Voltage Stability in Large Marine-Integrated Electrical and Electronic Power Systems

Giorgio Sulligoi, *Senior Member, IEEE*, Andrea Vicenzutti, *Student Member, IEEE*, Vittorio Arcidiacono, and Yuri Khersonsky, *Life Senior Member, IEEE*

***Abstract*—Offshore oil and gas vessels operating in deep and ultra-deep waters demand larger and more sophisticated power and control systems. This tendency brings new challenges in integrated power system's design, especially for platforms/vessels requiring both dynamic positioning and high levels of redundancy. Voltage stability is essential in such systems, being in islanded operation (with related limited power generation) and with continuously changing load demands. In particular, voltage stability issues can arise due to the increasing amount of power electronic converters installed onboard, used to feed variable frequency drives and other electronic loads. Indeed, most of these have a controlled front-end, whose control can affect network voltage with a destabilizing effect named constant power loads (CPLs) instability. Such a behavior deserves special attention in islanded power systems, mostly if the quota of power electronics loads on the total installed power reaches very high values (up to the 85% for new large all electric ships). This paper initially focuses on the CPL voltage instability. Two different models to assess voltage stability in marine systems with high penetration of electronic power conversion are given, focusing on a design-stage assessment. Using the conditions obtained by such models, a practical stability analysis methodology is proposed, to help assessing voltage stability already at design stage, to avoid equipment retrofits during vessel building or commissioning. Finally, some practical case studies are discussed, and solutions to overcome the CPL instability are suggested.**

***Index Terms*—AC power system, constant power load (CPL), dynamic positioning, electronic power converters, integrated electrical and electronic power systems, marine power systems standards, ships, stability assessment, voltage stability.**

I. INTRODUCTION

MARINE POWER systems have experienced a rapid evolution in the last decades, starting from the simple lights and radio electric supply systems adopted in the mechanical propelled ships from the early nineteenth century. The adoption of electric propulsion, together with the electrification of most of the onboard loads, has led to a revolution in both design and use of modern vessels. The drivers for this evolution process were efficiency, performance, reliability, quality of service, and safety. Nowadays, the will to achieve ever-higher performance levels for the stated drivers is causing further changes in marine electrical systems, pushing toward a pervasive presence of power electronic converters. Indeed, marine-integrated electric power systems (IEPSs) are rapidly evolving to the integrated electric and electronic power system (IEEPS) concept. The replacement of mechanical-driven equipment (such as pumps and compressors) with electrical driven ones is not sufficient anymore to achieve the high standards expected by the owners, so a step forward is ongoing: the introduction of high rates of electronic power converters to feed the loads. The adoption of variable frequency drives allows removing the complex and inefficient mechanical flow regulation equipment, thus allowing a more reliable, efficient, and performing operation. Moreover, the increasing interest into artificial lift systems, which are becoming more and more common in both onshore and offshore oil and gas installations, promotes an important rise into the total electric power to be installed onboard, causing, at the same time, a growth in the rate of loads supplied by electronic power converters. Indeed, these are necessary to regulate the production flow rate, achieved by changing the speed of electric pumps installed in the well. Besides the flow regulation application, electronic power converters are increasingly being adopted in marine power systems, whether they are integrated in UPS systems, or necessary for the new automation systems. Their utilization makes it possible to: achieve higher performance, increase redundancy, increase reconfiguration options, and raise overall efficiency. However, a drawback may arise, which is constant power load (CPL) voltage instability. In fact, a CPL tends to absorb a constant electric power in spite of the disturbances on supply network, behaving like a nonlinear load with a peculiar characteristic: when system's voltage drops, it increases the absorbed current. This behavior, which is the opposite of a conventional linear load (such as an induction motor), could cause instability in system voltage. CPL instability has been extensively analyzed in dc [1]–[5] and ac distribution systems [6]–[12]. The analysis in ac is more difficult, due to the increase in system's variables. In this paper, two models to assess stability in ac power systems in the presence of CPL loads will be presented, also trying to give a simplified approach dedicated to early design-stage assessment. The CPL behavior of electronic power converters is the downside of one of the main advantages of electronic power conversion: the ability to decouple the loads from the power supply, keeping constant voltages and/or currents supplied in spite of input variations. Indeed, the decoupling is achievable thanks to the

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G. Sulligoi, A. Vicenzutti, and V. Arcidiacono are with the Department of Engineering and Architecture, University of Trieste, 34127 Trieste, Italy (e-mail: gsulligoi@units.it; avicenzutti@units.it; vittorio.arcidiacono@libero.it).

Y. Khersonsky, retired, resides in Sunnyvale, CA 94087 USA (e-mail: ykhersonsky@ieee.org).

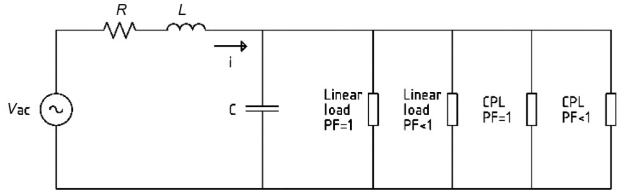

Fig. 1. Equivalent single-phase steady-state model (50/60 Hz).

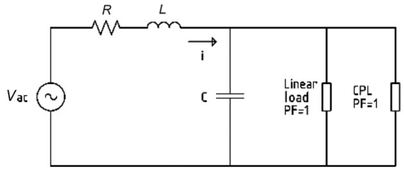

Fig. 2. Simplified equivalent single-phase steady-state model (50/60 Hz).

high control bandwidth, obtainable using static devices, which is directly linked with the control law embedded into the converter itself. When the converter control bandwidth is too high (set in such a way to tightly regulate the output variables), it can behave like a CPL. The possible destabilizing action of the converter depends not only on the bandwidth but also on system parameters and working point. Indeed, the same converter can hinder the stability of a system (behaving like a CPL) while in another can have no impact. In this paper, the assumption of ideal CPL loads has been made, with infinite control bandwidth, which is commonly considered as the worst case for stability. In the following, we present a methodology to assess system stability using the simplified models obtained beforehand. Finally, case studies will be shown, together with a discussion on system parameters influence and possible solutions to avoid instability.

