The Influence of Wind Park Krš-Pađene on Reliability Indices of 110 kV Transmission Network

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***Abstract*—This paper presents the reliability assessment of the southern part of Croatian transmission network and the influence of the wind farm on reliability indices. Croatian Electric Utility (HEP) Renewable Energy Sources with partner C.E.M.P. is developing wind farm in the region near town Knin. Wind farm will have installed capacity of 100 MW in the first phase. In the second phase additional 40 MW is planned to be installed. For the purpose of this paper, it was assumed that wind farm consist of the 50 turbine units, 2 MW each. Reliability assessment was performed, and reliability indices were computed for the case before and after construction of the wind farm. The reliability is analyzed using state enumeration method and NEPLAN software. Input data were obtained from annual reports of HEP TSO (Transmission System Operator) and statistic analysis of data was performed first. Since there are no statistical data for new cables and transformer stations that are constructed, input data for them were taken from the relevant literature. Probability of wind farm production level is taken from measured wind statistics. In reliability assessment Markov state space model of the wind generator, busbars, transformers, breakers and disconectors was used. Load is modeled at the output substation busbars with maximum active and reactive power. The simulations are performed in order to calculate reliability indices before and after the construction of wind farm. Conclusions and comments on the results are presented at the end of the paper.**

I. Introduction

The wind power generation is becoming increasing in many countries (Croatia as well) as a results of technology improvements, decreasing technology costs, active government policies for renewable energy sources, environmental concerns etc. Even through 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 generating system. Wind is not always available and conventional sources must supply the load demand in these quiescent periods. Wind variability confronts the operator with the technical problems of matching the load to the available power and protecting the wind turbine generator from gales [1]. Integration of large wind farms with utility grids raises questions regarding the reliability of the overall system and how the system reliability is influenced by factor such as the wind regime. The goal of electrical power system is secure and reliable electricity supply of costumers at minimum costs.

Due to the complexity of power system, its stochastic nature and its extremely large number of component, performing an adequacy assessment and analyzing the system performance for a practical system, is a very sophisticated work and requires a long computational time. Such analyses include many aspects such as load flow analysis, contingency assessment, generation rescheduling, transmission overload alleviation, load curtailment etc. The analytical approach is one of the most common methods applied for reliability assessment of power systems. Results obtained from applying this approach provide an appropriate benchmark for evaluating the system performance and its reliability. Reliability is the probability of a device or system to perform its function adequately, for the period of time intended, under the operating conditions intended [2].

In this paper, the reliability assessment of the southern part of Croatian transmission network HEP TSO Split in the region around the town Knin is performed using NEPLAN software. Motivation for this analysis is planned construction of new wind farm with installed capacity of 100 MW in that region. The reliability indices were computed for two cases: before and after construction of a new wind farm.

Structure of this paper is as follows: first, a brief theoretical introduction to Markov model and wind turbine reliability model is done in Section II. In Section III, methodology for reliability indices calculation is presented. Section IV deals with technical data about wind park and suggested computer model of wind park and local transmission system. The explanation of simulation cases and discussion on results are done in Section 5. Short conclusion and comments on the model are made at the end of the paper.

II. Mathematical Model of Components

This section explains basic theoretical backgrounds of reliability assessment in power system. The basic concept of power system reliability assessment is the calculation of reliability indices of power system or its parts based on the

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available data for reliability and availability of power system components. Power system reliability indices can be calculated using a variety of methods. The two main approaches are analytical and simulation. The analytical state enumeration method is used in this paper. Analytical techniques represent the system by a mathematical model and evaluate the reliability indices from this model using direct numerical solutions. They generally provide expectation indices in a relatively short computing time. Unfortunately, assumptions are frequently required in order to simplify the problem and produce an analytical model of the system [3].

A. Markov Processes

The behavior of the components and the system can be described using Markov process. It is stochastic process that can be described with two random variables: state of the component (system) and duration time. Both of these state variables can be discrete or continuous. Markov chain is when both of the state variables are discrete. Markov process is when state of the component variable is discrete and time variable is continuous. The theoretical development of the Markov approach is discussed in considerable detail by Feller [4] particularly with regard to processes that are discrete in time and space. The reliability problem normally deals with a system that is continuous in time and discrete in space [5].

