Power Quality Investigation on a Ship's Power System

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***Abstract* —** The ship's power systems have limited power. It consists of separate consumers with power commensurable with generators' power. Thus, the powerful consumers worsen the quality of power and especially strong is this worsening in the presence of electric propulsion power system. In this article, it is presented mathematical model of four node ship's power system, including four generators, electric propulsion system based on induction propulsion motor, supplied by frequency's converter. With the use of the models are investigated different working regimes of propulsion system and ship's power system. Some of received results are presented in the article including the frequency's spectrum of regime's parameters.

***Keywords* —** ship's power systems, electrical propulsion system, mathematical model, power quality

I. Introduction

The contemporary ship's power systems become more powerful due to increase of the consumer's power and in the presence of electrical propulsion system, voltages over 1000 V are used. The electro drives, especially the propulsion power systems, draw the largest power. There is increase in the use of regulated drives, controlled with the help of converters representing non-linear load.

The ship's power systems have limited power and the separate consumers have power commensurable with the power of the generators. Thus the powerful consumers worsen the power quality and especially strong is this worsening in the presence of electrical propulsion power system [1,2].

Significant part of used electronic devices (control systems, controllers, navigation devices etc.) are sensitive in regard of power quality and the problems caused by the use of power electronics. The work of electrical machines, cable nets and condensers is worsen as well.

There are problems with power quality not only in the static working regime but they increase significantly by switching. The harmful consequences of the bad quality could also be summarized as disturbances in the work of electronic equipment; increase of reactive losses; worsening of insulation and even damage of equipment; immerge of resonance effects.

In order to overcome the harmful influence of electricity's bad quality different resources are used: application of multiphase electrical machines and static converters; specific control of static converters; simple and active filters; parallel, consecutive and combine system devices; power quality conditioners [3,4].

In order to choose a concrete resource for improvement of electricity's quality and its control it is necessary to investigate the working regimes of ship's power system and the indices of quality of electricity in static and dynamic regimes.

Two methods for assessment of electricity's quality are used – through measurement of qualitative indices of electricity in reals systems (after their development) [5,6,7], and through mathematical modelling of processes (by design of the systems) [8,9].

The modelling of the processes in the unified ship's power systems, containing electrical propulsion, enables the performance of primary accurate evaluation of electromagnetic compatibility in that systems [8,9].

In most publications about investigation of the electricity's quality are used approximate methods or simplified schemes or models. In [8] are used accurate models of power system's elements (synchronous generator, static converter and induction motor) but the investigated system is one node and contains generator and motor.

In this article is presented a model of 4-nodes unified ship's power system, including electrical propulsion system, 4 synchronous generators (with different electric power) and equivalent static and dynamic loads included in circle distribution network.

Using the proposed model are investigated the normal and average regimes caused by different types of disturbances outlining part of received results and qualitative indices of electricity.

II. Investigated Ship's Power System

Fig.1. presents the scheme of investigated ship's power system. The ship's power system has two generators SG2 and SG4 with power 670 kVA and two generators SG1 and SG3 with power 910 kVA. The propulsion power system consists of propulsion induction motor with power of 1500 kVA and back-to back converter. In each knot of the system are connected equivalent static loads with power of P=100 kW and Q=10 kVA. The resistances of the lines connecting the generators in closed contour. On the figure with arrows are indicated the directions of the system's elements currents and the lines of distribution network.

This document is under project BG05M2OP001-2.009-0037-C01 "Support for the development of PhD students, post-doctoral students, young scientists and lecturers in the Nikola Vaptsarov Naval Academy", with the beneficiary of the Nikola Vaptsarov Naval Academy, Varna, Bulgaria funded by the Intelligent Growth Science and Education Operational Program, co-financed by the European Union through the European structural and investment funds.

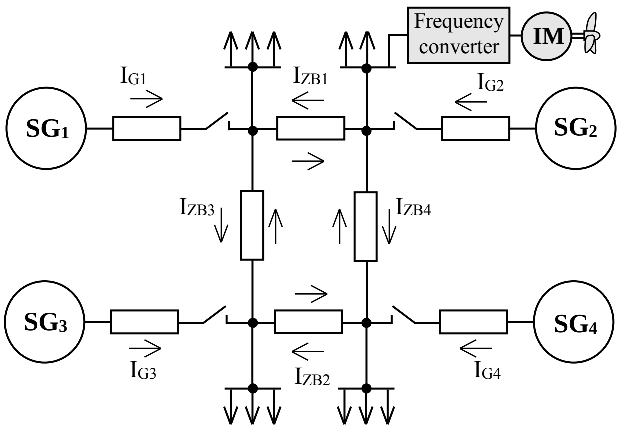

Fig.1. Scheme of investigated ship's power system

III. Mathematical Model of the Investigated Ship's Power System

For the targets of the investigations we will use an universal algorithm for transient electromechanical processes calculation in power systems with arbitrary elements number and network structure [13,14,15]. In this algorithm, elements models (synchronous generator and static load) are written in Cauchy form.

