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ABSTRACT

The paper will present the process of the planned grid connection scheme optimization for wind power plants. At start the overview of the current status and trends will be observed alongside a short description of the Croatian power system specifics. The special highlight will be given to the wind energy integration. Following, the potential problems regarding the reduced inertia, more complicated protection requirements and regulation issues will be shortly described. The paper will provide technical description and graphical representation of potential grid connection solutions. Then, description of the calculation of different scenarios of load flows to select the optimal grid connection solution will be explained. The prerequisite for the power flow calculations is always the development of the thorough grid model which will also be described briefly. Furthermore, the relevant and influencing new network changes and users must be chosen to measure their influence through inclusion into the model and future scenarios selection importance will be discussed. Based on the determined grid connection point and terrain characteristics optimization of the wind power plant layout needs to be done to reduce the losses combining the statistical analysis and power flow analysis. This results in the transformer stations positions selection and desired voltage level selection. Finally, estimation and analysis of grid connection costs and potential production levels shapes the final recommendations. Throughout the paper described general methodology will be applied to a hypothetical case study and results and conclusion will be shown.

KEYWORDS

grid connection, wind power, losses minimization, power flows, grid limitations, scenario simulation

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1. INTRODUCTION

The electric power sector is currently undergoing unprecedented changes [1]. The environmental impacts the modern society is producing are being mitigated through an attempt to reduce the greenhouse emissions [2] from all sources, namely power and energy and transport sectors [3], [4]. The massive deployment of variable and limitedly predictable electricity generation from renewable energy sources (RES) [5] requires power system planners and operators to re-evaluate the way power systems are studied, designed and operated since passive integration of RES might result in significant over investments driven by needed improvements on the distribution grid level [6], [7]. Considering this challenge optimization and policy changing is used in many segments of the process offering a solution including for example integration on the local level [8], through multi-energy systems [9], [10], energy storage [11] ,[12] or wind energy monitoring and smarter integration [13].

This shift creates potential problems with reduced inertia, frequency oscillations and tertiary reserve. The frequency is a very important parameter for safe and reliable electric power system (EPS) operation [14] and must have approximately constant value because of rotating machines and because of other devices which use frequency for time measurement. The frequency stability of power system mostly relies on the inertia in the rotating masses of synchronous generators [15]. The kinetic energy of the rotating units prevents sudden changes in voltage and current frequency when a disturbance occurs in a system. The problem arises with a significant RES integration because on the one hand the conventional power plants disconnect from the grid thus kinetic energy decreases [16], [17] and on the other hand, RES are usually connected to the EPS via power electronics and because of this indirect connection they lack inertia response to oppose frequency change. These mentioned changes cause the reduction of system inertia which is manifested in a higher value of the rate of change of frequency (ROCOF) as well as a lower frequency nadir (the most important aspect of frequency behavior following the sudden loss of generation is the point at which frequency is arrested or the frequency nadir [18]). Power system dynamic response depends on power plant type, power system regulation energy and inertia and type of connected consumers [19].

According to the data from in the European Union (EU) [20] new 422 GW RES capacity were installed, covering 17% of total demand. The wind increased from a total of 141.416 MW to 154.324 MW in 2016. The total electricity capacity in the period from 2000 to 2016 increased by 32%.

In Croatian electric power system, the wind power plants (WPP) integration has doubled in the last 5 years and at the end of 2018, the total installed WPPs capacity was 576 MW. According to the ten-year network development plan of the Croatian TSO (transmission system operator) for the period 2017-2026, the total capacity of planned WPPs is 1460 MW within that period [21]. This large share of the wind energy aimed to use the potential of the wind resource in coastal region [22] and to be integrated into the Croatian electric power system is the main drive to observe carefully each individual project that is being considered. Providing a detailed analysis and consideration of various scenarios can achieve an efficient plan for the connection of all planned future wind power plants. This paper recognizes the importance of:

- detailed and accurate analysis of technical requirements for wind power integration and a distinct definition of worst-case scenarios and recognizing specifics for WPP integration in Croatia;
- preserving the stability of the power system as a whole which can be endangered if attention is not given to the protection, fault-tolerance, frequency and voltage regulation issues;

- assessment of the connection costs for wind power plant projects that at the same time preserve the system integrity and leave enough opportunity for the investors that usually do not have great interest in power system stability [23].

The novelty of the paper is the application of methodology which consist of the of universal definition of scenarios and their probability of occurrence weight factors. The probability weight factors are defined based on the historical data and empirical experience. These scenarios are then used to extract power flow analysis conclusions and costs estimation ensuring that with limited number of simulations wide range of possible grid conditions are considered. Additionally, the limiting scenarios are identified within the range of representative grid states which eliminates the need to simulate boundary grid conditions which are highly improbable to occur but are theoretically possible.

The rest of the paper is organized as follows: in section 2 the specifics and short description of Croatian electric power system are given. In section 3 the current status of the wind power integration in Croatia is overviewed. Section 4 presents the potential problems the wind power plants integration can cause or face. The section 5 presents summary of the grid connection results of a case study. The section 6 concludes the paper.

2. SPECIFICS OF CROATIAN ELECTRIC POWER SYSTEM

Electric power system (EPS) of Croatia consists of generation facilities and plants, a transmission and distribution network and electricity customers. In order to ensure high stability and quality of electricity supply, Croatian EPS is connected to the EPSs of neighboring countries and systems of other ENTOS-E members, which together constitute the synchronous network of continental Europe. Customers in Croatia are supplied with electricity from power plants in Croatia and with electricity purchased from abroad. Croatia’s EPS 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 control area by Croatian Transmission System Operator (HOPS). Together with the Slovenian power system and the power system of Bosnia and Herzegovina it constitutes the control block SLO – HR – BIH within the ENTSO-E association, Total installed generating capacity in Croatian EPS in 2017 was 4777 MW. In general, a peak hourly load occurs in summer due to mild winters and high summer temperatures. The peak load of 3,079 MW was recorded on 4 August 2017 at 14.00 h, and the minimum load of 1305 MW was recorded on 18 September which is correlated to monthly used energy (Figure 2).

