Investigation of voltage/frequency modulation in ship electric networks with pulsed loads according to STANAG 1008 design constraints

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SYNOPSIS

The future electric power system of naval warships in the context of the All Electric Ship (AES) will supply energy to sophisticated systems for propulsion, electric guns, electric launchers, high power sensors, navigation etc. Some of the conventional and mainly of the new systems, referred as "pulsed loads", require high power, for short intervals and are the main cause of the power supply quality phenomenon referred as "voltage/frequency modulation". The aforementioned may affect the operation of sensitive several subsystems of the ship such as radarscopes, communication equipment, missile guidance systems, gear systems etc. In NATO standard STANAG 1008 2% and 0,5% limits are set for voltage and frequency modulation, respectively. Furthermore in STANAG 1008 design constraints exist for the reactive and active power of the pulsed load, in order voltage/frequency modulation not exceed the above-mentioned limits. Although STANAG 1008 does not directly apply to AES, but only to Low Voltage systems, it can be used as a discussion reference for standards for the LV sub-networks of AES. The STANAG 1008 design constraints seem to be a method leading to a rather rough estimation of pulsed loads acceptable operational limits. In this paper, an effort is made to examine and validate the STANAG 1008 design constraints, via simulations in Matlab/Simulink, taking into account certain parameters affecting the entire phenomenon such as : periodicity, duty cycle, time-profile and point of connection of the pulsed load, the voltage level and system impedance at the point of connection, the operational characteristics of the generators and their associated frequency and voltage controllers, loading of the generator at the time of pulsed load occurrence etc. A further effort to investigate the voltage and frequency modulation phenomenon in AES electrical power system configuration (HV, electrical propulsion) is made. Finally, general conclusions are derived, as well as directions and methodologies that could be possibly adopted regarding pulsed loads limitation in conjunction with voltage/frequency modulation limits.

Key-Words : ship electric power system, AES, pulsed loads , voltage and frequency modulation, modeling

INTRODUCTION AND BACKGROUND

One of the significant issues of Power Supply Quality (P.S.Q.) in continental and in ship electric networks is the "Voltage and Frequency Modulation". *"Modulation"* is defined as *"voltage and frequency periodic or quasi-periodic variations such as might be caused by regularly or randomly repeated loading with frequency less than nominal"*. Electric loads causing "modulation" are loads which require high power (in the wide range from several kWs to few GWs) for a very short time interval (in the order of a few seconds or even up to some milliseconds) and are known as *"Pulsed Loads"*.

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Representative examples of pulsed loads are controlled heaters, sonars, radars, Electromagnetic Aircraft Launch Systems (EMALS) and Electromagnetic Guns (such as Rail Guns, Coil Guns, Lasers, High Energy Microwaves). Following the current trends, it is expected that the systems will be among the dominating ones aboard the All Electric Ship (AES). Pulsed loads of rather small power demand are directly connected to the electric power grid, whereas the ones of larger power demands are coupled to the network via the intervention of *energy storage devices* and *Pulsed Forming Networks* (PFN). In this latter case, the power system does not actually see the real behavior of the pulsed load itself, but of these intermediate systems. Experience from continental and onboard power systems indicates, that the primary effects of pulse loading are manifested in the areas of voltage flicker, dynamic and transient stability, excitation of torsional frequencies in generators etc. Voltage and frequency modulation may affect the operation of several subsystems of the ship such as radarscopes, communication equipment, missile guidance systems, gear systems etc. For some indicative work on pulsed loads as well as on their impact on ship electrical power systems, the reader could refer to BIBLIOGRAPHY.

STANAG 1008 (Edition 9, promulgated August 24, 2004) [1], the NATO naval standard dealing with Power Supply Quality (P.S.Q.) issues, defines voltage and frequency modulation disturbances and sets related limits for LV (440 V, 115 V, 60 Hz, 400 Hz) shipboard electrical power systems. STANAG 1008 concerns only the *Ship Service Power Supply System* and explicitly excludes electric propulsion systems. However, as up-to-date there is not a NATO standard for the All Electric Ship electrical power system (HV, electrical propulsion), STANAG 1008's rules can be used as reference base of discussion. Furthermore, even in AES networks there will be LV service power system with equipment of more or less similar technology to that of the conventional ships, and therefore, with similar operating constraints concerning voltage and frequency modulation as stipulated by STANAG 1008. Relative discussion can be traced in the document [2] of NATO AC/141(MCG/6)SubGroup/4, which is the NATO Group responsible for STANAG 1008.

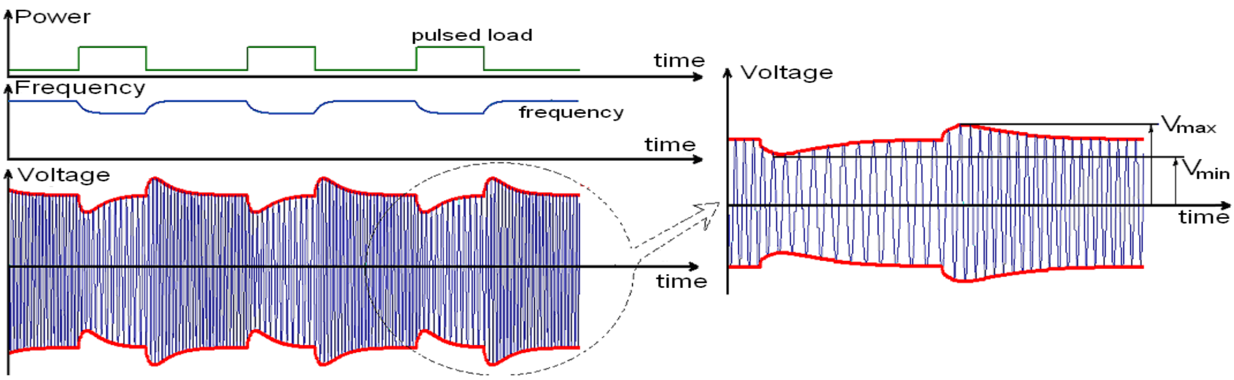

Fig. 1. Voltage and frequency modulation

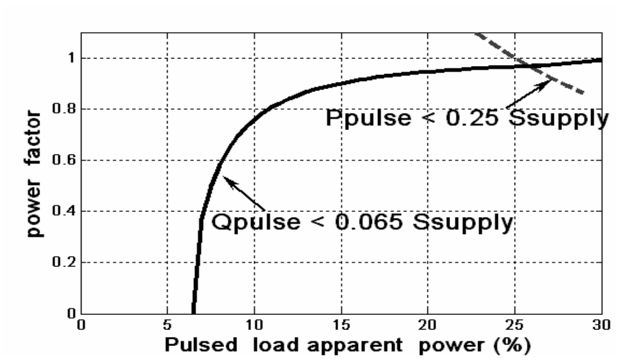

Fig. 2a Limit-curves for pulsed load operation according inequalities (2.a)

