

# On electric load characterization and categorization in ship electric installations

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## SYNOPSIS

Each load of a ship's electric network can be characterized by several operating parameters, which are not always readily available or even easily measured. In most cases, the manufacturer provides the so-called nameplate data, which do not at all suffice for the purposes of many studies performed during design and construction or operation and planned maintenance stages.

This paper makes the effort to define, analyse and discuss the issues related to the characteristic parameters of onboard electric loads, in an attempt to highlight some fundamental steps for establishing classification criteria, according to which electric loads are grouped into categories. The paper focuses on the discussion of "load demand profile", "load factor" and "priority index" in conjunction to methodologies of studies. Further a two-stage methodology is presented, which can estimate both the typical load curves of each consumer and the consumer clusters together with their respective representative load curves.

Key-Words : ship electric load characterization, load profile, load factor, priority index.

## INTRODUCTION AND BACKGROUND – SCOPE OF WORK

Each equipment (also called "load" or "consumer") of a ship electric network can be characterized and categorized by several operating parameters, of which not all are always readily available or even easily measured. However, these parameters are required in many ways in categorizing loads onboard and in performing several useful studies such as load estimation, power sources selection, power cable rating, short circuit analysis, load shedding, Harmonics, Modulation etc, as indicatively is summarized in Table I. The advent of All Electric Ship (AES) with the integrated full electric propulsion schemes and the extensive electrification of all systems onboard magnify this problem to a significant extent.

The characteristic parameters of an electric load can be classified according to the following points of view :

A) the so-called nameplate data provided by the manufacturer, which remain constant and of the same value regardless the network to which the equipment is connected or its use in general. Such characteristics include nominal operating voltage and frequency, AC/DC power supply, nominal power, Linear / Non-linear voltage-current characteristic, Current Harmonic distortion etc.

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B) there are certain characteristics which, for a specific equipment, are not constant but vary as a function of operation time and the conditions of operation each moment, being independent of the network the equipment is connected as well as independent of any other operating equipment. Typical examples are the power efficiency and the power factor.

C) those characteristics, the values of which vary depending on the network the equipment is connected, as well as the rest of the operating equipment in the same network and depending on ship type, state and mission. Typical examples are the Load demand profile, the Load factor and the Priority Index.

**Table I** Indicative overview of the use of load characteristic parameters in some methodologies of studies

Characteristic Parameter of a consumer	Studies						
	Load Estimation	Power Sources	Cable Rating	Short Circuit	Load Shedding	Harmonics	Modulation
Operating voltage		X					
Supply type		X					
Operating frequency		X					
Nominal, operating power	X			X	X	X	X
Power factor	X		X				
Power Efficiency	X		X		X		
Harmonic distortion ( IHD, THD, TDD )		X				X	
.....							
<b>Load demand profile</b> ( including related parameters obtained from it, see text )	X		X	X	X	X	X
<b>Priority index</b>		X			X		
.....							

Besides the well-known consumer characteristic parameters according to the above (A) point of view, there are certain – like the “Load demand profile” i.e. the *chronological energy demand curve of the load*, the “Load factor” and the “Priority index” – of primary importance, which should be involved in many electric analyses and studies.

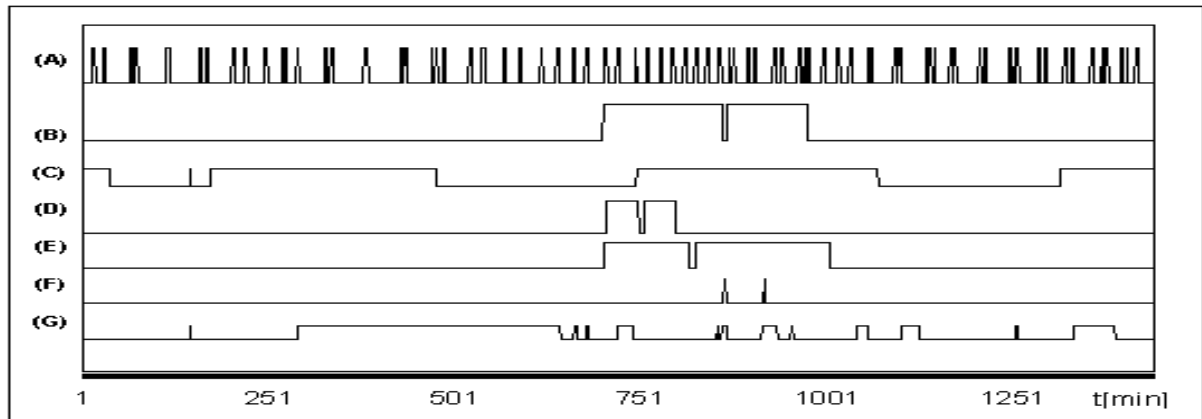
In the first part of the paper an effort is made to define, analyze and discuss those parameters of onboard consumers, in an attempt to highlight some fundamental steps for establishing additional classification criteria, according to which electric loads could be grouped into *categories*. Likewise the parameters’ role and usefulness to several studies of ship electric systems is considered. Then the paper focuses further on electric load profile classification. A two-stage methodology is presented, which estimates both the typical load curves of each consumer and the consumer clusters together with their respective representative load curves, in order to successfully describe the respective behavior. The same process can be repeated for the load curves of generators (for each one and for the total set), in order to find out the typical behavior of the ship total load demand.

As a case study, results from the application of the developed methodology on a set of consumers and generators of Hellenic Navy MEKO type frigates are presented, in order to find out the similarities and dissimilarities in the electricity load behaviour.

### LOAD DEMAND PROFILE, LOAD FACTOR, PRIORITY INDEX

In this section the characteristic parameters of “Load demand profile”, “Load factor” and “Priority index” are defined and commented.

**Load demand profile  $P_d(t)$**  : the load demand of several loads is not at all constant, varying with time. Hence, depending on the “Ship Operating Condition” (SOpC) – often categorized in warships in the following four (4) main states : “SHORE”, “ANCHOR”, “AT SEA” and “GENERAL QUARTER” –, the load demand can vary between zero and the equipment nominal power. In Fig 1 examples of daily ON/OFF chronological curves of seven different electrical consumers “AT SEA” are presented, based on records taken on board from HN MEKO type frigates by the control and monitoring “NAUTOS” system every 1 min [1].



**Fig 1** Examples of *Load demand profiles*  $Pd(t)$  ( ON/OFF status ) of ship consumers "AT SEA".  
 (A) Leak Oil Pump, (B) Fuel Booster Pump, (C) Fuel Purifier, (D) H.P. Compr.,  
 (E) GT Enclosure Fan, (F) CCP Control Oil Pump, (G) Lub Oil Pump for Main Gear.

These daily load demand profiles of each consumer vary from day to day, even if the Ship Operating Condition is unchanged, but their picture remain more or less the same. Hence, a first approach categorization of consumers could be according their load demand profiles e.g. :

category 1 : Pulsed-load- or quasi-Pulsed-load profile, i.e. quasi-periodic operation with "ON/OFF" period of some minutes (e.g. Leak Oil Pump (A))

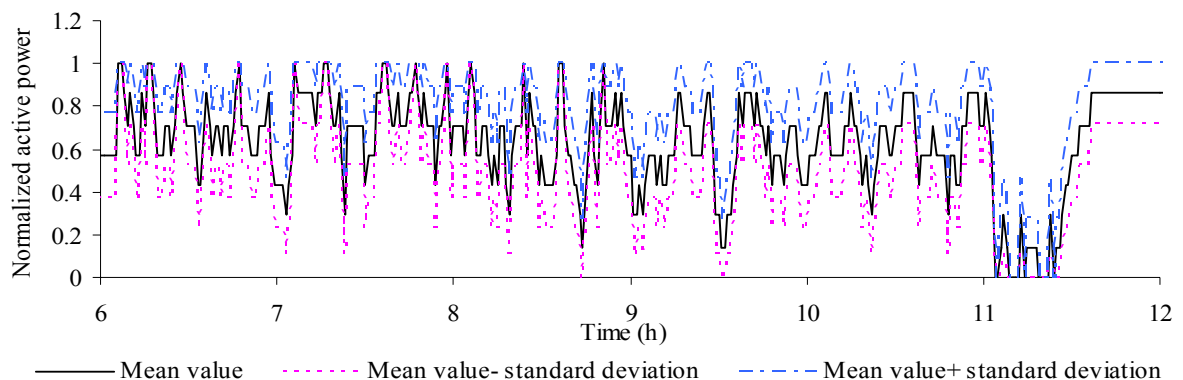
category 2 : Quasi-periodic-profile with "ON/OFF" period of some hours (e.g. Fuel Purifier (C))

category 3 : The most time is "OFF" and operate only for a relative short time ( 1-2 hours ) (e.g. Fuel Booster Pump (B), H.P. Compressor (D), GT Enclosure Fan (E))

etc

A more adequate categorization can be realized by using statistical tools or pattern recognitions methods, as it is proposed in the last section of this paper. With those methods a respective "*representative load demand profile*" for each consumer or for a set of different consumers can be estimated to.

