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WIND ENERGY: PERFORMANCE ANALYSIS OF WIND GENERATORS INSTALLED IN NORTHEAST BRAZIL IN FACE OF DISTURBANCES IN THE CONNECTION NETWORK

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Abstract: The greater need for electrical energy brings with it the constant search for potential sources for generating electrical energy. The Brazilian interconnected electrical system is expanding, with the change in the energy matrix mainly through renewable sources, with an intermittent characteristic, typically coupled to the grid using power electronics equipment. These energy uses have characteristics that cause the propagation of electromagnetic phenomena throughout the network where they are connected. In view of this, this work aims to evaluate the withstandability of wind turbines to voltage sags, due to the occurrence of short circuits in the basic transmission network, as well as to carry out the study of harmonic distortions caused by the generation of wind energy in the system. To develop this analysis, a case study is carried out in a wind complex located in northeastern Brazil. The system modeling is carried out using the ATPDraw and HarmZs software, using equivalent models of the wind complex. The voltage drop simulations carried out demonstrated the existence of points allowing the wind farm machines to be disconnected, in accordance with current guidelines, in the first and second neighborhood. The results of the harmonic distortion simulations indicate that the performance of the studied wind farm already presents an adequate individual harmonic distortion rate and also that the installation of a future capacitor bank must reduce the harmonic distortion rate for most frequencies.

Keywords: Renewable Energy, Sustainability, Wind Energy, Electricity Quality, Harmonics, Slump Supportability.

INTRODUCTION

The evolution of agricultural and industrial processes, as well as the growing technological advancement of electronic devices, associated with the population’s easier access to these products, brings with it a greater need for electrical energy consumption in the world. Based on this need, alternatives to already established energy sources have been adopted, as well as sustainable alternatives, such as the commercial generation of electrical energy through primary wind sources.

In Brazil, renewable plants account for 91% of installed capacity in May, of which around 52.97% of the total comes from hydroelectric plants (ANEEL, 2023). As a consequence of this high percentage of hydroelectric plants, the national energy system is more exposed to water shortages, such as that of 2021, one of the largest since records began in 1930. When hydroelectric plants are unable to meet demand, thermoelectric plants are activated, as they were from October 2020 until the end of this scenario, according to EPE (2021).

The generation of electrical energy through wind farms has presented itself as an excellent one with great growth in recent years, in which according to ANEEL (2023), in May 2023 it reached 13.34% of the energy matrix.

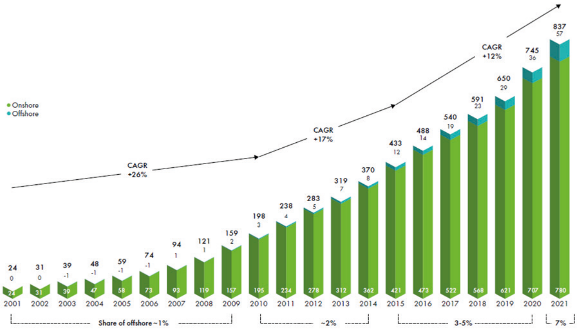
However, there are challenges involved in connecting these sources to the SIN (National Interconnected System), as they are generally concentrated far from large load centers, increasing losses in the system, incompatibility between generation and demand, respectively voltage drops and frequency deviations (ACKERMANN, 2005). Another characteristic is the intermittency of this source, which results in a great need for theoretical basis, analysis of the propagation of the electromagnetic phenomena involved and the main consequences they have on the electrical system to which they are connected.

THEORETICAL BACKGROUND AND METHODOLOGY

The technical theory of wind energy generation is based, with an understanding of all components and systems, in addition to the regulatory environment in force in Brazil. The voltage sags study is carried out using the computational tool, ATPDraw (Alternative Transient Program). The simulation to verify the harmonics generated by the wind farm in the PAC is carried out using CEPEL's HarmZs software. The case study addresses a PAC substation located in the northeast region of Brazil, which has a total of 149 wind turbines totaling approximately 312.9 MW of installed power, with 34.5 kV feeder circuits, distributed among three step-up transformers for 230 kV.

WIND ENERGY SCENARIO

In 2021, the global wind industry had its second best year, with almost 94 GW of installed capacity, with a forecast of reaching the mark of 110 GW of new installations by 2026 (GWEC, 2022, p. 9 - 11). According to Graph 1, it is possible to observe the evolution of global installed capacity over the last 22 years.



Graph 1: Historical development of wind generation facilities.

Source: GWEC (2022).

In Brazil in 2021, installed wind generation capacity reached the 20 GW mark, corresponding to approximately 70% of all wind capacity in Latin America, being the second largest source of energy generation in the country (GWEC, 2022, p. 127).

As EPE (2020) describes in its "National Energy Plan 2050", based on an evolution in energy consumption multiplied by three times that of 2015 and considering the competitiveness of renewable energy sources, it is estimated that the installed capacity of wind sources reaches between 110 and 195 GW.

In 2021, it was possible to implement the regulatory framework for the offshore sector, due to the publication of Decree 10,946/2022, providing for the transfer of physical resources, as well as the use of natural resources for the generation of electrical energy in offshore plants. EPE predicts that offshore wind capacity installed at sea will reach 16 GW by 2050 with a CAPEX reduction of 20%, where CAPEX is the acronym for the term, in English, Capital Expenditure, which means "capital expenditure", is intended for The company's intangible assets, therefore, correspond to the portion of the company's resources that will be allocated to capital goods (GWEC, 2022, p. 127 - 128).

WIND TURBINES

They are systems for converting wind energy into electricity, with subsystems for controlling the location and positioning of the blades and nacelle, including frequency conversion systems, if any. The components are characterized into four elementary construction groups: System for capturing wind, mechanical transmission system, system for generating electrical energy and the structural group (GOVEIA, 2018, p 32). The main components of the wind turbine are illustrated in Figure 1.

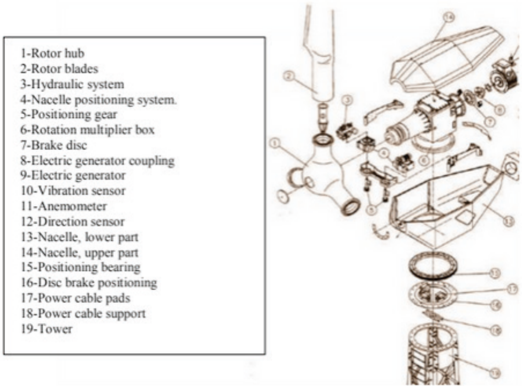


Figure 1: Components of an Aerator.

Source: CEPEL (2014).

USED EQUIPMENTS

We can classify the type of turbine by its arrangement in relation to the axis, as follows: vertical axis turbines and horizontal axis turbines.

Turbines with a vertical axis are characterized by the possibility of mounting at ground level, with no type of control required for wind tracking, as they have the same properties in all directions (VIAN et al., 2021, p. 17).