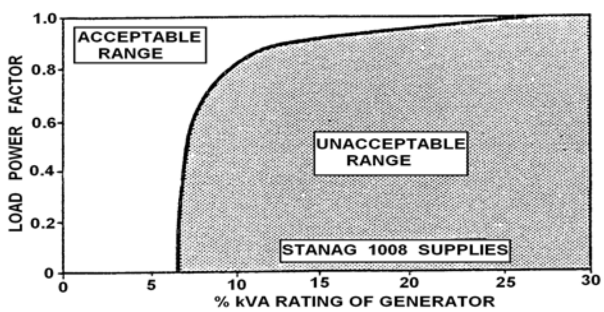

Fig. 2b P.F.(S%) limit-curve for pulsed load operation according STANAG 1008

In Fig. 1, voltage and frequency modulation provoked by a rectangular pulsed load is shown. For quantifying voltage and frequency modulation the difference between maximum and minimum value is used as a percentage of the double of the nominal value as shown in Equation (1) :

$$\Delta V = \frac{V_{max} - V_{min}}{2V_n} \;, \qquad \Delta f = \frac{f_{max} - f_{min}}{2f_n} \tag{1}$$

It is underlined that in formula (1) all voltages are to be in rms values, or peak values or mean values.
The limits for voltage and frequency modulation according to STANAG 1008 are **2%** and **0.5%** respectively.

It is worth noting, that in some cases in other merchant and national naval standards slightly different definitions and limits are used. Although this paper is not aiming at standards comparison, in DISCUSSION AND CONCLUSIONS section some comments are also made on this.

According to design constraints of STANAG 1008 (Edition 9, ANNEX B "User Information and Constraints ", paragraph 9.d), in order voltage/frequency modulation not to exceed the above-mentioned limits, reactive and active power of the pulsed load should satisfy the following inequalities :

$$Q_{pulse} < 0.065 * S_{supply} \quad \text{and} \quad P_{pulse} < 0.25 * S_{supply} \tag{2}$$

(P_{pulse}, Q_{pulse} = active, reactive power of the pulsed load, S_{supply} = full rated apparent power of the supply at the occurrence of the pulse).
Letting $S_{pulse} = (P_{pulse}^2 + Q_{pulse}^2)^{1/2}$ be the apparent power and $P.F. = P_{pulse} / S_{pulse}$ the power factor of the pulsed load, the inequalities (2) are equivalent to

$$P.F. * x < 0.25 \quad \text{and} \quad P.F. > [1 - (0.065/x)^2]^{1/2} \quad \text{where } x = S_{pulse} / S_{supply} \tag{2.a}$$

The graphical representation of inequalities (2.a) is shown in Fig. 2a, with pulsed load relative apparent power $x = S_{pulse}/S_{supply}$ expressed in percentage [hereinafter S%]. In Fig. 2b the corresponding **pulsed load limit curve P.F.(S%)** of STANAG 1008 is shown, defining the ***"acceptable"*** and ***"unacceptable"*** range of pulsed load operation.

This guideline for the pulsed load acceptable operational limits seems to be a method leading to a rather rough estimation of pulsed loads limits, as it considered only S_{pulse} / S_{supply} and *P.F.* but it does not take into account certain additional parameters affecting the entire phenomenon such as :

- periodicity of modulation (pulse repetition frequency)
- duration of the pulsed load (duty cycle)
- profile of the pulsed load
- point of connection of the pulsed load onto the electric grid
- system impedance
- operational characteristics of the generators and their associated frequency and voltage controllers
- loading of the generator at the time of pulsed load occurrence

In this paper, in continuance of previous work of the authors [3], [4] and [5], an effort is made to investigate, via simulations in Matlab/Simulink [6], the influence of most of the aforementioned parameters on the voltage and frequency modulation of the electric network. Thus, a simplified parametrical model of the electrical network of a naval warship, comprising a pulsed load, is developed, in order to study the phenomenon at a first approximation. Concerning the topology of the ship electric network, two main configurations are considered.
In the first one, the LV generator set supplies only a conventional service load along with a pulsed load of rectangular profile, which is directly connected to the electric network, running simulations by varying several of the parameters mentioned above. The obtained results concerning pulsed load limits are compared with the P.F.(S%) limit-curve proposed by STANAG 1008, corresponding to *2%* and *0.5%* limits for voltage/frequency modulation. In addition, the effect of varying these modulation limits on the pulsed load acceptable operational characteristics is investigated.
In the second configuration, the AES concept is taken into account (the generator set supplies all three : propulsion, service and pulsed loads) and the P.F.(S%) pulsed load limit-curve for the LV part of the system is investigated. In this case two different pulsed load profiles are studied :
- a rectangular one corresponding to a pulsed load directly connected to the electric network ,
- an impulse one corresponding to an intermediate capacitive energy storage device, which then supplies the pulsed load demand.

Finally, in the paper, general conclusions are derived, as well as a proposition for generalization of the STANAG 1008 P.F.(S%) limit curve.

CONVENTIONAL SHIPBOARD ELECTRICAL SYSTEM

Model of Ship Electric Network

In this case study concerning the conventional configuration of a shipboard electrical power system is considered in a simplified form as shown in Fig. 3, where the points MP (measurement points) denote where voltage

modulation is estimated. The generating set is aggregated in a 2MVA, synchronous generator driven by diesel engine (equivalent to typical generating sets) is considered to supply the service load and a pulsed load. A 440/115V voltage transformer is also used for the 115V system supply. The generator parameter values are also summarized in Fig. 3. The block diagrams of generator control system are shown in Figs. 4a and 4b while the parameters of AVR and governor are summarized in table I. For the AVR an IEEE type 1 model is used. Moreover, a pulsed load model of rectangular form was used with period equal to 0.3 sec and 50% duty cycle. The length of the 440V system cables was assumed to be 100m and 50m for the 115 V systems, respectively.
In the examined operating scenarios some of the previously referred parameters are changed selectively to study their impact to the modulation phenomenon.

