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Integration of Wind Power Plants in The Electric Power System: A Case Study in Piauí – Brazil

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ABSTRACT: *Environmental politics have been encouraging the use of the renewable source of Electrical Power, and among these the most noticeable one in the Brazilian Power System scenario is Wind power, which accounts for more than 4% of the total national installed power capacity, and has high prospects to reach almost 10% at the end of the construction of every project planned by the government. Despite the fact that wind power production is expanding in Brazil. This work presents data about the integration of wind farms into the power system of the state of Piauí, displaying the current scenario of the state and projecting a future scenario based on information from projects related to power generation.*

I. INTRODUCTION

The installed capacity of power generation from wind resource utilization and the insertion of this energy in the electric power System (SEP) are growing significantly in Brazil and in the world. In some areas of Germany, Denmark and Switzerland, for example, wind generation supplies more than 18% of the total demand, supply the total demand of 31.45% German province of Schleswig-Holstein (T. Ackermann, 2005).

In Brazil, during the year of 2014, according to the Global Wind Energy Council (GWEC), there was an increase of 2,472 MW in installed capacity of wind power generation, which at the time corresponded to a growth in excess of 70%. In the year 2015 that number exceeded 6.5 GW and get near 16 G.W. after completion of the construction of all the projects provided for by the national electricity Agency (ANEEL) (GWEC, 2015); (ANEEL, 2015). These new ventures will be responsible for the expansion of the national interconnected system (SIN) and the modification of the SEP of some Brazilian States, such as the State of Piauí in the Northeast region, which are being installed three wind farm complexes whose total capacity exceed 1.2 GW generation. The factors that influence the quantity and management of power generated by wind power plants are not only related to the weather conditions of an area, but also to the design of wind turbine, so to perform actual case studies (S. Heier, 2014).

This work was conducted the survey of information about wind farm complexes installed in the State of Piauí in the Northeast region, demonstrating the configuration of each complex, as well as the way that these will be connected to the National Grid (SIN). Simulations were performed using a wind power plant model, which have turbines with double-fed Induction Generators (GIDA) provided by Matlab®.

II. ELECTRIC POWER SYSTEM DO PIAUÍ

The degree of the effects from wind power generation depends mainly on the degree of penetration of this on the net and also the level of robustness of the system. In the case of the State of Piauí in the Northeast region, the degree of penetration of wind power is low and the Electric Power System can be considered robust by being integrated into The National Grid.

Although, in the year 2015, the State of Piauí in the Northeast region has not yet reaching peaks of demand in excess of 1000 MW and the installed capacity of power generation exceeds this value, even after the integration of the new wind farm complexes to Electric Power System do Piauí, the State still will not be self-sufficient with regard to supply their energy demand since the electric power produced by wind farm complexes cannot be fully injected in distribution system the State due to technical restrictions as penetration levels the same in a power system.

In Table I are shown the data (April 2015) provided by ANEEL on the installed capacity of power generation in the Piauí State before and after the construction of the wind farm complexes that are being installed in the State.

The data from table I shows that the energy matrix of the State of Piauí in the Northeast region will be modified considerably after the completion of the construction of the new ventures, allowing the creation of two scenarios for the Electric Power System do Piauí, a previous and another after the beginning of the complex operating wind farms.

Type	Enterprises in operation		Projects under construction or with construction not started		All the developments after completion of the works All the developments after completion of the works	
	Granted power (kW)	%	Granted power (kW)	%	Granted power (kW)	%
Wind-Generating Central	88.000	22,67	1.243.804	88,95	1.331.804	74,55
Hydroelectric Power Plant	237.300	61,14	0	0	237.300	13,28
Thermoelectric Power Plant	62.815	16,18	154.500	11,05	217.315	12,16
Total	388.115	99,99	1.398.304	100	1.786.419	100

Table I: Granted power of enterprises in the State of Piauí.

2.1 Current Scenario

The wind farms in operation in the State of Piauí in the Northeast region, prior to construction of the wind farm complexes located in the southeast of the State, concentrated in the coastal region and together have 88 MW of generation installed capacity.