II. Modeling for CPL Voltage Stability Analysis

A. Complete System Model—Steady State

An IEEPS consists of many different loads, fed through a distribution system by various power sources. Common power sources are diesel or gas turbine generators, but also feeders from land (shore connections for ships, submarine cables for offshore fixed platforms) or feeders from other installations (power supply of satellite offshore platforms). The distribution system could be really varied, ranging from simple single busbar radial distribution to complex multibusbars ring topologies with distributed generation. For what it concerns loads, most common are electric motors, powered either with or without electronic power converters, but also lighting and automation systems. Whatever the system is, through the application of Thévenin theorem, it can be modeled as a single concentrated power source feeding a set of equivalent loads through a concentrated parameters model of the network. A steady-state, single-phase equivalent model of the system is shown in Fig. 1. The entire network and generating system (composed by generators, cables, busbars, and transformers) are modeled by an ideal voltage generator (V_{ac}) feeding a RLC network, whose parameters are obtainable through Thévenin theorem as a composition of the component ones. All the loads connected to the distribution system are modeled into four different equivalent loads (whose total power is the sum of the single component ones) depending on their power factor (PF) and CPL behavior. The distinction between loads with unity PF and loads with nonunity PF is relevant for an exact analysis, because these two types of loads have to be modeled in different ways. Indeed, a unity PF load can be seen as a resistance, while a nonunity PF one introduces a reactive (i.e., inductive) component. This inductance adds a state variable to the system, causing the complexity of the model to increase, thus complicating the CPL voltage instability study. Moreover, the PF of single loads in the majority of cases depends on their working points, such as indirect online induction motors, or also in thyristor converters. In this paper, a simplified approach is given, to aid system designers in preliminary design stage. Due to that, in the following study, a major simplification hypothesis is adopted: all the loads are considered as unity PF, leading to the simplified equivalent single-phase steady-state model shown in Fig. 2. Such assumption makes it possible to assess system stability in an analytical and simple way, even if it can lead to a slight underestimation of the instability. In fact, the inductive components of the nonunity PF CPL loads worsen the stability (as clearly demonstrated in [7]), so ignoring them could lead to systems that are stable on paper but unstable when built. However, two reasons allow ignoring such components. The first is the focus on design-stage assessment applied in this paper. Indeed, for such application, this approximation could be acceptable, because at this design-stage system, parameters are only roughly defined. The second is the kind of power electronics converters commonly used in marine power systems. In fact, the highest power converters onboard a ship are propulsion ones, which can be either thyristor-based converters or voltage-source ones. In the former case, the PF can be lower than unity, due to the converter operation. However, such converters have a reduced control bandwidth, due to both propeller-axis mechanical constraints and intrinsic reasons (switching frequency limited by the network frequency). Due to that, thyristor-based converters can be hardly considered as CPL, thus limiting their impact on stability study. In the latter case, two additional cases can happen, depending on network converter's front end. If a diode front end is used, the resulting PF is sufficiently high to allow considering it to be equal to unity, while in case of an active front end, it depends on the embedded control law. The most reasonably one, thus commonly applied, involves keeping a unitary PF on network side, allowing applying the stated simplification without impairing the analysis. For what it concerns small power loads, their converters have common diode front end, allowing modeling them as unity PF loads. The PF of remaining loads, such as direct online motors, cannot be simply approximated to unity, but the modern approach, as stated previously, is to increase the rate of converter-driven applications, thus limiting the power of such loads.

B. Single-Phase Dynamic Model

A first analysis could be done considering a single-phase dynamic model of the system, following the approach given in [7]. For voltage-stability assessment, it is possible to apply the small-signal modeling approach, studying the variations of the system variables around a working point. Due to that, source system's voltage will be considered constant, due to the slower dynamic of generator's voltage controls with respect to CPL voltage-instability phenomena.

As well known, a CPL load can be modeled at small signals as a negative resistance (through linearization around an equilibrium point [8]), whose magnitude can be defined as follows:

$$R_{\text{cpl}} = \frac{V_0^2}{P_0} \tag{1}$$

where

R_{cpl} CPL loads equivalent resistance module;
V_0 busbar voltage at working point;
P_0 CPL loads total power.

For what it concerns linear loads, their small-signal model is a positive resistance, whose value does not depend on busbar's voltage but only on nominal voltage and loads equivalent power

$$R_{\text{lin}} = \frac{V_n^2}{P_{\text{lin}}} \tag{2}$$

where

R_{lin} linear loads equivalent resistance module;
V_n busbar nominal voltage;
P_{lin} linear loads total power.

Regarding the electric power source and the distribution network, the small-signal approach does not affect their models, being considered as linear. Using the stated load models, it is possible to define the small-signal equivalent circuit for the system, shown in Fig. 3. To avoid excessive notation effort during the analysis, the variables have been depicted without the variation symbol Δ; nevertheless, they have to be considered as variations with respect to the steady-state working point. Applying the Laplace transformation, the small-signal transfer function $(\Delta V_0(s)/\Delta V_{\text{ac}}(s))$ can be obtained [7], as shown in the following equation:

$$\frac{V_0}{V_{\text{ac}}} = \frac{\frac{1}{\text{LC}}}{s^2 + \left[\frac{L + \frac{RCR_{\text{lin}}R_{\text{cpl}}}{R_{\text{cpl}} - R_{\text{lin}}}}{\text{LC}\frac{R_{\text{lin}}R_{\text{cpl}}}{R_{\text{cpl}} - R_{\text{lin}}}}\right] s + \left[\frac{R + \frac{R_{\text{lin}}R_{\text{cpl}}}{R_{\text{cpl}} - R_{\text{lin}}}}{\text{LC}\frac{R_{\text{lin}}R_{\text{cpl}}}{R_{\text{cpl}} - R_{\text{lin}}}}\right]} \tag{3}$$

where

V_{ac} synchronous generators' internal emf (source system voltage at nominal working point). It can be considered equal to V_n for early design-stage assessment, but it depends on generator internal impedances and voltage droop constant;
R total series resistance between synchronous generators' internal emf (generation system) and busbar;
L total series inductance between synchronous generators' internal emf (generation system) and busbar. In small-signal modeling, it is composed of distribution system's series inductance and generators' subtransient reactance *x"*.

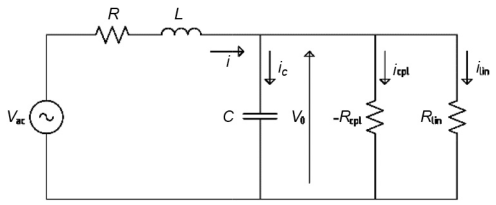

Fig. 3. Small-signal equivalent circuit for single-phase model.