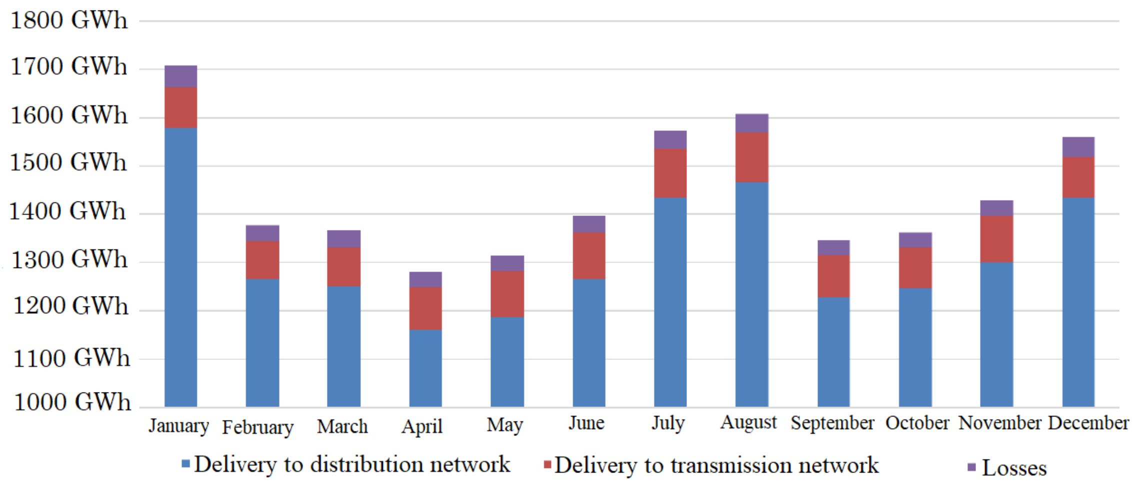

Figure 1 Demand in the transmission network of the Republic of Croatia in 2017

The Figure 2 shows Croatia's transmission system which consists of six 400 kV substations, fourteen 220 kV substations and one hundred and fifty-five 110 kV switchyards and 110/x kV substations (at the end of 2017). Also, Fig. 3 shows the approved connection capacity of power stations connected to the transmission system: 276 MW at voltage level of 400 kV, 1551 MW at voltage level of 220 kV, 2271 MW at voltage level of 110 kV and wind power plants with total installed capacity of 529 MW. Only one power plant (Velebit Pumped Storage Hydro Power Plant) is connected to the 400 kV grid. Regarding the protection system of the Croatian EPS the total system inertia has been sufficient. It directly affects the frequency gradient (ROCOF) during a system disturbance, the value of frequency nadir (the lowest frequency during a system disturbance) and the moment of a frequency nadir, Higher values of system inertia constant, on the one hand, cause smaller ROCOF and consequently the turbine regulators have more time to react and increasing inertia creates redundancy in the system.

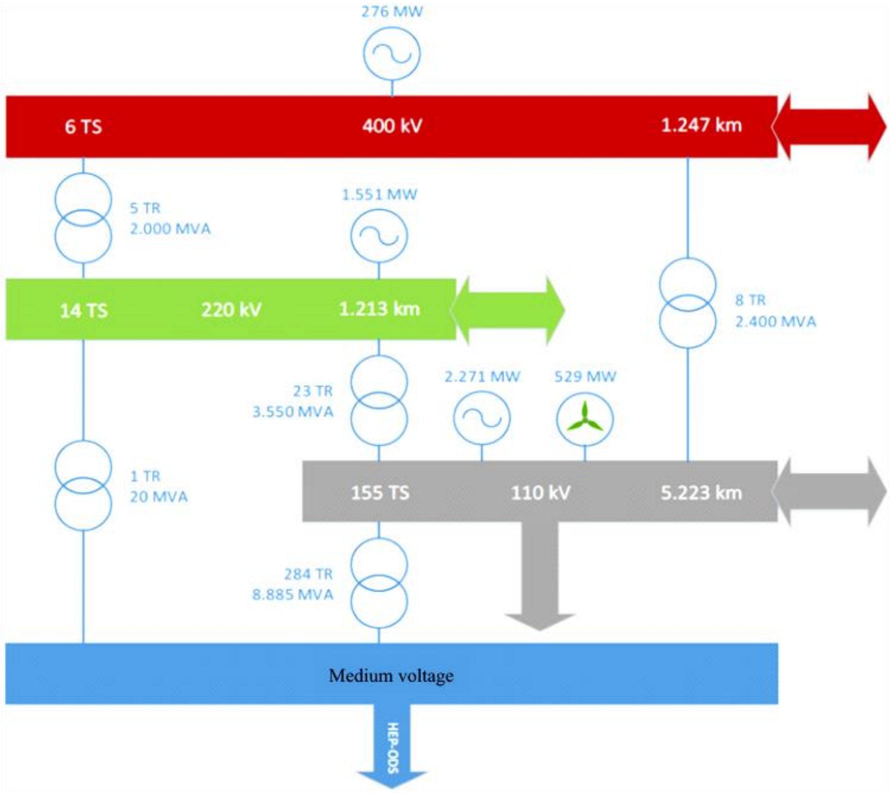

Figure 2 Technical indicators of the EPS in Croatia by voltage at the end of 2017 [24]

3. WIND POWER PLANTS IN CROATIAN ELECTRIC POWER SYSTEM

Croatian transmission system has a unique and distinctive topology which makes the power flow control demanding. The backbone 400 kV network is long and it connects thermal power units that make almost half of the installed capacity and the majority of them are located in the central north part of the country and the coastal region where majority of wind generation is located (Figure 3). Additionally, almost all hydro power plants are situated in this coastal southern part of the country. This can present a potential problem since in certain regions of the EPS the available inertia can be smaller.

The detailed data for all the wind power plants connected to the Croatian power system are shown in the table below (Table 1).

Table 1. Croatian currently operational wind power plants data

WPP	Installed (MW)	Manuf. and model	Type (no.) of turbines	Location (county)	Connection voltage (kV)	In service
Ravne	5.95/5.95	Vestas V52-850kW	2 (7)	Zadar	10	2005.
Trtar-Krtolin	11.2/11.2	Enercon E-48 800kW	4 (14)	Šibenik-Knin	30	2007
Orlice	9.6/9.6	Enercon E-44 900kW	4 (11)	Šibenik-Knin	30	2009.
Vrataruša	42/42	Vestas V90-3.0MW	3 (14)	Primorje	110	2010.
ZD6	9.2/9.2	Siemens SWT 2.3-82VS	4 (4)	Zadar	35	2011.
Pometeno Brdo	20/20	Končar KO-VA 57/1MW	4 (15)	Split-Dalmatia	110	2010.
Crno Brdo	10.5/10	Leitwind LTW77 1.5MW	4 (7)	Šibenik-Knin	10	2011.
ZD2 and ZD3	36.8/36	Siemens SWT 2.3-93	4 (16)	Zadar	110	2011.
Ponikve	36.8/34	Enercon E-70 2.3MW	4 (16)	Dubrovnik-Neretva	110	2012.
Jelinak	30/30	Acciona AW82-1.5MW	3 (20)	Šibenik-Knin	110	2013.
Kamensko-Voštane	42/40	Siemens SWT 3.0-101	4 (14)	Split-Dalmatia	110	2013.
ZD 4	9.2/9.2	Siemens SWT 2.3-93	4 (4)	Zadar	10	2013.
V. Glava, Bubrig	43.7/43	Enercon E-82 2.3MW	4 (19)	Šibenik-Knin	110	2014.
Zelengrad-Obrovac	42/42	Vestas V90-3.0MW	3 (14)	Zadar	110	2014.
Ogorje	42/44	Vestas V112-3.0MW	4 (14)	Split-Dalmatia	110	2015.
Rudine	34.2/34.2	GE 2.85-103	3 (12)	Dubrovnik-Neretva	110	2015.
Glunča	20.7/23	Siemens SWT 2.3-93	4 (9)	Šibenik-Knin	110	2016.
Katuni	34.2/39.9	GE 2.85-103	3 (12)	Split-Dalmatia	110	2016.
(ZD6P)	44.2/45	Siemens SWT 3.4-108	4 (13)	Zadar	110	2017.
Lukovac	48.75/48	GE 2.85-103	3 (16)	Split-Dalmatia	110	2018.