A. Model of Synchronous Generator

The model of the synchronous generator will have the following shape:

$$\frac{d}{dt}\begin{bmatrix}\boldsymbol{I_s}\\ \boldsymbol{I_r}\end{bmatrix}_{Gj}=\begin{bmatrix}\boldsymbol{H_s}\\ \boldsymbol{H_r}\end{bmatrix}_{Gj}+\begin{bmatrix}\boldsymbol{B_{ss}} & \boldsymbol{B_{sr}}\\ \boldsymbol{B_{rs}} & \boldsymbol{B_{rr}}\end{bmatrix}_{Gj}.\begin{bmatrix}\boldsymbol{U}_{Gj}\\ u_{fj}\end{bmatrix};$$
$$\frac{d}{dt}\omega_{kj}=\frac{1}{\tau_{mj}}\left(T_{mj}+T_{Gj}\right); \tag{1}$$

where: subscript *s* refers to the stator parameters and variables, and subscript *r* - rotor; the elements of matrices and vectors $\boldsymbol{H_{Gj}}$ and $\boldsymbol{B_{Gj}}$ are in function of the stator and rotor resistance and inductive impedance and the rotor angular speed $d,q,0_j$ ω_{kj} ($\boldsymbol{H_{Gj}}$ function and currents); T_{mj} - diesel engine torque; T_{Gj} - the generator electromagnetic torque; τ_{mj} - the diesel and generator mechanical time constant; u_{fj} - field voltage; $\boldsymbol{U}_{Gj}$ - vector of stator voltage; $j=1,2,3,4$ - generator number.

B. Model of Induction Motor

The model of the induction motor will have the following shape:

$$\frac{d}{dt}\begin{bmatrix}\boldsymbol{I}_s\\ \boldsymbol{I}_r\end{bmatrix}_{Mj}=\begin{bmatrix}\boldsymbol{H}_s\\ \boldsymbol{H}_r\end{bmatrix}_{Mj}+\begin{bmatrix}\boldsymbol{B}_{ss}\\ \boldsymbol{B}_{rs}\end{bmatrix}_{Mj}.\boldsymbol{U}_{Mj};$$
$$\frac{d}{dt}\omega_{rj}=\frac{1}{\tau_{mj}}\left(T_{mj}-T_{bj}\right); \tag{2}$$

where: subscript *s* refers to the stator parameters and variables, and subscript *r* - rotor; the elements of matrices and vectors $\boldsymbol{H}$ and $\boldsymbol{B}$ are in function of the stator and rotor resistance of motor and inductive impedance and the rotor angular speed $d,q,0$ ω_k ($\boldsymbol{H_{Gj}}$ function and currents); $\boldsymbol{U}_{Mj}$ - vector of stator voltage, τ_{mj} - the mechanical time constant of load and motor, $T_{bj}=k_j.\omega_{rj}^2$ - mechanical breaking moment of pump, T_{mj} - electrical torque of motor; the elements of matrices and vectors $\boldsymbol{A}$ and $\boldsymbol{B}$ are in function of the stator and rotor resistance of motor and inductive impedance and the rotor angular speed ω_r and axes $d,q,0$ ω_k; $j=1,2,3,4$ - motor number.

C. Model of RL Load

$$\frac{d}{dt}\boldsymbol{I}_{Lj}=\boldsymbol{A}_{Lj}.\boldsymbol{I}_{Lj}+\boldsymbol{B}_{Lj}.\boldsymbol{U}_{Lj}=\boldsymbol{H}_{Lj}+\boldsymbol{B}_{Lj}.\boldsymbol{U}_{Lj} \tag{3}$$

where**:** a_{ij} and b_{ij} are function of active and inductive resistance of symmetrical load and angle speed of rotating coordinate system $d,q,0$:; r_l, l_l - active and inductive resistance of load; $j=1,2,3,4$ - number of loads.

D. Model of Transmission Lines

$$\frac{d}{dt}\boldsymbol{I}_{TLij}=\boldsymbol{A}_{TLij}.\boldsymbol{I}_{TLij}+\boldsymbol{B}_{TLij}.\left(\boldsymbol{U}_i-\boldsymbol{U}_j\right)=$$
$$=\boldsymbol{H}_{TLij}+\boldsymbol{B}_{TLj}.\boldsymbol{U}_{ij} \tag{4}$$

where: $j=1,2,3,4$ - number of lines; a_{ij} and b_{ij} are function of active and inductive resistance of transmission line and angle speed of rotating coordinate system $d,q,0$; $\boldsymbol{U}_i$, $\mathbf{U}_{\boldsymbol{j}}$ - voltage vector of adjacent node of network; $\boldsymbol{H}_{TLij}=\boldsymbol{A}_{TLij}.\boldsymbol{I}_{TLij}$.

