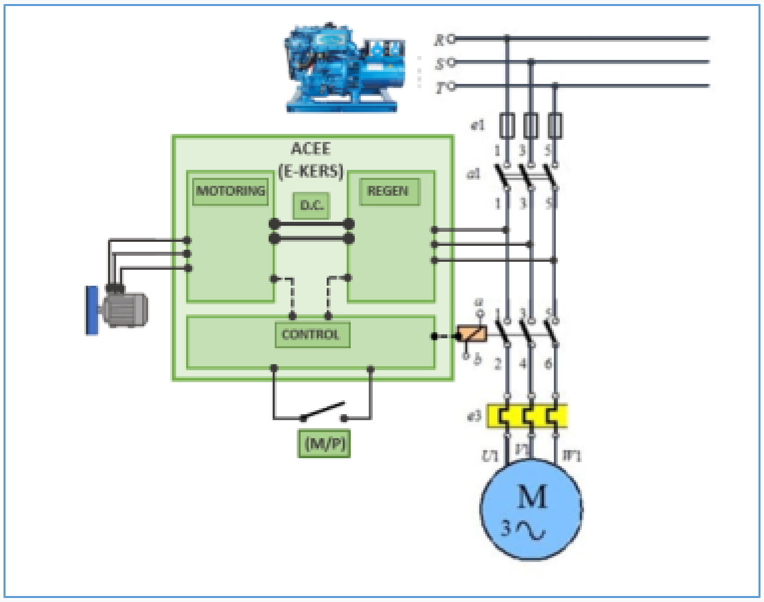


Fig. 14 Electrical connection of a kinetic accumulator of electrical energy (ACEE) to the Grid. Source: Own

The system provides active and reactive energy, the latter from the capacitors that the system equips, including those of the frequency converters (VSD) that the (ACEE) system assembles.

5 SIMILES OF REACTIVE ENERGY

5.1 The Human Body

Imagine a person pushing a car on a slippery floor. The friction of the feet with the ground, combined with the weight, is what allows the horizontal force considered useful (active) to be exerted. The weight is at 90º and although necessary, it is not considered a useful (reactive) force.

The rearmost leg forms an angle equal to the power factor. It is of maximum propulsive efficiency, when its cosine is close to 1.

This situation is of maximum risk of falling as we approach the limit of the coefficient of foot-ground adherence, since the coefficient of friction is usually less than that of adherence.

It would be desirable to have another leg, further forward towards the car, which only exerts vertical force with respect to the ground, it is not propulsive efficient, but it prevents the fall. ***It is the function of reactive energy.***

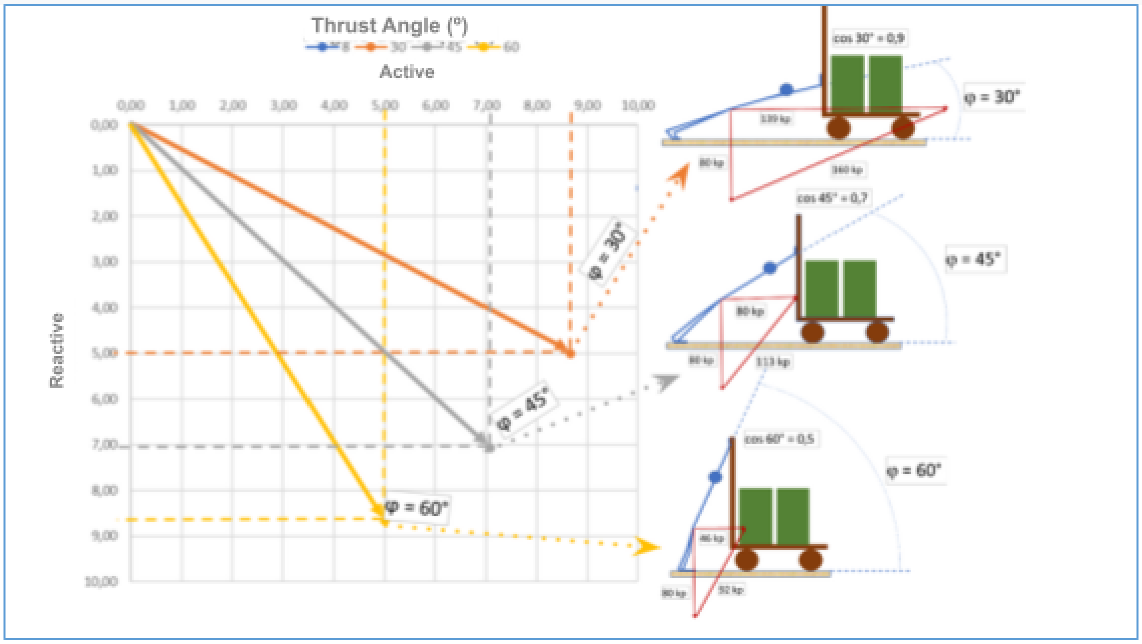


Fig. 15 Human body simile of the Reactive Power. Source: Own

6 CONCLUSIONS

Power control (P) and, above all, reactive power (Q), favors the stability of power generation plants.

The ability to regulate reactive energy in a generator set is very important for the stability of the generated voltage.

On-board power generation plants are traditionally designed to deal with loads with power factor cos ϕ= 0,8.

This traditional design is insufficient for starting large induction motors, such as those in transverse bow thrusters.

If the on-board power plants can work with power factors of 0,4 or lower, they are more stable and do not drop.

Although these motors start with the star-triangle system, in some cases they can cause the plant to fail at the time of the star-triangle commutation.

In the plant reproduced experimentally, with the reference generator set cos ϕ= 1, when starting a 4 kW induction motor without load, a couple of plant failures have been achieved, out of 10 starts. The rest of the starts without plant failure produced a voltage dip >60% and >1,530 ms. of duration.

This induction motor consumes 5,1 A at no load, that is, an acceptable percentage of the nominal current of the alternator, which is 10 A in permanent regime.

To demonstrate that it is a problem of the capacity of the generator set to work with low power factors, a generator set with less active power has been built, but capable of working with a power factor of cos ϕ= 0,5, 4,6 kW-8,5 kVA with a satisfactory result: There has been no plant failure in hundreds of tests.

The voltage dip is much smaller, <40% deep and <840 ms in duration.

Increasing the power of the alternator kVA with respect to the classic design, in order to cope with the lower power factors of cos ϕ= 1, which many electric motors demand during their start-up, is not technically or administratively possible in many cases.

In these cases, it has been shown that it is possible to install a kinetic accumulator of electrical energy system (ACEE), that allows to cushion and/or avoid the voltage dip associated with the start-up of large electrical motors in the installation. It consists of an electric motor the size of the alternator to be reinforced, with a flywheel and the appropriate electronic controllers.

The kinetic accumulator of electrical energy system (ACEE), can have a cost 10 times higher than that of an oversized alternator, to be able to work with power factors of cos ϕ 0,4.

It can be a solution, so as not to dismantle the existing one in a specific plant, especially if the engine room is overwhelmed, since the (ACEE) system, in addition to being scalable in power and of low maintenance, is easily located.

Maritime authorities should require the recording of the depth and duration of the voltage drop associated with the start-up of the largest electric motors in the installation, on each ship.

These measurements require instrumentation and knowledge that shipowners can subcontract to specialized companies, these companies represent a business opportunity for the new generations of naval engineers and especially for the emerging profession of Electrotechnical Officer (ETO) [12]

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