Voltage and Current Spikes & Transients - Power Supply Quality aspects for the AES

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Abstract: In this paper a discussion of the sources and effects of Voltage and Current spikes and transients in shore and ship electric power networks and the characterization parameters and methods are presented. Moreover, the paper investigates, discusses and compares the relevant issues dealt by different standards (international and national, military and commercial) applied to shipboard applications, taking into account the standard status of similar continental power systems and the perspective of the AES technology.

Keywords: Spikes, Transients, Ships, PSQ, AES

1. Introduction

Power Supply Quality (PSQ) is a term referring to a wide variety of disturbances in electric networks either ship or continental ones [1], [2], [3], [4].
Electric networks suffer from "short time duration non-periodical disturbances" of voltage and current caused by switching operations (making or breaking), short-circuits or even lightning strikes. The name of these disturbances varies depending on certain characteristics of them. Thus, terms like sags, swells, voltage surges, current surges, spikes, transients etc are often met in relevant documents.
Voltage and Current spikes and transients have several adverse consequences in shore and ship electric power networks such as equipment failure and improper operation of the entire system (insulation breakdown, errors in data-processing equipment etc). It is worth noting that these types of failures are not often acknowledged as consequences of power supply voltage or current surges. In contrast to the All Electric Ship (AES) perspective domination, no significant results (even for more conventional type ships) from investigating and classifying these phenomena have been recently reported following up the extensive electrification, the technological progress in the field of sophisticated power subsystems installed onboard, as well as in the domain of Surge Protective Devices (SPD) and measurement equipment. On the contrary, most ship-standards have been based on measurements and analyses/approaches performed almost twenty to thirty years ago, while no actual amendments on this topic have been made.

Power Quality standards in general, define measurement and characterization methods (indices and features) that are used as a tool for the application of the standards. Terminology is also established in detail. Standards set limits for the characteristics of several electromagnetic phenomena (a) for the electromagnetic environment (global limits), that is the maximum allowed levels of pollution in a system (b) for load emissions in order to ensure that global limits are not violated (c) for the load immunity levels in order to achieve compatibility between the system and the equipment. Standards have multiple recipients: measuring equipment manufacturers, equipment manufacturers, system designers and system operators.
In the following, after a short discussion on the characteristic parameters of the Spikes & Transients, we investigate, discuss and compare, the relevant issues dealt by different standards in view of the current and forthcoming status of ship electric networks. Some comments, which can eventually be amendments, are made too, so that the updated knowledge on nature and consequences of spikes and transients is taken into account.

2. Characterization parameters

In the literature (including relevant standards) there has been a significant work on voltage (and current) surge issues in Low Voltage (LV) AC power systems [5–28].
In IEEE 1159 [6], which is one of the key-standards on PSQ, power electromagnetic phenomena are classified into 7 groups. Groups 1 and 2 are transients and short duration variations. Each group is subdivided further into classes with specific characteristics, as it can be seen in Table I. More details are given next

Impulsive and oscillatory transients

An impulsive transient is a sudden, non-power frequency change in voltage or current, or both, that is unidirectional in polarity. Lightning and switching actions are typical causes of impulsive transients. For an oscillatory transient the instantaneous values of voltage or current change polarity rapidly. Capacitor switching is the most common cause of such transients.
Voltage transients are a threat for electrical insulation. Additionally, considering end-user equipment operation,

semiconductor devices (like thyristors) can be initiated by the rate of voltage change leading to a failure of the device or damage or even errors (for data processing devices) [20]. Transients can cause tripping of adjustable speed drives due to the increase in voltage in the dc link and the consequent operation of the overcurrent or overvoltage protection. Regarding surge protective devices transients in voltage as well as in current are crucial. Failures have been identified that are linked to current and not to energy.

Transients are characterized considering the actual values of the voltage waveform. The peak voltage, rise time and energy (the integral of the transient over the duration) of voltage are features that are usually extracted from the waveform. Other values that are used for characterization purposes are duration, time to crest, time to half the crest, frequency and energy. Considering the above features different classes have been proposed in standards [6], [7]. Source and surge impedance, system's configuration and components effect significantly the characteristics of transients. Researchers have shown that characterization of transients cannot be limited to a single value like energy in voltage [20], [21]. Several characteristics must be considered because different types of loads appear to be sensitive to different transient characteristics. The importance of the current during the transient has been also shown [19].