C total capacitance connected in parallel to the busbar.

The stability of the system is tightly connected with the poles of the transfer function obtained, so two different approaches can be applied: calculation of the transfer function poles, to verify if they have positive real part (unstable poles); application of stability criteria, such as Routh–Hurwitz. By applying the second method to (3), the following necessary and sufficient conditions for small-signal stability can be deduced [7]:

$$R_{\text{cpl}} > (R \| R_{\text{lin}}) \tag{4}$$

and

$$P_{\text{cpl}} < P_{\text{lin}} + \frac{RC}{L} V_0^2. \tag{5}$$

Usually, series resistance (*R*) in power systems is very small. Above all, this is true in marine applications, where the extension of cables is small compared to land ones. Therefore, constraint (4) is generally satisfied, making (5) the most restrictive over the CPL loads quota.

It must be remarked that these equations were obtained on a single-phase system to assess stability at early design stage. If this model is applied to assess three-phase systems stability (through equivalent single-phase modelization), a more precise stability assessment can be done, such as the one shown in the following, or the ones available in literature [6], [9]–[11].

C. Three-Phase (dq) Dynamic Model

If the system considered has a three-phase distribution system (which happens in almost every case given the power levels of an IEEPS), a more complex analysis can be done, based on a three-phase modelization. In this case, the system is studied applying the *dq*-transformation, considering all the interactions between the *d* and *q* axes. The result is a model having double state variables than the previous one, making it difficult to manage it using the Routh–Hurwitz criterion. For this reason, in this case, an analysis of the system eigenvalues (using a state-space model) is better suited to assess stability.

The vector variables' single-phase equivalent circuit of the system to be analyzed is shown in Fig. 4. Three major changes have been done in this representation with respect to the previous one: all the variables (voltages and currents) are now vectors (hence, the above dash on variables), reactances are now operational functions, and all the components are represented in per unit (hence the notation in lowercase). While the first two come directly from the *dq*-transformation representation, the latter has been adopted to ease the use of this method in

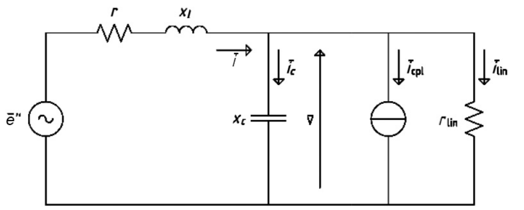

Fig. 4. *dq* variables circuit for three-phase system.

large and complex power systems. The mathematical relations between relative (per unit) and absolute representations are well known, so they will not be repeated in this paper.

Defining as reference for *dq*-transformation, a vector in phase with the busbar voltage, and without depicting Δ symbol in the variables (as before), the following equations for small-signal system's representation can be written [13] in the vectors' components according to *d* and *q* axes:

$$v = v_d \tag{6}$$

$$x_l = x\left(j + \frac{p}{\Omega_n}\right) \tag{7}$$

$$x_c = \left[y\left(j + \frac{p}{\Omega_n}\right)\right]^{-1} \tag{8}$$

$$v_d = xi_q - \frac{p}{\Omega_n}xi_d - ri_d \tag{9}$$

$$v_q = -xi_d - \frac{p}{\Omega_n}xi_q - ri_q \tag{10}$$

$$i_{cd} = -yv_q + \frac{p}{\Omega_n}yv_d \tag{11}$$

$$i_{cq} = yv_d + \frac{p}{\Omega_n}yv_q \tag{12}$$

$$i_{\text{cpld}} = -\frac{1}{r_{\text{cpl}}}v_d \tag{13}$$

$$i_{\text{cplq}} = \frac{1}{r_{\text{cpl}}}v_q \tag{14}$$

$$i_{\text{lind}} = \frac{1}{r_{\text{lin}}}v_d \tag{15}$$

$$i_{\text{linq}} = \frac{1}{r_{\text{lin}}}v_q \tag{16}$$

$$i_d = i_{cd} + i_{\text{cpld}} + i_{\text{lind}} \tag{17}$$

$$i_q = i_{cq} + i_{\text{cplq}} + i_{\text{linq}} \tag{18}$$

where

$p = \frac{d}{dt}$	differential operator;
$j = \sqrt{-1}$	imaginary unit;
Ω_n	system's nominal angular frequency;
r	source system's equivalent series resistance, calculated through Thévenin theorem;
$x = \Omega_n L$	source system's equivalent inductive reactance, calculated through Thévenin theorem;
$y = \Omega_n C$	source system's equivalent capacitive susceptance; calculated through Thévenin theorem;
v_k	component on axis *k* (with $k = d, q$) of busbar voltage vector ***v*** ;
i_{hk}	component on axis *k* (with $k = d, q$) of current *h* (with $h = c$, cpl, lin). For current's definition, refer to Fig. 4;
i_k	component on axis *k* (with $k = d, q$) of busbar current vector ***i*** ;
r_h	Value of linear ($h =$ lin) or CPL ($h =$ cpl) equivalent resistance in per unit.

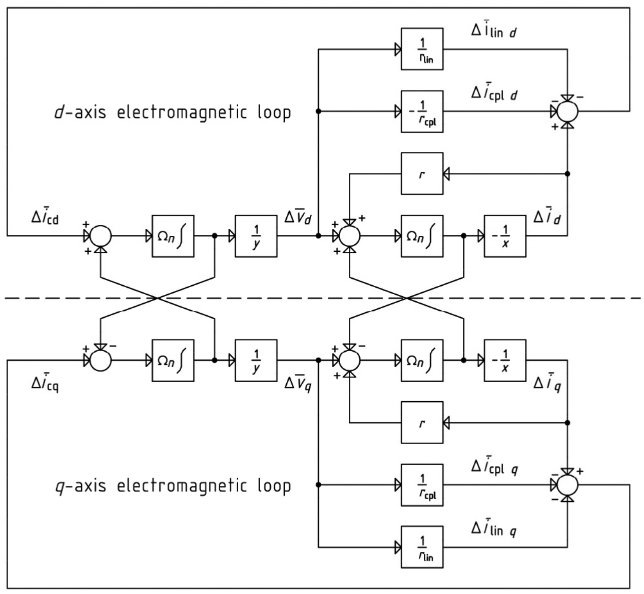

Fig. 5. Block diagram of three-phase *dq* system model.

