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Contributions for improving the stability of marine power generation plants

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ABSTRACT

The Electrical Engineering department of the University FNB/UPC -Barcelona Tech. conducted a large set of real tests on a hybrid propulsion platform with compressed natural gas (CNG) fuel at the facilities of Marina Barcelona 92 in 2018, to simulate the electrical transients that may cause dangerous situations such as "Blackouts" in marine power generation plants.The commercial generator set used in this hybrid platform is composed of a reciprocating alternative internal combustion engine of 91 kW and a synchronous alternator of 175 kVA and a set three squirrel-cage induction motors of different ratings (i.e., 20 kW, 22 kW and 55 kW). It should be underscored that, as can be seen, the rated apparent power of the synchronous generator has been slightly oversized when compared with the rated active power supplied by the prime mover. In fact, the latter is defined as one of the main criteria of this article.As mentioned above, the synchronous alternator has been oversized, mainly to overcome the effects caused by the induction motors during its on-line starting, to fulfil smooth recovery while avoiding a general "blackout". With this purpose in mind, one of the main goals of the article is to demonstrate that the proposed criteria are useful during severe transients, which are likely to cause undesired events in the ship.The transient originated by the induction motors during the on-line direct starting causes large overcurrent. Therefore, by oversizing the alternator and adding more inertia to the electrical system (i.e., the electrical system of the ship), we achieve a better response during this contingency. Indeed, this design criterion has not been taken into consideration by the maritime sector, which most of them are only designed for the steady state at a particular point of operation. Therefore, this point stresses the fact that without considering this design criterion, the electrical system may become more vulnerable.The aforementioned "Power Blackouts", have historically produced numerous accidents (officially reported by the "Maritime Accident Investigation Commissions" of the most developed countries), sometimes associated with undesirable consequences.A set of 5 technical recommendations and good practices has been studied and tested to improve the stability of the on-board electrical system.

Abbreviations: IM, Induction Motor; GE, Power Generation system Genset; RICE, Reciprocating Internal Combustion Engine; VSD, Variable Speed Drive; CB, Circuit breakers; PMSG, Brushless permanent magnet control for synchronous generator; CNG, Compressed Natural Gas; BSDG, Black Start Diesel Generators.

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1. Introduction

As we advance technologically in addition to the traditional cargo ships, the types of specialised vessels are increasing and new models are in demand. The techniques of safely storing and flow transferring so-called dangerous products, due to their possible contaminating impact, as well as the risk of fire and/or explosion, coupled with the new hybrid and electrical propulsion systems have facilitated this increase, with electricity being crucial for the safety and efficiency of the vesselś operations [1,2]. Since large cruises are increasing in all over the world, making the on-board "Power Generation Plants" dependable become an essential task for the life of the thousands of people that travel continuously on them [3,4]. Table 1.Table 2.Table 3.

Generally, the on-board electricity supply is based on a balanced three-phase alternating current system, 400/440 V, 50/60 Hz provided by the electrical generators, which in turn, are driven by a prime mover [5,6,7].

A widely used source to feed theses generators are the so-called reciprocating internal combustion engine (RICE). Useful data regarding the types of electrical machines,protections, combustion engines and its main characteristics can be found in: [8,9,10,7].

Given the large amount of electrical loads in these cruises, larger electrical machinery, as well as larger electrical installations and equipment, are required. Furthermore, due to the disruptive change in the propulsion technology (i.e., the hybrid gas-electric systems), the way these installations are planned and operated is changing. A particular issue derived from these electrical systems occurs when large currents are transmitted (i.e., due to the high number of loads) resulting in unacceptable percentages of electrical

Table 1
Main Ship Sanitation Certificate-SSCC.

SSCC Classification Sociiety	Permanent voltage variation	Transient voltage variation	Permanent frequency variation	Transient frequency variation	THD of the nominal voltage
ABS	**+6%, −10%**	**±20% (1,5s.)**	**±5%**	**±10% (5 s.)**	**not to exceed 8% and any single order harmonics not to exceed 5%**
BV	**+6%, −10%**	**±20% (1,5s.)**	**±5%**	**±10% (5 s.)**	**not to exceed 5% and any single order harmonics not to exceed 3%**
DNV-GL	**±2,5%**	**−15% to + 20%**	**±5%**	**±10%**	**IEC 61000–2-4 Class 2. In addition, no single order harmonic shall exceed 5%**
Lloyds R.S	**±2,5%**	**−15% to + 20% (1,5 s.)**	**±5%**	**±10% (5 s.)**	**not to exceed 8% of the fundamental for all frequencies up to 50 times the supply frequency**

Table 2
Official Reports of the Spanish "CIAIM" during the years 2009 to 2019.

Ship Owner	Name of the Ship	Place	Date	Failure Reported	Source of the information	Event description
Armas Shipping company	"Volcán de Taburiente"	Port "Santa Cruz La Palma" (Spain)	15/07/2018	**Power Blackout**	Spanish Journal "Público"	Drifting in front of the harbour, integrity risk.
Trasmediterránea	"Albayzin"	Lanzarote Island (Spain)	24/08/2017	**Power Blackout**	Spanish Journal "Laprovincia.es "	Drifting with 244 passengers & integrity risk.
Armas Shipping company	"Volcán de Tamasite"	Port "De la Luz" (Spain)	22/04/2017	**Power Blackout**	Ministerio de Fomento España Informe CIAIM Report 05/2018	140 Ship Passengers needed medical assistance.
FRS IBERIA, SL	"Ceuta Jet "	Port "Algeciras " (Spain)	5/03/2015	**Power Blackout**	Ministerio de Fomento España Informe CIAIM Report 27/2015	Drifting to the "Isla Verde" dock.
Naviera Murueta	"Luno"	Port "Bayona " (France)	5/02/2014	**Power Blackout**	Ministerio de Fomento España Informe CIAIM Report 34/2014	Shipwreck breaking the ship in two.
Acciona-Trasmediterránea	"Almudaina II"	Ibiza-Barcelona (Spain)	30/07/2006	**Power Blackout**	Spanish Journal "El País"	Drifting for 7 h, integrity risk.

Table 3
Summary of the Criteria.

Criteria N°	Keyword	Short Description
1	Sequence of events	Of the Induction motors
2	Oversize the alternator	For correct supply of the transient currents
3	E-Control Systems*	For Active and Reactive Controls
4	Load Frequency control	Torque-Speed or v3VI cos φ
5	Voltage control	v3VI sin φ

*The term E-control is referred as An accurate design of the governor and AVR control and its settings.

losses, which at the same time, this may cause noticeable operational voltage regulations. The established limits in terms of regulation (for the Ship sanitation certificate- SSCC) for voltage and frequency drop during stable and transient operation are defined down below: [11,12,13].

In the cases of very high currents , it is recommended to reduce it by increasing the voltage level of the grid. Thus, rated voltages levels of 3,3 kV and 6,6 kV are really common in these ships, while a rated voltage of 11 kV can be found mainly in Ferries [14,15,16].

During emergencies, in order to avoid a general "blackout", exceeding the previously summarised limits is allowed [17].

On the other hand, the quality of the waveform should be as sinusoidal as possible with the minimum content of harmonics. Note that, this may result in a difficult task due to the proliferation of non-linear loads in the ship. [18,19,20,21]

The on-board electrical installations require a good grounding system to: [22]

- Protect electrical installations.
- Having a low enough impedance to avoid risky over-voltages during "ground" faults and provide an equipotential platform on which electronic equipment can operate.
- Prevent any hazard when being exposed to dangerous voltage potentials for their integrity.
- Keep the system within reasonable limits under bypass conditions and ensure that the breaking voltages of the insulating materials are not exceeded.

In the MB92 experiment, an IT grounding system has been implemented, meaning the neutral was isolated, and all metallic equipment is "ground" unwired, also including the propellers, which have a degree of IP 68.

Even though the type of grounding and its effects in the electrical systems is a broad subject which has been an object of analysis in many scientific studies, a general idea and useful information about the grounding procedures and main techniques can be found [10,23,24].

The term "blackout" has been widely used in electrical power systems, and there are several works that have analysed the origins and consequences of these high-level contingencies. Nevertheless, power blackouts also occurred in the maritime sector. The following references provide useful reports about both types of scenarios [14–18]. An "Electrical Blackout" is one of the most dangerous and risky situations for a ship, especially when navigating and manoeuvring in traditional vessels, but even more so in specialised or electrical ships where energy is essential for propulsion and the maintenance of safety conditions of the crew, the ship and the cargo itself [25,26,27].

The occurrence of an "Electrical blackout" can be caused by different types of random events. However, the most common are due to the generator tripping for rotor over-speeding, and/or for under-over frequency events. On the other hand, if a fault occurs (i.e., a short circuit), depending on the type of configuration of the electrical network (i.e., either radial or meshed) an interruption may shut down the electrical system, as it occurs in distribution networks . It is worthwhile to note that the transient studied in the present paper (the transient due to the induction motors) has not been deeply analysed in the previous studies, however, it can cause the same consequences as for the previous events [28].

In addition to the previously mentioned events, a "Frequency event "is likely to occur if the imbalance between the load and generation active-power capacities becomes non-zero. Thus, a positive imbalance may imply the rotor deceleration causing an under-frequency event [29]. On the contrary, a negative imbalance may cause an over-frequency event due to the rotor acceleration. Since the number of loads is a known variable, the most likely event that can happen is the loss of generation power (e.g., one generator is tripped due to a fault or even due to an internal engine failure), resulting in an under-frequency event. Lastly, it has to be noted that, another positive aspect of oversizing the alternator is the increasing inertia, which helps to damp such events [30].

Once the blackout has occurred, the so-called "black start" is known as the process of restoring an electric power plant to operate from total or partial shutdown.In the absence of grid power, a so-called black start needs to be performed to bootstrap the power grid into operation. To that purpose, the powerplant is usually equipped with small diesel generators, commonly known as the "black start diesel generator" (BSDG), which can be used to start larger generators (of several megawatts capacity).

Another useful solution to achieve a successful black start maybe some sort of battery-based energy-storage (BEES) devices [31,32,33,34,35].

