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Analysis of the Integration of Wind Energy Generation in the National Transmission System (NTS)

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Abstract

Background/Objectives: A case study is presented where a 1.432 MW wind power connection with DFIG (doubly-fed induction generator) technology is analyzed in the stability of the National Transmission System (NTS). Hence, the STN's database from 2017 is used in DIgSILENT with different demand scenarios and their respective generation dispatch units. **Methods/Statistical Analysis:** A scan was executed on the flaws in circuits close to the connection of wind energy parks in La Guajira by calculating the percentage of events that generate the disconnection of wind turbines due to voltage sags and swells. The stability in frequency in response to these generation losses is also analyzed**. Findings:** Regarding the contingencies that were simulated, the outcome was seen in overshoot events of wind turbines due to transitory peaks in voltage during flaws that could not be solved with external reactive compensation. The stability in frequency related to these overshoots is greatly affected on disconnections higher than 400 MW. After verifying the reactive power injection from the converter of the DFIG model in DIgSILENT based on the compliance with electrical parameters supplied by manufacturers, 58% did not meet these technical specifications so a wind turbine model is necessary to grasp the internal operation of the converter. **Conclusion:** This allows the identification of possible solutions to stability issues that contribute to the operational and regulatory changes to define technical technology-related requirements and the connection of wind turbines in Colombia.

Keywords: DFIG Wind Turbine, DIgSILENT, Stability, Voltage Supportability, Wind Energy

1. Introduction

Currently, there are high expectations in Colombia for the connection of 3.000 MW of wind energy, using doubly-fed induction generators (DFIG) in wind turbines according to previous studies[1] and the normativity in countries such as Chile and Panama[2,3] that demand the installation of electric generators with wind turbines.

The Planning Unit for Energy and Mines (UPME in Spanish) identified the technical and economic viability of incorporating wind energy generation, finding that the benefits in terms of price, emissions, execution time and complementariness justified the construction of transmission lines for wind energy projects. As a consequence, the Ministry of Mines and Energy (MME) issued Resolution n° 40095 which includes transmission work required in the NTS for the connection of wind

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energy parks in La Guajira[4]. Since then, as a requirement to connect to the National Transmission System (NTS), the Planning Unit demanded connection and information studies on the resource to the promoters of wind energy projects. For the development of the analysis, the NTS long-term database from 2017 was used which was provided by the Market Experts Company (XM) and modeled in DIgSILENT[5], keeping the demand modeling and voltage dependence. The wind turbine generator from the Jepirachi Park was replaced by an induction generator model as seen in real scenarios and the SVC model from Chinu was updated including its degraded modes so it always stays between the limits of its capacity.

For Phase 1 of Renewable, a total of 1.451 MW were received from which 201 MW of the Mauripao wind energy project are requested for Phase 2 and 200 MW of the Windpeshi wind energy project are used to connect directly in the Substation Cuestecitas of 500 kV [5]; Resolution n° 40629 modified expansion work related to the integration of the wind energy resource with entrance date of November 2022.

In 2015, UPME requested to the consultant PHC Integrated Services Co. an analysis of the regulatory aspects that will involve the participation of renewable sources within the National Interconnected System (NIS). For this study, PHC considered a network which is highly superior to the expansion plan and proposed supportability curves in voltage and frequency for wind turbine generators that wish to connect to the NTS[6].

INTERCOLOMBIA Co. developed a new study in[1] considering the expansion plan network currently in force and obtaining as a result the following recommendations:

- **Do not use** wind turbine generators with Type I - Induction Generator (IG) technology due to its effects in voltage stability and harmonic impedance *Z(w)* while using other technologies at the same time. Type I wind turbines greatly limit the connection capacity of the substation and require the implementation of large compensation schemes.
- **Use** wind turbine generators with DFIG technology due to their economic viability and the capacity they have to operate in a wide range of wind speeds and generate both active and reactive power.

Considering the recommendations shown and the review of international normativity where only the installation of electric generators with Type III and IV wind turbines is allowed[3], DFIG (Type III) is a viable option for the connection of wind energy generation in electric systems. This technology has voltage control and the capacity to control real power and reactive power at high speeds; it is constructively similar to a winding rotor induction motor but with a rotor connected to the network through electronic power equipment such as converters. It has a stator directly connected to the network which allows the converter to be designed only for 30% of the nominal power of the machine[7,8].

