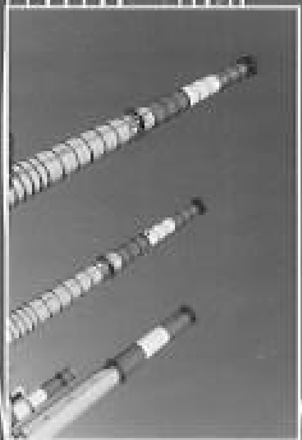
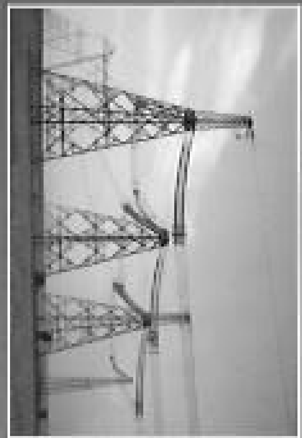
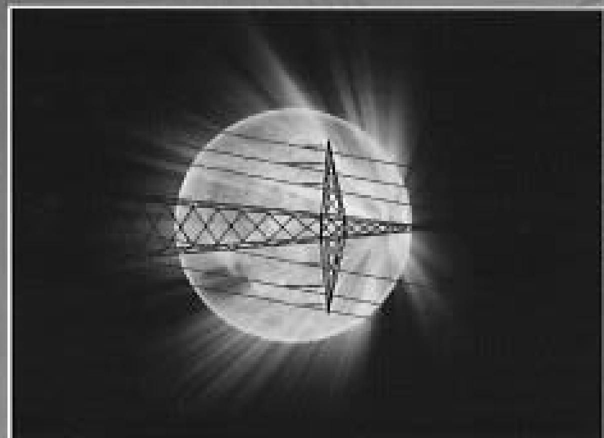
ISSN br. 0354-8651

List Saveza energetičara
Broj 1-2 / Godina XIX / Mart 2017.
UDC 620.9

energija

■ ekonomija ■ ekologija


ENERGETIKA 2017

ENERGETIKA 2017.

XXXIII međunarodno savetovanje

energija
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ekologija

ENERGETIKA 2017.

Pokrovitelj savetovanja

Ministarstvo rudarstva i energetike,
Ministarstvo prosvete, nauke i tehnološkog razvoja,
Ministarstvo poljoprivrede i zaštite životne sredine,
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ZBORNIK RADOVA
Zlatibor, 28.03. - 31.03.2017

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UDC: 621.311.24.004

Comparative Analysis of Energy Production of Wind Turbines with Double-Fed Induction Generator (DFIG) and with Conventional Induction Generator

ABSTRACT

In this paper, a comparative analysis of the energy production obtained from wind turbine with two different types of induction generators modeled for the same location is presented. Both induction generators – double-fed induction generator (DFIG) and the conventional induction generator (IG) are simulated using the same input wind conditions. The analysis was done using real measured data for the entire 2012 at the location of recently developed wind park location near the city of Bogdanci, South Macedonia.

The objective of this paper was to compare obtained results using mathematical model developed in Matlab/SIMULINK environment with the really achieved production at the same site, proving the model accuracy. The results show that DFIG yields up to 40% larger energy production in relation to conventional IG and should be considered for locations with time-varying wind conditions.

Key words: power generation, renewable sources, wind turbine, DFIG, induction generator

УПОРЕДНА АНАЛИЗА ПРОИЗВОДЊЕ ЕНЕРГИЈЕ ВЕТЕРНИХ ТУРБИНА СА ДВОСТРУКО-НАПАЈАНИМ АСИНХРОНИМ ГЕНЕРАТОРОМ (DFIG) И СА КОНВЕЦИОНАЛНИМ АСИНХРОНИМ ГЕНЕРАТОРОМ

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АБСТРАКТ

У овом раду, приказана је упоредна анализа производње енергије добијене из ветроелектрана са две различите врсте асинхроних генератора на истој локацији. Оба асинхрона генератора – двоструко-напајани асинхрони генератор (DFIG) и конвенционални асинхрони генератор (IG) се симулирају коришћењем истим условима ветра. Анализа је извршена применом реално измерених података за целу 2012 годину на локацији недавно развијеног ветерног парк на локацији у непосредној близини града Богданци, на југу Македоније.

Циљ овог рада је био да се упореде добијене резултате уз помоћ математичког модела развијеног у Matlab/SIMULINK окружењу са стварно остварене производње на истолокации и под истим условима, тиме доказујучи тачност модела. Резултати показују да ветрогенератор са DFIG даје і до 40% већу производњу енергије у односу на ветрогенератора са конвенционлним ИГ и треба истог користити за локације са временски променљивим условима ветра.

Кључне речи: електроенергетика, обновливи извори, ветерне турбине, DFIG, асинхрони генератор

1. INTRODUCTION

The kinetic energy of the wind for years was used by the people to aid in their everyday work such as in windmills for milling grains, for pumping water for irrigation or drinking, for pressing grapes or olives, etc. In the recent years, the kinetic energy of the wind is mainly used for producing electricity as the most sophisticated energy resource. The kinetic energy of wind using so-called wind turbines firstly is converted into mechanical energy at the turbine's shaft and later this mechanical energy is transformed into electrical energy utilizing various types of electric generators, e.g. DC generators or AC synchronous or induction generators [1].