B. Markov Model of Reparable Components with two Different States

Power system elements (transformers, generators, lines, cables, busbars, etc.) can be considered as reparable components. Regarding to reliability of supply, they can have two different states – they are either available (ready to operate) or unavailable, i.e. blocked [6-7]. Two states component model is the model most simplified in use, since it gives the best description of the continuous operation of a component. It is presented in Fig. 1.

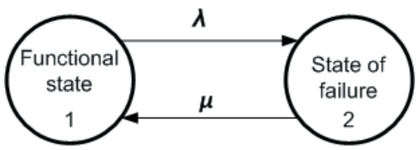

Fig. 1. Model of a component with two states

Symbols:

- 1 = functional component ,
- 2 = blocked component,
- λ = component failure intensity,
- μ = component repair intensity.

Probability of being in a state 1 and 2 is:

$$P_1 = \frac{\mu}{\lambda + \mu}, \quad P_2 = \frac{\lambda}{\lambda + \mu} \tag{1}$$

Frequency of being in a state 1 and 2 is:

$$f_1 = \lambda \cdot P_1 = \frac{\lambda\mu}{\lambda + \mu}, \quad f_2 = \mu \cdot P_2 = \frac{\lambda\mu}{\lambda + \mu} \tag{2}$$

C. A Wind Turbine Output Characteristic

The electric output of the wind turbine (WT) 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.

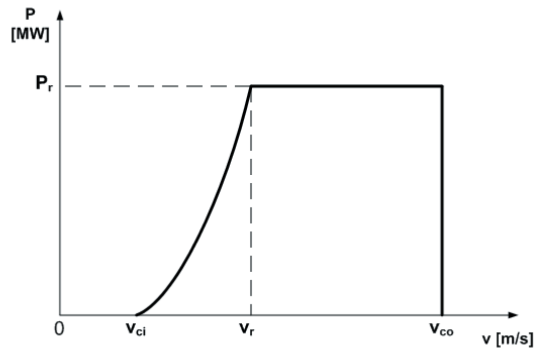

Fig. 2. Wind turbine output characteristic

The parameters in Fig. 2 are:

- P_r = rated power output,
- v_{ci} = cut-in wind speed,
- v_r = rated wind speed,
- v_{co} = cut-out wind speed.

The WT power output can be calculated as [6]:

$$P = \begin{cases} 0 & 0 \le v \le v_{ci} \\ (A + Bv + Cv^2)P_r & v_{ci} \le v \le v_r \\ P_r & v_r \le v \le v_{co} \\ 0 & v \ge v_{co} \end{cases} \tag{3}$$

The constants A, B and C may be found as functions of v_{ci} and v_r using the following equations [6]:

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

$$B = \frac{1}{(v_{ci} - v_r)^2}\left[4(v_{ci} + v_r)\left[\frac{v_{ci} + v_r}{2v_r}\right]^3 - (3v_{ci} + v_r) \right] \tag{5}$$

$$C = \frac{1}{(v_{ci} - v_r)^2}\left[2 - 4\left[\frac{v_{ci} + v_r}{2v_r}\right]^3 \right] \tag{6}$$

D. Wind Turbine Reliability Model

In this paper, Markov model with two states is used for WT reliability model. The output power of WT depends on wind speed. Based on the real wind speed measurement [8] in Croatia, the wind speed probability distribution is derived and shown in Fig. 3.

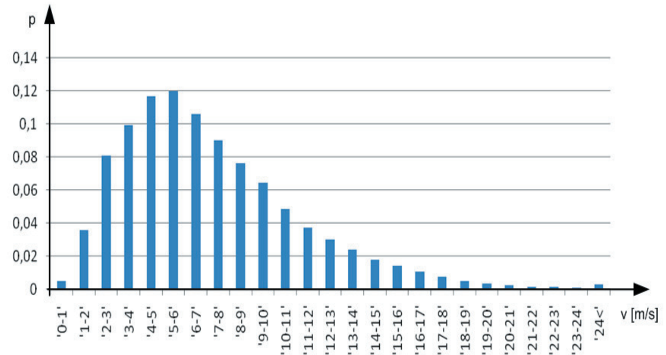

Fig. 3. Wind speed probability distribution

According to equation (3) and probability distribution, WT output characteristic is made. Rated power of WT is 2 MW. Fig. 4 represents the output characteristic of used WT.

