

# SIMULATION OF POWER FLOWS IN CROATIAN POWER SYSTEM

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## Abstract

This paper presents a practical and valid computer model of the Croatian electric power system using PowerWorld Simulator 11.0. The complete Croatian electric power system is plotted in the PowerWorld single line diagram. Required parameters for transmission lines, transformers, generators and loads are entered in the computer model. All input data are obtained from the Croatian electric company HEP. The power system is divided into five control areas: control area 1 (Croatia), control area 2 (Hungary), control area 3 (Slovenia), control area 4 (Bosnia and Herzegovina) and control area 5 (Serbia). In this way, the created computer model is used to simulate power flows in the Croatian electric power system for 2005.

Two sample cases are simulated. The first is the single solution of power flows when electric system is at its peak load (March 2 2005 in 8:00 PM). The second case is the time step simulation of power flows for every hour in 2005 year. Simulation results are presented as charts for all relevant elements of the Croatian electric power system. In order to evaluate credibility of the electric power system model, the computer model is compared with real measured values for energy losses in the model and energy losses that are measured in the real system. Consumed electric energy, peak load, losses that are obtained from the simulation are comparable with those from the official HEP web pages. The Croatian electric power system created in this paper can be used for further research such as fault analysis, energy interchange, power system planning etc.

**Keywords:** Computer model, power system, Time step simulation, power flows

## Presenting Author's biography

**Krešimir Fekete** ([kfekete@etfos.hr](mailto:kfekete@etfos.hr)) was born on August 28, 1983. in Osijek. He obtained his diploma degree in 2006. in field of Electrical Power Engineering from the Faculty of Electrical Engineering, J.J. Strossmayer University in Osijek, Croatia. His graduation thesis was "Simulation of power flows in Croatian power system using PowerWorld 11.0 software". Currently he works in the Power System Department within the Faculty of Electrical Engineering, University in Osijek.



## 1 Introduction

Nowadays, an electrical power system is one of the fundamental links of the modern civilization since the entire technical development is based upon quality supply of the electrical energy. Today's life is inconceivable without electrical energy used for heating and cooling, lighting, industry etc. But it is necessary to generate electrical energy (to be precise convert one form of energy to electrical), transmit it from producer to large consumers (towns, villages, industry etc.) and in the end distribute it to the tariff consumers. This means that all components of the system must perfectly function in order to guarantee a constant secure and reliable supply.

This paper describes the simulation of power flows in the Croatian Power System using PowerWorld Simulator 11.0. The main task of this paper is to plot the whole Croatian transmission network (for voltage levels 400/220/110 kV) in the PowerWorld single line diagram. The next step is to enter all necessary parameters for every element of the system. In order to obtain the simulation, it is necessary to enter load duration curve for every consumer for each hour during the year 2005. And at the end, the simulation results are shown in the form of tables and diagrams.

## 2 Mathematical model of power flows

PowerWorld is used for the Newton-Raphson power flow method, including the modeling of power restoration switches, load tap changer (LTC) transformers to alleviate the overloading of transmission lines and transformers, generation rescheduling and load shading. The total (complex) neto power entering the network at bus  $i$  is:

$$S_i = P_i + jQ_i \quad (1)$$

where  $P_i$  is the real power and  $Q_i$  the reactive power leaving bus  $i$ . Both of these powers are the differences of the respective powers generated ( $P_G$ ,  $Q_G$ ) the load ( $P_L$ ,  $Q_L$ ) at bus  $i$ , i.e.  $P_i = P_{Gi} - P_{Li}$  and  $Q_i = Q_{Gi} - Q_{Li}$ , where  $G$  is the subscript for the generated powers and  $L$  for the loads. Complex power is calculated by the following equation:

$$P_i - jQ_i = \sum_{k \neq i} \left[ j \bar{V}_i^* \bar{V}_k \frac{B_{ik}}{2} + \bar{V}_i^* \bar{V}_i \bar{Y}_{ik} - \bar{V}_i^* \bar{V}_k \bar{Y}_{ik} \right] \quad (2)$$

