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METHODOLOGY FOR ASSESSING THE EFFECTS OF COMBINED CYCLE PLANT CHARACTERISTICS ON THE QUALITY OF GENERATED ELECTRICAL POWER

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Abstract: This paper deals with the assessment methodology for the impact of combined cycle plant characteristics on the quality of the produced electrical power. The aim of this work is to develop the assessment methodology with the use of an algorithm based on a flowchart of the system. The research methodology includes an analysis of the non-steady state phenomena with use of a MATLAB-Simulink environment and an analysis of the steady-state phenomena based on the theoretical calculations and analytical models of a combined cycle plant of the COGES type, connected with the processes of producing and converting of thermal and electrical power in the considered systems. A key point of the study is to check that the voltage frequency modulation on the shaft of the gas turbine is included in the limits defined by the appropriate requirements of the related IEEE Std 45™-2002 standard.

Keywords: combined cycle plant, non-steady state phenomena, steady-state phenomena, analytical models, simulation research, electrical power quality, impact assessment.

1. INTRODUCTION

This paper, as a continuation of the study presented in paper [Chinhenha and Mindykowski 2018], focuses on issues related to analysing the operating properties of selected configurations of ship power plant, for the purposes of measurements, control and diagnostics of ship systems. In particular, it concerns identifying the relations between the selected ship power plant operating parameters and energy parameters. In considering the phenomenon of significant time lags in accessing full power for gas and steam cycle installations, a methodology is studied to assess the effects of COGES (Combined Gas Turbine-Electric and Steam Turbine) system characteristics on the output voltage quality of a gas turbine generator in the context of standard requirements [IEEE Std 45™ 2002]. A novel feature is the algorithm used to assess the effects of the cogeneration gas and steam turbine system characteristics on the quality of the generated electric energy, based on a flowchart of the system.

2. WHY ARE COGES SYSTEMS WORTHWHILE ON SEA VESSELS?

Electric ship propulsion is currently a popular choice among shipowners, especially for passenger ships and LNG transport vessels. Despite the many advantages of Diesel-fuelled engines, their main drawback is the scale of pollution emissions. As environmental protection standards are becoming increasingly stringent, there is a growing need for an optimal alternative to Diesel-electric propulsion systems, which still utilise Diesel fuel. The COGES propulsion system is one proposal for an alternative propulsion system, primarily chosen for the significantly reduced pollution emissions. On the other hand, gas turbines have greater specific fuel consumption compared to Diesel engines, which is a noticeable disadvantage. However, certain analyses indicate [Haglind 2008; MacArthur 2011; Cwilewicz and Górski 2014] that a COGES propulsion system can remain profitable compared to Diesel-electric propulsion, particularly on passenger ships where the higher up-front investment can be compensated by increased passenger capacity. Environmental protection requirements have necessitated the use of natural gas as fuel for ship engines. It is believed that burning natural gas is significantly less harmful to the environment than traditionally used sources of oil, especially heavy fuel oil. Turbines are the simplest thermal engines. They are characterised by high reliability and ease of operation. A disadvantage is that they have a lower efficiency than Diesel-fuelled engines, which is one reason why Diesel engines have dominated as propulsion systems installed in modern ships. An analysis concerning turbine propulsion leads to the conclusion that combined turbine propulsion systems can achieve equivalent or even better efficiency than Diesel propulsion systems. This is achievable if a COGES propulsion system is used. The efficiency of a COGES propulsion unit depends on the degree of energy utilisation by the gas turbine exhaust. Exhaust energy is used to generate electrical energy by steam turbogenerators. Propulsion unit power depends on the ship size, mass and speed. Efficiency depends on energy division between gas and steam turbines. A high exhaust utilisation ratio results in a higher efficiency of the generated steam, enabling higher Diesel engine efficiency (currently 50–51% for Diesel engines).

Numerous analysis of total efficiency for various types of ship power plants can be found in the literature, e.g. in [MacArthur 2011], where overall efficiency as a function of propulsion system output power is compared – Fig. 1.

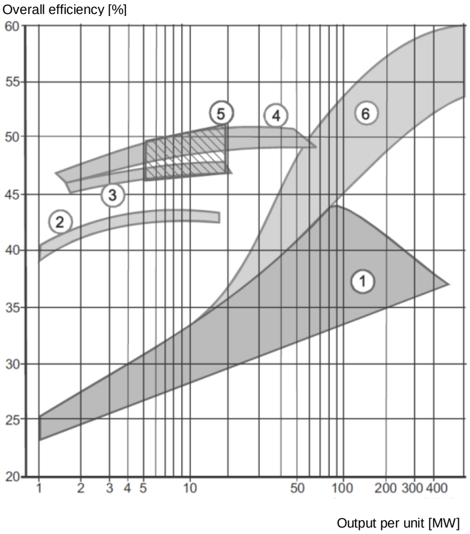

Fig. 1. Overall efficiency of different propulsion system types: 1 – gas turbine, 2 – petrol engine, 3 – medium speed four-stroke Diesel engine, 4 – low speed two-stroke Diesel engine, 5 – medium speed four-stroke Diesel engine in a combined system with a steam turbine driven by steam from the waste heat boiler, 6 – COGES turbine combined system (gas turbine working with a steam turbine), based on [MacArthur 2011]

The ability to achieve a high overall efficiency, reaching 60% for COGES units, comes at a price: a long time to reach rated total power (TG+TP) at the gas turbine output, and this power appears with a certain delay. This time stems primarily from the thermodynamic processes occurring in the steam turbine.