Generator 440V, 60Hz, P_n=2 MVA	
Parameter	**Value**
r_a	0.0036
X_d	1.56
X'_d	0.296
X''_d	0.177
X_q	1.06
X''_q	0.177
X_l	0.052
T'_{do}	3.7 sec
T''_{do}	0.05 sec
T''_{qo}	0.05 sec
H	1.07 sec
F	0.1

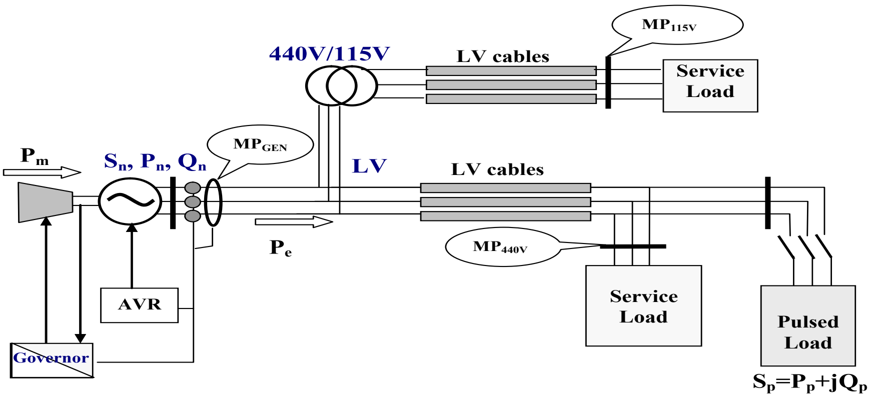

Fig. 3 Topology of ship electric network equivalents examined for a conventional ship.
MP : "Measuring" point – Values of Generator parameters

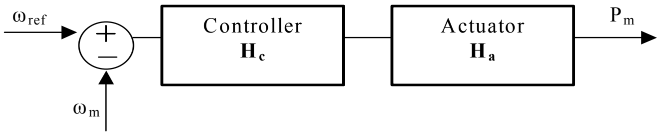

Fig. 4a Governor block diagram. ω_{ref}, ω_m : reference and measured rotating speed , P_m: mechanical power

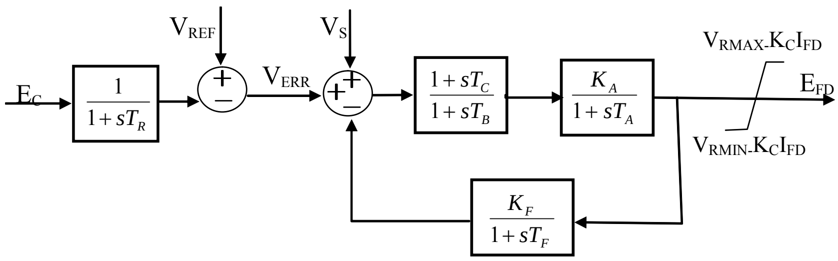

Fig. 4b AVR system block diagram.
E_{FD} **:** Field voltage reference , V_{ref} **:** Voltage reference , E_C **:** measured voltage , **Vs** : stabilization voltage signal

Table I Parameters of the governor and AVR

GOVERNOR		**AVR**	
$H_c = \frac{K(1+T_3 s)}{1+T_1 s+T_1 \cdot T_2 s^2}$	$H_a = \frac{1+T_4 s}{s(1+T_5 s)(1+T_6 s)}$		
Parameter	**Value**	**Parameter**	**Value**
K_f	40	*LPF time constant* $T_r(s)$	20e-3
$[T_1, T_2, T_3]$	[0.01, 0.02, 0.2]	*Regulator gain and time constant* $[K_{fr}, T_{fr}(s)]$	[200, 0.001]
$[T_4, T_5, T_6]$	[0.25, 0.009, 0.0384]	*Exciter* $[K_e, T_e(s)]$	[1, 0]
$[T_{min}, T_{max})$	[0.1, 1]	*Transient gain reduction* $[T_b(s), T_C(s)]$	[0 0]
T_d *(Engine time delay)*	0.024	*Damp filter gain and time constant* $[K_{fd}, T_f(s)]$	[0.001, 0.1]
P_{m0}	0.5	*Field saturation parameters* **[A, B]**	[0, 0]
		Regulator output limits $[V_{Rmin}, V_{Rmax}(p.u.), K_C]$	[-11.5, 11.5, 0]

Characteristic results of the dynamic behaviour of the electric network studied are given next.
System response for no load – full load operation and vice versa was obtained for the aforementioned parameters as shown in Figs 5a, 5b and 5c. System frequency recovers 3 sec after full load application while within about 1.5 sec AVR stabilizes generator terminal voltage.
Results concerning repetitive pulsed load application are shown in Figs 6a, 6b and 6c. The produced power by the generator, the rms voltage at service load bus and system frequency are obtained for a rectangular-profile pulsed load. Characteristics of the examined pulsed load are : peak absorbed power equal to 15% of generator nominal apparent power, 0.3sec period, duty cycle 50% and power factor 0.8 inductive. Loading of the generator just before the application of the pulsed load is almost 48% while cables' length 100m for the 440V and 50m for the 115 V. It is obvious from Figs 6a-6c that immediately after pulsed load application a sub-transient phenomenon occurs, which should be included in voltage frequency modulation estimation.

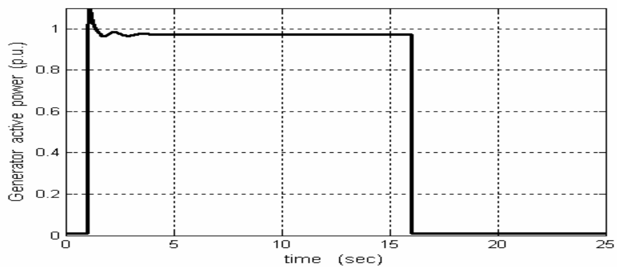

Fig. 5a No-load –full-load generator test, generator active power.

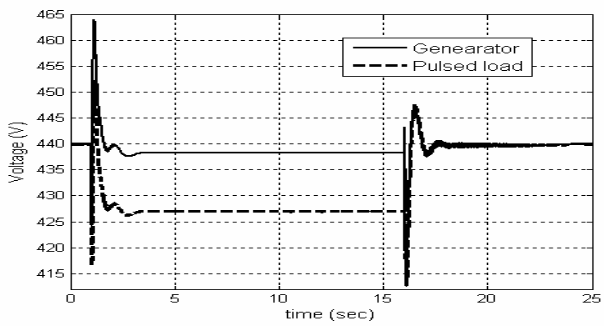

Fig. 5b No-load –full-load generator test. Voltage variation at Generator and at Pulsed load (service load) buses

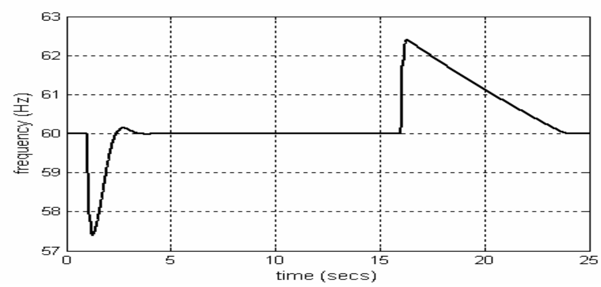

Fig. 5c No-load –full-load generator test, frequency variation.

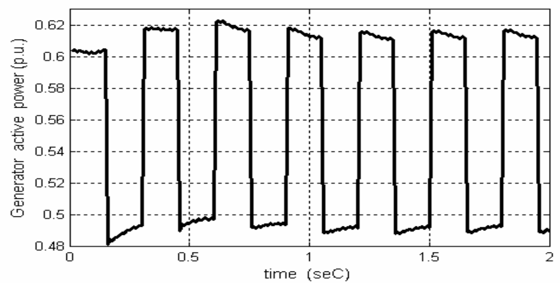

Fig. 6a Generator active power.