For the EPS with the small inertia constant, the ROCOF during a disturbance will be greater. Newly designed machines have smaller inertia constants (2-3 MWs/MVA) than older designed machines (10 MWs/MVA) due to the tendency for savings of materials which means construction of less massive generators. The ROCOF changes need to be accounted for when designing the protection system.

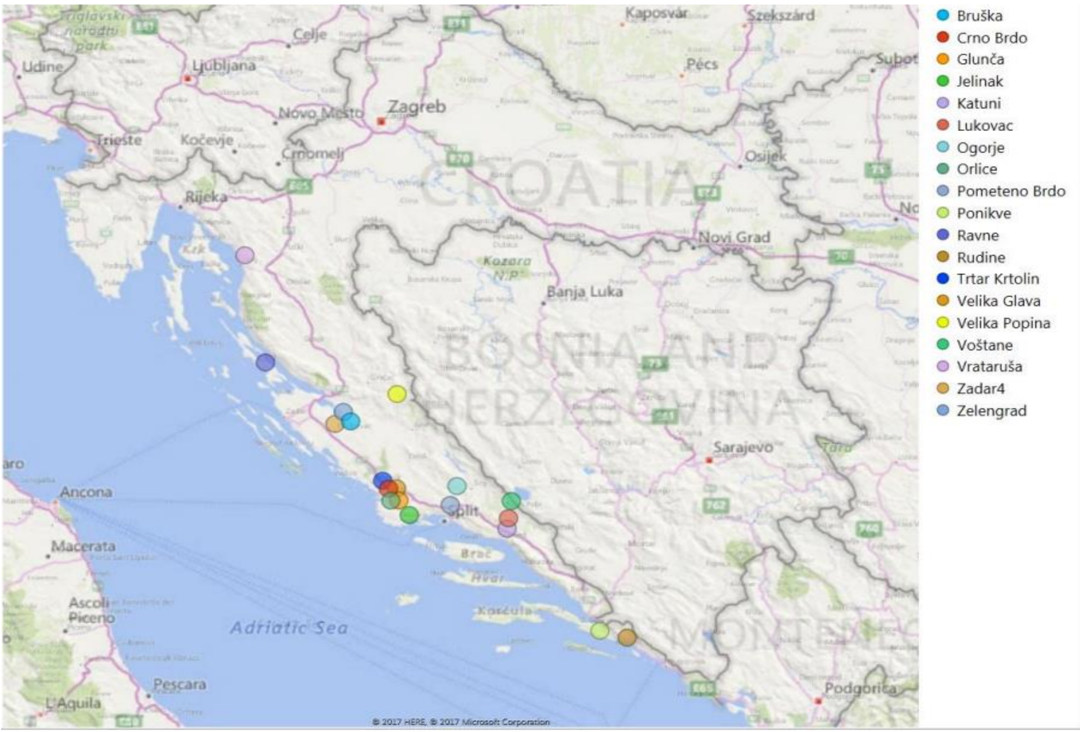

Figure 3 Wind power plant locations in Croatia [25]

Besides the wind power plants listed in the Table 1, there are several WPP in test operation or scheduled for construction completion in the coming year (Table 2).

Table 2. Planned wind power plants to enter the operation in the period 2018-2020

WPP	Capacity (MW)	Connection voltage (kV)
Zelengrad – Obrovac	12	110
Krš – Pađene	142	220
ST 3-1/2 Zelovo	33	110
Bruvno	45	110
Konavoska brda	120	220
ZD2P	48	110

According to available data (Table 1), it can be concluded that almost all wind farms in Croatia are equipped with Type 3 (doubly-fed induction generator-DFIG - Figure 4) and Type 4 wind turbines (synchronous generator with permanent magnets - Figure 5) except the Ravne-Pag wind farm, which is equipped with Type 2 wind turbine generator (an induction (asynchronous) generator with a wound rotor). Type 1 WTGs are not present according to the available data and will not be considered. It is important to note that different generator types contribute differently to the system frequency stability issue and have different addition to the system inertia. The values of ROCOF greater than 1 Hz/s are critical and, in some cases, can drive the system to unpredictable system states which are hard for protection system to react properly to. Therefore, the system inertia needs to be kept sufficient.

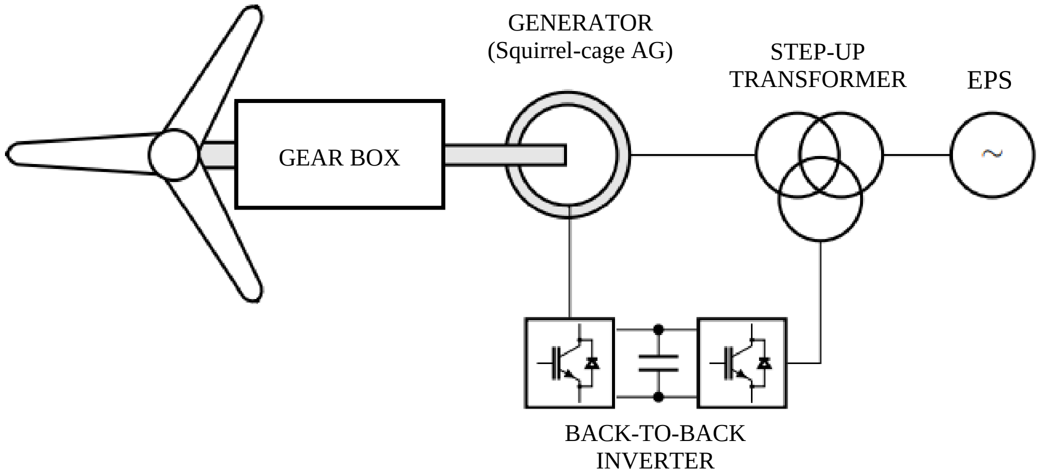

Figure 4 Scheme of Type 3 wind turbine generator (DFIG)