The main disadvantages that end up making this type of turbine configuration unfeasible are the fact that it has an intrinsically low power coefficient, as well as having a high weight in relation to its produced power (MANWELL et al., 2002, p. 146), in which when compared to a horizontal axis turbine ends up generating less energy. Additionally, there is a construction difficulty in large turbines, due to the need to install tie rods at the top of the turbine (EWEAO, 2012, apud VIAN et al., 2021)

Horizontal axis wind turbines act thanks to the lifting force, with their axis parallel to the ground. HAWT (Horizontal Axis Wind Turbine) rotors are classified by the type of rotor control, orientation and their alignment in relation to the wind (MANWELL et al., 2002, p. 3), and in upwind turbines the winds affect the front part of the turbine sweep area, in the case of downwind winds affect the back of the turbine (PINTO et al., 2013, p. 86).

Variations in the atmospheric pressure field caused by terrestrial heat transfer cause the movement of air from high to low pressure, in which even though there are pressure forces in the vertical direction, they end up being canceled by the action of gravity, this way, the winds move predominantly in the horizontal direction, due to the reaction of horizontal pressure gradients (MANWELL et al., 2002, p. 24).

The construction practice of horizontal axis turbines tends to have high heights, as winds generally tend to be stronger and with less turbulence as ground elevation is gained, so the highest tower as possible is always sought, this height being defined by greater energy capture versus increased cost (MANWELL et al., 2002, p. 321; VIAN et al., 2021, p. 17).

The main elements that make up the construction of horizontal wind turbines are: blades, nacelle, rotor, speed multiplier, electric generator, support towers, control systems and all sensors necessary for operation.

The Rotor is composed of the support hub and the wind turbine blades, considered one of the most important parts of the wind turbine due to the total cost versus system performance (MANWELL et al., 2002, p. 4).

Blades, can be a set, most often with three blades, aimed at use in machines for generating electricity, among the main characteristics of the blades can be described: aerodynamic performance, rigidity and lightness. The blades are developed to take on trapezoidal or rectangular contours, for high aerodynamic performance. In large and medium-sized units, trapezoidal blades are most commonly used. The materials used to make the blades are fiber-reinforced polymers (plastics), with fiber-reinforced polyester or epoxy being the most commonly used in the manufacture of blades. of glass. Carbon fiber or aramid fiber can also be used as reinforcement, according to Pinto et al. (2013, p. 90), carbon fiber stands out for its high modulus of elasticity and mechanical resistance compared to steel, as well as a reasonable resistance to fatigue.

The Nacelle, being the heaviest part of the structure, is the compartment where all the most important components are located and protects the entire assembly that contains the gear, generator, gearbox, bearings, axles, control system, brakes and turbine turning mechanisms. In large wind turbines, Nacele has maintenance accessories, allowing access for specialized professionals to carry out the necessary checks (MERLIN, 2022).

The function of the speed multiplier is to multiply the speed of the rotor rotation rate, moving from the range of tens of rpm to around hundreds or thousands of rpm, transmitting this speed to the generator drive shaft (MANWELL et al., 2002, p. 4).

Elastic coupling is the mechanical element that makes the appropriate connection between the speed multiplier shaft and the electrical generator.

An electrical generator is the equipment responsible for converting mechanical energy on its shaft into electrical energy at its terminals, according to Pinto et al. (2013, p. 159) there are two types of machines most used by wind turbines, namely:

- Asynchronous machine, also known as induction, whose main characteristic is the difference in speed between the generator rotor and the rotational speed of the stator's rotating field, the rotor is not synchronized with the rotating field (PINTO et al., 2013, p.160 - 161);
- Synchronous machine that has a rotor with a stationary armature with windings, the field in this rotor is created by a permanent magnet or an external DC current in its windings, so that the electrical frequency produced is directly linked to the mechanical speed of rotation (CHAPMAN, 2013, p. 192 - 196).

TOPOLOGIES

Wind turbines convert the kinetic energy of the wind, coming from air particles that collide with the blades, generating torque and consequently the rotary movement in the rotor that is transferred to the generator shaft, the element responsible for converting the mechanical energy transmitted into energy. electricity, then being made available to the concessionaire's network (PINTO et al., 2013, p. 79; VIAN et al., 2021, p. 30), as illustrated by Figure 2.

The generators used in the production of wind energy are: Direct Current (DC) Generators, which are generally used in small turbines (MANWELL et al., 2002, p. 219), but due to the fact that they have an unfavorable power to mass ratio and greater need for maintenance, there is a growing lack of interest in its use (PINTO et al., 2013, p. 160); Alternating Current (AC) generators, with two models used, asynchronous generators (squirrel cage induction generator and wound rotor) or synchronous generators (wound rotor generator or permanent magnet) (SÖDER; ACKERMANN, 2005, p. 65).

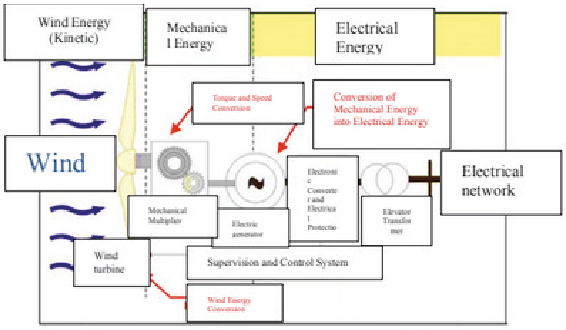


Figure 2: The principle of converting the kinetic energy of the wind into electrical energy.

Source: (PICOLO; BÜHLER; RAMPINELLI, 2014)

The main topologies can be classified based on the type of generator in relation to its operating speed, fixed or variable. According to Söder and Ackermann (2005, p.53) in fixed speed machines, the rotor speed is independent of the wind speed, being determined only by the frequency of the power supply, mechanical transmission ratio and design characteristics of the generator, generally connected directly to the electrical network.

With regard to variable speed machines, according to Energie (2001, p. 10), their main characteristic is the fact that the generator is connected to the electrical grid through an electronic inverter, in this topology the rotation speed of the rotor of the generator is related to the wind speed on the blades, in which the inverter will convert the voltage and frequency generated at the generator terminals to the voltage and frequency of the connected network.

Type A - Fixed speed wind turbine and squirrel cage induction generator (SCIG)

The squirrel cage asynchronous induction generator is connected directly to the grid (SÖDER; ACKERMANN, 2005, p.57), its rotation variation is reduced and depends on its slip factor. This type of wind turbine requires a gearbox to increase the rotational speed of the generator rotor enough for it to operate within the appropriate slip range, due to its typical reduced number of poles. For starting, a system is normally used to reduce the current when connecting to the electrical network, using a Soft-starter. As the type A system extracts reactive power from the network, a capacitor bank system must be used for reactive compensation (SÖDER; ACKERMANN, 2005, p. 57). According to Pinto et al. (2013, p.79), this type of configuration was widely used in the 1980s, which is currently being replaced through repowering. The details of this configuration can be seen in Figure 3.

Type B - Limited Variable Speed Wind Turbine and Wound Rotor Induction Generator (WRIG)

In this type of configuration, a wound rotor induction generator is used. The network connection mode is identical to the type. It is distinguished by the presence of rotor resistance control, which allows generator slip and rotation speed to be controlled (SÖDER; ACKERMANN, 2005, p.57), improving the set's performance. According to Pinto et al. (2013, p.79) and Söder and Ackermann (2005, p.57), this type of configuration was used in the mid-90s. Figure 4 illustrates the details of the configuration.