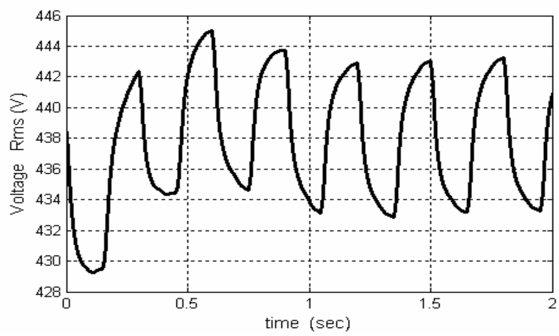

Fig. 6b RMS voltage at service load bus

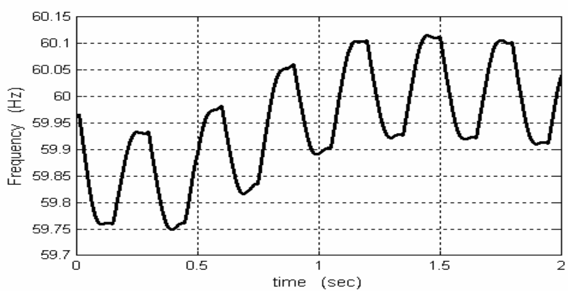

Fig. 6c System frequency

Simulation results for the conventional ship network

The electrical network shown in Fig. 3 is simulated for different operating scenarios with a rectangular profile pulsed load on the 440 V side. The obtained results concerning pulsed load limits are compared with the P.F.(S%) limit-curve proposed by STANAG 1008 [inequalities (2), (2.a) and Fig. (2)] and commented next. The standard voltage/frequency modulation limits, 2%, 0.5% are considered for all operating scenarios. The basic parameters of the system model provided before are used for the simulation of the assumed operating scenarios. Generally, in most of the following scenarios only one basic parameter is changed and the rest are maintained constant, examining in this way the extent that the specified parameter affects the results. Before any of the following simulations the system is initialized properly and then it is simulated for a time interval of 2 sec (except for cases that pulsed load period greater than 0.6sec is examined) iteratively for different pairs of values of apparent power and power factor of the pulsed load, until the values of either of the STANAG 1008 modulation limits are obtained, so that the corresponding P.F.(S%) curve point is determined.

Loading of the generator (Fig. 7)
First the loading of the generator just before the application of the pulsed load is considered as a parameter. For 10, 20, 40, 60% generator base loads, the system is simulated repeatedly and the respective P.F.(S%) limitation curves are extracted. It can be seen that the limitation curves are only slightly displaced and that the increase of generator base load tends to decrease the unacceptable operating area.

Subtransient reactance X'' (Fig. 8)
Next the system is simulated with the generator sub-transient reactance X'' varying between 11% and 20%. From the respective P.F.(S%) curves obtained, it is yielded that generator sub-transient reactance affects considerably the obtained unacceptable operating area, leading to the conclusion that it is one of the parameters, that must be considered in the design of such a system.

inertia H (Fig. 9)
Similar simulations were performed for generator inertia constants, H varying between 1 and 1.5 sec. For this range of values considered, no significant effect is observed on the P.F.(S%) curves except from power factors bigger than 0.8, where curves begin to separate for small generator inertia values. A long series of simulation results also led to the conclusion that average frequency modulation decreases almost linearly with inertia constant increase. This is expected as the bigger the generator inertia the lower the speed variations due to load changes.

AVR gain, K_V, and ***Governor gain, K_f***
A wide range values for *AVR gain, K_V,* (= 100 – 400) and *Governor* gain, K_f (= 30 – 60) are used. It seems that both these gains have weak effect on P.F.(S%) curves.

Cable's length (Fig. 10)
The assumed impedance of the cables is 0.15+0.35j (ohm/km), while the corresponding length varies between 50 and 500 m. In this case study, the base load of the generator is 10% while the period and the duty cycle of the pulsed load are 0.4sec and 60%, respectively. Evidently the cable length affects significantly P.F.(S%) curves : the longer the cables, the bigger the obtained unacceptable operating area.

Pulsed load period (Fig. 11)
The basic parameter of this case is the pulsed load period, T, varying from 0.02 and 1.6 sec. Simulation time is 2 sec except from the case T=1.6 sec that simulation duration is 6.5secs in order to permit the system reach *"balanced"* operation. The obtained results show that pulsed period is a critical factor affecting significantly the shape of the limitation curves and their position on the P.F.(S%) plane : the higher the pulsed load period is the bigger the obtained unacceptable operating area.

Pulsed load duty cycle (Fig. 12)
In this case study the system is simulated with pulsed load duty cycle taking the values 15, 30, 50 and 90%, while the period of the pulsed load is equal to 0.3sec. It is obvious from the obtained curves that also the pulsed duty cycle is a critical factor : the higher the duty cycle is, the bigger the area corresponding to unacceptable operation is obtained.

Pulsed load power vs pulsed load repetition frequency for P.F. = 1 (Fig. 13)
In Fig 13 several simulation results corresponding to pulsed loads with P.F. = 1 (e.g. diode switched heaters) are combined so that the maximum permitted pulsed load active power is plotted vs repetition frequency of the pulsed load. One can conclude that increasing the repetition frequency of a pulsed load increases its permitted nominal power.

Df % versus DV % for all the cases studied (Fig. 14)
In Fig 14 frequency modulation values are plotted vs. voltage modulation values for all examined scenarios. It is obvious that voltage modulation limit is exceeded more than frequency limit, leading to the conclusion that voltage limit is tighter than the frequency limit. Another remark on the plot is that almost never both limits are exceeded.

DV% at several buses : MPG, MP115V, MP440V (Fig. 15a, 15b)
The plots of the voltage modulation at 115V and generator load bus vs the voltage modulation at 440 V service load bus are given in Figs 15a, 15b. It can be seen that voltage modulation at generator bus and at 115V bus are always smaller than that of the 440 V service load bus. Therefore, studying modulation of 440 V leads to safe results for the entire system.

