Simulation of a Shipboard Electrical Network (AES) Comprising Pulsed Loads

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SYNOPSIS

In the advent of All Electric Ship (AES) and electric warship in particular, several sophisticated and energy demanding electric systems are to be installed aboard including propulsion motors and pulsed loads. The latter require high power for a very short interval and therefore introduce certain severe power quality problems to the ship electric network, especially referring to voltage and frequency modulation. In this paper, an initial attempt is made to study thoroughly these modulation phenomena caused by pulsed loads. Thus, the typical electric network of a warship in the context of the AES is considered, focusing mainly on appropriate modeling and studying the consequences of a pulsed load along with the propulsion motors and the generator set. More specifically, a generating set of two synchronous generators, a large propulsion asynchronous motor, the electrical loads of the system through a MV/LV transformer and a pulsed load. The studied pulsed load is a rail gun which uses the stored energy of a large capacitor. All models are developed by using Matlab toolboxes, namely Power Systems Blockset and Simulink. The developed pulsed load model is fully parametric enabling the analysis of various case studies. Critical factors are investigated, while power quality indices for the assessment of voltage or frequency modulation as referred in the relative standards are calculated. Finally, general conclusions are drawn regarding the problems that will be emerged at the future integration of electrical pulsed loads into warships, the design of their power systems and the energy storage systems in order to ensure operational characteristics imposed by relative standards.

Key-Words : AES, pulsed loads, modulation, power quality, railgun, simulations

INTRODUCTION AND BACKGROUND

The future electric power system of naval warships in the context of AES will supply energy to sophisticated systems for propulsion, navigation, weapons etc. [1]-[5]. Some -new naval weapon systems, referred as “pulsed loads”, require high power (in order of several GWs) for a very short time interval in the order of a few seconds and even milliseconds. The operating characteristics of the aforementioned emerging electrical loads will pose many new challenges for these power systems as they lead to voltage and frequency modulation in an Integrated Power System (IPS). The aforementioned may affect the operation of several subsystems of the ship such as radarscopes, communication equipment, missile guidance systems, weapon systems, gear systems etc [3].

In this paper the electrical network of a warship in the context of AES with a pulsed load installed is modeled - for this study a railgun is assumed -. Railguns utilize the Lorentz electromagnetic force to propel an

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electrically conductive projectile. The developed projectile velocity is in order of 3500 m/s and they absorb extremely high currents in time intervals in the order of milliseconds.

Critical factors that are expected to affect simulation results are the duration of the charging, capacitor's size, other parameters of the storage system for example the resistance connected before capacitor, the kind of the charging system e.g. controlled or uncontrolled rectifier. Also, the parameter values of the generator set control system are also expected to affect significantly the simulation results. Results taken by time-domain simulations are compared to the ones derived using standard equations like those proposed by STANAG 1008, [6].

This paper aims :
- To make a short but coherent introduction to pulsed loads and voltage/frequency modulation.
- To develop a detailed model of a shipboard electrical network (AES) comprising pulsed loads i.e. railgun for this case study. This model is fully parametrical enabling the examination of the system for different cases.
- To study different cases considering different system parameters .
- To indicate the value of the application of time-domain simulations to complex, multivariate systems such as an IPS comprising pulsed loads.

MODULATION / PULSED LOADS

Voltage and frequency periodic or quasi-periodic variations such as might be caused by regularly or randomly repeated loading with frequency less than nominal are referred in shipboard Standards (STANAG 1008, IEEE 45 and USA MIL-STD-1399) as *"modulation"*. In Fig. 1, voltage and frequency modulation is shown. For quantifying voltage or frequency modulation the difference between maximum and minimum value is used as a percentage of the double of the nominal value as shown in Equation (1):

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

2% and 0.5% limits are proposed for voltage and frequency, respectively.

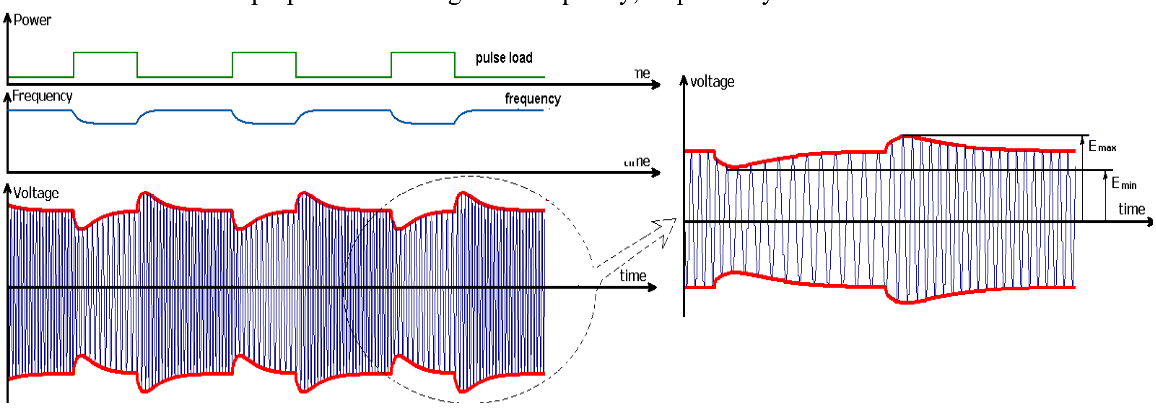


Fig. 1. Voltage and frequency modulation

The future electric power system of naval warships in the context of AES will supply energy to sophisticated high power systems like propulsion and pulsed loads. The latter require high power (in the order of several MWs) for a very short time interval (in the order of milliseconds) and are the main cause of voltage/frequency modulation. Examples of pulsed loads include Electromagnetic Aircraft Launch Systems (EMALS), Electromagnetic Guns (such as Rail Guns, Coil Guns, Lasers, High Energy Microwaves) and Communication-Navigation systems (Radars, sonars) etc. Experience from power systems indicates that the primary effects of pulse loading are manifested in the areas of voltage flicker, dynamic and transient stability etc [8].

