Journal of Energy and Power Engineering 8 (2014) 1293-1300

Impact of Wind Power on the ATC Values in Hydro-Dominated Power System

Krešimir Fekete, Goran Knežević and Ljubomir Majdandžić

Faculty of Electrical Engineering, Power System Department, University of Osijek, Osijek 31000, Croatia

Received: March 01, 2014 / Accepted: April 02, 2014 / Published: July 31, 2014.

Abstract: The wind power generation is increasing in many countries as a result of decreasing technology costs, active government policies for renewable energy sources, environmental concerns, etc.. This paper investigates the impact of wind power generation on ATC (available transmission capacity) calculation. In order to determine the maximum incremental MW transfer possible between two parts of a power system without violating any specified limits, ATCs are calculated. When calculating ATC values, it is necessary to assume production and consumption pattern in power system. Production of wind power depends on the wind speed, which is a random variable and it is impossible to forecast exactly the production of wind power that is needed for the ATCs calculation. In order to investigate influence of the stochastic wind power production on the ATCs value, computer model of Croatian electric power system is made in Power World Simulator. ATCs are calculated for southern part of Croatian power system in which besides wind power, hydro power plants are only type of power generation. Available wind speed measurements are used as input data for wind power production. The results of the ATC calculation for different scenario of wind power production and location in the Southern Croatian power system are presented and discussed in the paper.

Key words: Available transmission capacity, wind power, hydro power, computer model, transmission system.

1. Introduction

Economics has dealt in detail with transportation networks. However, these networks generally assume a free choice among alternate paths between source and destination nodes and implicitly assume that goods can be stored when they cannot be moved. The transmission system does not in general exhibit these properties. Electric energy cannot be stored. Given a set of source and destination power entry and removal sites, the ability to control which transmission paths the electric power takes is limited. Physics of the power system, governed by Kirchhoff's Laws, dictate how much of the energy being moved from one node to another flows on each of the branches in the system [1].

Phase shifting transformers and high voltage power electronics that can control the power flow over an individual branch are very rare and expensive. Every branch in the electric transmission system has a limit on the amount of power that can be transferred at a given time. This limit is due to thermal limits of conductive wire, voltage limits and stability limits [1]. In order to determine the maximum incremental MW (megawatt) transfer possible between two parts of a power system without violating any specified limits, ATCs (available transmission capacities) are calculated. The fundamental definitions of transfer capacities used in this paper are based on the publication from ENTSO-E (European Network of Transmission System Operators for Electricity) [2]. ATC in the power system is the amount in which the power transmitted between different areas (zones or buses) of the system can be increased without compromising its safety.

The renewable energy generation (especially wind power) is increasing in many countries as a result of technology improvements, decreasing technology costs,

Corresponding author: Krešimir Fekete, Ph.D., senior research assistant, research fields: power system analysis, power system optimization and electricity markets. E-mail: kfekete@etfos.hr.

active government policies for renewable energy sources, environmental concerns, etc.. Even though wind generation has many advantages in terms of interacting with the environment, concern has been raised about its variable nature and how it will affect the rest of an electric power system [3]. Wind is not always available and it is almost impossible to forecast the wind speed for some longer time horizon. Since the production and consumption of power system need to be specified for the ATC calculations, uncertainty regarding the production of WPP (wind power plant) should be taken into account. This paper presents a calculation of the ATCs in the power system with WPP and HPP (hydropower). In order to illustrate ATCs calculations in power system with WPP and HPP, southern part of Croatian power system is chosen for case study. The whole Croatian power system is plotted as the single line diagram in Power World Simulator [4]. Developed computer model is used to calculate ATC values for different scenario of WPP production and location in southern Croatian power system.

Structure of this paper is as follows: in Section 2, a brief theoretical description of transfer capacities and its calculations is done. Main features of WPP stochastic production are presented in Section 3. In Section 4, a computer model of the Croatian power system is presented. Descriptions of the case study simulations and presentations of the results are done in Section 5. Based on the results, a conclusion is given in the last chapter.

2. Transfer Capacities

2.1 Power Flow Calculations

The power flow study is the basis of any analysis or design of power systems. This study is performed in steady state and in balanced system under certain operating conditions, i.e., a specific load and generation pattern [5].