Equations (7)–(18) can be represented in a graphical way (Fig. 5), to highlight the interactions between the *d* and *q* axes cycles, ignored in the previous modelization.

In this case, the only way to assess system's stability is to analyze the eigenvalues of state matrix **A** associated with the system, to highlight the ones with positive real parts. Assuming the following state variables:

$$x_1 = i_d$$
$$x_2 = v_d$$
$$x_3 = i_q$$
$$x_4 = v_q$$

the following state matrix can be written:

$$A = \Omega_n \begin{bmatrix} -\frac{r}{x} & -\frac{1}{x} & 1 & 0 \\ \frac{1}{y} & \frac{1}{y}\left(\frac{1}{r_{\text{cpl}}} - \frac{1}{r_{\text{lin}}}\right) & 0 & 1 \\ -1 & 0 & -\frac{r}{x} & -\frac{1}{x} \\ 0 & -1 & \frac{1}{y} & -\frac{1}{y}\left(\frac{1}{r_{\text{cpl}}} + \frac{1}{r_{\text{lin}}}\right) \end{bmatrix}.$$

The analytical equation expressing eigenvalues of **A** is too awkward to be included into this paper and does not contribute in a significant way to the stability assessment. In fact, the simplest way to study the stability of this system is to evaluate the eigenvalues using a numerical computing software, by substituting system's data into the matrix.

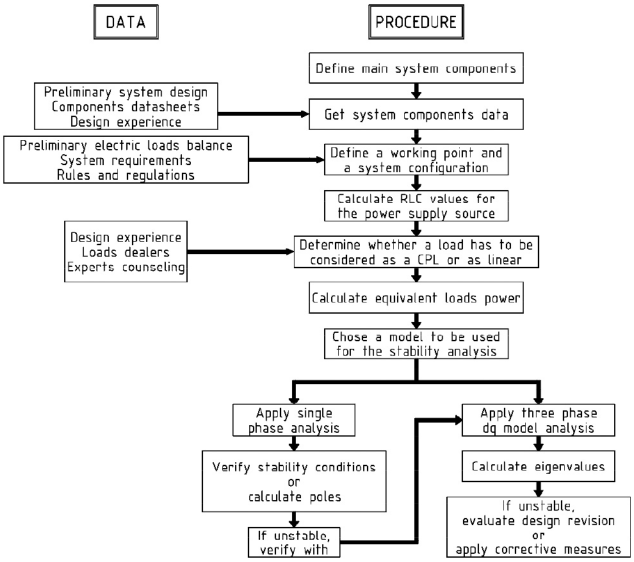

Fig. 6. Proposed practical stability analysis procedure.

The *dq* three-phase model has four eigenvalues, in spite of the two poles of the single-phase model previously presented. It requires more calculation effort and does not bring about analytically explicit stability equations as the previous model. Nevertheless, it is an exact analysis for three-phase systems, allowing assessing stability in conditions near the stability borderline, where the application of the single-phase model becomes unreliable for three-phase systems. Besides the presented modelization, other stability analysis approaches for ac three-phase system can be found in literature, such as [6]–[12].

III. PROPOSED PRACTICAL STABILITY ANALYSIS APPROACH

Whatever the model chosen for the analysis will be, it is necessary to define both the methodology to assess IEEPS stability and parameters required for the study. In this paper, a systematic approach is proposed, with the aim of simplifying the application of theoretical analysis previously stated. The procedure proposed by the authors is concisely shown in Fig. 6, while a complete examination of the single step is presented in the following. As can be seen, the procedure starts from the "main system components definition." Since the stability assessment can be obtained both on design stage and already built systems, this step can be carried out in two different ways. When the system is in design stage, this step is dedicated to the definition of IEEPS essential components, such as generators and loads (this usually comes from the system design procedure). Otherwise, when the assessment of an already-built system has to be done, this step is dedicated only to the definition of components that are relevant for the study with the exclusion of those that are not. This usually comes from experience, but some indications are given later in this paper.

A. System Components Data Retrieval

Once the system is known, the stability assessment procedure can properly start. An important step is the gathering of IEEPS components data. This can be done from preliminary system design, components datasheets, or design experience. The relevant data to be known for a proper analysis are as follows:

1) generators—power, subtransient reactance x'', stator resistance r, capacitance to ground (if applicable);
2) cables—resistance, reactance, and capacity for every relevant cable (parallel-connected bundles of cables have to be properly handled);
3) transformers—short-circuit voltage $v_{cc}\%$, or equivalently short-circuit impedance z_{cc}, and short-circuit PF $cos\phi_{cc}$;
4) harmonic filters and PF correction systems—resistance, reactance, and capacity;
5) loads—power, feeding method (direct online or through converter);
6) load converters (where applicable)—control bandwidth, input filter parameters (mainly capacity).

The amount of information gathered during this step has a strong impact on the system's stability assessment. In fact, the effectiveness of the stability analysis is strictly related to the amount of system collected data. Due to that, more information is gathered, the better it is. However, in order to reduce the burden of such assessment, it will be possible to ignore part of the data (and/or whole system components). Obviously, by doing so, the study will become less accurate.

B. Working Point Definition

The following passage is the definition of a working point for the system. This is rather relevant, because, especially in an islanded system (such as ships or offshore platforms), system configuration greatly varies during operation. In fact, for such systems, it is usual to connect and disconnect generators following the instant power required by loads, trying to reach the most efficient, yet safe in case of faults, configuration. Moreover, the loads' power changes usually lead to different configuration of harmonic filters and/or PF correction systems. For these reasons, a separate stability assessment has to be done for each possible configuration, to guarantee stability in every operating condition. These different IEEPS configurations can be obtained from system's electric load balance, while in case of design-stage assessment, the source has to be the preliminary load balance.

A short yet not exhaustive list of data that could be relevant for the definition of system working points could be:

1) number and power of running generators;
2) power of connected loads;
3) harmonic filters connected (if present);
4) PF correction systems connected (if present);
5) main-switchboard-expected voltage (relevant if voltage droop regulation is active and no master automatic voltage regulator is adopted).