Impulsive Transients			
Rise time	5 nsec	1 msec	0.1 msec
Duration	< 50 nsec	50 nsec -1 msec	> 1 msec
Oscillatory Transients			
Frequency	< 5 kHz	5-500 kHz	0.5-5 MHz
Duration	0.3 – 50 msec	20 μsec	5 μsec
Short duration variations – Voltage dips & Interruptions			
Duration	0.5-30 cycles	30 cycles - 3 sec	3 sec - 1 min
	Short duration variations – Voltage swells		
Duration	0.5-30 cycles	30 cycles - 3 sec	3 sec - 1 min

Table I : Categorization of electromagnetic events according to IEEE 1159 (transients and short duration variations).

Voltage dips and swells

Voltage dips are events that present a temporary decrease in the rms voltage in one or more phases. They are caused by a increase in current somewhere in the system e.g., during faults, motor starting and transformer energizing [26]. A voltage swell is a temporary increase in rms voltage. Swells are usually caused by fault conditions and do not exceed 1.7 pu in magnitude. A swell appears in the unfaulted phases during a single line-to-ground fault in an ungrounded or impedance grounded system.

Voltage dips are responsible for the tripping of computers, electronic equipment and process control equipment. The behavior of these types of equipment can be a reset, incorrect operation or shutdown depending on the design and the inherent protection system of the load. For adjustable speed drives, depending on the load of the drive, the reduction in speed or torque might not be tolerated, by the process driven by the drive. Problems are also caused to the drive controller or the PWM inverter. Induction motors might not also manage to reaccelerate after the reduction in speed that is caused by the voltage dip [3]. Contactors are also sensitive to dips. Like transients, swells can be harmful for electrical insulation.

Voltage dips and swells are characterized by their rms magnitude and duration. Duration is the time that the rms voltage remains below a certain threshold and dip magnitude is the remaining rms voltage considering the phase with the maximum voltage. A typical threshold is 10% of the pre-event voltage. Fault dip magnitude depends on the impedance of the source (system's strength), system configuration, fault impedance, fault type and distance to the fault. For motor starting, the dip magnitude depends on the impedance of the source, the size of the motor and its characteristics. The magnitude of dips during transformer energizing depends on the source impedance, the switching instant, the remaining flux etc. Fault-induced events (dips and swells) present the most severe characteristics. Their duration depends on the protection system operation. That varies from half-cycle (fuse operation) to several cycles (operation of circuit breakers). Advanced methods have been proposed that consider all three phases motivated by the fact that the relation between the phases is important for the equipment performance [3] or by the fact that valuable information can be extracted considering all three phases [26].

3. Comparative analysis and evaluation of Shipboard Standards

3.1 General overview of standards

In Table II a comparative presentation of permissible limits of voltage spikes and transients of several shipboard standards and classification society rules is made. As mentioned above, the approach in the ship system technology is not as detailed as in shore applications.

3.2. Military Standards (STANAG 1008, USA-MIL-Std-1399)

The specifications of the electrical power plants in NATO naval vessels are laid down in STANAG-1008 [15] which is a document that has come out of USA MIL-STD-1399(NAVY)–Section 300A [16] under the responsibility of the NATO AC/141(NG/6)SubGroup/4. This group has produced several documents the most representative of which are [29-34]. According to USA MIL-STD-1399(NAVY)–Section 300A and to Editions 7, 8 and 9 of STANAG 1008, which hold for about seventeen years the definitions and the limits for voltage transient and spikes can be summarized as follows (in parentheses the Ed.9 changes), as seen also in Figure 1 :

Voltage transient is a sudden change in voltage (Ed.9: in the peak amplitude of the voltage), which exceeds the user voltage tolerance limits for a time longer than 1 msec and less than 2 sec (Ed.9: the typical time duration is between a fraction of a cycle and 2 sec). Limits : AC systems +/-16%

(under circumstances +/-22%). 24V DC systems 18-35V. **Voltage spike** is a voltage transient of short (less than 1 msec) duration (Ed.9: A voltage spike is usually less than a quarter cycle in duration). Limits : AC systems 2.5kV (440V supply) or 1kV (115V supply). 24V DC systems 600V.