The total (complex) net power entering the network at bus i is:

$$S_i = P_i + Q_i \tag{1}$$

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) and consumed (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. The general expression of net active and reactive power entering bus i:

$$P_i = \sum_k U_i U_k Y_{ik} \cos(\delta_i - \delta_j - \theta_{ik}) \tag{2}$$

$$Q_i = \sum_k U_i U_k Y_{ik} \sin(\delta_i - \delta_j - \theta_{ik}) \tag{3}$$

where, U_i and U_k are magnitudes of voltages at buses i and k, Y_{ik} is magnitude of the element in the i-th row and k-th column of bus admittance matrix, δ_i and δ_j are arguments of corresponding bus voltages and θ_{ik} is the argument of admittance Y_{ik}. It should be observed that Eqs. (2) and (3) are non-linear and the numerical solution is based on an iterative Newton-Rapshon method [6].

The PTDF (power transfer distribution factors) introduced in Ref. [7], are used as a linear approximation to estimate the change in power flow due to a particular transfer, and identifies which flow paths are the most affected [5]. They are usual method for ATC calculations. To calculate PTDF, the generation sources, loads and flow directions should be specified. This calculation also depends on the power system model used. It can be calculated from an AC or DC load flow. On the assumptions of DC load flow, the PTDF are simplified and linearized obtaining good approximations to the calculated AC load flow. The DC model is the most commonly used. $PTDF_{ij,\,mn}$ is the fraction of a transaction from zone m to zone n that flows over a transmission line connecting zone i and zone j. The equation for the PTDF is [8]:

$$PTDF_{ij,mn} = \frac{X_{im} - X_{jm} - X_{in} + X_{jn}}{x_{ij}} \tag{4}$$

where,

x_{ij} is reactance of the transmission line connecting zone i and zone j;

X_{im} is entry in the i-th row and the m-th column of the bus reactance matrix X.

The change in line flow associated with a new transaction is then:

$$\Delta P_{ij}^{New} = PTDF_{ij,mn} \cdot P_{mn}^{New} \quad (5)$$

where,

i and j are the buses at the ends of the line being monitored;

m and n are the "from" and "to" zone numbers for the proposed new transaction;

P_{mn}^{New} is new transaction amount in MW.

2.2 Transfer Capacities Definitions and Calculations

The fundamental definitions of transfer capacities are based on publication form ENTSO-E (European Network of Transmission System Operators for Electricity) [2]. The relations between these capacities can be seen on Fig. 1 [9].

TTC (total transfer capacity) is the maximum possible exchange between two areas compatible with operational security standards applicable at each system if future network conditions, generation and load patterns were perfectly known in advance [2].

TRM (transmission reliability margin) is a security margin that copes with uncertainties on the computed TTC values arising from Ref. [2]:

- Unintended deviations of physical flows during operation due to physical functioning of load-frequency regulation.
- Emergency exchanges between TSO (Transmission System Operators) to cope with unexpected unbalanced situations in real time.
- Inaccuracies, e.g., in data collection and measurements.

TRM is connected with real-time operations. Its value is determined by each TSO with a view to ensuring power system stability.

NTC (net transfer capacity) is the maximum possible exchange between two compatible areas taking into account the technical uncertainties on future network conditions. It is defined as [2]:

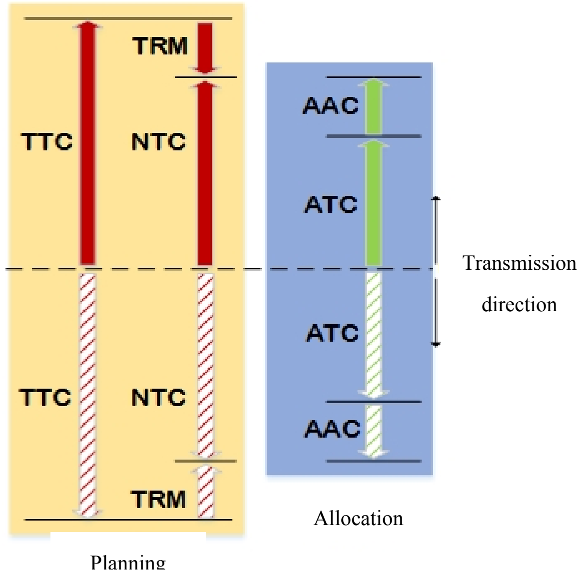

Fig. 1 Definitions of transfer capacities.

$$NTC = TTC - TRM \quad (6)$$

TTC, *TRM* and *NTC* may vary along different time frames.