E. Model of Distribution Network

The above-mentioned models of the ship's power system components, representing differential equation systems, are presented in the form of Cauchy so that they can be explored using explicit numerical integration methods.

On the right side of these systems there are unknown voltage vectors at the nodes of the distribution network. At first, the circular distribution network lines are topologically sorted into branches of tree (lines 1, 2, 3) and the chord (line TL_{34}).

These voltages are calculated by the non-iterative algorithm proposed in [13,14,15]. Its essence consists in writing Kirchhoff's first law in differential form and excluding the derivatives of the currents through the right parts of the differential equation systems of the elements (1), (2), (3).

Using the derived algebraic equation, the voltage of the first node is calculated. Then, with the help of the equations of the lines, the voltage vectors of the other nodes of the distribution network are calculated again.

After that is creates the sum vectors $\boldsymbol{I}_{\Sigma j}$, $\boldsymbol{H}_{\Sigma j}$ and matrixes $\boldsymbol{B}_{\Sigma j}$ of the nodes. After that is write the Kirchhoff's first law in differential form, excluding the currents of the lines $\boldsymbol{I}_{TLij}$:

$$\frac{d}{dt}\boldsymbol{I}_{\Sigma 1}+\frac{d}{dt}\boldsymbol{I}_{\Sigma 2}+\frac{d}{dt}\boldsymbol{I}_{\Sigma 3}+\frac{d}{dt}\boldsymbol{I}_{\Sigma 3}=0 \qquad (5)$$

We write expressions of nodes voltages 2, 3, 4 through the line equations (4):

$$\begin{aligned}
&\boldsymbol{U}_2-\boldsymbol{U}_1=-\boldsymbol{Z}_{TL12}.\boldsymbol{I}_{TL12}-\boldsymbol{L}_{TL12}.\frac{d}{dt}\boldsymbol{I}_{TL12}=\\
&=-\boldsymbol{Z}_{TL12}.(\boldsymbol{I}_{\Sigma 2}+\boldsymbol{I}_{\Sigma 4})-\boldsymbol{L}_{TL12}\frac{d}{dt}(\boldsymbol{I}_{\Sigma 2}+\boldsymbol{I}_{\Sigma 4})\\
&\boldsymbol{U}_4-\boldsymbol{U}_2=-\boldsymbol{Z}_{TL43}.\boldsymbol{I}_{TL43}-\boldsymbol{L}_{TL43}.\frac{d}{dt}\boldsymbol{I}_{TL43}=\\
&=-\boldsymbol{Z}_{TL23}.\boldsymbol{I}_{\Sigma 4}-\boldsymbol{L}_{TL23}\frac{d}{dt}\boldsymbol{I}_{\Sigma 4};\\
&\boldsymbol{U}_3-\boldsymbol{U}_1=-\boldsymbol{Z}_{TL31}.\boldsymbol{I}_{TL31}-\boldsymbol{L}_{TL31}.\frac{d}{dt}\boldsymbol{I}_{TL31}=\\
&=-\boldsymbol{Z}_{TL31}.\boldsymbol{I}_{\Sigma 3}-\boldsymbol{L}_{TL31}\frac{d}{dt}\boldsymbol{I}_{\Sigma 3};
\end{aligned} \qquad (6)$$

By substituting the derivatives of the currents in (5) and (6) by right side of $\frac{d}{dt}\boldsymbol{I}_{\Sigma j}$ and $\frac{d}{dt}\boldsymbol{I}_{TLij}$ we will get an algebraic system of equations for calculating the nodal voltages:

$$(\boldsymbol{1}+\boldsymbol{L}.\boldsymbol{B}).\boldsymbol{U}=-[\boldsymbol{L}.\boldsymbol{H}+(\boldsymbol{L}+\boldsymbol{Z}).\boldsymbol{I}] \qquad (7)$$

where: $\boldsymbol{L}$, $\boldsymbol{Z}$, $\boldsymbol{B}$ - diagonal cellular matrices;

$\boldsymbol{U}=[\boldsymbol{U}_1,\boldsymbol{U}_2,\boldsymbol{U}_3,\boldsymbol{U}_4]^T$; $\boldsymbol{I}=[\boldsymbol{I}_1,\boldsymbol{I}_2,\boldsymbol{I}_3,\boldsymbol{I}_4]^T$;

$\boldsymbol{H}=[\boldsymbol{H}_1,\boldsymbol{H}_2,\boldsymbol{H}_3,\boldsymbol{H}_4]^T$.