**Representative load demand profile  $Pd,r(t)$**  : this load curve gives the probability of the consumer to be on status "ON" for each time step. For example, if the respective mean value is 0.7, it means that this consumer will be "ON" with 70% probability percentage and it will be "OFF" with the rest 30% probability percentage. Alternatively, this probability expresses the presumable normalized active power with respect to the nominal (peak) load of each consumer. In Fig 2 the normalized representative daily chronological load curve for the refrigeration plant of HN MEKO type frigate is presented (a segment is shown, between 6 to 12 hour) with the confidence limits of the variations (mean value  $\pm$  standard deviation), which has a probability of occurrence equal to 68.27% assuming a normal distribution.



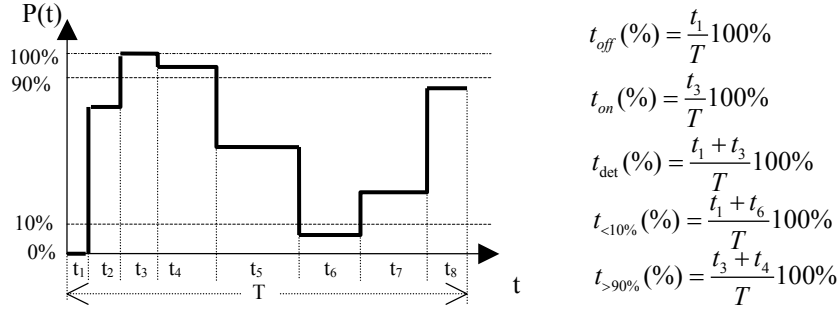
**Fig 2** Representative daily chronological ON/OFF load curve for the refrigeration plant of MEKO frigate at "SHORE" with respective deviation using the proposed methodology of last section of this paper.

The following "*characteristic time period percentage indices*" (as are explained in Fig. 3) of the representative daily chronological ON/OFF load curve for each consumer can be calculated, in order to characterize the load profile in more details :

(a) *off - time period index*  $t_{off}(\%)$  : time percentage for which the typical load is always *OFF*, meaning that the respective load is zero.

(b) *on - time period index*  $t_{on}(\%)$  : time percentage for which the typical load is always *ON*, meaning that the respective load is maximum.

(c) *deterministic time period index*  $t_{det}(\%)$  : time percentage for which the typical load is deterministically known (constantly always *ON* or always *OFF*), meaning that the respective load is unchanged for specific time intervals of the day. It is also equal to the sum of the off-time period index  $t_{off}(\%)$  and the on-time period index  $t_{on}(\%)$ .



**Fig 3** Explanation of the characteristic time period percentage indices

(d) *lower 10% time period index*  $t_{<10\%}(\%)$  : time percentage for which the typical load is equal or lower than 10% of the maximum demand, meaning that the respective load has 10% or lower possibility to be *ON*.

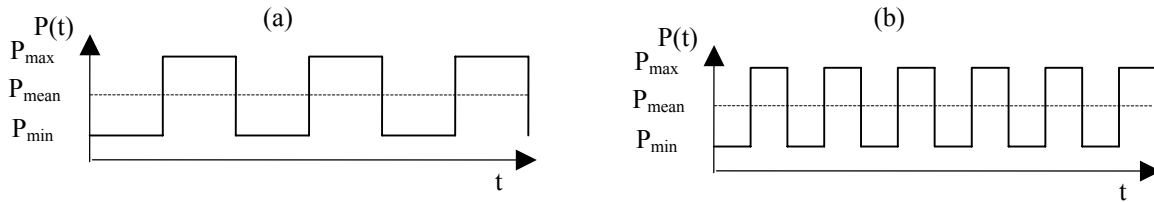
(e) *upper 90% time period index*  $t_{>90\%}(\%)$  : time percentage for which the typical load is equal or upper than 90% of the maximum demand, meaning that the respective load has 90% or higher possibility to be *ON*.

**Load factor  $f_s$**  : indicates the relative (%) load of the equipment, specifying how much power is absorbed in an actual operating condition. It varies between 0% and 100%. It is defined as the ratio of the actual energy required on a daily basis ( or any other plausible period  $T$  ) over the energy corresponding to the nominal / maximum demand power,  $P_{nom}$ , for the same time interval :

$$f = \frac{\sum_i P_i * \Delta t_i}{T * P_{nom}} 100\% \quad , \quad T = \sum_i \Delta t_i \quad (1)$$

where  $P_{nom}$  the nominal power and  $P_i$  the operating power level during time interval  $\Delta t_i$ ,

The load factor is a classical index, but it can not describe the load profile curve successfully, as it can be comprehended from the example of Fig 4, where the consumer of Fig 4.a fatigues the ship's generators less than the consumer of Fig 4.b for the same peak load, load factor and power factor, because the number of the load demand changes are fewer. If an energy storage system is used, the second consumer will need smaller battery system than the first one. These inferences cannot be drawn without the consumers' load profiles.



**Fig 4** Indicative load curves of electricity consumers with the same max load, load factor and power factor

**Priority index** : index showing the relevant criticality of an installed load on the safe accomplishment of the vessel's missions and its survivability. This index is not static and unique, but depends on the particular conditions of each ship situation (ship's state and mission).

It plays a significant role in certain studies like :

- Load shedding system
- Emergency generator rating
- Back-up feeder installation (double cabling)
- Extra local power supply unit prescription

## CORRELATION TO METHODOLOGIES OF STUDIES

In the following paragraphs of this section the conjunction of characteristic load parameters to some methodologies of studies is presented.

### Load Estimation

An important issue in designing the electrical plant of a ship, is the selection of the optimum number of generators as well as the rated power output of them, that should be installed. This choice is influenced by the type and the purpose of the ship, and depends upon the maximum expected load, based on the “*Load Estimation*” in different operational states of the ship [2], [3].

The purpose of electric “Load Estimation”, is to define the “*total average daily required load*” TPdl of the electrical network. It is based on the use of *daily “load factor”* fs,j for every consumer ( the j<sup>th</sup> one) and for each “*Ship Operating Condition*” (SOpC) as already defined. Taking in to consideration the *Power Efficiency* η<sub>j</sub>, the “*average daily required load*” Pdl,j from the j<sup>th</sup> consumer, is :

$$Pdl,j = (P_{nom,j}/\eta_{j}) \cdot fs_{j} \quad (2)$$

If N<sub>tot</sub> consumers are operated in a certain (SOpC) and N<sub>j</sub> (j = 1, ..., m) is the number of the “same” consumers (N<sub>tot</sub> =  $\sum^m N_{j}$ ) then the estimation of TPdl for that (SOpC) is :

$$TPdl = \sum^m ( N_{j} \cdot Pdl_{j} ) \quad (3)$$

In the Standardization of NATO Military Navies [4], [6], the fs factors are given for various consumers and (SOpC), for different types of warships. These are indicative values, which can be revised during the design of the electrical plant of the ship. The final choice of the value to be used, should be taken with respect to the characteristics of every consumer, as well as the gained experience from already existing systems. The calculated TPdl must be increased by a factor, in order to cope with future load requirements. The selection of the number and output power of the generators is done according to the redundant power, which is defined by the adopted Standardization [5], [6].