Fig. 2 shows the dynamics of the energy generation process in a COGES system (TG+TP) compared to the typical momentary power p(t) delay characteristics for a gas turbine $p_{TG}(t)$ and steam turbine $p_{TP}(t)$, respectively, simplified to first order inertia.

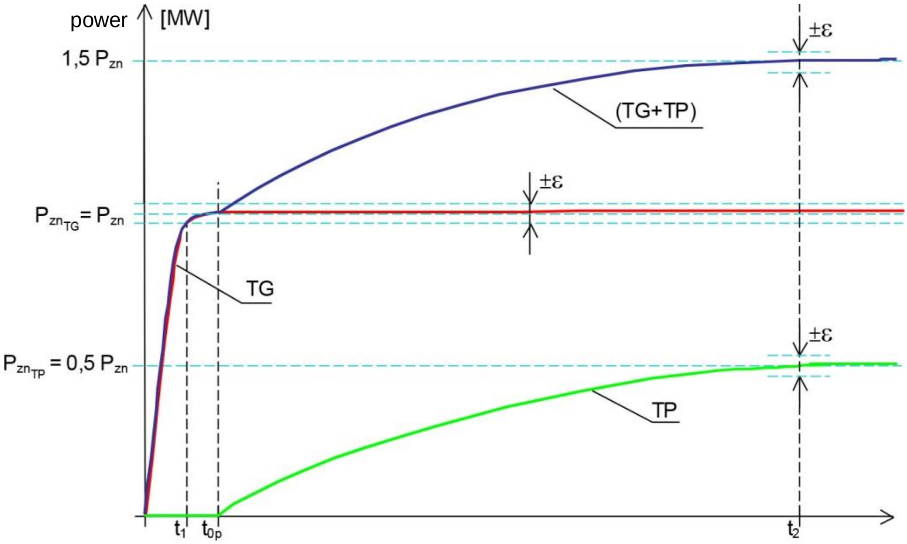

Fig. 2. Dynamics of the energy generation processes for the system equipped with turbines operating in a combined cycle plant (TG+TP, curve), TG – gas turbine response, TP – steam turbine response

3. OBJECT OF THE STUDY

The object of this study was an installation equipped with turbines operating in a gas and steam cycle plant. Such units, in versions designed for use on ships to generate electric energy and propulsion, are discussed in, for example, [Giblon 1979; Cwilewicz 2004; Domachowski and Dzida 2004; Haglind 2008; Cwilewicz and Górski 2014; Larsen, Sighthorsson and Haglind 2014; Rivera-Alvarez, Coleman and Ordonez 2015; Herdzik and Cwilewicz 2017].

An example of a simplified COGES configuration is shown in Fig. 3.

Two theoretical thermodynamic cycles can be identified in the configuration shown, i.e. a Brayton-based gas cycle and a Rankine-based steam cycle, where the working media are combustion exhaust gases and steam, respectively. A brief overview of the theoretical basics of the functioning of these cycles can be found in [Chinhenha 2012; Chinhenha and Mindykowski 2018], while a description of recent cogeneration system solutions and a thermo-economic analysis of selected combined systems is available in [Bernard 2016; Kasilow and Kholodkov 2017].