REGISTER	VOLTAGE TRANSIENT	VOLTAGE SPIKE
ABS (2005) **BV**(2003) **DNV**(2001) **GL**(2004) **PRS** (2002) **RINA**(2005)	±20% (1,5s)	No
(LRS) (2001)	+20%, -15% (1,5s)	No
IEEE Std 45-1998	±16%(2s)	±2500V (380V – 600V)
		1000V (120V-240V)
STANAG 1008 (Ed.8, Ed.9)	±16%(2s) [±22%(2s)]* 18-35V, 24Vdc	2.5kV, 440V 1kV, 115V 0.6kV, 24Vdc
USA MIL-Std-1399	(like ST.1008)	(like ST.1008)
TEST PROCEDURES		
STANAG 1008 (Ed.8, Ed.9)	Standard lightning impulse acc. IEC 60060 -1. HV Test Techniques – Part 2 Test Procedures (Section IV)	
MARINE JIS (2001)	e,g, for control & instrumentation equip. : ±20% (1,5s) Burst / Fast Transient acc. to IEC61000-4-4(1995) Surge / Slow Transient acc. to IEC61000-4-5(1995)	
ABS (2005)	Burst / Fast Transient acc. to IEC60100-4-4(1995) Surge / Slow Transient acc. to IEC60100-4-5(1995)	

* under some circumstances

Table II : Comparison of shipboard Standards regarding transients and spikes

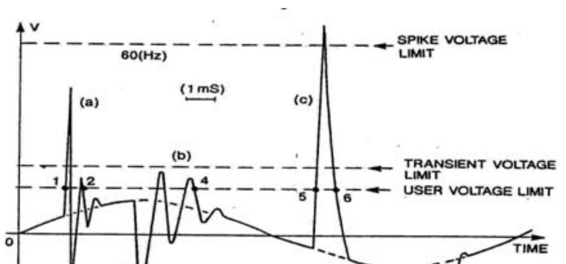

Figure 1 : Transients conditions according STANAG 1008, Ed.8 . (a) acceptable spike, (b) acceptable transients, (c) unacceptable spike, (d) unacceptable transient.
t(1,2) and t(5,6) < 1msec. t(3,4) and t(7,8) > 1msec.

The terminology and the "philosophy" of STANAG 1008 in not always consistent with the standards that are widely used in continental systems. For example in STANAG 1008 the term "spike" is used to describe (what in IEEE 1159 is described as "impulsive transient") and the word "transient" is used to describe anything that is longer than 1 msec (or longer than "a fraction of a cycle" in Ed. 9), which differs from the IEEE 1159 terminology (Table I). These differences impose difficulties in applying IEEE documents into naval electrical systems.
Other sources of skepticism regarding STANAG 1008 are described next.

3.2.a Spike peak limits

The spikes limits [2.5kV for 440V supply & 1kV for 115V supply] in USA MIL-STD-1399(NAVY)–Section 300A and in STANAG 1008 have been the outcomes mainly of the measurements of two projects in year 1972 [27] and in years 1978-1981 [28] on U.S. Navy vessels. These limits are also adopted in IEEE Std 45-1998 [12]. These figures are based on the statistic curves of the frequency of occurrence in excess of the spike level. These limits are often criticised, however in the absence of more recent surveys there has been no changes. Additionally, the extended use of surge protection devices has led several researchers (who performed measurements) to conclude that the issue of spikes is not as important as it used to be. It must be highlighted at this point that a change in these limits should be the result of systematic surveys considering the points of measurement with respect to the surge protection devices. This issue has been risen already in continental systems and it has been demonstrated that without appropriate measurements the results can be misleading [17], [22].

