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Stability Analysis of Wind Energy Generation in the Electrical System of Puerto Rico

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Abstract. The Puerto Rico Electric Power Authority has proposed increasing the renewable energy generation of the island to an estimated 1,600MW. This will be accomplished by adding alternative energy sources (e.g. wind, solar, land fill gas, and waste) distributed throughout the island. Environmental benefits and increased energy independence should be weighed against the potential impact that increased generation of renewable energy will have on the electrical grid. Renewable energy sources are a variable source of energy due to their dependency on natural resources, creating a strain on the electric grid. In this study, a stability analysis of the electrical power system of Puerto Rico is conducted by observing the impact of the proposed increase in wind power generation.

Index Terms – Electrical System, Power Generation, P-V Curve, Renewable Energy, Wind Energy, Simulation, Stability Analysis

1. Introduction

An electrical power grid is a network that connects electricity generation with consumers. The grid is composed of four basic components: generation, transmission, distribution and electricity users [1]. Figure 1 illustrates the components that make up the electrical power grid scheme.

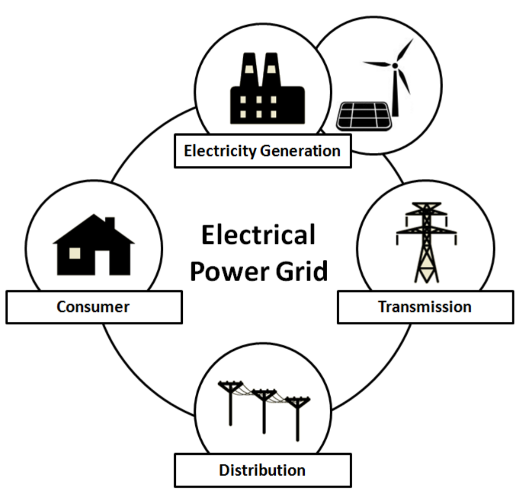

Fig. 1: Electrical Power Grid Structure

To meet rising energy demand, dependency on crude oil, coal and natural gas has increased in hopes of meeting the world's energy requirements [2]. To efficiently supply power to consumers, it is important to maintain stability on the electrical grid. The stability of the electrical grid is achieved by maintaining a balance between power generation and power consumption. There is a growing interest in renewable energy sources, particularly solar energy and wind energy that provide electricity without increasing harmful carbon dioxide emissions [3]. Due to dependency on natural resources, the use of electricity from solar and wind can be intermittent, causing instability in the electrical system. The Puerto Rico Electric Power Authority (PREPA) has proposed increasing the renewable energy generation of the island. In this study, a stability analysis of the electrical grid is performed by increasing the power generation in different sectors of the electrical power system of Puerto Rico.

This article is organized as follows. Section 2 presents the characteristics of the electrical system of the island of Puerto Rico. Section 3 describes system voltage stability and P-V curve analysis. The simulation of the electric power system is shown in section 4. Results of the P-V curve analysis are shown in section 5. Finally, section 6 presents the conclusion.

2. Electric System in Puerto Rico

Puerto Rico's power grid operates traditionally, with the rare exception that ownership is exclusive to the Puerto Rico electric company, locally known as the "Autoridad de Energía Eléctrica" (AEE). It is responsible for generating, transmitting and distributing electricity to 1,449,211 customers. The transmission system in Puerto Rico consists of 2,416 miles of 230kV, 115kV and 38kV of sub-transmission lines. The distribution system is made up of 33,169 miles of above ground and underground wiring and 293 substations. Power is generated primarily through thermoelectric, coal and natural gas; however, renewable sources such as hydroelectric, solar, wind, waste-to-energy and landfill gas are also used.

A. MAIN ENERGY GENERATION

Despite the variety of power generation types, sixty-eight percent (68%) of the total energy produced on the island is fuel-oil based, fifteen percent (15%) is coal, and another sixteen percent (16%) comes from natural gas.

- ***Thermoelectric:*** The main generation system is composed of five major thermoelectric power plants distributed throughout the island: South Coast (990MW), Aguirre Complex (900MW and 990MW), San Juan (400MW and 440MW), Palo Seco (602MW) and Cambalache (247.5MW). The total installed capacity is 5,839MW.
- ***Coal:*** AES is a privately owned company that generates electricity using coal. They are located in the municipality of Guayama and possess an installed capacity of 454MW.
- ***Natural Gas:*** EcoEléctrica is a local energy company that utilizes natural gas in order to generate electricity. Their plant is located in the municipality of Peñuelas and has an installed capacity of 540MW.