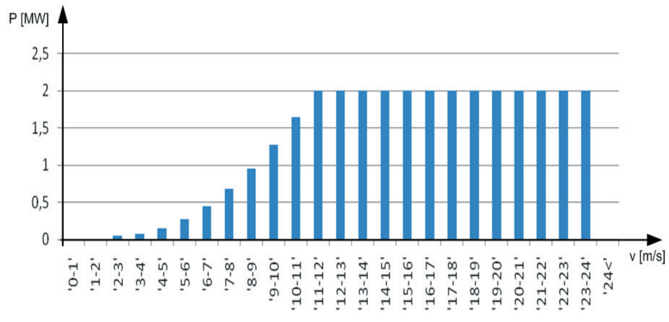

Fig. 4. Output characteristic of 2 MW WT

Cut-in speed of used WT is $v_{ci}=2.5\ m/s$, rated speed is $v_r=12\ m/s$ and cut-out speed is $v_{co}=24\ m/s$. When output power is between 80% and 100% of rated power, it is assumed that WT is in functional state (available). For all other output powers, WT is not available (state of failure). Based on the measurement statistics, availability of used WT is $A = 0.205578$ an unavailability is $U = 0.794422$.

III. Reliability Indices Calculation

In this paper NEPLAN software is used for reliability assessment. NEPLAN applies system state enumeration method based on Markov model explained in previous chapters [9]. The enumeration method is analytical approach where all relevant possible states of the system are analyzed one by one. A fast "topological" state enumeration method is used which ensures that each possible system state is only analyzed once.

Realistic state frequencies (average occurrences per year) are calculated by considering only the transitions from a working state to outage one and back again. Calculation of power flow is performed using Newton-Raphson method. In reliability evaluations, calculation of load flows must be repeated for each state that is simulated in the process and several times if the system load changes are considered.

The network reliability assessment produces two sets of indices:

- Load point indices
- System indices

The expected values of supply interruption indices on consumer busbars (load point) are calculated in the following way:

Supply interruption probability:

$$P_k = \sum_j P_j \cdot P_{kj} \tag{7}$$

Supply interruption frequency (1/year):

$$f_k = \sum_j f_j \cdot P_{kj} \tag{8}$$

Expected undelivered power due to interruption (MW/year):

$$\Delta L_k = \sum_j L_{kj} \cdot f_j \tag{9}$$

Expected undelivered energy (MWh/year):

$$\Delta W_k = \sum_j L_{kj} \cdot r_{kj} \cdot f = \sum_j L_{kj} \cdot P_{kj} \cdot 8760_j \tag{10}$$

Expected supply interruption duration (h/year):

$$r_k = \sum_j r_{kj} \cdot f_j = \sum_j P_{kj} \cdot 8760 \tag{11}$$

where:

- P_j = event probability *"j"*,
- P_{kj} = probability of consumption in point *"k"* being higher than the maximal power that can be supplied (determined by the power flow analysis, $P_{kj} = 0$ if consumption is not higher than the possible power that can be supplied, $P_{kj} = 1$ if it is),
- f_j = event frequency *"j"*,
- L_{kj} = undelivered power at point *"k"* due to event *"j"*,
- r_{kj} = mean time of supply interruption duration at point *"k"* due to event *"j"*.

System indices of the network reliability assessment are:

- **SAIFI** - System Average Interruption Frequency Index [1/C/yr], is the mean interruption frequency found by dividing by the total number of customers in the analyzed system,
- **SAIDI** - System Average Interruption Duration Index [min/C/yr], is the mean time per year that customers are interrupted, by dividing by the total number of customers in the analyzed system,
- **CAIDI** - Customer Average Interruption Duration Index [h], is the mean duration per interruption,
- **ASAI** - Average Service Availability Index is the probability of having one or more loads interrupted,
- **F** – System Load Interruption Frequency [1/yr],
- **T** – System Load Interruption Mean Duration [h],
- **Q** – System Load Interruption Probability [min/yr],
- **P** – Total interrupted Load Power [MW/yr],
- **ENS** - Energy Not Supplied [MWh/yr], the total amount of energy which is expected not to be delivered to the loads.