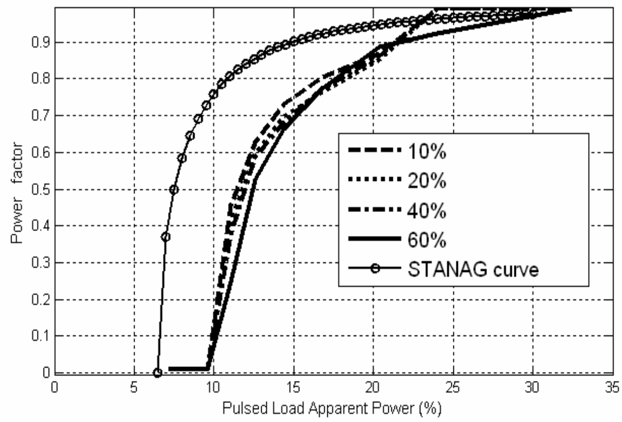

Fig. 7 P.F.(S%) limitation curves for generator base load

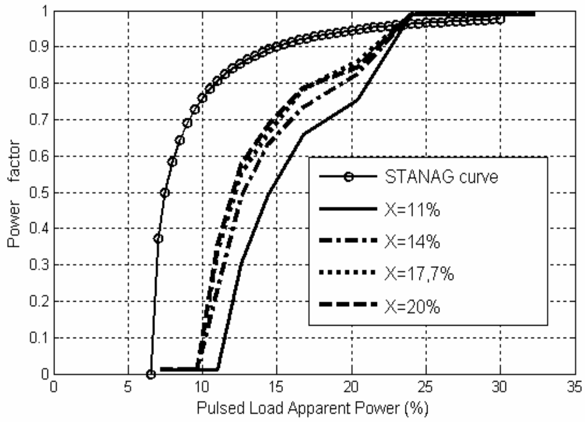

Fig. 8 P.F.(S%) limitation curves for different generator sub-transient reactance

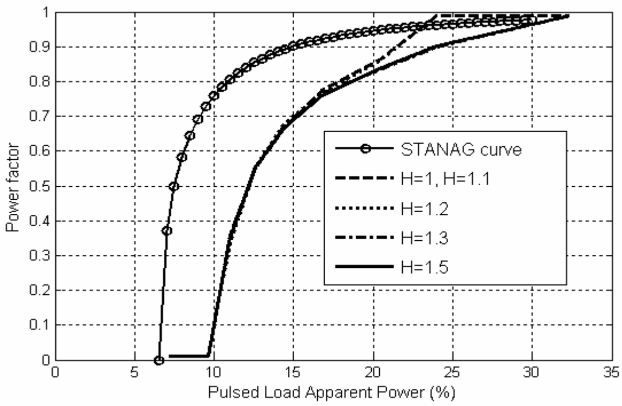

Fig. 9 P.F.(S%) limitation curves for different inertia constants

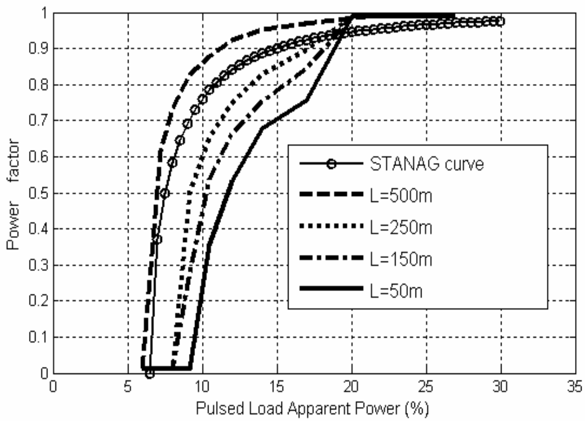

Fig. 10 P.F.(S%) limitation curves for different cable lengths

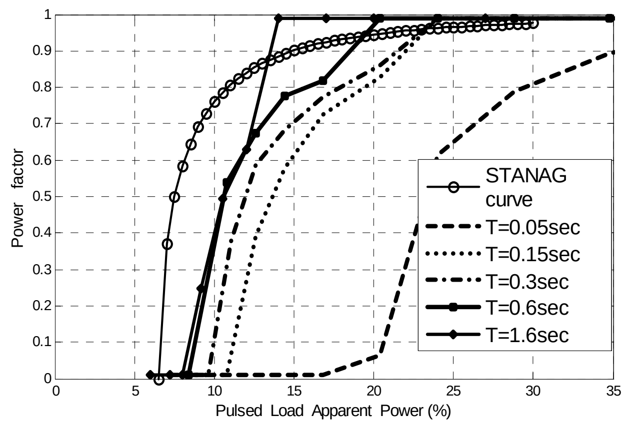

Fig. 11 P.F.(S%) limitation curves for different pulsed load period

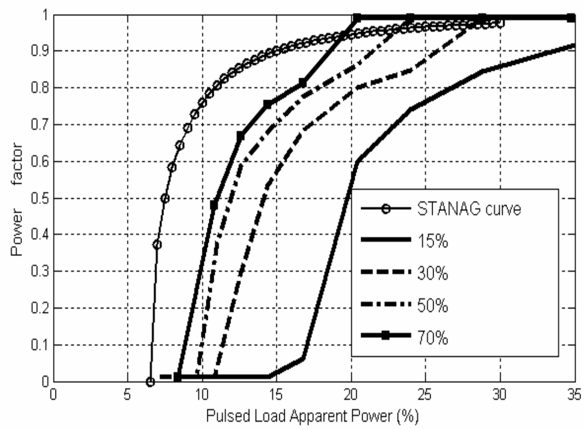

Fig. 12 P.F.(S%) limitation curves for different pulsed load duty cycles

Voltage modulation limit variation (Figs. 16, 17)

The extent that the voltage modulation limit affects the limitation curves is investigated, too. A relatively unfavorable scenario with generator base load 15%, cable length equal to 250m, pulsed load period T=0.6sec and duty cycle = 50% is investigated. Voltage modulation limits equal to 1.5, 1.7, 2, 2.3 and 2.5 (%) are considered. From the curves in Fig. 16 and the corresponding 3D-diagram of Fig 17 it is concluded, that the P.F.(S%) curves are displaced almost symmetrically around the 2% limitation curve for different voltage modulation limits.

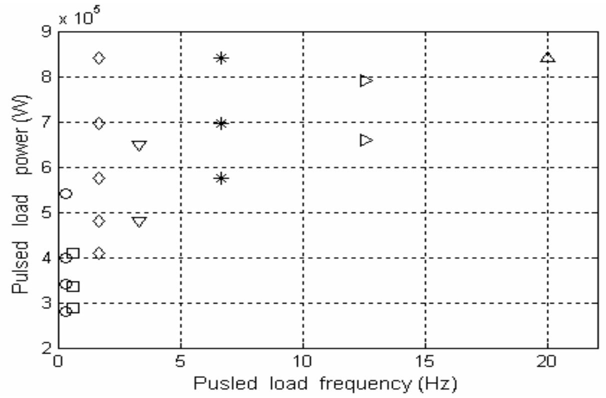

Fig. 13 Pulsed load apparent power vs pulsed load frequency (for P.F. = 1)