Frequency and voltage modulation may affect the operation of several subsystems of a ship such as radarscopes, communication equipment, missile guidance systems, weapon systems, gear systems etc [3]. The limits for frequency and voltage modulation according to STANAG 1008 [6] and USA MIL-STD-1399 are 0.5% and 2% respectively.

Pulsed loads integration requires an efficient power generator set in conjunction with an adequate and well-designed complementary energy storage system. The required discharge characteristics determine the storage system to be used. Thus, several energy storage alternatives exist, namely Electrochemical (e.g. Batteries and

Capacitors), Mechanical (e.g. Flywheels) and Electromagnetic (e.g. Superconducting Magnetic Electric Storage) systems. Finally, referring to possible ways of assessing power quality problems related to pulsed loads, a fairly efficient implement for this, is time-domain simulations via appropriate computer simulation tools (Matlab, PSCAD, etc.) [9].

CASE STUDY

In Fig. 2 a simple overview of the simulated network is shown as modeled in Matlab/Power System Blockset environment. There are two engines powering medium voltage (MV) generators of 30 MW and 10 MW nominal power respectively, generating at 4.16 kV. The main MV load is a 30 MW Propulsion Induction Motor that is controlled by a Pulse Width Modulated four-quadrant power converter using IGBTs for the output and input bridges.

Ship's auxiliaries have their main supplies fed through a MV/LV transformer that replaces the generator sets of traditional installations. The railgun system is directly connected to the MV supply without the use of voltage transformer.

Harmonic distortion problem is not present as the injected to the network harmonics by the propulsion motor inverter are low due to the used *L-C-L* output filter and the employed hysteresis current control technique. Harmonic distortion problem due to the used diode rectifier at the input of the pulsed load is also low due to the used *L-C-L* output filter and it should be mentioned that it is present only during the charging of the energy storage system. For the simulation of the Synchronous Generators and the employed control systems standard well-known detailed models implemented in *Matlab Power Systems Blockset* that correspond to commercial generators, are used. The models developed for the separate subsystems of the network –railgun, propulsion asynchronous motor- are described next.

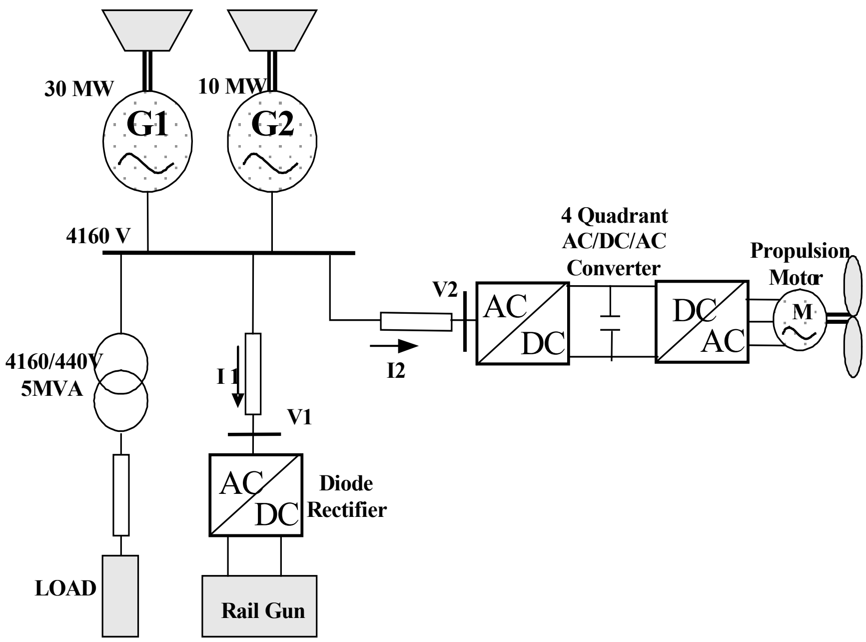


Fig. 2. Electrical system configuration

Railgun model

Railguns are being pursued as weapons with projectiles that are given extremely high velocities and do not contain explosives [10]-[11]. The developed projectile velocity is in order of 3500 m/s that make its kinetic energy equal or superior to the energy yielded of an explosive-filled shell of greater mass. This would allow more ammunition to be carried, eliminate the hazards of carrying explosives, greater range, less bullet drop and wind drift.

The operation concept of a Railgun system is shown in Fig 3. Railguns utilize the Lorentz electromagnetic force to propel an electrically conductive projectile that is initially part of the current path. Sometimes they also use a movable armature connecting the rails. The current flowing through the rails sets up a magnetic field between them and through the projectile resulting in a mutual repulsion of the rails and the acceleration of the projectile along them.