TYPE C - Variable speed wind turbine and doubly fed induction generator or (DFIG)

This configuration, also known as DFIG (Doubly-fed Induction Generator), uses a brush-wound rotor induction generator and a partial power frequency converter in relation to the generator of approximately 30% of the nominal capacity, responsible for compensating reactive and a smoother system connection (SÖDER; ACKERMANN, 2005, p.58-59). This type of actuation allows greater flexibility in terms of speed variation, with the rotor frequency being varied from -40% to +30% in relation to synchronous, increasing efficiency and improving the interface of the wind turbine with the electrical grid. Even so, it is generally necessary to use a gearbox to increase the rotational speed of the turbine shaft. Details of this configuration are illustrated in figure 5.

Type D - Complete variable speed wind turbine and permanent magnet synchronous generator (PMSG) or wound rotor synchronous generator (WRSG)

The Type D configuration features a synchronous generator coupled to an integral power frequency converter, which can be a multipole generator that does not require the use of a gearbox (SÖDER; ACKERMANN, 2005, p. 59). The generator rotor can be made of permanent magnets or a wound rotor (MANWELL et al., 2002, p.235). The frequency converter compensates the reactive power, connects to the electrical grid and allows the turbine speed to vary freely. Figure 7 illustrates the characteristics of this configuration.

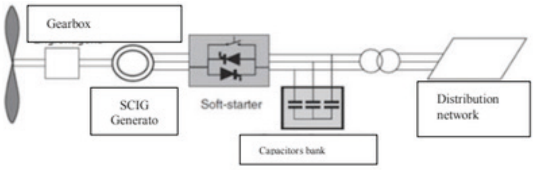


Figure 3: TYPE A Fixed Speed Wind Turbine Configuration

Source: Adapted from Söder and Ackermann (2005)

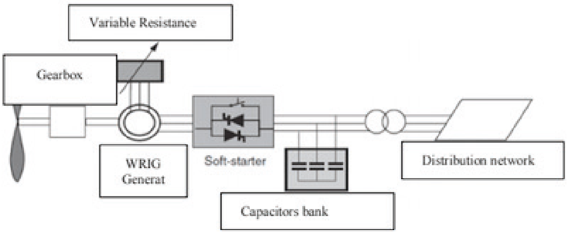


Figure 4: TYPE B Limited Variable Speed Wind Turbine Configuration

Source: Adapted from Söder and Ackermann (2005)

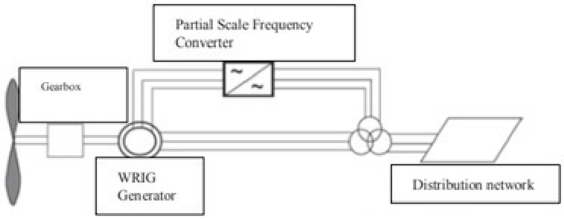


Figure 5: Configuration of the TYPE C or DFIG variable speed wind turbine

Source: Adapted from Söder and Ackermann (2005)

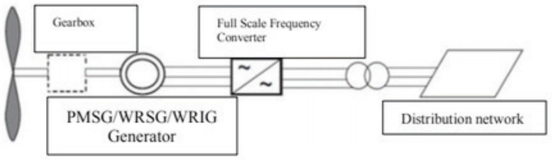


Figure 7: Variable speed wind turbine completes with frequency converter in full scale TYPE D

Source: Adapted from Söder and Ackermann (2005).

Frequency converters

Variable speed wind turbines generate variable voltage and frequency, due to this characteristic, they are not directly connected to the grid, therefore the application of converters is necessary for the operation of these systems and their connection to the grid. The following types stand out: network-commutated inverter systems and self-commutated inverter systems (ENERGIE, 2001, p.10).

Grid-switched inverters are based on conventional thyristors, through switched switching, having a lower cost, low losses and the need for connection to the grid for their operation. Their main negative point is the consumption of reactive energy and the production of large harmonics (SÖDER; ACKERMANN, 2005, p. 73). According to Energie (2001, p.10) thyristor-based inverters produce integer harmonics of 5th, 7th, 11th, 13th order, making it essential to use filters.

Self-commutated inverters are based on

GTO (gate switchable thyristors), with a switching frequency of 1kHz and insulated gate bipolar transistors (IGBT) with a switching frequency of 2 to 20kHz (SÖDER; ACKERMANN, 2005, p.60- 61). According to Energie (2001, p.11), these inverters are pulse width modulated (PWM) with the most frequent use of IGBTs, their main advantage is the control of active and reactive power, as well as the supply of reactive power by the PWM inverter.. According to Söder and Ackermann, (2005, p.106) this model's main advantage is the control of active and reactive power. However, it brings with it the disadvantage of producing harmonic currents of the order of kHz, making it essential to use filters to reduce these high frequency harmonics.

With regard to switched autos, the back-to-back converter can be highlighted, one of the most used in variable speed wind turbines and the object of study in this work, therefore, it will be covered in more depth than the others. Back-to-back is the most used frequency converter today, as it is bidirectional with two VSC (*Voltage Source Converter*) converters, modulated by pulse width (PWM). Its main element is the IGBT insulated gate transistor, acting as a bidirectional switch. The capacitor between the inverter and the rectifier allows the network and generator to be compensated without affecting the other side of the converter. The power flow in the network is controlled to maintain the voltage on the DC link constant to meet the magnetization and rotor speed. Figure 8 shows details of the structure of this converter.

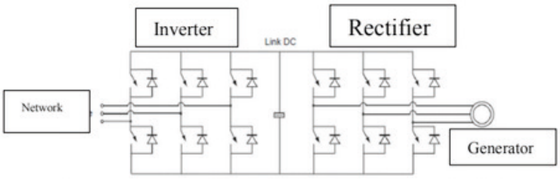


Figure 8: Back-to-back Frequency Converter Structure

Source: Adapted from Söder and Ackermann (2005).

CONNECTION TYPES

A system equipped with wind generation may have more than one connection configuration with the rest of the electrical system due to its geographic location or technical and commercial feasibility of connection with other agents. Systems are classified as isolated, grid-connected or hybrid systems depending on availability and connection feasibility. They are also classified as onshore or offshore depending on the installation location, whether on land or at sea.

Isolated systems

An isolated power system is one that does not have interconnection with an electrical energy transmission or distribution concessionaire from which it would receive voltage and frequency control services and constant supply of electrical energy capable of absorbing imbalances between generation and consumption. In the case of an isolated wind system, it is made up of wind turbines, a load regulator and an energy storage system (batteries, for example). The storage system is necessary to meet demand in times of insufficient wind.

Systems connected to the network

In the system connected to the electricity grid, energy storage under the responsibility of the local grid is not necessary. For this system, the essential energy to power the loads is supplied by the wind generator, with the electrical grid supplying the demand when the energy generated by the wind generator does not meet the demand. If the energy demand requested by the load is lower than that produced by the wind turbine, the surplus is delivered to the grid.