### Power Source selection

The selection of power sources is of primary importance, as several parameters of the consumers have to be taken into account. Thus, the nature of the power supply, i.e. AC or DC, the level of nominal *operating voltage* and *frequency* as well as the fuel type used have to be judged thoroughly. Furthermore, depending on the criticality (*priority index*) of the loads considered, back-up alternative sources e.g. UPS’s, SMES’s etc are investigated. Moreover, highly non-linear loads provoking significant *harmonic distortion* are isolated from the general mains either via the intervention of appropriate filters or by supplying them via independent sources.

### Power Cable Rating

During electric installation design study, cable rating of the power distribution cables supplying equipment with electric power, is mainly based on their *nominal power*. As several equipment do not operate at their rated values, but have a rather intermittent operation, in certain cases standards permit that cabling is of lower dimensions than the nominal one. This lower sizing of the cables is based on the partial loading conditions of the equipment and moreover on their power profile, which as discussed in this paper can be estimated at several approximation levels, the first of which is the *load factors fs’s*. Furthermore according to classification society rules the power cable size can be reduced in case of intermittently operating equipment and in particular, when the equipment works only for a short interval (of e.g. 1 hour) followed by a long cease of operation (e.g. *load profiles category of load (D)* in Fig 1).

### Short Circuit Studies

Short circuit calculations have become more important than in the past due to the introduction of high voltage applications, especially referring to ship electric propulsion cases. Although required by certain classification society rules even at low voltage (<1000 V) operation levels, short circuit calculation studies are most important at higher voltage for rating electric equipment onboard and circuit breakers, in particular.

Short circuit studies and protection device rating for shipboard installations are performed according to IEC 61363 [7], which stipulates that all calculations have to be done considering the instantaneous loading conditions

of major loads and large power motors, in particular just before the short circuit fault occurs. This load contribution is in the order of 15% -20% [8] of the total short circuit current, while the most tangible manner to estimate it is via the *load factors*, *fs*'s, which reflect the partial loading power demand of the operating equipment.

### Load Shedding

As a common practice, major combatant naval ships have *load-shedding systems*, that automatically disconnect pre-selected loads from the ship's distribution system, whenever an overload condition develops, in order to ensure the survivability of the electrical power system and ship [9], [10], [11], [12], [13], [14]. Overload conditions occur whenever an on-line generator suddenly fails, or a large demand of power comes out when some of ship's generators are secured. So the loads installed onboard fall in one of several stages of a *shedding scheme*, in the context of which they are characterized as main or secondary, or vital (and semi-vital) and non-vital. The secondary or non-vital loads are those, which do not adversely affect ship's operations and survivability for long and consequently are shed first in order to overcome the overload condition. Essentially all shipboard loads are characterized by a *priority index*, which is attributable to them not beforehand - by the manufacturer -, but instead after the loads are installed and operated in the specific ship's electric network. These "static" classical and usually *dual* load-shedding schemes do not flexibly respond in complex scenarios of different ship's situations, during which rare but hazardous conditions may occur, where, after having shed all non-vital loads, the available power still can not cover all vital loads. In such situations, ship's command may face the dilemma to shed loads that are equally vital for the ship. Consequently a shedding scheme is needed, that would be more flexible and usable for the ship's command, based on "*dynamic load prioritization*" according to actual ship's state and mission. The advancement towards such flexible shedding schemes calls for improvements in the methods of evaluating an installed load's priority.

As a *first step* comes the method of applying different priority indexes to the same load according to each of ship's states and missions, so creating a "*dynamic multi-staged shedding scheme*" [14]. In contrast with traditional static shedding schemes that have two (at most three) stages, dynamic multi-staged scheme is more selective and situation-adaptable, consequently making more efficient use of the available power. In that way the vitality of a load will be better tied to each of the ship's actual situations and there will be less loads for each priority group, making shedding more gradual. Such a dynamic multi-staged shedding scheme is based on a *priority table*, as indicatively is shown in Table II. In this Table the following 'operational' categorization is used : Floating, Navigating and Fighting [ with the sub-states : Anti Aircraft Warfare (AAW), Anti Surface Warfare (*ASurW*), Anti Submarine Warfare (*ASubW*) ]. Electrical loads are characterized by a priority index of the type  $i_m$  for the 'm' ship's state or mission which is set to **1** for the most vital loads (for that state) and **6** for the least vital. Several examples that follow depict the use of the priority table :

**Table II** Ships' state/mission-dependent load priority table

System / priority		State / Mission				
		Floating	Navigating	Fighting		
				AAW	ASurW	ASubW
1	Platform Control System	3	1	2	2	2
2	Refrigeration plant	6	6	6	6	6
3	Fire-fighting pump	1	3	2	2	2
4	Bilge pump	1	3	2	2	2
5	Chiller Units	5	5	2	2	2
6	Propulsion motors 1 <sup>st</sup> increment	3	1	1	1	1
7	Propulsion (motors) 2 <sup>nd</sup> increment	4	2	1	2	1
8	Propulsion (motors) n-1 <sup>st</sup> increment	5	4	2	3	2
9	Propulsion (motors) n <sup>th</sup> increment	6	4	3	4	3
10	Steering System 1	3	1	1	1	1
11	Steering System 2	5	2	2	2	2

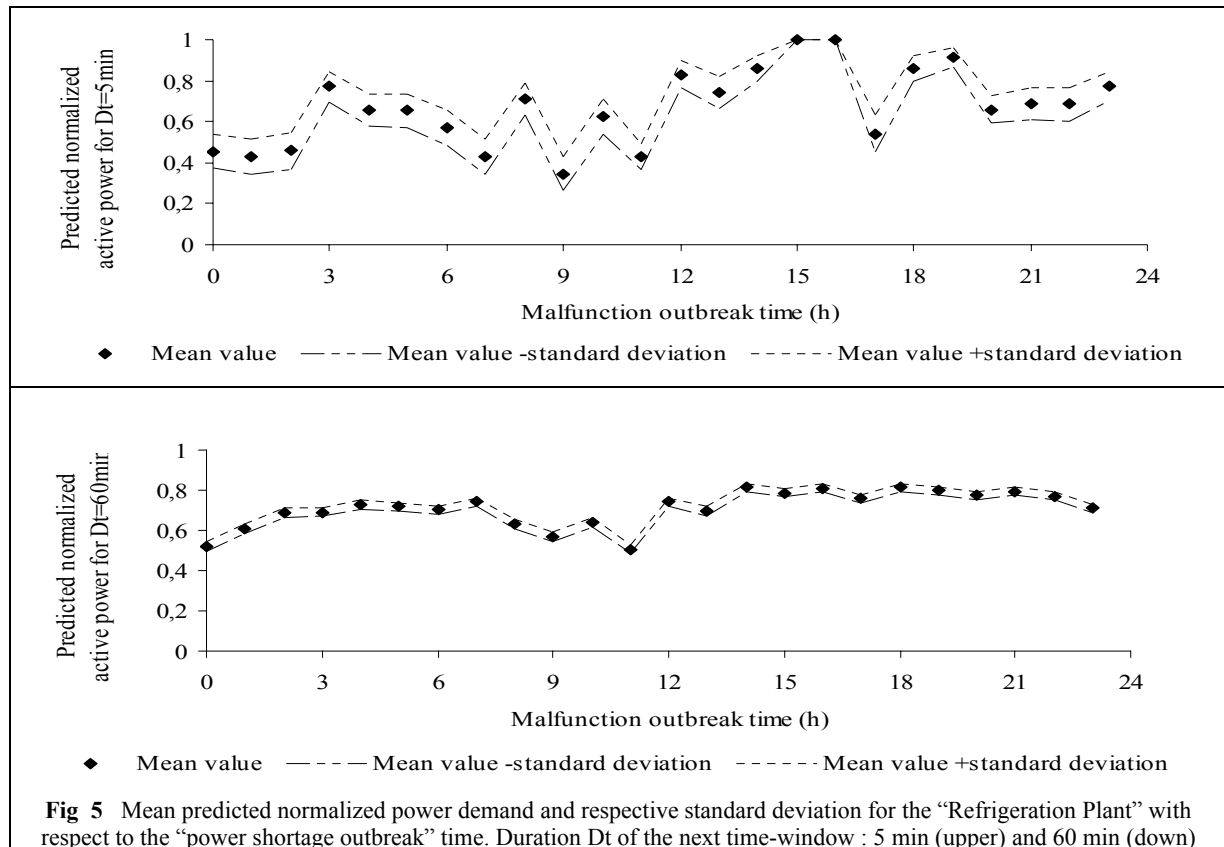
System / priority		State / Mission				
		Floating	Navigating	Fighting		
				AAW	ASurW	ASubW
12	Gyrocompass 1	4	2	1	1	1
13	Gyrocompass 2	5	3	2	2	2
14	Combat System	5	5	1	1	1
15	Navigation Radar	3	2	3	3	3
16	Close Range Defense Weapon	5	4	1	1	3
17	ESM	6	5	1	1	3
18	ECM	6	5	1	1	5
19	Surveillance Radar	6	4	1	1	2
20	Weapon Guidance Radars	6	6	1	1	4
21	Air Missile Launcher	6	6	1	3	5
22	Sur. Missile Launcher	6	6	5	1	4
23	Sonar	6	6	5	4	1
24	Torpedos' systems	6	6	6	5	1
25	Gun	6	6	1	1	3