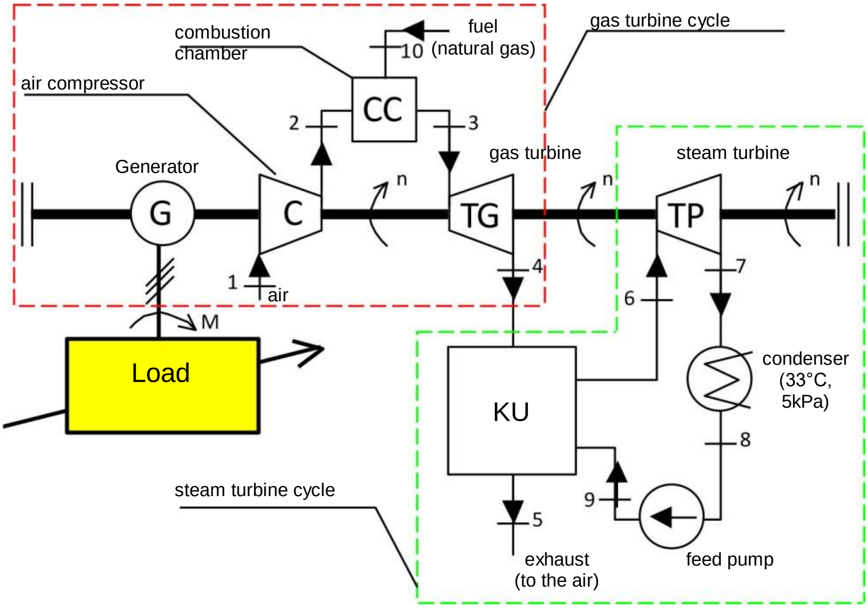

Fig. 3. Simplified diagram of the system – a combined cycle plant, G – generator, C – compressor, CC – combustion chamber, TG – gas turbine, KU – waste heat boiler (steam), TP – steam turbine, M – load torque on the gas turbine generator shaft

4. PROBLEM DEFINITION

Considering the main advantages and disadvantages (see Section 2) of COGES ship power plants (Fig. 3), it is important to analyse selected static and dynamic parameters of the system, in the context of the potential to improve the efficiency and dynamics, considered jointly, of the electric power generation process. Fig. 2 indicates that the momentary power p(t) dynamics of a system equipped with turbines operated in a gas and steam cycle are heavily dependent on the dynamic properties of each cycle. Based on the state of the art and on an analysis of the technical and maintenance documentation of selected turbines (i.e. [KB7 Steam Turbine Technical and Maintenance Documentation]), the following can be considered a valid form of response to a step function, which is a function of momentary power, p(t), with the changes in the cycles shown in Fig. 2:

- TG cycle response: $$p_{TG}(t)=K_g\left(1-e^{-t/Tg}\right)=P_{zn}\left(1-e^{-t/Tg}\right), \qquad (1)$$

where K_g [kW], T_g [h] – gas cycle amplification factor and time constant, respectively,

- TP cycle response: $$p_{TP}(t) = K_p\left(1 - e^{\frac{-(t-t_{0p})}{Tp}}\right) = 0{,}5P_{zn}\left(1 - e^{\frac{-(t-t_{0p})}{Tp}}\right), \qquad (2)$$

where:

K_p [kW], T_P [h] – steam cycle amplification factor and time constant, respectively,

t_{0p} [h] – steam cycle transport delay time,

- (TG+TP) cycle response:

$$p_{TG}(t) + p_{TP}(t) = p_{G+P}(t) = \begin{cases} P_{zn}\left(1 - e^{-t/Tg}\right) & \text{dla } t < t_0 \\ P_{zn}\left(1 - e^{-t/Tg}\right) + 0{,}5P_{zn}\left(1 - e^{\frac{-(t-t_{0p})}{Tp}}\right) & \text{dla } t \geq t_0 \end{cases} \qquad (3)$$

For the assumed equal value of rated power P_{zn} for both components, i.e. TG and TP, then $K_p = K_g$, a value that within the assumed adjustment error range ±ε is reached after time t_1 for the gas turbine cycle (usually within the range $1/4\text{ h} < t_1 < 1/2\text{ h}$) and after time t_2 for the steam turbine cycle (usually $t_2 < 4$ h, although the t_2 component is the transport delay time, frequently estimated at $t_{0p} = 1/2$ h). The rated power of the steam cycle with a waste heat boiler is markedly lower than the gas cycle rated power. In solutions known from the literature concerning this subject, the rated power of a combined cycle does not exceed $1.5P_{zn}$ of the steam cycle, and therefore $K_p < K_g$ in equations (1) and (2).

In the example shown in Fig. 2, the combined cycle power will be reached after time t_2, which stems from the resultant characteristic as a sum of the characteristics of the individual cycles. Assuming that the actual characteristic p(t) of a COGES unit depends on the engineering solutions and operating parameters of the gas cycle and steam cycle, and that load torque M on the shaft of generator G driven by output gas turbine TG (Fig. 3) can vary in time, it is reasonable to evaluate the charts of voltage U(t) of generator G in terms of the requirements concerning energy quality in ship systems [IEEE Std 45™ 2002]. Periodic changes in voltage and frequency are typical for most ship electric power systems, and also occur during steady states. During the research conducted by the Gdynia Maritime University team, numerous examples of such disturbances were observed [Tarasiuk and Mindykowski 2015]. Sample charts of changes in effective voltage and frequency values observed on a chemical tanker (ship power plant configuration not a COGES system) are shown in Fig. 4 [Tarasiuk 2009].