The load flow equations are obtained from this by separating the real and imaginary parts. Substituting

$$\bar{V}_i^* = V_i e^{-j\delta_i},$$

$$\bar{V}_k^* = V_k e^{-j\delta_k},$$

$$\text{and } \bar{Y}_{ik}^* = Y_{ik} e^{-j(\pi/2 - \alpha_{ik})}$$

where  $V_i$ ,  $V_k$  and  $Y_k$  are the magnitudes of the corresponding complex quantities,  $\delta_i$  and  $\delta_k$  the angles of corresponding voltages, and  $\alpha_{ik} = \arctan(R_{ik}/X_{ik})$ , with  $R_{ik}$  and  $X_{ik}$  being the resistance and the reactance of line  $ik$  respectively, the real and imaginary parts become respectively:

$$\begin{aligned} P_i &= \sum_{k \neq i} \left[ V_i^2 Y_{ik} \sin \alpha_{ik} - V_i V_k Y_{ik} \sin(\delta_k - \delta_i + \alpha_{ik}) \right] \\ Q_i &= \sum_{k \neq i} \left[ V_i^2 Y_{ik} \cos \alpha_{ik} - V_i V_k Y_{ik} \cos(\delta_k - \delta_i + \alpha_{ik}) - \frac{1}{2} V_i^2 B_{ik} \right] \end{aligned} \quad (3)$$

If the generated powers (except at the slack bus whose voltage is used as a reference) and the bus loads in the system are all known, the set of two load flow equations (3) for each bus, can be solved for the bus voltages  $V_i$  and angles  $\delta_i$ . From the solution, the power flows in line  $ik$  become:

$$\begin{aligned} P_{ik} &= V_i^2 Y_{ik} \sin \alpha_{ik} + V_i V_k Y_{ik} \sin(\delta_{ik} - \alpha_{ik}), \\ Q_{ik} &= V_i^2 Y_{ik} \cos \alpha_{ik} - V_i V_k Y_{ik} \cos(\delta_{ik} - \alpha_{ik}) - \frac{1}{2} V_i^2 B_{ik} \end{aligned} \quad (4)$$

where  $\delta_{ik} = \delta_i - \delta_k$ . It should be observed that equations (3) are non-linear in magnitudes and angles of the voltages. The numerical solution is based on an iterative Newton-Raphson method.

## 3 PowerWorld Simulator 11.0

PowerWorld Simulator 11.0 is a power system simulation package designed to be user friendly and highly interactive. The first thing to be noticed before using PowerWorld is that the program operates in two modes: Edit Mode and Run Mode. The Edit Mode is used to construct new simulation cases or to modify existing cases, while the Run Mode is used to perform the actual power system simulation.

The main advantage of PowerWorld is the user friendly visual display of the power system which is represented with a single line diagram. The purpose of the single line diagram is to display information about the power system graphically. The actual three-phase power system components are represented using a single line diagram. That is possible due to the fact that a three-phase power system is symmetrical i.e. voltage and current are balanced. When single line diagrams are used, it is possible to deal with unbalanced case. Every unbalanced three-phase power system can be decoupled in three single line systems: positive, negative and zero sequence. For this case the PowerWorld requires the positive, negative and zero sequence impedances for transformers, generators and lines. All three impedances for a generator are shown in Fig.1. Thus PowerWorld can simulate unbalanced

faults such as single line-to-ground fault, line-to-line fault, double line-to-ground fault etc.

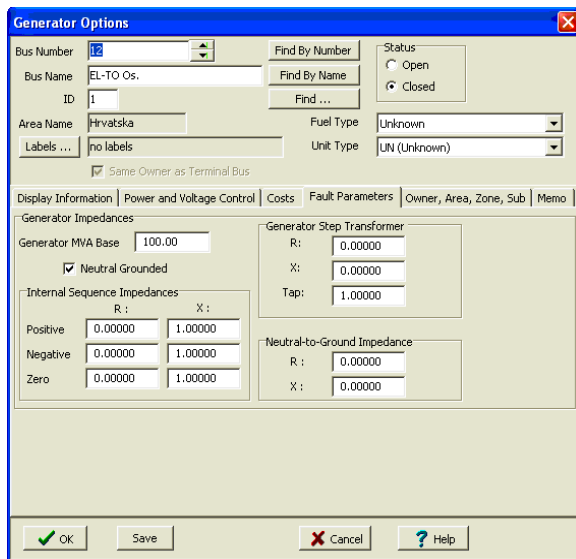


Fig. 1 Dialog box for generator impedances

Additionally, a key aspect of the simulator is the easy way which allows one to examine and modify many objects shown in the single line diagram. It is possible to change parameters and geometry of the transmission line during simulations (opening or closing lines, increase or decrease generator output power etc.). After the single line diagram is created in the Edit Mode, it is necessary to switch to the Run Mode and start the simulation. The simulation can be either a single solution of power flow or a time step simulation that simulates the power flow during the desired time. We can observe events in the power system and actively participate in power system control once the simulation is activated. Thus a better understanding of the power system operation is achieved.