a. When ship's state is set to 'floating' (that is, ship cannot fight and can hardly navigate) loads that can directly contribute to that goal – as the fire and the bilge pumps – become the most vital and their priority index is set to 1. Fire and bilge pumps have an intermediate priority for the other ship's states, in a sense that are not immediately vital, but can become so anytime the ship is in a fighting state. On the other hand, loads like the sonar and the missile launcher get low priorities for the 'floating' state.

b. Between two similar redundant systems (e.g. the gyrocompasses and the steering systems), one is marked as "first", having always a higher priority than the other for any state. In case that the first one is not useable, the second gets the priority of the first. The same principle applies for more than two similar redundant systems.

c. The first gyrocompass is not vital when ship struggles to float and so its priority index is (indicatively) 4, it is not vital but would be good to have when ship cannot fight but tries to navigate and so its priority index is then (indicatively) 2, but is absolutely vital – having the highest priority 1 – when the ship fights.

Ideally and to the upper theoretical limit this dynamic multi-staged load prioritization could lead in a scheme, where all installed loads have different priority indexes for each one of the possible ship's states and missions, thus avoiding situations to have the dilemma of shedding one of two equally-vital loads, since then there will not be such loads. Since this is not expected to be technically achievable, the *second step* towards a dynamic multi-stage shedding scheme is a feasible method for selecting between loads with equal priority-index. This option is given by the use of the "Representative load demand profile"  $Pd,r(t)$ . During extreme power-shortage cases, it is proposed to examine the possibility of shedding those loads that, as indicated by their "Representative load demand profile", are less likely to absorb power during the immediately *next time-window* of the crisis periods. In other words, in that particular time-window the reduced probability of a load to demand power, will dictate its usefulness.



Lets take the "Representative load demand profile" of the "Refrigeration Plant" of HN MEKO type frigates [see Fig 2] only as an indicative example to illustrate the concept, because it is of course not at all a vital load in a short-time crisis situation. Fig 5 shows - for two selected *next time-window* of different duration  $Dt$  [ 5 min and 60 min respectively ] - the resulting dependence of the "mean predicted normalized power demand"

$$Pd,r,m(Dt,t) = (1/Dt) \int_t^{t+Dt} Pd,r(\tau).d\tau$$

on the time  $t$  in which a ship-power-shortage is supposed to occurs [ the "power shortage outbreak" time ]. The calculations for the specific example have been done for 24 discrete points  $t_0$  ( $t_0 = 0, 1, 2, \dots, 24$  h). In contrast to the 60 minutes' the diagram for the 5 minutes 'next time-window'

shows a larger variation and deviation as it was intuitively expected. Next, if for example the shedding dilemma occurs exactly at 03:00, the probability of the refrigeration plant to demand power in the next 5 minutes is close to 0.8 and consequently this load won't be shed in respect with an other equally vital load, the corresponding diagram of which gives e.g. a 0.4 at that particular time of the day. Alternatively, instead of using the "mean predicted normalized power demand"  $Pd,r,m(Dt,t)$ , the product  $Pd,r,m(Dt,t) \times Pop$  - denoting the "predicted power demand" -, could be used for selecting the shedding of a load among equally vital ones. This product, beyond the probability of a load to demand power in a 'next time window', also includes the level of that demand and so it could be used for an optimum shedding selection.

### Harmonics

Harmonic power quality, a problem of extensively electrified networks with several adverse consequences [15], [16], [17], refers to the existence of distorted periodic voltage or current waveforms, which, can be expressed via mathematical Fourier analysis, as the superposition of an infinite series of frequencies, the fundamental one (the so-called power frequency) and its multiples, the high-order harmonics :

$$v(t) = \sum_{n=1}^{\infty} V_n \sqrt{2} \sin(n.\omega t + \theta_{v,n}) \quad i(t) = \sum_{n=1}^{\infty} I_n \sqrt{2} \sin(n.\omega t + \theta_{i,n}) \quad (4)$$

The level of distortion is measured, besides the individual voltage and current harmonics  $V_n$  and  $I_n$ , equation (4), via the Total Harmonic Distortion (**THD**) , i.e the portion of high order harmonics with reference to the fundamental component :

$$THD_V = \frac{\sqrt{\sum_{n=2}^{\infty} V_n^2}}{V_1} \quad THD_I = \frac{\sqrt{\sum_{n=2}^{\infty} I_n^2}}{I_1} \quad (5)$$

It is worth noting that according to THD definition, both the fundamental component and the high order harmonics should be measured simultaneously. However, should in (5), the fundamental equals an *average* quantity over a specific time interval, as happens in current, then the index is called Total Demand Distortion (**TDD**).

Harmonic distortion is actually faced by most standards as voltage quality, as voltage can be directly controlled and regulated by the power system ( limits set by standards : between 1.5% and 3% for any high-order voltage harmonic and between 5% and 8% for the  $THD_V$  ). However, considering that current distortion is also reflected to voltage one, via the voltage drop on circuit impedances, much attention must be paid to current quality defined by the entity of loads installed onboard or at least the major ones, i.e. those of significant power demand and where power electronic converters involved, in particular.

Current distortion limits are clearly set only by USA MIL-STD-1399(NAVY)-Section 300A [18], IEEE-519 [19] and by the (no more valid) Edition 8 of STANAG 1008 [20.a]. IEEE-519 restricts both, each harmonic separately as well as the entire high order spectrum expressed by  $TDD_I$ . In addition, the % restrictions of high order current harmonics set by the two standards refer to different values of the fundamental, as :

- According to USA MIL-STD-1399(NAVY)-Section 300A (and Edition 8 of STANAG 1008) the high harmonics for each load  $I_n$  should refer to the *rated (nominal) full load fundamental current*  $I_{1,FL}$ , as defined by equipment manufacturers. It is noticed, that as has been reported in numerous technical papers [21], [22], [23], [24], [25], [26], their distortion limits of current harmonic distortion set, are rather strict. Edition 9 of STANAG 1008 [20.b], (valid since 2004), on the other hand sets no tangible numerical limits, but only defines courses of actions to be taken depending on the *sum*,  $\Sigma P_{dist,k}$ , *of the rated power of harmonic pollutant devices*  $P_{dist,k}$  with respect to the ratio of the  $Max,k(P_{dist,k})$  to the *system short circuit capacity*,  $S_{sc}$ .
- while, according to IEEE-519 they refer to ( *actual average maximum load* ) (at the Point of Common Coupling, PCC) fundamental components. It is further noted; IEEE-519's restrictions depend on the odd or even nature of the current harmonic order.

Neither of the standard reference values is readily available or can be estimated without knowing the power factor and the harmonic spectrum at the average and rated full load respectively.

Although, IEEE-519 does not directly implies to shipboard installations, but rather to industrial units, it can apply to ships, too considering that a ship is actually a compact power plant of industrial nature.