The Pedra do Sal wind power plant has an installed capacity of 18 MW, corresponding to 20 wind turbines of type E-44/900 kW manufactured by Wobben/Enercon, that have low speed and synchronous generators operating at variable speed, being that the transmission line (LT) of 138 kV is connected to a distribution substation. Probably due to the high cost of this turbine type when compared with the other models, this is the only plant that uses this type of turbine in the State.

The plants of Delta da Parnaíba, Porto das Barcas and Porto do Sal have installed capacity of 30 MW, 20 MW and 20 MW, respectively, using turbines manufactured by Vestas company, who own inductive generators doubly fed, pitch control and adjustment system of active and reactive power that seeks to maintain the balance of voltage at the connection point, also connected to one of distribution through a LT of 138 kV. This type of generator operates at variable speed under a large, but limited speed range, thus allowing the search for maximum power production from the rotational speed control of the same. Other advantages are the individual control of active and reactive power, its self-magnetization, its ability to generate reactive power, and an increase of 2 to 3% of the generation capacity due to the type of connection. As disadvantage the need of using collector rings and a converter that generates harmonics that should (R. Custódio,2009), (A. Khaligh and C. O. Omer, 2010).

As seen, all the power plants located in the North of the State are connected to the distribution network through transmission lines of 138 kV, that was only viable due to low generation capacity installed and also to the low level of penetration of wind energy in the locality. The same type of connection will not be applied to the new wind farm complexes due to the large capacity, which would result in a considerable penetration of wind energy in Electric Power System of Piauí and may cause power quality related problems and instability in the system. Therefore, these wind farm complexes will be connected to SIN through LT exclusive, which will reduce the impacts on the quality of the energy supplied to the final consumer and shall have only the downside of owning higher cost than the connection by means of medium-voltage transmission lines (S.W. Mohod and M.V. Aware, 2013).

2.2 Future Scenario

Wind farm complexes that are not yet in operation, but are being built are: Wind Complex Chapada do Piauí, Wind Complex Chapada do Piauí II and the Wind Complex Caldeirão do Piauí, which will have an installed capacity of generating 415.1 MW, 231.6 MW and 415.8 MW, respectively, after completion of construction of the plants of each complex. Possessing turbine engines with generators of type double fed induction and connection to SIN through LT 230 kV and 500 kV, a part of the complex Chapada do Piauí connects to SE Picos and the other party, as well as other complex will connect to a switching substation, energized by the LT 500 kV, which connects

the SE São João do Piauí with SE Milagres in the state of Ceará.
The Electric Power System in the State of Piauí will be modified with the construction of switchgear substation and other elevatory substations, resulting in the image shown in Fig. 1, found on the website of the Hydroelectric Company of São Francisco (Chesf).

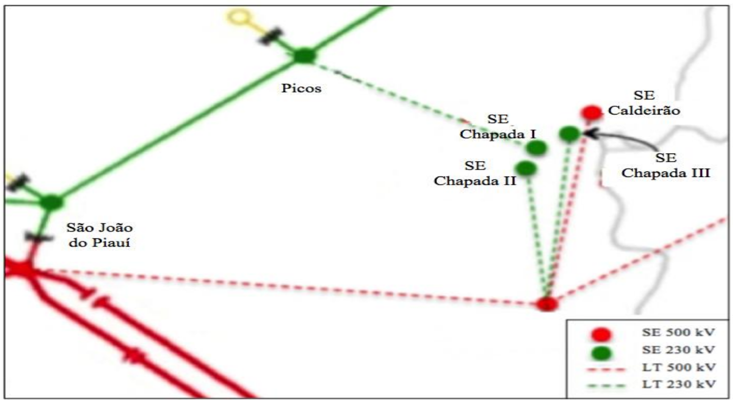

Figure 1: SEP of Piauí after the integration of the new wind farm complexes.