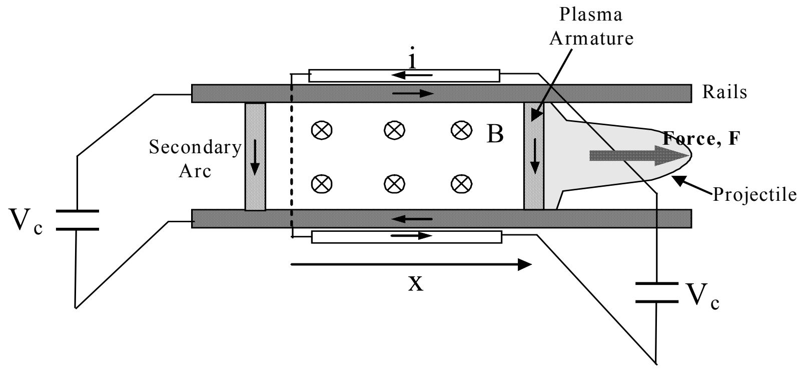


Fig 3 Railgun operation concept

The complexity in railgun design comes from:

1. The need for strong conductive materials in order to survive the violence of an accelerating projectile, and heating due to the large currents and developed friction. The force applied on the rails consists of a force equal and opposite to the force propelling the projectile applied along the length of the rails and a sideways force caused by the rails being pushed by the magnetic field.
2. Power supply design. The power supply must be able to deliver large currents. Capacitors and compulsators are being common soolutions.

Futhermore, arcing develops as rail/projectile clearances increase which causes rapid vaporization and damage to the rail and the insulator surfaces..

Railgun model developed in this paper consists of Equations (2)-(9), [12]:

$$L_{rail}(x) = \mu_0 \frac{sep}{r_w} x \tag{2}$$

$$L(x) = L_0 + L_{rail}(x) \tag{3}$$

$$\frac{d\lambda}{dt} = \mathrm{V_c\text{-}iR_{tot}} \tag{4}$$

$$\lambda = \mathrm{L(x)\cdot i} \tag{5}$$

$$\mathrm{F} = \frac{1}{2} i^2 \frac{dL(x)}{dx} = \frac{1}{2} i^2 \mu_0 \frac{\mathrm{sep}}{r_w} \tag{6}$$

$$\gamma = \frac{F}{M} \tag{7}$$

$$\frac{dv}{dt} = \gamma \tag{8}$$

$$\frac{dx}{dt} = v \tag{9}$$

Where,

L_{rail} : Rail inductance dependent on the projectile position
L(x) : Total rail inductance
λ : Magnetic flux
F : Force applied to the projectile of mass M
γ : Projectile acceleration
v : Projectile velocity
sep : Rails separation distance
r_w : Rails width
V_c : Capacitor voltage
R_{tot} : Resistance of railgun system

In this paper it is assumed that the energy storage for railgun supply is a capacitor (Fig. 4). The capacitor is connected to the AC supply via a diode rectifier and a resistance bank. The resistance bank is used to vary the resistance between the diode rectifier and the capacitor in order to limit accordingly the peak absorbed current and consequently the capacitor rate of charging. The capacitor voltage, system loading, rate of charging are taken into account and the respective resistances are connected, changing in this way the value of the equivalent total resistance. Finally, when the capacitor is charged the diode rectifier is disconnected from the AC supply and the railgun is ready to fire.

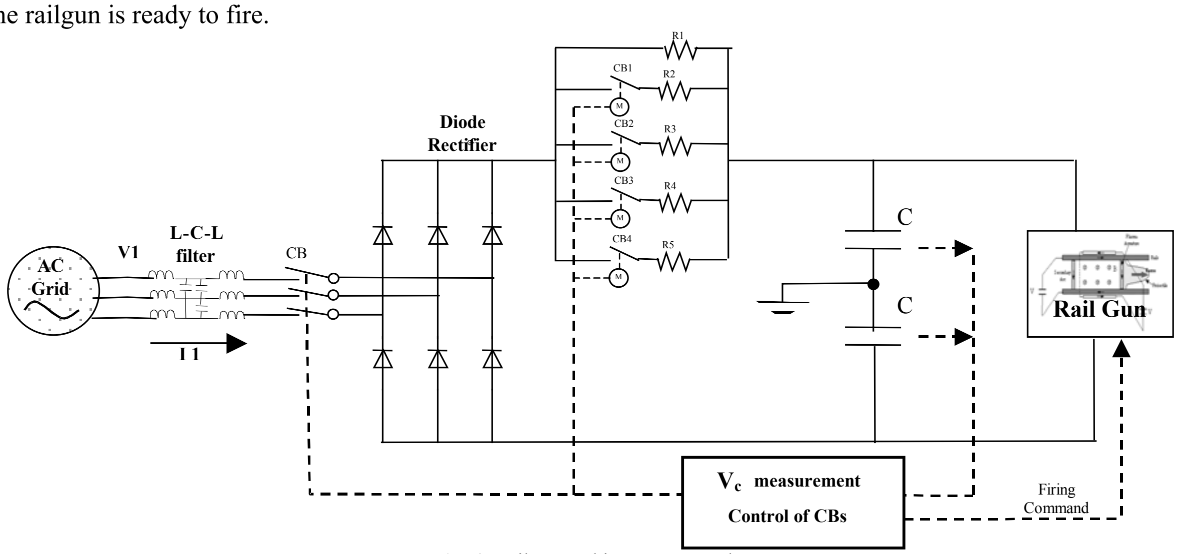


Fig. 4. Railgun and its power supply.

The sequence of the closing/opening orders to circuit breaker (CB), and railgun firing interval is shown in Fig. 5.

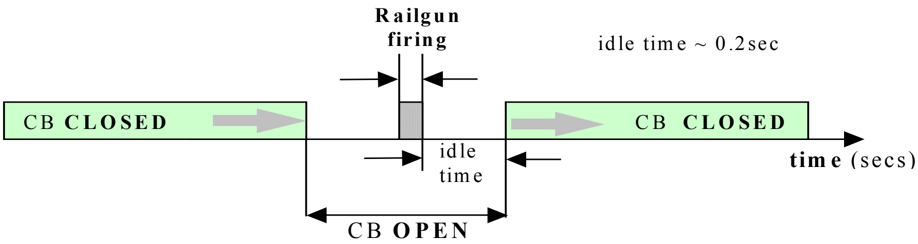


Fig. 5. Sequence of the closing/opening intervals of circuit breaker CB and railgun firing.

