SATURATED STEAM TURBINE OPERATION MODELING WITH APPLICATION AT NPP CERNAVODA

I.PRISECARU, D.DUPLEAC [*]

Lucrarea prezintă rezultatele cercetării în scopul dezvoltării de modele matematice pentru componentele centralei nucleare de la Cernavodă şi anume turbina cu abur saturat. Modulele pentru simularea grupurilor de trepte şi modulul pentru simularea extracţiilor de abur şi sau umiditate la prize sunt module noi, originale. Modelele matematice au fost implementate în codul de calcul MMS cu ajutorul programului CompGen. Sunt descrise rezultatele obţinute pentru un regim tranzitoriu ce constă în reducerea puterii turbinei de abur.

The paper presents a part of a work in developing mathematical models for the components of the nuclear power plant with application to the Cernavoda NPP focusing to the steam turbine model development. The whole steam turbine configuration is modeling in modular form. Thus, four interconnected modules are using that describe the turbine stages, the steam extraction, the intermediate moisture separator and steam reheated and the turbine governor valve. The authors propose a new mathematical model for the turbine stages and steam and/or humidity extractions at turbine casings. The mathematical models have been implemented in the MMS code using the CompGen tools. The results obtained for the transient represent a steam turbine power reduction is presented.

Keywords: steam turbine, nuclear power plant, mathematical model, MMS

Introduction

For the steam turbine configuration, more complex or simple mathematical models are mentioned and described in the literature. The mathematical models of the MMS program [1,2] are very general with a smaller degree of precision due to the exclusive usage of theoretical relations for the variation of the internal efficiency and for the calculation of the steam energy loss at the exit from the low-pressure body of the turbine.

The mathematical model and simulation module developed respect the modularity principle. The whole turbine is modeled using four modules that are interconnected to simulate the real turbine: the stage group module, the steam extraction module, the intermediary system module (moisture separator and reheater) and the admission valves module.

[*] Prof. , Reader, Dept. of Power Plant, University “Politehnica” of Bucharest, Romania

The modules for the simulation of the stage group and for the steam or moisture extraction are new and original, created especially for solving quickly and with a great accuracy the behavior of the turbine in transitory regimes. This paper underlines the model of those components. The other two modules are based on elements described in [1,2,3,4].

Stage group mathematical model

By stage group we understand one or more stages in which the steam detention is done with the same internal efficiency. The model, as shown in Fig.1, was created for the simulation of a turbine stage group between two steam and/or moisture extractions.

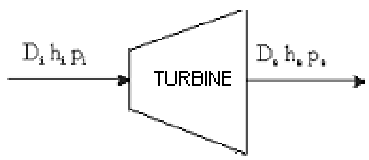


Fig. 1 The „stage group" model

The model use lumped parameters approach and is one-dimensional. In the construction of the mathematical model for a stage group, the following simplifying hypothesis and limitations where introduced [3]:

- The turbine is considered an adiabatic enclosure;
- No heat loss is present;
- The temperature of the turbine case is not modeled;
- Steam loss from the turbine is neglected;
- The accumulation of energy or mass in the turbine is neglected;
- The internal efficiency is calculated for the entire stage group using the General Electric method [5]: the internal efficiency is calculated in relation to the flow rate at the inlet, the pressure ratio at the inlet and outlet and the average steam humidity.

The turbine model takes into account the following phenomena:

- The variation of the steam flow rate through the turbine due to the changing of the pressures at the inlet or outlet or to the steam enthalpy at the inlet;
- The variation of the internal efficiency.

The variation of the steam enthalpy at the turbine outlet taking into accounts the exhaust losses at the low-pressure assembly.