Sistemas *offshore*

Offshore wind energy sources are called the production of electrical energy through the kinetic energy of the wind, installed in the high seas (MANWELL et al., 2002, p.461). These installations are subject to higher wind speeds and less turbulence due to wind shear, but they are expensive and require vessels for access, which must be considered in project feasibility studies (MANWELL et al., 2002, p.461).

Power transmission is also more expensive, according to Manwell et al. (2002, p.449), from installation, operation, maintenance and environmental licensing. The factors that define the distances from offshore wind power plants are the depth of the water and the basic conditions of the seabed. According to Energie (2001, p.6), shallow waters limit the access of vessels, cranes, foundation drilling platforms and other equipment, as well as the visual impact caused by the installations, generally in coastal areas and with possible natural tourist attractions in the region.

POWER QUALITY PROBLEMS CAUSED BY GRID-CONNECTED WIND SYSTEMS

The connection of wind energy systems to the grid affects the quality of the electrical voltage, due to the electrical characteristics of the wind turbine determined by the manufacturer, as well as the region in which it is installed (SÖDER; ACKERMANN, 2005, p. 79). Power quality is checked by several parameters, in general, the voltage and current injected into the electrical network must be as close to a sinusoidal shape. Therefore, controlling the total harmonic distortion rate (THD) of the generator current and the electrical grid is of paramount importance, the lower the THD, the better the quality of energy that the wind system can provide. Synchronous generators, when connected to a large constant voltage network, allow controlling active and reactive power by controlling the unit's excitation. Variable speed turbines have electronic power converter systems between the generator and the grid, which additionally perform the speed adjustment between the variable speed generator and the approximately fixed frequency grid.

When operating wind farms, variations in average energy production combined with the generator's need for reactive energy can cause permanent voltage fluctuations in the system to which it is connected. Weak subnetworks, with much lower synchronizing torque and short-circuit power in relation to the remaining neighborhood of the network, may be more susceptible to voltage fluctuations (MANWELL et al., 2002, p. 436), according to Söder and Ackermann (2005, p.84) variable speed wind turbines tend to produce very low voltage variations.

However, the use of this power electronics in variable-speed wind turbines in continuous operation produces harmonic currents, which have frequencies that are multiples of the grid frequency, meaning that their total harmonic distortion must be controlled, as well as the need for regulation by the concessionaire (MANWELL et al., 2002, p.436; SÖDER, 2005, p.84;).

POWER QUALITY

The main guidelines for the requirements necessary for installations that are part of the Electrical Power System, from the technical aspect of electrical energy quality, are governed by two main documents, the PRODIST, written by Aneel, and the Network Procedures, written by the ONS.

PHENOMENA ASSOCIATED WITH ELECTRICAL ENERGY QUALITY STANDARDIZED IN PRODIST (ANEEL)

In PRODIST, the quality of electrical energy is subdivided into product quality and service quality, with product quality defined as the compliance of the delivered voltage sinusoid and with service quality defined as continuity of electrical energy supply (ANEEL, 2022). In Brazil, as determined by Aneel, the electrical energy quality requirements contained in module 8 of PRODIST must be met, with applicability to consumers, generating plants, distributors, agents importing and exporting electrical energy, transmitters holding DITs and the ONS.

Permanent regime and transitional regime phenomena are defined in PRODIST with indicators to be monitored regarding product quality. Permanent regime phenomena include voltage variation, power factor, voltage harmonics, voltage imbalance, voltage fluctuation and frequency variation (ANEEL, 2022). The transient regime phenomenon for assessing QEE is the short-term voltage variation.

HARMONIC DISTORTIONS

Harmonic distortions are phenomena associated with deformations of the voltage wave, which must be a pure sinusoid with a fundamental frequency located within the range of 59.9 to 60.1 Hz under normal conditions (ANEEL, 2022).

The information on harmonic distortions of the voltage wave is obtained through 1008 (one thousand and eight) valid records per calendar month, obtained successively with 10-minute intervals between them, totaling 7 days of measurement. It is recommended to obtain additional consecutive records if purging is necessary due to an interruption in the voltage supply or the occurrence of VTCD (ANEEL, 2022). Table 2. Presents the maximum allowable values of harmonic distortion.

Furthermore, if the measurement is made using VT - potential transformers, with type V connection, the limits for DTT3 95% are reduced to half the value declared in Table 2 (ANEEL, 2022). In PRODIST there is no mention of specific permissible values for harmonic distortion limits for nominal voltages equal to or greater than 230 kV, leaving only the ONS Network Procedures in these cases.

Indicator	V_n <2,3 kV	2,3 kV≤V_n <69 kV	69 kV ≤ V_n < 230 kV
DTT95%	10,00%	8,00%	5,00%
DTTp95%	2,50%	2,00%	1,00%
DTTi95%	7,50%	6,00%	4,00%
$DTT_3$95%	6,50%	5,00%	3,00%

Table 2: Allowed limits of harmonic distortion.

Source: Adapted from ANEEL (2022)

PHENOMENA ASSOCIATED WITH ENERGY QUALITY STANDARDIZED IN NETWORK PROCEDURES (ONS)

Submodule 2.9 of the Network Procedures contains the minimum requirements to be met by installations that contain elements with non-linear or special characteristics that are detrimental to QEE in the Basic Network. Among the regulated phenomena are the limits of harmonic distortion.

Harmonic distortion

Voltage harmonic distortion is evaluated against individual and global limits (ONS, 2022). Both are evaluated directly through measurement campaigns applied to the PAC when the connection is exclusive. When there is more than one installation, the global limits are evaluated in the same way and the individual limits are verified based on calculations in conjunction with the measurement applied to the PAC. From the previously obtained harmonic distortion indicators, the DTHTS95% indicator is calculated, first obtaining the value that was exceeded in 5% of the records obtained in a period of 1 day (24 hours), considering the value paid in intervals of 10 minutes and then Once these values are obtained, the highest value obtained on a daily basis over 7 (seven) consecutive days is used. The value used for each calculation period must be the highest value obtained between the three phases (ONS, 2023). The limits are presented in Table 7 and Table 8.

DTHI of harmonic order h	Vn < 69 kV		69 kV ≤ Vn	
	Odd	Pair	Odd	Pair
2 ≤ h ≤ 7	5,00%	2,00%	2,00%	1,00%
8 ≤ h ≤ 14	3,00%	1,00%	1,50%	0,50%
15 ≤ h ≤ 25	2,00%	1,00%	1,00%	0,50%
26 ≤ h	1,00%	1,00%	0,50%	0,50%
DTHTS95%	6,00%		3,00%	

Table 7: Global limits for DTH and DTT 95% indicators

Source: Adapted from ONS (2021)

DTHI of harmonic order h	Vn < 69 kV		69 kV ≤ Vn	
	Odd	Pair	Odd	Pair
2 ≤ h ≤ 25	1,50%	0,60%	0,60%	0,30%
26 ≤ h	0,70%	0,60%	0,40%	0,30%
DTHTS95%	3,00%		1,50%	

Table 8: Individual limits for DTH and DTT 95% indicators

Source: Adapted from ONS (2021)

STUDY MODELS FOR ELECTRIC POWER QUALITY

The objective of QEE studies in the power system is to evaluate the operational impact of new installations at the PAC Common Coupling Point. Studies are conducted to evaluate the integration of new facilities, interaction between existing facilities, or a combination of both. When carried out appropriately, they make it possible to identify the characteristics of future connections in the design stages and when carried out with the installation in operation, they allow the phenomena to be characterized, allowing rationalization of the operational condition of the installation.