As we know, the kinetic energy of the wind has a stochastic nature, so one cannot predict its availability, speed and direction of the wind at any point of time, thus the rotation speed of the wind turbine, and accordingly the rotor speed of the generator could not be constant with the time. Therefore, the frequency of induced electric voltage cannot be constant, too, resulting with problems for direct connection of the wind turbines to the common electricity grid. This problem is usually solved using an adequate frequency converter that converts the generated voltage and frequency by the wind generator into suitable network voltage and frequency of the grid to which the wind turbine is connected. This process usually is call synchronization of the wind turbine with the power grid. These power converters consist of various power electronic elements, mostly IGB transistors and power diodes that regrettably cause additional power losses and reduce the efficiency of the turbines.

To aid in these matters, recently was proposed a special construction of the induction generator, so-called double-fed induction generator, or shortly DFIG *(Doubly-Fed Induction Generator) [2], [3]*. DFIG is AC induction machine that has two windings, in the stator and in the rotor, wherein both windings carry a significant portion of the active power between the generator's shaft and the power grid. In this case, the stator and the rotor windings are connected to the power sources, which are mechanical energy at the generator's shaft, at one side, and grid energy, on the other side, with different frequencies. The most common case is that the stator's windings are connected directly to the three-phase grid network while the rotor's windings are connected also with the three-phase grid network, however indirectly through specially designed three-phase power converters. The biggest advantage of this DFIG is its ability to operate at different speeds of the incoming wind, this having a significantly larger operational range in comparison with the conventional induction generator (IG). This is due to the fact that the power converters are not connected to the stator's windings, but rather to the rotor's windings, thus enabling the adjustment of the rotor speed with the variations of the stator generated synchronous magnetic field at different turbine speed propelled by various wind speed.

In this paper, the authors briefly describe the differences in the operation and the generated power between wind turbine with DFIG and wind turbine with conventional IG. The comparison is based on the real measured data of the wind speed for a period of one whole year at the Bogdanci wind farm located in the southeastern part of the Republic of Macedonia. On the basis of the operational characteristics and the developed mathematical model, comparison between two types of generators was done for the active and reactive output power. The objective of this work was to compare the production results already generated at the wind power plant with the simulated results for the same input data and at the same location for DFIG-driven wind turbines, using program package Matlab/SIMULINK. The compared simulated results showed large compliance with the experimentally obtained ones. The simulated results using DFIG-driven wind turbines at the same location and for the same average wind speed could yield up to 40% higher energy production, in comparison with the energy production by conventional IG-driven wind turbines.

2. WIND TURBINE ENERGY CONVERSION

Wind turbine is an electro-mechanical device that converts kinetic wind energy into electrical energy. Wind is a clean renewable energy source that does not emit any harmful gases and can constantly be used for electricity production as a result of its renewable characteristic. There are several commercial types of wind turbines today in operation. However, all work on the basis of a single principle - transformation of the mechanical momentum carried by the aerodynamic forces on the blades of the turbine rotor into mechanical energy on the turbine's shaft and later into an electrical energy by means of electric generator. Most of the wind turbines today in their drive train include a gearbox, a mechanical gear drive transmission system between the turbine and generator. Its task is to transform the large but low speed momentum at the shaft of the turbine into a smaller but high speed rotation momentum at the shaft of the generator. Some of the modern types of wind turbines are gearless and use complex power converters to adjust the low speed of the turbine shaft and low frequency generated power into desired voltage and frequency of the power grid [1].

Albeit the turbine type and construction, the generated power of a wind turbine equals to:

$$P_m = \frac{1}{2}\rho A v^3 C_p(\lambda) \quad (1)$$

or

$$P_m = \frac{1}{2}\rho \cdot r^2 \pi v^3 C_p(\lambda) \quad (2)$$

where, P_m is the power of wind in *[W]*, ρ is the air density in *[kg/m³]*, *A* is the surface area covered by the blades of the turbine in *[m²]*, *r* is the radius of the turbine rotor in *[m]*, *v* is wind speed in *[m/s]*, $C_p(\lambda)$ is the coefficient of Betz, and λ is speed coefficient at the tip of the blades, calculated using the expression:

$$\lambda = \frac{v_{per}}{v} \quad (3)$$

where, v_{per} is the peripheral speed of rotation of the blades and *v* is the speed of unimpeded wind.

Having in mind that the air density and the radius of the turbine rotor are fixed for particular location and turbine design, while the wind speed changes stochastically and cannot be controlled by the user, the only parameter that can be controlled to maintain maximum power output, is the coefficient of Betz, $C_p(\lambda)$.

This coefficient has the maximum theoretical value of 0.593 and it is strongly and non-linearly related to the pitch angle of the blades and the incoming wind speed. The turbine quality largely depends of this coefficient that varies for different turbine type and turbine manufacturer. A typical characteristic of the coefficient $C_p(\lambda)$ is presented in *Fig. 1*. Most wind turbines start producing electricity at an initial wind speed the so-called the cut-in wind speed between 3 and 4 *[m/s]*. Then they reach their rated power at a wind speed of