B. RENEWABLE ENERGY GENERATION

Puerto Rico has counted on hydroelectric means for generating electricity for the last century. Over the last decade, it has moved towards investing in different conventional forms of renewable energy.

- ***Hydroelectric*:** Given its limitations, hydroelectric power currently accounts for approximately one percent (1%) of the total energy demand of Puerto Rico The hydroelectric system has an available capacity of 81.7MW, providing clean, economical, renewable energy. Currently, the hydroelectric system of Puerto Rico is composed of 21 plants or generation units and 13 reservoirs. Of these plants, 9 are available for generation and 12 are in repair.
- ***Wind Energy:*** Given Puerto Rico's geography, wind is a favorable choice of alternative energy to aid in reducing harmful emissions. In Puerto Rico the best winds can be found near the coast and in the northern, eastern and southern regions of the island [4]. Wind energy can reach a capacity of 382.9MW distributed along 10 proposed projects spread throughout the island.
- ***Solar Energy:*** Given the current technology, it would be difficult to implement large-scale solar power generation in Puerto Rico. This is due to both poor solar cell efficiency and a lack of usable land for the installation of solar panels. In spite of this, investment in solar generation has steadily risen. There are a growing number of solar energy projects in Puerto Rico. Currently there are close to 46 proposed projects in total, reaching a capacity of 1,157.4MW.
- ***Waste-to-energy and Landfill Gas:*** Other forms of renewable energy in Puerto Rico are waste-to-energy and landfill gas, generating 89MW and 11.5MW respectively.

Figure 2 shows the location of the main energy generation as well as the existing and proposed wind farms that will be distributed around the island of Puerto Rico.

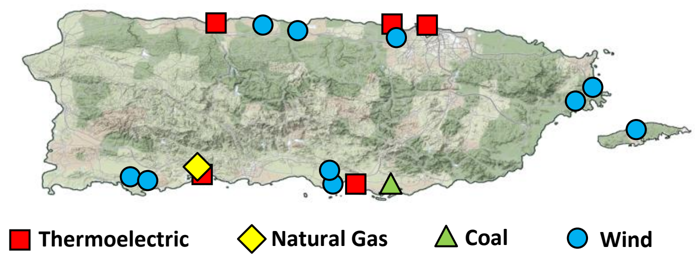

Fig. 2: Main and Wind Power Generation in Puerto Rico

Table I illustrates the quantity and generation capacity of both, main and renewable generation in the electrical system of Puerto Rico.

TABLE I: Electricity Generation Types in Puerto Rico

Generation Type	Qty	Capacity (MW)
Thermoelectric	5	5,839.0
Hydroelectric	9	81.7
Wind Power	10	382.9
Solar Power	46	1,157.4
Waste-to-energy	2	89.0
Landfill Gas	4	11.5

3. Power System Stability Analysis

A power system is considered to be stable if it can remain in operating equilibrium under normal conditions and if it has the ability to return to an acceptable operating point after suffering a disturbance. On the contrary, if after suffering a disturbance, the system is not able to return to its normal operating conditions, and there are abnormalities in system characteristics (e.g. voltage, frequency and rotor angle), it is said to be unstable. Stability in a system can be determined by observing rotor angle, frequency and voltage stability [5]. Figure 3 illustrates the different power system parameters that can be observed to determine system stability.