Propulsion motor model

The three level neutral point camped input and output inverter circuit is proposed for the propulsion motor (Fig.6) . The connection of the propulsion motor to the grid is achieved via a voltage source converter cascade, to control the power absorbed by the motor and also to provide the variable speed mode of operation. The motor and the grid -side converters both employ PWM techniques. This system gives full four-quadrant power control and operates with a fully sinusoidal current and a unit power factor. It can be connected to the network via a front-end filter without the need of a transformer. The drive is also able to provide reactive power to the network in order to control the voltage and to regenerate into the AC supply system, [13]. This specific type of converter is expected to be the major solution for future drive systems as it ensures complete isolation between the motor and the AC supply (motor dynamics are almost unaffected during AC transients) and excellent operational characteristics.

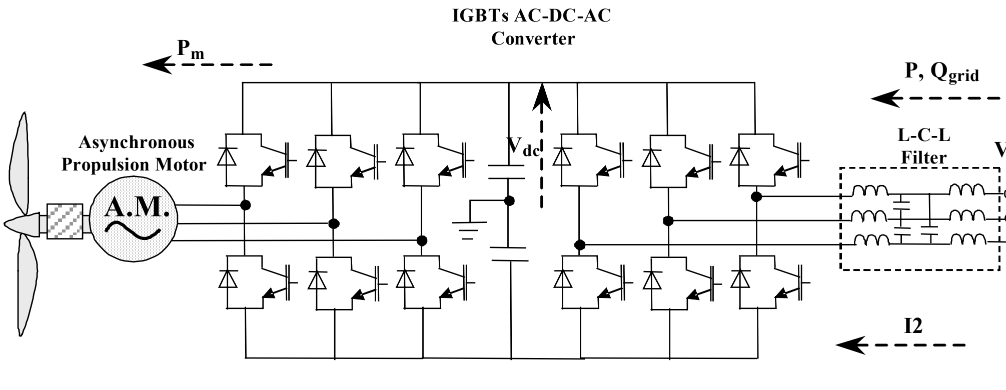


Fig. 6. Propulsion system

Induction machine is represented by the well-known fourth order model expressed in the arbitrary reference frame, as described in [14]. The control system of the grid side converter is shown in detail in Fig 7, where the major control loops of the *dc* voltage and the output reactive power are distinguished. The first loop controls the injected to the grid active power, in order to maintain the dc voltage at its set value, $V_{dc,ref}$ while the second controls the reactive power exchanged with the grid.

Energy flow balance is achieved by controlling dc voltage level as it depends on the difference between the power absorbed by the asynchronous motor and the power absorbed the grid, as given in Equation (10).

$$CV_{dc}\frac{dV_{dc}}{dt} = P_{grid} - P_m \tag{10}$$

The reference values for the instantaneous output *dq* current components in the synchronously rotating reference frame are calculated from the measured phase voltages and the reference values of the converter active and reactive powers as shown in Equations (11) and (12), [15]:

$$I2_{d,ref} = F(P_{grid}*, Q_{grid}*, V2_d, V2_d) = \frac{V2_d}{V2_d^2 + V2_q^2}P_{grid}* + \frac{V2_q}{V2_d^2 + V2_q^2}Q_{grid}* \tag{11}$$

$$I2_{q,ref} = G(P_{grid}*, Q_{grid}*, V2_d, V2_d) = \frac{V2_q}{V2_d^2 + V2_q^2}P_{grid}* - \frac{V2_d}{V2_d^2 + V2_q^2}Q_{grid}* \tag{12}$$

A narrow enough hysteresis band is used in order to eliminate the produced harmonics but also maintenance of low switching losses is taken into account The references of the phase currents produced, are led to a Pulse Width Modulator in order to produce the firing pulses for the IGBTs [16]. Reference of reactive power is set to 0 for this study.