III. COMPLEX INTEGRATED WIND TO SYSTEM POWER OF PIAUÍ STATE

Wind farm complexes installed in the southeast of Piauí have some similar characteristics with each other, how the wind turbine type used and the high voltage system. However, the turbines used may have different settings, as the value of unitary power, because they have different manufacturers, which affects the amount of wind turbines used in each complex and the total power of wind farms contained in each complex.

3.1 Wind power complex Chapada do Piauí

The Wind Complex Chapada do Piauí has 415.1 MW of generation installed capacity and consists of 14 wind farms, as shown in table II, contained in the report of environmental impact of the wind farm Complex.
The hubs of the turbines are positioned at different altitudes according to the model of turbine. For example, the hub of the GE models are positioned at 80 metres high, while the turbine Games is positioned at a height of 78 meters.
This complex will have two substations, the SE Chapada I and SE Chapada II, and the first 7 wind farms in Table I are connected to SE Chapada I and the last seven parks are connected to SE Chapada II. The connection of this wind farm to the SIN will be made through two transmission lines that can be seen in Figure 1, the LT 230 kV that will SE Chapada I to the SE Picos and the LT 230 kV that will SE Chapada II to the switching substation to be built.

The Wind Complex Chapada do Piauí has turbines with doubly fed induction generators whose output voltage is 690 V. With the goal of minimizing losses in the transmission output voltage is increased to 34.5 kV by transformers installed next to each turbine. After raising the tension level the energy generated goes to a collector system that carries all the electricity generated by the turbines for an elevatory substation and later for the SIN.

Windfarm	Number of Turbines	Turbine model	Total Power
Ventos de Santa Joana IX	16	GE 1.85-82.5	29,6 MW
Ventos de Santa Joana X			
Ventos de Santa Joana XI			
Ventos de Santa Joana XIII			
Ventos de Santa Joana XII	17	GE 1.7-100	28,9 MW
Ventos de Santa Joana XV			
Ventos de Santa Joana XVI			
Ventos de Santa Joana II	15	Gamesa G97 Class 2A	30 MW
Ventos de Santa Joana VI			
Ventos de Santa Joana VIII			
Ventos de Santa Joana XIV			
Ventos de Santo Onofre I			
Ventos de Santo Onofre II			
Ventos de Santo Onofre III			

Table II: Complex Wind parks Chapada do Piauí

3.2 Wind power complex Chapada do Piauí II

The Chapada do Piauí Complex II, whose generating capacity will be of 231.6 MW, has similar features to the Chapada do Piauí Complex. This complex has the same types of wind turbines, the GE 1.7-100 unit power equal to 1.7 MW and the GE 1.85-82.5 unitary power of 1.85 MW, with 80 meters high towers and power of approximately 30 MW for wind farm, as can be observed in table III, obtained through the Environmental impact report of the Piauí II wind farm Complex.

Windfarm	Number of Turbines	Turbine model	Total Power
Ventos de Santa Joana IV	16	GE 1.7-100	29,6 MW
Ventos de Santa Joana I	17	GE 1.7-100	28,9 MW
Ventos de Santa Joana V			
Ventos de Santa Joana VII			
Ventos de Santo Augusto IV			
Ventos de Santa Joana III	16	GE 1.85-82.5	30 MW
Ventos de Santo Augusto V			

Table III: Parks of Chapada do Piauí II wind farm Complex.

This complex will have a substation, SE Chapada III, which will connect to the SIN through a 230 kV transmission line that will go from SE Chapada III to switchgear substation, as can be seen in Fig. 1.

3.3 Wind power complex Caldeirão do Piauí

The Wind Complex Caldeirão do Piauí has installed generation capacity of 415.8 MW. Consists of 15 wind farms, each with an installed generation capacity of 29.7 MW. These in turn consist of 11 wind turbines 2.7 MW ECO model 122 produced by Alstom installed in 80 meters high towers, as can be seen in Table IV, contained in the report of environmental impact of wind farm Complex Caldeirão do Piauí. Unlike the turbines used in wind power Complex Chapada do Piauí, the turbines of this complex have generators with output voltage of 1,000 V, which is raised to 34.5 kV in order to drain the electricity generated by the turbines through a 34.5 kV collector system that connects to an elevatory substation of 34.5/230 kV that will connect to SIN through the LT of 230 kV, SE Caldeirão/ Switchgear substation, which should be replaced in the future by a LT of 500 kV.