Because the mass accumulation is neglected in the turbine, the equation for the conservation of mass between the inlet and the outlet takes the following form:

$$D_i = D_e = D \tag{1}$$

Also, the energy accumulation in the turbine is neglected, thus the steam enthalpy at the outlet of the stage group is (Fig. 2 a):

$$h_e = h_i - k_\eta \eta_i \left(h_i - h_T\right) \tag{2}$$

To improve the results of the model a correction of the internal efficiency with the adjustment coefficient k_η is necessary.

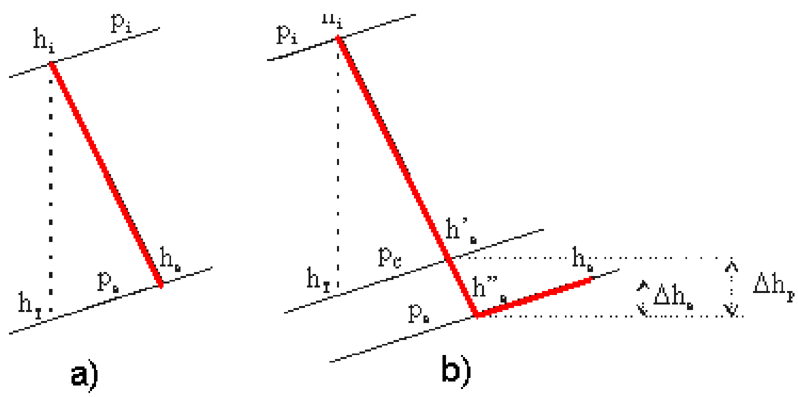


Fig. 2 Steam expansion in a intermediary group (a) and in a terminal group (b)

For determination of the internal efficiency of the stage group the General Electric methodology was adapted [5], processed [6] and checked in the calculation at the different power states of the NPP Cernavoda [7].

This method estimates the internal efficiency as a product between the base efficiency and one or more corrections depending on the turbine parameters. Both the internal efficiency and their corrections were determined throughout an exact calculus „stage by stage" for a great number of cases and were synthesized in mathematical expressions and calculus diagrams. In Table 1 are presented the cases taken in consideration (Q_i is the flow rate at the turbine inlet, and u – main moisture in the turbine). In Fig. 3 the variation of the base internal efficiency for the stage groups of the high-pressure assembly are presented [4].

Table 1

Calculus of the internal efficiency of the turbine

Operational regime	High pressure assembly	Low pressure assembly superheated steam	Low pressure assembly moist steam
Base efficiency	C3 (Q_i,p_i,p_e)	C3(Q_i,p_i,p_e)	C4 (p_i,p_e)
Flow rate correction			C5(Q_i,p_i,p_e)
Moisture correction	C2 (p_i,u)		1-u·C7 (p_i,p_e)