VOLTAGE SAGS

In Brazil, the ONS determines the minimum conditions that the wind farm must satisfy to enable its connection to the SIN, through its Network Procedures in submodule 2.1, which establishes the main technical requirements for connecting the generating park to the basic grid.

During the occurrence of a short circuit in the SIN, as it is a strong network, which has a much higher short circuit power when compared to the wind farm, the voltage drops until the point is disconnected from the failure, through the activation of the protection (circuit breaker). In order to guarantee the reliability of the electrical power system, the ONS requires that if there are voltage variations at the connection point, during the occurrence of short circuits in the network, the generating unit must operate without disconnecting its machines, to guarantee the restoration of system voltage, as shown in Figure 11.

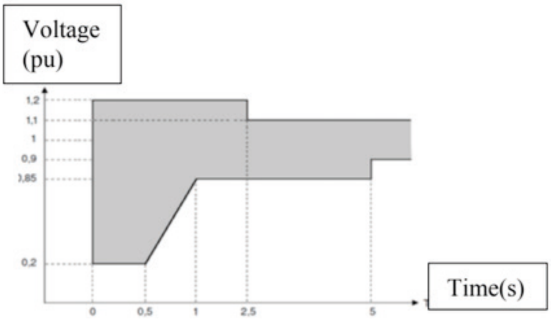


Figure 10: Voltage at the wind turbine or inverter terminals of the generating station.

Source: (ONS, 2023)

When carrying out short-circuit studies in the SIN, it is necessary to meet the minimum requirements, established by the ONS network procedures in submodule 2.3 - Assumptions, criteria and methodology for electrical studies. To enable a greater understanding of the topic, the ONS provides a document called "Guidelines for the Preparation of Basic Projects for Transmission Enterprises", which was prepared in conjunction with ANEEL, EPE, transmitters, entrepreneurs, research center and universities, published in 2013.

To verify the voltage drop levels that can be felt at the connection point, a fault simulation was carried out on all lines that make up two neighborhoods, for LTs greater than 100 km, or the number of neighborhoods that have at least 100 km of LT between the studied point and the network equivalents, as foreseen in the ONS network procedures submodule 2.3. Three-phase, two-phase and phase-to-ground faults were considered, all solid, with a duration for protection action of 100 ms, for system points at 500 kV, and 150 ms seconds, for system points at 230 kV, according to values established by the procedures network submodule 2.6. Based on these parameters, the system and its equivalents were modeled in the ATPDraw software, in order to identify possible sensitivity points at which the machines could be disconnected.

WIND TURBINE MODELING

The connection configurations of generators in available wind farms vary according to the electrical characteristics, as each type has a specific protection system, which can be advantageous to the system, as in the event of system failures, only 5 to 15% of the turbines are disconnected from the grid, resulting in less generation loss (MULJADI; GEVORGIAN, 2011). However, such simulations require greater analysis of the studied model and its basic electrical configurations.

Bearing in mind that a wind complex comprises the installation of several wind turbines and their associated collector networks, where in the event of a fault in the system, the total short-circuit current of this complex is the sum of the individual contributions of each generator, which makes the analysis is very complex (MULJADI; GEVORGIAN, 2011).

With regard to Type 4 wind turbines (PMSG), present in the analyzed generating plant, even the system operating at a frequency of 60 Hz, due to the fact that the generator is connected directly to the converter, operating in isolation from the system, due to the variable speeds to which it is subjected, its windings are operating at variable frequencies. Therefore, according to Muljadi and Gevorgian (2011), the short-circuit power contribution is limited by its nominal current, or slightly above it, generally designed with a margin of 10% above its nominal capacity during faults.

Due to the fact that such parameters are controlled by the converter, according to Muljadi and Gevorgian (2011), wind turbines can be represented by a constant three-phase current source during a short circuit, respecting the protection limits of the machine's converter. This type of simplification makes it possible to model the wind complex as a whole and optimize simulation processing resources. Data from the synchronous generators that are used in the wind generation system studied and the respective short circuit data are presented in Table 9.

Equipment	**Voltage (kV)**	**Imax Seq.+ (A_{rms})/unit.**	**FP CC (short)**	**FP pre foul**	**VP1**	**VP2**
47 Wind Generator x 2.1 MW	34,5	50,76	0,1	1,00	0,50	0,85
50 Wind Generator x 2.1 MW	34,5	50,76	0,1	1,00	0,50	0,85
52 Wind Generator x 2.1 MW	34,5	50,76	0,1	1,00	0,50	0,85

Table 9: Short circuit data for each wind turbine

Source: Own authorship (2023)

Cable type	**R1 (Ω/km)**	**X1 (Ω/km)**	**C1 (μF/km)**	**R0 (Ω/km)**	**X0 (Ω/km)**	**C0 (μF/km)**
CAIRO	0,1425	0,3875	0,0116	0,3207	2,0340	0,0043
150 mm2	0,2647	0,1500	0,1846	1,6862	0,0890	0,1846

Table 10- Parameters of collection network cables

Source: Own authorship (2023)

SYNCHRONOUS GENERATOR MODELING

The synchronous generator model comes from the analysis of the voltage phasor diagram, in which for a given Vt at its terminals an internal voltage Ea is required, which has voltage drops caused by the armature reaction Xar, dispersion reactance Xir, represented together by Xs, called synchronous reactance, and the armature resistance Ra (STEVENSON, 1986).

In short-circuit studies according to Kindermann (1997), it is possible to represent the synchronous generator only by an alternating voltage source in series with its subtransient synchronous reactance. This modeling is more conservative because the absence of armature resistance results in higher short-circuit current values than would occur if it were considered.

MODELING OF THE COLLECTION NETWORK

The internal distribution networks, which connect the wind generation plant installations with the collector substations, are powered at a voltage level of 34.5 kV. The modeling of this system was carried out using parameters concentrated in the PI model ($\boldsymbol{\pi}$), in % based on 100 MVA. Table 10 presents data on the connection cables for the wind farm's collection networks.

MODELING OF TRANSMISSION LINES

The modeling of the system's transmission lines was carried out in accordance with the guidelines for preparing basic transmission projects (ONS, 2013), as well as, in compliance with network procedures 2.3 (ONS, 2022), which guide the representation of the transmission line. distributed parameter transmission.

The data from the transmission lines of the power system connected to the wind generation system are based on a power of 100 MVA, obtained by ONS data in the ANAFAS software.

TRANSFORMER MODELING

A transformer can be modeled based on its winding resistance, inductive reactance Xs, which represents the voltage drop caused in the secondary by differences in the fluxes linking the windings. However, for most simulations carried out in power systems, according to Stevenson (1986) and Kindermann (1997), a simplification can be made to the model, thus ignoring the magnetization current, considering that it is much lower than the current of the load.