An important advantage of these types of generators in wind energy systems in comparison to other technologies is that it can both absorb and inject power into the network; however, the behavior regarding voltage drops has its deficiencies since in most cases DFIG systems are disconnected from the network to protect the converter on the rotor's side. Nowadays, due to the sustained growth of wind energy sources, the control methods have shown advances that can deal with these situations without the need to disconnect the wind energy park[9].

In this context, the lack of normatively in regulatory aspects that make viable the participation of wind energy in the Colombian electric market have a non-controllable character and lead to the displacement of another type of generation such as hydraulic or thermic energy which provide more security to the system in terms of stability due to the high inertia of its technologies. Hence, the impact of this type of generation in the stability of NTS has to be analyzed so that it can participate in proposals and possible solutions to implement before the National Operation Council (CNO in Spanish) and the Transmission Planning Consulting Committee (CAPT in Spanish) according to the current and future needs of the system.

2. Methodology

Initially, the incorporation of 1.232 MW wind power was considered in La Guajira which includes eight wind energy parks: two parks proposed by ISAGEN of 16 MW each that will connect in 2018 to the Cuestecitas - Puerto Bolivar circuit of 110 kV close to Jepirachi and the Windpeshi Park of 200 MW will be located 100 km north from the current Cuestecitas Substation of 220 kV. However, there is a current demand to connect to the Cuestecitas Substation of 500 kV in 2019. Additionally, five wind energy parks of 200 MW each are proposed with a supposed capacity from the promoting agents' in[5] where it is evidenced that the typical power of the parks with most connection possibility in 2022 and 2023 is 200 MW.

All the parks in the wind energy project in La Guajira are implemented in DIgSILENT and were modeled with the template WECC WTG Type3 2,0MVA included in its 2017 version library which has a DIFG technology wind turbine represented in the network through a static generator with a connection node and the initial adjustments for the calculation of the charge flow and dynamic simulations: these machines operate under a composite model that includes seven controls in DSL language[11].

In the case of the five 200 MW parks, 100 generators of 2 MW were used which implies a total of 100 converters equivalent to ± 60 MVAr of dynamic compensation (30% of the nominal power)[8]. Figure 1 shows that each park is connected to the Collector Substation of 1500 kV via: a double AC circuit of 110 kV - 950 A over an extension of 50 km, a 500/110 kV transformer of 250 MVA, a 110/10 kV transformer of 250 MVA and 100 10/0.96 kV coupling transformers of 2.5 MVA. The 500 kV network is represented in black, the 100 kV network is represented in red and the park's network is represented in blue. No half-voltage connection cables or internal networks were considered.

According to the UPME announcement, the location of the Collector 1 Substation will be limited to a 5 km radius measured from the coordinates 1225439.132E and 1810763.931N which are located