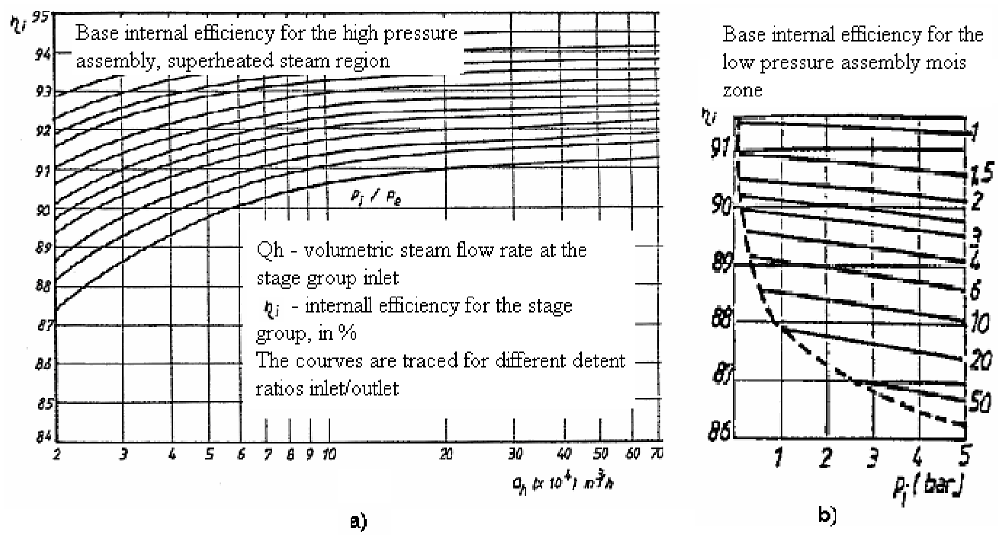


Fig. 3 Low pressure base internal efficiency:
superheated steam zone (a) and the moist zone (b)

The type of turbine assembly (high or low pressure) for each stage group is determined by the pressure at the inlet. For the NPP Cernavoda turbine, if the pressure is over 10 bar for calculating the internal efficiency the functions c3 and c2 are used; otherwise the functions c3 / c4, c5 and c7 are used. If the stage group is placed at the end of the turbine the expansion is calculate in a bigger number of steps (Fig. 2 b). In a first step, the expansion to a conventional calculated pressure, p_C = 0.05 bar, for the internal efficiency the functions *c*4, *c*5 and *c*7 are used. Thereafter, the final point h'_e is corrected with Δh_p, correction that takes into account the fact that the expansion is actually realized until p_c not until p_C. So the h_e'' enthalpy is reached, enthalpy that must also be corrected by Δh_e, correction that takes into account the exhaust losses. In this case the equation (2) is modified as follows:

$$h_e = h_i - k_\eta \eta_i \left(h_i - h_T\right) - \Delta h_p + \Delta h_e \tag{3}$$

The following relation gives the mechanical power developed by the stage group:

$$P_m = D\left(h_i - h_e\right) \tag{4}$$

The flow rate in the turbine is calculated using an extended Stodola [9]:

$$\frac{D}{D^*} = \sqrt{\frac{\rho p_1}{\rho^* p_1^*}} \sqrt{\frac{1-\left(\frac{p_2}{p_1}\right)^2}{1-\left(\frac{p_2^*}{p_1^*}\right)^2}} \tag{5}$$

in which D^*, ρ^* and p^* refer to an known regime (usually at full power), and the index 1 and 2 refers to the sections of the turbine between which the flow rate D is calculated.

Grouping the known terms in one single constant value and writing the equation between the inlet and the outlet of the stage group the following relation for the flow rate results:

$$D = k_D \sqrt{\rho_i p_i \left[1-\left(\frac{p_e}{p_i}\right)^2\right]} \tag{6}$$

where: k_D is a flow rate constant; ρ_i is the steams density at the turbine inlet. In Fig. 4 the block diagram of the „stage group" model is presented.

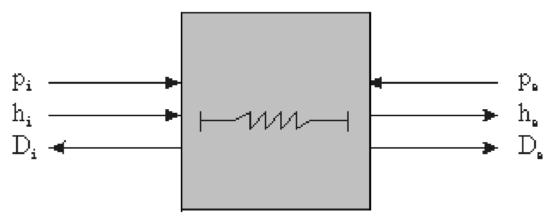


Fig. 4 Block diagram for the „stage group" model

For the models parametrization the following functional data are needed: p_{i_n} - the pressure at the turbine inlet at the nominal regime; p_{e_n} – the pressure at the turbine outlet at the nominal regime; h_{i_n} – enthalpy at the turbine inlet at the nominal regime; h_{e_n} – enthalpy at the turbines outlet at the nominal regime; D_n – steam flow rate through the turbine at the nominal regime; p_i – pressure at the turbine inlet at the initial regime; p_e – pressure at the turbine outlet at the initial regime ; h_i – enthalpy at the turbine inlet at the initial regime.