Additionally, valuable devices to deal with some of the previously mentioned contingencies can be solutions based on hybrid energy storage systems (HESS) where a battery, a flywheel (B/FW), and a battery/ultra-capacitor (B/UC) are integrated.

1.1. International committees

Unfortunately, there are many examples of the severe consequences of "Electrical Blackouts" in ships; many countries have developed their own Government Departments of "Maritime Accident Investigation Commissions", to report, analyse and recommend improvements for safety sea, such as:

- CIAIM: "Comisión de investigación de accidentes e incidentes marítimos". (Spain)
- DMAIB: Danish Maritime Accident Investigation Board (Denmark)
- Trafi: Finnish Transport Safety Agency (Finland)
- BEAmer: Bureau d'enquêtes sur les événements de mer (France)
- MCIB: Marine Casualty Investigation Board (Ireland) DiGiFeMa: Direzione Generale per le Investigazioni Ferroviarie e Marittime (Italy)

- MAIB: Marine Accident Investigation Branch (UK)
- SHK: Statens haveri kommission (Sweden)
- Marine Accident and Incident Investigation Committee" (Cyprus)
- TM: Marine Safety Investigation Unit (Malta)

1.2. Blackouts in ships

As an example: The ferry "Volcán de Tamasite" of the company "Armas Shipping" during the trip Gran Canarias - Tenerife suffered an accident when leaving Puerto de la Luz. The ship, which was adrift due to a "Power Blackout", failed to restart the main engines (RICE) and crashed frontally against the dock. Fig. 1 shows the accident.

At least ten of the 140 passengers on the ship needed medical assistance. In addition, the pier breakwater was seriously damaged by the collision.

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You Tube, April 22nd 2017 / Facebook, April 22nd 2017/ Puentedemando.com , April 22nd 2017

1.3. Proposed criteria

In this paper, human errors during the operation are not taken into consideration. Thereby, the current assessment will only cope with the events and disturbances originated by the system and will dismiss human errors.

In power systems, when a large-scale interruption occurs (i.e., either due to voltage or frequency collapse) it is called a "Blackout" or "Power blackout". Having said that, a distinction between an interruption and a "blackout" has to be done. While the first event belongs to a large-scale event (i.e., it involves a large system), the second one is a local contingency. Similarly, a luck of active-power may affect the whole system in a ship, meanwhile, in case a fault occurs in one cable in a parallel branch, the protective devices (i.e., overcurrent relays) will clear the fault, thus causing an interruption to the downstream loads.

The main international standards associated to naval generator analysis, design and reliability are those contained in the following rules:

- ISO 8528 that specifies the principal characteristics of alternating current (AC) generators under the control of their voltage regulators when used in generating set applications.

The rest of the references are inserted in this paper.

Some technical considerations can help us to explain how these "Power Blackouts" are produced:

If the alternator apparent power has the same rated value as the combustion engine active-power rating, the system will be able to operate below its rated power. However, the system will be slightly stressed for slight overloading conditions. For instance, the on-line direct starting of the induction motors belongs to one of these overloading scenarios.

Criteria 1: "Identify the most critical transients" by defining both the duration and the magnitude of the originated overcurrent. In several cases it is possible to modify the start sequence to improve the response of the system [36].

Active Power (Torque and Speed) are provided by the prime mover, in this case, the main engine (RICE) feed by the fuel flow, while the reactive-power output is provided by the alternator excitation current, which is governed by the automatic voltage regulation(AVR).

Techniques to minimise the overcurrent originated by electric motors are as follows:

- Starting using an autotransformer.
- Wye-delta start.
- Resistor-based starting.
- Starting taking advantage of a frequency inverter
- Soft starter (e.g., by using resistances or impedances connected with the stator winding)

Criteria 2: "Oversize the alternator to provide an additional inertia to the system and increase the short-circuit fault current capacity".

Criteria 3: "An accurate design of the governor and (AVR) control and its settings". A proper regulation of the prime mover admission flow rate and its regulator type, gains and constants as well as the (AVR) regulator settings is a vital task. The latter is cru-

Fig. 1. Crash of a Drifting Ferry against a Dock in Las Palmas 22/04/2017.

cial to avoid larger voltage overshoots following a contingency. If the reader is interested in (AVR) design, a comprehensive study comparison about the main settings and time constants can be found in [37,38].

The operational voltage regulation problem depends, in a high extent, the response time for both the governor and (AVR). Since the governor control of torque-speed it is measured in a matter of tenths of s, the voltage/reactive-power is sensed in tenths of a ms, due to its associated technologies [38].

Criteria 4: “Load frequency control”. In terms of frequency stability, the engine rated active-power plays a pivotal role. Therefore, the critical aspect of maintaining frequency between acceptable thresholds, the governor system has to be able to increase or decrease the flow rate to meet demand. As introduced earlier, the alternator inertia can help to stabilise the system providing an additional inertia [39].

Criteria 5: “Operational Voltage Regulation”. This criterion is focused on maintaining the voltage within acceptable levels in steady-state as well as prevent a voltage collapse by providing reactive-power during severe contingencies (i.e., transients such as faults, induction motors transients, sudden load connections).

An optimal voltage regulation can be successfully achieved by properly regulating both the (AVR) settings (i.e., gains and time constants) and its sensitivity capabilities [40].

It is important to emphasise the fact that in the “maritime sector” this criteria is often ignored, and this has caused many miss operations and serious damages.

The complete description of this and the results are given in Chapter VII : “Conclusions.”

1.4. Theoretical assessment

This subsection aims to demonstrate the feasibility and appropriateness of the proposed contribution, which in turn, will reinforce the previously defined criteria.

As has been mentioned above, the behaviour of the electrical system during the transient originated by the induction motors is the main pillar of this article. Thereby, the equations of the system have to be adequately defined.

Since a transient state is defined as a transition between two points of operation (i.e., between two stable states), to properly initialise a transient such as the one object of study, the steady-state before the on-line direct starting is of paramount importance. To that end, section II.4.1 focuses on analysing the system in a steady state before the contingency. After that, in the following subsection, the mathematical equations of the induction motors and the synchronous generator are detailed.

1.4.1. Steady state

Since in a steady-state model the derivatives are assumed to be zero, the equations of the transient behaviour will be used to obtain the steady-state model. If the machine is fed through a symmetric system of voltages (i.e., only the direct-sequence component of the voltage is considered), phase-voltages take this form:

$$\begin{aligned} Vsa &= \sqrt{2}V\sin(\omega st+\varphi) \\ Vsb &= \sqrt{2}V\sin(\omega st+\varphi-120^{0}) \\ Vsc &= \sqrt{2}V\sin(\omega st+\varphi+120^{0}) \end{aligned} \tag{1}$$

Equations (1) Phase-Voltages.

If the machine is considered under steady-state (i.e., derivatives are set to zero), the set of equations expressed in dq components are as afollows:

$$\begin{aligned} Vsd &= Rsisd \\ 0 &= Rrird + lr(\wp\omega m)\, irq + lm\ (\wp\omega m)\ isq \\ Vsq &= Rsisq \\ 0 &= Rrirq - lr(\wp\omega m)\, ird - lm\ (\wp\omega m)\ isd \end{aligned} \tag{2}$$

Equations (2) Set of Equations expressed in dq.

Given the fact that the speed derivative is zero due to the equilibrium between torques during the steady-state, the mechanical equations are neglected.

The active and reactive-power drawn by the machine acting as a motor in dq components are defined in equations (3):

$$\begin{aligned} P &= vsd\cdot isd + vsq\cdot isq \\ Q &= vsq\cdot isd - vsd\cdot isq \end{aligned} \tag{3}$$

Equations (3) Active & Reactive Power.

The equations to compute both active and reactive powers in steady-state and considering abc reference frame are expressed in equations (4):

$$\begin{aligned} P &= \mathrm{Re}\{Vsa\cdot Isa^{*} + Vsb\cdot Isb^{*} + Vsc\cdot Isc^{*}\} = 3\mathrm{Re}\{Vs\cdot Is^{*}\} \Leftrightarrow (VS(2)=0\ \&Is(2)^{*}=0) \\ Q &= \mathrm{Im}\{Vsa\cdot Isa^{*} + Vsb\cdot Isb^{*} + Vsc\cdot Isc^{*}\} = 3\mathrm{Im}\{Vs\cdot Is^{*}\} \Leftrightarrow (VS(2)=0\ \&Is(2)^{*}=0) \\ S &= Vsa\cdot Isa^{*} + Vsb\cdot Isb^{*} + Vsc\cdot Isc^{*} = 3\{Vs\cdot Is^{*}\} \Leftrightarrow (VS(2)=0\ \&Is(2)^{*}=0) \end{aligned} \tag{4}$$

Equations (4) active & reactive power in steady-state.

In equations (4) sub index (2) is referred to inverse-sequence component, therefore, if there is only direct sequence component for stator voltages and currents, the active and reactive powers drawn by the induction machine can be computed as 3VI*. The single-line diagram of the IM electrical model is depicted in the following Fig. 2.

where Xsd is the stator leakage reactance, Xrd is the rotor leakage reactance, XM is the magnetising reactance, and S is the slip between the synchronous speed and the rotor mechanical speed. These reactances are computed as equations (5):

$$M = \frac{Xm}{\omega}; Ls = \frac{Xsd + Xm}{\omega}; Lr = \frac{Xrd + Xm}{\omega} \tag{5}$$

Equations (5) reactance calculation.

The initial point of operation of an induction machine can be defined utilising the torque-speed curve provided by the manufacturer.

1.4.2. Transient state

Induction machine equations

In order to perform the IMs for transient analysis, we have the next equation (6):

$$v = Ri + \frac{d\phi}{dt} \tag{6}$$

Equations (6) equation for IMs transient analysis.