3.2.b Spike waveshape, Test-impulse, Test-methode

Measurements and theoretical analysis show that most voltage spikes in small-size low-voltage systems (as ship systems) have oscillatory waveshapes, unlike the unidirectional waves usually specified in high-voltage insulation standards [5], [18], [23], [24]. In STANAG 1008 only the "Lightning-Impulse"-IEC 60060-1 (Figure 2 up) is recommended for test purposes. However, other standards include also the "Ring Wave"-0.5µsec-100kHz (Figure 2 down, from IEEE "Surge-Trilogy" [5]).

3.2.c Voltage/spike Transient Envelope

STANAG 1008 Ed.8 distinguishes without intermediate area in the amplitude(DV)-duration(Dt) envelope between "spike" and "transient". e.g. it permits in a 440V system a voltage disturbance of e.g. 2000 V, if it has a duration of e.g. 990 µsec - because it is a "spike" - but if the duration is a little longer, e.g. 1010 µsec, the permitted value is much smaller (only 759 V = $1.22x\sqrt{2}x440$ V) - because it is a "transient". This sharp distinction between "spikes" and "transients" areas in STANAG 1008, is a theoretical one and has nothing to do with the real natural phenomena. Other standards (e.g. ITIC [8], DIN VDE 0160 A1 [9], USA MIL-STD-704E [11]) use an intermediate area in the amplitude-duration envelope, even if there are some variations. Figure 3 shows that in ITIC curve, compared to Fig. 11 of STANAG 1008, two different areas are defined (for oscillatory and impulsive transients) having different slopes. Additionally, in Ed.9 of STANAG 1008, as described above, the decisive characteristics for distinguishing transients from spikes are not clear (see the shadow area in Figure 3) and this can lead to confusion (for example a disturbance of 3 msec duration and peak magnitude of 900 V is acceptable as a spike but not acceptable as a transient).

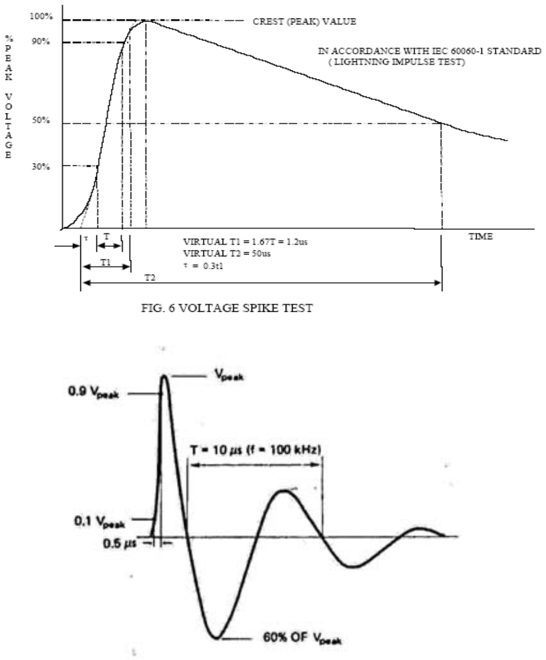

Figure 2 : Test waveshapes, (up): "Lightning-Impulse" IEC 60060-1, (down): "Ring Wave"-0.5μsec-100kHz [IEEE "Surge-Trilogy"].

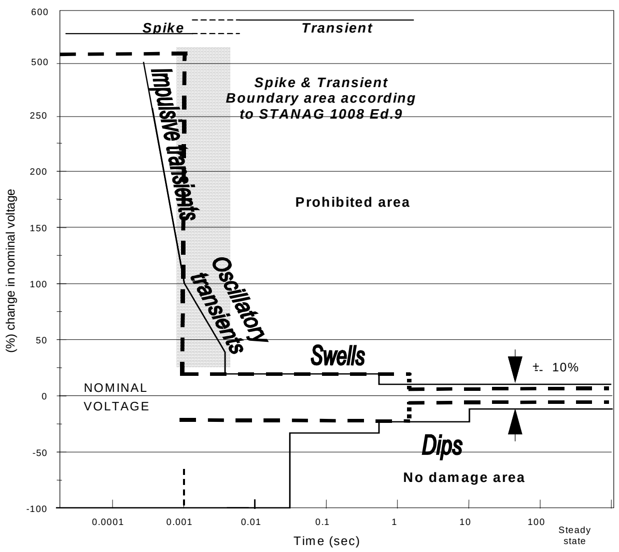

Figure 3 : ITIC compared to STANAG 1008 (dashed line) (applicable to 120 V equipment – 60 Hz)