IV. Wind Park Krs-Padene and Computer Model

A. Technical Description of Wind Park

Wind park is planned to be built near town Knin in Southern Croatia (region Dalmatia). It will have installed capacity of 100 MW in the first phase. In the second phase additional 40 MW is planned to be installed. Only the first phase is analyzed in this paper. Fig. 5 represents WT ENERCON E-82 that will be used for the wind park. 50 WT will be installed in the first phase. Basic technical data of wind turbine are presented in Table I.

Fig. 5. WT ENERCON E-82

Wind park will be connected to the transmission network via new transformer station 110/30 kV. Substation will have three transformer of 63 MVA rating.

B. Computer Model of a Wind Park

Two NEPLAN models of HEP TSO transmission network Split are created: one before installing the new wind park and other after installing it. Computer model contains in detail modeled transmission network, generators, transmission lines, transformers, loads, busbars, cables, breakers etc. of southern Croatia (Transmission Area Split). Wind park is modeled as 50 generators with installed capacity of 2 MW each

The new transformer substation (110/30 kV) with thre transformers rated power 63 MVA each and associated two 110 kV transmission lines connected with TS 110/35 kV Knin are also modeled. The rest of transmission system is modeled also. Computer model of wind park is given in Fig. 6.

In reliability assessment Markov state space model of primary substation components such as busbars, transformers, breakers and disconnectors was used. Transmission lines and generators are also modeled in reliability assessment. Load is modeled at the LV side of transformer substation busbars with maximum active and reactive power. All necessary data for reliability analysis are obtained from the available statistical publications of Croatian electric utility HEP [10]. Since there are no statistical data for new transformers and lines, input data for them were taken from the relevant literature [11] and [12].

TABLE I
Wind Turbine Basic Data

Rated power	2000 kW
Rotor diameter	82
Tower hight	70m, 78m, 98m, 108m
Turbine	Without gearbox, variable speed, varijabilna „pitch“ control
ROTOR	
Type	With active „pitch“ control
Rotacion direction	Clockwise
Plate numbers	3
Working plane	5281 m^2
Blade material	Fiberglas; integrirana zaštita od groma
Wind generator speed	6 – 19,5 okr/min
Maksimum speed	25 80 m/s
Generator	„Direct drive“ synchronous with rings
Grid connection	Inverter
Braking mechanism	3 independant „pitch“ mechanism with emergency power supply; braking rotor; lock-up rotor
Blade control	Active
Switch on speed	2,5 m/s
Rated speed	12 m/s
Switch on speed	22-28 m/s
SCADA control	ENERCON SCADA