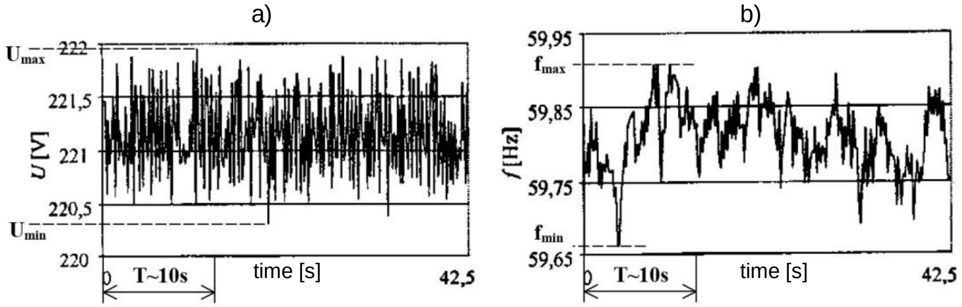

Fig. 4. Changes in effective values of voltage (a) and frequency (b) in the electric power system of a chemical tanker in a quasi-steady state (for this specific system configuration)

In our opinion, one important research issue is to verify whether the voltages, particularly frequency changes for different generator shaft load torque values, are within the limits specified in the requirements of the applicable standards. In terms of the characteristics of electric power quality for alternating current systems, the applicable standards include requirements concerning frequency, voltage, voltage curve deformations, and parameters acceptable in emergencies. The generator voltage frequency values will primarily depend on the settings of the rotational speed set by the regulator used for the TG gas turbine, and intuitively, depend significantly on the profiles of the thermodynamic processes in the COGES system (Fig. 2). The generator voltage values, which must also meet the requirements of the standard [IEEE Std 45$^{\underline{TM}}$ 2002], appear easier to meet. This stems from the fact that they are controlled by the excitement current value of the voltage regulator, whose operation is essentially independent of the thermodynamic processes in the COGES unit. However, an undoubtedly interesting and, in our opinion, original research problem for the class of systems in question, is whether voltage frequency modulation, defined as periodic changes in frequency $\delta_{okr}f$, meet the condition specified in the applicable standard [IEEE Std 45$^{\underline{TM}}$ 2002] concerning its acceptable values, for different types of load torque M(t) on the shaft of generator G:

$$\delta_{okr}f = \frac{f_{max} - f_{min}}{2 \times f_{nom}} \times 100 \le 1/2\% \quad , \qquad (4)$$

Frequency modulation (periodic frequency changes) is defined as the acceptable periodic change in frequency during normal system operation, which can be caused by repeated regular and random changes in the load. For definition purposes, the frequency change period should not exceed 10s [IEEE Std 45$^{\underline{TM}}$ 2002]. During the first stage of the study, shaft torque changes can be assumed, defined as:

- step $$M(t)=\begin{cases}0 & \text{dla} \quad 0<t<t_1 \\ M_o & \text{dla} \quad t\geq t_1\end{cases}, \tag{5}$$
- impulse $$M(t)=M_0\left(1+\sin 2\pi f_{pm} t\right), \tag{6}$$

where:

M_o – load torque constant components,
f_{pm} – load torque pulsation frequency, usually taking values from 0.2 Hz to several Hz.

Additionally, under operating conditions, the requirements concerning frequency tolerance, transient frequency component and the worst-case frequency deviation are all important [IEEE Std 45$^{\underline{\text{TM}}}$ 2002]. Frequency tolerance δf_t means the highest frequency deviation under normal operating conditions at steady state. Transient frequency component δf_p means an abrupt change in the frequency, exceeding limit frequency tolerance δf_t, and returning to within these limits in the required return time, then remaining within the limits. Therefore, the limit value of parameter δf_t is defined as two components related to the values of frequency deviation and time to return to the required value. The worst case frequency deviation δf_{max} encompasses the tolerances, transient components and periodic changes. A summary of the limit frequency parameters required by the standard [IEEE Std 45$^{\underline{\text{TM}}}$ 2002] is provided in Table 1.

Similarly, requirements concerning voltage parameters in ship alternating current electric power systems concern voltage tolerance, transient voltage component, voltage modulation (periodic voltage changes), voltage asymmetry tolerance, and worst-case voltage deviation encompassing tolerances, transient components, periodic changes, and voltage asymmetry tolerance [IEEE Std 45$^{\underline{\text{TM}}}$ 2002].

Table 1. Limit values of frequency parameters for electrical power quality in ship systems according to IEEE Std 45$^{\underline{\text{TM}}}$ 2002

Parameter	Symbol	Limit value
Nominal frequency	f_n	50/60 Hz
Frequency tolerance	δf_t	±3%
Transient frequency component: a) value b) time	δf_p	a) ±4% b) 2 s
Frequency modulation (periodic frequency changes)	$\delta_{okr} f$	0.5%
Worst case frequency deviation	δf_{max}	5.5 %

Additionally, acceptable values concerning voltage curve deformations and emergency situations were studied in relation to the voltage characteristics. It is worth emphasising that requirements similar to those of the American standard [IEEE Std 45$^{\underline{TM}}$ 2002] are defined in a European standard [PN-IEC 60 092-101-2002]. Other than the standards mentioned, requirements concerning the frequency and voltage parameters in ship electric power systems are also the object of classification society regulations.