POWER SYSTEM DATA

The parameters of the transformers that make up the SIN, as well as the equivalent transformers, generated by calculating the system equivalent in the ANAFAS software, which are provided by the ONS technical data.

STEADY-STATE HARMONICS

The ONS states that there are still limitations in the harmonic flow models and it is recommended in the Network Procedures, in its Submodule 2.3, the adoption of the locus method (LG) for evaluating performance in relation to harmonic distortion. The study is conducted in order to obtain harmonic voltage distortion values from the harmonic currents generated by non-linear equipment present in the system. The general form is equated by Ohm's Law, where a voltage is obtained by dividing a current by two admittances in parallel. This representation was chosen because it is easier to study different configurations of the external network. The model is represented as shown in figure 11.

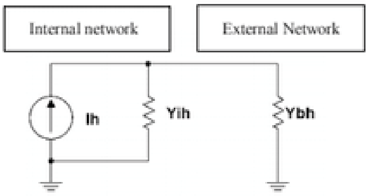


Figure 11: Norton equivalent circuit for simulating harmonic distortion.

Source: Own authorship (2023)

A harmonic frequency circuit is adopted as shown in Figure 11, with Yih representing the complete Internal Network. For each harmonic frequency, a point cloud of the External Network Ybh is generated, composed of the equivalent admittances of the external network in its complete configuration and in all its n-1 contingency configurations, for the harmonic in question and for the inter-harmonics of h-1 to h+1 in the annular LG method or for interharmonics from h-0.5 to h+0.5 with a step of 0.1 h in the polygonal LG method. With the Ybh cloud available, the minimum distance between its envelope and Yih is calculated.

The harmonic current source in Figure 11 is the parallel aggregation of the individual currents of the nonlinear equipment. For this purpose, only the maximum (worst case) aggregate magnitudes are considered, in accordance with IEC 61000-3-6. The magnitudes of the harmonic currents of each equipment must be obtained via measurement, with the exception that additionally, couplings via inverters must have the measurement certified in accordance with IEC 61400-21.

MODELING RESISTANCE AS A FUNCTION OF FREQUENCY

It is required to correct resistance values as a function of frequency for network elements under harmonic distortion study to be accepted for integration of installations into the SIN (ONS, 2018). Internally to the HarmZ software, a single resistance correction model is provided, prepared to be used directly on the network data modeled at fundamental frequency according to input data for power flow studies using the Anarede software. The HarmZ software manual contains resistance correction parameters depending on frequency to be used if you do not have your own study.

RESULTS AND DISCUSSIONS

This chapter presents the results and discussions of voltage sags simulations carried out in the ATPDraw software and steady-state harmonics in the HarmZs software. Voltage sagging studies modeled in simulation software must seek the best representation of the phenomena involved in the analyzed process, so that it is possible to present results of the same nature and with values very close to those physically expected. On the other hand, there is a very detailed content of data that was taken into account, so that the harmonic distortion study is approved by the ONS.

STEADY-STATE HARMONIC SIMULATION RESULTS

A limited study was carried out regarding harmonic distortion, considering only one park that is part of a wind generation complex. The Internal Network and the harmonic sources do not correspond to the entire project, however the External Network is representative of the voltage distortion characteristic due to the currents generated in the non-linear elements present.

In the wind farm studied, there is no violation of the individual harmonic distortion limits of order 2 to 50 stipulated in Table 8. The global distortions contained in Table 7 were not considered as a complete study of the wind generation complex would be necessary.

The future presence of the capacitor bank in the substation's 34.5 kV bus creates a lower impedance path for higher frequencies, an expected characteristic of the frequency response of the capacitors. Furthermore, there is no resonance effect which is accentuated with the insertion of the bench. A lower impedance resulting from the Internal and External networks causes less voltage distortion for equal distortion currents. Figure 12 shows the frequency response seen from the PAC according to the model in Figure 11.

The result in Figure 12 was obtained with the HarmZ frequency response auxiliary tool. Table 1 contains the results of the calculations for harmonics with non-zero current that prove Figure 12. Table 2 presents the same calculations for the case of the future capacitor bank connected to the system.

Table 3 presents the result of the difference in distortion between the two cases, where there is an increase in harmonic distortion in orders from 2 to 8 due to the shift in the resonance frequency. For higher harmonic orders, reduction occurs due to the reduction of impedance in most of the frequency spectrum. Furthermore, the total harmonic distortion does not violate the established limits and is reduced with the insertion of the capacitor bank due to the impedance reduction, as shown in Table 4.

h	|I Norton| (pu)	Yi (pu)	**Ymin (pu)**	**DHI Max (%)**
2	0,000008	2,954345-j34,882358	41,155648	0,00002
3	0,000008	1,418559-j23,169316	27,462161	0,000031
4	0,000005	0,840754-j17,138987	20,312193	0,000026
5	0,000098	0,570080-j13,427060	15,858502	0,00062
7	0,00006	0,329285-j9,019869	10,480503	0,000568
8	0,000044	0,266601-j7,569236	8,674222	0,000502
9	0,000015	0,221707-j6,394775	7,189962	0,000205
10	0,000038	0,188499-j5,411725	5,926028	0,000642
11	0,000022	0,163395-j4,565984	4,81617	0,000464
13	0,000008	0,129026-j3,151581	2,88613	0,00027

14	0,000008	0,117125-j2,538454	2,004034	0,000399
15	0,000021	0,107652-j1,967415	1,144287	0,001826
16	0,000007	0,100112-j1,427083	0,299134	0,002313
17	0,000021	0,094189-j0,908058	0,127075	0,016879
23	0,000012	0,088866+j2,188151	2,853996	0,000435
29	0,000018	0,307959+j7,574258	1,947456	0,000912
35	0,000056	5,391980+j24,050754	13,021658	0,000426
37	0,000214	6,801367+j40,452086	34,524409	0,000619
41	0,000261	4,674078-j21,230198	20,53904	0,001269
43	0,000153	1,581376-j18,476130	16,198031	0,000942
47	0,000046	0,404821-j7,610947	1,736566	0,002643
49	0,000027	0,291366-j5,368183	0,75872	0,003581

Table 1: Harmonic distortion results without capacitor bank

Source: Own authorship (2023)

h	**|I Norton| (pu)**	**Yi (pu)**	**Ymin (pu)**	**DHI Max (%)**
2	0,000009	2,954915-j34,445067	40,719815	0,000023
3	0,000011	1,424410-j22,414945	26,709472	0,000039
4	0,000008	0,864756-j15,875687	19,051643	0,000044
5	0,000221	0,672057-j11,104208	13,543342	0,001632
7	0,00059	6,404037-j22,687074	24,989356	0,002362
8	0,000101	0,797256-j11,625802	12,752978	0,00079
9	0,000018	0,451729-j8,899609	9,702447	0,000186
10	0,000031	0,335249-j7,297675	7,816501	0,000391
11	0,000013	0,274460-j6,122776	6,376336	0,000204
13	0,000003	0,210621-j4,375586	4,112777	0,000067
14	0,000002	0,192145-j3,672563	3,140611	0,000074
15	0,000005	0,178660-j3,039830	2,218291	0,000228
16	0,000001	0,168805-j2,458270	1,314965	0,000108
17	0,000004	0,161778-j1,913954	0,422239	0,000897
23	0,000001	0,165193+j1,081461	1,756228	0,00006
29	0,000001	0,410806+j5,708946	1,13805	0,000072
35	0,000001	5,120083+j16,710173	9,359756	0,000013
37	0,000003	2,692380+j18,822304	12,556153	0,00002
41	0,000017	28,100304+j23,939597	36,55428	0,000045
43	0,000013	19,074368-j32,661798	35,954546	0,000036
47	0,000002	1,625626-j10,455137	4,038926	0,000042
49	0,000001	0,916514-j7,035098	1,755999	0,000046