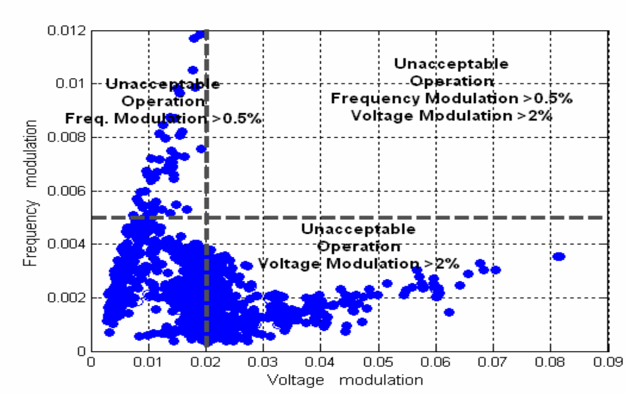

Fig. 14 Df % versus DV % relation. Total statistic of all the cases studied

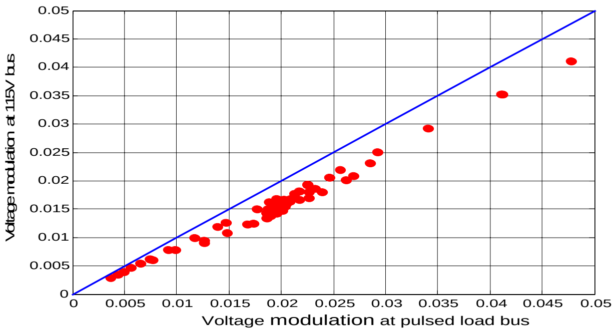

Fig. 15a 115V bus Voltage modulation vs Pulsed load bus Voltage modulation

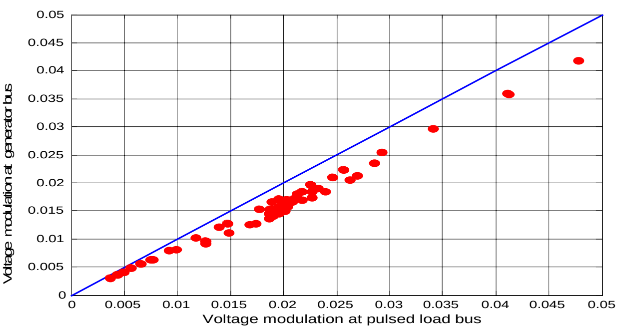

Fig. 15b Generator bus Voltage modulation vs Pulsed load bus Voltage modulation

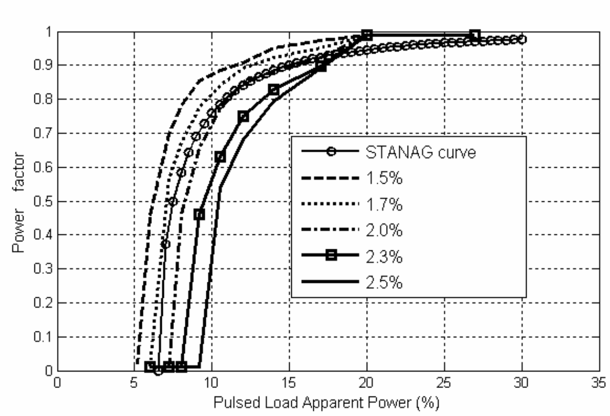

Fig. 16 P.F.(S%) limitation curves for different voltage modulation limits

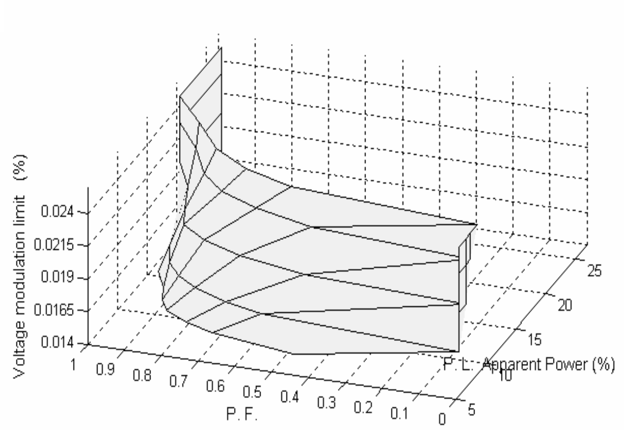

Fig. 17 3-D diagram of Fig. 16

AES SHIPBOARD ELECTRICAL SYSTEM

In this case, the electrical network of a warship in the context of AES with a pulsed load installed, as shown in Fig. 18, is studied. The generating set is aggregated in a 35 MVA, synchronous generator operating at 4.16 kV. The parameters of the generator are also summarized in Fig. 18, while the control system parameters remain the same with those of Table I. The main HV load is a Propulsion Induction Motor assumed to operate at constant power mode during the simulation intervals. Ship service loads have their main supplies fed through HV/LV transformers that replace the generator sets of traditional installations, therefore most of the results obtained in the case study of conventional ship are expected to be more or less the same for this LV sub-system considering that their technology is supposed to remain the same. Of course, the modulation problems have to be investigated in the entire system of AES. Within the framework of this paper, some preliminary investigation

results in simplified AES configuration are presented concerning the point of connection of the pulsed load (at LV or at HV) as well as the pulsed load profile (rectangular or impulse form).
Basic system characteristics used for the simulations described next are, HV cable length 250m, 440V cable length 100m, 115V cable length 50m, generator base load 53% of its nominal power, pulse load period 0.6sec, pulsed load duty cycle 50%.

Generator 4160V, 60Hz P_n=35 MVA	
Par.	**Val.**
r_a	0.00285
X_d	1.305
X'_d	0.296
X''_d	0.232
X_q	0.475
X''_q	0.243
X_l	0.18
T'_d	1.9 sec
T''_d	0.05 sec
T''_{qo}	0.1 sec
H	2.1 sec
F	0.08

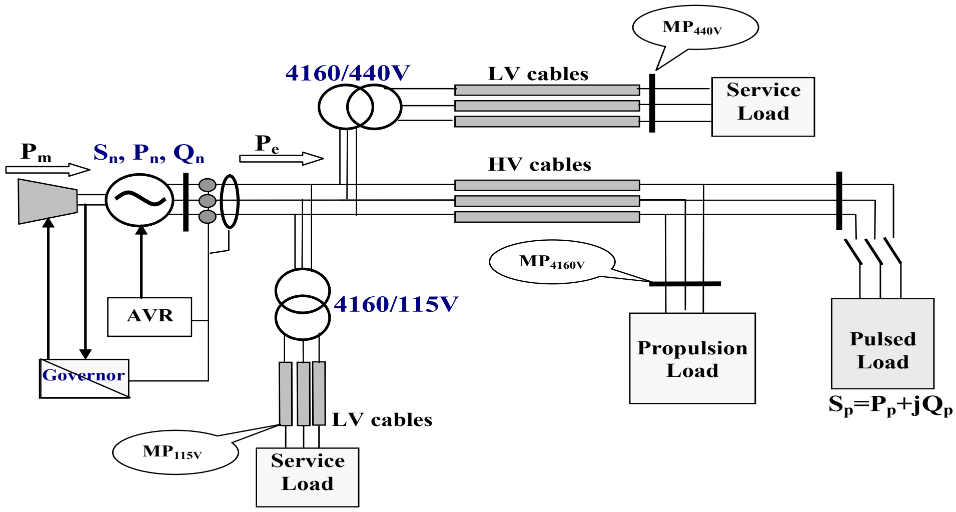

Fig. 18 Topology of ship electric network equivalents examined for the AES concept.
MP : "Measuring" point – Values of Generator parameters

First, a rectangular pulsed load is assumed to be installed either at 440 V system (e.g. service load bus) or at 4160V supply system. The system is simulated for various pulsed load nominal powers and power factors to identify the point of the limitation curves corresponding to 2% and 0.5% voltage and frequency modulation respectively in 440 V part of the system. As it is shown in Fig. 19 the operating unacceptable area is increased, if the pulsed load is installed at 440V bus.