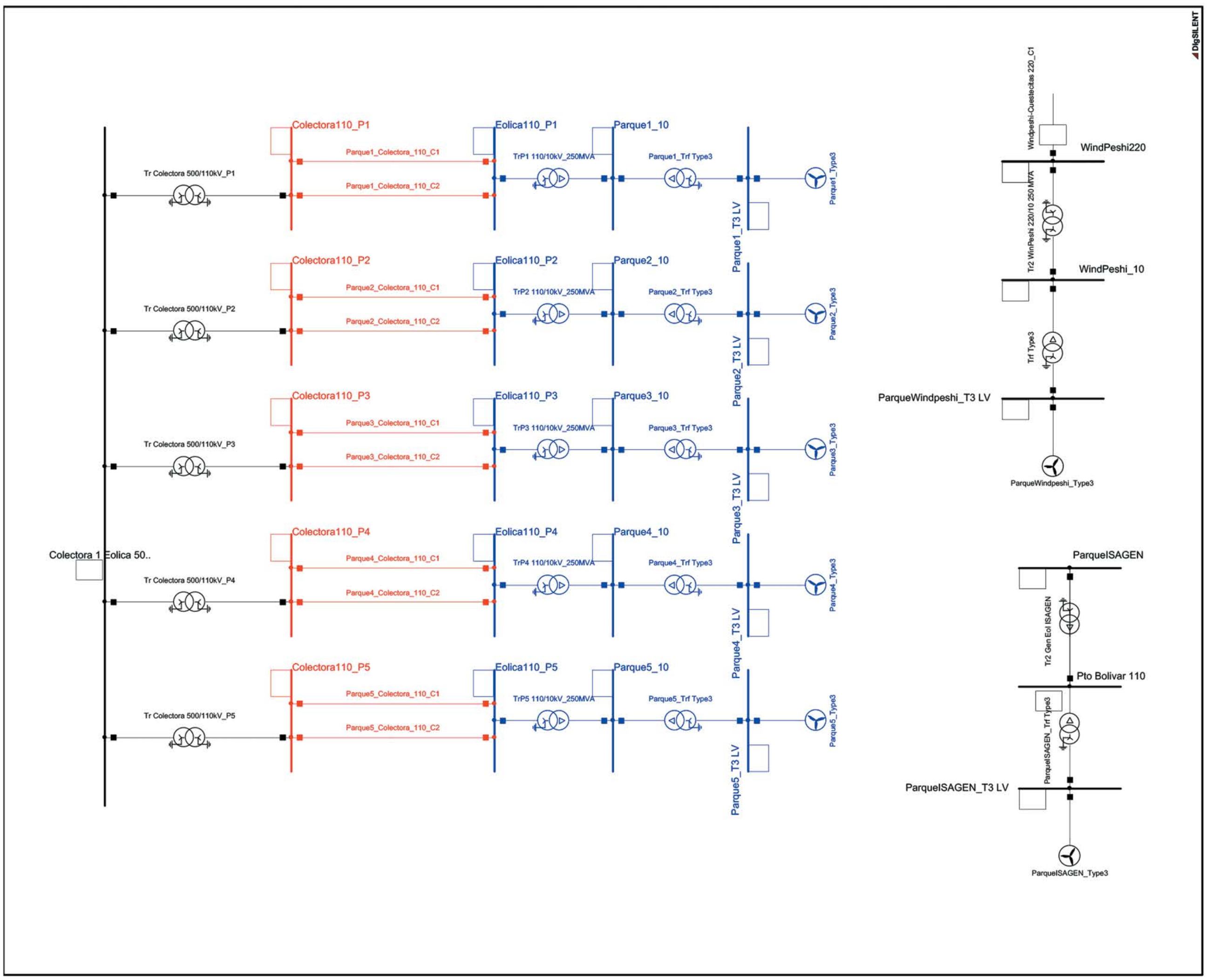

Figure 1. Connection of five wind energy parks to the Collector 1 substation of 1500 kV - Source: Authors.

in the municipality of Uribia in the La Guajira department[12].

The distances between the parks and the Collector 1 Substation were set at 50 km to improve the stability by considering the location of the proposed wind energy projects and the real elements which could be possibly used for future connections. Figure 2 shows the connection between the Collector 1 and the Cuestecitas substations through a double AC circuit of 500 kV-950 A of 120 km with four 60 MVAr reactors in the edges of both lines[12]. The backup work comes from Cuestecitas - Copey 500 kV and Cuestecitas - La Loma 500 kV which is currently included in the current expansion plan of UPME.

The demand of the NTS which was used corresponds to long-term projections made by XM in the years 2022 and 2023 due to the uncertainty of the connection that is currently seen in the proposed wind energy projects due to a lack in infrastructure and regulations. It is expected that 1.232 MW of wind energy power are available for installation in La Guajira. Each year, three demand scenarios were presented:

- P04_MinTerEol - Simulation scenario with minimum demand and thermal-wind dispatch (maximum power transfer from the Atlantic Coast to the inland of the country
- P15 _MedEol - Simulation scenario with medium demand and wind energy dispatch

The criteria and technical requirements for the analysis are defined in terms of the normativity and technical review for wind energy generation in electric systems, by comparing and verifying the common aspects of network codes in Chile and Panama[2,3] with the report of regulatory recommendations for the incorporation of wind turbines that the PHC agency made in Colombia[6].

To study the stability of the NTS by incorporating wind power in La Guajira with the mentioned considerations, the following analyses are set:

2.1 Loss from Wind Turbines Due to Voltage Sags and Swells

Based on the defined criteria, the supportability limits are verified when dealing with voltage sags and swells to determine whether the loss from wind turbines is produced due to a contingency. The effect of contingencies depends on the several factors: type of