For a three-phase system, in the abc reference frame and for both the stator and rotor, the set of equations is expressed in the equations (7):

$$\begin{aligned} vsa &= Rs \cdot isa + \frac{d\phi sa}{dt} \\ vsb &= Rs \cdot isb + \frac{d\phi sb}{dt} \\ vsc &= Rs \cdot isc + \frac{d\phi sc}{dt} \\ vra &= Rr \cdot ira + \frac{d\phi ra}{dt} \\ vrb &= Rr \cdot irb + \frac{d\phi rb}{dt} \\ vrc &= Rr \cdot irc + \frac{d\phi rc}{dt} \end{aligned} \tag{7}$$

Equations (7) equations for IMs transient analysis in three-phase.

The matrix expression of equations (6) is now equations (8):

$$\begin{bmatrix} vs\ abc \\ vr\ abc \end{bmatrix} = \begin{bmatrix} Rs & 0 \\ 0 & Rr \end{bmatrix} \begin{bmatrix} is\ abcs \\ i\,r\ abc \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} \phi s\ abc \\ \phi s\ abc \end{bmatrix} \tag{8}$$

Equations (8) matrix expression of Equation (6).

Equations (7) are equivalent to equations (9) as follows:

$$\begin{aligned} v = Ri + \frac{d\phi}{dt} = Ri + \frac{d}{dt}\{M(\theta m)\ i\} = Ri + \frac{dM(\theta m)}{dt}\frac{d\theta m}{dt} i + M(\theta m)\frac{di}{dt} \\ v = Ri + \frac{dM(\theta m)}{dt}\omega m \quad i + M(\theta m)\frac{di}{dt} \end{aligned} \tag{9}$$

Equations (9) equivalent to Equation (7).

where the subtitles r and s are referred to rotor and stator dϕ/dt, is the flux linkage derivative, vabc is the voltage vector and iabc current vector, M is the inductance matrix. The inductance matrix depends on the rotor position M(θm), and consequently, a transformation is required to avoid this dependence. Thus, the three axes in the abc reference frame, are converted into a two axes system through the Park's transformation. Note, that the Parks' transformation in fact, results in a dq0 system. However, the zero-sequence component is not accounted here due to the fact that the induction motors have no neutral connection (i.e, an isolated wyre).

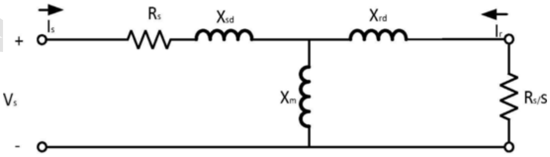

Fig. 2. Electrical Model of the Induction Motor for Steady-State Analysis.

It is important to note that once this transformation is done, assigning a reference is essential. The most common references are as follows; fixed reference $\psi = 0$ (stator reference), rotating reference $\psi = \omega m$ (rotor reference) or even a rotating synchronous reference $\psi = \omega s$ (synchronous reference), where ωs is $2\pi f$ and f is the system frequency, in this case 50 Hz. For this particular case, the stator reference is used, resulting in a fifth order model as follows:

$$\begin{gathered} Vsd = (Rs + ls\frac{d}{dt})isd + M\frac{d\ ird}{dt} \\ 0 = (Rr + lr\frac{d}{dt})ird + M\frac{d\ isd}{dt} + lr(\wp\omega m)\ irq + M\ (\wp\omega m)\ isq \\ Vsq = (Rs + ls\frac{d}{dt})isq + M\frac{d\ irq}{dt} \\ 0 = (Rr + lr\frac{d}{dt})irq + M\frac{d\ isq}{dt} - lr(\wp\omega m)\ ird - M\ (\wp\omega m)\ isd \\ \Gamma em - \Gamma load = J\frac{d\omega m}{dt} \\ \omega m = \frac{d\theta m}{dt} \end{gathered} \tag{10}$$

Equations (10) fifth order model.

where the subtitles r and s are referred to rotor and stator, the R is resistance value, L inductance value, ωm mechanical speed, ω electrical speed, d is referred to direct axes and q quadrature axes. In a single squirrel-cage induction machine the term of rotor voltages can be neglected due to the short-circuit connection in the rotor winding.

The two axes in stator reference frame are displayed in Fig. 3.

It is worthwhile to point out that, even though the induction motor coupled with a propeller in water applications, the torque is speed-dependent. Nevertheless, to simplify calculations, this torque will be considered fixed.

Accordingly, the fifth-order adopted model of the induction machine, expresses the rotor power as in equations (6):

$$\mathrm{Pr} = -\mathrm{Re}\left\{ Rr\,\overrightarrow{ir}\,\overrightarrow{ir^*} + \overrightarrow{ir^*}\frac{d\psi r}{dt} + j(\omega s - \omega r)\overline{\psi r}\,\overline{ir^*} \right\} \tag{11}$$

Equations (11) rotor power.

where the first term of equations (6) represents the rotor losses, the second the magnetic-flux derivative and the third the electromagnetic power.

Synchronous machine equations

The electrical equations in dq axes of the synchronous generator are defined by the fifth-order model equations (12):

$$\begin{aligned} vsd &= -Rs\ isd + \frac{d\ \psi sd}{dt} - \omega r\psi q \\ vsq &= -Rs\ isq + \frac{d\ \psi sq}{dt} - \omega r\psi d \\ efd &= Rfd\ \ ifd + \frac{d\ \psi fd}{dt} \\ 0 &= Rkd\ ikd + \frac{d\ \psi kd}{dt} \\ 0 &= Rkq\ ikq + \frac{d\ \psi kq}{dt} \end{aligned} \tag{12}$$

Equations (12) electrical equations in dq axes of the synchronous generator.

where the term efd is the field voltage and the rest of subtitles have been defined above. Note that the field voltage value depends on the (AVR) parameters. In order not to unnecessarily extend the document, in the following references a detailed comparison between types of excitations and (AVR) can be found [40]. Essentially, what characterises the type the response of an (AVR) is the type of regulator and its settings (i.e., P, PI or PID regulators) as well as the reference values type of control (i.e., voltage control or isochronous mode). Lastly, note that a detailed explanation about the (AVR) used in our study is provided in section III.1.4.

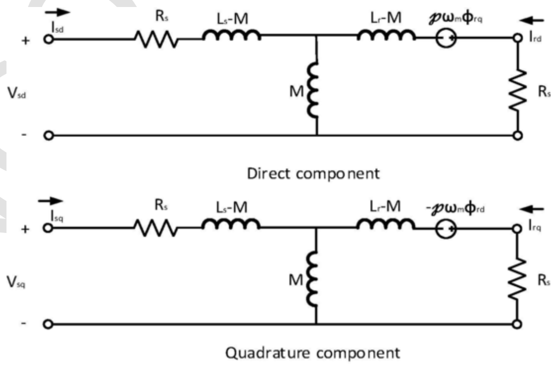

Fig. 3. Electrical Model of the Induction Machine in dq Components.

2. Equipment and procedure for experimental validation

The Electrical Engineering department of UPC located in the "School of Nautical Studies of Barcelona" (FNB / UPC -Barcelona Tech), conducted a complete test program in order to demonstrate the dependability of the proposed stability criteria for onboard generator during transients produced by direct on-line induction motors (IM) starting. Additionally, in the case of the propeller induction motor (IM), tests were carried with and without a variable speed drive (VSD) [41].

A preliminary study has been carried out by the same authors to evaluate the stability during severe electrical transients for the hybrid propulsion platform at the Barcelona Marina 92 dock, with no submerged operational propeller. Moreover, a maths three-phase model has been developed to carry out a model validation, see: [42]

The present article goes beyond the aforementioned study, thus, by adding a submerged propeller to observe the differences in the system behavior with and without load.

A large test program and data set were captured registered and evaluated in this complete hybrid electric propulsion system platform; see Fig. 3 below.

Criteria 1: Direct on-line Start Sequence of the induction electrical motors to produce, measure and record strong current transient.

Criteria 2: Oversize of the alternator

Tests are recoded to verify the Criteria 3 (Efficiency of the E-Control Systems).

This test platform has an essential variation when compared with a conventional power plant: the power of the alternator (175 kVA) is almost double the power of the reciprocating internal combustion engine (91 kW).

This completely intentional act has a double beneficial effect ,on the one hand compensating for the fact that the maximum overload capacity of a synchronous alternator (Criteria 5) is 3 times its nominal current yet the induction motors (IM) it feeds can consume up to 7 or 8 times its nominal current , on the other hand the benefit of its greater kinetic energy due to its greater mass (Criteria 4**)** which acts as a kinetic energy accumulator, also helps in cases of transient due to start of induction motors (IM).

The Power part of the test platform showed in Fig. 4, is composed of:

- Compressed Natural Gas (CNG), bottles at 100 bars of pressure with their reduction system device at 1 bar
- Reciprocating 4 S internal combustion engine, with power of 91 kW and Otto thermodynamic cycle operating with (CNG)
- Electrical Alternator, 175 kVA Synchronous machine with a (AVR) system supplied by a Brushless Permanent Magnet Synchronous Generator (PMSG), one of the best control systems of Voltage and Reactive Power.
- Submerged 22 kW Propeller Induction Motor (IM) supported by a strong metallic fixation structure in which two load cells are included to measure the tensile forces. The propeller is also equipped with an adjustable pitch system control to modify the load as well as two different types of blades, metallic and polymer, for the same purpose.
- Auxiliary 20 kW induction Motor (IM), with just its Inertial load.
- Auxiliary 55 kW induction Motor (IM) with an electromagnetic brake of 150 kW fed by batteries to manage the level of load.
- Variable speed drive (VSD) of 75 kW only for the propeller (IM), with a contactor bypass in case of breakdown, allowing the transient regime and the cyclic overload of the propeller to be studied.

The tests were carried out at the Marina Barcelona 92 harbor, during the week starting February 5th, 2018.