Based on the turbine parameters at the nominal regime, the correction k_η and the flow rate constant k_D is determined.

$$k_\eta = \frac{h_{i\_n} - h_{e\_n}}{\eta_i \left(h_{i\_n} - h_T\right)} \tag{7}$$

$$k_D = \frac{\sqrt{\rho_{i\_n} p_{i\_n} \left[1 - \left(\frac{p_{e\_n}}{p_{i\_n}} \right)^2 \right]}}{D_n} \qquad (8)$$

where h_T is the enthalpy at the turbine outlet following the theoretical expansion at full power, and ρ_{i_n} is the density at the turbine inlet at full power. The initial enthalpy at the turbine outlet is determined with the relation (3) and the initial flow with the relation (6).

Turbine moisture extraction mathematical model

This model (Fig. 5) was created for simulating an intermediary pressure inlet port with or without moisture extraction.

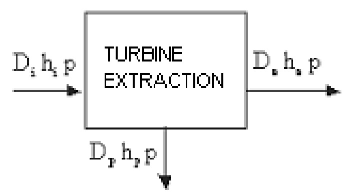


Fig. 5 Turbine moisture extraction model

The turbine moisture extraction model neglects energy storage but considers the variation of outlet steam pressure and enthalpy. There is is also a possibility of taking into consideration port to have a moisture extraction for the inlet. The mass conservation equation is [8]:

$$\frac{dp}{dt} = \frac{D_i - D_e - D_p}{k_p} \qquad (9)$$

where: p- inlet port steam pressure; k_p –constant which takes into consideration the model inertia in terms of pressure variation in a dynamic state. The chosen value after testing is 1.8 10^{-5} kg/Pa.

Outlet enthalpies are calculated with the following relations. If the inlet port has moisture extraction, then the following relation is considered true:

$$h_p = h_e = h_i \qquad (10)$$

Else the enthalpy h_e is corrected considering the moisture extraction efficiency as follows: from Table 2 the moisture extraction efficiency ε is interpolated linearly, after pressure p, and the moisture percentage extracted through inlet port on inlet steam flow is calculated:

$$a = \varepsilon\left(1 - x_i\right) \tag{11}$$

where x_i is steam quality at inlet. The steam quality at the outlet is calculated by:

$$x_e = \frac{x_i}{1-a} \tag{12}$$

With steam quality so obtained, the enthalpy h_e is then determinate and the inlet port enthalpy is calculated:

$$h_e = h'(p) + x_e\left[h''(p) - h'(p)\right] \tag{13}$$

$$h_p = \frac{h_i D_i - h_e D_e}{D_p} \tag{14}$$

Table 1

Moisture Extraction efficiency for CNE Cernavoda turbine

p (bar)	0.2	0.3	0.4	0.5	0.6	0.7	1	2	3	4
ε (%)	6	5.95	5.85	5.4	5	4.6	4.15	3.7	3.6	3.6

In Fig. 6, the pressure inlet port block diagram is shown.

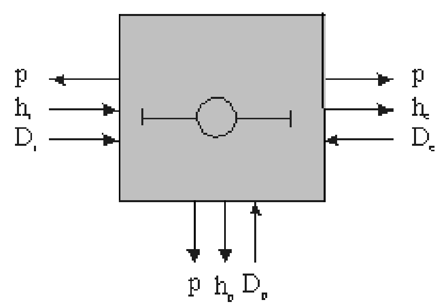


Fig. 6 Block diagram of the turbine moisture extraction model

For the model parametrization the following operation data are necessary: p – inlet port initial pressure; h_i – initial enthalpy at inlet; D_i –initial steam flow at inlet; D_p – inlet port initial steam flow; *sep* – validation indicator for the internal moisture separation. With this parameters the exit steam flow is calculated:

$$D_e = D_i - D_p \tag{15}$$

If *sep* indicates that the inlet port has no moisture separation then the enthalpy h_e and h_p are calculated with relation (10). Else the two enthalpies are calculated with relations (11 ÷ 14).