Anyhow, the limit values of IEEE-519 depend on the voltage level of the electric system studied and the *ratio of short circuit current over maximum load current*, the latter being the *“average of maximum loads achieved on a 12-monthly basis”*  $I_{1,avFL}$ . Considering that many devices onboard are often over-dimensioned in order to meet future needs, working, thus, often in partial load conditions, this average maximum value of the fundamental must be, somehow, identified.

After the author’s proposition [27], at an initial approximation of applying IEEE-519, considering that for each load the corresponding PCC is the system power outlet where it is connected, the average maximum load can be estimated by the load factors  $f_s$ . In case of diversified  $f_s$  values for several operation states, the worst cases leading to maximum operating currents ever encountered should be considered. Nevertheless, although the average load can be assessed via the load factors, the average fundamental current still cannot be identified, as the average power factor has to be estimated, too.

### Modulation – Pulsed Loads

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”. Electric loads causing “modulation” are the so called “*Pulsed Loads*” (like, controlled heaters, sonars, radars, Electromagnetic Aircraft Launch Systems and Electromagnetic Guns). Following the current trends, it is expected that these systems will be among the dominating ones aboard the AES. Voltage and frequency modulation may affect the operation of several subsystems of the ship. The limits set - for the *LV Ship Service Power Supply System* - by different standards ( e.g. STANAG 1008, USA MIL-STD-1399(NAVY)-Section 300A, IEEE Standard 45 ) for frequency modulation is normally 0.5%, while for voltage modulation varies between 1% and 5%.

According to design constraints of Edition 9 of STANAG 1008, in order voltage/frequency modulation not to exceed the STANAG limits, the following inequalities should be satisfied :

$$P.F.*x < 0.25 \quad \text{and} \quad P.F. > [ 1 - (0.065/x)^2 ]^{1/2} \quad \text{with} \quad x = S_{pulse}/S_{supply} \quad (6)$$

where

$S_{supply}$  = full rated apparent power of the supply at the occurrence of the pulse

$S_{pulse}$  = the apparent power of the pulsed load

and  $P.F.$  = the power factor of the pulsed load

But as it is shown by some of the authors in [28], besides  $S_{pulse}$  and  $P.F.$ , additional Pulsed-Load parameters affect the entire phenomenon of modulation, like the pulse repetition frequency (periodicity), the duration of each pulse (duty cycle), the profile of each pulse etc. All these parameters can be found by analysing the “*Load demand profile Pd(t)*” main parameter.

## LOAD PROFILE CATEGORIZATION

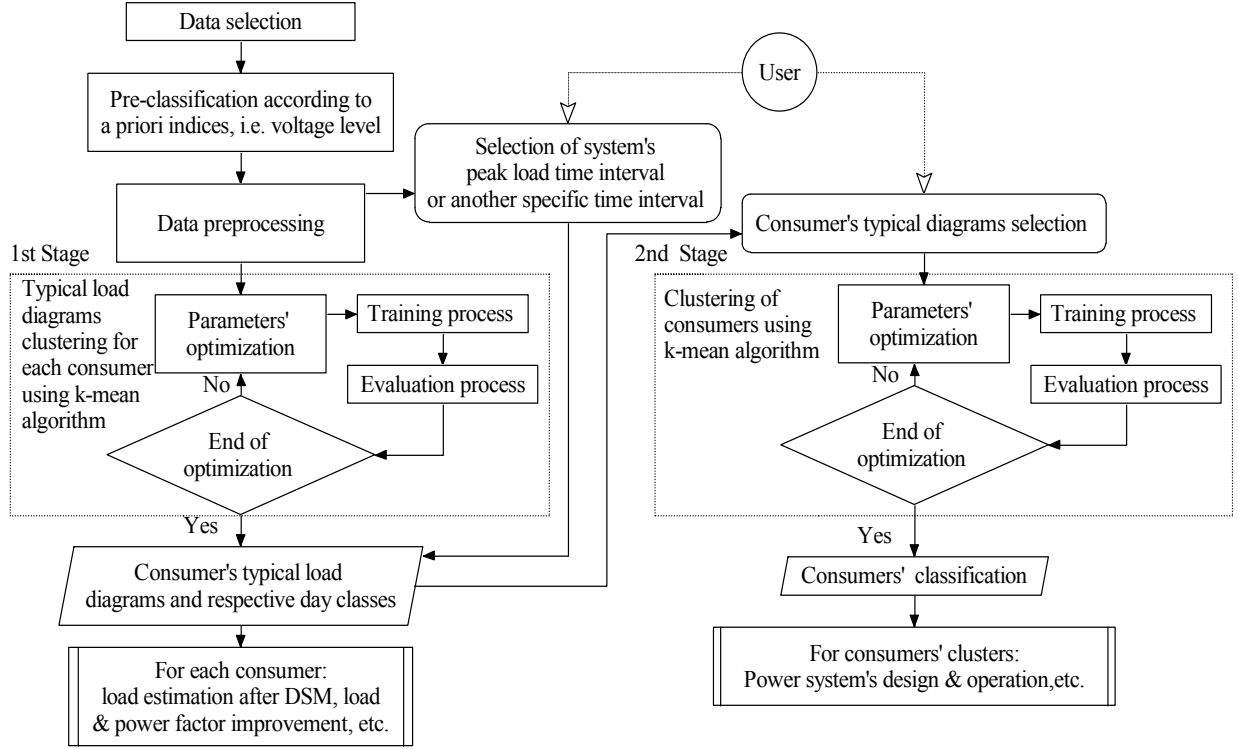
### Two-stage Pattern Recognition Methodology for Classification of Consumers

The load curves of the consumers influence the design and the operation of the ship’s power system significantly. In general the “*chronological load curves*” of each consumer can be registered using proper metering systems. In order to evaluate the “*representative load profile*” of each consumer in a typical “*time interval*” ( = corresponding “typical days”), the clustering of the chronological load curves is realized. The representative load profiles of all consumers can be clustered in order to find out the similarities and dissimilarities in the electricity load behavior of different consumers in a ship.

The classification can be contacted by pattern recognition techniques [29], [30], [31], [32], [33], data mining [34], wavelet packet transformation [35] and Fourier analysis. Conventional tools, like statistical techniques [36], need the knowing of the “typical days”, which can be defined by the ships’ head engineers.

One of the major issues is the definition of the typical time interval. In the classical (continental or autonomous) power systems the load curve’s time interval is usually a day for a study time period from a few weeks [29] to one year [30]. In ships’ power system the respective time interval is in general not already known.

The classification of the typical load profile of one consumer (equipment) as well as the classification of a number of consumers is achieved by applying a pattern recognition methodology consisting of two stages which has the following basic steps and its flow chart is shown in Fig 6 :



**Fig 6** Flow chart of two stage pattern recognition methodology for the classification of consumers.

1. *Typical load curves clustering for each consumer – First stage application of pattern recognition methods* : For each consumer, a number of clustering algorithms (k-means, adaptive vector quantization, fuzzy k-means, hierarchical clustering, self-organized maps) can be applied. Each algorithm can be trained for the set of load curves and evaluated according to various adequacy measures (the mean index adequacy, the clustering dispersion indicator, the similarity matrix indicator, the Davies-Bouldin indicator, the modified Dunn index, the scatter index, the mean square error and the ratio of within cluster sum of squares to between cluster variation (WCBCR)). In this paper the k-mean clustering model is used with the *WCBCR* criterion, which will be analyzed in the next section. The parameters of the algorithm are optimized, if necessary. This process is repeated for the total set of consumers under study. Special consumers, such as seasonal or emergency ones (e.g. turnery machines, fire-pumps, etc.) can be identified. These results can be combined with the ships' operational mode. In the same stage the size of time interval (1, 2, 3, 4, 6 hours, half or one day) can be investigated.

2. *Selection of typical chronological load curves for consumers* : The typical load curves of consumers, that will be used for the final clustering of the total set of the consumers, are selected by choosing the type of typical time interval (such as the most populated one, the time interval with the peak demand load, etc). It is possible to omit the consumer's typical load curves clustering, if the user wishes to compare the consumer's behavior in specific time intervals, such as the time interval of system peak load, the mean value of time intervals in anchor, etc. In this last case, the consumers' behavior is not entirely representative for the period under study.