Windfarm	Number of Turbines	Turbine model	Total Power
Ventos de Santa Angelina	17	Alstom ECO 122	29,7 MW
Ventos de Santa Bárbara			
Ventos de Santa Edwirges			
Ventos de Santa Fátima			
Ventos de Santa Regina			
Ventos de Santo Adriano			
Ventos de Santo Albano			
Ventos de Santo Amaro			
Ventos de Santo Anastácio			
Ventos de São Basílio			
Ventos de São Felix			
Ventos de São Moisés			
Ventos de Santa Veridiana			
Ventos de Santa Verônica			

Table IV: Wind farms Wind complex Caldeirão do Piauí.

IV. SIMULATION OF THE WIND FARM COMPLEXES

In order to study the individual behaviour of each new wind farm complexes were carried out computer simulations using Matlab ® and its model of wind power plant that can be seen through the power_wind_dfig command. The wind power plant model provided by the power_wind_dfig command is shown in Fig. 2.

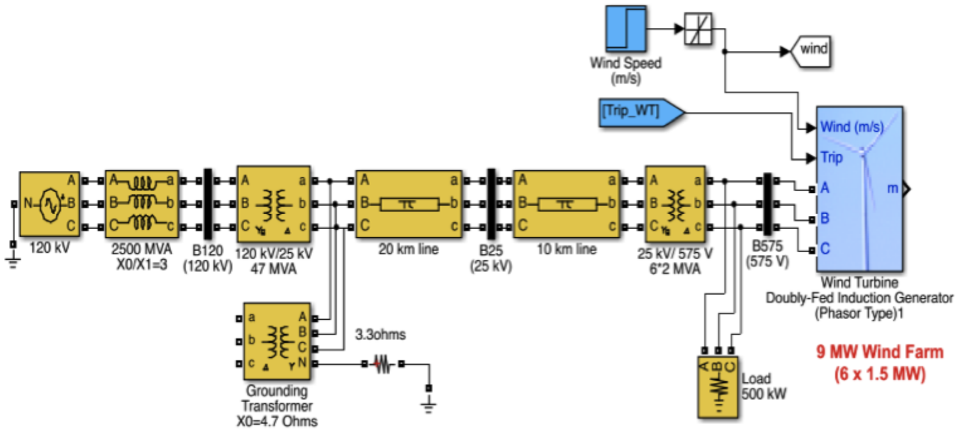

Figure 2: Using wind power turbine model with inductive generators twice as food. Source: the author.

The model presented in Fig. 2, represents a 9MW wind power plant, composed of six wind turbines of 1.5 MW, connected to the network by LT of 25 kV and LT of 120 kV. Has resistive loads and engines connected to a 25 kV bus, the simulation of a lack in the 25 kV bus. In the simulation, using the Matlab ® program, the wind is represented in form of ramp as seen in Fig. 3.

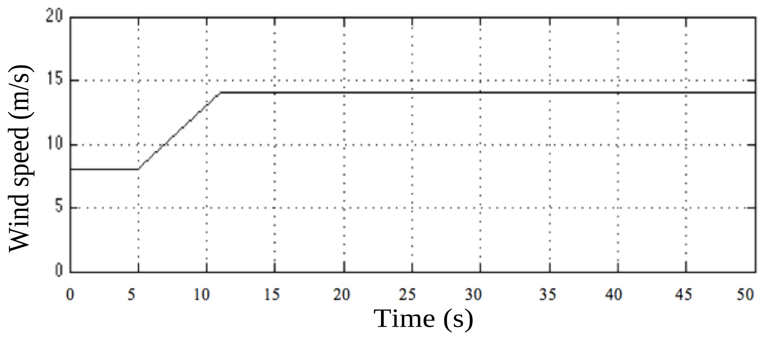

Figure 3: Wind speed during simulation.