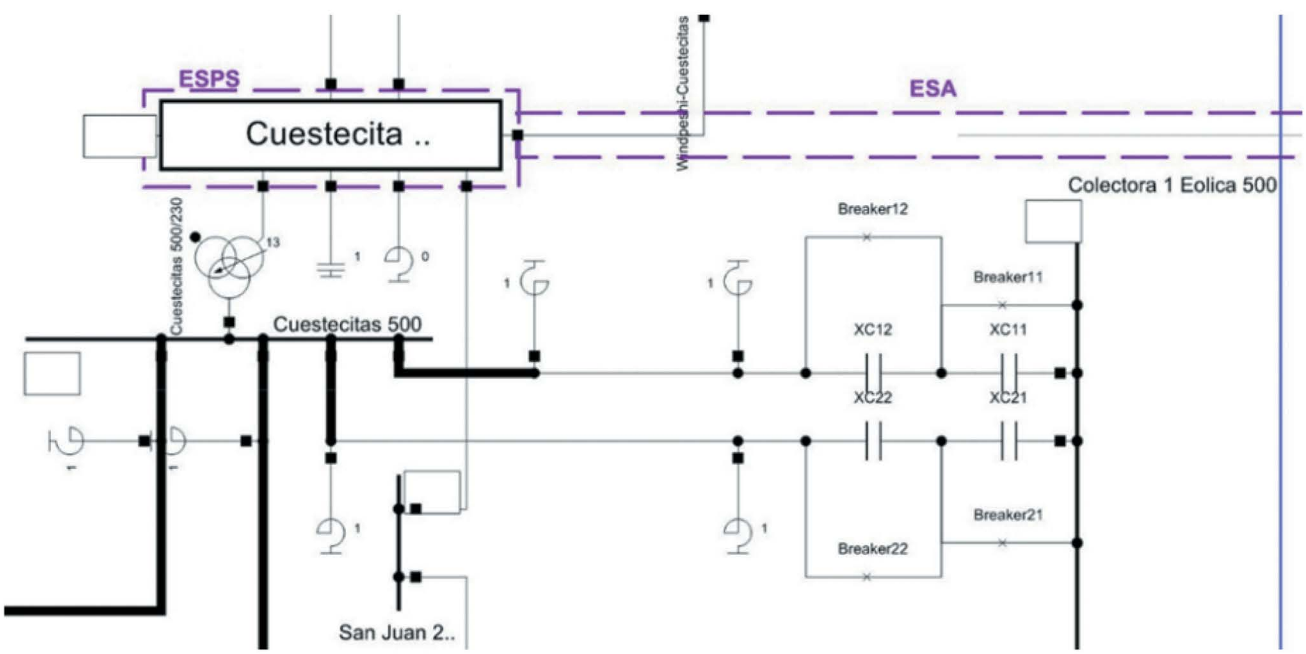

Figure 2. Connection between the substations of Cuestecitas 500 kV and Collector 1500 kV - Source: XM.

failure, failure impedance, location of the failure, failure scenario, etc.

A scanning of the 50% failures over one of the circuits of the Cuestecitas - Collector 1 connection with 1500 kV in the proposed scenarios to calculate the percentage that generates the disconnection of wind turbines. These simulations are also performed in failures in circuits close to the connection of wind energy parks, such as the Cuestecitas - Copey 500 kV, Cuestecitas - La Loma 500 kV and La Loma - Ocana 500 kV lines.

2.2 Stability in Frequency against Losses from Wind Turbines

When there is a contingency that causes the disconnection of wind turbines, the frequency of the system can have strong variations due to the unbalance between generation and demand; in some cases, to move the frequency back to nominal values, the Automatic Load Disconnection Scheme (ALDS) is activated. In this analysis, the frequency of the NTS is verified when 200 MW of wind power is disconnected manually (200 MW, 400 MW, 600 MW, 800 MW and 1000 MW in the worst case scenario): the minimum demand for 2022 with minimum inertia in the NTS works with 433 s of total inertia (100 MVA base) in the NTS.

3. Results and Discussion

The voltage supportability limits under operation failures were plotted in DIgSILENT by defining the limits of the report from PHC as a guideline to continue the stability simulations and the other proposed recommendations in their report[6]; they are strict enough and are dimensioned with approximate characteristics in the Colombian electric system, guaranteeing the principles of quality, reliability and security defined in the network codes in force[13].

The analyses presented focus on the criteria of voltage under operation failures and operation ranges in frequency. The others are outside our scope of interest. The CPF does not apply in this case since it was considered to always work with the nominal power of wind turbines, while keeping the speeds constant. Additionally, the reactive power and voltage control is derived from the wind turbines chosen for the wind energy project. It normally controls the reactive power according to a fixed power factor and must control voltage under contingencies.

3.1 Loss from Wind Turbines Due to Voltage Sags and Swells

To analyze the loss from wind turbines under failures in the system considering 1.232 MW of wind power, a failure was simulated in one of the Cuestecitas - Collector 1 circuits which is the most delicate contingency in this wind energy project. The failure was set in 50% of the line as monophasic and triphasic types of 5 Ω each with a 0.1 second clearance and definitive disconnection. The simulation time was 10 seconds.36 cases of failures were simulated (18 cases of monophasic failures and 18 cases of triphasic failures) which had the voltage monitored in one of the five parks connected to the Collector 1 Substation in Windpeshi and ISAGEN; these cases, were simulated in the three scenarios proposed for 2022 and 2023.