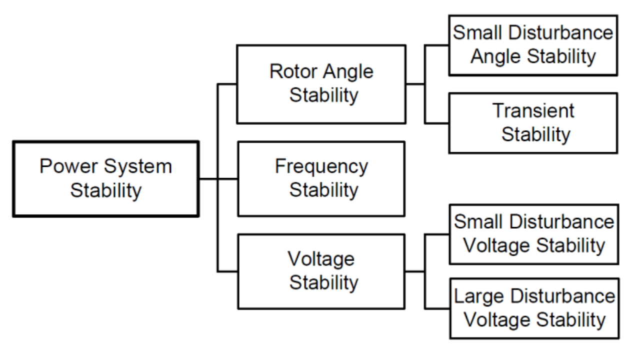

Fig. 3: Power System Stability Diagram

In many electrical systems, specific measures are taken to maintain voltage stability, especially in systems where long transmission lines are weak and are used to supply heavy loads. In an electrical power system, voltage stability is the ability of a power system to operate under acceptable voltages at all buses in the system under normal and irregular conditions [6]. Blackouts are one of the many consequences of lack of stability in electric systems. The major problem associated with a stressed system is voltage instability or voltage collapse. Voltage instability is the absence of voltage stability and results in either a progressive fall or rise of voltage magnitude of some buses in the system. Transmission of large amounts of power over long electrical distances is the main cause of voltage instability [7]. When considering voltage stability, attention is paid to power transfers between generation and load centers. The system can be represented by an equivalent generator that can be modeled in the steady state by an equivalent voltage source behind an equivalent reactance [8]. Figure 4 illustrates and example of the standard two bus system.

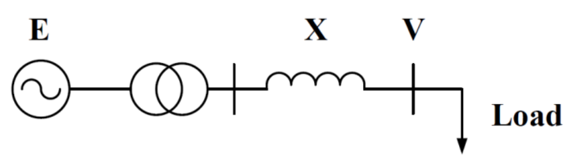

Fig. 4: Standard Two Bus System

Under balanced three-phase, steady-state sinusoidal conditions, the system operation can be described by the power flow equations for active and reactive power [9]. The mathematical expressions that describe active and reactive power are shown in equations (1) and (2) respectively.

$$P = -\frac{EV}{X}\sin\theta \tag{1}$$

$$Q = -\frac{V^2}{X} + \frac{EV}{X}\cos\theta \tag{2}$$

In this equation, P and Q are the active and the reactive power respectively, consumed by the load. The variable E is voltage at the source, V is the load bus voltage magnitude, X is the impedance in the transmission line and θ is the phase angle difference between the load and the generator buses. Solving (1), (2) with respect to V yields equation (3), known as the P-V curve equation.

$$V = \sqrt{\frac{E^2}{2} - QX \pm \sqrt{\frac{E^4}{4} - X^2P^2 - XE^2Q}} \tag{3}$$

For a two bus system, the P-V curve is drawn by increasing the load until the voltage reaches a critical value [10]. Figure 5 shows the voltage stability P-V curve.

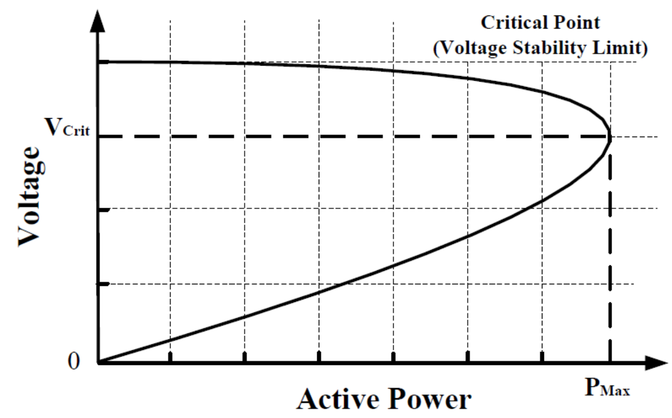

Fig. 5: Voltage Stability P-V Curve

The P-V curve is a graph of active power at a node or bus as a function of node or bus voltage. The point on the curve where the maximum power occurs is known as the critical point and is considered to be the voltage stability limit [11]. The critical point describes the point where any further increase in power will result in an unstable point. Because of dependence on natural resources, renewable energy is a variable power generation that can cause instability in a system due to abrupt changes in power generation [12]. To study the variable effects of wind energy on the system, wind turbines are connected at different locations and at different penetration levels (0%, 25%, 50%, 75% and 100%) in order to investigate the effect on the system voltage stability. There exist several methods for voltage stability analysis, including P-V curves and Q-V curves. The P-V curve analysis consists of a sequence of power flow solutions that increase the transfer of power while at the same time observing how voltages in the system react. For this reason, wind turbines were modeled and integrated into the electrical system and a P-V curve analysis is performed [13]. The non-linear relationship between voltage and power transferred in the system makes it necessary to perform the entire power flow solution. Simulation allows the P-V curve to be plotted by varying the reactive and active loads, yielding the collapse margin. The P-V curve analysis is used to obtain the effects of wind power generation on voltage stability in Puerto Rico's electrical power system.