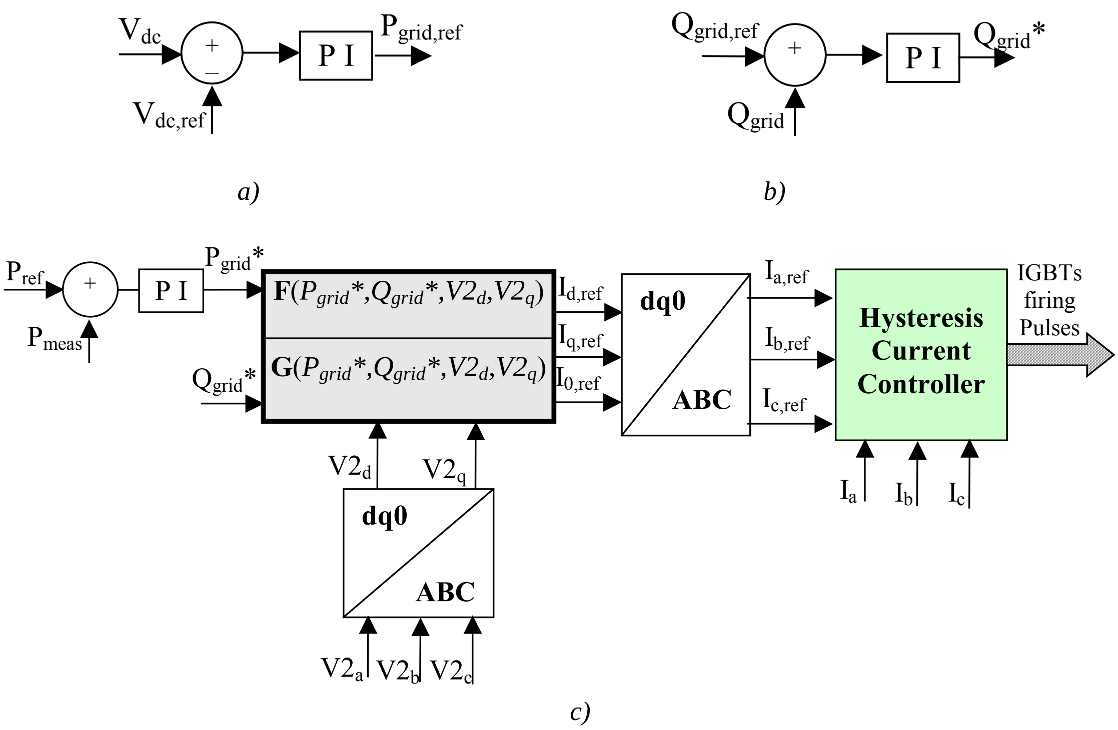


Fig. 7. Control system of grid-side inverter.

The motor control system consists of two major loops as shown in Fig. 8, one for the rotating speed and the other for the rotor's flux. Indirect field-oriented voltage control is applied to the asynchronous motor. The difference between the reference rotating speed and the measured one is fed as input to the torque controller. As mentioned before, the desired electromagnetic torque is achieved by the application of an indirect field oriented voltage control scheme. Knowing the value of the desired electromagnetic torque, the q-axis current component in the field-oriented frame is given by Equation (13), [17], [18]:

$$I_{qs}^{e*} = \frac{4L_r' T_{em}^*}{3PL_m \lambda_{dr}^{'e*}} \tag{13}$$

It is also known that, when properly oriented, the slip speed and the d,q-axis current components in the field oriented frame are related as, [17], [18]:

$$\omega^* = \omega_e - \omega_r = \frac{r_r'}{L_r'} \frac{I_{qs}^{e*}}{I_{ds}^{e*}} \tag{14}$$

Rotor flux can be controlled by regulating I_{ds}^{e} (^{e}: reference to field oriented frame). Given some desired level of the rotor flux, the desired value of the d axis current component can be obtained from Equation (15), [17], [18]:

$$I_{ds}^{e*} = \frac{r_r' + L_r' p}{r_r' L_m} \lambda_{dr}^{'e} \tag{15}$$

The above conditions ensure decoupling of the rotor voltage equations. The desired voltage components in the field-oriented frame are obtained by exploiting the induction machines parameters. The only drawback of this control scheme is that it requires accurate knowledge of the machine parameters, so it is commonly used with on-line parameter adaptive techniques for tuning the value of the parameters used in the indirect field controller ensuring in this way successful operation.

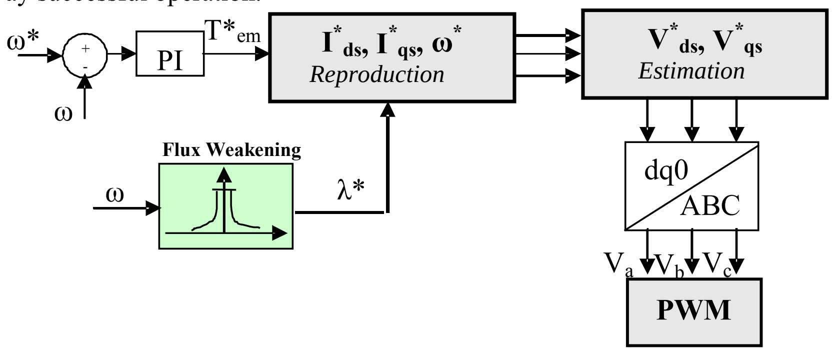


Fig. 8. Indirect field-oriented voltage controller

SIMULATION RESULTS

In this paragraph simulations results are given. First, the extent that the projectile mass and the capacitance used affect the remaining voltage on the capacitor is examined by taking advantage of the developed railgun model. Railgun system is simulated for four different values of the projectile mass and the capacitance of the used capacitor. It is expected that the higher the capacitance and the lower the mass used the higher the remaining capacitor voltage after projectile launching. The worst-case scenario, which is the lower observed remaining capacitor voltage, is selected in order to simulate the electrical network.

Then, the above system is simulated for the selected capacitance and projectile mass but different values of the resistances at the resistance bank are used. This will result in various values of the charging current and also rates of charging of the capacitor affecting in different extent the voltage and frequency of the network. The above will be quantified by the simulation results of the studied system.

The way that the parameters of the synchronous generators and their control systems affect the transient phenomenon is not examined as it is obvious that exciter and governor responses are affected by the values of their control systems parameters and consequently affect network voltage and frequency waveforms. However the aforementioned parameters and time constants of commercial generators are standardized and will be used as standard input for system design.

The different projectile masses, capacitances used and the values of the remaining capacitor voltages are shown in Table I. The respective simulation results concerning the rails current, applied force to the projectile, projectile's velocity and capacitor voltage are shown in Fig. 9 and 10. It is obvious from the obtained results that as the projectile mass increases the remaining capacitor voltage decreases while increase of the capacitance yields to increase of the remaining voltage. The way that the above quantities are related is shown in diagrams of Fig. 11.