F. Model of Back-to-Back Converter

The switching function method is used for the rectifier model:

$$\frac{d}{dt}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}=\frac{1}{L}.\begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix}-\frac{R}{L}.\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}-\frac{U_{dc}}{L}.\begin{bmatrix} (2S_a-S_b-S_c)/3 \\ (2S_b-S_c-S_a)/3 \\ (2S_c-S_a-S_b)/3 \end{bmatrix}=$$

$$=\frac{d}{dt}\boldsymbol{I}_{\boldsymbol{abc}}=\frac{1}{L}.\boldsymbol{U}_{\boldsymbol{abc}}-\frac{R}{L}.\boldsymbol{I}_{\boldsymbol{abc}}-\frac{U_{dc}}{L}.\boldsymbol{S} \qquad (8)$$

where: $\boldsymbol{U}_{\boldsymbol{abc}}$, $\boldsymbol{I}_{\boldsymbol{abc}}$ - vectors of stator voltages and currents; $\boldsymbol{S}$ - a vector of the switching functions, whose elements accept values 1 or 0 corresponding to a conductive or non-conductive state of the diodes; U_{dc} - output voltage of the rectifier; R,L - active and inductive resistance in the rectifier circuit.

After transformation of system (6) into axes $d,q,0$:

$$\frac{d}{dt}\boldsymbol{I}_{\boldsymbol{dq}}^{\boldsymbol{R}}=\frac{1}{L}.\boldsymbol{U}_{\boldsymbol{s}}-\frac{R}{L}.\boldsymbol{I}_{\boldsymbol{dq}}^{\boldsymbol{R}}-\frac{U_{dc}}{L}\boldsymbol{P}.\boldsymbol{S}-\boldsymbol{W}.\boldsymbol{I}_{\boldsymbol{dq}}^{\boldsymbol{R}} \qquad (9)$$

where: $\boldsymbol{P}$ - matrix for direct transformation of Park;

The voltage of direct current converter is calculated:

$$\frac{d}{dt}U_{dc}=\frac{S_{dc}.I_C}{C} \qquad (10)$$

where: S_{dc} - switching function of direct current converter; $I_C=I_R-I_I$.

The equations of the output voltage of inverter:

$$\begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix}=\frac{1}{3}\begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix}.\begin{bmatrix} S_{1a}S_{2a} \\ S_{1b}S_{2b} \\ S_{1c}S_{2c} \end{bmatrix}.U_{dc} \qquad (11)$$

where: S_{kj} - switching functions of inverter; k - inverter arm number; i - number of valve in arm $(i=1,2)$.

Current of direct current side:

$$I_I=S_{1a}.S_{2a}.i_a+S_{1b}.S_{2b}.i_b+S_{1c}.S_{2c}.i_c \qquad (12)$$

Output inverter voltage is transform to axes $d,q,0$:

$$\begin{bmatrix} u_d \\ u_q \\ u_0 \end{bmatrix}=\frac{2}{3}\begin{bmatrix} cos\theta_k & cos(\theta_k-120^\circ) & cos(\theta_k+120^\circ) \\ -sin\,\theta_k & -sin(\theta_k-120^\circ) & -sin(\theta_k+120^\circ) \\ 1/2 & 1/2 & 1/2 \end{bmatrix}\times$$

$$\times\begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix}=\boldsymbol{U}_{\boldsymbol{dq0}}^{\boldsymbol{I}}=\boldsymbol{P}.\boldsymbol{U}_{\boldsymbol{abc}}. \qquad (13)$$

Equations of output filter in axes $d,q,0$, are:

$$\begin{aligned}
&\frac{d}{dt}\boldsymbol{I}_{\boldsymbol{Lf}}=\frac{1}{L_f}.(\boldsymbol{U}_{\boldsymbol{I}}-\boldsymbol{U}_{\boldsymbol{T1}})-\frac{\boldsymbol{Z}_{\boldsymbol{L}}}{L_f}.\boldsymbol{I}_{\boldsymbol{Lf}};\\
&\frac{d}{dt}\boldsymbol{U}_{\boldsymbol{T1}}=\frac{1}{C_f}.(\boldsymbol{I}_{\boldsymbol{Lf}}-\boldsymbol{I}_{\boldsymbol{T1}})-\frac{\boldsymbol{Y}_{\boldsymbol{C}}}{C_f}.\boldsymbol{U}_{\boldsymbol{T1}};
\end{aligned} \qquad (14)$$

where: $\boldsymbol{I}_{\boldsymbol{Lf}}$ - vector of the inductance current of the filter; $\boldsymbol{U}_{\boldsymbol{T1}}$ - vector voltage of the filter capacitor (on the primary side of the transformer); $\boldsymbol{U}_{\boldsymbol{I}}$ - vector of the output voltage of inverter; $\boldsymbol{I}_{\boldsymbol{T1}}$ - current vector of the primary side of transformer; L_f , C_f - inductance and capacity of the filter; R_L - active resistance of the inductance from the filter;

$$\boldsymbol{Z}_{\boldsymbol{L}}=\begin{bmatrix} R_L & -L_f.\omega_k \\ L_f.\omega_k & R_L \end{bmatrix};\ \boldsymbol{Y}_{\boldsymbol{C}}=\begin{bmatrix} 0 & -C_f.\omega_k \\ C_f.\omega_k & 0 \end{bmatrix}$$

IV. Investigation of Processes in Studied Ship's Power System

Using the developed mathematical model of unified ship's power system including electrical propulsion, random transition processes cad be simulated, that are caused by disturbances/amendments in the elements of their regulators, in the distribution network, in the static converter and propulsion motor.