3.2.d Voltage and current spikes

The voltage spike test that STANAG 1008 proposes is a lightning impulse with characteristics that are based on the concept of energy (100 joules on 2 ohm load). It has been shown ([20], [21]) that the concept of energy (defined in such a way) in an undefined power system is a misleading oversimplification. Energy is important for metal-oxide varistors however the energy that such a device must handle depends on amplitude, waveform, source impedance and varistor characteristics and not only on the energy calculated by the voltage waveform. From the load side, it is important that there are cases where the failure mechanism is totally independent from energy. Current surges have also a critical effect on the failure mode and they are also system depended. By excluding current from the analysis and measurements it might make difficult the interpretation of a problem [19].

3.2.e Severity assessment of short duration variations [dips and swells]

For events of duration of several cycles STANAG 1008 uses the voltage peak as a measure of the voltage disturbance severity unlike IEEE and IEC methodology that uses rms values for the same purpose (the way that rms is calculated is described in detail: window, interval, etc). Although peak value is appropriate for impulsive and oscillatory disturbances, rms is the most appropriate way of describing events like voltage dips and swells. Peak voltage is not always representative of the actual event especially in the presence of harmonics. Monitoring equipment is nowadays able to calculate on-line rms values and store them as a memory saving option. Figure 4 (up) shows the measurement of a voltage waveform during transformer energizing. It can be seen that there is an asymmetry between the negative and positive peak voltages due to the unsymmetrical nature of the transformer inrush current. In Figure 4 (down) the rms voltage is shown (using a one-cycle window and a one sample interval) as well as the positive peak voltage values. It can be seen the difference between the two is significant.

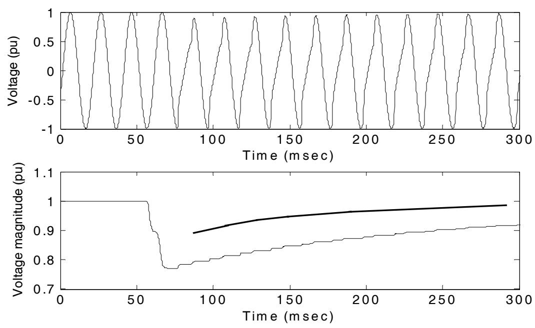

Figure 4 : (up): Voltage waveform during transformer energizing, (down): rms voltage and positive peak voltage (thicker) line

3.2.f Supply Interruptions

Although USA MIL-STD-1399(NAVY)–Section 300A (a source document for STANAG 1008) considers supply interruptions as a power quality parameter, STANAG 1008 does not, due to the fact that is described in the next paragraph. Power supply interruptions are an important aspect of power quality and it must be included in a monitoring survey with all the relevant details (cause and duration) in order to evaluate the performance of the electrical system, identify the weak components, apply enforcements and select appropriate power quality mitigation equipment.

3.2.g Appicability of STANAG 1008 in fault conditions

STANAG 1008 states that:*« 4. The definitions, user information and characteristics in this agreement refer essentially to a healthy electrical power supply system and include transient conditions that result from normal system operations, such as motor starts and switching events.* The STANAG does not describe system behaviour under abnormal conditions, *e.g. short circuit faults, loss of generator sets or malfunction of associated controls, as this behaviour depends heavily on the design characteristics of individual systems.»*. Consequently, STANAG 1008 does not include limits and guidelines with respect to abnormal conditions for the design of naval systems although these conditions produce transients and spikes are even more severe than the ones in normal system operations. However, it is important to take into account abnormal conditions (a) in the design stage in order to minimize their impact by making appropriate decisions from a system point of view (b) in coordinating load immunity and protection devices (surge protection, ups, flywheels etc) and (c) in designing appropriate protection devices and equipment with higher immunity to power quality parameters.