The criterion for voltage operation under failures defined by PHC indicates whether the contingency leads to the disconnection of wind turbines. Wind turbines are not programmed to automatically disconnect when voltage surpasses the established criteria after observing the voltage behavior once the failure is cleared. Figures 3-4 show the simulation of monophasic and triphasic failures in the most critical scenario by visualizing the behavior of voltage during and after the failure in one of the parks connected to the Collector 1 Substation.

Figure 3 shows that during the monophasic failure, voltage reached a peak that surpassed the limit of High Voltage Ride-Through (HVRT) leading to the disconnection of wind turbines. This inconvenient could not be solved with external reactive compensation (Compensation in series, SVC and STATCOM) since it is a product of a transitory overvoltage where voltage returns to the operation limits afterwards.

When there is a triphasic failure, Figure 4 shows the same behavior of voltage (wind turbine overshoot), recovering within the criteria. The voltage fluctuations were presented in both contingencies and are exclusively due to the problems of wind turbines control adjustments since the power and load conditions are not modified in any way.

In total, the disconnection percentage during monophasic failures was 11% caused by transitory overvoltage during contingencies that cannot be solved for additional compensation. For the triphasic failure scenario, the percentage notably increased

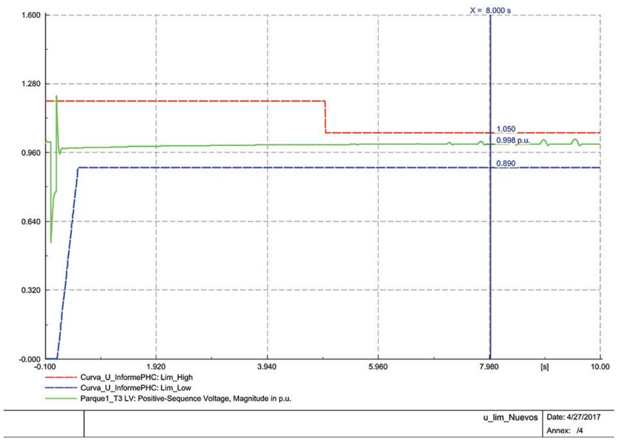

Figure 3. Voltage of Park 1 during and after a monophasic failure of 5 Ω (P20_MaxHidroEol 2023 scenario) Source: Authors.

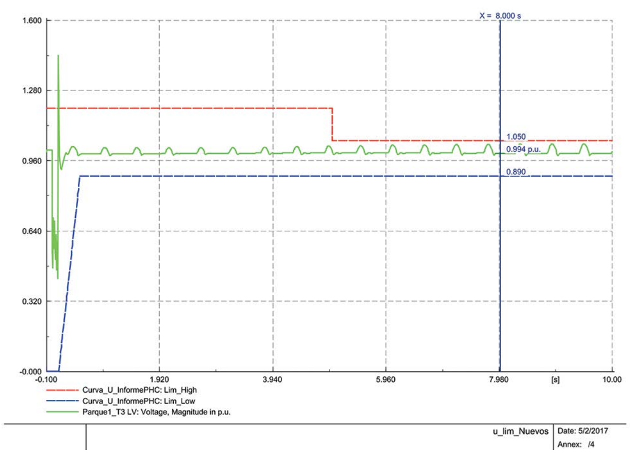

Figure 4. Voltage of Park 1 during and after a monophasic failure of 5 Ω (P20_MaxHidroEol 2023 scenario) Source: Authors.

to 72% and was related to the previously mentioned causes.

To determine if the reactive power delivered by the DFIG is complying with the 0.6 MVAr limits that was established in the converters, the load flow values show that the reactive power delivered to the system by each wind energy park after the simulated failures varies from 45.62 and 52.8 MVAr. After the contingencies, the voltage from all wind energy parks recovered and reached values similar to the load flow in normal operation conditions. Hence, there was no deficit in the reactive power during failures.

Moving on with the methodology, monophasic failures were simulated in circuits close to the connection of wind energy parks such as the lines of Cuestecitas - Copey 500 kV, Cuestecitas - La Loma 500 kV and La Loma - Ocana 500 kV. In all cases, the percentage of disconnection of DFIG wind turbines under contingencies was reduced to 0%. After the failure events, the voltage from the bars where Windpeshi, the five parks and the parks of ISAGEN are connected kept recovering and reached values close to the load flow under normal conditions. The reactive power delivered by each wind energy park during a failure varies between 39.5 and 58.2 MVAr. This amount of MVAr is higher than the one found in the Cuestecitas - Collector 1500 kV line.