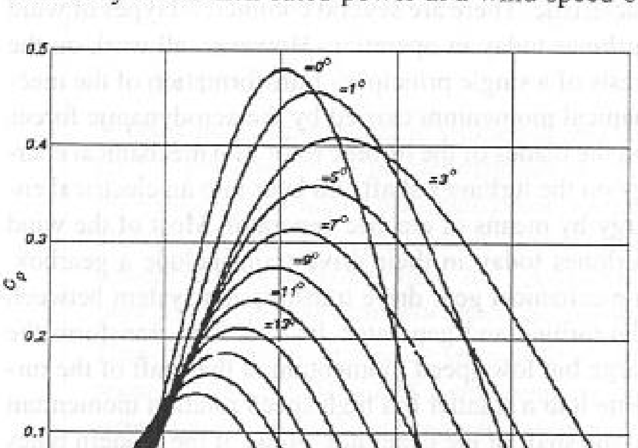


Fig. 1. - *Typical $C_p(\lambda)$ characteristic of a wind turbine.*

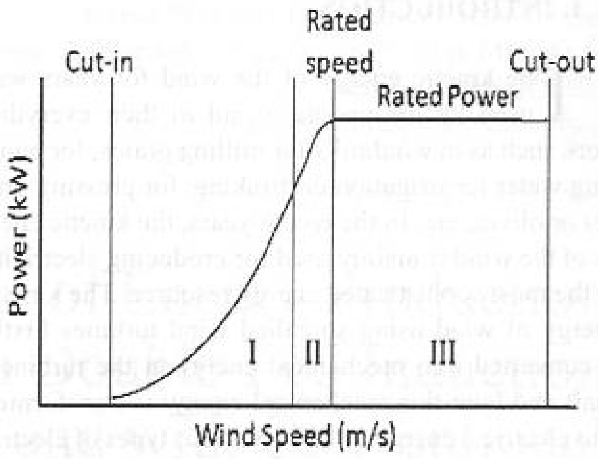


Fig. 2. - *Wind turbine power curve*

about 10 – 15 *[m/s]*. Finally, the wind turbines are cut from the grid at wind speed ≥ 25 [m/s], usually called as cut-out wind speed (see *Fig. 2*).

Analyzing *Fig. 1*, one can conclude that in the area of small and medium wind speeds, pitch angle is controlled so that the wind turbine can operate at an optimum mode. However, in the area of high speed using the pitch angle, part of the kinetic energy of the wind is discharged or lost in order to protect the wind turbine and its vital parts. Wind turbines usually deliver maximum power at wind speeds ranging from 10 to 15 *[m/s]*. For wind turbines with variable speed of rotation, the steering of the turbine is also done with the help of dynamic pitch angle regulation. As a result of this regulation and in order to maintain maximum power output of the turbine at various wind speed, the speed of the turbine is continuously adjusted based on the speed of the incoming wind. The dependence of the wind turbine power output on the rotational speed is graphically presented in *Fig. 3*. Moreover, from the (3) it can be concluded that the top speed at the tip of the blades of a wind turbine varies in a wide range depending on the value of the speed value of the incoming wind. However, from (2), it can be seen that the

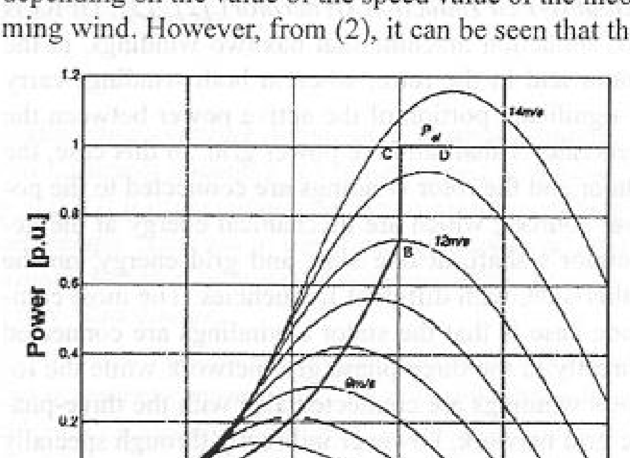


Fig. 3. - *Dependence of the wind turbine power output of rotational speed (per unit values).*

turbine achieves maximum power only when working with the same maximum power coefficient $C_p(\lambda)$. To achieve this goal, the rotor speed should be set so that it follows the appropriate change of the speed of the value of the incoming wind [1].

The technology for the operation of wind turbines at variable speeds with DFIG efficiently solves this problem. The rotor speed can be always controlled by means of managing the difference between the output electric power and power taken away from the wind. With dynamic pitch control DFIG-driven turbines could regulate the power extracted from the wind's kinetic energy and using converter could actively manage the power output of the turbine. As a result of these two regulations, one could successfully manage the speed of rotation of the rotor.

3. DOUBLE-FED INDUCTION GENERATOR (DFIG)

If we look at a wind turbine with conventional IG in terms of variable speed of rotation, then a squirrel-cage rotor induction machine could be used, because the frequency management is performed on the stator side. For such machine to operate in a generator mode, it is necessary its rotor speed to be higher than its synchronous speed, i.e. the rotor speed must be over-synchronous speed [4]. The more speed changes, becomes more difficult to achieve stable speed regulation. This is because for wind turbines directly connected to the grid the change in frequency is performed on the stator side using adequate energy convertors. The disadvantage of this approach is emphasized at large power generation where huge current leaks through the energy converter become unavoidable, and converter losses became significant. Thus, DFIGs were introduced in the wind turbine technology in which the power converters for frequency control are located on the rotor side, i.e. they adapt the frequency of rotor turning not frequency of the synchronous field of the stator [5]. A schematic block diagram of DFIG-driven wind turbine is presented in *Fig. 4*.