The simulation uses a system of pitch control as a way to control the rotational speed of the turbine blades. Fig. 4, also created from simulations, shows the variation in degrees from the axis of the shovels during the simulation and the result of the control of the rotational speed of the blades. Due to differences between the parameters of the simulation and the tension level standards adopted in Brazil, the pre-existing model of the simulation had to be amended to resemble the power transmission system that connects the wind farms to SIN and also in order to possess the same installed generation capacity of the complex.

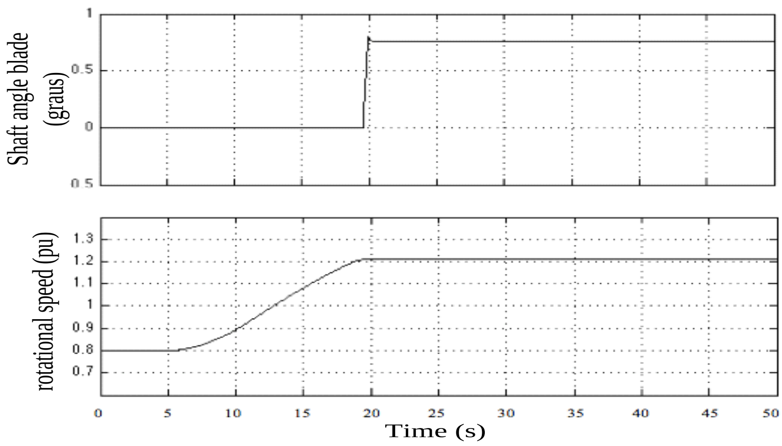

Figure 4: Performance of pitch control and changing the rotational speed of the turbine blades due to increased incidence of wind speed in spades.

4.1 Wind power complex Chapada do Piauí

Knowing that the first seven parks in the table II are connected to SE Chapada I through the same LT implemented the simulation of the connection of these parks to SIN, as can be seen in Fig. 5.

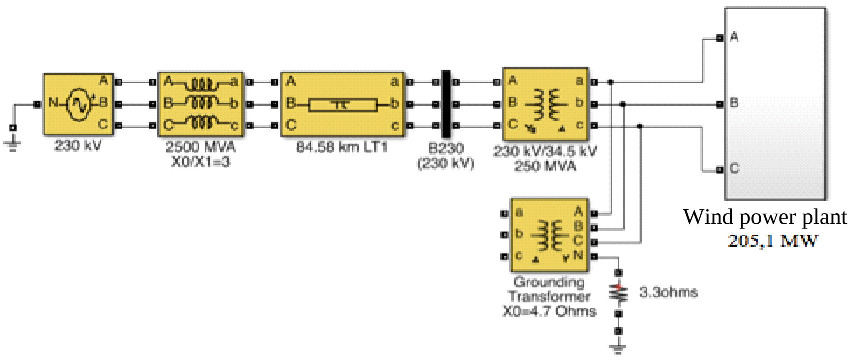

Figure 5: Connection of wind farms that make up the Wind Complex Chapada do Piauí and that together total 205.1 MW to the network through a LT 230 kV.

The simulation in the Matlab® from the Chapada do Piauí wind farm complex that will be connected to SIN by LT of 230 kV, whereas the maximum production scenario and activating the reactive control offered by the model, the data exposed in the graphs in Fig. 6. Based on Fig. 6 (a) and 6 (b), it can be observed that with the increase of the rotational speed of the blades for increased production of active power. Observing Fig. 6 (d), it should be noted that initially the output voltage that was zero passes to get close to their face value, with some variation due to reactive power control. Through the Fig. 6 (c) realize that the complex initially consumes reactive network, but that after a small time interval the reactive control system can control this. Note that upon reaching the stall point there is an abrupt increase in the number of active power generated and an increase in the consumption of reactive power, which are stabilized immediately after the point (T. Burton et all, 2001).