All possible disturbances are simulated whereby the main attention is on the work of electrical propulsion system and its impact on the electricity's quality.

Below is presented part of the received as a result of the simulation characteristics.

A. Case study 1: Speed change

It is simulated the change of speed rotation of the ships' propeller by $t = 4$ sec.

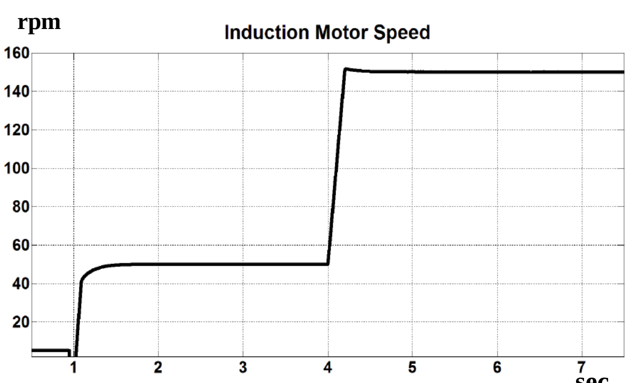

Fig.2. Induction motor speed

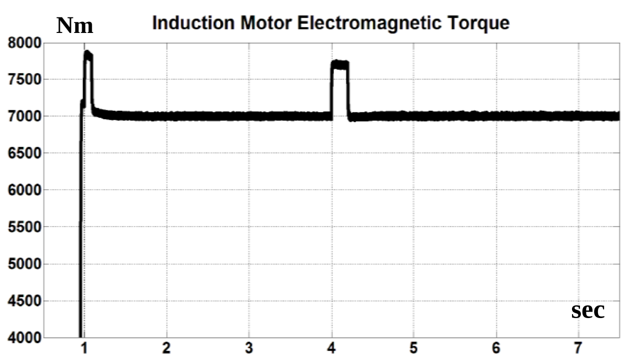

Fig.3. Induction motor electromagnetic torque

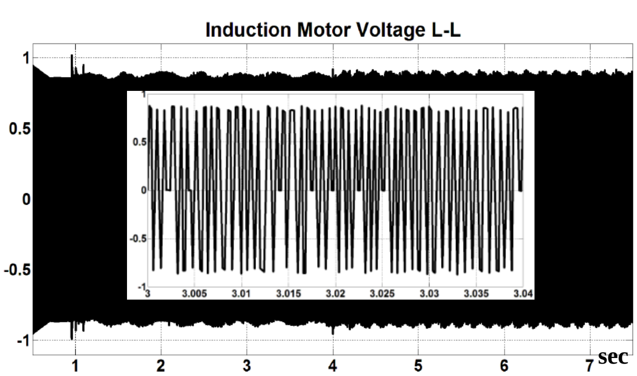

Fig.4. Induction motor line-to-line voltage

B. Case study 2: Break torque changing

It is simulated the change of resistance torque of the ships' propeller by $t = 4$ sec.