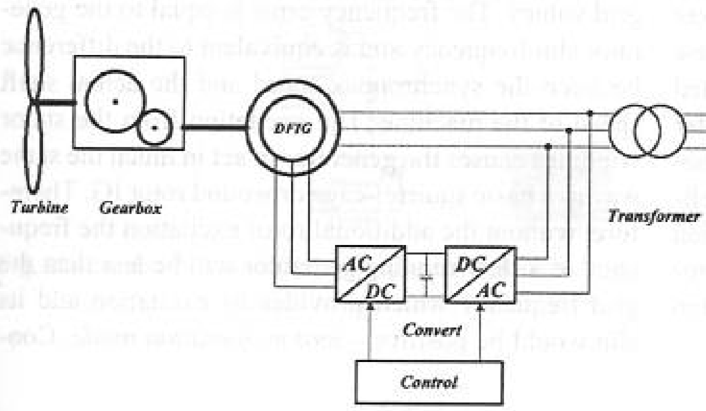


Fig. 4. - *Schematic block diagram of the DFIG-driven wind turbine.*

3.1. DFIG vs. conventional IG

In *Fig. 5*, the conventional IG-driven wind turbine with constant rotation speed is presented. Between turbine rotor and the induction generator an asynchronous multiplier i.e. gearbox is placed, typically a three-degree ratio up to 1:100. Thus, as IG usually four- or six-pole three-phase machine could be used to provide generated power with as close as possible frequency as the power grid. Such type of IG is quite simple, usually with squirrel-cage rotor and it is directly connected to the power grid of 50 or 60 Hz, using only a device that reduces the starting or short-circuits currents *(i.e. soft-start device)* which occur when the generator is switched to the grid. The load of the generator is limited by aerodynamic performance of the turbine blades, i.e. *"Stall principle"*, while the speed of the entire drive train *(turbine, gearbox and the generator)* varies very little around the nominal speed of the generator. The slip value of the IG is usually around *-1%* to *-2%*, thus the rotor losses have tolerably low values. Wind turbine cannot operate without connection to the power grid from which it takes reactive power for magnetization of the IG. In practice,

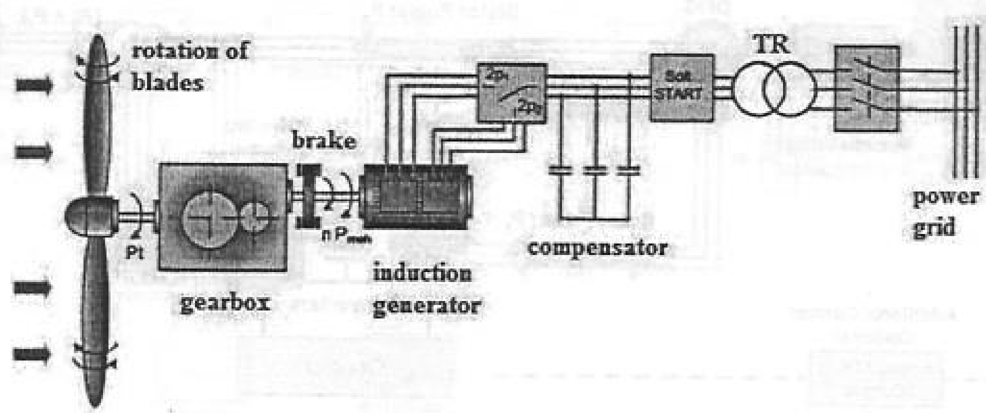


Fig. 5. - *Conventional two pairs of poles IG-driven wind turbine with constant rotational speed and two gears.*

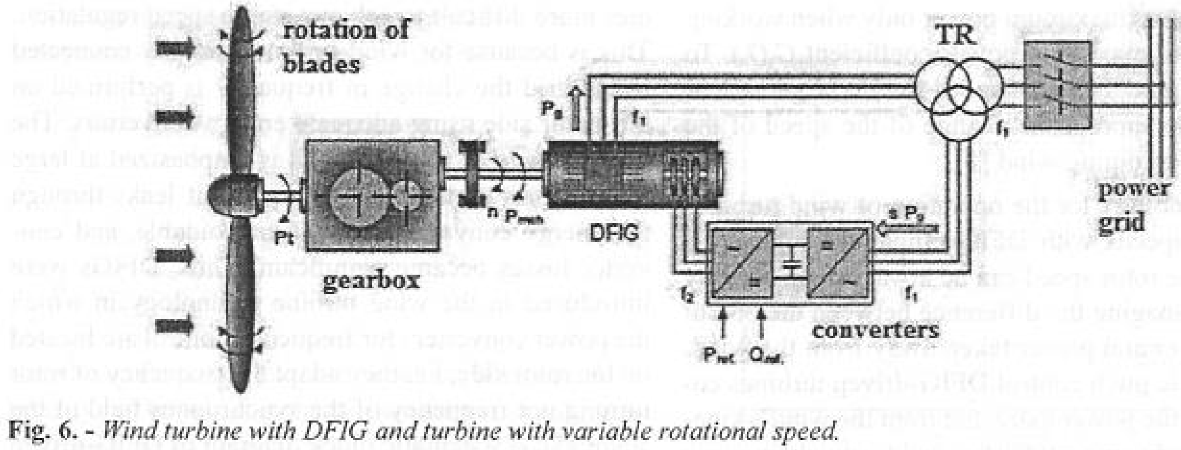


Fig. 6. - *Wind turbine with DFIG and turbine with variable rotational speed.*

fairly applied option is conventional squirrel-cage IG with variable number of pairs of poles and usually two gears as illustrated in the *Fig. 5* [5], [6].