### 3.1 Creating a single diagram

After the simulator is activated by the left mouse click which opens the menu FILE and the next left click on the NEW CASE opens a new, blank simulation case. When a new case is opened, the screen becomes white and all menus become available.

The single line diagram is created inserting its elements (buses, generators, transformers, lines, loads etc.) from the TOOLS palette. When the element is selected, a dialog box for input parameters appears on the screen. All element parameters of the power system are entered in per unit using the base power  $S_B = 100$  MVA. Equation (5) is used for lines:

$$\begin{aligned} R &= R_1 \cdot l \cdot \frac{S_B}{U_n^2} \\ X &= X_1 \cdot l \cdot \frac{S_B}{U_n^2} \end{aligned} \quad (5)$$

where:

- $R$  – resistance of line expressed per unit,
- $R_1$  – resistance of line in Ohms/length unit,
- $L$  – length of line in km,
- $S_B$  – base power in MVA,
- $U_n$  – rated line to line voltage in kV,
- $X$  – reactance of line per unit,
- $X_1$  – line reactance in Ohms/km.

Equation (6) is used to calculate the transformer impedance.

$$\begin{aligned} Z_T &= \frac{u_{k\%}}{100} \cdot \frac{S_B}{S_{nT}} \\ R_T &= P_{Cu} \cdot \frac{S_B}{S_{nT}^2} \\ X_T &= \sqrt{Z_T^2 - R_T^2} \end{aligned} \quad (6)$$

where:

- $z_T$  – winding impedance per unit,
- $u_{k\%}$  - short circuit voltage in percentage,
- $S_B$  – base power in MVA,
- $S_{nT}$  – rated power in MVA,
- $R_T$  – winding resistance per unit,
- $P_{Cu}$  – copper losses in MW,
- $x_T$  – winding reactance per unit.

### 3.2 Performing power flow simulation

When we switch to the Run Mode, PowerWorld automatically checks the case. If there are no errors in the case, the simulation can be activated. In this case, simulator will perform single solution of power flows i.e. it will calculate the solution for one moment depending on the input data. It is often useful to know how the power system behaves during a period of time when its parameters are changing (loads, generation, line status etc.). It is possible to execute PF/OPF/SCOPE (power flows / optimal power flows / security constrained power flows) for a number of time points in the Time Step Simulation module. Before the Time Step Simulation is activated, it is necessary to enter time points and all data linked with them. First, we open the Time Step Simulation dialog in the TOOLS palette. Subsequently, the beginning and the end of the simulation (its time duration) as well as the number of time points needs to be specified. Progress of the Time Step Simulation can be observed in the bottom of the screen, as shown in Fig 2.

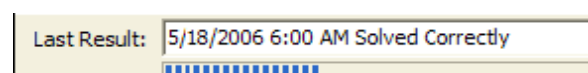


Fig. 2 Progress of the Time Step Simulation

The simulation results will be saved in the pop up menu Results in a tabular form. It is also possible to display the results as a chart using Plot Column(s) function.

#### 4 The Croatian power system

By its size, the Croatian power system is one of the smallest power systems in Europe. Due to its geographical position and location of generating plants, electricity is transported for most of the year from the south to the north and vice versa, and from the north toward the east. The Croatian power system is a member of the UCTE synchronous zone. Union for the Co-ordination of Transmission of Electricity (UCTE) is the association of transmission system operators in continental Europe. By reconnecting the UCTE synchronous zones 1 and 2, the Croatian power system has become a transit system. The Croatian power system is one control area controlled by HEP TSO (Croatian electric company - transmission system operator). Together with the Slovenian power system and the power system of Bosnia and Herzegovina it constitutes the control block SLO – HR – BIH within the UCTE grid. The total installed capacity of generating plants is 3745 MW, 2079 MW of which is in hydro power plants and 1666 MW is in thermal power plants. The basic data of the Croatian power system in 2004 and 2005 can be seen in Table 1. Results of the simulation will be compared to Table 1.

