Operation of hydro and thermal power plants in a complex power system

František Janíček, Anton Causevski, Dragan Minovski

Abstract
This paper presents the methodology for power generation demand/supply planning in a complex electric power system. The model objective is to find an optimal power supply that meets the electricity demand, and takes into account the operating conditions of power generating stations. The model and the developed computer program are applied to the Macedonian Power System to provide a realistic application example. The results show the behavior of hydro and thermal power plants in dependence on their technical characteristics and electricity demand.

Keywords: hydrology, Hydro Power Plant (HPP), Thermal Power Plant (TPP), modeling, electricity, generation.

1. MODEL FOR OPERATION OF POWER PLANTS

This paper outlines the improvements of the original mathematical model [1, 3, 4]. The total interval of time under consideration (lasting T) is subdivided into several elementary subintervals (lasting dt). The optimization procedure can be applied to different time intervals in each specific application. The calculations can be performed on time intervals wider than 24 hours, such as: on monthly, weekly and daily basis. Also, the calculations can be performed with time subintervals down to 1 hour, or less, depending on the available data. The model includes energy balancing, the power balancing in each time interval, as well as water balancing for the hydro power plants and energy balancing for thermal power plants. Suppose the Generation System consists of K –Thermal Power Plants and M- Hydro Power Plants and N, V are the connected systems or import. The objective function is:

$$\begin{aligned}&\sum_{k=1}^{K}\sum_{t=1}^{T}\left(K_k(P_{k,t})+B_k\cdot(P_{k,t}-\overline{P_{k,Tkp}})^2\right)\cdot\Delta t+\\&\sum_{n=1}^{N}\sum_{t=1}^{T}\left(K_n(P_{n,t})+A_n\cdot(P_{n,t}-\overline{P_{n,Tnp}})^2\right)\cdot\Delta t+\\&\sum_{v=1}^{V}\sum_{t=1}^{T}\left(K_v(P_{v,t})+C_v\cdot(P_{v,t}-\overline{P_{v,Tvp}})^2\right)\cdot\Delta t\rightarrow\min\end{aligned} \quad (1)$$

where: $K_i(P_{i.t})=P_{i,t}\cdot\left(A+B\cdot P_{i,t}+C\cdot P_{i,t}{}^2\right)$ i=k,n,v

The model also includes the following conditions:

- power balance for total load:

$$\sum_{k=1}^{K}P_{k,t}+\sum_{n=1}^{N}P_{n,t}+\sum_{m=1}^{M}P_{m,t}=P_{l,t} \quad (2)$$

- power balance for peak load:

$$\sum_{m=1}^{M}P_{m,t}+\sum_{v=1}^{V}P_{v,t}=k_v\cdot P_{w,t} \quad (3)$$

- energy balance for each TPP:

$$\sum_{t=1}^{T}P_{k,t}\cdot\Delta t=W_k \quad (4)$$

The model offers a high degree of flexibility, and can be applied in different situations because the optimization period can be conveniently subdivided into as small subintervals as desired. In order to achieve this flexibility, model improvements were introduced with respect to the terms covering the hydro power plants and the thermal power plants energy change representation.
The additional improved conditions for hydro power plants are the following:

a) HPP's generated electricity managing expressed as:

$$S_m\cdot\sum_{t=1}^{T}\left(\frac{W^{out}_{m,Tmw}-W^{in}_{m,Tmw}}{\sum\limits_{\Delta t\in Tmw}\Delta t}\right)^2\cdot\Delta t \quad (5)$$

where: $W^{in}_{m,tmw}=\sum\limits_{\Delta t\in Tmw}P^{in}_{m,t}\cdot\Delta t$ is the inflow energy resulting from water inflow in a reservoir and $W^{out}_{m,Tmw}=\sum\limits_{\Delta t\in Tmw}P_{m,t}\cdot\Delta t$ is the generated energy resulting from water outflow. This is particularly important for regulating the discharge as well as water storage level in the reservoir.