To compare the construction differences between the previously explained conventional IG-driven wind turbine with constant rotational speed and DFIG-driven wind turbine with variable rotational speed, we use the *Fig. 6*. Under this case, the connection is realized with AC excitation current brought to the rotor windings, the frequency converter *(i.e. cycloconverter or bidirectional static frequency converter),* which is connected to the same power grid as the stator windings, as shown in *Fig. 6*. Due to this double-sided brought of excitation, this type of construction for the IG was named double-fed induction generator (DFIG). While the stator winding are connected to the power grid with rated frequency of 50 *[Hz]* over three-phase power transformer, the rotor windings are connected to the same power grid using a frequency converter and a custom transformer. In such construction scheme, because the stator field has fixed frequency defined by the frequency of the power grid, the rotation speed of the turbine could be harmonized with the rotor speed to achieve the optimum energy extraction from the turbine [5], [6].

The DFIG, besides getting its excitation current from the grid through the stator windings, also permits a second excitation current input, through slip rings to a wound rotor permitting greater control over the generator output. It consist of a 3 phase wound rotor generator with its stator windings fed from the grid and its rotor windings fed via a back-to-back converter system in a bidirectional feedback loop taking power either from the grid to the generator or from the generator to the grid. The basic generation principle of the DFIG can be easily grasped from the schematic operational diagram shown in *Fig. 7* [5].

The DFIG feedback control system constantly monitors the stator output voltage and frequency and provides error signals if these are different from the grid values. The frequency error is equal to the generator slip frequency and is equivalent to the difference between the synchronous speed and the actual shaft speed of the machine. The excitation from the stator windings causes the generator to act in much the same way as a basic squirrel-cage or wound rotor IG. Therefore, without the additional rotor excitation the frequency of a slow running generator will be less than the grid frequency which provides its excitation and its slip would be positive – *motor operation mode*. Con-

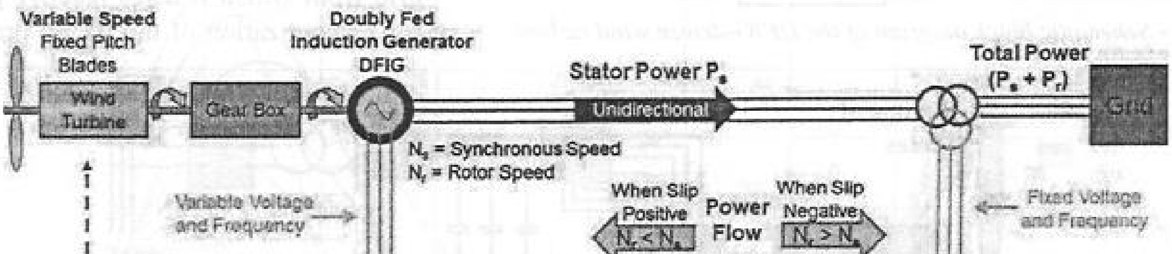


Fig. 7. - *Schematic operational diagram and power flow of typical DFIG-driven wind turbine.*

versely, if it was running too fast, the frequency would be too high and its slip would be negative – *generator operation mode*. The rotor acts as a storage barrier – it absorbs power from the grid to speed up and delivers power to the grid in order to slow down. Finally, when the machine is running synchronously, the frequency of the combined stator and rotor excitation matches the grid frequency, there is no slip and the machine will be synchronized with the grid.

4. MODELING OF THE POWER PLANT USING MATLAB/SIMULINK

Using the simulation program Matlab/SIMULINK simulations of two kinds of wind turbine systems were developed, one for conventional IG, and the other for DFIG [4] – [6]. The models we accommodated using already developed model of a wind power plants with installed capacity of 9 *[MW]* with a set of 6 wind turbines, each with an installed capacity of 1.5 *[MW]*, and connected over 25 *[kV]* local distribution system with the 110 [kV] transmission power grid. The output of those two wind farms was determined by the actual monthly average values for the wind speed, which were obtained as average values of the wind speed measured at intervals of 10 *[min]* each day during 2014 at the location Bogdanci [8]. The duration of each simulation was 30 seconds. The Matlab/SIMULINK scheme for both IG and DFIG models are presented in *Fig. 8* and *9*, while the turbines' output characteristics for IG-driven and DFIG-driven models are presented in *Fig. 10* and *11*, respectively [5] – [7].