Table 2: Harmonic distortion results with capacitor bank

Source: Own authorship (2023)

h	DHI Max in relation to the state of the capacitor bank (%)		
	Connected	Off	Reduction
2	0,000023	0,00002	-0,000003
3	0,000039	0,000031	-0,000008

4	0,000044	0,000026	-0,000018
5	0,001632	0,00062	-0,001012
7	0,002362	0,000568	-0,001794
8	0,00079	0,000502	-0,000288
9	0,000186	0,000205	0,000019
10	0,000391	0,000642	0,000251
11	0,000204	0,000464	0,00026
13	0,000067	0,00027	0,000203
14	0,000074	0,000399	0,000325
15	0,000228	0,001826	0,001598
16	0,000108	0,002313	0,002205
17	0,000897	0,016879	0,015982
23	0,00006	0,000435	0,000375
29	0,000072	0,000912	0,00084
35	0,000013	0,000426	0,000413
37	0,00002	0,000619	0,000599
41	0,000045	0,001269	0,001224
43	0,000036	0,000942	0,000906
47	0,000042	0,002643	0,002601
49	0,000046	0,003581	0,003535

Table 3: DHI reduction after insertion of the capacitor bank

Source: Own authorship (2023)

DHT Max in relation to the state of the capacitor bank (%)		
Connected	Off	Reduction
0,003161	0,01787	0,014709

Table 4: DHT reduction after insertion of the capacitor bank

Source: Own authorship (2023)

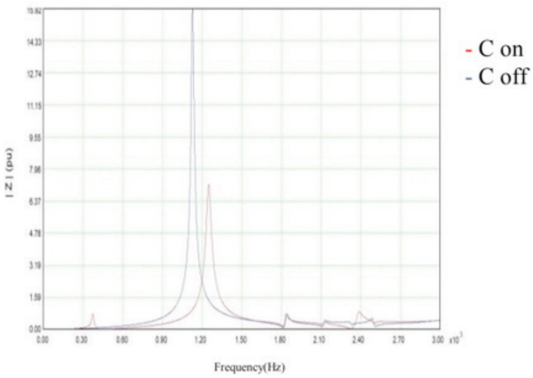


Figure 12: Frequency response of the PAC with and without capacitor bank

Source: Own authorship (2023)

VOLTAGE SAGS SIMULATION RESULTS

This item aims to present the results obtained during the simulation of voltage sags, felt on the PAC's 230 kV bar, due to the occurrence of short circuits, from single-phase, two-phase-to-ground and three-phase-to-ground. The most frequent failures were taken as a premise, which are momentary failures, in which after a certain time they self-extinguish, returning the system to its normal post-fault conditions. The initial operating conditions of the system in permanent regime, such as voltage and power levels provided by the group of wind turbines studied, were carried out using the ANAREDE software, based on the SUMMER 2023/2024 average case.

SHORT CIRCUIT LT 230 KV BPAC-BAR01

The wind farm studied is located in Rio Grande do Norte, has a total of 149 wind turbines, which total approximately 312.9 MW of installed power and are connected to the 34.5 kV bars BARGG1, BARGG2 and BARGG3. The collector networks are powered by 34.5 kV, which directs all the power generated via overhead and underground cables to the 230 kV step-up transformer, which is connected to the 230 kV BAPAC bar.

The subsidence felt by the PAC, during the execution of a three-phase short-circuit to ground in the middle of the LT 230 kV BPAC-BAR01, which is located between the wind farm and the BAR01 bus in the first neighborhood, in a failure of this characteristic lasting 150 milliseconds, voltage drops occur that reach values of approximately 0.089 p.u as illustrated in Figure 13.

The value of the short-circuit current found in the ATPDraw simulation was approximately 9.3 kA, aiming to estimate a reference parameter for the study, the same simulation was carried out in the ANAFAS software, which has the specific objective of carrying out analysis of short circuit in the Brazilian electrical system, being the tool recommended by the ONS for companies in the sector. The short-circuit current result found during the ANAFAS simulation was approximately 9.6 kA, therefore, there was a difference of 3.3% between the values obtained in the two systems, thus, it is understood that for simulations of short circuit, due to the high currents involved in these analyses, the results are within acceptable parameters and validate the values found in the modeling carried out in ATPDraw.

SHORT CIRCUIT IN OTHER NEIGHBORHOODS

The verification of the voltage drop caused in the PAC, which are felt by the wind turbines, due to the occurrence of phase-to-ground, two-phase-to-ground and three-phase-to-ground short circuits in all other neighborhoods, were simulated using the same process presented previously, which made it possible to survey all p.u. voltage sagging levels, which the wind farm is subject to during faults, based on the values of short-circuit simulations from the ATPDraw software. Table 10 presents the results of voltage sags obtained by short circuit location.

Short circuit location	**Phase-ground (p.u)**	**Two-phase-ground (p.u)**	**Three-phase-ground (p.u)**
LT 230 kV BPAC-BAR01	0,122	0,192	0,089
LT 230 kV BAR01-BAR02	0,371	0,274	0,198
LT 230 kV BAR01-BAR03	0,431	0,290	0,186
LT 230 kV BAR03-BAR06 C1	0,814	0,707	0,665
LT 230 kV BAR03-BAR06 C2	0,828	0,698	0,653
LT 230 kV BAR03-BAR05 C1	0,725	0,530	0,483
LT 230 kV BAR03-BAR05 C2	0,673	0,463	0,419
BAR 04 500 KV	0,599	0,450	0,447

Table 10: Parameters of collection network cables

Source: Own authorship (2023)

The simulation was carried out with the same characteristics and short circuit locations, using the ANAFAS software in all the most relevant neighborhoods, according to the transmission studies manual and network procedures prepared by the ONS, to which the wind farm is connected. The comparison of short-circuit current values obtained by the ATPDraw software with ANAFAS served as a reference parameter and identification of possible simulation errors. However, the results found in the ATPDraw simulations were satisfactory and in line with the values obtained by ANAFAS.