b) HPP's water spending control expressed as:

$$\sum_{Tmj=1}^{Tmv}\mu_{mj}\cdot\left(V^{out}_{m,Tmj}-V^{in}_{m,Tmj}\right) \quad (6)$$

where: $V^{in}_{m,Tmj}=\sum\limits_{\Delta t\in Tmj}Q^{in}_{m,t}\cdot\Delta t$ is the inflow water volume in the HPP "m" reservoir during the time period Tmj expressed using the inflow volumetric flow rate $Q^{in}_{m,t}$ and

$V^{out}_{m,Tmj} = \sum_{\Delta t \in Tmj} Q^{out}_{m,t}\left(\frac{P_{m,t}}{H_{m,t}}\right)\Delta t$ is the outflow water volume in the HPP's "m" reservoir during the time period Tmj expressed using the discharge flow rate $Q^{out}_{m,t}$. This condition is for the control of water outflow (HPP power generation control) during the time period Tmj.

The additional improved conditions (5) and (6) are particularly important for the reservoirs with small water inventories compared to the water inflow during the analyzed period. This model feature helps to provide an appropriate treatment that is consistent with the reservoir water inventories (some reservoirs can be treated on yearly basis, whereas other reservoirs on seasonal, monthly, weekly, or daily basis).

2. APPLICATION ON MACEDONIAN POWER SYSTEM

The Macedonian Power System consists of hydro and thermal power plants. Each HPP (total 9) is represented by technical characteristics for hydraulic equipment: water reservoir, tunnel, penstock, turbine, water and power installed capacity. Another necessary information is the data for water natural inflows into water reservoirs. Table 1 gives the basic data for the existing hydro power plants in Macedonia (all are in operation except Sv. Petka with proposed installed capacity of 100 m3/s and reconstructed HPP Matka with installed capacity of 40 m3/s.

Dependence on hydraulic characteristics of the HPP, as well as their generating role in Macedonian electric system, the hydro power plants in Macedonia are divided into two groups:

1. Storage HPPs:
    1. derivation with large net height according to water discharge: *Vrutok, Globocica*
    2. with turbine house near dams, where water discharge has significant influence on water level variation
       large size: *Kozjak, Tikves, Spilje*
       small size *Sv. Petka, Matka*
2. run of river HPPs: *Vrben, Raven*

The two hydropower cascades in optimization process are also taken into account:

- cascade of the Treska river consists of: HPP Kozjak , HPP Sv. Petka, HPP Matka
- cascade of the river Crn Drim consists of: HPP Globocica, HPP Spilje

The basic data of the hydro power plants in Macedonia are given in Tab.1.

	HPP	No. Of units	Q_{ins} (m^3/s)	H_{gros} (m)	Net power (MW)	Rese-rvoir ($10^6 m^3$)
1	Globocica	2	54	110	42	15
2	Spilje	3	108	95	84	212
3	Tikves	4	144	100	116	272
4	Vrben	2	8	196	12,8	0
5	Vrutok	4	32	574	172	277
6	Raven	3	32	74	21,6	0
7	Kozjak	2	100	102	80	260
8	Sv.Petka	2	100	40	36,4	1
9	Matka 1	2	40	27	8,2	1
Total		24			573	1038

Tab.1 Basic data for the hydro power plants in Macedonia

The thermal power plants in Macedonia are operating with maximum capacity according to the coal supplypossibilities. The basic data for TPPs are given in Tab.2.

TPP	Fuel	No. units	Pmin (MW)	Pmax (MW)	W_{yearly} (GWh)	Planed outgages (days)
Bitola	Lignite	3	140	209	1400	45
Oslomej	Lignite	1	80	109	650	60
Negotino	Oil	1	140	198	1200	45

Tab.2 Basic data for the thermal power plants in Macedonia

The electricity demand is supposed to be 8000 GWh in a year with hourly distribution (8760 time subintervals). The analyses are given for the average hydrology where the water inflows are taken for 74% of hydrology according to statistical data.