While most of these have an evident correlation with the stability assessment, it is not apparent the main-switchboard voltage would have. On the contrary, main-switchboard voltage has a strong impact on stability, both in absolute value and in variations with respect to nominal value. Indeed, as can be seen in (1), the small-signal model of CPL depends on system

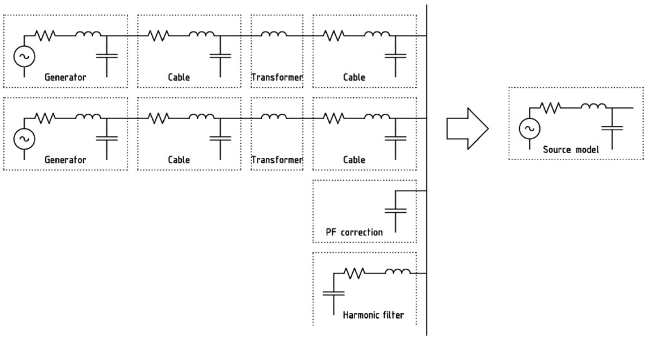

Fig. 7. Example of source system simplification.

voltage (in particular, it has quadratic correlation), so also small variations, such as those given by the voltage droop regulation, have strong effect.

C. Source System Modeling

Having defined the system components and the working point, it is now possible to start the calculation of source system's RLC parameters. The system has to be modeled as a network of impedances (resistance, inductance, and capacity of all system components) and ideal voltage sources (generators' internal EMFs), then, through the application of Thévenin theorem, voltage and RLC components of source system can be calculated (Fig. 7). To ease such process, three-phase systems can be analyzed through their single-phase equivalent models, though limiting such simplification only to this aim. Through design experience, and/or an evaluation of the data gathered during previous steps, some considerations can be done, achieving important simplifications. First of all, in the majority of marine installation, the power system has a reduced reach, so cables are never too long (<300 m). Moreover, when the distribution of high power is needed, cables in parallel are used to improve capacity. Therefore, cables inductance and resistance can be ignored without a significant impact on the stability assessment. Obviously, if a particular application needs long cables (such as good artificial lift), these parameters must be considered. On the contrary, if there are harmonic filters or PF correction systems connected to the switchboard, the capacitance of the cables can be ignored. This is because the above-mentioned components usually have internal capacitance two or more magnitudes higher than the cables one. Concerning harmonic filters, they usually have also a PF correction function, so their internal capacitance has always to be taken into account. On the contrary, their internal resistance and inductance can be easily ignored because they have low values for the harmonics orders relevant for marine power systems. Finally, load-converters input filters have to be carefully considered, because, if no other components are connected to the switchboard, their internal capacitors, together with the cables' parasite ones, are the only capacitive elements in the system.

D. Loads Classification

The following step of stability-assessment procedure is the division of loads in the main categories previously stated: CPL and linear. This in fact is only reduced to the determination of which loads should be regarded as CPL and which should not, given the simplification adopted previously for modeling (to ignore loads' PF). A first rough division is achievable separating direct online loads (such as electric motors or heaters), from loads fed by electronic power converters. While the former loads are essentially linear, the latter cannot be considered fully composed by CPL, because the CPL behavior comes from the control bandwidth of the converters, not from the converters themselves (as stated in Section I). Therefore, between loads fed through power converters, a further distinction has to be done, analyzing their control characteristics. If the converter supplier specifies its control bandwidth, the following simple condition can be applied:

1) IF bandwidth $\ll \omega_{\mathrm{RLC}}$, THEN load IS linear;
2) ELSE load IS CPL.

where

$\omega_{\mathrm{RLC}} = \frac{1}{\sqrt{\mathrm{LC}}}$ source system cut-off angular frequency.

This condition is not correct from a theoretical point of view, because the rigorous approach that should be adopted is the analysis of source input and load output impedances, to assess if converter and source system interact in frequency domain at some point [14], [15]. If this interaction is present, the load can be regarded as CPL, otherwise as linear. Nevertheless, for a simplified approach (such as design-stage one), the previously stated condition could be sufficient, assuring that the converter's load-side regulation does not cause input variables' variations in a frequency bandwidth that interact whit source-system poles. If no data about converters are available, either because datasheet does not specify control bandwidth or electronic power converter has not been already chosen, an estimation has to be done, based on design experience. Roughly, it can be assumed that:

1) converters supplying electronic loads (such as automation systems, UPS, or PCs) can always be regarded as CPL;
2) converters feeding main propulsion systems can be considered as linear, because their bandwidth is reduced on purpose to avoid mechanical damage on propulsion mechanical side, and also because the inertia of the vessel makes a too high dynamic performance useless;
3) electronic power converters used for dynamic positioning thrusters' drive can be considered as CPL, due to the high control bandwidth required for precise positioning. Some particular cases could arise, regarding low dynamic positioning (DP) class requirements (lower positioning precision can lead to a lower thruster control dynamic);
4) drives for general-purpose induction motors (such as pumps and fans) can both be CPL or linear, depending on their performance requirements.

Having separated loads in CPL and linear, the two equivalent loads' power can then be calculated as the sum of all loads' power in the two categories.

E. System Stability Assessment

At this stage, one of the two stability analysis methods has to be chosen. In single-phase systems, the only option is to apply the single-phase model. Stability can then be assessed by exactly applying the analytically explicit stability conditions (4) and (5). For what concerns three-phase systems, considerations must be made. A fast assessment could be achieved applying the single-phase model (either verifying conditions (4) and (5), or calculating the poles of transfer function (3) and checking if they have positive real parts), using the parameters calculated through the single-phase equivalent model for the three-phase real system. If such evaluation leads to a system stable with proper margin, the assessment could be considered concluded. Otherwise, if the system is near stability border, both in or out, the exact assessment is most suited, achievable through the three-phase *dq* model. With the latter, the only viable option is the calculation of the system's state-matrix eigenvalues, to verify their position in the complex plane. If the eigenvalues have negative real part, the system is stable, otherwise is not. If unstable, a proper redesign or the application of corrective measures has to be done.

IV. CASE STUDIES

In this section, two case studies will be presented: an all-electric cruise ship and a dynamic positioned off-shore platform. For both, two situations are considered, to prove their different behavior depending on the working point. It will also be done a comparison between the proposed two-stability analysis models. The two application cases have been selected due to the high penetration of electronic power conversion already present nowadays, making them a good example of what an IEEPS could be. In fact, the passage from IEPS to IEEPS is in course and cannot be ignored anymore from a technical/practical point of view.