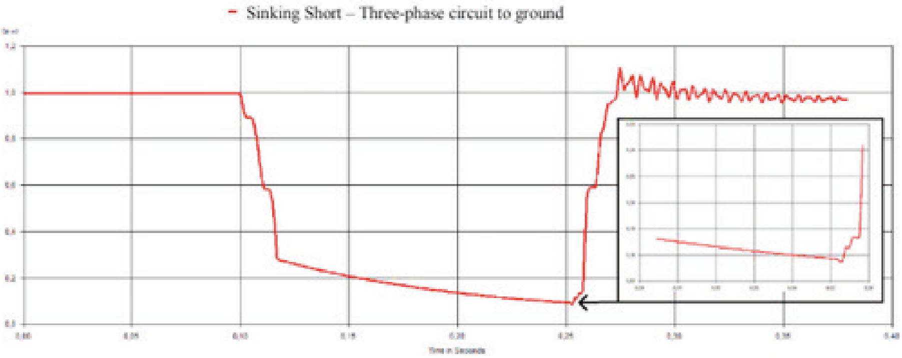


Figure 13: Voltage drop in the PAC bus due to a three-phase-to-ground short circuit in bar 1

Source: Own authorship (2023)

Short location	**Phase-to-ground**			**Phase-Phase-Ground**			**Phase-phase-phase-ground**		
	Icc ANAFAS (kA)	**Icc ATP Draw (kA)**	**Δ (%)**	**Icc ANAFAS (kA)**	**Icc ATP Draw (kA)**	**Δ (%)**	**Icc ANAFAS (kA)**	**Icc ATP Draw (kA)**	**Δ (%)**
LT 230 kV BPAC-BAR01	9,62	9,30	3,4	7,51	7,33	2,5	8,72	8,68	0,5
LT 230 kV BAR01-BAR02	8,99	8,56	4,9	9,04	9,06	0,3	8,66	8,78	1,4
LT 230 kV BAR01-BAR03	11,62	11,51	0,9	13,89	13,94	0,3	14,42	14,45	0,2
LT 230 kV BAR03-BAR06 C1	12,94	13,03	0,7	16,96	16,71	1,4	18,11	18,17	0,4
LT 230 kV BAR03-BAR06 C2	11,55	11,50	0,4	17,39	17,13	1,5	18,85	18,68	0,9
LT 230 kV BAR03-BAR05 C1	18,08	18,21	0,7	22,08	22,04	0,2	22,94	23,61	2,9
LT 230 kV BAR03-BAR05 C2	22,72	22,63	0,4	25,68	25,65	0,1	26,13	26,86	2,8
BAR 04 500 kV	22,96	22,59	1,6	24,16	24,26	0,4	24,44	25,22	3,2

Table 11: Results obtained in simulations using ATPDraw and ANAFAS software

Source: Own authorship (2023)

When comparing the results between the ATPDraw and ANAFAS software, it was verified that in 75% of the simulations, the values of percentage variations in short-circuit current were less than 2%, with the largest percentage variations recorded still being below 5%, as shown in Table 11.

Based on the results of the short-circuit simulations and their corresponding values of voltage sags, observed in the 230 kV BAPAC bar, due to faults in the transmission lines, previously presented in table 24, a graphical representation of these values was created by middle of figure 16.

According to the voltage sags withstandability curve, established by the ONS network procedures, in which, during the occurrence of an event in the SIN, which causes the network's effective voltage to drop to values below 0.2 p.u., the disconnection of wind farm machines is permitted to ensure the protection of equipment involved in the energy generation process.

Based on the results presented, it appears that there are points of short circuit occurrence, which are below the red line of 0.2 p.u. highlighted in Figure 16. It is possible to identify that all faults that occur in the transmission line that connects the 230 kV BAPAC bus to the 230 kV BAR01 bus in the first neighborhood have values lower than 0.2 p.u., a result already expected due to the radial characteristic of the analyzed section.

However, it is possible to note that there are two more points, which have residual voltage values lower than 0.2 p.u., caused by the occurrence of a three-phase-to-ground short circuit in two transmission lines, which are located between the first and second neighborhood., the LT 230 kV BAR01-BAR02 and the LT 230 kV BAR01-BAR03.

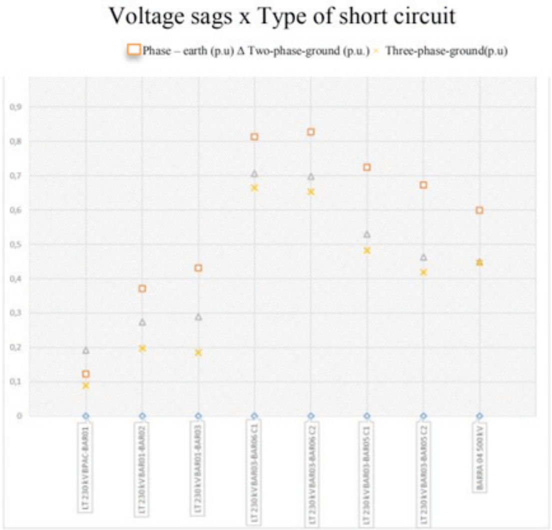


Figure 16- Voltage dip x type of short circuit

Source: Own authorship (2023)

CONLUSIONS

The present work presented an overview of the analysis and performance behavior of a wind farm already installed and in commercial operation in Brazil, the performance criteria of resistance to voltage sag in short circuits and the influences of harmonic distortion on the other two quality parameters in steady state and in fault condition.

In order to analyze the vulnerability of wind turbines, simulations were carried out of the occurrence of short circuits in the vicinity of the region's transmission system, which results in a drop in residual voltage in the system. According to ONS network procedures, the wind complex must withstand sags of the order of 0.2 p.u., so that it can contribute to the restoration of voltage to its nominal limits, during and after the occurrence of faults.

Based on the results obtained, it was identified that there are some types of faults, mainly for three-phase faults, which, if they occur in certain neighborhoods, because residual voltage drops greater than those stipulated by current guidelines. wind farm. Bearing in mind that such a scenario in the SIN may represent the absence of a source of contribution to the recovery of voltage levels, during and after the fault, it is of great relevance that with the growth of the installed load of this type of source in the system, there are network expansion planning studies, which guarantee reliability and take into account such operational conditions.

Given this context, it is worth highlighting that this work approached a qualitative analysis for a case study, which in turn, can encourage the emergence of new works, which propose different solutions for connecting these sources in the system, as well as technologies that allow the its improvement, from a technical, operational and regulatory point of view in dealing with the phenomenon addressed.

The study of behavior in relation to harmonic distortion limits was conducted in order to bring an academic work closer to the study and presentation model required by the ONS.

The decomposition of the system into harmonic circuits ends up generating new non-linear circuits, due to the non-linear characteristic of the resistances as a function of frequency variation. Multiplying the harmonic current values by some constant, with the aim of approximating the distortions resulting from several parks connected to the same collector substation is not a valid model, despite the similarities. Therefore, to evaluate the global limits of harmonic distortion, a complete study of the wind complex is required.

The entry into operation of a future capacitor bank is evaluated, with a reduction in network impedance without an increase in resonance. This reduction mitigates the generation of distortion voltages. The quantification of these effects is possible to be analyzed with the methods presented in this work but not with the academic license of HarmZ.

As for suggestions for future studies, it is proposed to analyze energy quality in terms of voltage imbalance when cyclical speed variations occur in wind generation systems, studying variables such as: wind speed; burst speeds; variety of wind variations in addition to the usual network disturbances.

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