Tab. 1 Basic data of the Croatian power system

Maximum load	23.12.2004 at 18:00	2.3.2005 at 20:00		
Amount (MW)	2793	2900		
Minimum load	2.5.2004 at 6:00	22.5.2005 at 6:00		
Amount (MW)	1024	1044		
Electricity consumption	GWh		%	
	2004	2005	2004	2005
Total available energy	16095	16707	100	100
Transmission losses	587	560	3.7	3.4
Delivered to distribution	15328	15795	95.2	94.5

The transmission network is a part of the Croatian power system and comprises transformer substations, switchyards, overhead lines and underground cables. Electricity is transmitted through the network of 400, 220 and 100 kV voltage levels. Key data for Croatian transmission network are shown in Table 2.

Tab. 2 Basic data of the Croatian transmission network

Substation		
Voltage level	Number	MVA
400/x kV	5	4 100
220/110 kV	6	2 270
110/x kV	101	4 673
Total:	112	11 043
Lines		
Rated voltage	Total length (km)	
400 kV	1 158.9	
220 kV	1 233.5	
110 kV	4 782.2	
Total:	7 232.4	

#### 5 Power flows simulation results of the Croatian power system

The whole Croatian power system is plotted as the PowerWorld single line diagram. It means that all generation and transmission networks 400/220/110 kV are presented. The distribution network is substituted with consumers on the secondary winding of the transformer 110/x kV. All necessary busbar, line, generator, transformer and load parameters are entered. The single line diagram is divided into 5 control areas: Croatia (control area 1), Hungary (control area 2), Slovenia (control area 3), BiH (control area 4) and Serbia (control area 5). A small part of the single line diagram is shown in Fig. 3.

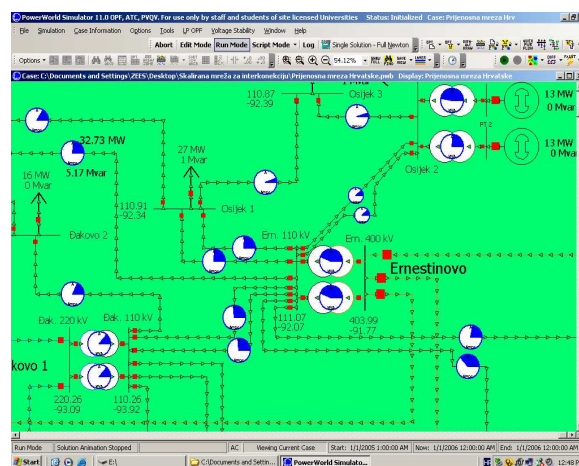


Fig. 3 Transformer station 400/110 kV Ernestinovo displayed in single line diagram

Simulation of power flows is accomplished under the following procedure:

Single solution of power flows when the system is at its peak load (peak load of the Croatian power system

is 2900 MW). PowerWorld performs a simulation for one time point only.

Time step simulation of power flows for the whole 2005. PowerWorld will perform power flow simulation for every hour in 2005 (8760 hours) and save the results in the .tsb file (time simulation binary).

### 5.1 Solution of power flows for peak load in 2005.

After the simulation is completed, it is possible to view all results in the drop down menu Case Information. Power flow results (power, voltage, voltage angle, losses etc.) for every power system component can be seen there. Fig. 4 shows the drop down menu Case Information/Case Summary for current case from which the main characteristics can be read:

266 buses;

81 generators;

135 loads;

371 lines and transformers;

2906.8 MW – system load;

3021.4 MW – system generation;

114.6 MW – system losses or percentage:

$$P_{g\%} = \frac{P_g}{P_G} \cdot 100\% = \frac{114.6}{3021.4} \cdot 100\% = 3.7\% \quad (7)$$