Table I. Quantitative comparison among studied scenarios

Scenario No 1 (C=1.2 mF)		**Scenario No 2** (m=4 kg)	
Projectile mass (kg)	**Voltage** remaining on the Capacitor (V)	**Capacitance** (mF)	**Voltage** remaining on the Capacitor (V)
1	3753	**1.2**	**1983**
2	2985	1.8	3131
3	2427	2.4	3745
4	**1983**	3	4148
* Highlighted cells correspond to the selected scenario – lower remaining voltage			

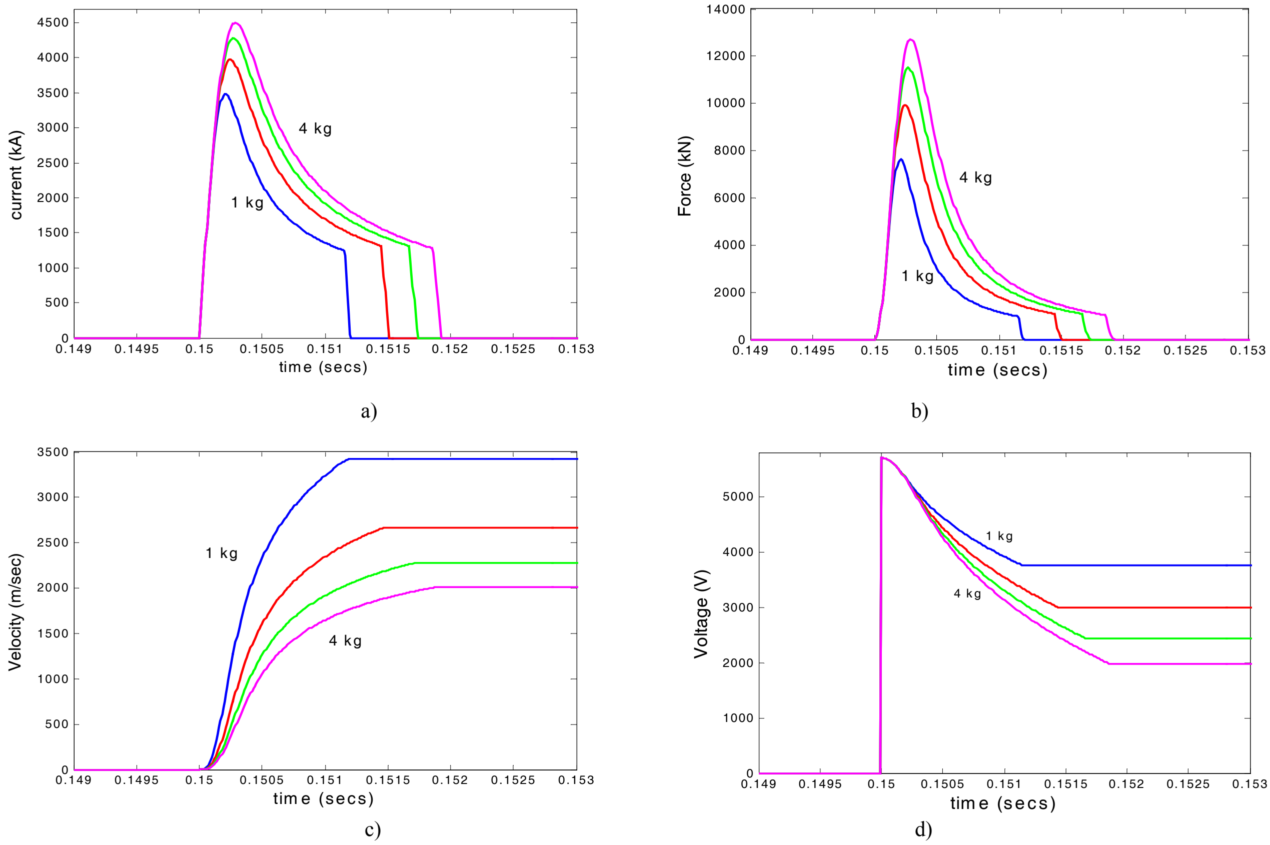


Fig. 9. Railgun simulation for different values of the projectile mass

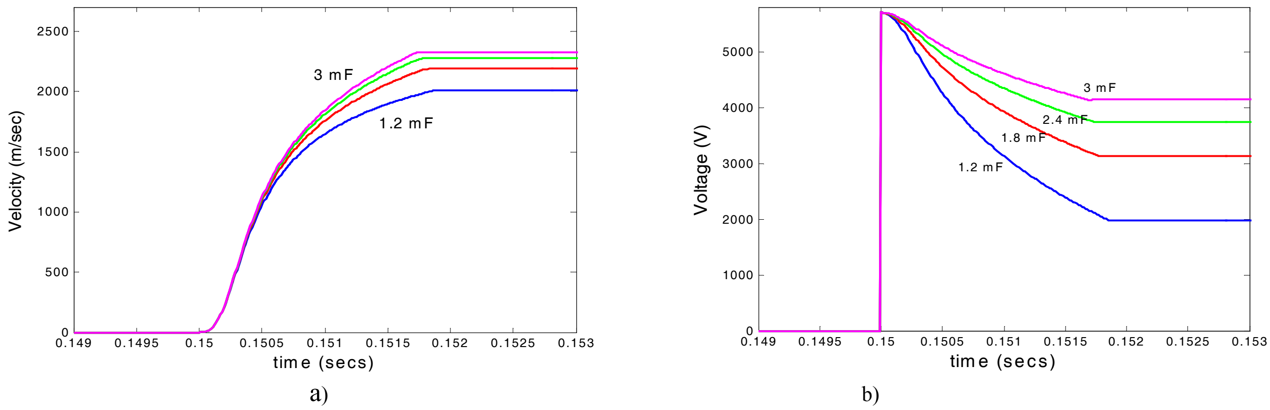
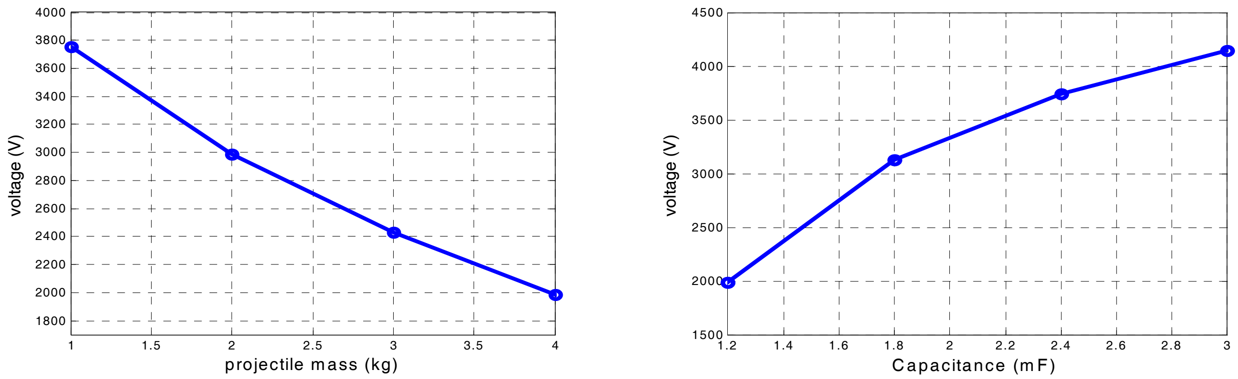