4. Puerto Rico Electrical System Simulation

Using the *PowerWorld* simulation software, we are able to study the dynamic behavior of the transmission system by simulating the generation and transmission lines around Puerto Rico. *PowerWorld* is used to analyze stability in a selected bus, as different percentages of wind power generation are integrated into the system. The design consists of 44 buses, 15 generators, 61 transmission lines (including transformers), 24 loads and 15 shunt capacitors. Capacitors were added in specific busses in the system, for parallel compensation in the power lines to obtain the desired voltage values. The generators where modeled using the two-axis generator model and are designed to generate

3300MW to supply a fixed load of 3220MW [14]. These generators represent the main thermoelectric plants. Figure 6 illustrates the designed *PowerWorld* simulation diagram describing the generation and transmission of the power grid in the island of Puerto Rico.

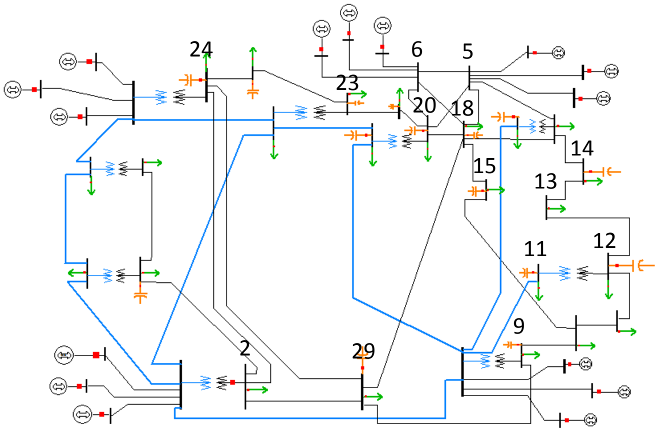

Fig. 6: PowerWorld Simulation Diagram

Ten wind farms were connected to the transmission system at buses 2, 9, 11, 12, 13, 14, 20, 23, 24, and 29 in order to simulate the proposed wind energy projects. These wind farms are grouped and separated by their locations (north, east and south) in order to establish three different case scenarios. Each one of these case scenarios was simulated with four different percentages of wind power generation. These case scenarios aid in simulating the variability that the proposed increase of renewable energy generation has on the electrical system of the island. Power generation in northern, eastern and southern wind farms are increased to 25%, 50%, 75% and 100% of their proposed installed capacity. The different percentages of power generation introduced into the electric system of Puerto Rico are shown in Table II.

TABLE II: Wind Power Generation Case Scenarios

Zone	Location	Power Capacity (MW)			
		25%	50%	75%	100%
North	Barceloneta	18.8	37.5	56.3	75.0
	Manatí	12.5	25.0	37.5	50.0
	Dorado	11.0	22.0	33.0	44.0
East	Fajardo	5.0	10.0	15.0	20.0
	Naguabo	6.5	13.0	19.5	26.0
	Vieques	5.0	10.0	15.0	20.0
South	Santa Isabel	2.5	5.0	7.5	10.0
	Santa Isabel	23.8	47.5	71.3	95.0
	Guayanilla	4.6	9.2	13.8	18.4
	Guayanilla	8.6	17.3	25.9	34.5
Total		**98.2**	**196.5**	**294.7**	**382.9**

The energy generation introduced in these locations represents the proposed increase of alternative energy in Puerto Rico's electrical system.

5. Simulation Results

Using the constructed *PowerWorld* simulation, P-V curves are plotted for each of the three case scenarios at four different wind power generation percentages. The P-V analysis for all case scenarios is performed on bus 15 because it is considered to be significant to the electrical system [15]. Results that prove to have greater voltage stability are selected for power flow analysis in order to observe if there are any anomalies present in the electric system.

A. P-V CURVE VOLTAGE STABILITY ANALYSIS

Power system stability analysis is performed to help determine if the system remains stable after adding different increases of power generation. In each case scenario (northern, eastern and southern), the voltage stability of the system is studied by observing the critical voltage and the collapse margin on bus 15. This is achieved by performing a P-V curve analysis in order to study the impact an increase in power generation will have on the electrical system.