3. *Clustering of consumers - Second stage application of pattern recognition methods* : The clustering k-mean method is applied for the set of the consumer's typical load curves. After algorithm' calibration, the clusters of consumers and the respective classes representative load curves are formed.

The first stage of the methodology can be also used for the load curves classification of generators or of the ship's total demand, in order to formalize the respective load behaviour.

### Mathematical Modelling of Clustering k-mean Method and WCBCR Adequacy Measure

Firstly,  $N$  chronological load curves of a simple consumer are given. Each curve has  $d$  measurements evenly sampled in the respective time interval. The  $\ell$ -th curve is represented as the vector  $\vec{x}_\ell = (x_{\ell 1}, x_{\ell 2}, \dots, x_{\ell i}, \dots, x_{\ell d})^T$  with dimension  $d$  (called *training or input vector*). The clustering is realized using the k-mean technique for a given number of  $M$  clusters (also called *centers*) ( $M \leq N$ ). The  $j$ -th cluster forms

a *typical load profile* represented by the vector  $\vec{w}_j = (w_{j1}, w_{j2}, \dots, w_{ji}, \dots, w_{jd})^T$  of  $d$  dimension. This vector expresses the cluster's center. The corresponding set of the clusters is the *classes' set*, which is defined by  $W = \{\vec{w}_j, j = 1, \dots, M\}$ . The subset of input vectors  $\vec{x}_\ell$ , which belong to the  $j$ -th cluster, is  $\Omega_j$  and the respective population of load curves is  $N_j$ .

The  $k$ -means clustering method is an iterative procedure. Initially the weights  $w_{ji}$  of the  $M$  clusters should be determined. In the classical model a random choice among the input vectors is used [30], [31] (each  $\vec{w}_j$  is corresponded to a specific randomly chosen  $\vec{x}_\ell$ ). In the developed algorithm the  $w_{ji}$  of the  $j$ -th center is initialized as:

$$w_{ji}^{(0)} = a + b \cdot (j-1)/(M-1) \quad (7)$$

where  $a$  and  $b$  are properly calibrated parameters [32]. For each training vector  $\vec{x}_\ell$  its Euclidean distances  $d(\vec{x}_\ell, \vec{w}_j)$  are calculated for all centers. The  $\ell$ -th input vector is put in the set  $\Omega_j^{(0)}$ , for which the distance between  $\vec{x}_\ell$  and the respective center is minimum. When the entire training set is presented, the new weights of each center are calculated as :

$$\vec{w}_j^{(1)} = \frac{1}{N_j^{(0)}} \sum_{\vec{x}_\ell \in \Omega_j^{(0)}} \vec{x}_\ell \quad (8)$$

where  $N_j^{(0)}$  is the population of the respective set  $\Omega_j^{(0)}$ . This process is repeated until the maximum number of iterations (*epochs*) is used or the weights do not significantly change.

During *epoch*  $t$  for each training vector  $\vec{x}_\ell$  its Euclidean distances  $d(\vec{x}_\ell, \vec{w}_j)$  are calculated for all centers. After the presentation of the entire training set the new weights of each center are calculated as :

$$\vec{w}_j^{(t+1)} = \frac{1}{N_j^{(t)}} \sum_{\vec{x}_\ell \in \Omega_j^{(t)}} \vec{x}_\ell \quad (9)$$

where  $N_j^{(t)}$  is the population of the respective set  $\Omega_j^{(t)}$  during epoch  $t$ . The algorithm's main purpose is to minimize the appropriate error function  $J$ , which is given by:

$$J = \frac{1}{N} \sum_{\ell=1}^N d^2(\vec{x}_\ell, \vec{w}_{k:\vec{x}_\ell \in \Omega_k}) \quad (10)$$

After the conversion of the model, the respective adequacy measure is the ratio of the sums of the distance's square between each input vector and its cluster's representative vector and the distances of the clusters' centres, which is called "*Within Cluster sum of squares to Between Cluster variation Ratio*" (**WCBCR**) [30], [37] :

$$WCBCR = \frac{\sum_{k=1}^M \sum_{\vec{x}_\ell \in \Omega_k} d^2(\vec{w}_k, \vec{x}_\ell)}{\sum_{1 \leq q < p}^M d^2(\vec{w}_p, \vec{w}_q)} \quad (11)$$

The process is repeated for different pairs of  $(a, b)$  [2] (which is the main difference with the classical model). The pair with the minimum WCBCR measure is finally proposed and the respective final vectors of clusters  $\vec{w}_{j:1, \dots, M}$  are used. From these  $M$  typical clusters one is chosen as the *representative load curve*, which can be e.g. the most populated one.

The mathematical modeling is the same for clustering of  $N$  consumers using the respective representative load curves as input vectors, in order to categorize the consumers in groups with similar load behaviour.

### Application of the Methodology to a Set of Consumers of Hellenic Navy MEKO Type Frigates

The developed methodology was applied on the data concerning 6 consumers of HN MEKO type frigates electrical system, whose maximum peak load ranges between 3.5 kW and 60 kW. The respective data are the 1-minute ON/OFF normalized load values for each individual consumer for a period of eleven days during November 1997 and January 1998, while the respective consumers are presented in Table III.

**In the first stage** of the methodology the typical load curves of each consumer are determined. It is supposed that the time interval is a day. The representative consumer's typical day has been chosen to be the most populated one. The analysis of the "Refrigeration Plant" is presented in detail, while additional consumers can be analyzed in a similar way. The respective set of the daily chronological curves has 11 members. No curves were rejected through data pre-processing. The optimization process of the k-mean parameters ( $a$ ,  $b$ ) is similar to the respective one of [30], [37] and it is omitted.

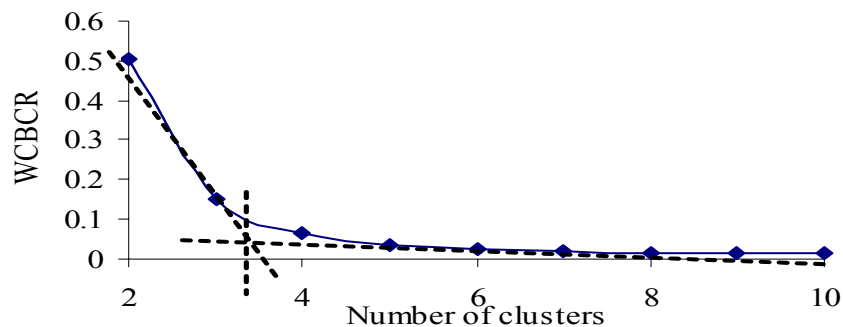
**Table III** Results from the 1<sup>st</sup> Stage of the Methodology for 6 consumers of HN MEKO Type Frigates

Type	Consumer description	Total number of clusters	Population of the representative cluster	ON/OFF load factor for representative cluster (%)
a	Chiller	4	7	97.0
b	HP compressor FWD/AFT	3	9	1.5
c	Refrigeration plant	4	7	70.9
d	LP compressor FWD/AFT	4	6	13.0
e	Sanitary pump	3	8	9.1
f	Boiler	4	8	26.5