Fig. 10. Railgun simulation for different values of the capacitance



a) b)

Fig. 11. Relation between projectile mass, capacitance and remaining voltage.

The above described electrical network is simulated for the selected capacitance and projectile mass – corresponding to lower remaining voltage scenario - but for different values of the resistances used at the resistance bank, R=0.1, 0.15 and 0.4, with R1=R, R2=R, R3=R/3, R4=R/4 and R5=0 (see Fig. 4.).

It should be mentioned that resistances are connected when capacitor voltage exceeds the following respective levels of 3100, 3500, 3900 and 4200V. It is assumed that during the simulation the propulsion motor is operated at 67% of its nominal power corresponding to almost 20 MW with unit power factor and no increase or decrease on the absorbed power occurs. The parameters used for the MV cables are R=0.15 Ohms/km, X=0.35 Ohms/km, C=0.6 uF/km.

Rms voltage variations at different points of the network together with the system frequency are given in Fig. 12 and 13. Produced power by the generators, propulsion motor power, capacitor voltage and the waveform of the current I1 at the input of the diode rectifier are also shown in Fig. 14, 15.

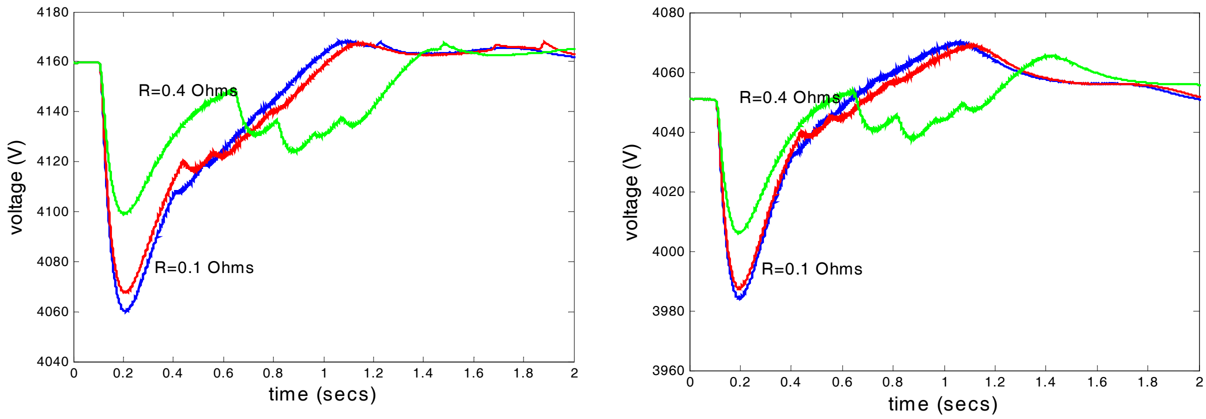


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Fig. 12. a) Voltage at railgun bus – V1(see Fig. 2). b) Voltage at propulsion motor bus – V2 (see Fig. 2).

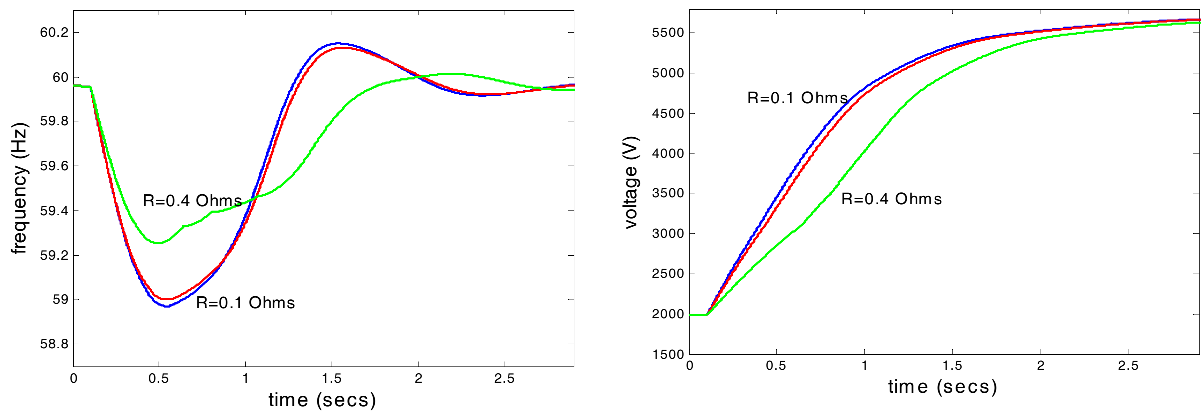

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Fig. 13. a) System frequency b) Capacitor voltage