Turbine governor valve model

The theory developed in [1] was used for the turbine governor valves model.

Fig. 7 Turbine governor valves model

The turbine governor valves model considers the following phenomena: steam flow variation through valves D_i and steam pressure variation at outlet valves, p_e. The equation of mass conservation was written in the same way as in the MMS model [1]:

$$\frac{dp_e}{dt} = \frac{D_i - D_e}{k_p} \tag{16}$$

Neglecting the energy storage in valves, the energy conservation equation is:

$$h_e = h_i \tag{17}$$

For flow determination through valves the following equation is used [1]:

$$D_i = Y_v N_v k_D \left[1 - 0.725 \frac{p_i - p_e}{p_i}\right] \sqrt{\rho_i \left(p_i - p_e\right)} \tag{18}$$

where: D_i –steam flow at inlet valves; D_e –steam flow at outlet valves; h_i – steam enthalpy at inlet valves; h_e - steam enthalpy at outlet valves; p_i – steam pressure at inlet valves; p_e – steam pressure at outlet valves, N_v - the number of valves; Y_v – turbine valve position; k_D – admission valves conductance; k_p – pressure constant; ρ_i – steam density at inlet valves.

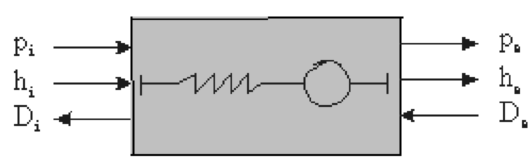


Fig. 8 Turbine governor valves blok diagram

Moisture steam separator reheater model

The moisture steam separator reheater (MSSR) integrates in the same cylindrical sheath the separator and the reheater. Here the steam moisture is removed through an inertial effect. The reheater consists of a U bundle pipes in which the saturated steam is overheated from the main steam. The model is divides in four areas: preseparation zone which include the drainer; postseparation area; volume outside of the pipe (with superheated steam); volume inside the pipe (with main steam). The first and second separator zones and the superheater intertubular space volumes are considerate to be storage volumes, while the tubular space volume is considered to be a resistive element.

Moisture separation reheater model was created considering the following assumptions:

- the two-phase fluids are in a thermodynamic equilibrium;
- the main steam is condensing;
- moisture separation efficiency was considerate as constant throw MSSR.

Moisture steam separation reheater model simulates the following phenomena: level modification in drainer; heat transfer in superheater; cold steam quality variation given by moisture removal.

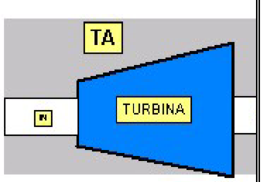
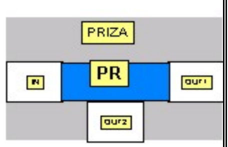
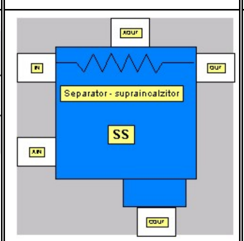
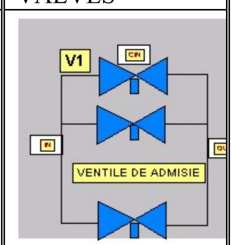
The moisture steam separation reheater mathematical model use the conservation equations to determinate the density and enthalpy variation. Mass and energy conservations equations allow evaluation of outlet superheater pressure, and the energy conservation equations permits determination of outlet superheater enthalpy.

Results

The mathematic model was implemented in MMS code with *CompGen TM Release 6.0 Level 1.5*. tools, as shown in Table 3.

Table 3

Turbine modules

STAGE GROUP	EXTRACTION	SEPARATOR	TURBINE GOVERNOR VALVES
			

Each module is interconnected with other modules (among those created or already in the MMS library) and is autoparametrized introducing initial data (constructive and functional data).