3.3. Particular aspects of AES

The eventual complete electrification of all systems onboard according to All Electric Ship (AES) concept is expected to emerge complicated transient phenomena and spikes to a significant extent. Thus, considering the great variety of electric loads to be installed onboard in conjunction with their huge energy demands leads up to the conclusion that almost all AES- evolution trends would be inherently correlated to several adverse power quality phenomena. More specifically:

Motor drive converters applied main and auxiliary propulsion systems would provoke significant harmonic power quality problems (in case of normal “as designed” steady-state operation) but also not easily predictable switching transients mainly due to problems during commutation of power electronic switches.

Pulsed loads, dedicated mainly to modern weapon systems onboard, are, by default, a major voltage dip source due to the huge amount of energy demand for extremely small time interval, marring the reliability of AES itself.

The introduction of high voltage (i.e. voltage levels above 1000 V) increases the requirements for insulation in either steady- or transient- state as all pieces of equipment are to be subjected to harmful high-valued short-circuit currents, transient overvoltages and surges. Concerning the initial peak value of spikes, as widely known from experience on continental grid, the stray capacitances of all components onboard would play an important role.

The alternative integration of HVDC power supply (e.g. in case of fuel cell applications) has been reported to introduce several switching transients as circuit breaking of a DC current is a significant burden emerging significant temporary but harmful overvoltages [35].

Zonal concept and ring type networks designed to increase power supply reliability offering multiple ways of providing critical loads with electric energy could magnify power quality problems if the system protection scheme is not well set according to appropriate selectivity criteria, permitting incidents taking place on one source side to be seen and expanded to the other.

Economic operation of the gigantic electric system installed requires minimum number of operating generators in combination well balanced load sharing of both propulsion and service loads. The latter prescribes a large central scale system monitoring all energy requirements on a real-time basis and reconfigure load feeding dynamically, which actually means a significant number of switch change-over operation with the subsequent switching transients.

Standards like STANAG-1008 which is supposed to be the most favorable for AES should be adopted taking into account all these considerations on forthcoming power quality problems. This can be done by :

- Prescribing the nature and categorizing if possible all spike-related events expected to take place in AES’s installations.
- Recommending alleviating measures to reduce such power quality phenomena (e.g. by suggesting the characteristics of corresponding protective devices e.g. surge protection devices, filters, snubber circuits).
- Intermediate steps through this standardization can not but comprise both performing test measurements on actual AES sub-systems under construction as well as simulations of several sequence of events.

4. Conclusion

In this paper different aspects of voltage and current spikes as well as transients were presented from the naval power system point of view with respect (a) to the existing shipboard standards and (b) the standards, practice and research for continental power systems. The causes as well as the effects of these phenomena were discussed and emphasis was given to the methods that are used for their characterization.

Several continental and shipboard standards are compared in the way that they treat spikes and transients. It is shown that different limits are used for transients and also that in some cases, spikes and relative testing procedures are not considered. Special attention was given to STANAG 1008 for warships. First, it was discussed that in Ed. 8 of this document spikes are distinguished from transients differently than in continental standards. In Ed.9, for the distinction a boundary area between the two is implied although in continental standards this issue is clearly defined. Additionally, it is shown that although in continental standards sophisticated curves are used for setting limits for transients and spikes STANAG 1008 does not consider an intermediate area between the two leading to problems in its application. Other issues are also highlighted regarding spikes (peak limits and the limitations of the "energy concept"), the waveforms proposed for testing and the way severity is assessed (peak vs rms voltage). Additionally, the absence of interruptions in the event list of STANAG 1008 is addressed. Finally, it is discussed the fact that STANAG 1008 intents to cover only normal operation conditions without providing guidelines for abnormal conditions that typically produce more severe events.

Experience gained in continental systems regarding power quality issues is valuable for naval systems and it can be exploited by the corresponding standards as long as a common framework is established. By taking advantage of the developments in measurement equipment and the research in power quality, naval standards can provide guidelines for design and operation that will ensure higher levels of power quality in ships, an issue which becomes more important due to the eventual complete electrification of all systems onboard.

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