3.2 Stability in Frequency against Losses from Wind Turbines

In minimum demand scenario in 2022 (lowest inertia of the NTS), the effect over the frequency of the NTS was verified with 1000 MW of wind power connected to the Collector 1 substation. The limits compared were the definitive stages in the ALDS (Automatic Load Disconnection Scheme) in force for NTS[14] and the operation ranges in frequency for the recommended wind turbines for the PHC consultant.

Figure 5 shows how the frequency evolves after the loss in wind turbines from voltage sags and swells. With the disconnection of 200 and 400 MW of wind power, the frequency showed some variations but none reached any stage of the ALDS. In the case of the overshoot of wind turbines of 600 and 800 MW, the frequency lowered to a minimum of 59.395 and 59.317 Hz respectively which caused the first stage of the ALDS to intervene. Finally, with the disconnection of the five parks connected to the Collector 1 Substation (equivalent to 1000 MV), the frequency reached a minimum value of 59.152 Hz leading to the intervention of the first two stages of the ALDS. The operation limits in frequency for the wind turbines proposed by the PHC were not reached in any of the cases.

With the previous results, 1.000 MW of wind energy power connected to the Collector 1 Substation, no problems were found in the simulation of the most frequent and relevant failures in the connection of La Guajira. It was then decided to simulate the most delicate