5. STUDY METHODOLOGY

Tests of the effects of combined gas and steam turbine system characteristics on the quality of the generated electric power concern two issues: analysis of dynamic states using the MATLAB-Simulink environment, and analysis of steady states based on theoretical calculations and the analytical models of a COGES system, related to the processes of generating and processing heat and electric power in the systems in question.

5.1. Use of the MATLAB-Simulink environment to analyse transient states

The tests were performed in the MATLAB-Simulink software environment using the Simscape tool (sub-program). Simscape expands Simulink's capabilities with tools for modelling and simulating multi-domain physical systems, such as mechanical, hydraulic or electric systems. Simscape Power Systems and Simscape Fluids modules were used for the study. The essence of these tools is the ability to model the complex interactions occurring in multi-domain systems. In the COGES system here, the normative requirements concern the quality of the electric power generated in the system, and in particular frequency parameters of the voltage of generator G subjected to a variable load by frequency M(t) on its shaft.

In the version of the COGES system assumed in the Simulink software (Fig. 6), a gas turbine with a combustion chamber and compressor, a generator with controlled load, waste heat boiler, steam turbine with a condenser and pre-heater and control blocks for their corresponding system elements were considered. Gas turbine shaft (and generator) rotation speed was controlled by adjusting the fuel dose in the combustion chamber. Most commonly, three PID regulators can be found in the gas turbine regulator block, which adjust the shaft speed, turbine inlet temperature, and compressor surge margin. Shaft load torque change control, representing for example the states on activation or deactivation of the ship's steering thrusters, or sea undulation, was executed in the model of the COGES system in the Simulink software using a block described as "Load control", which works with the generator. The scheduled simulation tests using the model shown in Fig. 6 included, first, determination of the parameters of transient characteristics

$p_{G+P}(t) = f(t)$, e.g. based on equation (3), and $p_{G+P}(t) = P_{ust}$, for a steady state; and second, verification of the $\delta_{okr}f < (\delta_{okr}f)_{dop}$ (4) condition for different characteristics of load M(t), e.g. expressed in equations (5) and (6). Variable load M(t) (Fig. 5a and b) were executed by the block named "Load", as in the figure below (Fig. 6). Additionally, the other frequency parameters of the voltage produced in the generator were determined, as summarised in Tab. 1.

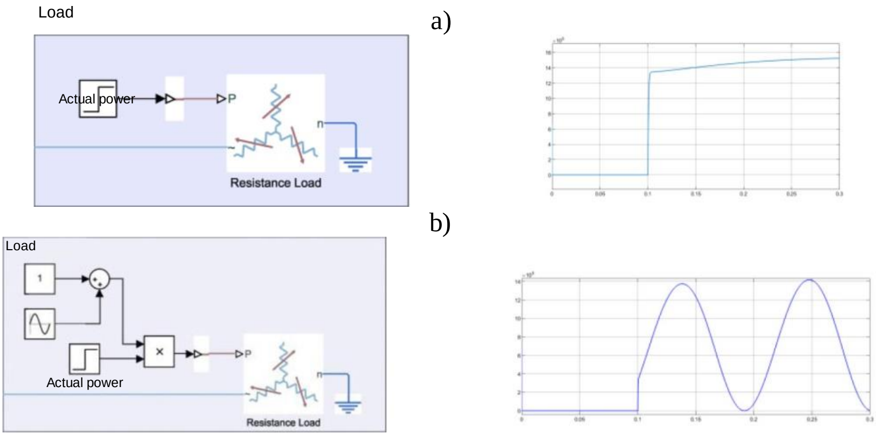

Fig. 5. Execution and sample charts of variable load M(t) in the MATLAB-Simulink software: a) Heaviside step load, b) impulse load as per equations (5) and (6), respectively

5.2. Use of an analytical model to analyse steady states

The theoretical calculations based on relations concerning thermodynamic cycles known from literature related to this subject, as well as the use of the previously prepared analytical model of a gas and steam cycle [Chinhenha 2012; Chinhenha and Mindykowski 2018], enable determination of the power and efficiency of the gas and steam system under steady state conditions. These values correspond to the power and efficiency of a COGES system for time $t_2 = t_{ust}$ (Fig. 2) and can form a point of reference for comparison with the results of dynamic state tests performed using the MATLAB-Simulink environment, obtained from the transient state tests.