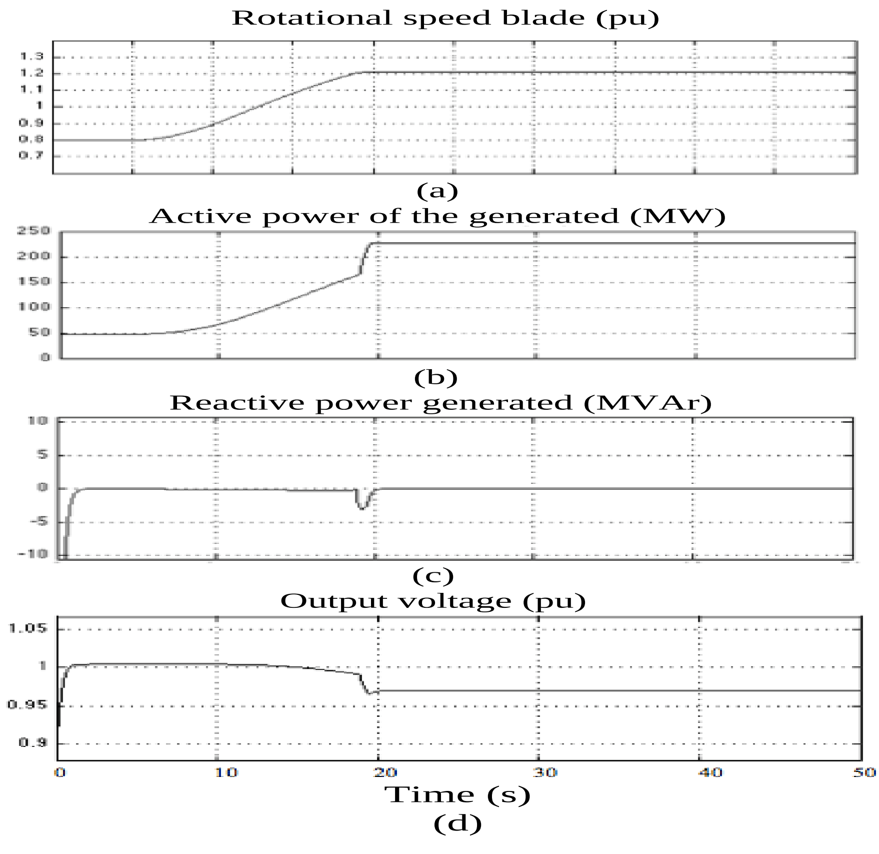

Figure 6: Graphics obtained from wind power Complex simulation Chapada do Piauí, part 1.

The other wind farms wind power complex that will be connected to switch substation are represented together in the simulation shown in Fig. 7.

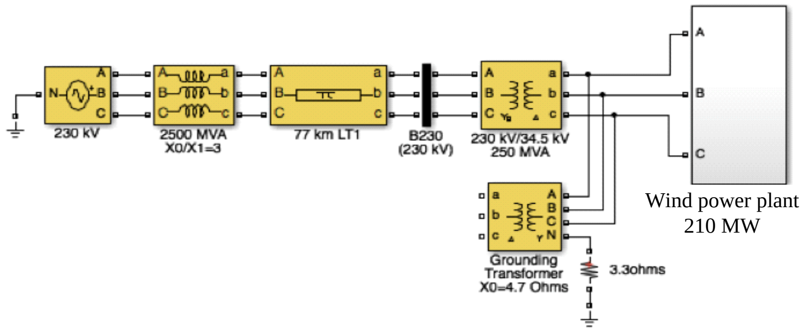

Figure 7: Connection of wind farms that make up the Wind Complex Chapada do Piauí and that together amount to 210 MW to the network through a LT of 230 kV.

The results obtained in the simulation of this second part of the wind farm complex are shown in Fig. 8.