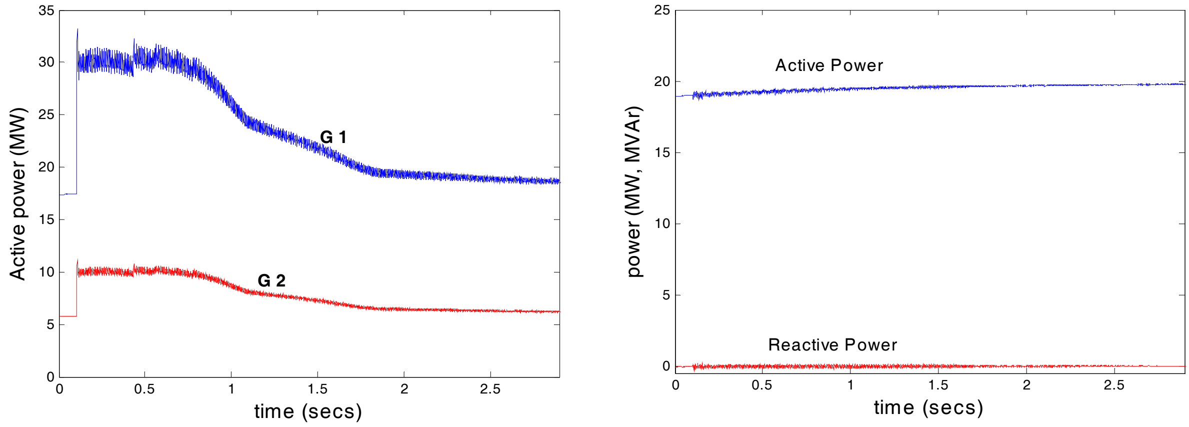

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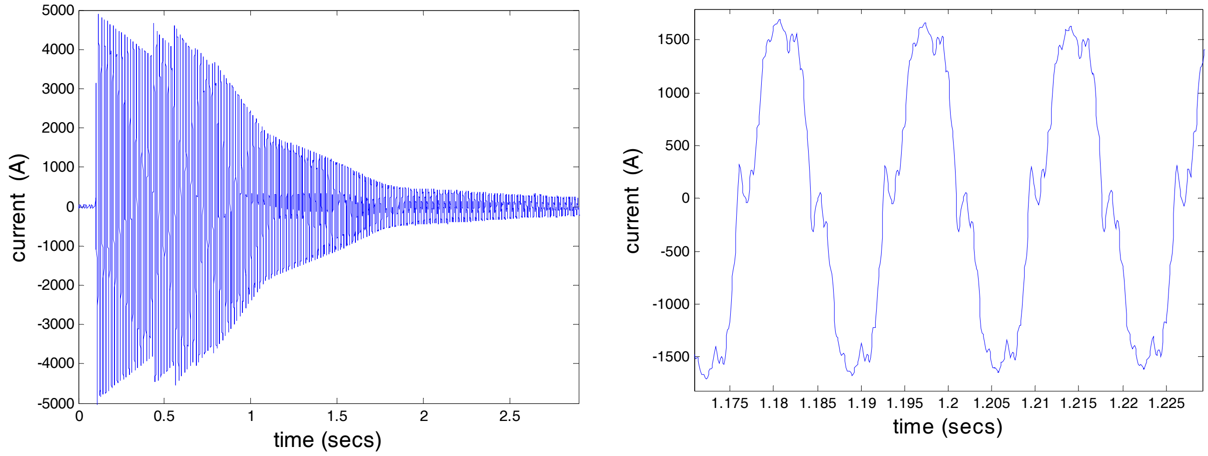
Fig. 14. a) Produced power by Generators(R=0.15Ω) b) Absorbed active, reactive power by propulsion motor (R=0.15 Ω)



a) b)

Fig. 15. a) I1 current (see Fig 2) absorbed by diode rectifier during charging (R=0.15 Ω) b) snapshot of the I1 current (R=0.15 Ω)

The voltage and frequency modulation are calculated according to equation (1) for three different scenarios and are shown in the Table II. Voltage modulation is within the limit (2%) given by STANAG 1008 however frequency exceeds the 0.5% limit in all cases given by the same standard.

Table II Voltage, Frequency Modulation

R (Ohms)	Voltage Modulation (%)	Frequency Modulation (%)
0.1	1.3	0.98
0.15	1.2	0.94
0.4	0.82	0.63
* Projectile mass=4 kg, Capacitance=1.2 mF		

It is obvious from the above results that voltage and frequency modulation shall be strongly affected by various factors as the internal parameters of the railgun, control systems etc. Time-domain simulations seem to be the most proper way to design such a system in contrast to empirical formulas suggested by standards which can only give preliminary estimations for pulsed loads limits ignoring the inherent characteristics of the system.

CONCLUSIONS

The simulation results of a warship in the context of AES comprising a pulsed load, which was assumed to be a railgun, indicated the following:

- Development of detailed models of all subsystems of an IPS is very useful in order to assess voltage and frequency modulation.
- The railgun model is useful to determine the internal conditions before its energy storage system is connected to the network in order to charge the capacitor.
- Time-domain detailed simulations of the AES system seem to be dictated in order to ensure secure and accurate design of the electrical network.

In conclusion, future integration of electrical pulsed loads into warships will pose new challenges in the design of their power systems in order to ensure operational characteristics imposed by standards. Energy storage systems will play significant role in the operation of an IPS. The used energy storage technology must be adequate to achieve the power and energy levels required for naval applications within the allowable technical, economic, size and weight constraints.

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