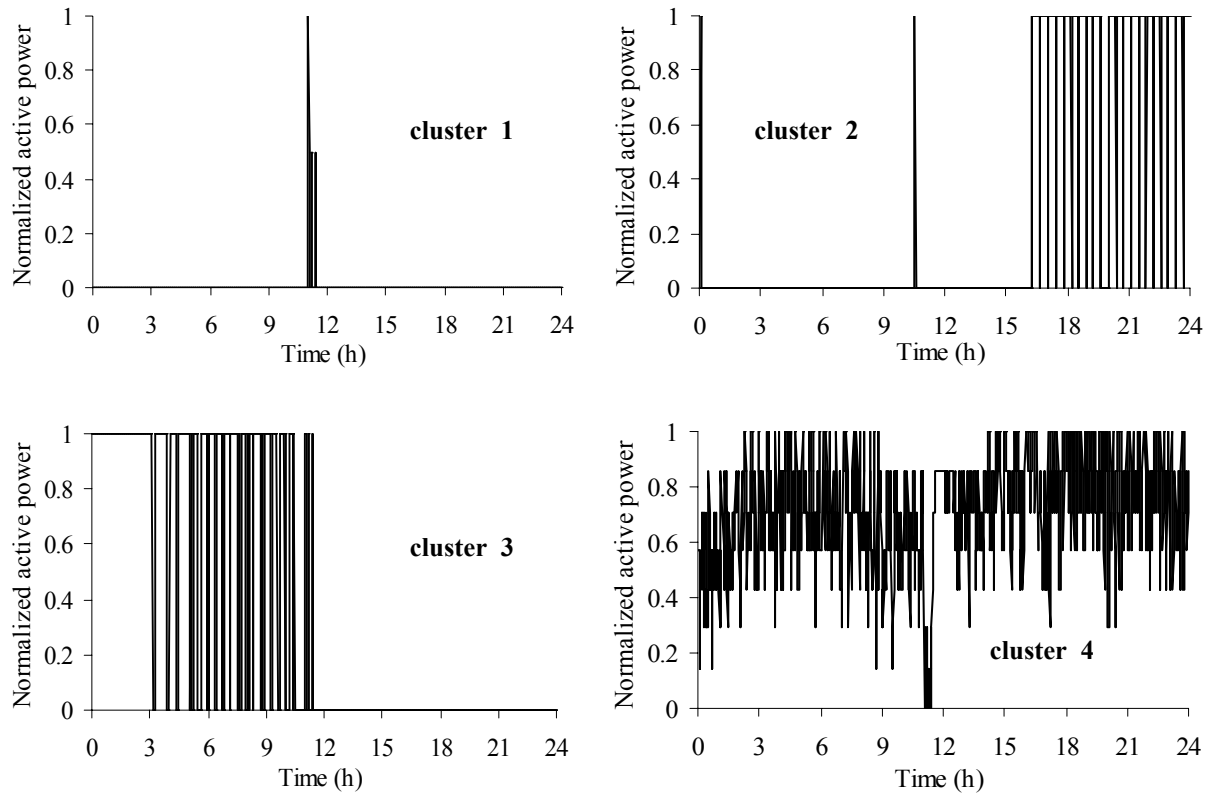
In Fig. 7, the WCBCR measure of the k-mean model for 2 to 10 clusters is presented for the set of 11 training patterns of the refrigeration plant. The number of clusters, which provides satisfactory results for the study of load demand behaviour of a specific consumer, corresponds to the knee of the curve [30], [31], [32], [33]. If this knee is not clearly shown, the tangents are drawn estimating the knee for 4 clusters. The results of the respective clustering for 4 clusters using the developed k-means model with the optimization of the WCBCR adequacy measure are presented in Fig 8. The load demand behaviour of the refrigeration plant during the under study period can be observed through the respective curves. Cluster 1 represents practically the zero demand, cluster 2 the start up, cluster 3 the stop of the plant and the cluster 4 the representative typical day. The respective days per cluster are 2, 1, 1 and 7. In Fig 2 the 4<sup>th</sup> respective chronological ON/OFF load demand curve is represented with the confidence limits of the variations (mean value  $\pm$  standard deviation). The last ones have a probability of occurrence equal to 68.27% assuming a normal distribution. It is mentioned, that there is a period of almost zero demand around 11:30. In Table IV the clusters of the respective daily chronological ON/OFF load curves are registered per day for three different populations of clusters (2, 4, 6). It is worth noting that the load curves of certain days ( January 2 and 3 ) are in all clustering cases separated from all rest curves, because the frigate was in a different operating condition, in comparison to the other days.

The same process was repeated for the remaining 5 consumers of Table III, where the load curves of each customer are qualitatively described by using 1-4 clusters. In Table II the respective results (the total number of clusters, the population of the representative cluster, the ON/OFF load factor of the representative cluster) are registered. In Fig 9 the respective representative chronological ON/OFF load curves for all consumers considered are presented.

In Table V the "characteristic time period percentage indexes" of the representative cluster for each consumer are calculated.



**Fig 7** WCBCR measure of the k-mean model for 2 to 10 clusters for the set of 11 training patterns of the refrigeration plant and the use of the tangents for the estimation of the knee



**Fig 8** The typical daily chronological ON/OFF load curves for the Refrigeration Plant for 4 clusters

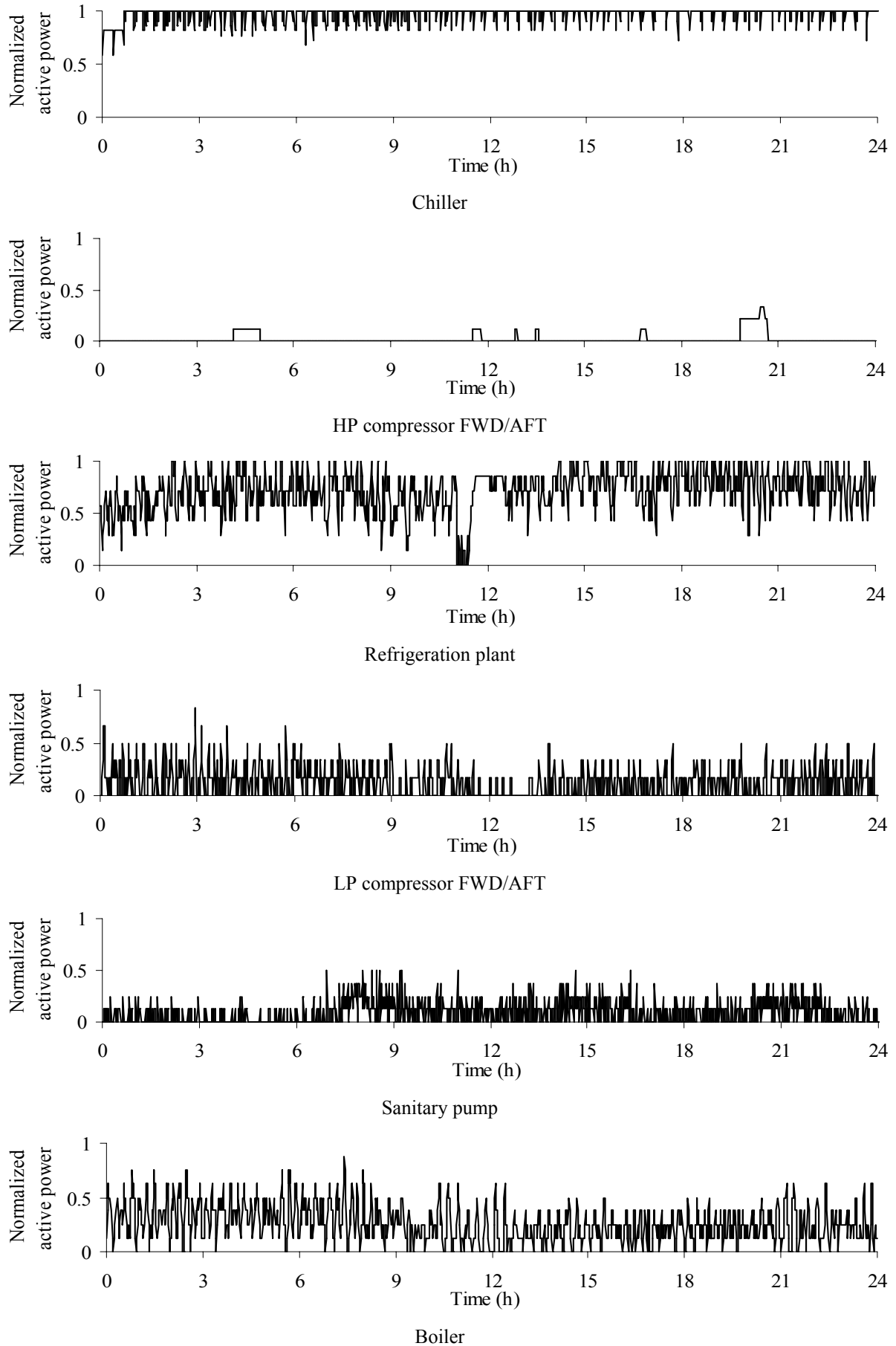
**Table IV** Clusters calendar of the Refrigeration Plant load demand curves for the study period