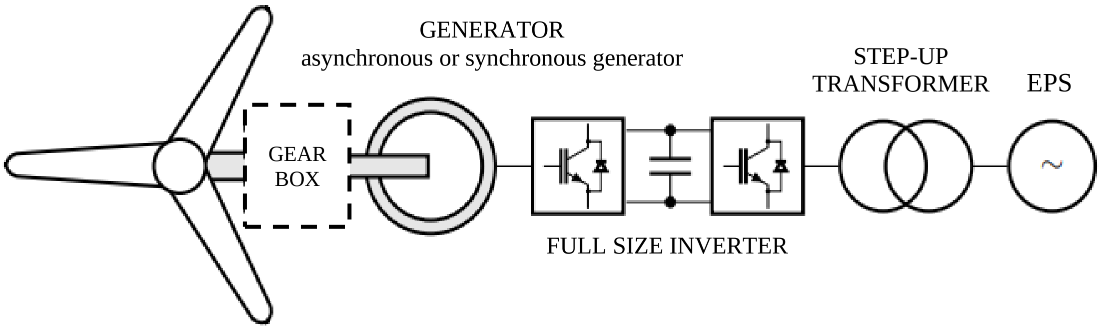

Figure 5 Scheme of Type 4 wind turbine generator (SGPM)

4. THE ISSUES OF WPP INTEGRATION IN CROATIAN POWER SYSTEM

The wind power plants integration introduces new challenges in EPS operation due to its variable and unpredictable nature as was already mentioned in the introduction. The facts causing problems for the power system operation and planning are: the geographic location of WPPs and insufficient transmission capacity of the grid at that locations and unpredictability of wind speed and direction. Hence, the issues should be considered from different aspects regarding:

- Grid local characteristics;
- Electric power system operation and planning;
- Dynamic behavior and protection issues of EPS with a significant wind penetration.

WPP integration in Croatia is specific for its low geographical dispersion. The largest distance between two WPPs is about 300 km, while 13 out of 16 WPPs with 75% of total WPP installed capacity is located on the area with similar wind climate (110 x 70 km2 - Figure 3). Along with significant wind variability, it strongly affects WPP total output variability.

In normal EPS operation, the main impacts on balancing the system are the deviations of planned consumption and WPPs generation. The mentioned deviations are independent variables and it is very important whether the deviations are superimposed or annulled. Maintaining a system balance when deviations occur between forecasted and realized WPP generation can be a problem. In 2017, the average WPP generation forecasting error was 5,56% (29,4 MW) of installed capacity. Maximum positive forecast error (forecast higher than output) was 180,8 MW, and maximum negative forecast error (forecast larger than output) was -253,9 MW (Figure 6).

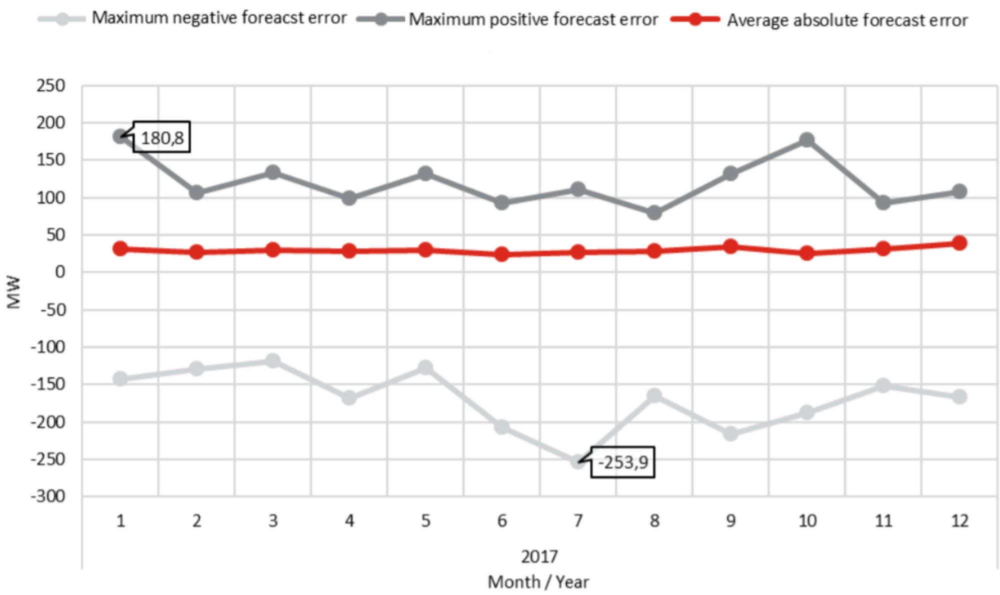

Figure 6 Maximum positive, maximum negative and average absolute forecast error of wind power plant hourly output [26]

Along with WPP generation forecasting error, of particular importance is also a WPP output variation. In other words, the difference between hourly WPP outputs in two consecutive hours is shown. The largest positive hourly WPP output variation was 219,7 MW, the largest negative hourly WPP output variation was -122,4 MW, average positive hourly WPP output variation in given timeframe was 108,62 MW, while average negative hourly WPP output variation was -93,65 MW [26]. Larger forecast error assumes larger regulation capacity needs and balancing energy causing, therefore, higher costs in this segment. Since WPPs do not participate in primary and secondary frequency regulation in Croatia's EPS, the conventional power plants are responsible for generating necessary balancing energy. Additionally, WPPs are commonly treated as a negative load from the EPS operator's perspective. However, regarding WPPs capability to regulate reactive power and their distribution of WPP on the transmission network, the voltage conditions at point of common coupling (PCC) could be improved. The issue of high voltage conditions in Croatia EPS during night hours is partially solved requiring WPPs to operate in PCC with cos φ = 0.95 (cap.) in a time frame from 11:00pm to 08:00am, otherwise they operate with cos φ = 1 which yield the highest incomes. The requirement to regulate the voltage can significantly lower required investment into the transmission grid reinforcement thus enabling the lower connection costs of new generators. The same requirement can help during the contingency (N-1) analysis and voltage levels since the TSO requires to maintain the same level of system security that should not be deteriorated after the connection of new production units.

5. WIND POWER PLANT CONNECTION CASE STUDY

The general flow of the grid connection procedure for a wind power plants and all generators in general is depicted on figure below (Figure 7).