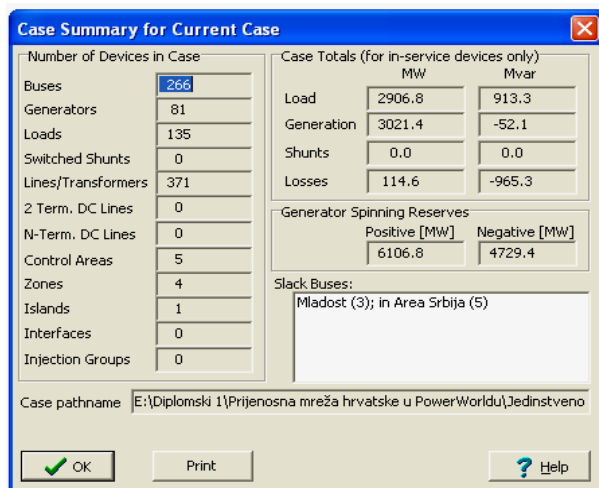


Fig. 4 Case Summary for the Current Case drop down menu

### 5.2 Time step simulation of power flows for the Croatian power system in 2005.

Before the time step simulation is executed, it is necessary to copy load data for every hour in 2005 (totally 8760 hours) from the Excel table to the PowerWorld Time Step Simulation dialog box.

Subsequently, it is possible to start a simulation. It runs about 4 hours on a computer of average configuration. PowerWorld will save the results as a table in the Time Step Simulation dialog box. It is also possible to display results as a chart and that option is visually much better. Simulation results of the most significant parts of the Croatian power system will be presented in this chapter.

#### 5.2.1 TS 400/110 kV Ernestinovo

Fig. 5 and Fig. 6 present the voltage change (voltage rate and voltage angle) during the year 2005 on the 400 kV bus in TS 400/110 kV Ernestinovo.

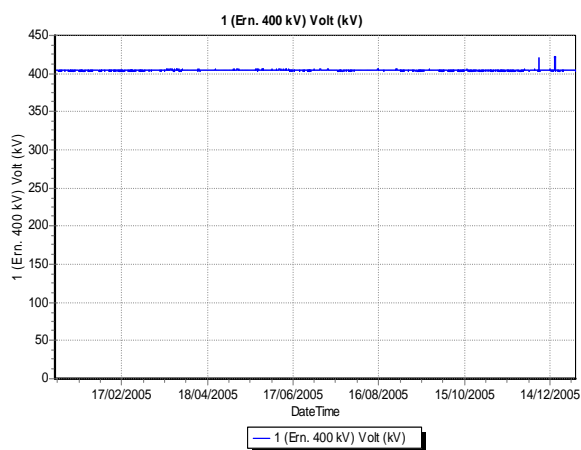


Fig. 5 Voltage during 2005. on the 400 kV bus Ernestinovo

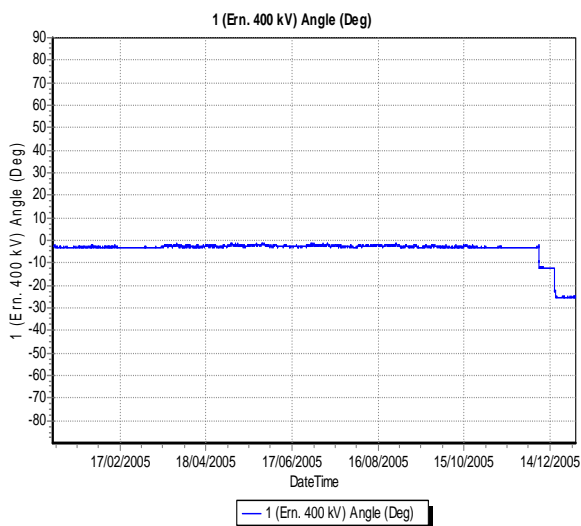


Fig. 6 Changes of the phase angle during 2005. on the 400 kV bus Ernestinovo

Power flow through the transformer 400/110 kV Ernestinovo is shown in Fig. 7. Values of MW are negative because the diagram shows energy flows from 110 kV side to 400 kV side whereas the actual energy is reverse.



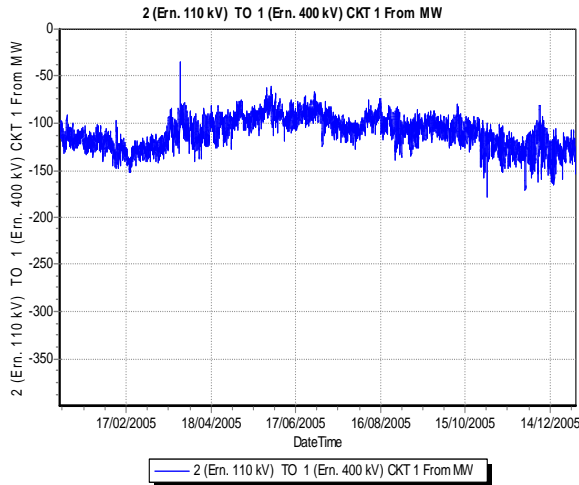


Fig. 7 Active power flow through the transformer 400/110 kV Ernestinovo during 2005.