For the CNE Cernavoda turbine, the four conceived modules were connected with other MMS modules for the modeling of the entire turbine, such as: nine *„STAGE GROUP”* modules, seven *„EXTRACTIONS”* modules, one *„SEPARATOR”* module, one *„TURBINE GOVERNOR VALVES”* module, and other modules from MMS library. In Fig. 9 the modeling diagram is presented. The obtained results for the steady state show that the modules are stable and the parametrization was made correctly.

Using this diagram, steady state and transitory regime can be simulated. As an example a transient regime is presented. The transient regime consists in a ramp power decrease from 100% to 80% full power followed by a power ramp increase to full power (Fig. 10).

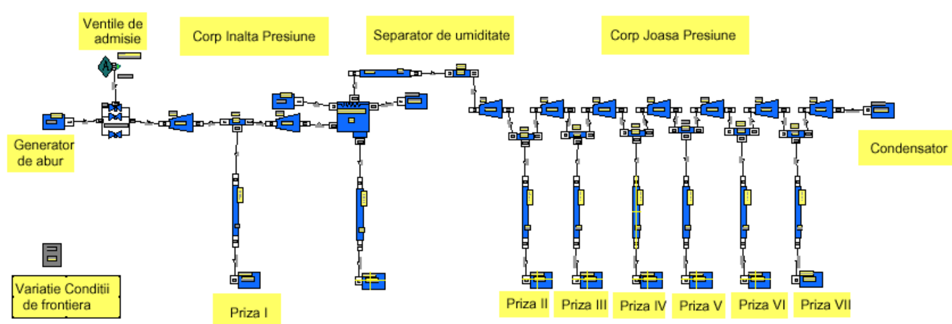


Fig. 9 MMS turbine module illustration

The obtained results for this transient (with variation of the valve position and variation of inlet port limit pressure) show that the new modules have an evolution without fluctuations, to a new steady state. For the three power levels of 100%, 80% and 60% full power, the values of a significant parameters obtained with MMS were compared with those given by General Electric. The relative error is less than 5%. That means that the created modules can be used not only for the qualitative analysis, but also for the exact calculation of partial load.