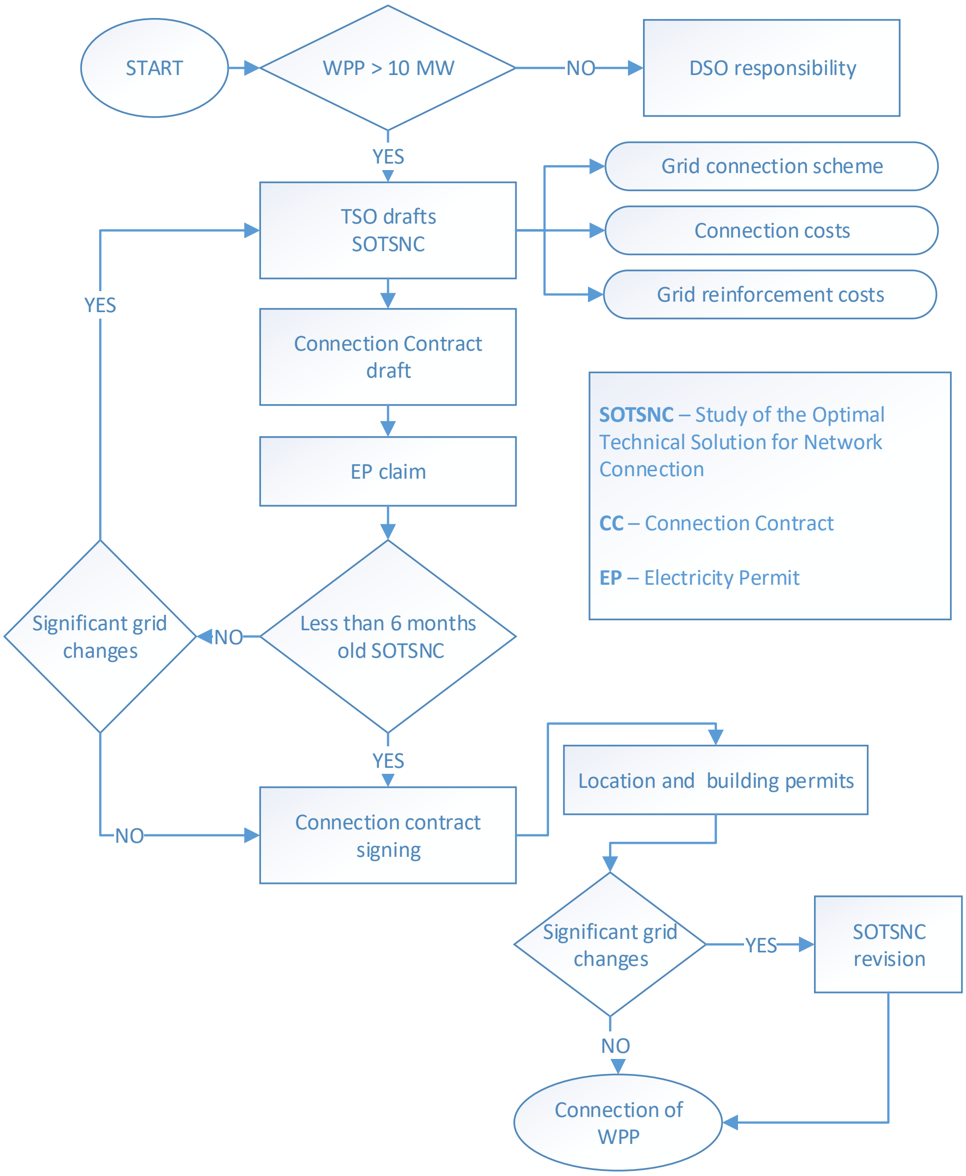

Figure 7 General flow chart of the WPP gird connection procedure

The critical part is the one that is observed more closely in this paper, the SOTSNC (Study of the Optimal Technical Solution for Network Connection) of the illustrative case-study example.

The wind potential in certain parts of the Croatia, like mountainous region of Lika (Figure 8) still provides good foundation for development projects. Including the information that current wind turbines range from 5,5 to 6,0 MW and have competitive prices the investment into a new WPP can be achieved if the connection and gird reinforcement cost do not exceed certain percentage of the total investment (usually 10-15% of the total investment is considered to keep the project above the profitability margin).

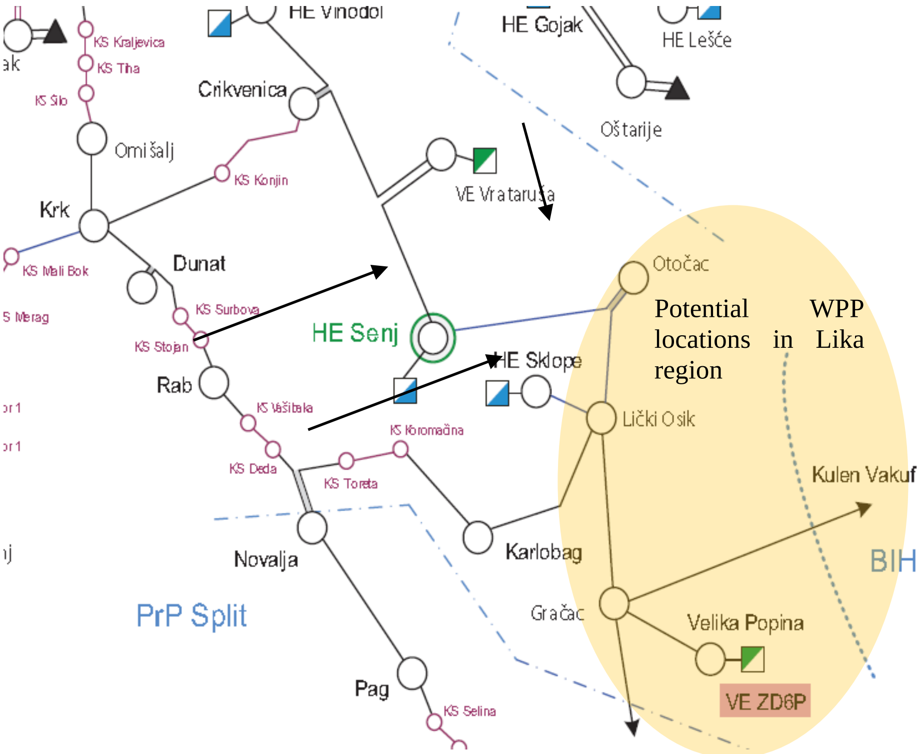

Figure 8 Approximate geographical location of WPP and relevant current and planned transmission system infrastructure

There are several possibilities for the potential WPP locations to be connected to the transmission network. They are comprehensively shown on the figure below (Figure 9) which defines viable solutions for the predicted installed power scale.