- ***Northern Wind Farms***: There are three proposed wind farm projects for the northern part of Puerto Rico; Barceloneta (75MW) Manatí (50MW) and Dorado (44MW). The total installed capacity of these projects is 169 MW. Figure 7 illustrates the P-V curve analysis results on bus 15 obtained by integrating different percentages of power generation.

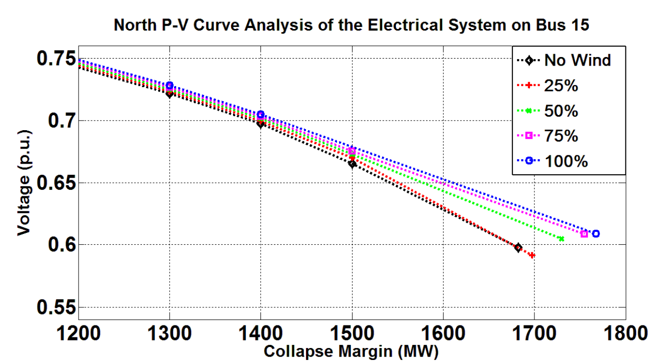

Fig. 7: P-V Curve Analysis of the Electrical System on Bus 15

As power generation in the wind farm is increased to 25%, the critical voltage is reduced. The level of wind energy introduced into the system does not seem to vary the collapse margin significantly, but does comprise a change in the behavior of the critical voltage. P-V curve analysis on bus 15 shows that increasing the proposed power generation from 25% to 100% will increase the critical voltage. Wind power generation levels below 25% will decrease the critical voltage. Table III summarizes the results obtained from the northern P-V curve analysis on bus 15.

TABLE III: Northern P-V Curve Analysis Results

Wind Penetration Levels	Critical Voltage (p.u.)	Collapse Margin (MW)
0% (No Wind)	0.598	1682.5
25% (42.3MW)	0.591	1697.5
50% (84.5MW)	0.605	1730.0
75% (126.8MW)	0.608	1755.0
100% (169.0MW)	0.609	1767.5

- ***Eastern Wind Farms***: There are three proposed wind farm projects for the eastern part of Puerto Rico; Fajardo (26MW), Naguabo (20MW) and Vieques (20MW). Vieques is a small island located to the southeast of the mainland. The total installed capacity of these projects is 66MW. Figure 8 illustrates the P-V curve analysis results on bus 15 obtained by integrating different percentages of power generation.

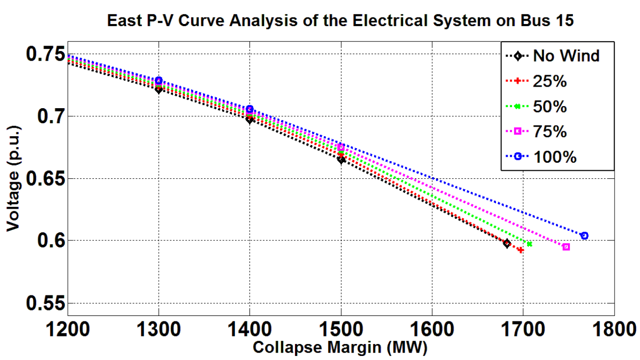

Fig. 8: P-V Curve Analysis of the Electrical System on Bus 15

As the percentage of wind energy generation increases from 0% to 75%, the critical voltage on bus 15 decreases. Only when power generation is increased to 100% does the critical voltage increase. Table IV summarizes the results obtained from the eastern P-V curve analysis on bus 15.

TABLE IV: Eastern P-V Curve Analysis Results

Wind Penetration Levels	Critical Voltage (p.u.)	Collapse Margin (MW)
0% (No Wind)	0.598	1682.5
25% (16.5MW)	0.592	1697.5
50% (33.0MW)	0.597	1707.5
75% (49.5MW)	0.595	1747.5
100% (56.0MW)	0.604	1767.5

- ***Southern Wind Farms***: There are four proposed wind farm projects for the southern part of Puerto Rico; two projects in Santa Isabel (10MW and 95MW) and two more in Guayanilla (18.4MW and 34.5MW). The total installed capacity of these projects is 157.9MW. Figure 9 illustrates the P-V curve analysis results on bus 15 obtained by integrating different percentages of power generation.