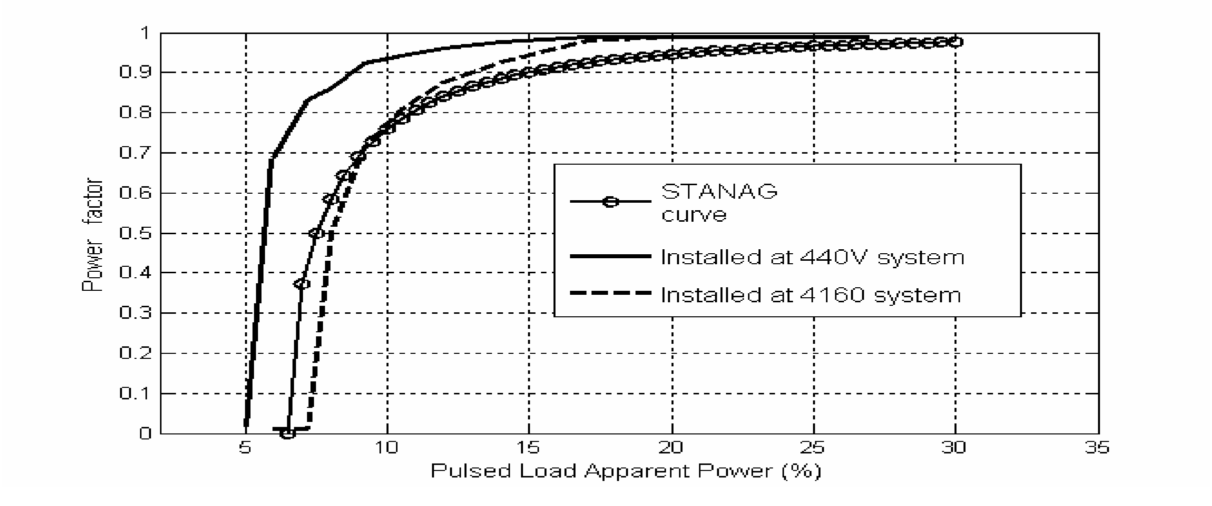

Fig. 19 P.F.(S%) limitation curves for different pulsed load installation points

Next the effect of the pulsed load profile is examined. Two different pulsed load configurations are used :

(a) Pulsed load of impulse profile.
This is the typical case of a rail-gun supplied via a capacitive energy storage system. To obtain the aforementioned profile the model of a diode rectifier supplying a capacitor through serial small resistances is used. The pulsed load (discharges the capacitor) is represented by a shunt variable resistance

(b) Pulsed load of rectangular profile connected directly to the electrical network.

The respective results are shown in Figs. 20-22. In Fig. 20 the output active power of the generator is shown. The peak value of the generated power is almost the same in both cases, but not the time profile. In Fig. 21 system frequency variation is given where it is obvious that frequency deviates from the nominal value more in case of the rectangular shape pulsed load (as the system has to counteract to bigger absorbed energy by the pulsed load). In Fig. 22 voltage deviation at different points of the network is shown. The initial voltage sag corresponding to the first ms of pulsed load application is smaller in the case of rectangular pulsed load. However, a voltage overshoot occurs when pulsed load (of rectangular form) is disconnected resulting in this way a similar voltage modulation for both cases.

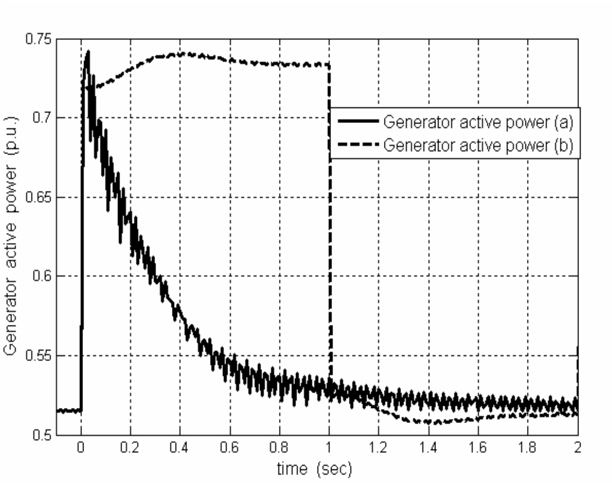

Fig. 20 Generator output active power for impulse (a) and rectangular (b) profile pulsed load.

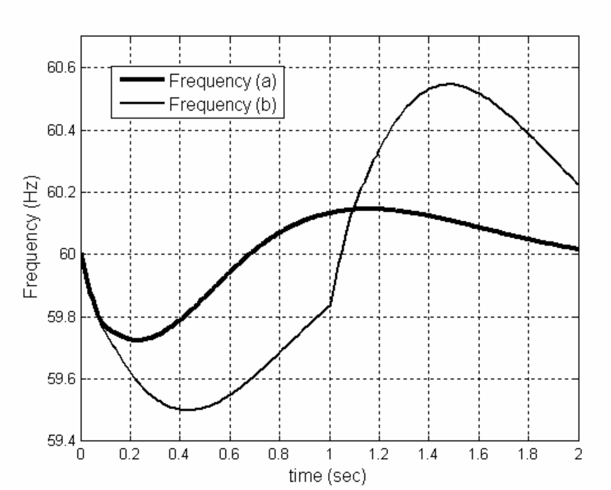

Fig. 21 System frequency for impulse (a) and rectangular (b) profile pulsed load.