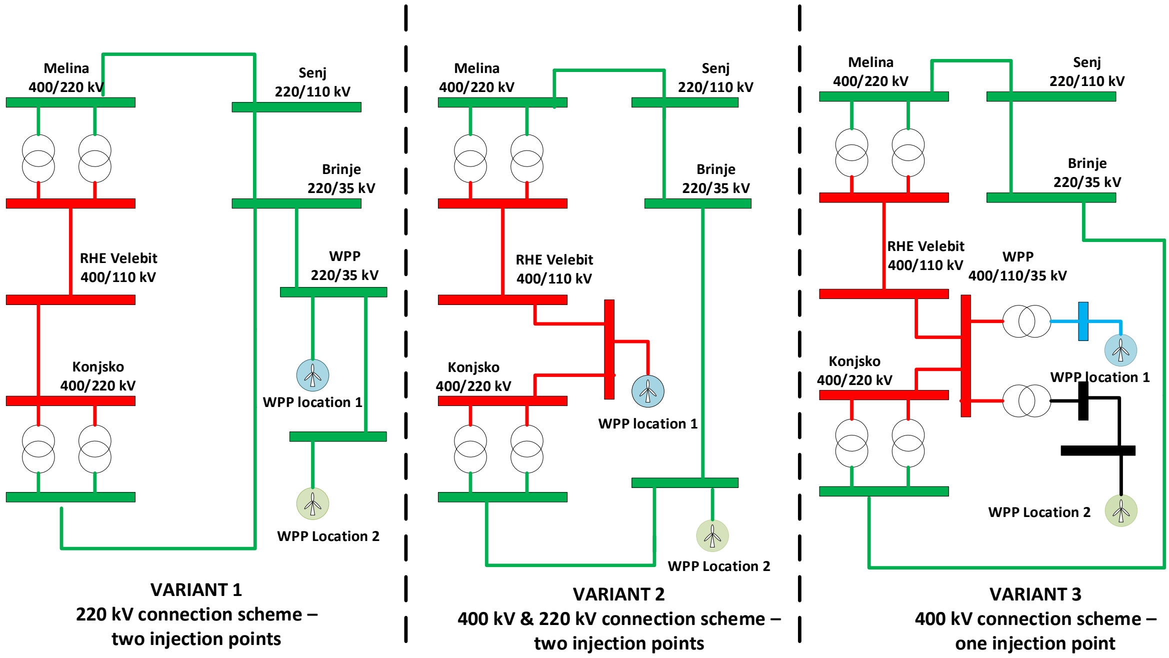

Figure 9 Possible grid connection variants

To asses different possibilities analysis was performed from three perspectives, EPS perspective, connection perspective and WPP structure perspective. Therefore, the general breakdown of results is done in a threefold way:

1. Electric power system requirement and scenario simulation aiming to determine under what conditions WPP can fit into the Croatian transmission system;
2. Connection requirements following the flow of energy from the wind turbines to the current electric power system infrastructure mainly determining the losses and costs of different connection variants and location of transformer stations;
3. WPP internal design and voltage level connected with the georeferenced power flow model.

For each of the three segments corresponding models were developed and the results are depicted in this section. The results are mutually influenced and need to be observed together in the final consideration.

5.1. Electric power system scenario selection

The scenarios selection needs to be performed in such a way to include the limitation and average scenarios and possible grid conditions (Table 3).

Table 3 Croatian currently operational wind power plants data

Power flow scenario analysis	**Total load (MW)**	**Solar scaling factor**	**Hydro scaling factor**	**Wind scaling factor**
Average hydrology – high demand	3300 (≈ P_{max})	100%	55%	60%
Average hydrology – avg. demand	2640 (≈70% P_{max})	100%	55%	60%
High hydrology – low demand	1750 (≈50% P_{max})	75%	100%	85%
High production – low demand	1650 (≈50% P_{max})	100%	80%	75%

Developed transmission network model (110 kV, 220 kV and 400 kV voltage levels) was performed in the PSS/E software [27] while considering neighboring countries and flows through interconnection lines (Figure 10).

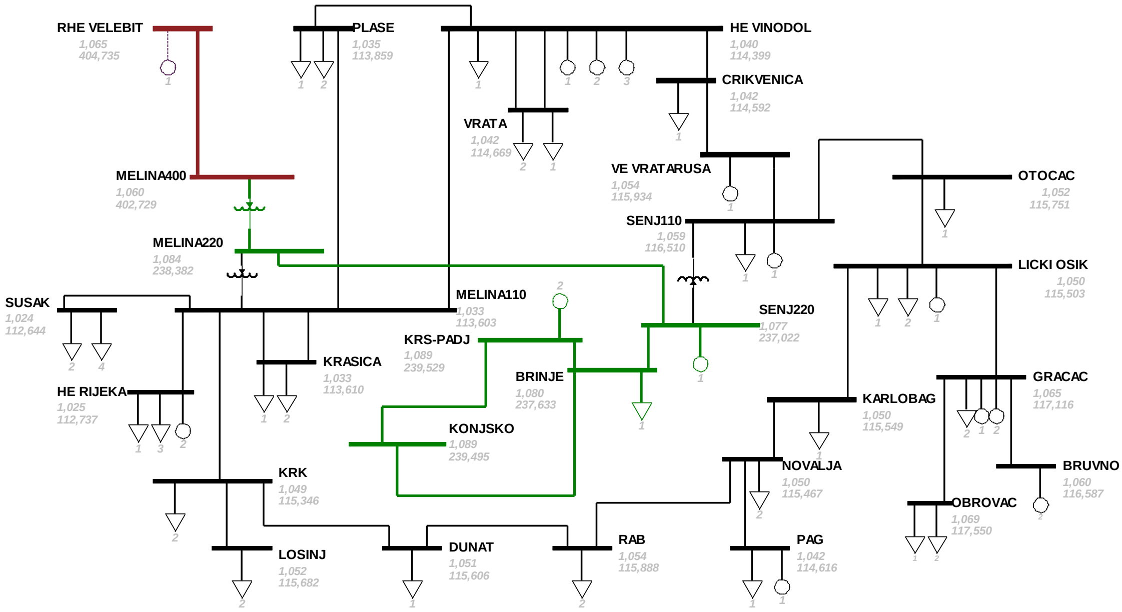

Figure 10 Observed segment of the Croatian transmission network with the inclusion of relevant planned projects

The results show that the limiting scenario is the high hydrology and low demand one when majority of the production from the south and coastal region needs to be exported to the northern parts of the country. This makes the system especially vulnerable to the outage of the main 220 kV and 400 kV routes. Table 4 shows an excerpt of the results.