The starting point for the theoretical analyses, in connection with Fig. 3, assumes a specific COGES unit based on the manufacturer's data, gas turbine input parameter values (shaft speed, compressor air flow rate, fuel feed to the combustion chamber) and the gas turbine output parameters, which are the steam turbine input parameters at the same time (exhaust gas temperature, enthalpy, exhaust mass flow rate). The limitation is the condition concerning exhaust gas temperature at the waste heat boiler outlet, T < 160°C, assuming a waste heat boiler efficiency within the range: 88 ... 92%, allowing us to estimate the amount of steam.

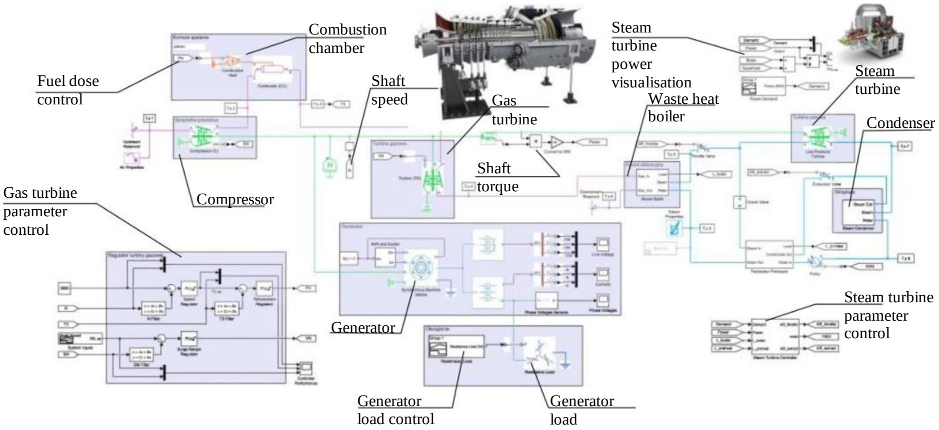

Fig. 6. Preliminary model of the COGES cycle plant in the Simulink software

The starting point for the theoretical analyses, in connection with Fig. 3, assumes a specific COGES unit based on the manufacturer's data, gas turbine input parameter values (shaft speed, compressor air flow rate, fuel feed to the combustion chamber) and the gas turbine output parameters, which are the steam turbine input parameters at the same time (exhaust gas temperature, enthalpy, exhaust mass flow rate). The limitation is the condition concerning exhaust gas temperature at the waste heat boiler outlet, T < 160°C, assuming a waste heat boiler efficiency within the range: 88 ... 92%, allowing us to estimate the amount of steam.

The steam turbine output values are: condensation pressure and condensation temperature. Two options were considered: a) estimating the gas and steam turbine power and efficiency based on equations known from the subject literature, resulting from the first and second law of thermodynamics, which describe and connect the analysed thermodynamic processes [Cengel and Boles 2005; Cengel 2007] and b) determining the power and efficiency of the gas and steam cycle based on the analytical models we developed [Chinhenha 2012; Chinhenha and Mindykowski 2018]. For example, estimating the values of gas turbine power and efficiency (option (a)) is done based on the following sequence of calculations:

$$T_{2S} = T_1 \left(\frac{P_2}{P_1} \right)^{\frac{\chi - 1}{\chi}} = T_1 . \pi^m \tag{7}$$

$$T_2 = T_1 + \frac{T_{2s} - T_1}{\eta_{is}} \tag{8}$$

$$T_3 = \frac{\dot{Q}_D}{\dot{m}_{ge}.C_{ppow}} + T_2 \tag{9}$$

$$T_{4S} = T_3.\pi^{-m} \tag{10}$$

$$T_4 = T_3 - \eta_{iT}\left(T_3 - T_{4s}\right) \tag{11}$$

$$L_{iTG} = C_{ppow}.T_1.\left[\frac{T_3}{T_1}\left(1 - \pi^{-m}\right).\eta_{iT} - \left(\pi^m - 1\right)\cdot\frac{1}{\eta_{iT}}\right] \tag{12}$$

$$P_{iTG} = \dot{m}_{ge}\cdot L_{iTG} \tag{13}$$

$$\eta_{iTG} = \frac{\frac{T_3}{T_1}\left(1 - \pi^{-m}\right)\eta_{iT} - \left(\pi^m - 1\right)\frac{1}{\eta_{iS}}}{\frac{T_3}{T_1} - 1 - \left(\pi^m - 1\right)\frac{1}{\eta_{iS}}} \tag{14}$$

The symbols T_1, T_2, T_3, T_4 correspond to the temperature values at points 1, 2, 3 and 4 in Fig. 3, while L_{iTG}, P_{iTG} and η_{iTG} are the internal unit work, power and efficiency of the gas turbine. Known values are T_1, T_4, π, χ, $\dot{m}_{ge}$, m, η, η_{iS}, η_{iT}, η_{eTG}.