**5.2.2 Power flows in control area Croatia**

Fig. 8 shows load MW during 2005 in the control area Croatia. The diagram has a specific curve form which represents the load duration with a maximum of 2900 MW 2.3.2005.

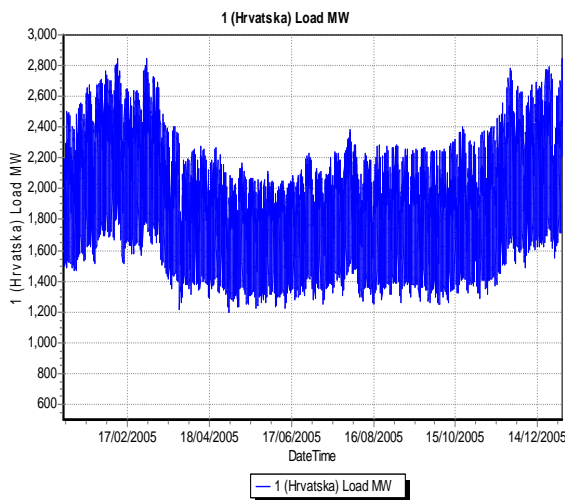


Fig. 8 Load MW in the control area Croatia during 2005.

The right-mouse click on the chosen column in the Time Step Simulation Dialog/Results and the left-mouse click on the Get Column(s) Metrics option open the Grid Metrics window. All values in the Grid Metrics window are expressed in MWh. The consumed electrical energy in the control area Croatia is 16 872 GWh, as shown in Fig. 9.

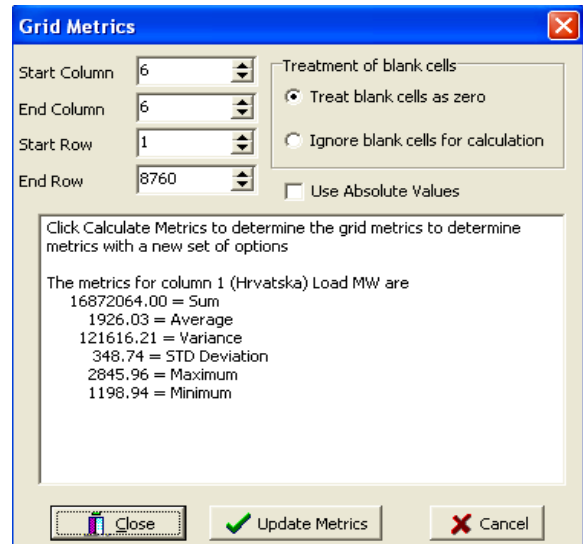


Fig. 9 Grid metrics Window

Fig. 10 shows losses in the control area Croatia during 2005.