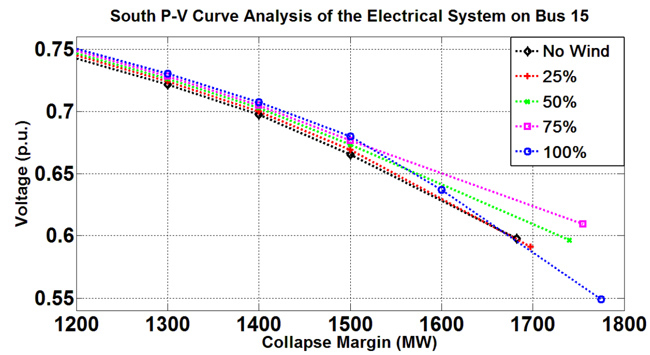

Fig. 9: P-V Curve Analysis of the Electrical System on Bus 15

Similar to what is seen in the northern wind farm, when increasing power generation in the south from 0 to 50%, the critical voltage decreases. Only when the power generation is increased to 75% does the critical voltage increase. When increased to 100% the critical voltage decreases drastically. Table V summarizes the results obtained from the southern P-V curve analysis on bus 15.

TABLE V: Southern P-V Curve Analysis Results

Wind Penetration Levels	Critical Voltage (p.u.)	Collapse Margin (MW)
0% (No Wind)	0.598	1682.5
25% (39.5MW)	0.591	1697.5
50% (79.0MW)	0.597	1740.0
75% (118.5MW)	0.609	1755.0
100% (157.9MW)	0.549	1775.0

Although the critical voltage does seem to improve when increasing power generation in the northern wind warms, the eastern and southern case scenario illustrates that in most cases the addition of wind farms does not have a positive effect in the critical voltage of bus 15, when the power generation in this respective wind farms is increased.

B. POWER FLOW ANALYSIS

In addition to voltage stability, a power flow analysis is performed in order to observe the behavior of the system when integrating wind power generation into the grid. The electrical system itself, without any wind power generation integrated, shows that certain transmission lines are overloaded. Transmission lines are not designed to deliver their maximum rated power [16]. The objective is to analyze any transmission line overloading that may occur in the system in order to see if the load on these lines is either relieved or worsened by adding wind power generation. Five different case scenarios are performed; No Wind, north (126.8MW), east (56.0MW), and south (118.5MW) as well as a case scenario integrating all wind projects (382.9MW).

In these case scenarios wind energy is introduced into the electrical system based on results obtained from P-V analysis. Table VI shows transmission line overloading in four selected transmission lines for all five case scenarios.

TABLE VI: Transmission Line Overloading

Bus		Overload Percentage (%)				
From	To	No Wind	North (75%)	East (100%)	South (75%)	All Wind (100%)
18	6	88%	89%	88%	86%	87%
18	5	106%	108%	108%	105%	107%
15	9	95%	93%	96%	97%	97%
29	2	82%	72%	74%	63%	63%

Power flow analysis on the base case scenario confirms that certain transmission lines are overloaded, including those connected to generators. Results indicate that wind power generation in all case scenarios significantly reduces the overloading percentage on line 29-2, including the case scenario with all wind farms. Whoever, there is an increase in overload percentage on transmission lines 18-5 and 15-9 from 106% to 108% in the northern and eastern case scenarios.

6. Conclusion

Puerto Rico possesses different means for electricity generation. A *PowerWorld* simulation of the electrical system is used in order to study the voltage stability on bus 15, using the P-V curve analysis in combination with the power flow of the system. It is important to understand that since wind turbines are a variable source of energy, they will pass through each percentage levels of generation at one point or another. For this reason it is ideal for the voltage stability to increase as wind power generation increases. Results indicate that increasing wind power generation on the northern wind farms from 50% to 100% increases the critical voltage on bus 15, while lower wind power generation levels (25%) will decrease the critical voltage. In the eastern wind farms; wind power generation levels at 100% of the installed capacity increased the critical voltage in the system. Wind power generation below 100% lowers the critical voltage. When analyzing results from the southern wind farms, it is evident that low wind levels (25% and 50%) decreases the critical voltage. Higher wind levels (100%) will also decrease the critical voltage drastically. Only when the power generation is at 75%, does the critical voltage increase. Although results indicate that the electrical system is stable at some wind power generation, the power flow of the system indicates that transmission lines in key areas are overloaded. Not only do they reach their rated limit but in some cases they exceed this point.

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