A. All Electric Cruise Ship Case Study

The cruise ship studied has a three-phase ac radial power system, with two main switchboards, normally tied, and six generators. The loads range from direct connected induction motors to propulsion drives, reaching a maximum rate of loads under electronic power conversion of about 85% (of total absorbed power). The main data are briefly described here:

1) main switchboard voltage: 11 kV;
2) four 16 MVA and two 11 MVA generators;
3) two 18-MW propulsion motors with cycloconverter drive;
4) three 2.2-MW thruster;
5) four 1.1-MW air-conditioning compressors.

Two working points have been analyzed, whose main parameters are shown in Table I. The main difference between the two is constituted by a 50% reduction in linear loads from working point 1 to point 2, while the reduction in source-system capacity is a consequence of loads variation. Composition of loads in the working points is also shown in Table I, to allow comprehending the different loads classification applied. In fact, the linear loads considered here are mainly induction motors, whose PF is rather low at low power. The PF correction is achieved through harmonic filters, with a variable PF correction level depending on connected loads. In Figs. 8 and 9 are compared the results obtained applying the two proposed models: the poles of transfer function (3) (single-phase model) are shown with a+, while the eigenvalues of state matrix A (three-phase *dq* model) are shown with an **x**. Furthermore, in Figs. 10 and 11 are shown magnifications of Figs. 8 and 9, to better appreciate the poles/eigenvalues on the positive side of the imaginary plane.

TABLE I
ALL ELECTRIC CRUISE SHIP MAIN PARAMETERS

Working point	Source system parameters			Linear loads power	CPL loads power
	R (Ω)	*L* (H)	*C* (F)	(MW)	(MW)
1	4.6E–3	3.84E–4	1.36 E–4	10.1	5.2
Loads composition				HVAC (full power), pumps and other loads	electronic hotel loads, UPSs, etc.
2	4.6E–3	3.84E–4	6.90 E–5	5	5.2
Loads composition				HVAC (half power), pumps and other loads	electronic hotel loads, UPSs, etc.

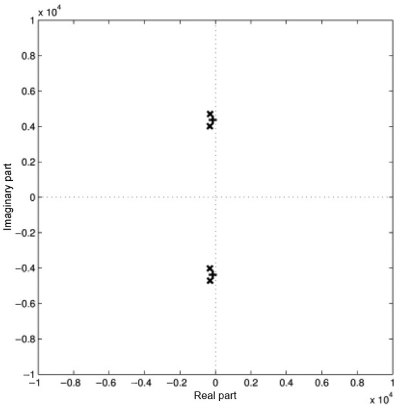

Fig. 8. All electric cruise ship case study—working point 1.

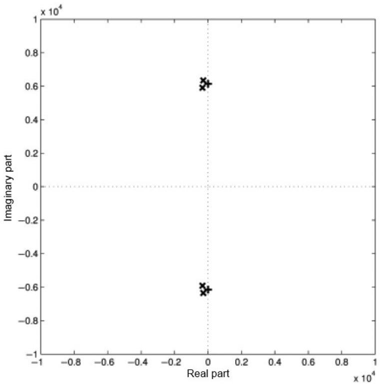

Fig. 9. All electric cruise ship case study—working point 2.

Analyzing Figs. 8 and 10 can be deduced that both the models give stable behavior, having poles/eigenvalues on the left-hand side of the plane, despite the approximation obtained by applying single-phase model analysis to a three-phase system. Conversely, from Figs. 9 and 11, it can be seen that the single-phase model points out an unstable system, while

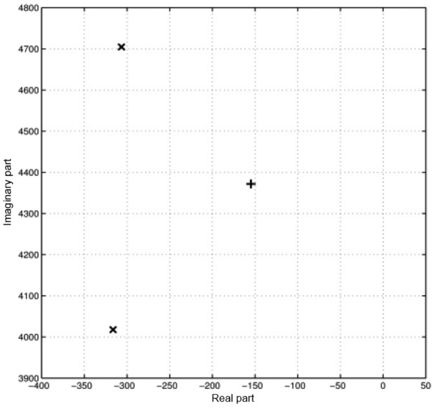

Fig. 10. AES case study—working point 1—zoom.

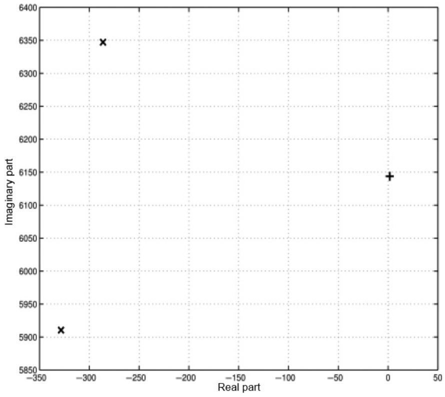

Fig. 11. AES ship case study—working point 2—zoom.

the three-phase *dq* model does not. Indeed, in case of working point 2, the simplest model gives positive real-part poles $(1.68 \pm j6.14\mathrm{E}+3)$, as it can be seen from Fig. 11. In this case, the use of single-phase model led to a wrong stability evaluation, due to its intrinsic approximations near the borderline between stable and unstable behavior; therefore, the three-phase *dq* model is more suitable for this assessment.

B. Dynamic Positioned Offshore Platform Case Study

The case study offshore platform presents a three-phase ac ring topology, with six distributed switchboards, each endowed with a generator. Even in this case, the loads range from induction motors to electronic power converters, with the particular case of dynamic positioning system.

Eight thrusters, supplied by a high-bandwidth electronic power converter and controlled by a complex automation system, assure precise positioning to the platform (such system may be considered as a CPL). Four thrusters are sufficient to keep platform position, but such a high number is installed to achieve a sufficient redundancy level. The most relevant platform data are:

1) six main switchboards in ring topology;
2) 11-kV medium-voltage distribution;
3) six 7 MW generators;
4) eight 5.5-MW converter-driven thrusters for dynamic positioning;
5) high-power pumps and electric motors for drilling section.