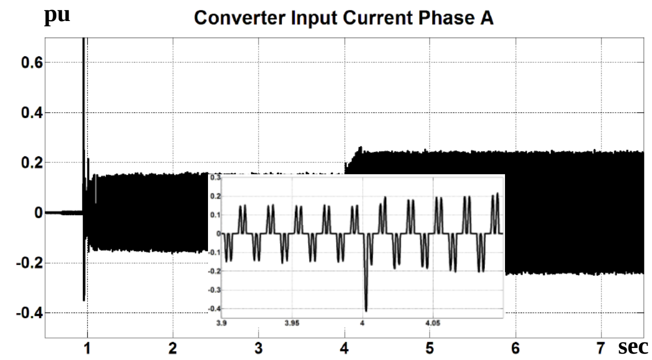

Fig.5. Converter input phase current

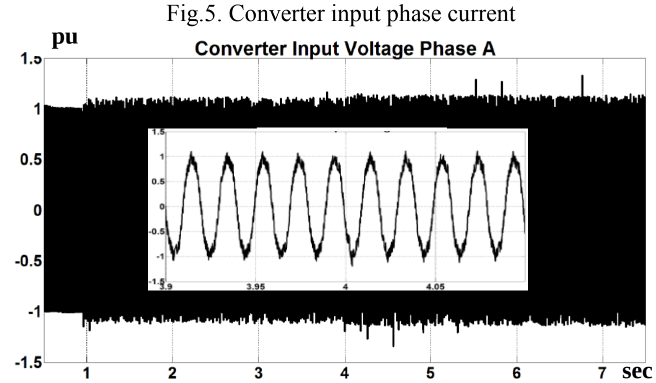

Fig.6. Converter input phase voltage

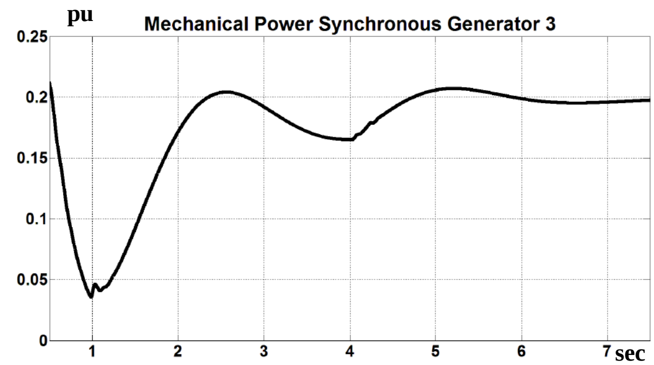

Fig.7. Mechanical power of synchronous generator No.3

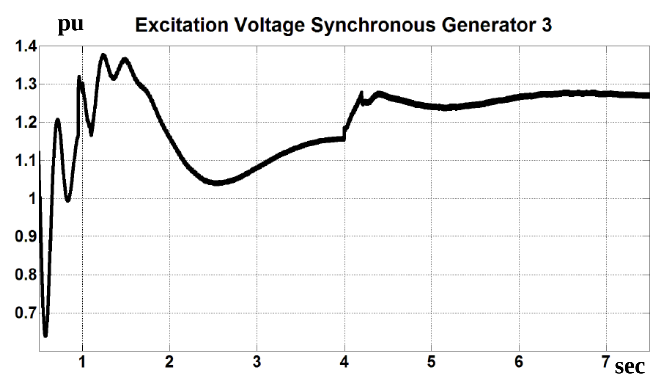

Fig.8. Excitation voltage of generator No.3

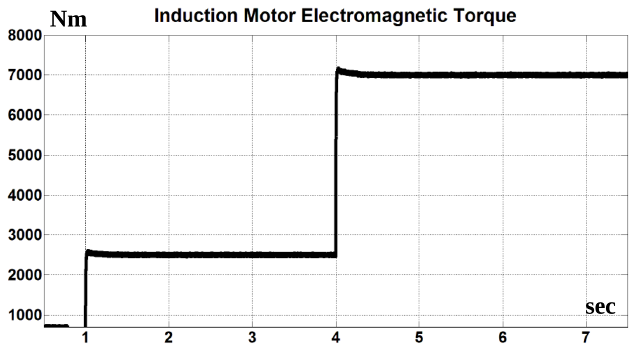

Fig.9. Induction motor electromagnetic torque

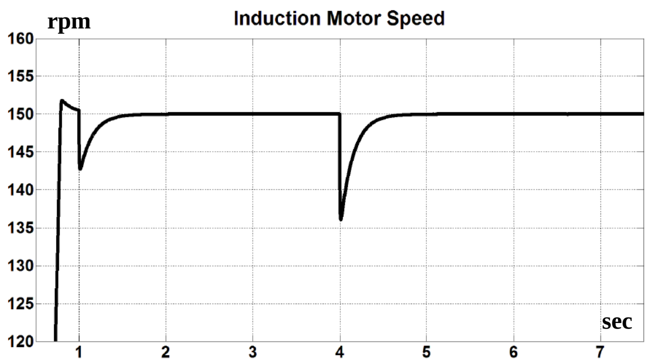

Fig.10. Induction motor speed

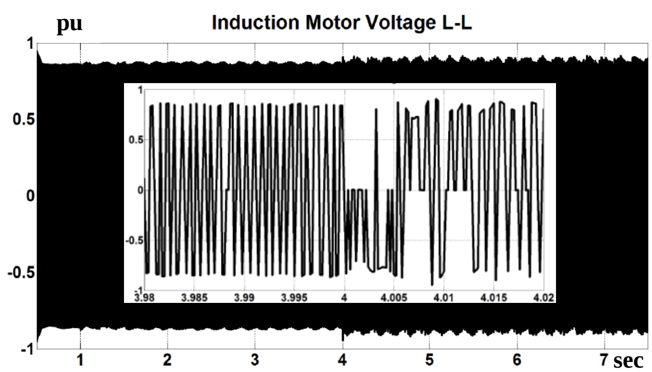

Fig.11. Induction motor line-to-line voltage

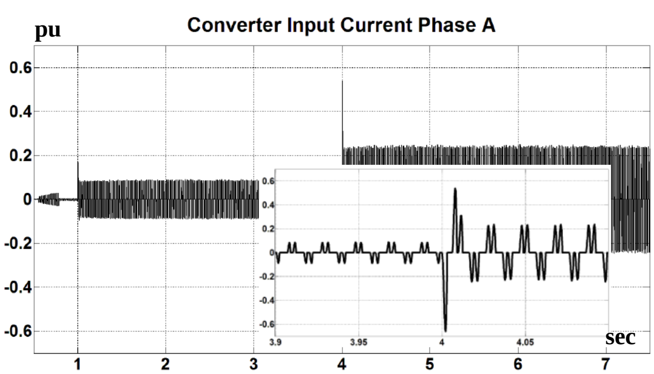

Fig.12. Induction motor line-to-line voltage