3. OPERATION OF MACEDONIAN POWER PLANTS IN MACEDONIAN POWER SYSTEM

In order to have realistic picture for operating modes of hydro power plants, the time intervals of one hour in ayear for the demand represent the seasonal as well as daily variations of the electricity needs. Based on statistical data for water inflows, and technical parameters for the reservoirs as well as for turbines and other hydraulic equipment in the HPP, the software tool gives the details about operating of each hydro power plant for each interval as the following: water discharge, water level in the reservoir, number of units engaged, and power output. The operating engagement of all thermal (lignite + oil) and hydro power plants with total electricity generation of 8000 GWh in a year is given in Fig.1.

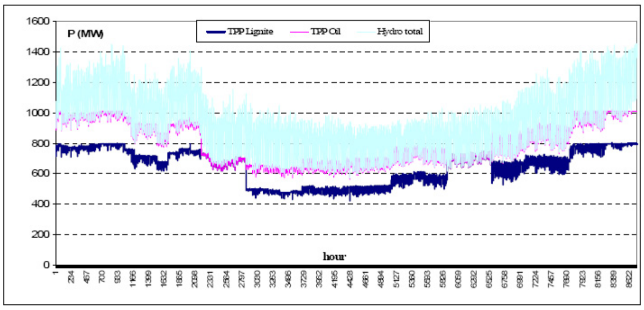

Fig.1 TPPs and HPPs hourly operation

The operating engagement of all hydro power plants with total electricity generation of 1473 GWh in a year is given in Fig.2.

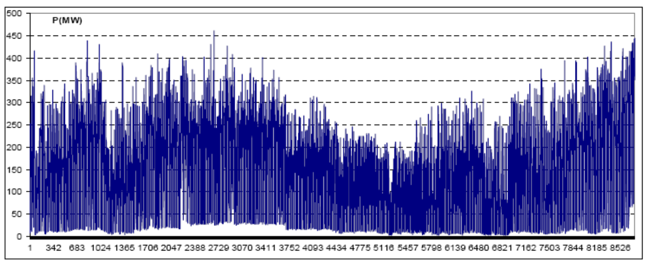

Fig.2 HPPs hourly operation

In order to have a better picture of the operation of thermal and hydro power plants, Fig.3 and Fig.4 state the electrical generation for all power plants in the last 52nd week (winter) and 13th week (summer) of the year. It is noticed that HPP Vrutok as a derivate HPP are works a short time in a day covering the high peaks, and the Kozjak, Tikves, Spilje and Globocica are in between Vrutok and run of river HPPs. The thermal power plants cover the base load.

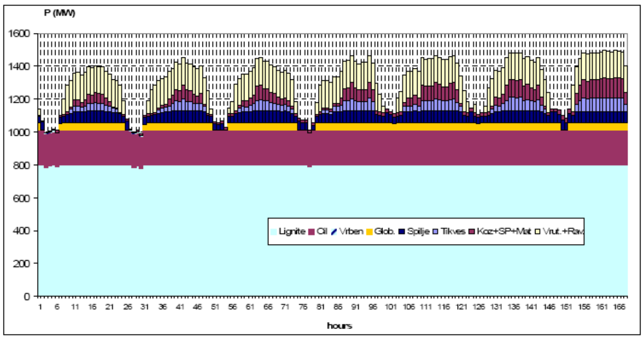

Fig.3 TPPs and HPPs hourly operation for 52nd week (winter)of the year

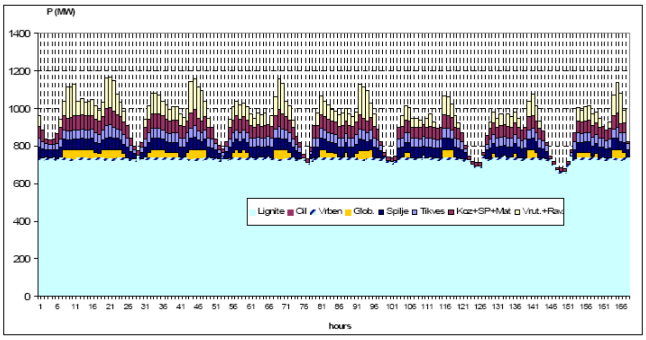

Fig.4 TPPs and HPPs hourly operation for 13th week (summer) of the year

Fig.5. shows the hourly operation of hydro power plants only for 13th week according to Fig.4.