TABLE II
OFFSHORE PLATFORM MAIN PARAMETERS

Working point	Source system parameters			Linear loads power	CPL loads power
	R (Ω)	L (H)	C (F)	(MW)	(MW)
1	16.7E–3	1.1E–3	1.4E–5	6	12
Loads composition				HVAC, DOL pumps and linear hotel loads	DP propulsion, other electronic loads
2	16.7E–3	1.1E–3	1.4E–5	17	1
Loads composition				HVAC, DOL pumps, linear hotel loads, DP propulsion	Other electronic loads

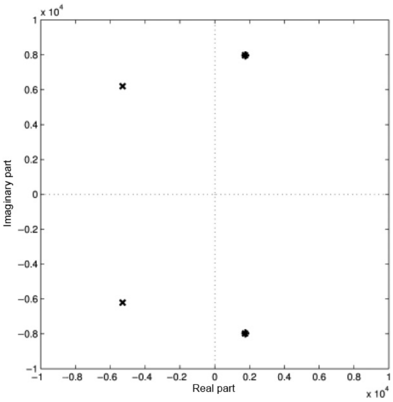

Fig. 12. Offshore platform case study—working point 1.

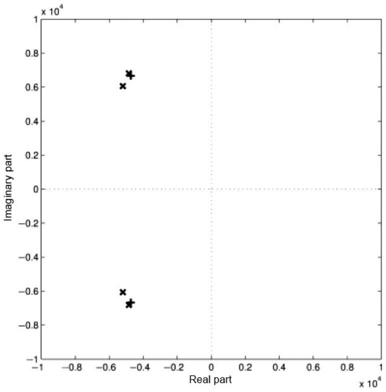

Fig. 13. Offshore platform case study—working point 2.

Two working points have been analyzed, whose main parameters are shown in Table II. As a simplifying hypothesis, the interconnection cables between the six switchboards have been ignored, allowing to consider all of them as a single switchboard (thus virtually transforming the ring bus in a single-point radial bus). In this case, the two working points differ in the attribution of the dynamic positioning thrusters in the first case to CPL, in the second case to linear loads. The results are shown in Figs. 12 and 13, with the same symbol attribution as before (+ for single-phase model and **x** for three-phase

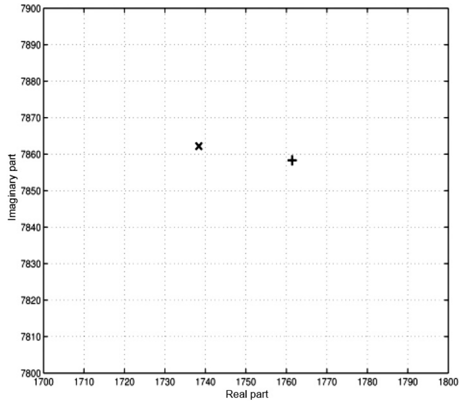

Fig. 14. O. P. case study—working point 1—zoom.

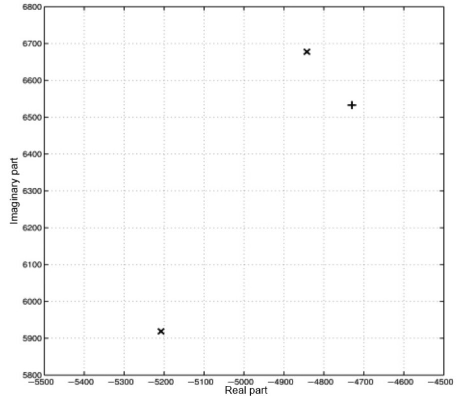

Fig. 15. O. P. case study—working point 2—zoom.

model). Moreover, Fig. 14 shows a magnification of the unstable poles/eigenvalues of the first working point laying in first quadrant, whereas Fig. 15 shows a magnification of the ones on the second quadrant for the second working point. In the first case, system is unstable for both the models proposed, as can be easily seen from Fig. 12: while two eigenvalues of matrix **A** are stable, with negative real part (left-hand side of Fig. 12), the other two are in the right part of the complex plane, thus being unstable (Fig. 14). Indeed, in Fig. 12, the two unstable eigenvalues of matrix **A** and the poles of (3) are nearly coincident, at the point that they can be distinguished. However, the difference between them can be appreciated in Fig. 14. For what it concerns the second case (Fig. 13), the system is stable in both the assessments done, with a more appreciable difference between the results for single- and three-phase models than in the previous case (Fig. 15).

V. SYSTEM PARAMETERS INFLUENCE AND POSSIBLE SOLUTIONS TO INSTABILITY

The voltage stability of an IEEPS depends on all its system components, making inapplicable the standard design process based on the study of each component apart from the others. Indeed, as demonstrated in this paper through the proposed models, the change of a single component (such as the change in system's capacitance due to loads connection/disconnection or the adoption of a more performing electronic drive) could have a relevant impact on overall system. Therefore, it is not possible to give indications on single-components influencing stability, as well as a single solution that will fit all IEEPSs. Every system has to be analyzed and designed as a completely new case. Nevertheless, some indications can be done referring to the concentrated parameters adopted in the models here presented (e.g., resistance, voltage, and loads power).

For what it concerns system resistance, its increase improves system stability, at the price of an overall efficiency reduction. For this reason, its modification is not a feasible way to improve stability. On the contrary, the struggle to reach a more efficient system goes also through the reduction of series resistances, leading to worsening in system stability.

Conversely, the series inductance has a destabilizing effect, so its reduction could be beneficial, but once again not feasible. In fact, the main inductances present in the system are the internal ones of generators and transformers, which are not modifiable. Some tuning could be done on converters input filters, but no relevant variations could be achieved in this way because their design depends on another significant issue present in IEEPS systems: power quality (in particular, harmonic disturbance).

The system capacity has a stabilizing effect, and its increase is the simplest solution to a voltage stability problem. This can be done by using harmonic filters (with the side effect of improving power quality if there is significant harmonic distortion in the system), or by adding PF correction systems. Conversely, it has to be remarked that high-voltage capacitors are expensive and dangerous (especially in marine power systems). Moreover, there is an upper limit to maximum capacity that can be added to an islanded ac system, being necessary to remain into the range of reactive power manageable by generators.

Another variable having a strong effect on stability is the system's voltage, improving stability as it increases. However, its definition is done considering many other constraints, so it is usually taken as given. The only viable option is the adoption of a master voltage regulator, to bring back main-switchboard voltage at nominal value, compensating the voltage drop caused by the reactive droop regulation.