The values of steam turbine power and efficiency can be estimated in a similar manner, considering the process parameters at points 6, 7, 8 and 9 in Fig. 3. The results obtained, due to the necessity to make numerous assumptions, e.g. in relation to the efficiency of many devices participating in the electric power generation process, are only estimates. In our opinion, more robust results can be obtained using an analytical model of gas and steam cycle cogeneration [Chinhenha 2012; Chinhenha and Mindykowski 2018] where the mean values obtained earlier for power and efficiency estimates are $\delta W_{(TG+TP)} = -2.4\%$ and $\delta\eta_{(TG+TP)} = +0.4\%$, respectively. The values provided are an approximate measure of the deviations in the characteristics determined by calculations using analytical models from the reference characteristics determined during the acceptance tests of actual power plants. The power and efficiency values of the combined cycle system in question are estimated in accordance with the formula based on three sets of variables working in sequence: input variables, intermediate variables, and output variables, with feedback to the input data start set at cycle end (Fig. 7). The input variables (temperature, pressure, flow rates, air and water specific heat) are determined using manufacturer's data for the combined cycle system analysed, as well as data obtained from thermodynamic charts and the EES (Engineering Equation Solver) software [Klein 2002; Cengel and Boles 2005; Cengel 2007]. Intermediate variables concern the model's constants (entropy, enthalpy, unit fuel consumption, unit air consumption) and calculated values (powers related to system elements of both turbines). The output variables are output power and overall efficiency of the gas and steam turbine combined system, calculated in an iterative procedure. For example, Tables 2, 3 and 4 show the calculation sequences for intermediate variables of the gas turbine (Tab. 2), intermediate variables of the steam turbine (Tab. 3), and output variables for the gas and steam cycle (Tab. 4).

Table 2. Calculation sequence for gas turbine intermediate variables

Parameter	Symbol	Equation
Power generated by the gas turbine	$\dot{W}_{TG} = P_{TG}$	$\dot{W}_{TG} = \dot{m}_3 C_{ppow}(T_3 - T_4)$
Power loss by the compressor	$\dot{W}_{PS} = P_{PS}$	$\dot{W}_{PS} = \dot{m}_2 C_{ppow}(T_2 - T_1)$
Power generated in the combustion chamber	$\dot{Q}_{KS}$	$\dot{Q}_{KS} = \dot{m}_{10}.PCI$
Compressor drive power	$\dot{W}_S = P_S$	$\dot{W}_S = \frac{\dot{W}_{PS}}{\eta_m}$
Turbine drive power	$\dot{W}_T = P_T$	$\dot{W}_T = \dot{W}_{TG}.\eta_m$
Power generated in the gas cycle (high)	$\dot{W}_{CG} = P_C$	$\dot{W}_{CG} = \dot{W}_T - \dot{W}_P$
Efficiency in the gas cycle	η_{CG}	$\eta_{CG} = \frac{\dot{W}_{CG}}{\dot{Q}_{ks}}$

Table 3. Calculation sequence for steam turbine intermediate variables

Parameter	Symbol	Equation
High-pressure turbine power	$\dot{W}_{WS} = P_{WS}$	$\dot{W}_{WS} = \dot{m}_6(h_6 - h_7)$
Pump power	$\dot{W}_B = P_B$	$\dot{W}_B = \dot{m}_8(h_8 - h_9)$
Power loss in the boiler	$\dot{Q}_K$	$\dot{Q}_K = \dot{m}_4 C_{ppow}(T_4 - T_5)$
Power in the steam cycle	$\dot{W}_{CP} = P_{CP}$	$\dot{W}_{CP} = \dot{W}_{WS} - \dot{W}_B$
Efficiency in the steam cycle	η_{CP}	$\eta_{CP} = \frac{\dot{W}_{CP}}{\dot{Q}_K}$

Table 4. Calculation sequence for the combined cycle plant variables

Parameter	Symbol	Equation
Power in the combined cycle	$\dot{W}_{CM} = P_{CM}$	$\dot{W}_{CM} = \dot{W}_{CG} + \dot{W}_{CP}$
Efficiency in the gas cycle	η_{CM}	$\eta_{CM} = \frac{\dot{W}_{CM}}{\dot{Q}_{KS}}$

5.3. Algorithm for assessing the effects of combined cycle system characteristics on the quality of generated electric power

Based on the initial tests concerning the modelling of COGES systems in the MATLAB-Simulink Simscape environment (Section 5.1) and on the simulation tests performed previously on the system in question, based on our own analytical model [Chinhenha 2012; Chinhenha and Mindykowski 2018], (Section 5.2), an assessment procedure algorithm was developed, shown as a flowchart in Fig. 7.