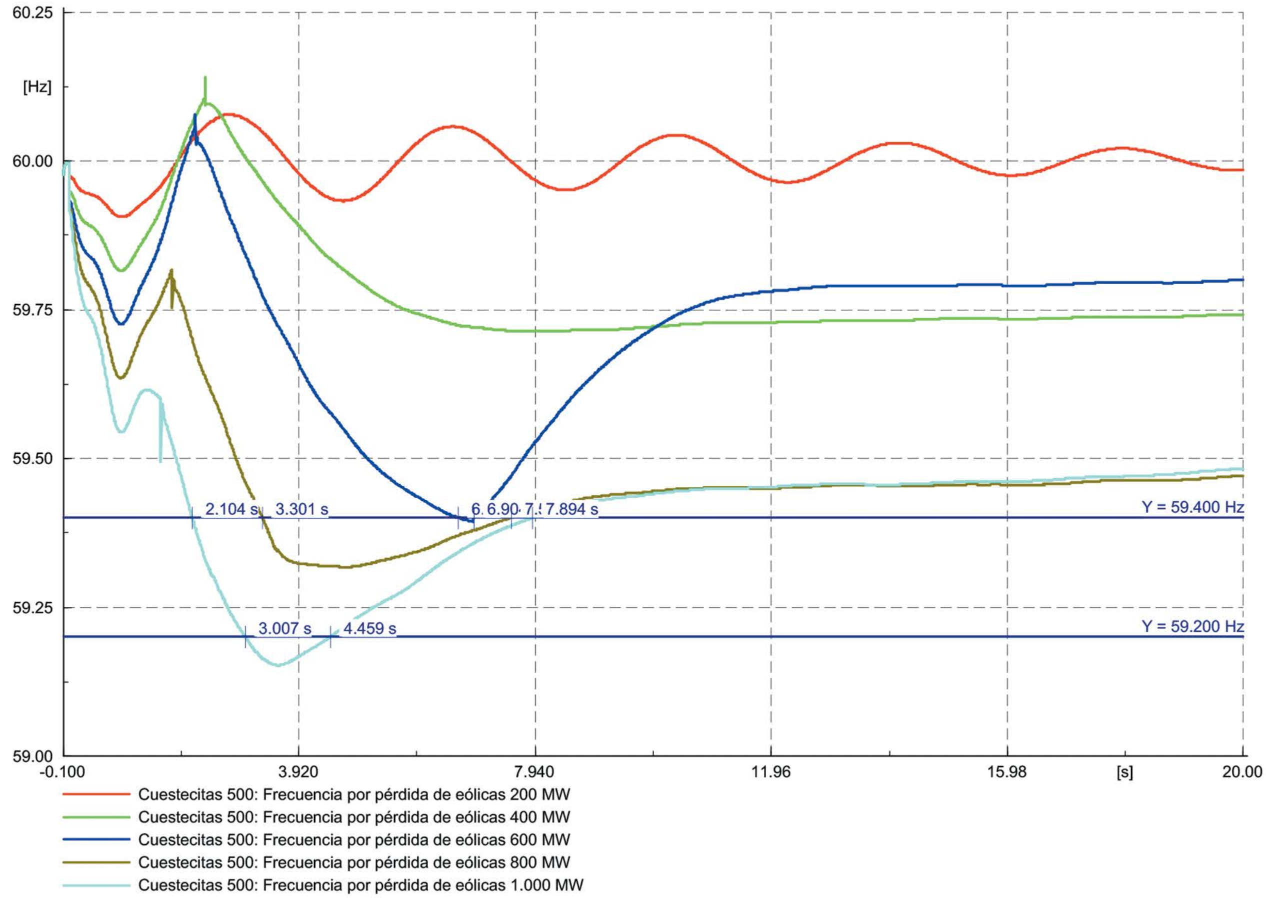

Figure 5. The frequency of the NTS by the disconnection of wind power in La Guajira (P04_MinTerEol 2022 scenario) Source: Authors.

contingency for the wind energy project including a sixth park that implies the connection of 1.200 MW with the purpose of verifying if the connection can support these failures in the system.

During the monophasic failures in the Cuestecitas - Collector 1 line with the same characteristics of the simulated cases, the voltage reached peaks that surpassed the HVRT limit causing the disconnection of the DFIG so the solution to these overshoots is not the installation of external reactive compensation. When triphasic failures occur, the same behavior was seen for the voltage with the disconnection of wind turbines as well as a recovery within the zone determined by the criterion.

Although the percentage of cases with disconnection of wind turbines for monophasic and triphasic failures went from 17% to 83% respectively due to the increase of 200 MW, the voltage on the bars descended during the contingency but completely recovered. The problems in the adjustments of the wind turbines control multiplied and reflect more pronounced voltage fluctuations.

Regarding the final values of the load flow after the failures, the voltage in the bars where the five parks are connected recover without any problem. However, the reactive power in each wind energy park which is delivered to the system during contingencies surpassed 60 MVAr, thereby indicating that the converters are not limiting their capacity and are internally supplying impossible amounts of current.

In Figure 6, it can be seen how the frequency is greatly affected after the loss of the wind turbines. The disconnection of 400 MW of wind power led to the frequency reaching the ALDS stages and a total collapse after 8 seconds. Regarding the operational limits proposed by PHC, with the disconnection of