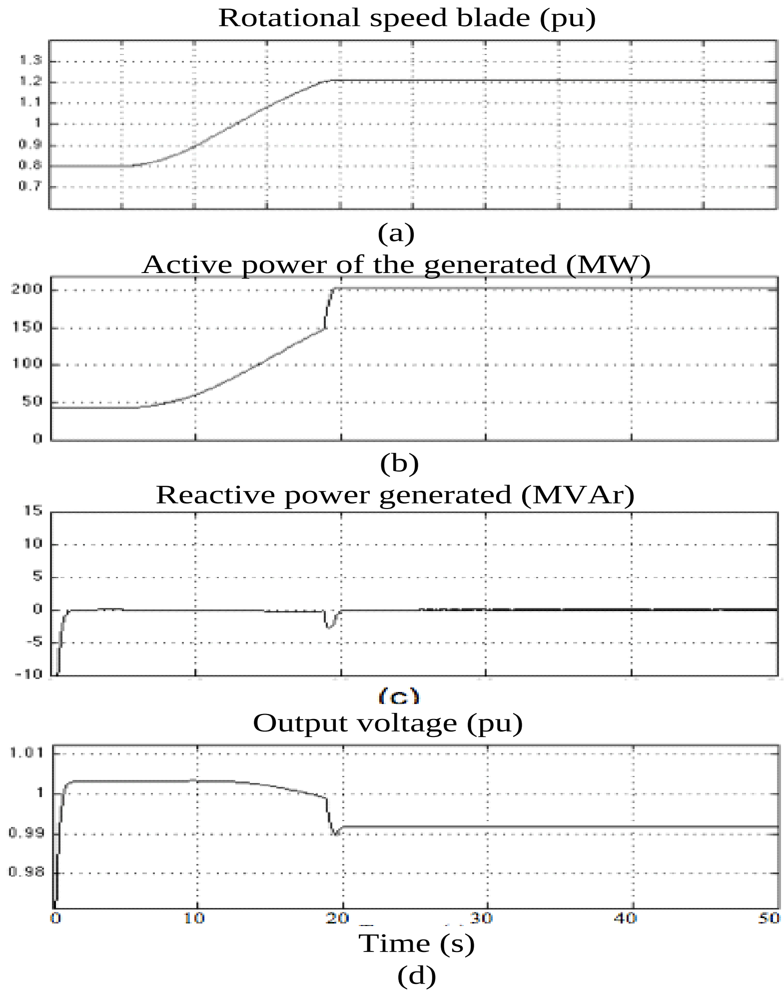

Figure 8: Graphics obtained from wind power Complex simulation Chapada do Piauí, part 2.

The data obtained in the simulation match those found in the simulation of the first part of the wind farm complex and serve to confirm the behavior of the wind farm complex.

4.2 wind power Complex Chapada do Piauí II

The simulation of this complex was carried out in a similar way the simulation contained in Fig. 5 and presented the results displayed in the graphs in Fig. 9. These results are similar to those obtained in the simulation part of the Piauí Wind Complex due to the proximity of its generation capacity values.