Table 4 Croatian currently operational wind power plants data

Scenario	Transmission line 220/110 kV	Before the WPP connection	After the WPP connection
		Loading [%]	Loading [%]
Average hydrology – high load	Senj–Melina	71	112
	Senj–Brinje	26	79
	Brinje–Krš-Pađene	29	33
	Brinje–Konjsko	18	26
High hydrology – low demand	Senj–Melina	81	121
	Senj–Brinje	31	81
	Brinje–Krš-Pađene	37	38
	Brinje–Konjsko	26	34

The same series of simulations were performed for the selected three grid connection variants. In conclusion the crude breakdown of results can be cast as following:

- Variant 1 has non-satisfactory power flow conditions and but is the most favorable from the cost estimation perspective;
- Variant 2 has in normal operation no significant impact on voltage/loading and no significant impact during contingencies (curtailment can be expected in contingency conditions (n-1 criteria)) and is in the middle of the range (in between variant 1 and variant 3) from the cost estimation perspective;
- Variant 3 is most favorable from the voltage/loading perspective and least favorable from the cost estimation perspective

The results are mutually influenced and need to be observed together in the final consideration.

5.2. Connection requirements optimization

Starting from the source, wind turbines, there are several aspects covered before the point of connection is reached including the electrical connection of the wind turbines inside the wind park and including the connection of the wind farm. To assess the losses the wind resource availability was assumed to follow the modified Weibull distribution and in general the assumed available outputs are given in the table below (Table 5).

Table 5 Expected available power distribution

Wind speed group	Hours a year (h)	Power generated (MW)
1	1409	0
2	699	1
3	774	10
4	864	20
5	824	45
6	726	75
7	666	115
8	496	175
9	471	230
10	366	270
11	382	300
12	247	310
13	835	315

The main question to be answered was how 110 kV connection line from the wind turbines compare to the 400 kV connection. Assumed route of the connection transmission line is depicted on the figure below (Figure 11).

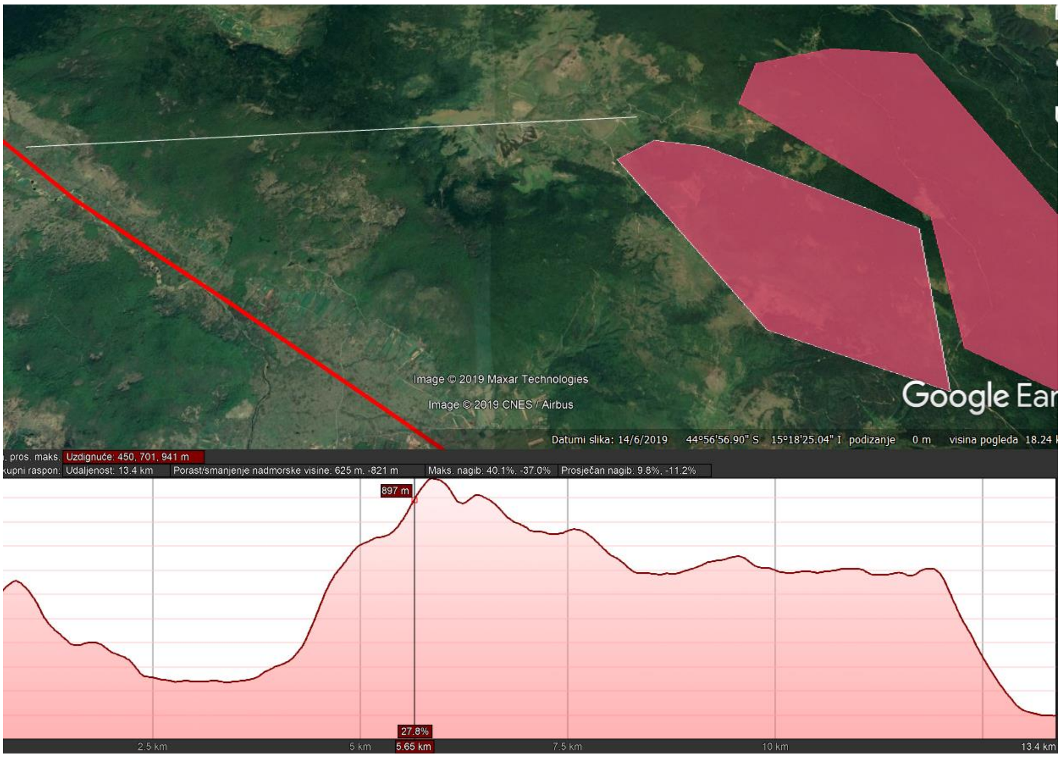

Figure 11 Predicted route from the WPP location 1 to the current EPS infrastructure

The model used to determine the losses amounts was developed in specialized software NEPLAN [28] and is shown on the figure below (Figure 12).