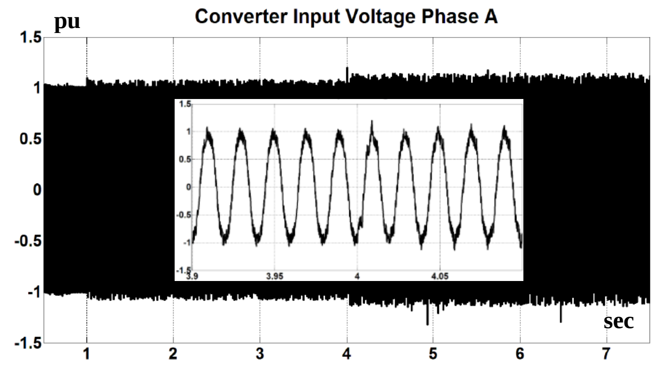

Fig.13. Converter phase input voltage

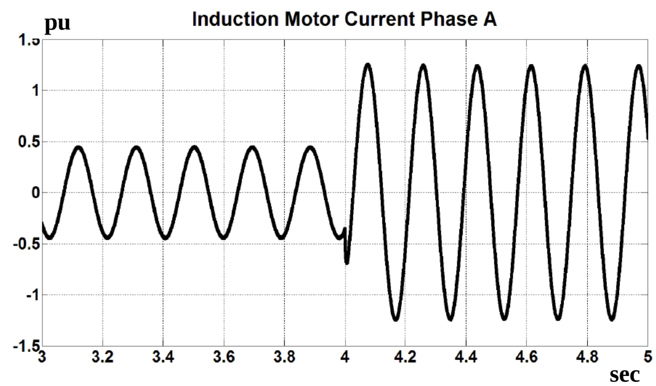

Fig.14. Induction motor phase current

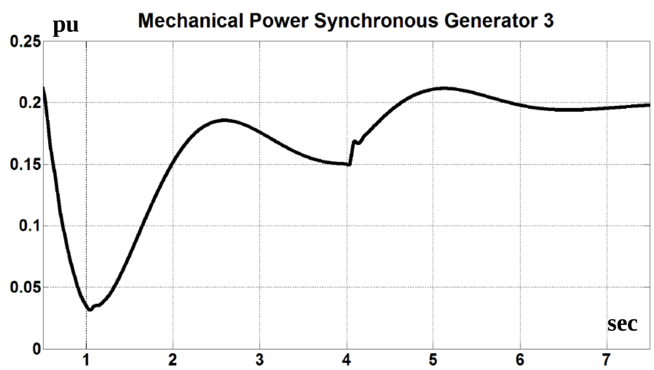

Fig.15. Synchronous generator #3 mechanical power

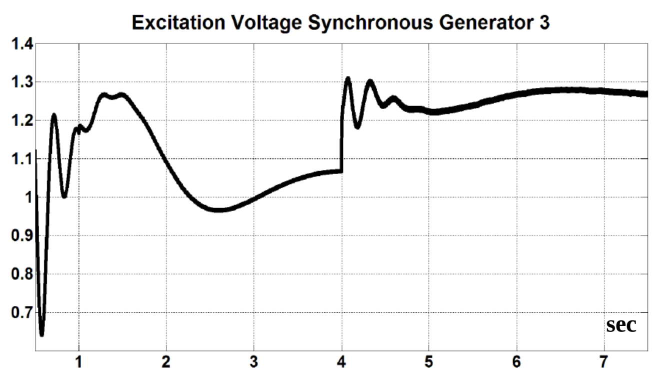

Fig.16. Excitation voltage of generator #3

V. Spectral Composition of Regime Parameters

The analysis of the spectral composition of the regime variables (currents and voltages) shows different total harmonic distortion (THD) of the variables depending on the location of non-linear elements in their working regimes as well as on the disturbing impacts.