5. OBTAINED RESULTS AND DISCUSSIONS

In the southeast part of the Republic of Macedonia near the city of Bogranci, at the location called Rave-

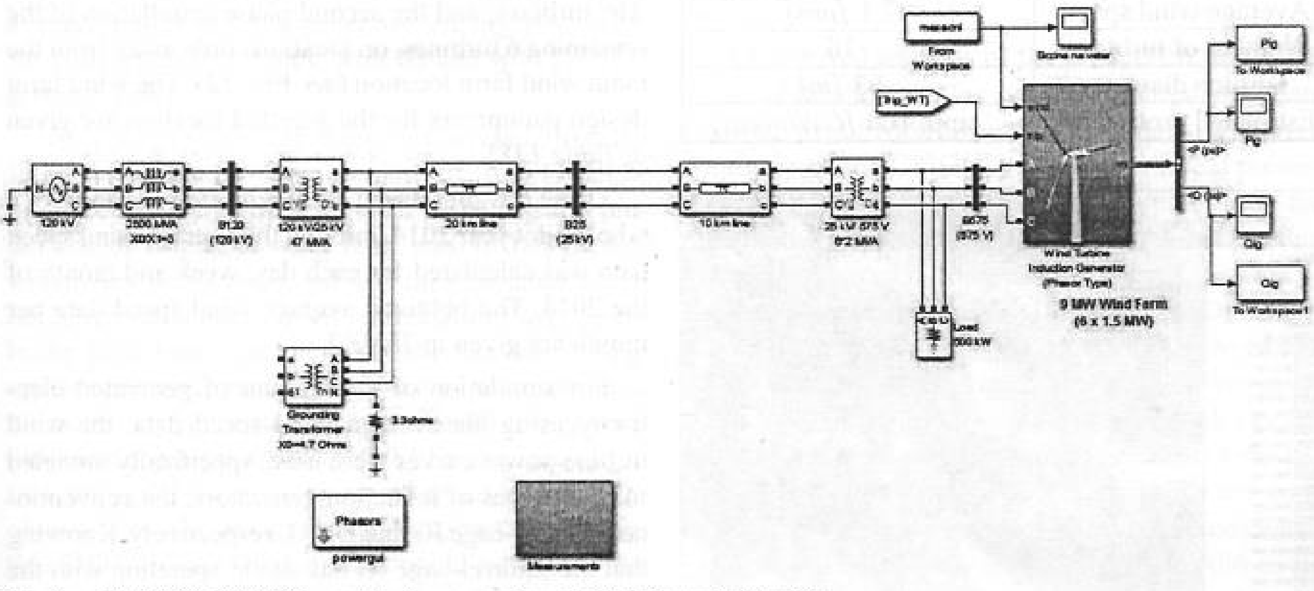


Fig. 8. - *Matlab/SIMULINK model of a conventional IG-driven wind turbine.*

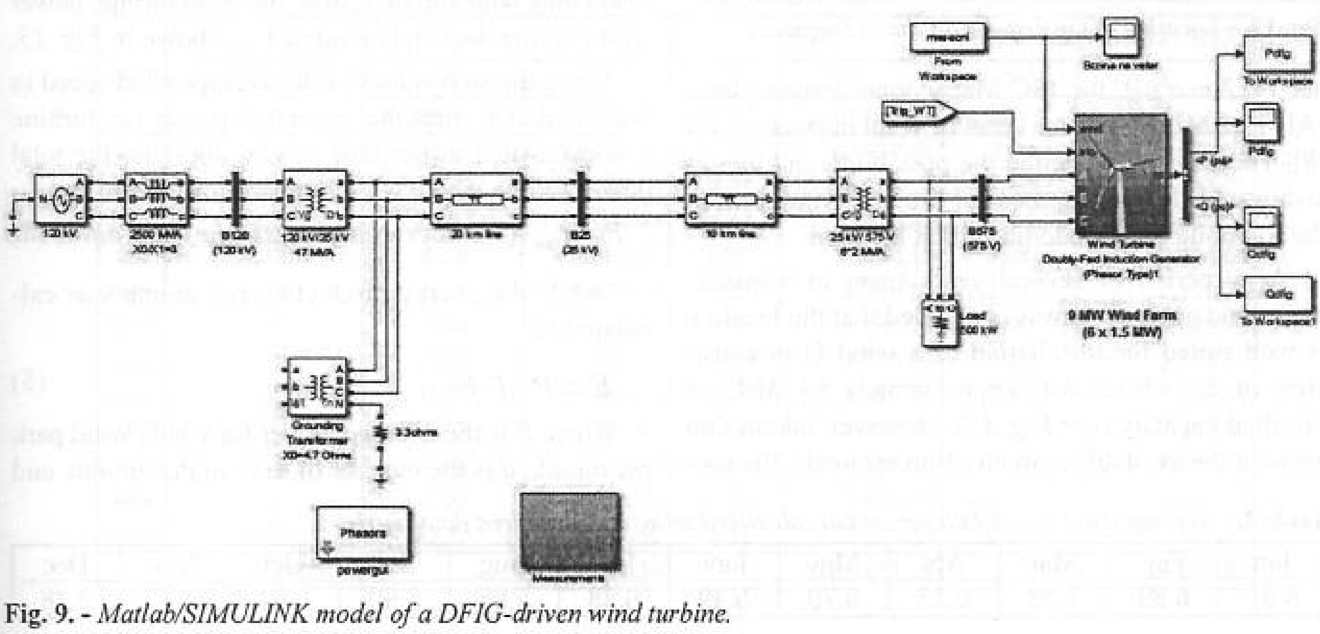


Fig. 9. - *Matlab/SIMULINK model of a DFIG-driven wind turbine.*

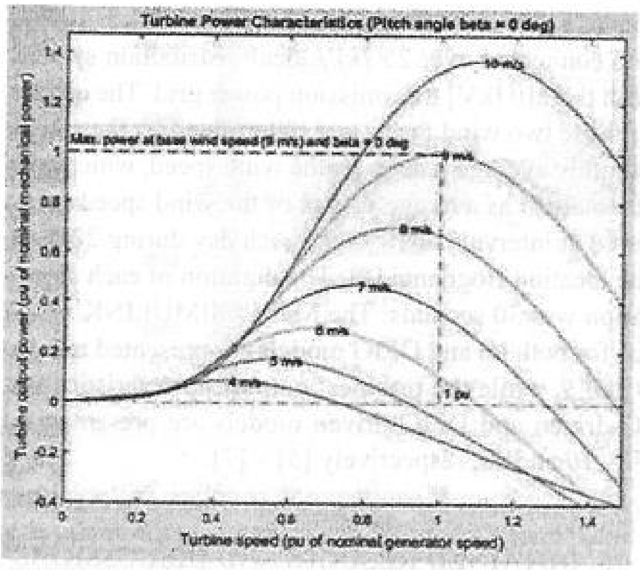


Fig. 10. - *Turbine characteristic (IG model).*

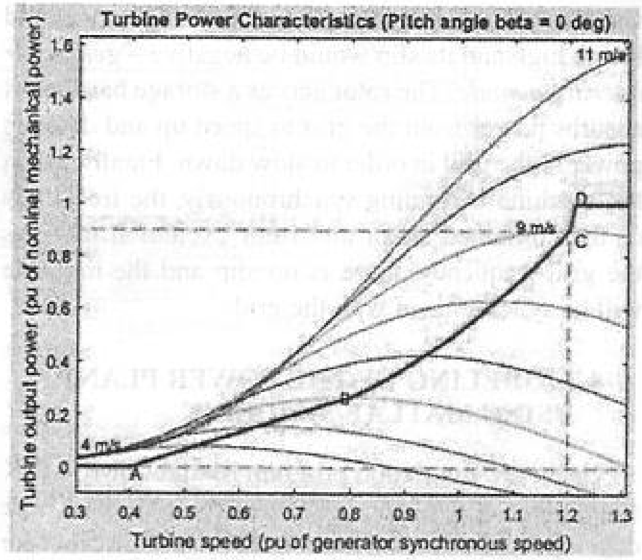


Fig. 11. - *Turbine characteristic (DFIG model)*

Table 1. - *Wind farm Bogdanci design data (I phase)*

Average wind speed	7.1 *[m/s]*
Number of turbines	16
Turbine diameter	93 *[m]*
Estimated production	app. 100 *[GWh/year]*

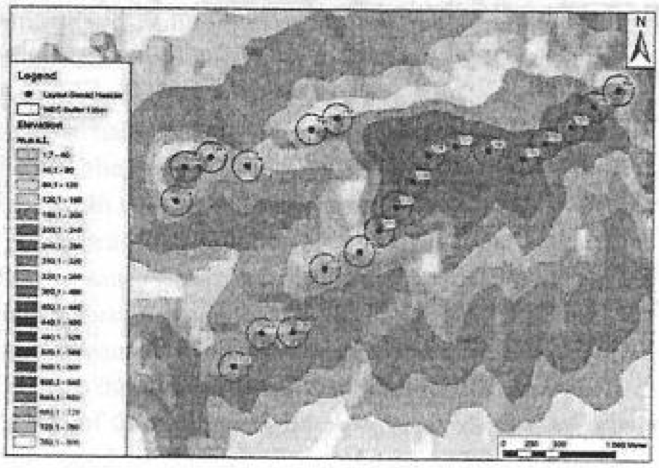


Fig. 12. - *Location of the first wind farm in Bogdanci*

nec *(472 m.a.s.l)*, the JSC Macedonian Power Plants (AD ELEM) did several years of wind measurements [8]. The aim was to define the possibility and the feasibility of the development of the first wind farm in the Republic of Macedonia, at that location.

After period of several years spent in measurements and analysis, it was concluded that the location is well suited for installation of a wind farm consisting of 22 turbines with approximately 50 *[MW]* of installed capacity (see *Fig. 12*). However, taking into account the available amount of investments, the project was split into two phases – first one installation of 16[th] turbines, and the second phase installation of the remaining 6 turbines, on locations little away from the main wind farm location (see *Fig. 12*). The wind farm design parameters for the selected location are given in *Table 1* [8].

Using raw measuring data taken every 10 min for a whole pilot year 2014, initially the average wind speed data was calculated for each day, week and month of the 2014. The obtained average wind speed data per month are given in *Table 2*.

For simulation of the amount of generated electricity using the average wind speed data, the wind turbine power curves were used, specifically modeled for both types of induction generators, the conventional squirrel-cage IG and DFIG, respectively. Knowing that the squirrel-cage IG has stable operation with the slip values of ± 10%, and the DFIG has large operational range with slip of ± 30%, the wind turbine power curve were adequately modeled, as shown in *Fig. 13*.