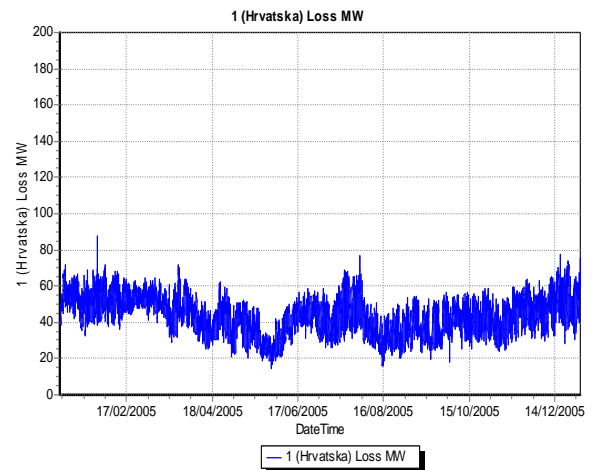


Fig. 10 Losses in the control area Croatia

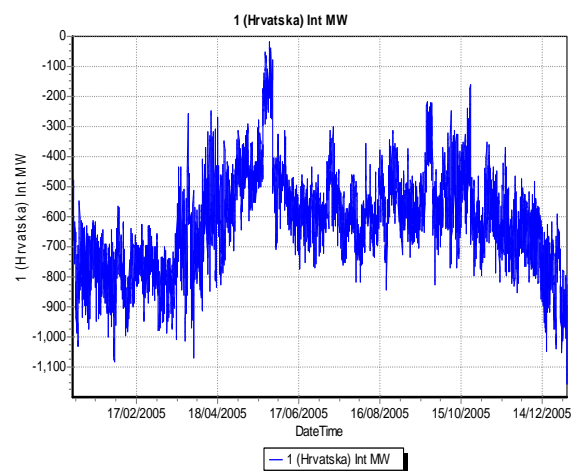


Fig. 11 Interchange MW in control area Croatia

Interchange MW in the control area Croatia is negative because Croatia imported electrical energy in 2005. Electrical energy imported by Croatia in 2005 was 5400 GWh, as shown in Fig. 12.

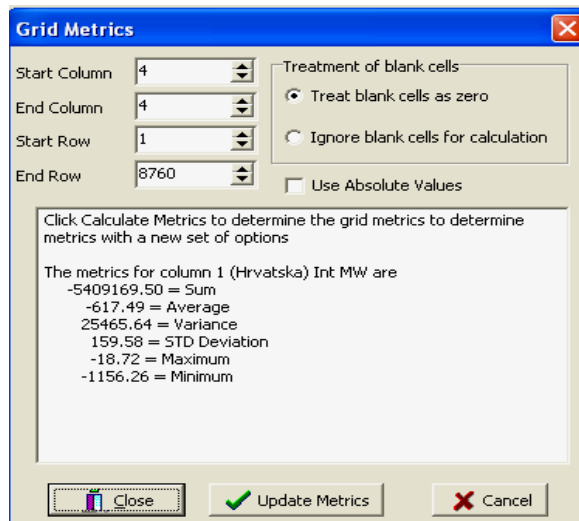


Fig. 12 Interchange MW in control area Croatia

## 6 Evaluation of the model

The main problem in this paper was to obtain a practicable and credible computer model of the Croatian electric power system using PowerWorld 11.0. The best method to evaluate credibility of the electric power system model is to compare losses of energy in the model with energy losses measured in the real system. Fig. 13 shows losses in control area Croatia that are obtained in the PowerWorld simulation.

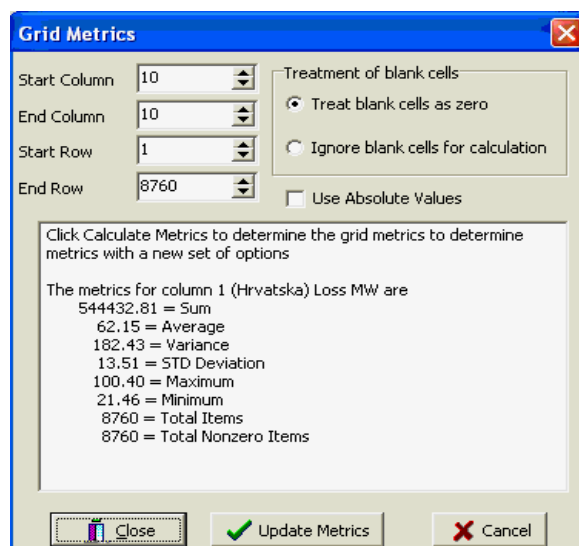


Fig. 13 Losses in control area Croatia obtained in simulation

It is viewable that losses are 544.432 GWh or in percentage:

$$P_{g\%} = \frac{P_g}{P_{UK}} \cdot 100\% = \frac{544.4}{16872} \cdot 100\% = 3.23\% \quad (8)$$

Losses that are measured in the real Croatian power system are shown in Table 1 and they are 560 GWh, which is in percentage 3.4%. It can be concluded that our model created in PowerWorld corresponds well with the real power system.

## 7 Conclusion

The software package PowerWorld Simulator 11.0 is a very useful tool which enables computer modeling and analysis of power system operation. Its main feature is the extremely user friendly graphics. Unlike the earlier versions, the new PowerWorld Simulator 11.0 enables time step simulation.

The focus of this paper was to model, plot and simulate the Croatian transmission power system in the PowerWorld software. The obtained simulation results are comparable to those on the official HEP web pages. The computer model corresponds well to the real power system operation situations. This model can also be used for fault analysis, electricity market analysis, voltage stability analysis and modeling of new investments.

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