AAC (already allocated capacity) is the total amount of allocated transmission rights prior to auctioning [2].

ATC (available transmission capacity) is the remaining part of NTC for further commercial activity after each phase or allocation procedure which is auctioned to market participants. It is defined as [2]:

$$ATC = NTC - AAC \quad (7)$$

With a view to determine transmission limit between two neighboring areas i.e., to calculate *ATC*, energy exchanges between areas are gradually increased, maintaining the loads in the whole system unchanged until security limits are reached. Starting from the common base case exchanges, the additional exchange is performed through increase of generation on the exporting side and an equivalent decrease of generation on the importing side. The generation shift is to be made stepwise until a network constraint is violated [9]. Network constrains consist of:

- thermal limits of the lines, transformers and associated equipment;

- limits arising from voltage and rotor angle stability;
- security limits (*n*-1 criteria).

Calculations of the *ATC*s are usually carried out in the computer software's that uses methods for power flow calculations (commonly used linearized models based on *PTDF*s). In this paper, Power World Simulator [4] is used.

3. Wind Power Production

The electric output of the WT (wind turbine) depends on the wind characteristics as well as on the aero-turbine performance and the efficiency of the electric generator. The output characteristic of WT is presented in Fig. 2 [10].

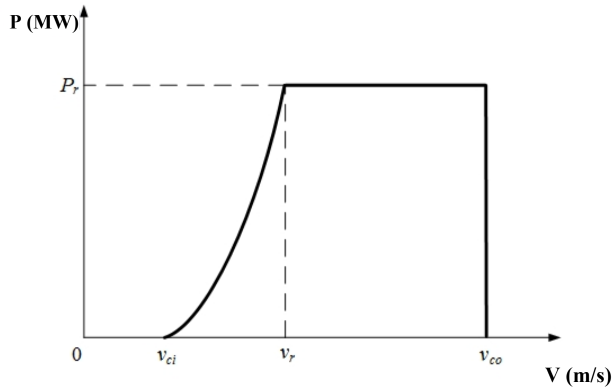

Fig. 2 Output characteristic of wind turbine.

The parameters in Fig. 2 are:

- v—wind speed;
- P—output electrical power of wind turbine;
- P_r—rated power output;
- v_c—cut-in wind speed;
- v_r—rated wind speed;
- v_{co}—cut-out wind speed.

The above parameters can be found in the technical data that manufacturers of wind turbine provide. The WT power output can be calculated as [11]:

$$P = \begin{cases} 0 & 0 \le v \le v_{ci} \\ (\mathrm{A} + \mathrm{B}v + \mathrm{C}v^2)P_r & v_{ci} \le v \le v_r \\ P_r & v_r \le v \le v_{co} \\ 0 & v \ge v_{co} \end{cases} \tag{8}$$

The constants A, B and C may be found as functions of v_{ci} and v_r using the following equations [11]:

$$\mathrm{A} = \frac{1}{(v_{ci} - v_r)^2}\left[v_{ci}(v_{ci} + v_r) - 4(v_{ci} \cdot v_r)\left[\frac{v_{ci} + v_r}{2v_r}\right]^3\right] \tag{9}$$

$$\mathrm{B} = \frac{1}{(v_{ci} - v_r)^2}\left[4(v_{ci} + v_r)\left[\frac{v_{ci} + v_r}{2v_r}\right]^3 - (3v_{ci} + v_r)\right] \tag{10}$$

$$\mathrm{C} = \frac{1}{(v_{ci} - v_r)^2}\left[2 - 4\left[\frac{v_{ci} + v_r}{2v_r}\right]^3\right] \tag{11}$$

Wind speed is a continuous random variable (direction and value vary continuously). The wind variation for a typical site is usually characterized using the so-called Weibull distribution. Several studies performed on this issue recommend it [5]. The probability density function of wind speed with the Weibull model is determined by the equation:

$$P(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} e^{-\left(\frac{v}{c}\right)^k} \tag{12}$$

where,

$P(v)$—probability density function of occurrence of wind speed v;

k—shape factor (m/s);

c—scale factor (m/s).