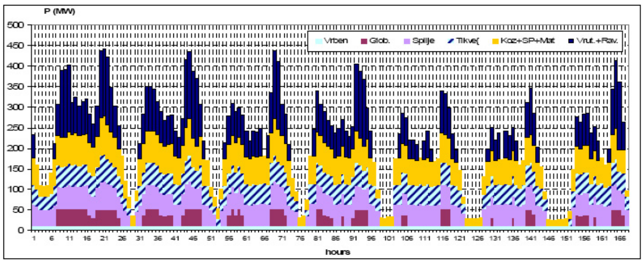

Fig.5 HPPs hourly operation for 13th week of the year

4. WATER DISCHARGE OF THE HPPs

The operation of HPPs can be illustrated by water discharge in each time interval. The white line is the water inflow for HPP Vrutok in Fig.6. The operation of the HPP Vrutok is mainly driven by the variable consumption. Taking into account the big water accumulation and relatively small water discharge, the HPP Vrutok has possibilities for yearly control of water inflows.

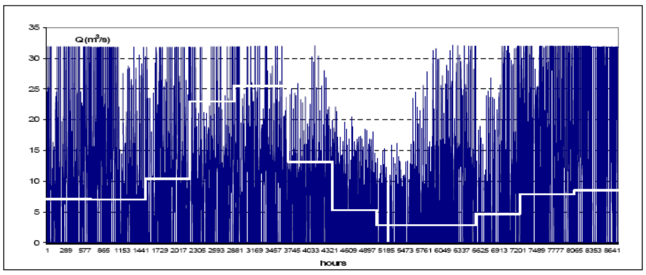

Fig.6 Natural water inflow and discharge for HPP Vrutok

The special operations of the cascade on Treska River (HPP Kozjak, Sv Petka and Matka) are given in Fig.7, 8 and Fig.9, respectively. HPP Kozjak has large water installed capacity according to water inflow, and its operation only a few hours a day. The gross head variation has a significant influence on electricity generation, so large discharging of the reservoir is not allowed.