Despite the high power of the electrical propulsion power system and the by it drawn non-sinusoidal current the frequency distortion (total harmonic distortion THD) of the net voltage is relatively low.

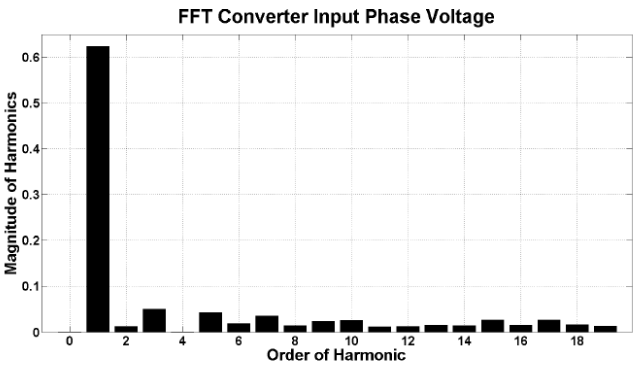

Fig.17. Harmonics of converter input phase voltage

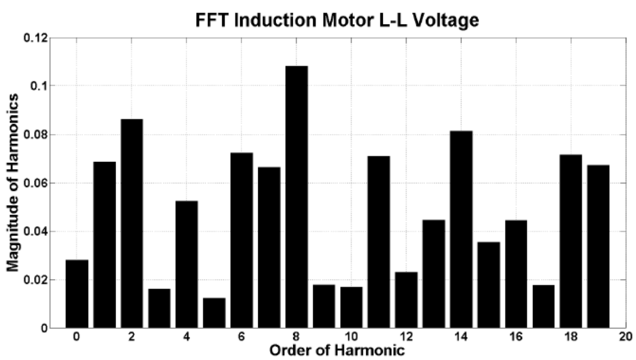

Fig.18. Harmonics of motor line-to-line voltage

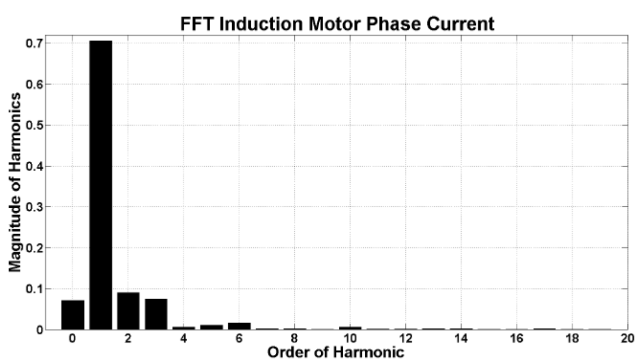

Fig.19. Harmonic of motor phase current

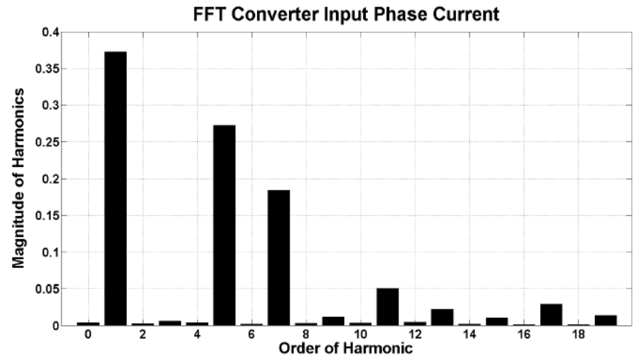

Fig.20. Harmonics of motor phase current

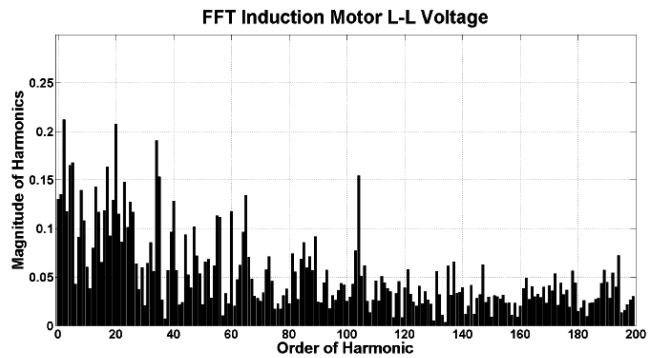

Fig.21. Harmonics of motor line-to-line voltage

VI. Conclusion

It is proposed non-iterative mathematical model of 4-node ship's power system, including 4 generators and electrical propulsion power system, that is used for simulation of different working regimes. The models describe in details (most accurate) the processes in the investigated system, what leads to the opportunity to investigate the processes, to adjust the regulators, to investigate the quality of electricity, to take measures for its quality improvement.

With the use of the quick transformation of Fourier are investigated the frequency spectra of main regime's parameters (currents and voltages) in several working regimes. The received results show that THD is in the admissible limits in the investigated regimes.

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