In this paper, real wind speed measurement data at the location Borajica, Croatia are used. Measured data are publicly available [12]. The relative frequencies of wind speed at location Borajica are shown in Fig. 3.

As can be seen from the Fig. 3, the distribution of wind speed is not symmetrical as a consequence of very high wind speeds in certain periods, although these are less frequent. Average wind speed is 8.69 m/s and the mode of the distribution, i.e., wind speed with highest probability is 7.5 m/s.

4. Computer Model of the Croatian Power System

The whole Croatian power system is plotted as the Power World Simulator single line diagram [13]. All generation and transmission network 400/220/110 kV are presented. The distribution network is substituted with consumers on the secondary winding of the

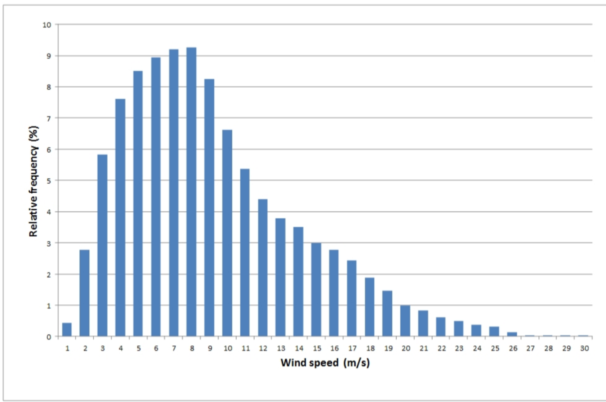

Fig. 3 Relative frequencies of wind speed at location borajica.

transformer 110/x kV. The Croatian power system is one control area controlled by CTSO (croatian transmission system operator). Based on the available data from HOPS [14], model is calibrated on the 2008. It has 274 buses, 82 generators, 132 loads, 294 lines and transformers. The total installed capacity of generating plants in 2008 is 3,653 MW, 2,088 MW of which is in hydro power plants, 1,565 MW is in TPPs (thermal power plants) and 348 MW in the nuclear unit Krško (50% of total available capacity) [15]. Detailed single line diagram of Croatian production and transmission system can be found in Ref. [16].

Thermal power plants are located in the central north part of the country and most of the hydro power plants are situated in the southern (coastal) part of the country [15]. The southern part of Croatian power system is particularly suitable for the construction of wind farms. Main economic activity in the Sothern Croatia (Adriatic coast) is tourism and it has impact on the Southern Croatian power system since tourism is a seasonal activity which results in extremely high electricity demand during the summer and extremely low electricity consumption during winter months. The outcome of the extreme electricity consumption during tourist season is 5 to 6 times lower peak demand in winter periods than during the summer [17]. Experience with the Southern Croatian power system show that the most problematic is winter period when often appear low consumption, along with high speed winds (high production of WPP) and large amounts of water in the hydrological reservoirs (high production in HPP). In these cases, due to high production of WPP and HPP and low consumption, it is necessary to transmit large amounts of energy to the northern part of the system (and export it to neighboring countries as well) causing substantial loading of transmission lines. The ATCs calculations in such conditions are very difficult and important. Case study presented in this paper is made on the basis of data for the winter period of 2008 (December) when large river inflows in southern Croatia are coincided with high wind speeds. Detailed informations about the selected example are given in the next chapter.

5. Case Study

5.1 Descriptions of the Case Study

The study of the effect of wind generation on the ATCs calculations is carried out on the computer model of Croatian power system explained in Section 4. For the production and consumption pattern, data for winter period 2008 are chosen and shown in Table 1.

Also, total import of electric energy in Croatia for chosen moment is 1,065.83 MW and total export of energy from Croatia is 916.94 MW so Croatian power system is net importing 148.89 MW. Together, domestic production and net import of energy gives total of 2,254.23 MW consumed in Croatia (2,198.6 MW is actual consumption and additional 55.63 MW represent energy losses in the Croatian transmission network). The position of Southern Croatian power system and location of HPPs in it, are presented in Fig. 4 (detailed single diagram of the studied system can be found in Ref. [16]).

The consumption and production describes above make base case for ATCs calculations. As can be calculated from the Table 1, in the base case Southern Croatian power system is producing 799 MW, consuming 557.7 MW and exporting to the north 241.3 MW. The production in Southern Croatia for base case consists of 6 HPPs presented in Fig. 4 and for which data are given in Table 2.