For better comprehension the power block diagram connection is shown below in Fig. 5:

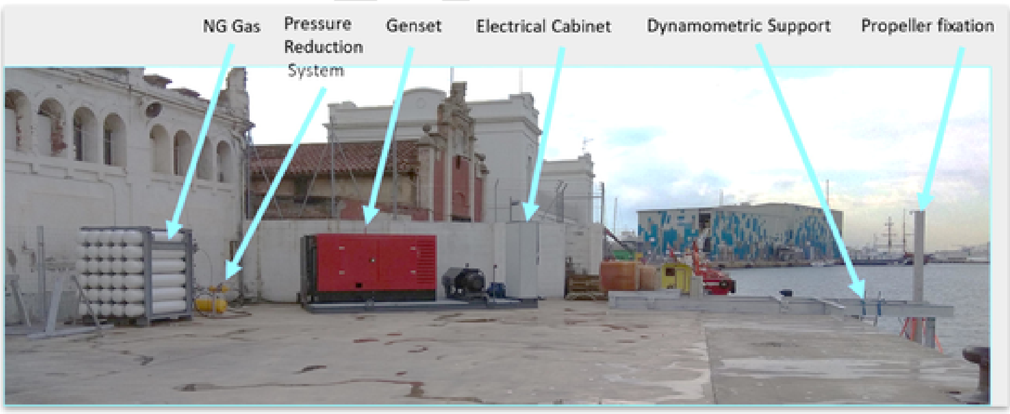

Fig. 4. Test Platform, a complete Hybrid Marine Electrical Propulsion Plant, General View"

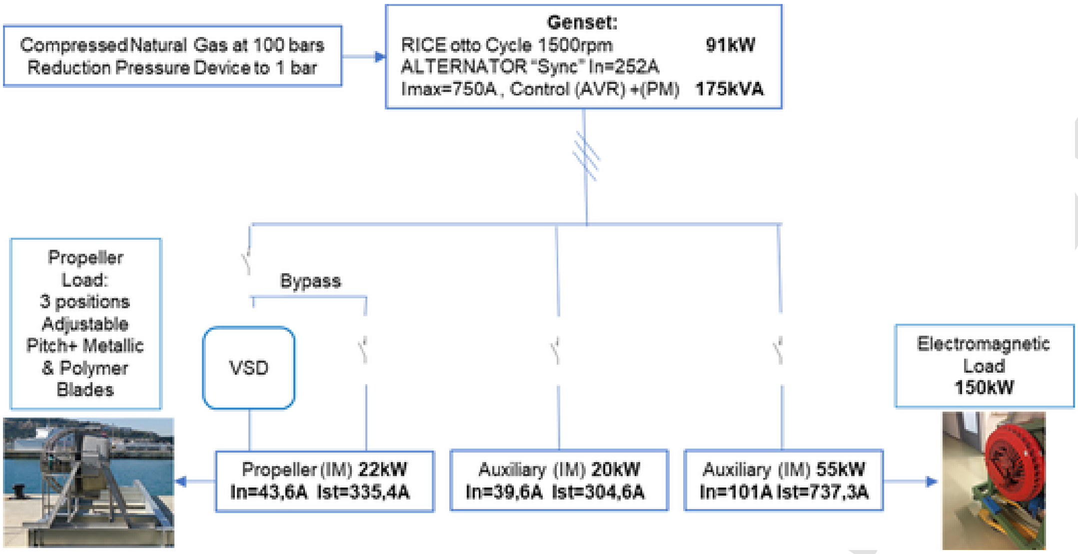

Fig. 5. Power Block Diagram.

2.1. Description of the tests platform

The main elements of the test propulsion platform are:

2.1.1. Propeller mechanical fixing

The adjustable-pitch propeller assembly was fixed by a vertical tube at a depth of 2.5 m with a very strong metal structure to withstand hard tensile forces and avoid vibrations that would not allow clear records to be obtained.

A special assembly was made to allow the free rotation of the propeller in 360° enabling forward, reverse and oblique movements to be simulated.

Special attention was paid to the safety of our human team working in the area by securely fixing the structure with redundant braces and having handles to hold in case of sudden jolts due to the start of the propeller induction motor. See Fig. 6 below: [43]

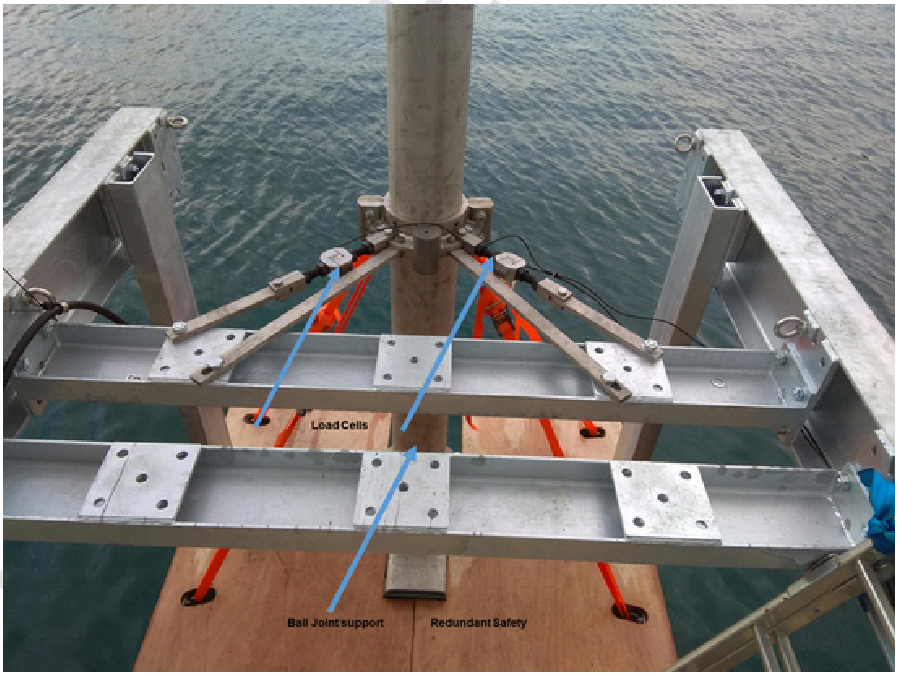

Fig. 6. Redundant Braces.

2.1.2. Reciprocating internal combustion engine (RICE)

The main characteristics are:

- Company Manufacturer: Power Solutions International "PSI"
- Engine capacity: 8.8 L
- No of cylinders: 8 in V disposition
- Type: V4 Stroke, Naturally Aspirated and cabinated as Stationary
- Bore: 110,5 mm
- Stroke:114,3 mm
- Power output: LNG at 1500 rpm, 94 kW (50 Hz); 1800 rpm, 113 kW (60 Hz)
- Power output: CNG at 1500 rpm, 91 kW (50 Hz); 1800 rpm, 109,2 kW (60 Hz)
- Exhaust back pressure [mm Hg] at 1500 rpm 26 mm, 1800 rpm 31,6 mm
- The mass flow rate of CNG at 1500 rpm 230 grs/hp-hour, 1800 rpm 590 grs/hp-hour

2.1.3. Alternator

The type of alternator installed in the Genset was Synchronous with an (AVR) system, provided by a Brushless Permanent Magnet Synchronous Generator (PMSG), to control Reactive Power-Voltage. The main features of the generator are detailed below:

- Apparent Power S = 175 kVA
- Voltage V = 400 V
- Nominal Current In (at rated power) In = 252 A
- Imax = 752 A (Short- Circuit Current)
- Mass = 659 Kg
- Inertia = 1.93 kgm2

2.1.4. Automatic voltage regulator (AVR)

The (AVR) system controls the excitation system to stabilise the output voltage against transient load variations, acting on the electromotive force through the excitation current. Its effectiveness was duly demonstrated during the test.

The main electrical data of the (AVR) system is:

AC Power input from the (PMSG) (Max. values): Vn = 170–220 V, 3 phases, In = 3 A/phase and f = 100–120 Hz.

DC Output of the (AVR) (Max. values): Vn = 120 V, In = 3.7 A (permanent) and Imax = 6 A (for 10 s).

2.1.5. Induction motors (IM)

The main characteristics of the Induction Motors (IM) selected, installed and connected on the platform to perform the test program are as follows: [44,45,46,47]

- IM (Electromagnetic Braking Motor): 55 kW, Pn = 55 kW, Vn = 400 V, Nominal speed = 1.484 rpm

  In = 101 A, Ist = 737,3 A

- IM (Propeller): 22 kW, Pn = 22 kW, Vn = 400 V, Nominal speed = 1.470 rpm

  In = 43,6 A, Ist = 335,4 A

- IM (Auxiliary): 20 kW, Pn = 20 kW, Vn = 400 V, Nominal speed = 1.470 rpm

  In = 39,6 A, Ist = 304,6 A

Where Pn is the rated power, Vn is the rated voltage, In is the rated current and Ist is the starting current.

2.1.6. Electrical cabinet and instrumentation

The start/stop orders of the induction motors during the test program were carried out manually and recorded by the multichannel network recorder, collecting data in 40 channels reading mechanical and electrical parameters such as Speed, Tensile Forces, Torques, Active Power, Reactive Power, Frequency, Current, and Voltage of the alternator and finally Current and Frequency from the VSD [48].

The personal computer (PC) correctly stored, managed and set up the information recorded.

The propeller induction motor (IM) was driven by a variable speed drive (VSD) of 75 kW with the possibility of direct Bypass, as shown in Fig. 5. The (VSD) and the main contactors, switches and protections were installed in the electrical cabinet [49].

The electrical power and control cabinet contains the following tools: [50,51]

- Personal computer (PC)
- Programmable logic control (Plc)
- Variable Speed Drive (VSD)

- Circuit breakers (CB)
- Data collection elements
- Data Communications units
- Temperature alarm propeller induction motor
- Other Protections

All these elements of the test platform described can be seen in Fig. 7 below.

For clarity, there follows a drawing of the block diagram corresponding to the logic of acquisition, registration and storage of the data obtained in the different tests carried out. See Fig. 8 below:

The protections incorporated by software in the alternator are listed below:

- Under frequency protection (UFP): The UFP is set to 95% of the nominal frequency, i.e. 47.5 Hz.
- Overcurrent protection: This parameter limits the starting current and cases of failure.
- Overvoltage protection (OVP): The OVP is set to 300 V with a fixed time delay of 1 s.
- Overexcitation protection (EPO): This feature allows the system to be disconnected in case the DC field voltage of the excitation system exceeds 75 V, considering a delay of 8–15 s.