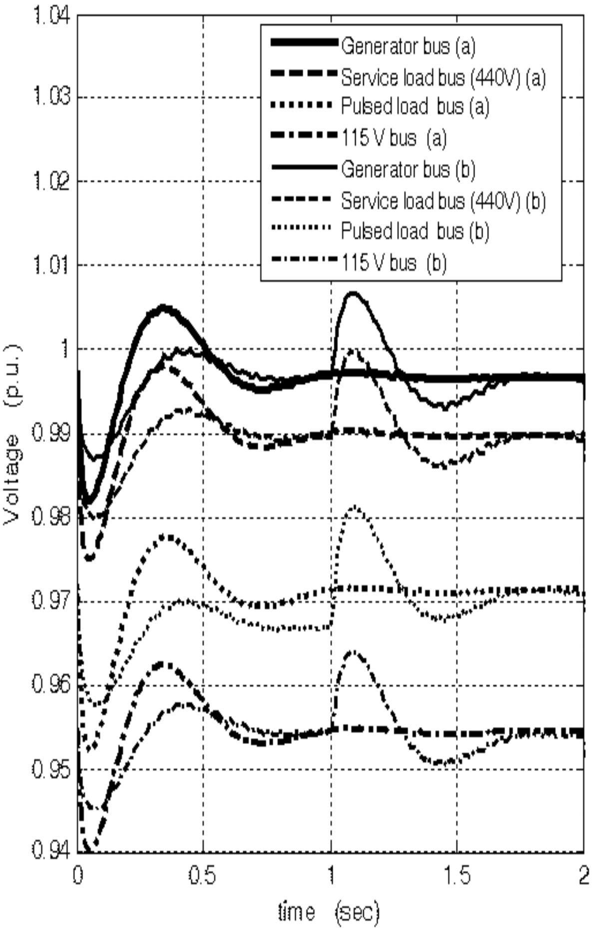

Fig. 22 RMS value of the voltage at characteristic system points for impulse (a) and rectangular (b) profile pulsed load.

DISCUSSION AND CONCLUSIONS

In this paper, simulation studies of a shipboard electrical network (being either conventional or in the context of AES) comprising a pulsed load from the point of view of STANAG 1008 design constraints have been presented, so that additional information compared to the deterministic methods by the STANAG 1008 is provided. Some of the conclusive remarks derived from the case study of conventional warship are summarized in the following :

- Modulation seems to be affected to a significant extent by certain basic characteristic parameters of the power system and the pulsed loads, such as: generator sub-transient reactance, cable lengths, pulsed load period and duty cycle. On the other hand, other parameters like generator loading or AVR's gain and speed governor's gains have a rather limited effect.
- Frequency modulation limits set by STANAG 1008 are not so easily violated as the corresponding voltage modulation ones. Furthermore, a case where both limits are violated seems improbable.
- Focusing only on 440 V bus seems to lead to safe conclusions, covering also generator and 115 V buses, regarding STANAG 1008 modulation limit violations.

- The limit curves P.F.(S%) of STANAG 1008 design constraints remain, in general, of the same form – regardless any right or left displacements and some occasional scratching mostly for higher power factors. Under these circumstances the authors suggest, as a further work, to investigate the generalization of the STANAG 1008 methodology. In particular, the proposition consists in generalizing the inequalities (2.a) by replacing the values 0.065 and 0.25 of STANAG 1008-Ed. 9 with the parameters $\boldsymbol{\alpha}$ and $\boldsymbol{\beta}$ respectively, so that the pulsed loads limitation will be expressed by the following inequalities

$$P.F.*x < \beta \text{ and } P.F. > [\,1 - (\alpha/x)^2\,]^{1/2} \text{ with } x=(S_{pulse}/S_{supply}) \text{ and } S_{pulse} = (P_{pulse}{}^2 + Q_{pulse}{}^2)^{1/2} \quad (2.b)$$

see also Fig. 23, where different values for $\boldsymbol{\alpha}$, $\boldsymbol{\beta}$ e.g. α=20, 23, 25, 30% and β= 5.5, 7.5, 10, 12.5% are used. Hence, further work on the topic could be the estimation of parameters α, β for different operating scenarios in conjunction with adaptation on simulation and/or experimental results, so that different limit curves P.F.(S%) will be valid for various power system and pulsed load parameters.

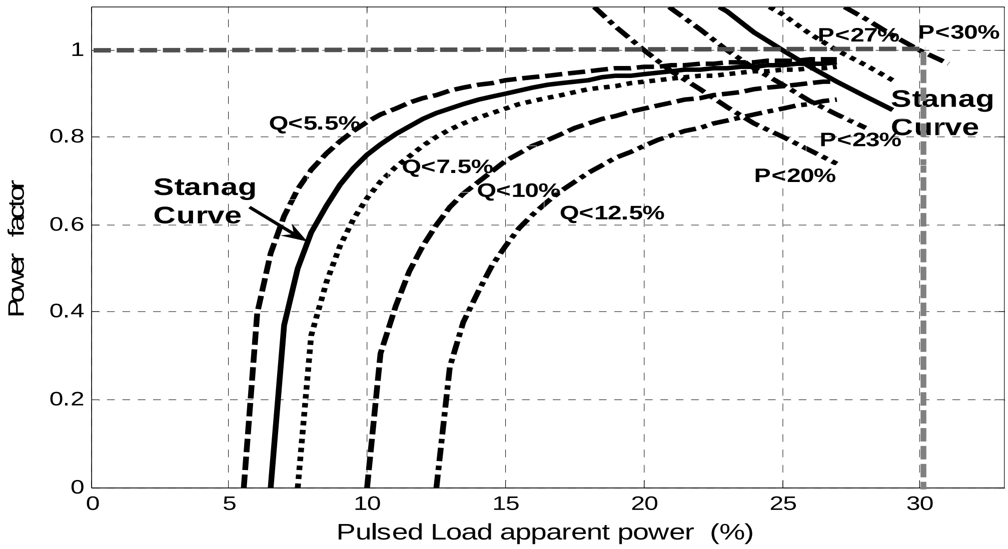

Fig. 23 Generalized pulsed loads limit-curves proposed

- Voltage modulation limit set by STANAG 1008 seems to need further attention as it influences the P.F.(S%) curves. It is worth noting that this limit varies in several standards, e.g. USA MIL-STD-1399(NAVY) [7] sets a value of 2% for types of power I and II, whereas for type III (400 Hz) a value of 1%. Moreover, IEEE Standard 45 [8], stipulates a corresponding general limit value of 5%. Evidently, more thorough investigation on the numerical value of this limit as well as its consequences is required, which is not at all an easy task due to lack of information.

Finally, regarding the forthcoming AES, although STANAG 1008 concerns only the *LV Ship Service Power Supply System* and not the electric propulsion systems (like those of AES), still it refers to AES configuration. More specifically, even in AES networks there will be LV service power system with equipment of more or less similar technology to that of the conventional ships, and therefore, with similar operating constraints concerning voltage and frequency modulation as stipulated by STANAG 1008. On the other hand, as up-to-date there is no NATO standard for the All Electric Ship electrical power system (HV, electrical propulsion), STANAG 1008's rules can be used a reference base of discussion. Anyhow, some preliminary investigation results in simplified AES configuration are presented concerning the point of connection of the pulsed load (at LV or at HV) as well as the pulsed load profile (rectangular or impulse form).

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