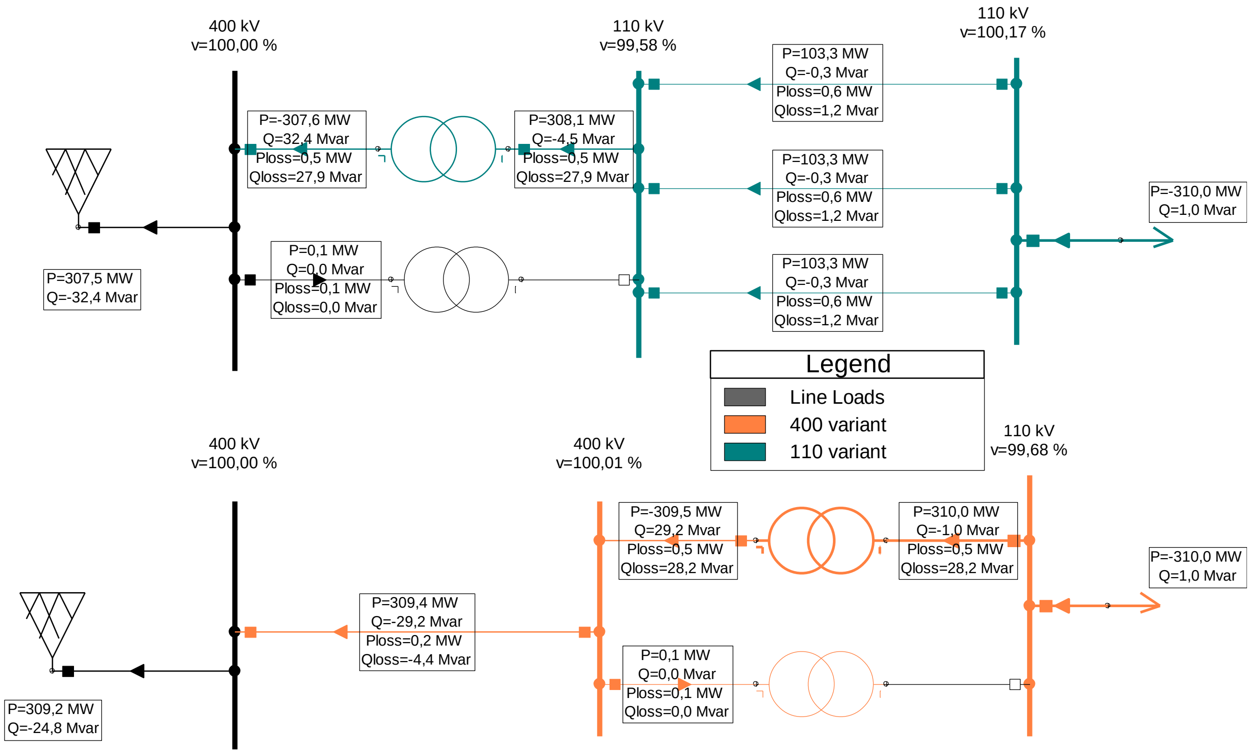

Figure 12 The comparison between 110 kV and 400 kV connection line variants

For the output power of 300 MW the loses amount to 3 MW which considering the predicted availability hours comes down to almost 1,5 GWh of energy losses. The difference approximation of losses for 110 kV and 400 kV connection routes on a yearly basis is ≈8 GWh which sums up for assumed energy price of 30 EUR/MWh to ≈240.000 EUR yearly. The difference stems from the additional losses that occur on the several 110 kV lines compared to one 400 kV line.

5.3. Wind power plant internal layout optimization

Based on the potential and assumed coordinates of the wind turbines the georeferenced electrical model of the WPP was created (Figure 13). All the distances between the turbines are equal to the real distances. Additionally, the elevation and topology have been considered to a certain degree when determining the cable routes.

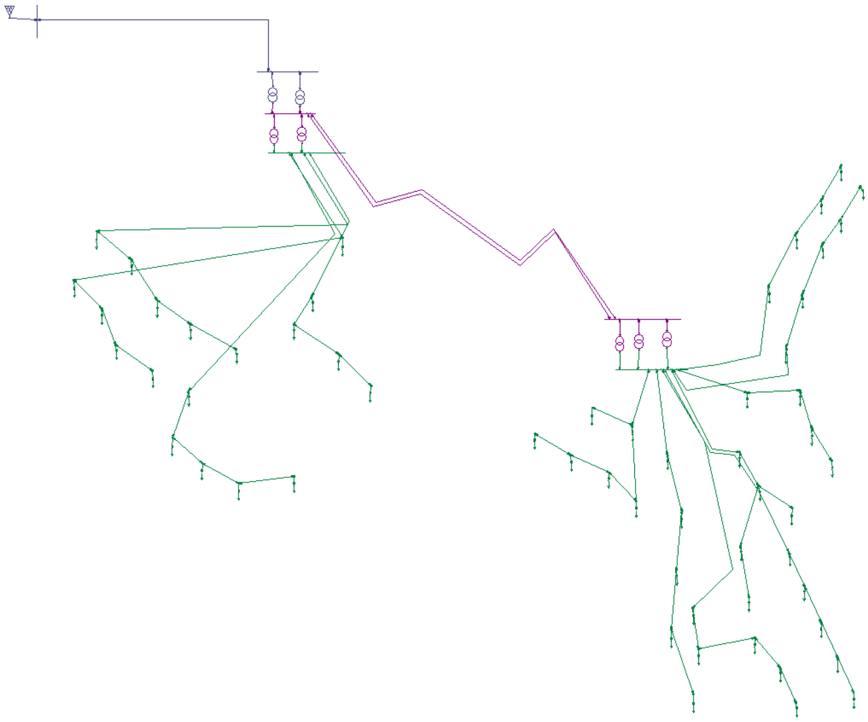

Figure 13 Part of the case study wind power plant georeferenced model

The layout that is depicted here uses the 30 kV voltage for the cables connecting the turbines (approximately 70 km) and uses the 110/30 transformation (4 transformers with total 400 MVA capacity) and 110 kV cables in length of approximately 11 km. The total losses on such layout are around 3,5 MW or 1% for the maximum output power. The losses up to a point of 110/400 kV transformation are around 2,5 MW level for a maximum power. This means that at the point where further step up voltage transformation is to be conducted the maximum output of the WPP is reduced for approximately 1% and then further reduced due to transmission and transformer losses to the point of connection (400 kV line Velebit-Melina) which means that approximately 310 MW out of maximum listed 315 MW (Table 5) is available at the PCC (point of common coupling). More detailed losses numbers are shown in the table below (Table 6) for the different voltage levels (internal WPP 30 kV, connecting 110 kV and 400 kV) and transformers.

Table 6 Medium voltage levels (30 kV and 110 kV) losses estimation of the WPP for the main targeted wind speed groups

Wind speed group	**WTG power generated (MW)**	**Total Losses (MW)**	**Losses 400 kV lines (MW)**	**Losses 110 kV lines (MW)**	**Losses 30 kV lines (MW)**	**Losses TR 400/110 (MW)**	**Losses TR 110/30 (MW)**
1	0	0,779	0,005	0,005	0,150	0,238	0,679
2	1	0,776	0,005	0,005	0,170	0,238	0,697
3	10	0,778	0,006	0,006	0,171	0,230	0,697
4	20	0,798	0,007	0,008	0,138	0,242	0,679
5	45	0,848	0,012	0,015	0,108	0,249	0,679
6	75	0,972	0,026	0,035	0,038	0,271	0,678
7	115	1,259	0,055	0,079	0,131	0,317	0,676
8	175	1,806	0,111	0,163	0,452	0,408	0,672
9	230	2,612	0,196	0,288	0,923	0,541	0,664
10	270	3,437	0,281	0,415	1,406	0,677	0,657
11	300	3,951	0,335	0,494	1,708	0,762	0,651
12	310	4,162	0,357	0,526	1,831	0,798	0,649
13	315	4,443	0,365	0,539	2,079	0,810	0,648

The production (generator) voltage and corresponding block transformation were not considered but they account for additional losses which are unavoidable and consist of transformer losses (e.g. 1 kV to 30 kV) and internal turbine losses. The 20 kV voltage level was discarded since it generated to much losses on the given distances.

6. CONCLUSION AND FUTURE WORK

This paper deals with the problems of the wind power integration into the Croatian electric power system. It gives an overview of the current status and detects some of the problems associated with wider integration of wind energy and other renewable energy sources in general. It shows through a case study multiple layers of simulation and calculation that needs to be done in order to optimize the grid connection scheme. The impact is threefold, from the electric power system perspective, through the connection variant to the internal wind power plant layout.

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