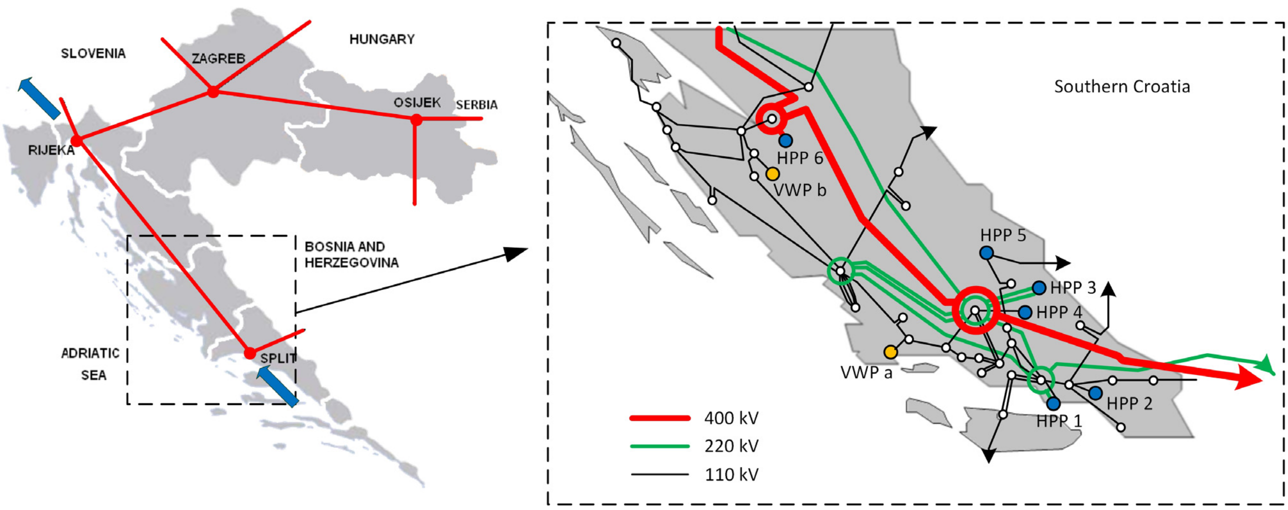

Fig. 4 Position of the southern croatian power system and location of the HPPs and VPPs.

Table 1 Production and consumption data in Southern Croatia used in case study.

	Southern Croatia	Total Croatian power system
Consumption (MW)	557.7	2,198.6
Total production (MW)	799	2,105.34
TPPs production (MW)	0	7,46.35
HPPs production (MW)	799	1,358.99

Table 2 Production in Southern Croatia.

Name	Production (MW)	Installed capacity (MW)
HPP 1	454	520
HPP 2	122	154.4
HPP 3	0	205.2
HPP 4	38	38.4
HPP 5	50	51.2
HPP 6	135	264
Total	799	1,233.2

The developed model is upgraded with VWP (virtual wind park) located either at location *a* (VWP *a* at Fig. 4) or location *b* (VWP *b*) depending on scenario. Both locations are connected to 110 kV grid. Virtual wind park is consist of 140 wind turbines, 1.5 MW rated power each [18], giving a total installed capacity of wind park of 210 MW. Data from wind speed measurements [12] (Fig. 3) are used to calculate the output power of virtual wind park. Eqs. (8)-(11) are used for calculations of wind parks output powers. It is important to mention that wind speed measurements are obtained for the height of 46 m [12]. Because a tower height of wind turbines [18] is 80 m, it is necessary to recalculated wind speed measured data to tower heights. A logarithmic law is used to quantify the vertical wind speed profile, assuming that the land is flat with a surface roughness z_0 [19]:

$$v_e = v_r \left[\ln(z / z_0) / \ln(z_r / z_0) \right] \tag{13}$$

where,

v_e is calculated wind speed at tower height;

v_r is measured wind speed at measurement height;

z is tower height.

Three characteristic values of wind speed are used for ATCs calculations: rated wind speed = 10.5 m/s (at this wind speed wind turbine starts to produce rated output power of 1.5 MW), average wind speed = 8.69 m/s and most probable wind speed, i.e., mode = 7.5 m/s. Output powers of VWP for characteristic wind speeds are:

Rated output power—$P_{VPP,\,r}$ = 210 MW,

Average output power—$P_{VPP,\,a}$ = 164.6 MW,

Mode output power—$P_{VPP,\,m}$ = 107.4 MW.