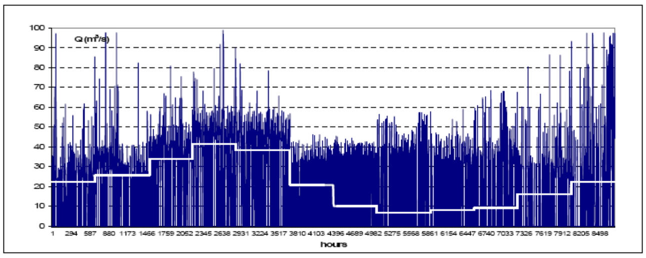

Fig.7 Natural water inflow and discharge for HPP Kozjak

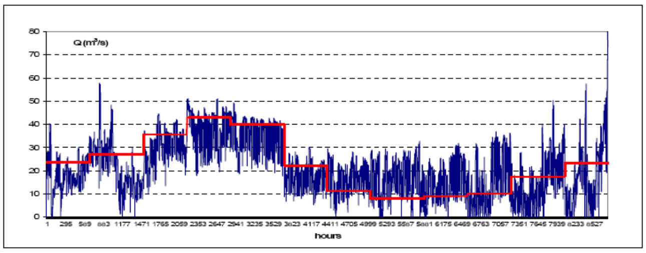

Fig.8 Natural water inflow and discharge for HPP Sv Petka

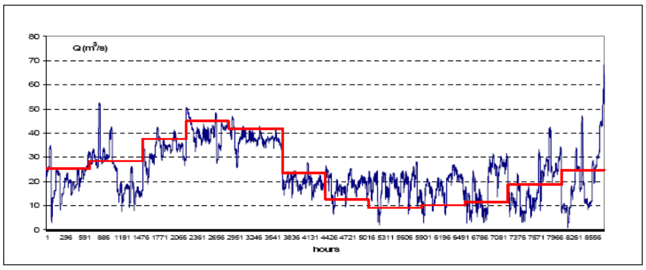

Fig.9 Natural water inflow and discharge for HPP Matka

HPP Tikves has very similar hydro technical parameters with HPP Kozjak and similar operating mode. HPP Globocica with Ohrid Lake as an accumulation has a role of derivation hydro power plant with large water inflow, which results in full capacity operation of 54 m3/s during the whole year (Fig.10). It means that the installed capacity can be extended for an additional unit.

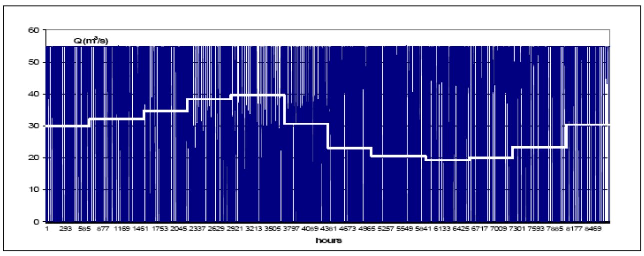

Fig.10 Natural water inflow and discharge for HPP Globocica

HPP Spilje has double factor of installed capacity according to average inflow, and an additional unit will significantly improve the operation and reduce the spillways in wet years.

5. OPERATING LEVEL OF THE WATER RESERVOIRS

The levels of the water reservoirs follow the operation of the hydro power plants while taking into account water inflow through the year. Fig. 11 gives the annual changing of the water level in gross head for HPP Vrutok which is about 8 meters. The same for HPP Kozjak is given in Fig.12.

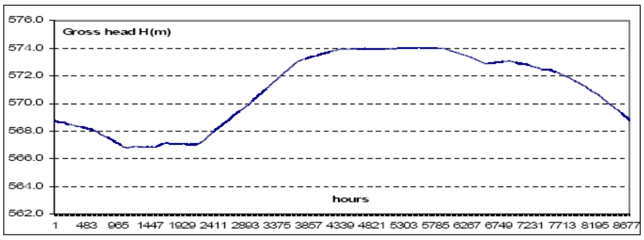

Fig.11 Annual gross head for HPP Vrutok

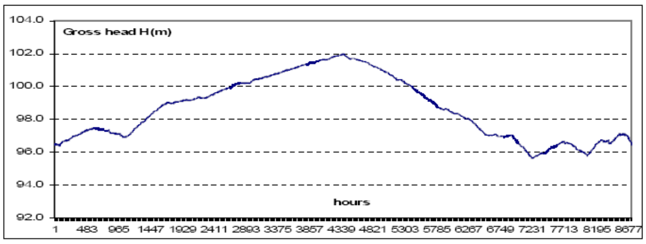

Fig.12 Annual gross head for HPP Kozjak

Particulary interesting is the changing of water levels in the accumulations of HPP Sv Petka and HPP Matka with small water reservoirs of about 1 mill m3, according to water discharging from Kozjak. Fig. 13 gives the annual gross head of Sv Petka which has the variation from 37 to 40m every day.