Using the step values of the average wind speed in the simulation, first the generated power per turbine was calculated in per unit values, and later the total power for the whole wind farm was calculated as:

$$P = P_{pu} \cdot (\textit{Number of turbines in the wind park}) \quad (4)$$

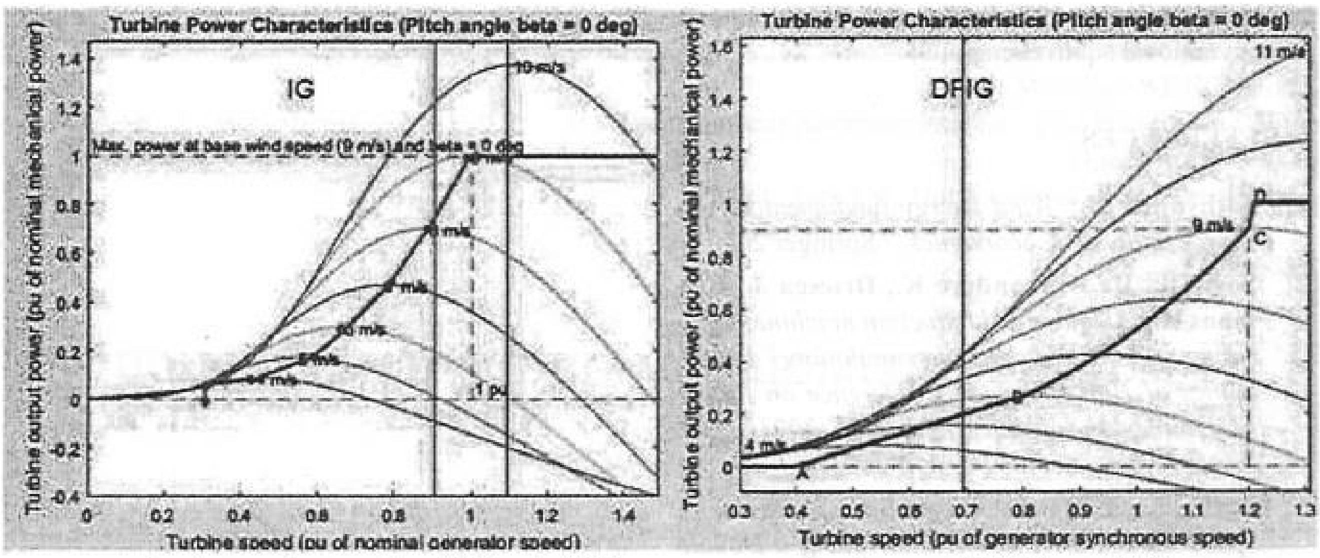
while the energy production per month was calculated as:

$$E = P \cdot d \cdot h \quad (5)$$

where P is the average power for whole wind park per month, d is the number of days in that month, and

Table 2. - *Average wind speed data per month calculated using raw measured data [m/s].*

Jan	Fev	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
8.91	6.89	7.88	6.13	6.70	5.49	6.38	5.65	5.90	5.62	5.02	7.48



operational range of conventional IG (s = ± 10%) operational range of DFIG (s = ± 30%)

Fig. 13. - *Comparison of the operational range of power curves between IG and DFIG.*

h is number of working hours. The comparison of the average power and the generated energy per month for both types of turbines, with IG and with DFIG is given in *Table 3*.

According to the information provided from the Energy Regulatory Commission of the Republic of Macedonia, for the same year 2014 [9], the production of Bogdanci wind farm was 70.386 *[MWh]* which very well correspond with the simulated results for IG-driven wind turbines, with error of app. 3,9%. In the same time, one could observe that due to large operational range of the DFIG-driven wind turbines, the electricity generation is larger than IG-driven wind turbines for about 30.686 *[MWh]* for the same location and at the same average wind speed, or larger for almost 41%. The results strongly suggest the benefits that DFIG-driven wind turbine could have over the conventional squirrel-cage IG-driven wind turbines.

6. CONCLUSIONS

A compared analysis of the production results for the same location and the same wind speed input data for two types of wind turbines, conventional IG-driven wind turbine and DFIG-driven wind turbine is presented in this paper. The results were compared with the measured real production data using IG-driven wind turbine and later the same data was used for simulation of replacement of the IG-driven with DFIG-driven wind turbines. Very good correlation between measured and simulated results for the IG-driven wind turbine with error of only 3,9% was achieved. Finally, the simulation showed that the replacement of the IG-driven with DFIG-driven wind turbines for the same location and under same operational conditions could yield increase electricity generation up to 40% in favor for DFIG-driven wind turbines. This is solely re-

2014	average wind speed *[m/s]*	IG		DFIG		Difference [DFIG - IG]	
		P	E	P	E	P	E
		[MW]	*[MWh]*	*[MW]*	*[MWh]*	*[MW]*	*[MWh]*
jan	8,91	30,14	22.434,51	28,05	20.857,46	-2,09	-1.577,04
fev	6,89	10,39	7.233,04	12,88	8.956,79	2,49	1.723,75
mar	7,88	19,87	14.798,47	19,34	14.376,82	-0,53	-421,65
apr	6,13	4,13	2.967,55	9,04	6.494,18	4,91	3.526,63
may	6,70	8,71	6.486,12	11,82	8.796,92	3,11	2.310,79
june	5,49	0,00	0,00	6,50	4.689,79	6,50	4.689,79
july	6,38	6,05	4.503,87	10,18	7.584,03	4,13	3.080,16
avg	5,65	0,86	629,69	7,07	5.267,76	6,22	4.638,07
sep	5,90	2,49	1.785,82	8,01	5.773,47	5,52	3.987,65
oct	6,62	0,65	492,83	6,99	5.188,35	6,34	4.695,52
nov	5,02	0,00	0,00	5,03	3.608,77	5,03	3.608,77
dec	7,48	15,95	11.852,46	16,52	12.276,85	0,57	424,39
	Total:		73.184,36		103.871,19		30.686,82

Table 3. - *Comparison between simulated results for wind farm with IG and DFIG.*

sult of the large operational range that DFIG has over the conventional squirrel-cage IG.

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