ATCs are calculated for transfer of energy from the south to the north (see the blue arrows on the Fig. 4). Case study is analyzed through the 4 different scenarios:

Scenario S1—VWP is located at the location VWP *a*. For the calculations of the ATC, energy is injected in node HPP1 and energy is withdrawn in node Slovenia;

Scenario S2—VWP is located at the location VWP *b*.

Energy is injected in node HPP1 and withdrawn in node Slovenia;

Scenario S3—VWP is located at the location VWP *a*. Energy is injected in node HPP2 and withdrawn in node Slovenia;

Scenario S4—VWP is located at the location VWP *b*. Energy is injected in node HPP2 and withdrawn in node Slovenia.

5.2 Results of the Simulation

Three *ATC* values are calculated for every scenario:

ATC_r—value of *ATC* when *VWP* production equals the rated output power (210 MW). The probability of that operating state is 17.364 % (this state is consist of all wind speed between rated wind speed and cut of wind speed—20 m/s);

ATC_a—value of *ATC* when wind speed equals the average value (8.69 m/s). The output power of *VWP* is 164.4 MW;

ATC_m—value of the *ATC* when wind speed equals the mode wind speed (7.5 m/s). The output power of *VWP* is 107.4 MW. The probability of that operating state is 9.264 %;

ATC_{bc} is calculated for the base case (without *VWP*). There are two values for ATC_{bc}—one when energy is injected in node HPP1 (S1 and S2) and another one when energy is injected in node HPP2 (S3 and S4).

The calculated *ATC* values for every scenario are presented in Fig. 5. *ATC* values are obtained for mean, mode and rated output power of virtual wind park and for base case (without *VWP*) as well.

Scenarios S1 and S2 show impact of *VWP* production to *ATC* values while scenarios S3 and S4 show that production of *VWP* does not affect *ATC* values. The main difference between scenarios S1, S2 and S3, S4 is the location of the source node for the *ATC* calculation. In scenarios S1 and S2, source node (node in which energy is injected) is HPP1 whose generators are connected to 110 kV and 220 kV grid. Thus energy from HPP1 is flowing partially through the 110 kV grid and partially through the 220 kV grid.

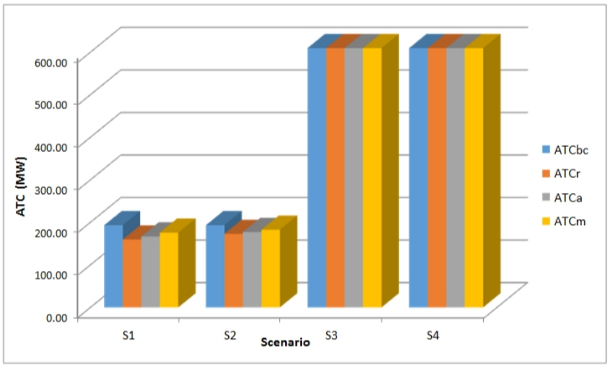

Fig. 5 Calculated ATC values for every scenario.

As previously mentioned, both locations of the *VWP* are connected to the 110 kV network and consequently production of *VWP* has an impact on *ATC* values for scenarios S1 and S2. In scenarios S3 and S4, source node is HPP2 whose generators are connected only to 220 kV grid and the influence of *VWP* production to *ATC* values is negligible.

As can be seen in Fig. 5, highest impact on the *ATC* value for scenarios S1 and S2 is when *VWP* is operating at the rated output power. Since production from *VWP* represents additional loading of 110 kV lines, and since part of the energy from HPP1 is flowing through the 110 kV network, the influence of the *VWP* on *ATC* value is negative.

6. Conclusions

This paper investigates the influence of the wind power production on the ATC calculation in hydro dominated power system. In order to illustrate the method, computer model of Croatian power system is created and additional virtual wind park is added to existing power system. Four scenarios with different virtual wind park and source nodes locations are assumed and corresponding ATCs are calculated. Numeric results included in this paper are only illustration of proposed method capabilities when applied to real power system, and outputs of simulation do not reflect the operation of actual system. Calculation results show the influence of virtual wind park location on ATCs. Besides the location, a key influence on the ATCs has VWP size compared to existing power system. A detailed analysis of influence of *VWP* on the value of the *ATC*s in Croatian power system can be found in the literature [20]. Calculation of *ATC*s includes stochastic nature of wind power production. Further work in this area includes investigations of coordinated operation of wind and hydropower in the moments when congestion are present in the power system.