Finally, the last but most significant parameter affecting system's voltage stability is the ratio between linear and CPL loads. Increasing the quota of CPL over the linear loads, stability worsens, so a viable option to achieve stability is to reduce CPL loads as much as possible. This is achievable with an accurate design of the electronic power converters, whose control bandwidth has to be a compromise between high performance and CPL behavior. Reducing the control bandwidth of the loads is one of the most powerful, yet complex, methods to assure voltage stability. The issue is that this action has to be done in collaboration with electronic power converters producers, during system's design stage, to adapt the loads to the system, rather than having to do the opposite (as usually happens).

Obviously, there are other methods in course of study to stabilize systems with a high quota of CPL loads (such as virtual resistance active damping [16] or static compensators application [10]). The issue is that such solutions usually require high power, high bandwidth converters, connected in parallel to switchboard or in series with the generators, making them an expensive and still futuristic solution.

VI. CONCLUSION

In this paper, an assessment of voltage stability in large marine-integrated electrical and electronic power systems has been made, applying a simplified approach focused on design-stage assessment. The CPL loads instability issue has been introduced, together with two different models to analyze the impact of these loads on the system (single-phase equivalent model and three-phase *dq* model). Then, a stability analysis approach has been proposed, to help in evaluating stability already present in system's design stage. The models have been then applied to two case studies, to highlight their differences.

The single-phase model has led to simple stability conditions, yet being inaccurate near stability border if applied for three-phase systems. Conversely, the three-phase *dq* model has led to more complex yet exact stability assessment for three-phase systems. The case studies have also demonstrated the applicability of the proposed practical stability analysis approach.

Finally, considerations on system's parameters affecting stability and possible solutions to instability issues have been presented, in addition to the stability studies recommended in [5]. Indeed, applicable standards are starting to address relevant power system issues, and recommending proper solutions and studies to ensure proper system operation [18].

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Giorgio Sulligoi (S'03–M'06–SM'15) received the M.S. degree (with honors) in electrical engineering from the University of Trieste, Trieste, Italy, in 2001, and the Ph.D. degree in electrical engineering from the University of Padua, Padua, Italy, in 2005.

He spent an internship with Fincantieri Electric Systems Office, Trieste, Italy, and a semester as a Visiting Scholar at the University College Cork, Cork, Ireland. In 2005, he joined MAI Control Systems, Milan, Italy, an Italian firm operating in the field of power stations and alternator voltage control systems. He joined the University of Trieste in 2007 as an Assistant Professor of Electric Power Generation and Control, has been tenured since 2010 and was appointed Assistant Professor of Shipboard Electrical Power Systems in 2012. In 2013, he received the National Qualification for the level of Associate Professor in Electrical Energy Engineering. He is the Founder and Director of the Department of Engineering and Architecture, Grid Connected and Marine Electric Power Generation and Control Laboratory (EPGC Laboratory), University of Trieste. He has authored/coauthored more than 70 scientific papers in the fields of shipboard power systems, all-electric ships, generator modeling, and voltage control.

Dr. Sulligoi is a member of the IEEE Industry Applications, IEEE Power Electronics, and IEEE Power and Energy Societies, where he serves on different Technical and Standards Committees.

Andrea Vicenzutti (S'14) received the M.Sc. (with honors) degree in electrical engineering from the University of Trieste, Trieste, Italy, in 2012. He is currently working toward the Ph.D. degree in electrical energy engineering at the University of Padua, Padua, Italy.

His research concerns marine power systems and is carried out at the Electric Power Generation and Control Laboratory, Department of Engineering and Architecture (DIA), University of Trieste.

Vittorio Arcidiacono received the Ph.D. degree in electronic engineering from the Polytechnic of Turin, Turin, Italy, in 1966.

In 1967, he joined the Italian Electricity Board (ENEL) (formerly National Electricity Board in Italy), Automatica Research Centre (CRA), Milan, Italy, where he has emerged as one of the leading experts in the fields of excitation and turbine control of generators, secondary and tertiary voltage control of extra high voltage (EHV) transmission systems, power system dynamics and stability, mathematical modeling, high-voltage direct current transmission systems (HVDC), and advanced power electronics. He was the Creator and the Designer of the secondary and tertiary voltage control of the Italian EHV transmission system. At ENEL, he became a Manager in 1978, Head of Systems Department in 1984, Vice Director in 1993, Director of the Automatica Research Centre in 1998, and retired in 2001. He currently cooperates with the Department of Engineering and Architecture (DIA), University of Trieste, Trieste, Italy, as a Research Director with the Electric Power Generation and Control Laboratory. He has authored/coauthored more than 200 scientific publications.

Yuri Khersonsky (M'75–SM'78–LSM'06) received the Electromechanical Engineer's Diploma (M.S.E.E.) and the Ph.D. degree in electrical engineering from Odessa National Polytechnic University, Odessa, Ukraine, in 1961 and 1973, respectively. He completed his doctoral studies at the Experimental Research Institute of Metal-cutting Machine Tools (ENIMS), Moscow, Russia.

He has diverse experience in research, development, production, marketing, and application of power electronics, electric drives, motion controls, and ship power distribution systems. Among his achievements are solid-state power converters and circuit breakers for the U.S. Navy, power conditioning systems for stationary fuel cell power plants, Servodrives for CAT scanners, machine tools and robots, industrial drives, and dc and ac permanent-magnet motors. He holds 5 patents and has authored more than 80 papers and 4 books.

Dr. Khersonsky is a member of the IEEE Industry Applications, IEEE Power Electronics, and IEEE Power Engineering Societies, and a member of the IAS Industrial Power Conversion, Industrial Drives, and Marine Industries Committees. He is a Life Member of the Naval League and the Surface Navy Association, a member of the American Society of Naval Engineers and the Institute of Marine Engineering, Science and Technology. He is the Chair of IEEE Std 1662-2008 "Guide for the Design and Application of Power Electronics in Electrical Power Systems on Ships," IEEE Std 1709-2010 "1 to 35 KV DC (Direct Current) Power Systems on Ships," and P1826 "Standard for Power Electronics Open System Interfaces in Zonal Electrical Distribution Systems Rated Above 100 kW." He is a Co-Founder of the IEEE Electrical Ship Technologies Symposium (ESTS) and served as a Technical Chair of the ESTS 2005, 2007, and 2009.