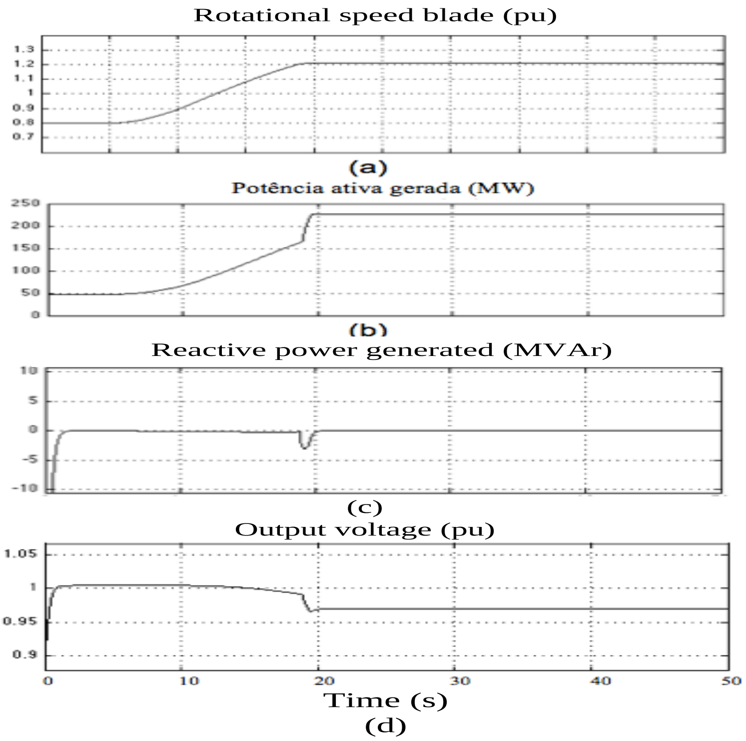

Figure 9: Graphics obtained from the simulation of the Piauí II wind farm Complex.

4.3 Wind power complex Caldeirão do Piauí

The Wind Complex Caldeirão of Piauí in the Northeast region consists of 15 wind farms totaling 415.8 MW of generation capacity. These parks will be connected individually to Caldeirão and then have its production disposed of through LT that connects the substation of complex with the Switchgear substation. This complex simulation results are shown in Fig. 10. As can be seen in Fig. 10 the active power behaves as expected, since the same increases as there is an increase in the rotational speed of the blades.

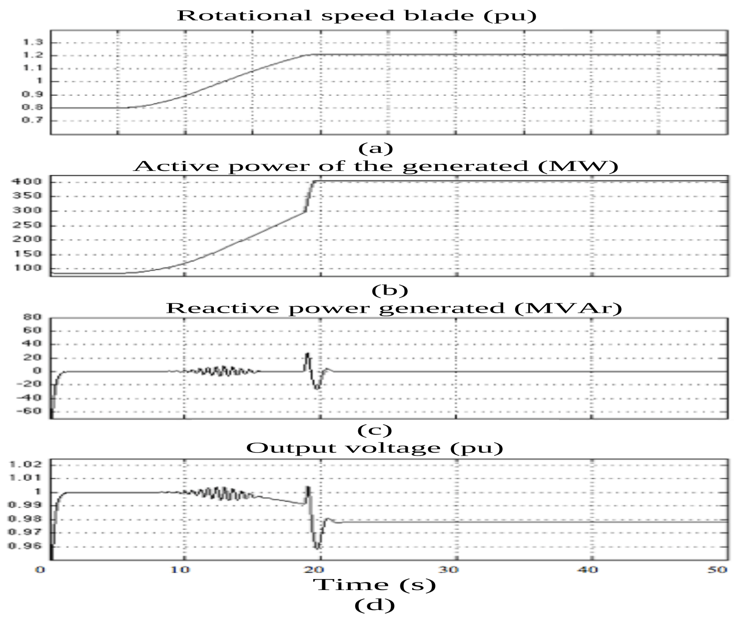

Figure 10: Graphics obtained from the simulation of the Wind Complex Caldeirão do Piauí.

Note in the graph of the reactive power generated this presents an oscillation in the range from 8 to 16 seconds that cannot be perceived in the results presented in Figs 6, 8 and 9. However, through additional simulations, it was noted that this oscillation increases according to the increase of the installed capacity of wind power complex generation. This oscillation is far more visible in the simulation of this complex because the power produced is disposed of by a single LT, which is approximately twice the power drained by the LT of other complexes. The output voltage also features an oscillatory period from 8 to 16 seconds longer than the presented in other simulations, and even expands according to the increase of the installed capacity of the complex generation.

V. CONCLUSION

In this work were presented data about the configuration of the wind farm complexes that will be integrated into the Electric Power System do Piauí as well as details about the connections to be adopted. The results obtained by means of the simulations show that the wind farms will be able to operate individually stably during the permanent regime, controlling their consumption of reactive power, thus ensuring the stability of the voltage level of the turbine. However, as the same may not operate individually, it is necessary to develop other computer simulations the real scenario, in order to obtain results of the simultaneous interaction of all complexes with the SIN. And the fact that the biggest challenges involving the integration of wind power plants are related to its controllability during transients, also creates the need to conduct further studies on the integration of the new wind farm complexes.

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