References

[1] Christie, R. D., Wollenberg, B. F., and Wangensteen, I. 2000. "Transmission Management in the Deregulated Environment." *Proceedings of the IEEE* 88 (2): 170-95.

[2] European Network of Transmission System Operators. 2001. *Definitions of Transfer Capacities in Liberalized Electricity Markets*. Final report.

[3] Chowdhury, A. A. 2005. "Reliability Models for Large Wind Farms in Generation System Planning." In *IEEE Power Engineering Society General Meeting*, 1926-33.

[4] Official Power World web site. Accessed January 20, 2014. www.powerworld.com.

[5] Luna, L., Martinez, J., Pacual, V., and Valino, V. 2011. "Impact of wind power generation on the ATC value." Presented at 17th Power Systems Computation Conference, Stockholm, Sweden.

[6] Van Ness, J. E., Griffin, J.H. 1961. "Elimination Method for Load Flow Studies." *AIEE Trans. on Power Apparatus and Systems* 80: 299-302.

[7] Sauer, P. W. 1981. "On the Formulation of Power Distribution Factors for Linear Load Flow Methods." *IEEE Transaction on Power Apparatus and Systems* 100 (2): 764-70.

[8] Knežević, G., Fekete, K., and Nikolovski, S. 2009. "Visualization of Voltage Profile and Power Flow in Croatian Power System." In *32nd International Convention on Information and Communication Technology, Electronics and Microelectronics (MIPRO)*, 381-85.

[9] Fekete, K., Knezevic, G., Nikolovski, S., Slipac, G., Sumper, A., and Ramirez, R. 2007. "Different Cross-Border Energy Transits in Future Croatian Power System." In *7th Balkan Power Conference (BPC)*, 52-8.

[10] Nikolovski, S., Topic, D., Fekete, K., and Slipac, G. 2011. "The Influence of Wind Park Krs-Padene on Reliability Indices of 110 kV Transmission Network." In *8th International Conference on the European Energy Market (EEM),* 870-875.

[11] Deshmukh, R. G., and Ramakumar, R. 1982. "Reliability Analysis of Combined Wind Electric and Conventional Generation Systems." *Solar Energy* 28 (4): 345-52.

[12] European Commission. 2007. "Assessment of Wind and Solar Energy Resources in a Pilot Croatian Region." European Commission CARDS program. Accessed January 20, 2014. http://www.eihp.hr/awsercro/awsercro.htm.

[13] Fekete, K., Nikolovski, S., and Baus, Z. 2007. "Simulation of Power Flows in Croatian Power System." In *6th Eurosim Congress on Modeling and Simulation,* 1-7.

[14] Official information from Croatian Transmission System Operator HOPS web site. Accessed January 20, 2014. www.hops.hr.

[15] Republic of Croatia Ministry of Economy Labour and Entrepreneurship. 2008. *Energy in Croatia 2008*. Annual Energy report.

[16] Croatian Transmission System Operator, Croatian Transmission System Scheme. Accessed January 20, 2014. http://www.hops.hr/wps/portal/en/web/hees/data/present.

[17] Capuder, T., Pandžić, H., Kuzle, I., and Škrlec, D. 2013. "Specifics of Integration of Wind Power Plants into the Croatian Transmission Network." *Applied Energy* 101: 142-50.

[18] Wind Turbine ACCIONA Windpower AW1500. Accessed January 20, 2014. http://maritimesenergy.com/flow/uploads/acciona_aw1500_information.pdf.

[19] Manwell, J. F., McGowan, J. G., and Rogers, A. L. 2002. Wind Energy Explained: Theory, Design and Application. Chicester: John Wiley&Sons Ltd.

[20] Fekete, K., Knežević, G., and Nikolovski, S. 2013. "Available Transfer Capacity Determination for Cross Border Energy Trading in Croatian Power System." In *8th International Conference on Deregulated Electricity Market Issues in South-Eastern Europe,* 1-5.