Fig. 7. Genset, IM Motors and Cabinet.

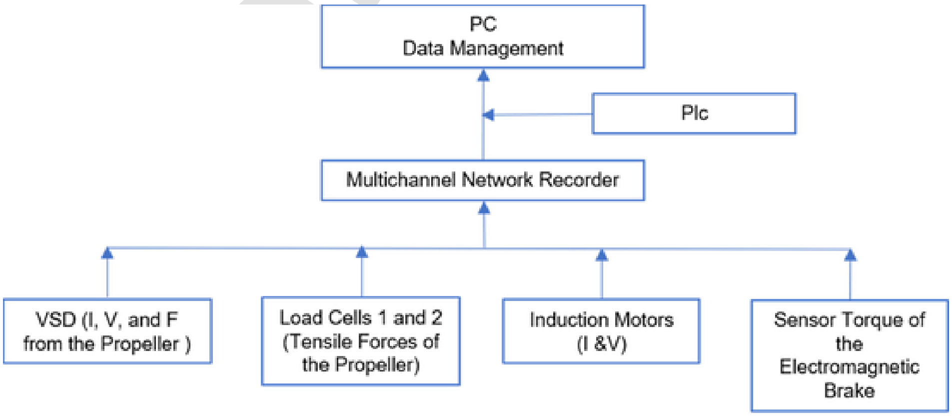

Fig. 8. Logic Block Diagram.

Fig. 9 shows the elements that compose the Electrical cabinet for Control & Operations.

3. Methodology

The method used in this work consisted of carrying out a set of tests to generate strong transients with the main target of finding stability criteria to establish limits of designing with commercial devices.

Of the many tests performed, we have chosen to show those that have given us more visibility of the problems during the direct on-íne start of the induction motors (IM), reaching limit conditions mainly in terms of Voltage & Frequency drop as well as Current rise, including situations of "Power Blackout".

For this purpose, the data has been generated with sufficient sampling criteria and through the following test blocks:

1. General transient as a first visualisation of the problems.Tests carried out the 8th February 2018.
2. Zoom1 :Direct on-line start of the 55 kW and 22 kW (IM).
3. Zoom 2 :Direct on-line start of the 22 kW (IM).
4. Zoom 3 :Start of the Propeller 22 kW (IM) with a (VSD).
5. Zoom 4: Start of the Propeller 22 kW (IM) with a (VSD) and Direct on-line Start of the 20 kW (IM) and 55 kW (IM). **"Automatic disconnection of the Electronic Drive (VSD) and the Propeller".**
6. Zoom 5 :Start of the Propeller 22 kW (IM) with a (VSD) and Direct on-line start of the 55 kW (IM).

"Automatic disconnection of the Electronic Drive (VSD) and the Propeller".

7. General transient as a first visualisation of the problems.Tests carried out the 9th February 2018.
8. Zoom 6 : Direct on-line Start of the 3 (IM), 22 kW, 55 kW and 20 kW.
9. Zoom 7 : Direct on-line start of the 20 kW and 55 kW (IM) with the 22 kW (IM) propeller motor working in direct on-line.

All these records, duly commented in detail and including data and graphs, are described in Chapter V: "Performed Test".

4. Performed tests

A set of tests were carried out with all the induction motors (IM) ; the figures and graphs below show the impact and variation in the mechanical and electrical variables such as: Tensile Forces, Voltage, Active Power, Output Current and Frequency of the alternator , and the Output Current and Frequency from the (VSD) during the start/stop transient process of the induction motors (IM).

The start/stop sequence of the induction motors (IM) during the days of tests shown below, had previously been studied in great detail in order to produce transient events and therefore find the main reasons for it.

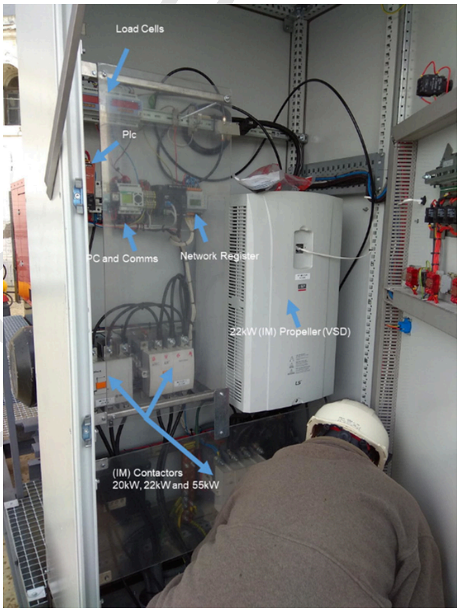

Fig. 9. Main Cabinet.

The main magnitudes recorded during the measurements are identified as follows:

- Variable Speed Drive (VSD) Output current (A) as blue.
- Variable Speed Drive (VSD) Frequency (Hz) as red.
- Tensile Force in Cell load n° 1 (kp) as yellow.
- Tensile Force in Cell load n° 2 (kp) as purple.
- Alternator, Voltage/10 (V) as green.
- Alternator, Active Power (kW) as blue.
- Alternator, Output current (A) as red.
- Alternator, Frequency (Hz) as blue.

The load in the 22 kW propeller induction motor (IM) was modified by changing the pitch and the blades type, in the 55 kW induction motor (IM) by adjusting the electromagnetic brake and in the induction motor (IM) 20 kW was always the inertial rotor influence.

4.1. Summary of the tests carried out the 8th February 2018, as a first visualisation of the problems

During the first day of tests February 8th, 2018, with the propeller equipped with metal blades that produce heavy load, 4000 lines of full data were recorded over slightly more than 9 min in total. The main highlights of the graphs are plotted and their values are indicated (x (date or sample), y(value)). The data sampling frequency during acquisition was Fs = 7.57 s / s.

Fig. 10 provides a general overview of the recorded events during the first tests. Particularly, by observing this figure, each test belongs to a particular time instant. As mentioned above, each magnitude is plotted in a different colour. Since in Fig. 10 all events are displayed in a time-series, in order to observe each particular event, Figs. 11, 12,13,14, and 15 display the results separately.

4.1.1. Direct on-line start of the 55 & 22 kW (IM)

Zoom n°1 Fig. 11 below, shows the following duty cycle of 68 s, that was carried out to force transient events:

1. Direct on-line start of the electromagnetic braking 55 kW induction motor (IM).
2. Stop of the electromagnetic braking 55 kw induction motor (IM).
3. Direct on-line start of the propeller 22 kW induction motor (IM) at maximum power of 22 kW, 50 Hz.
4. Stop of the propeller 22 kW induction motor (IM).

During the direct on-line start of the 55 kW induction motor (IM) we find a large current increase in the alternator (red) rising to 74.4 A for 2,6 s. There was also a slight increase in active power (less than 25 kW) followed by a Voltage reduction (-2,3%) and finally there was a full recovery of all the main parameters.

The same occurred at the direct on-line start of the 22 kW Propeller induction motor (IM), but reaching 48 A.for 1,8 s.and with a Frequency drop (-2%).

The Load cells registered mechanical vibrations after the stop of the 22 kW induction motor (IM) [52].

The reduced impact is clearly due to the oversizing of the alternator.

Criteria 2: Oversize of the alternator

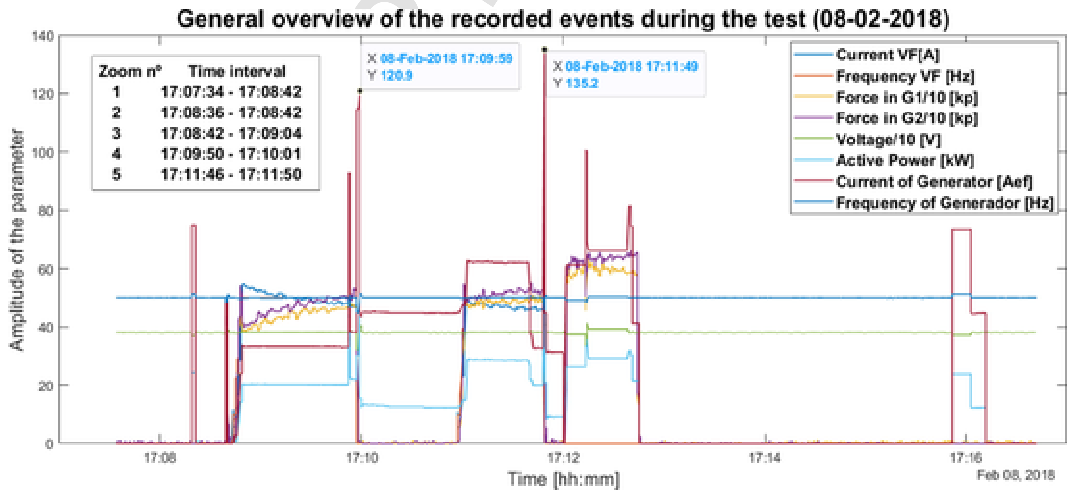

Fig. 10. General Overview 8-02-2018.

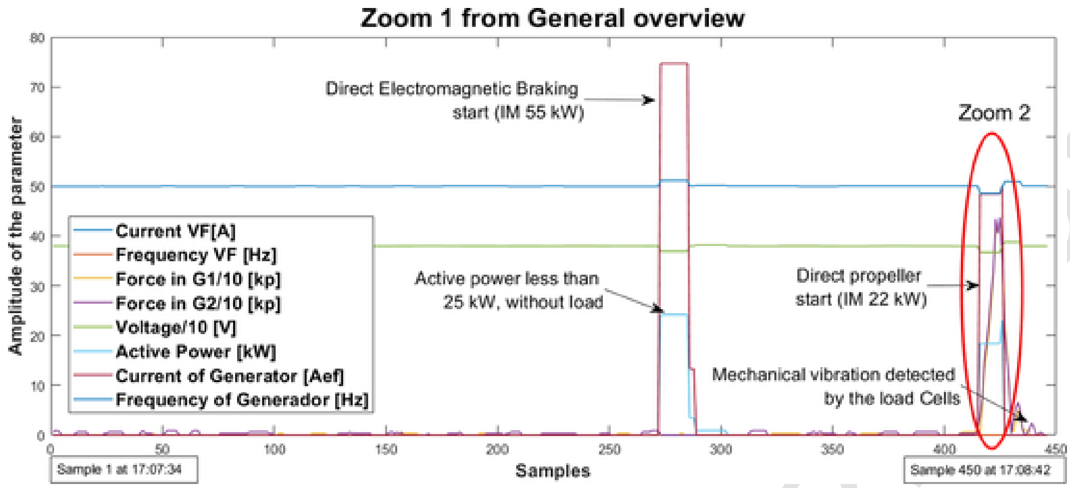

Fig. 11. Zoom n° 1.