Number of clusters	Date										
	November 1997								January 1998		
	20	21	22	23	24	25	26	27	1	2	3
2 (1 <sup>st</sup> -2 <sup>nd</sup> )	2 <sup>nd</sup>	2 <sup>nd</sup>	2 <sup>nd</sup>	2 <sup>nd</sup>	2 <sup>nd</sup>	2 <sup>nd</sup>	2 <sup>nd</sup>	2 <sup>nd</sup>	2 <sup>nd</sup>	1 <sup>st</sup>	1 <sup>st</sup>
4 (1 <sup>st</sup> -4 <sup>th</sup> )	4 <sup>th</sup>	3 <sup>rd</sup>	4 <sup>th</sup>	4 <sup>th</sup>	4 <sup>th</sup>	4 <sup>th</sup>	4 <sup>th</sup>	4 <sup>th</sup>	2 <sup>nd</sup>	1 <sup>st</sup>	1 <sup>st</sup>
6 (1 <sup>st</sup> -6 <sup>th</sup> )	6 <sup>th</sup>	3 <sup>rd</sup>	6 <sup>th</sup>	6 <sup>th</sup>	6 <sup>th</sup>	5 <sup>th</sup>	6 <sup>th</sup>	6 <sup>th</sup>	2 <sup>nd</sup>	1 <sup>st</sup>	4 <sup>th</sup>

**Table V** Characteristic time period percentage indices of the representative cluster for each one of the 6 consumers

Cons. Type	$t_{off}(\%)$	$t_{on}(\%)$	$t_{det}(\%)$	$t_{<10\%}(\%)$	$t_{>90\%}(\%)$ :
a	0,00	79,24	79,24	0,00	86,81
b	90,28	0,00	90,28	90,28	0,00
c	0,83	11,60	12,43	0,83	11,60
d	43,96	0,00	43,96	43,96	0,00
e	49,17	0,00	49,17	49,17	0,00
f	10,00	0,00	10,00	10,00	0,00

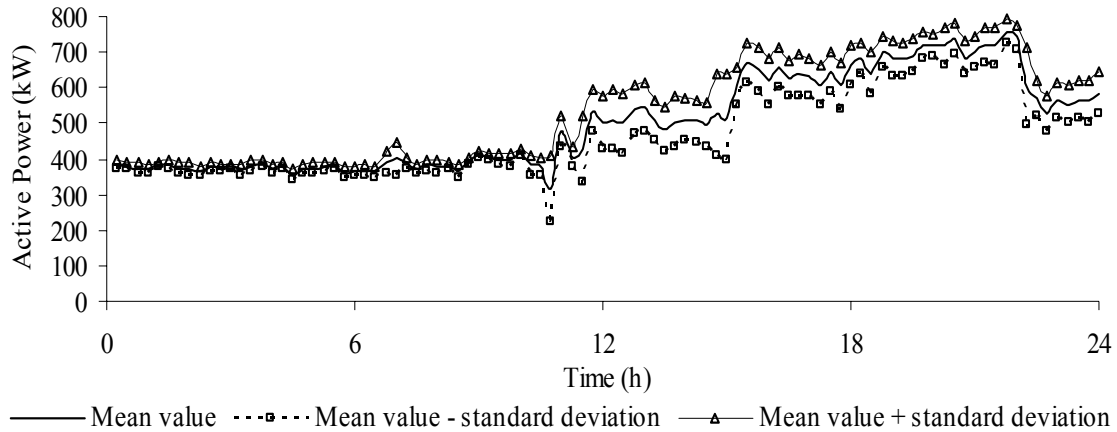
**In the second stage** the consumers' classification and the respective typical load curves can be calculated by similar way applied the k-mean method for the set of the representative consumer's typical load curves for the 6 consumers.



**Fig 9** The representative chronological ON/OFF load curves for each one of the 6 consumers

## Application of the Methodology to the Total Load Demand of Hellenic Navy MEKO Type Frigates

The first stage of the proposed classification methodology can be applied for the total demand of the HN MEKO type frigate. The respective active power of ship's generators was registered by the control and monitoring system "NAUTOS" every 15 minutes (the respective daily vector dimension is equal to 96), for a period of 20 days ( 8-31 January, 1998 ) with the ship in at "SHORE" condition. From the respective analysis the use of seven clusters is proposed. In Fig 10 the respective most populated representative chronological load curve with respective deviation is presented. In Table VI the clusters of the respective daily chronological load curves are registered per day for three different populations of clusters (4, 7, 10). It is mentioned that the load curve of 29 Jan 1998 is in all clustering cases separated from all rest curves, because the frigate was supplied by shore with power for 8 hours.



**Fig 10** The most populated representative chronological load curve for total load demand with respective standard deviation using k-mean algorithm, WCBCR indicator and 7 clusters for classification

**Table VI** Clusters calendar of the Generators total load demand curves for HN MEKO Type Frigates for the study period

Number of clusters	Date (January 1998)																			
	8	9	11	12	14	16	17	18	20	21	22	23	24	25	26	27	28	29	30	31
4 (1 <sup>st</sup> – 4 <sup>th</sup> )	2 <sup>nd</sup>	3 <sup>rd</sup>	2 <sup>nd</sup>	3 <sup>rd</sup>	4 <sup>th</sup>	3 <sup>rd</sup>	3 <sup>rd</sup>	3 <sup>rd</sup>	3 <sup>rd</sup>	3 <sup>rd</sup>	3 <sup>rd</sup>	3 <sup>rd</sup>	3 <sup>rd</sup>	3 <sup>rd</sup>	3 <sup>rd</sup>	2 <sup>nd</sup>	3 <sup>rd</sup>	1 <sup>st</sup>	3 <sup>rd</sup>	3 <sup>rd</sup>
7 (1 <sup>st</sup> – 7 <sup>th</sup> )	2 <sup>nd</sup>	4 <sup>th</sup>	3 <sup>rd</sup>	4 <sup>th</sup>	7 <sup>th</sup>	3 <sup>rd</sup>	4 <sup>th</sup>	4 <sup>th</sup>	5 <sup>th</sup>	6 <sup>th</sup>	5 <sup>th</sup>	5 <sup>th</sup>	5 <sup>th</sup>	5 <sup>th</sup>	4 <sup>th</sup>	2 <sup>nd</sup>	4 <sup>th</sup>	1 <sup>st</sup>	4 <sup>th</sup>	6 <sup>th</sup>
10 (1 <sup>st</sup> – 10 <sup>th</sup> )	2 <sup>nd</sup>	6 <sup>th</sup>	2 <sup>nd</sup>	6 <sup>th</sup>	10 <sup>th</sup>	3 <sup>rd</sup>	4 <sup>th</sup>	6 <sup>th</sup>	8 <sup>th</sup>	9 <sup>th</sup>	7 <sup>th</sup>	7 <sup>th</sup>	5 <sup>th</sup>	5 <sup>th</sup>	7 <sup>th</sup>	2 <sup>nd</sup>	4 <sup>th</sup>	1 <sup>st</sup>	6 <sup>th</sup>	9 <sup>th</sup>

## CONCLUSIONS

Besides the well-known characteristic parameters of ship electric loads (like nominal operating voltage and frequency, power efficiency, power factor, nominal and operating power etc), there are some additional load parameters of primary importance, in conjunction to methodologies of studies performed during ship design concerning Load Estimation, Load Shedding Schemes, Power Supply Quality (e.g. Harmonic distortion, Modulation ) etc.

Such parameters are e.g. the Load demand profile, the Load factor and the Priority Index and they depend on the network the equipment is connected, on the rest of the operating equipment in the same network and on the ship type, state and mission. The significance of the *Load demand profile*, i.e. the *chronological energy demand curve of the load* urges for developing *classification methodologies* based on statistical elaboration of measurements taken, as a fundamental step to characterize and categorize the typical behavior of consumers in ship electric installations.

Such work is expected to be useful in the context of the All Electric Ship.

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