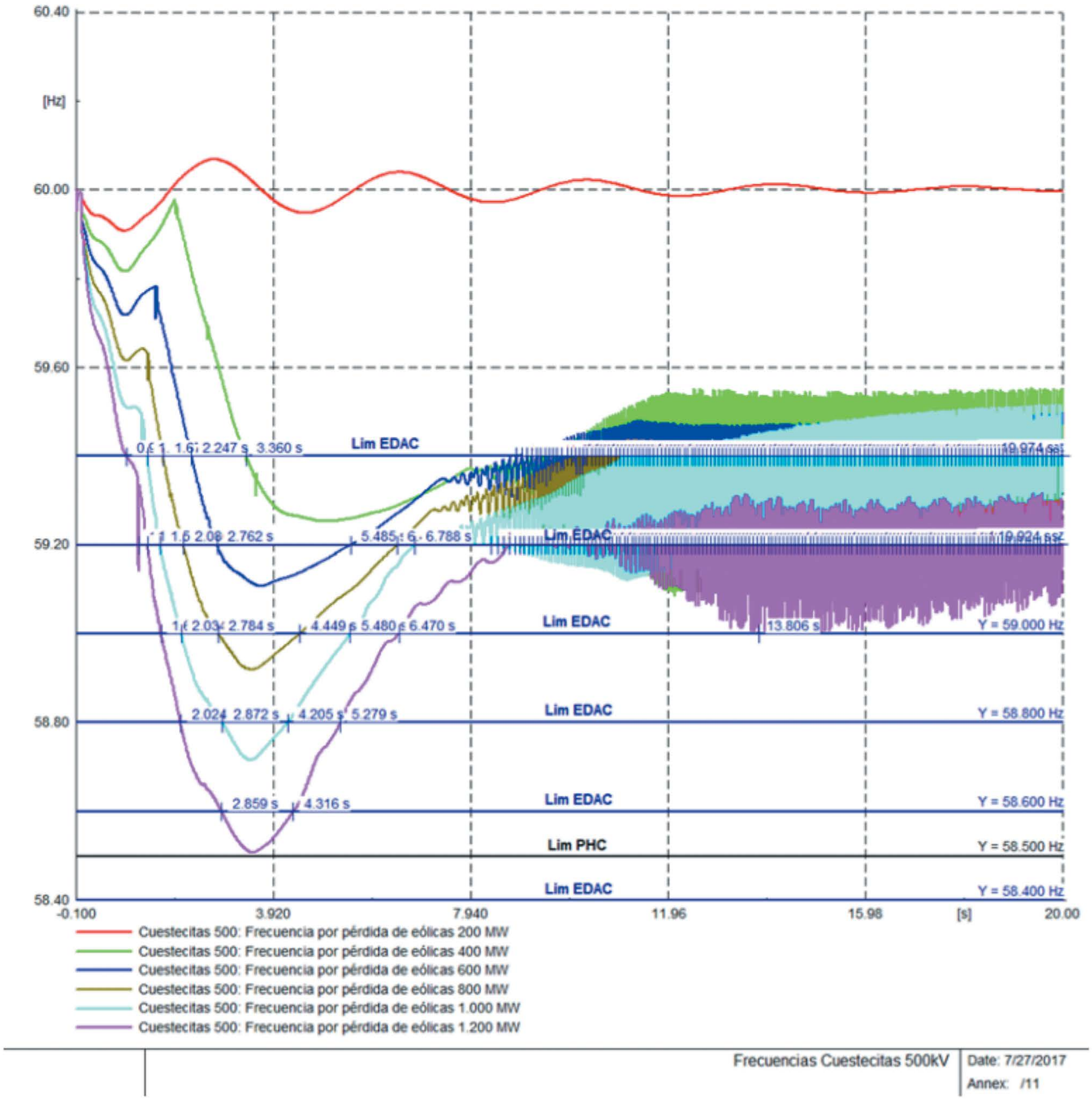

Figure 6. Frequency of the NTS during wind energy disconnection with six parks connected to the Collector 1 substation (P04_MinTerEol 2022 Scenario). Source: Authors.

1.200 MW the frequency reached a minimum value of 58.509 Hz that is about to cause an overshoot with a minimum temporization of 15 seconds according to the recommendations of the consultant.

The simulations in DIgSILENT indicate that the model is not limiting the capacity of the converter since the reactive power of the wind energy parks in some cases exceed 60 MVAr. Since the DFIG model in DIgSILENT does not allow the determination of internal variables such as the power of the converter, the Aliprantis[15] method was used to verify if the wind turbines can deliver this amount of reactive power and estimate the rotor and stator's currents in a DFIG and then compare them with the electric parameters given by the manufacturers of this technology so that the requirements are met.

The technical specifications were referenced according to the wind turbines manufacturers SUZLON[16] and VESTAS[17] and the authors of scientific literature[18,19] and no other manufacturers with real DFIG parameters could be consulted due to commercial secrecy.

The reactive power of the stator and the slippage of the motor are parameters established according to the operation of the wind turbine and can take different values in terms of speed and the power factor used. When the calculation method is implemented, currents, voltages and power in rotor and stator were determined. The values to compare with the technical parameters of the manufacturers are the currents in the rotor and the stator of the DFIG.

For the SUZLON wind turbines, the currents in the rotor exceed their maximum value. In the case of VESTAS V80, not only the currents in the rotor exceed their maximum value but also do the currents in the stator. The electric parameters of the DFIG found[18,19] have no references from manufacturers or other support of real suppliers; hence, they were calculated with fewer cases where their limits in rotor and stator currents are higher in comparison to the other manufacturers, leading to a higher compliance percentage. The voltage in the rotor does not exceed the maximum values given by the manufacturers. After analyzing the calculations obtained of the internal parameters of the DFIG, it was found out that 58% of them do not comply with the technical specifications given by the consulted manufacturers of wind turbines.

4. Conclusions

The results confirm that the use of DFIG wind turbines is the most viable option for the connection of wind power in the country considering that not all the technologies can be used and that it is not an eligible criterion in Colombian operation and regulation.

By increasing the wind power by 200 MW in the Collector 1 Substation, the impact of the failures in the Cuestecitas - Collector 1 line is greater and forces the other circuit to transport the power from all the parks reaching its maximum transfer limit. However, there is no significant difference between the 1.000 MW and 1.200 MW connections of wind power.

It was evidenced that it is necessary to have a more detailed wind turbine model that allows monitoring the internal operation of the converter to operate within the design limits and closer to reality. The DFIG model in DIgSILENT does not emulate the capacity limits of the converter so it is recommended to work with different software including a more specific wind turbine model.

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