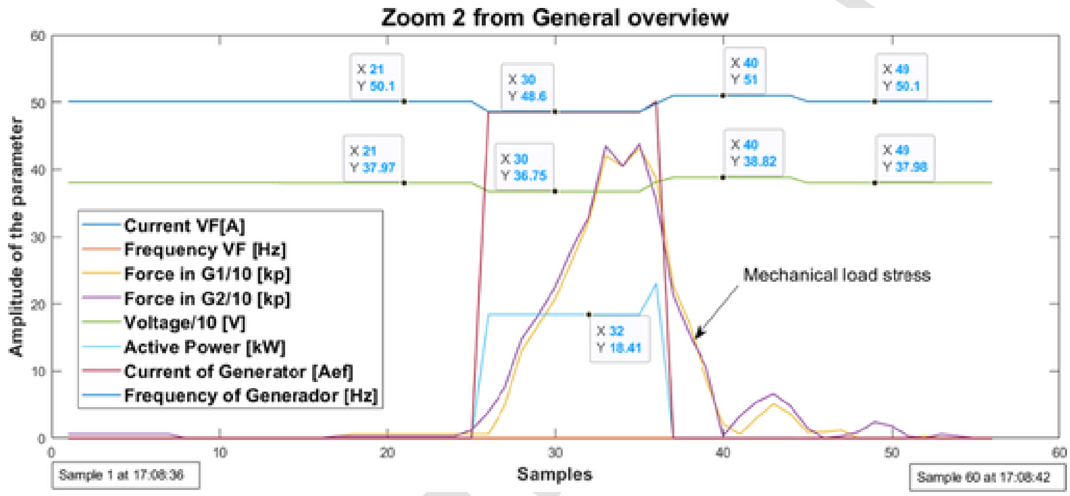

Fig. 12. Zoom n° 2.

4.1.2. Direct on-line start of the 22 kW (IM)

Zoom n° 2 Fig. 12 below, shows in more detail the transient events during the direct on-line start of the 22 kW Propeller induction motor (IM)

The following duty cycle of 6 s. was carried out to force transient events:

1. Direct on-line start of the propeller 22 kW induction motor (IM) at a maximum power of 22 kW, 50 Hz.
2. Stop of the propeller 22 kW induction motor (IM).

The generator voltage (green) and the frequency (blue) oscillate for 2 s., the frequency drops from 50.1 Hz to 48.6 Hz (-3%) followed by slight overspeed up to 51 Hz and a final recovery to the original value of 50.1 Hz [52].

There is a similar oscillation in voltage, from 379.7 V dropping to 367.5 V (-3%), and a slight overvoltage to achieve 388,2 V, with a final recovery to the original value of 379.8 V.

As in the previous tests, the smooth response achieved during the transient is due to the criteria mentioned below:

Criteria 2: Oversize of the alternator & Criteria 3: Efficient operation of the E-Control systems.

4.1.3. Start of the propeller 22 kW (IM) with a (VSD)

Zoom n° 3 Fig. 13 below,shows the following duty cycle of 22 s., to force transient events:

1. Start with a variable speed drive (VSD) of the Propeller 22 kW induction motor (IM) at a maximum power of 22 kW, 50 Hz

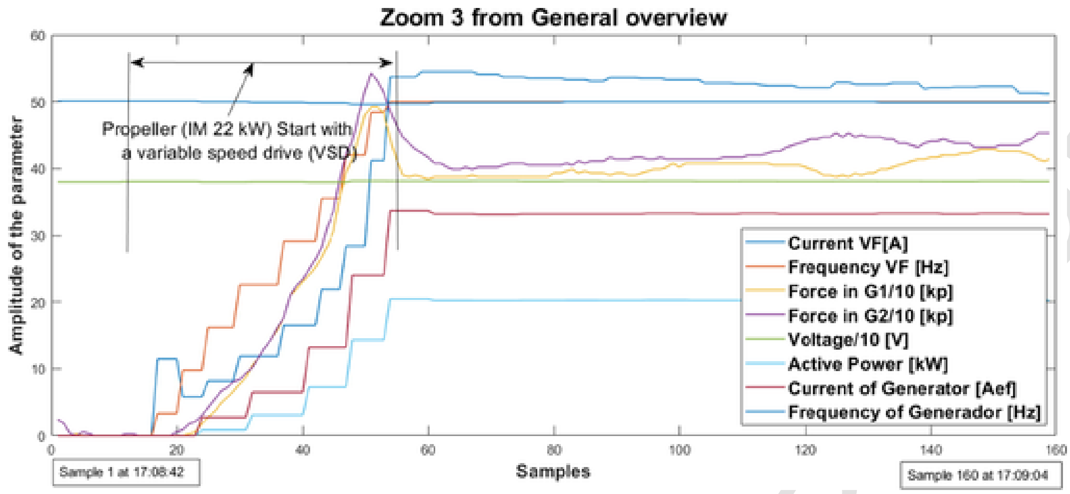

Fig. 13. Zoom n° 3.

The 22 kW Propeller induction motor (IM) follows the start ramp previously set up in the parameters of the electronic drive , step by step until reaching the nominal Frequency of 50 Hz (dark blue). The transient start takes 7,3 s. approximately and achieves the maximum tensile force of 355 kp, having a heavy load close to 22 kW, with 54 A (VSD) current consumption (blue), being the rated current of the induction motor (IM) 43,6 A.

Voltage and frequency remain stable; the rest of the variables follow the reference speed steps.

The VSD electronics is limiting the start current and this is the reason for the low impact.

4.1.4. Start of the propeller 22 kW (IM) with a (VSD) and the direct on-line start of the 20 kW & 55 kW (IM)

Zoom n° 4 Fig. 14 below, shows the folowing duty cycle of 11 s.,that was carried out to force transient events:

1. Propeller 22 Kw induction motor (IM) being driven by a (VSD) at the maximum power of 22 kW, 50 Hz.
2. Direct on-line start of the auxiliary 20 kW induction motor (IM), inertial load.
3. Trip of the (VSD), the orange line. **"Automatic trip disconnection".**
4. Direct on-line start of the auxiliary 55 kW induction motor (IM), inertial load.
5. 20 kW & 55 kW induction motors (IM) continues running with the inertial load.

During the transient start of the 20 kW induction motor (IM) which takes 550 ms, the generator current rises to 92,7 A from the 38 A that the (VSD) (red) was consuming, the frequency drops from 50,7 Hz to 46,9 Hz (-6,2%) (blue). In comparison, the active power increases with a gradient of 0.475 kWs/kVA of 20 kW (light blue) and voltage drops from 380,8 V. to 358,1 V (−6%) (green).

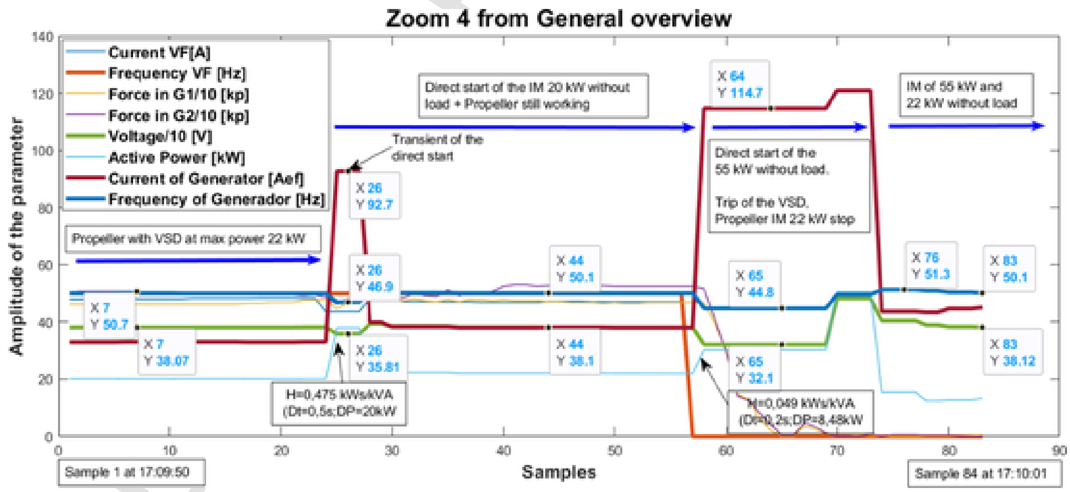

Fig. 14. Zoom n° 4.

Frequency and current of the alternator recovered at values of 50,1 Hz and 380 V respectively.

At the direct on-line start of the 55 kW induction motor (IM) after the (VSD) (Blackout) trip, the alternator current rises to 114,7 A from 40A (red) for 2,8 s. while the frequency drops to 44,8 Hz (−10,4%) (blue) and the voltage to 321 V (-15,5%) (green) to achieve a full recovery after the start transient time.

The active power increases with a gradient of 0.049 kWs / kVA to reach 8,5 kW.

Frequency and Current of the alternator recovered at values of 50,1 Hz and 381,2 V respectively.

The (VSD) was stopped automatically with a fast ramp, due to a “Blackout” The system remains stable after the start of the 20 kW induction motor (IM), but just at the start of the 55 kW induction motor (IM) the VSD trips due to the low frequency and the operational voltage regulation produced by the transient. (see the orange line).

These strong transients with drops of (-10,4%) in frequency and (-15,5%) in voltage, were recovered by the alternator after a few seconds, due to its oversize and the good control of the reactive power, thanks to its electronic voltage regulation “AVR” and the right sequence of direct starts as well as the automatic disconnection of the “VSD” of the 22 kW Propeller for “Blackout”.