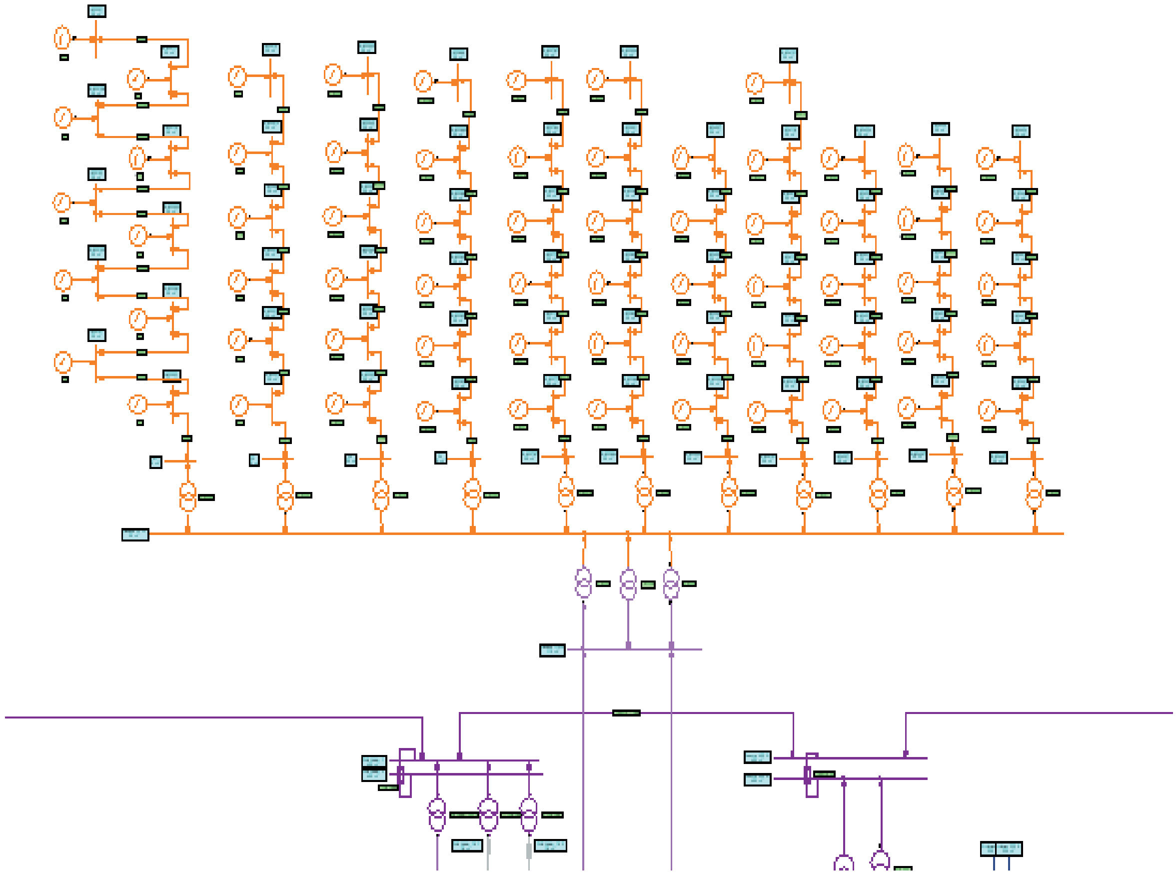

Fig. 6. Computer model of wind park integrated in HEP TSO Split

V. Simulations and Results

Reliability indices explained in Chapter III are obtained for every case. Summary results can be seen in Table II.

TABLE III
RELIABILITY INDICES

Index	Before wind park installation	After wind park installation	Unit
SAIFI	2.21622	0.676	1/C/yr
SAIDI	312.46818	98.27404	min/yr
CAIDI	2.34986	2.42293	h
ASAI	99.94055	99.9813	%
F	48.57329	32.60778	1/yr
T	2.66046	2.71584	h
Q	7753.64528	5313.45597	min/yr
P	1765.61928	514.85192	MW/yr
ENS	3843.94544	1193.04328	MWh/yr

As can be seen in Table I, after installation of wind park almost all reliability indices are improving significantly. Only indices CAIDI and T are higher when wind park is installed.

For example, Fig. 7 shows comparison of SAIFI (System Average Interruption Frequency Index) before and after wind park installation. In the second case, SAIFI approximately is four times less than in the first case.