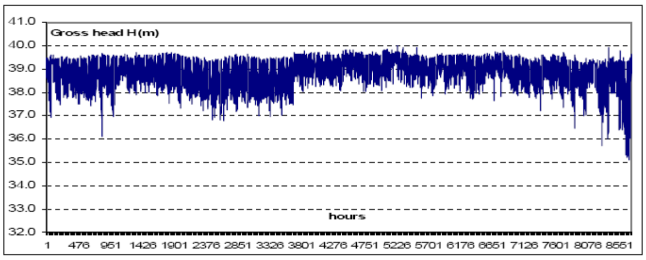

Fig.13 Annual gross head for HPP Sv Petka

The next Fig.14 and Fig.15 give the daily variation of water levels in the reservoirs for HPP Sv Petka and HPP Matka, respectively. The Fig.16 represents the cascade of the river Treska.

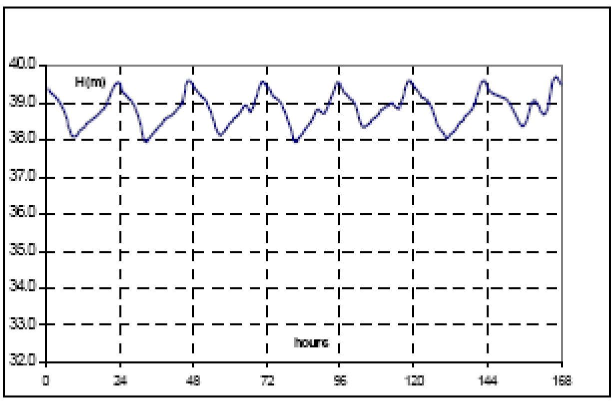

Fig.14 Level of the reservoir Sv Petka

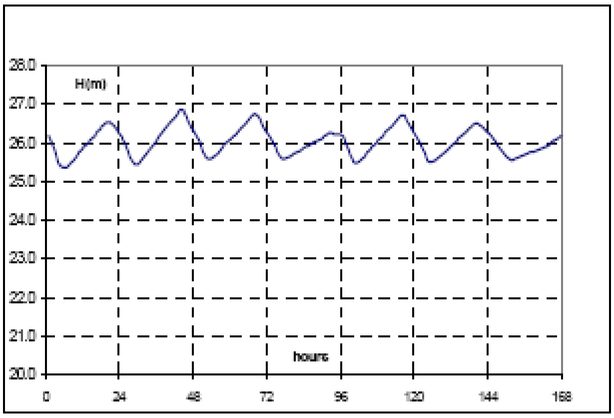

Fig.15 Level of the reservoir Matka

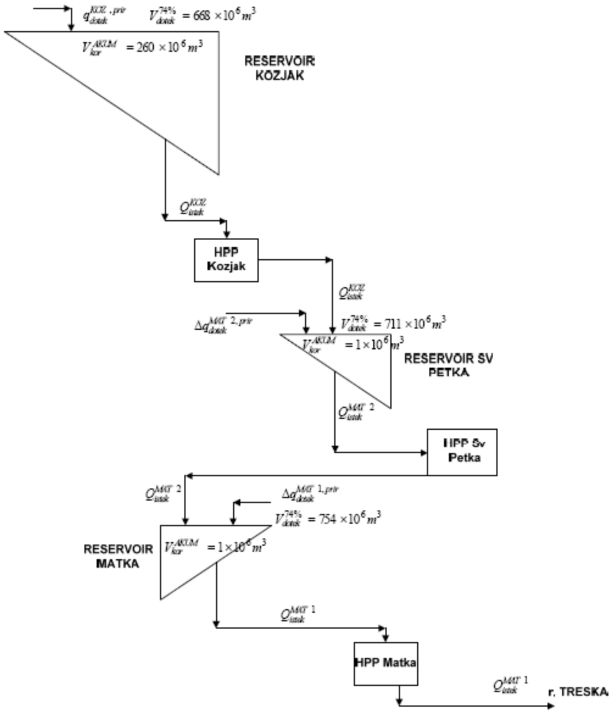

Fig.16 Cascade of the river Treska

CONCLUSIONS

The model for hourly operating mode in a year for electricity generation in a complex power system gives the real overall for each hydro power plant. In the test of Macedonian electric generation system, the hydro capacities are especially treated in order to find the optimal management of available water resources for electricity generation. HPP Vrutok and Globocica have relatively large reservoir capabilities (can save water during several years periods). The other HPPs, Kozjak, Tikves and Spilje, can save the water for less than a year, but on the other hand, the variation of the water level over 10 (m) will lead to significant energy losses. The model capabilities can be used to ensure an optimized energy generation in a power generation system, with an adequate energy supply that meets the projected energy demand for each time interval. The following points must be considered with the presented model, aimed at improving the operation of the power generation system:

- Defining power plant operation to meet the electricity demand in a given time interval;

- Managing the water resources for energy purposes;
- Influence of different hydrology in electricity generation for HPP;
- Influence of disturbance of hourly electric demand for operation of HPP;
- Determining the reservoir status of the existing storage HPP (water storage level during the period);
- Defining the operation of existing HPP (number of units, output power, water discharge, water reservoir level, water for irrigation, etc);
- Reducing the spillways in wet hydrology;
- Identification for enlarging the installed power for HPP with new turbine units or with enlarging the water capacity of existing turbine units;
- Special analysis for the hydraulic cascade of hydro power plants in order to find optimal operation according to water capacities and installed power.

Acknowledgement

This project was supported by the agency VEGA MS SR and SAV under Grant No. 1/3092/06, and Slovak Research and Development Agency under the contract APVV - 20-023505.

References

[1] BOSEVSKI, T., CAUSEVSKI, A.: "An Improved Method for Electricity Production Planning in a Complex Power System", Conference and Exhibition on Modeling, Testing &Monitoring for Hydro Power plants - II Conf.papers, pp.677-686, July 8-11 1996, Lausanne.

[2] C-a. LI, E.HSU. A.J. SVOBODA, C. I. TSENG, R.B. JOHNSON, "Hydro Unit Commitment in Hydro-thermal Optimization", *IEEE Transaction on Power Systems, Vol.12*, No.2, May 1997.

[3] CAUSEVSKI, A. "Analytical Numerical Improvements of the Models for Yearly Generation Planning in a Complex Power System," *the doctorial dissertation,* Faculty of Electrical Eng. Skopje, 2001.

[4] CAUSEVSKI, A., BOSEVSKI, T.: Improved model for electricity generation planning in the small economic autonomous power system, ETRAN 2003, Herceg Novi, 8-13 June 2003, Proceedings, Book I, pp. 341-343.

[5] Janíček, F., Gaduš, J., Smitková, M.: Renewable sources. Technologies for sustainable future. Bratislava : FEI STU, 2007. ISBN 978-80-969777-0-3.

[6] Pípa, M., Kubica, J.: Laboratory of renewable energy sources at FEI STU in Bratislava. In: EE journal of electrical and power engineering. - ISSN 1335-2547. - Vol. 14, num. 3 (2008), pp. 37.

[7] Janíček, F., Kubica, J.: Utilization of biogas in combined generation of electrical energy and heat in Slovakia. In: Electric Power Engineering 2007 : International Scientific Conference. Kouty nad Desnou, Czech Republic, 12.-14.6.2007. - Ostrava : Vysoká škola báňská - Technická

František Janíček

Slovak University of Technology in Bratislava (STU)
Faculty of Electrical Engineering and Information Technology
Department of Electrical Power Engineering
Ilkovičova 3,
812 19 Bratislava, Slovak Republic
frantisek.janicek@satuba.sk

Anton Causevski

Ss. Cyril and Methodius University in Skopje
Faculty of Electrical Engineering & IT – Skopje
Department on Power Plants & Power Systems
Karpos 2, PO Box 574
1000 Skopje, Republic of Maceodnia
caus@feit.ukim.edu.mk

Dragan Minovski

Slovak University of Technology in Bratislava (STU)
Faculty of Electrical Engineering and Information Technology
Department of Electrical Power Engineering
Ilkovičova 3,
812 19 Bratislava, Slovak Republic
dragan.minovski@stuba.sk