The generator inertia damped the speed vatiation, which is traduced in a smooth frequency deviation. Note that, in this case, there is only one generator, and therefore, the rotor speed deviations are directly traduced into frequency deviations.

Criteria 1: Start Sequence, Criteria 2: Oversize of the alternator, Criteria 3: E-Control systems, Criteria 4: Active Power & Criteria 5: Reactive Power.

4.1.5. Start of the propeller 22 kW (IM) with a (VSD) and direct on-line start of the 55 kW (IM)

Zoom n° 5 Fig. 15 below, shows the following duty cycle of 4 s.,that was carried out to force transient events:

1. Propeller 22 kW induction motor (IM) being driven by a (VSD) at full power and 50 Hz.
2. Direct **on-line** start of the 55 kW auxiliary induction motor (IM).
3. Trip of the (VSD), orange line **“Automatic trip disconnection”**.

With the alternator consumption current being 35 A (red), the direct on-line start of the 55 kW induction motor (IM) increases the current to 135,2 A and reduces the voltage to 320,2 V (-16%) (green). The transient takes 666 ms. Frequency variation was (-8,4%) to fall at 46,02 Hz.

The (VSD) was stopped automatically with a fast ramp, due to another case of **“Blackout”.** Just at the start of the 55 kW induction motor (IM), the VSD trips due to under frequency produced by the transient. (see the orange line).

The alternator would need an even a bigger oversizing due to the VSD trips of the Propeller induction motor (IM).

The system supports this strong transient but is out of tolerances in Voltage and Frequency, which incurs a strong risk of general **“Blackout”.**

Again, the impact has been absorbed by the alternator thanks to its oversize and the automatic voltage regulation device acting through the excitation current. The rotation inertia of the alternator damped the frequency variation.

Criteria 1: Start Sequence, Criteria 2: Oversize of the alternator, Criteria 3: E-Control systems, Criteria 4: Active Power & Criteria 5: Reactive Power.

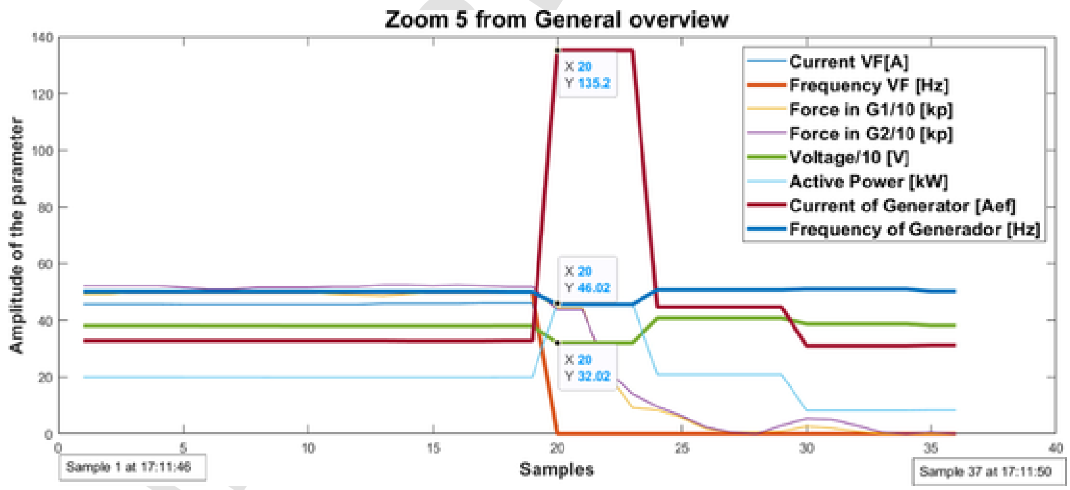

Fig. 15. Zoom n° 5.

4.2. Summary of the tests carried out the 9th February 2018, as a first visualisation of the problems

During the second day of tests February 9th, 2018, with the propeller equipped with metal blades that produce heavy load, full data were recorded over slightly more than 13 min in total. The main highlights of the graphs are plotted and their values are indicated (x (date or sample), y(value)). The data sampling frequency during acquisition was Fs = 7.57 s / s.

Fig. 16 provides a general overview of the recorded events during the tests of the second day. Particularly, by observing this figure, each test belongs to a particular time instant. As mentioned above, each magnitude is plotted in a different colour. Since in Fig. 16 all events are displayed in a time-series, in order to observe each particular event, Figs. 17 and 18 display the results separately.

4.2.1. Direct on-line start of the 3 (IM), 22 kW, 55 kW and 20 kW

Zoom n° 6 Fig. 17 below, shows the following duty cycle of 62 s.that was carried out to force transient events:

1. Direct on-line start of the propeller 22 kW induction motor (IM) at full power and 50 Hz.
2. Direct on-line start of the electromagnetic braking 55 kW induction motor (IM), inertial load.
3. Direct on-line start of the auxiliary 20 kW induction motor (IM), inertial load.
4. Stop of the 20 kW and 55 kW induction motors (IM).

Due to the second direct on-line start raises the alternator current again to 138 A, its transient takes 1,8 s. and finally, the direct on-line the first direct on-line start of the 22 kW (IM) the alternator current consumption raises to 62,5 A (red) and the transient takes 1,7 s.; start of the 20 kW raises the current even more to146 A (alternator nominal current 252 A) with a transient time of 2,1 voltage drop (-8%) and frequency (-13,3%).

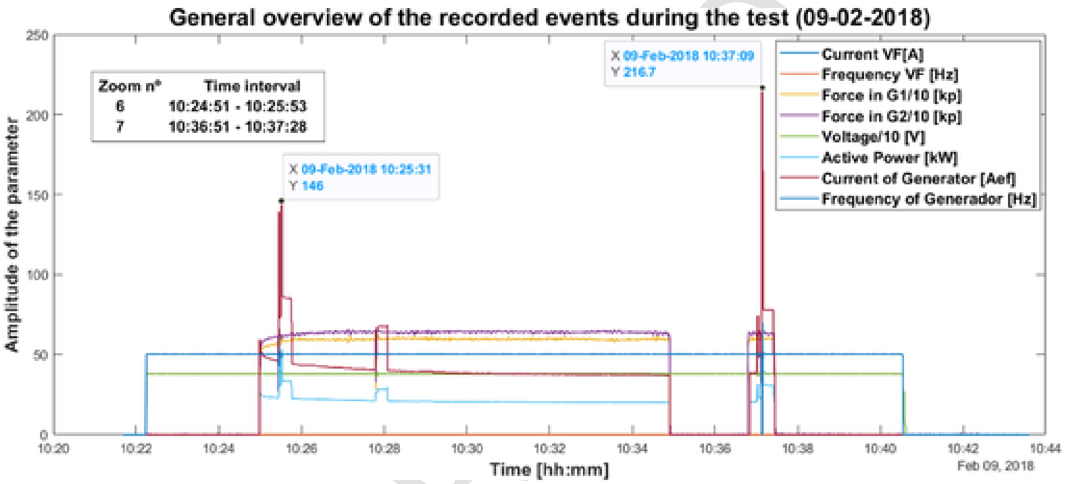

Fig. 16. General Overview 9-02-2018.

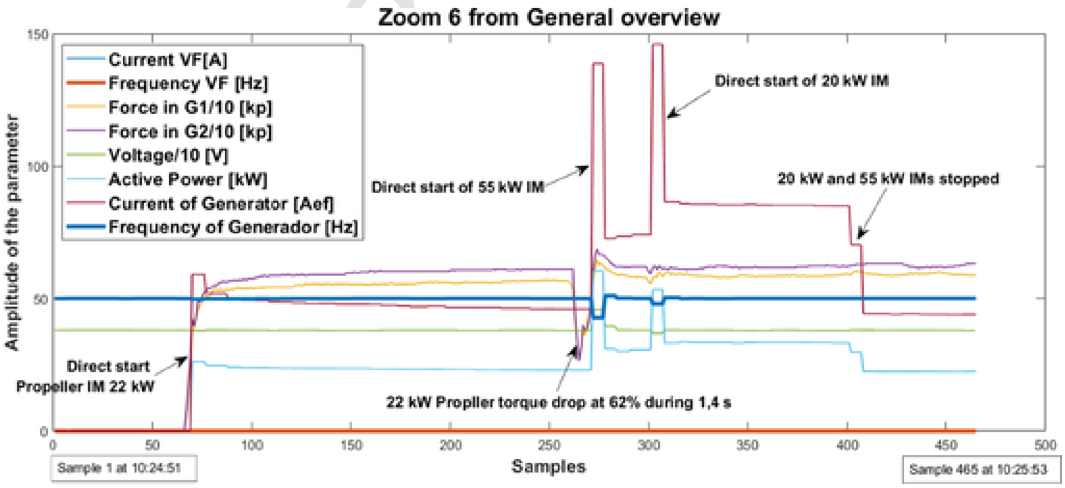

Fig. 17. Zoom n° 6.

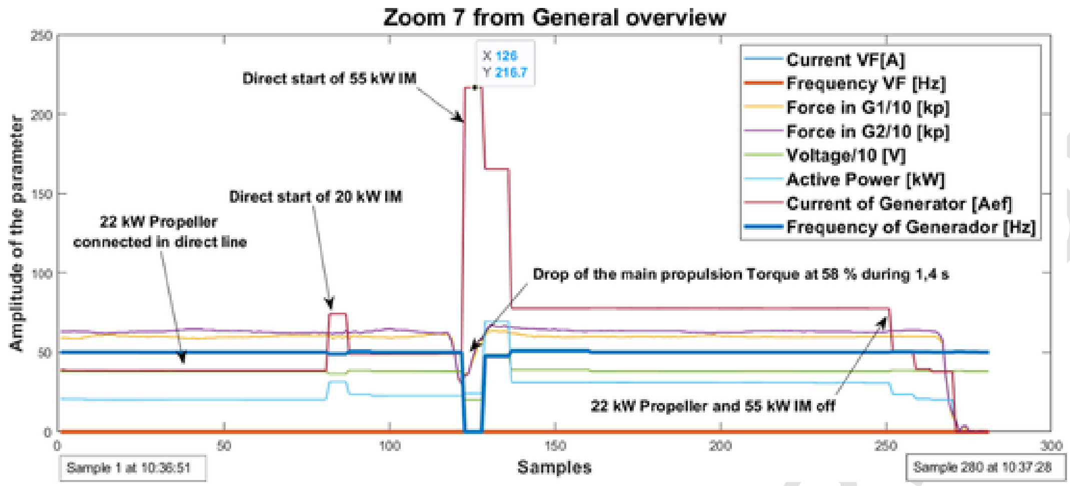

Fig. 18. Zoom n° 7.