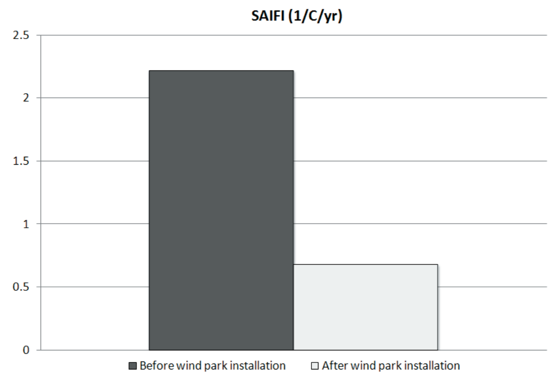

Fig. 7. SAIFI before and after of construction of the wind park

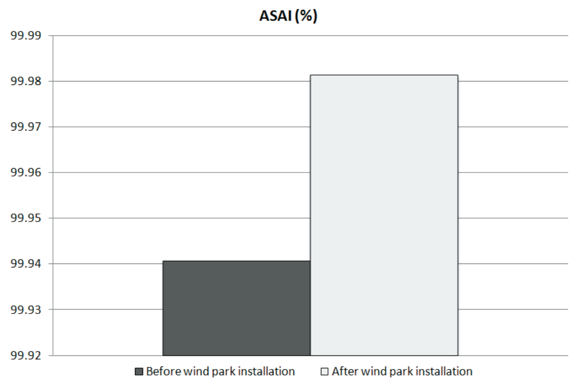

Fig. 8. ASAI before and after of construction of the wind park

As can be seen in Fig. 8 average system availability index ASAI is improved after wind park installation. Simulation shows positive effect of wind park on the system availability in the case of Krs-Padene.

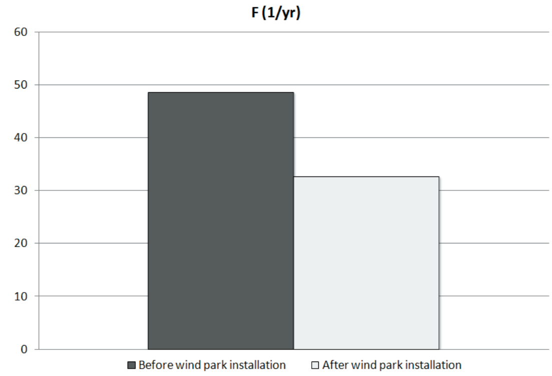

Fig. 9. Index F before and after of construction of the wind park

After wind park construction, system load interruption frequency F is decreased as can be seen in Fig. 9.

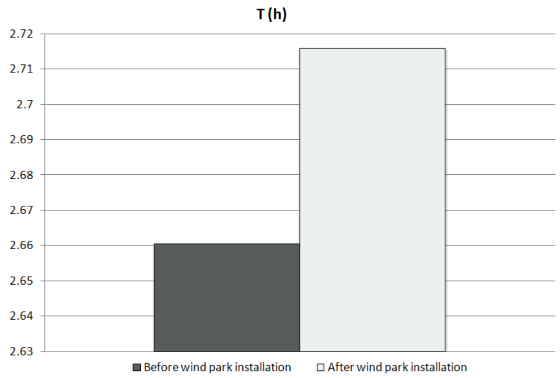

Fig. 10. Index T before and after of construction of the wind park

System load interruption mean duration T is increased in the second case. The reason is since more than 50 new components were added in system i.e. wind generators, transformers, cables and transmission lines.

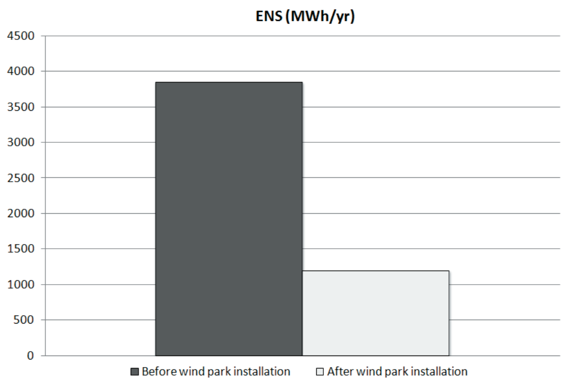

Fig. 11. ENS before and after of construction of the wind park

As an important index, ENS is decrease in the second case. The effect of the wind park is with very positive effect on customers in Knin region..

VI. Conclusion

Results of reliability assessments modeling and simulation of southern Croatian transmission network (HEP-TSO Split) are presented in this paper. Two cases are simulated: before and after installation of 100 MW wind park. Simulation were performed using Markov state space model and state enumeration approach implemented in NEPLAN software Results show improvement of almost all reliability indices which makes investment in new wind park justified and reasonable. Only the indices related with interruption duration time are worsening. The reason for that is in large number of new wind generators, cables and transformers (50) that are installed in the wind park. Repairing time for wind generator is higher than for conventional generator due to specific construction of the wind power plant.

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