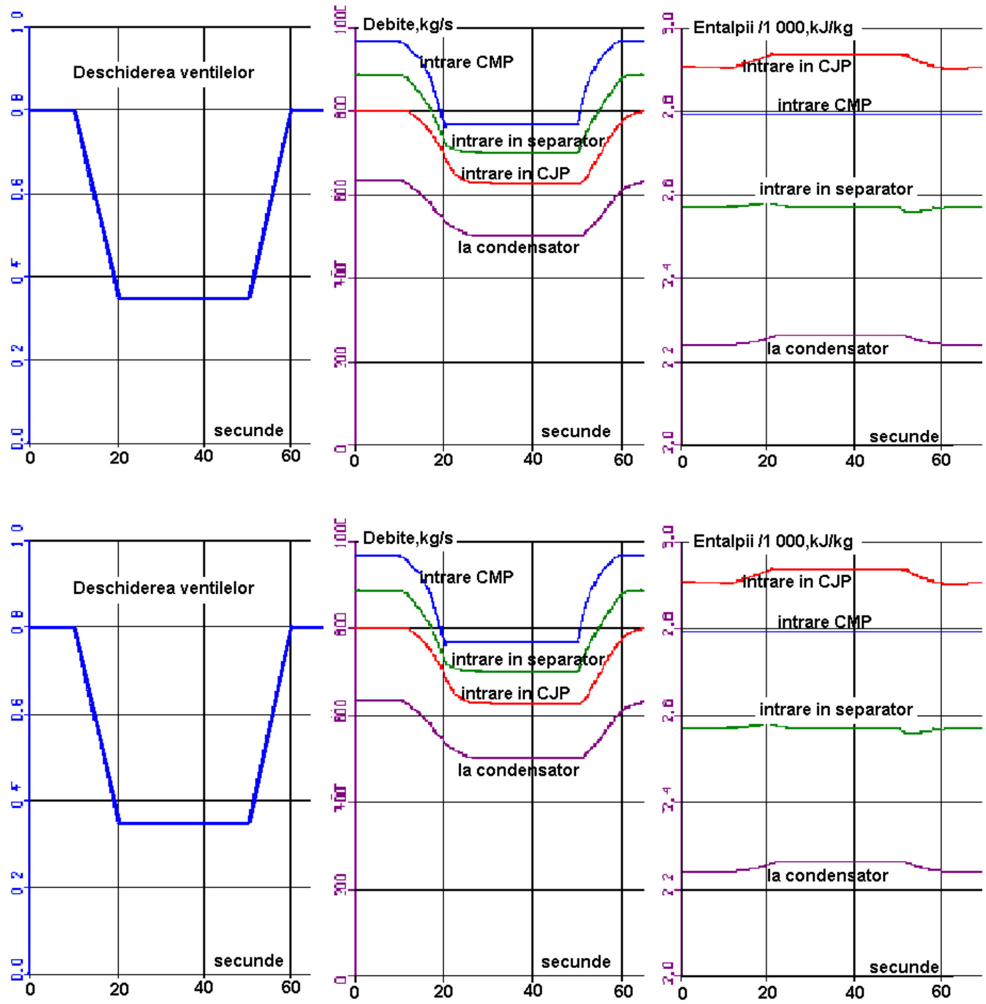


Fig. 10. Variation of flows and enthalpies in a turbine power change state

Conclusion

The paper present a work in developing mathematical models for the components of the nuclear power plant with application to the Cernavoda NPP focusing to the steam turbine model development. A new mathematical model for the turbine stages and steam and/or humidity extractions at turbine casings was proposed. The mathematical models have been implemented in the MMS code using the CompGen tools. The results obtained for the transient represent a steam turbine power reduction is presented. The results obtained for this transient show that the new modules give a relative error is less than 5% for the three power levels of 100%, 80% and 60% full power compared with those given by General Electric. Thereafter, the developed modules can be used not only for the qualitative analysis, but also for the exact calculation of partial load.

REFERENCES

1. Modular Modeling System – State of the art in computer simulation of nuclear and fossil power plants – Theory, B&W Nuclear Technologies,1995
2. Modular Modeling System, Release 6.0 – BASICS, ©nHance Technologies, 2002
3. *Dinculescu, C., Danila, N., Prisecaru Ilie. Stan,N.* - Modelarea matematica a regimurilor termice tranzitorii în echipamentele centralelor nucleare electrice. În:Buletinul IPB, Tomul XIII nr.4, seria Electrotehnica, oct.dec., 1981.
4. *Danila N., Prisecau Ilie* - Modeling and simulation of the Heat Exchangers Operation in Dynamic Condition. Revue Roumaine des scientes techniques. Serie: Electrotechnique et energetique, nr.3, jullet - spt. 1989, Editura Academiei.
5. *F.G. Baily and others* – Predicting the performance of 1800 rpm large steam turbine-generators operating with light water cooled reactors, Steam turbine-generators division, GET – 6020,New York, 1973
6. *N. Danilă, Ilie. Prisecaru*, ş.a. Centrale nucleare electrice. Editura Didactica şi Pedagogica Bucureşti, 1980
7. Institutul Politehnic Bucureşti – Analiza regimurilor operaţionale ale părţii clasice a CNE Cernavodă, Contract de cercetare 6-4-16/10.05.1984
8. *Ilie Prisecaru*, Modelarea şi simularea proceselor dinamice din CNE, Curs universitar,UPB, 2004
9. UPB, Facultatea Energetica – Adaptarea şi /sau realizarea de module MMS pentru studierea regimurilor dinamice operaţionale pentru componente şi sisteme din cadrul CNE Cernavoda , Contract 14-2/2002-2004