The appropriate sequence of switching operations, the size of the alternator (i.e., which has been oversized to provide larger inertia) and the proper AVR settings has provided an acceptable response.

It is worth noting that the AVR settings play a pivotal role in this assessment, thus providing the required reactive-power. Therefore, the type of control (i.e., voltage control or isochronous mode) will dictate the transient response.

Criteria 1: **Start Sequence, Criteria 2: Oversize of the alternator, Criteria 3: E-Control systems & Criteria 4: Active Power.**

4.2.2. Direct on-line start of the 20 kW & 55 kW (IM) over the propeller 22 kW (IM) in direct on-line

Zoom n° 7 Fig. 18 below, shows the duty cycle of 37 s. that was carried out to force transient events:

1. Propeller 22 kW induction motor (IM) being driven by a **contactor** at full power and 50 Hz
2. Direct on-line start of the auxiliary 20 kW induction motor (IM), inertial load
3. Direct on-line start of the electromagnetic braking 55 kW induction motor (IM), inertial load
4. Stop of all induction motors (IM), including the propeller

Given the observed voltage and frequency oscillations, it can be asserted that the induction motor operated by a switch provides a robust response when compared with the one supplied with VSD. Nonetheless, it is worth mentioning that, in terms of reliability, both options give us a dependable solution to achieve stable operation.

The control of the Propeller induction motor (IM) with a switch, helps to keep it working despite the large drop in Voltage and Frequency at the start of the 55 kW induction motor (IM). Driving the induction motors with a VSD is much more sensible than with a switch.

The RMS value of the current drawn by each motor when driving its propellers are as follows:

- The Propeller induction motor (IM) was consuming 30 A current (red) and the direct start of the induction motor (IM) 20 kW raised the alternator current to 70 A with a transient that takes 1,25 s.,
- The direct on-line start of the induction motor (IM) 55 kW raises the total current to 216,7 A (alternator nominal current 252 A) This last transient takes longer, 2,7 s. Voltage drops (-38%) and Frequency (-41%).

Note that the transient response has to be evaluated by observing the current waveform. However, these measurements are taken during the steady-state reached following the transient state caused by the motors starting the process.

As can be seen, an appropriate motor starting sequence, an oversized generator, as well as a proper voltage control implemented in the AVR, provides a robust response with avoids frequency and voltage out of range.

Criteria 1: **Start Sequence, Criteria 2: Oversize of the alternator, Criteria 3: E-Control systems, Criteria 4: Active Power & Criteria 5: Reactive Power.**

The torque falls for 1.4 s. was a reversible interruption of the propeller produced by the opening of the contactor due to the voltage drop.

In this set of tests we have proceeded to progressively separate starts and stops of three induction motors (IM) of 55 kW, 22 kW and 20 kW power, making up a total of 97 kW compared to a generator set consisting of a 91 kW thermal motor and an alternator of 175 kVA; despite this oversizing we have reached a current value close to the alternator nominal current of 252 A , which is almost twice the power of the combustion engine.

The rolling masses of the Thermal Motor and the alternator provide the necessary active energy, during the transients, to dampen the frequency drop.

Note that even with this oversizing:

- The maximum transient variation in Voltage recommended by the main Naval Classification Societies is ± 20%, and we have reached (-16%) in several cases and (-38%) in the last one. With a VSD it is easier to get a "Blackout "due to Voltage drop than with a switch.
- The maximum transient variation in Frequency recommended by the main Naval Classification Societies is ± 10%, and we have reached (-15,5%) and (-41%) in the last one.

While the deviations of the Voltage and Frequency happen during few seconds, the risk of a general "Blackout" is very significant.

The oversize of the alternator prevents the "Blackout" situation but is not enough to avoid unacceptable temporary interruptions of propulsion, due to the direct on-line start of other induction motors (IM) on board. This is an essential subject, principally when we are in manoeuvring mode in harbour operations.

This fact and the other results of the test records analysed have led us to the conclusions with respect to the main stability criteria that must be taken into account when designing and sizing a marine power generator set to prevent "Electrical Blackouts" .Further discussions are described in Chapter VI:"Discussions".

5. Discussions

The committees who evaluate the significant incidents in maritime affairs in each country has reported numerous cases where economic and social consequences occurred. A review of reported incidents can be found in section II.2 "Blackouts in Ships".

The use of the "Marina 92″ hybrid propulsion platform in Barcelona built in 2018, this time with a submerged propulsion propeller with real load, adjustable pitch blades, frequency inverters (VSD), induction motors (IM) with variable load and a 175 kW alternator in front of a thermal engine powered by 91 kW compressed natural gas, as well as all the electronic equipment necessary for the registration and processing of mechanical and electrical parameters, have allowed us to perform Start/Stop duty cycles of induction motors (IM) chosen in detail to simulate risk situations and to determine the criteria that help engineers to safely design the power plants of future ships.

The transient caused by the induction motors during the direct on-line start operation implies large over-currents (e.g., up to several times the rated current). Hence, the higher is the generator short-circuits current capacity, the lower will be the voltage and frequency drop during this transient.

Based on the previous premise, it is deduced that the generator (in this case a synchronous generator) has to be oversized to fulfil seamless transitions.

Based on the above, it seems clear that the traditional criteria established by the "practical engineers" in the maritime sector where the sizing of the alternator meets the load capacity, proved to be inappropriate for transient purposes. Thence, it can be highlighted the fact that if the size of the alternator has the same capacity as the load rated value, the stability of the system during this severe transient can be seriously undermined.

Lastly, it is worth pointing out the fact, that the manufacturer provides the motors rated value in kW and the alternator size is provided in kVA (i.e., its apparent power) therefore, this reinforces the thesis of oversizing the alternator.

The summary of the test and comments are listed in the below Table 4:

The correct dimensioning and selection of elements such as the electronic regulation (VSD) and the starter contactors of the electric motors, are essential to avoid these temporary losses of propulsion that can cause so much damage to the people on board and to the ship itself.

It has been demonstrated that the oversize of the alternator becomes a key to ensuring a stable source of energy onboard, as well as other factors described in Chapter VII: "Conclusions"

Table 4
Summary of the Tests.

Test Reference	Type of IM (Rated power)	Voltage Variationp (% of rated RMS value)	% F Variation	Current increase (% of rated RMS value)	Maximum current (A)	Event description
Fig. 11	55 & 22 kW	−2,3%	−2%	N/A	74,4 & 48	**Soft variations, No Failure**
Fig. 12	22 kW	−3%	−3%	N/A	43	**Soft variations, No Failure**
Fig. 13	22 kW VSD	Progressive	Progressive	VSD	54	**Very Soft variations, No Failure**
Fig. 14	22 VSD & 20 & 55 kW	−6% & −15,5%	−6,2% & −10,4%	+ 242% & + 300%	92 & 120	**Partial "Blackout" VSD Trip Over Current 120 A**
Fig. 15	22 VSD & 55 kW	−16%	−8,4%	386%	135,2	**Partial "Blackout" VSD Trip Over Current 135 A**
Fig. 17	22 & 55 & 20	−8%	−13,3%	+ 237%	148	**Strong variations 148 A, No Failure**
Fig. 18	20 & 55 & 22	−38%	−41%	+ 434%	217	**Very Strong variations252 A, No Failure**

6. Conclusions

After the analysis of the registered files, the first essential Criteria found lies in the correct start sequence of the onboard induction motors (IM). An in-depth study is required mainly for those of higher kW rating to avoid frequent "Blackouts" due to improper starting sequence. Electrical interlocks should prevent it from exceeding three times the nominal current of the alternator.

The second Criteria and probably the most important is the need to oversize the alternator to avoid problems in the operational voltage regulation after severe transients.In our test platform, the power of the thermal engine is 91 kW, and the electric generator is 175 kVA which has enhanced the stability during the direct on-line start of the induction motors (IM) due to the higher power generation capacity of the alternator.

The third Criteria for power system stability is the correct and efficient operation of the Electronic control systems, such as the Automatic Voltage Regulation (AVR) working in the platform that recovers voltage and frequency after hard transients, due to the direct start of induction motors (IM). These systems also prevent Variable Speed Drive trip situations or the temporary opening of the contactors, which are unwelcome in naval electric power applications.

The fourth Criteria found is the high inertia of the generation system. The fact that the alternator has almost twice the power of the heat-engine acts as a reservoir of kinetic energy that dampens the Frequency drop and also improves the stability of the system.

The fifth Criteria to take into account is the need to have Reactive power available, both for the creation of the magnetic field necessary to start the induction motors (IM), and for the operation of the power generation system. This is solved by increasing the power of the alternator kVA, and with a proper regulation of the voltage and reactive power control.

One last recommendation, but not less important, is the human factor, and specifically "Training of onboard team" in the modern electrical Power Systems, Alternators, Active and Reactive power, as well as having onboard enough tools to analyse in-depth the different scenarios that may arise." Oscilloscopes" and "Data loggers", etc. must be considered as essential nowadays.

This test platform has also demonstrated the possibility of reducing CO_2 emissions, which today is one of the leading short-term concerns in maritime transport. In addition, it has been found that such a hybrid-electric propulsion system is more efficient and faster in response time than conventional ones.

This paper reflects a small part of the cases tested. It is for the reader to reflect on the dimensioning of the different elements whose selection criteria exceed the scope of this work

Declaration of Competing Interest

The authors declared that there is no conflict of interest.

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