The starting point for building the algorithm is a manufacturer's data module for the COGES system configuration selected for assessment, and data concerning the corresponding thermodynamic cycles. The algorithm is based on two pillars and encompasses simulation tests using the MATLAB-Simulink environment to analyse transient states and the analytical calculations based on analytical models to analyse steady parameters in the COGES power system in the configuration in question.

Tests of the transient states of momentary power $p_{G+P}(t)$ enable determining power P_{ust} generated in the gas and steam cycle. The P_{ust} value will be compared to the value of output power P_{G+P}, determined on the basis of simulation tests using theoretical analysis and our analytical model for steady states. An important element of the algorithm developed is verification of the normative inequality describing the acceptable periodic frequency changes described in Section 4.

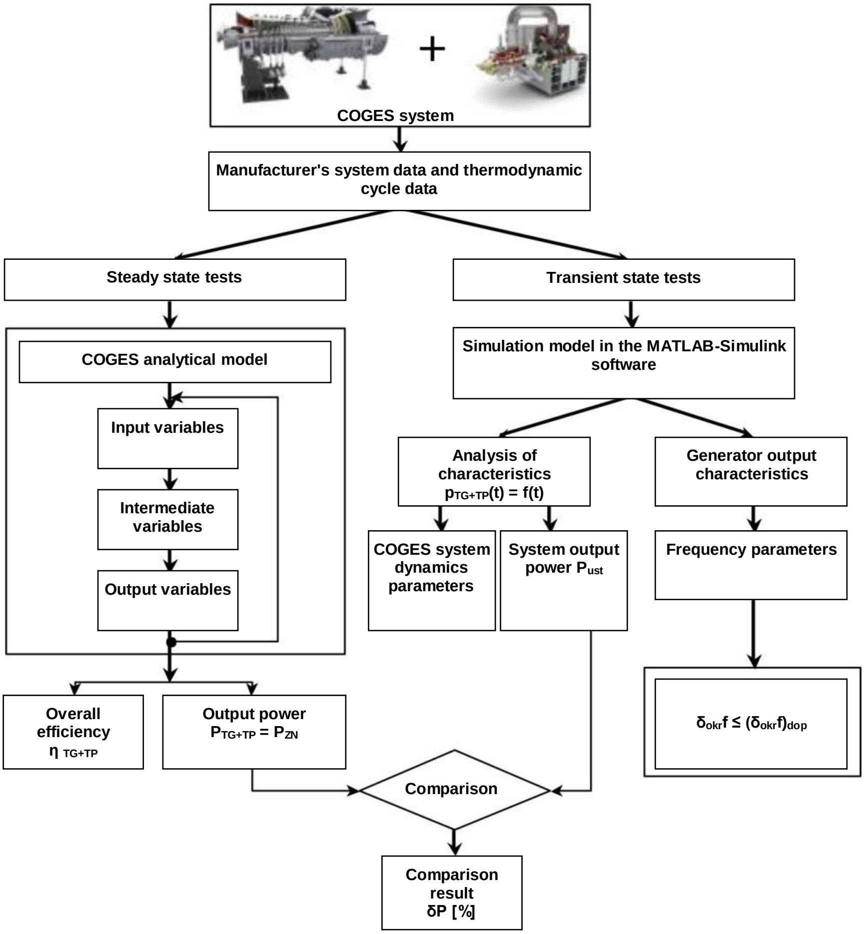

Fig. 7. Flowchart of the assessment procedure for the effects of the combined cycle plant characteristics on the quality of the generated electrical power

6. CONCLUSIONS AND DIRECTIONS OF FURTHER STUDIES

Based on a review of the literature concerning various propulsion system solutions on marine vessels, an ability to achieve the highest (within the propulsion system class in question) overall efficiency as a function of output power for a COGES system, while identifying a significant drawback of this solution at the same time. This drawback is the length of time to achieve rated power at the gas turbine output, even up to 4 hours. A separate issue is the quality of electric power at the gas turbine output after reaching full power for the gas and steam cycles. Among the quality parameters of electric power in ship alternating current electric power systems, defined not only in classification society regulations but also in the IEEE Std 45$^{\underline{TM}}$-2002 standard, among others, frequency parameters are particularly important in the system. The generator voltage frequency value primarily depends on the settings of the rotational speed regulator for the gas turbine, and intuitively, depends significantly on the profiles of the thermodynamic processes in the COGES system. Therefore, meeting the normative requirement concerning frequency modulation ("de facto" periodic frequency changes) is an important, and in our opinion, original research problem for the system class in question. Due to the complexity of the issue, stemming from the interactions between heat and electric power generation and the processes in the system analysed, it is necessary to first develop a suitable study methodology, and then an algorithm for assessing the effects of the gas and steam turbine combined system on the quality of the generated electric power. The next stage, outside the scope of this paper, will be to experimentally verify the correctness of the assessment algorithm developed, both in terms of the transient and steady state analyses, and the use of the MATLAB-Simulink environment and analytical models.

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