

## Analysis of Synthetic Inertia Applied to Wind Farms

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**Abstract**– This work aims to understand and analyze how synthetic inertia influences in the Brazilian electrical system. With the increase of renewable sources, mainly with the increasing advancement in distributed generation, largely due to the increase in photovoltaic energy and also by wind power plants, both being controlled by electronic converters, the kinetic energy has decreased, thus causing instability in the system, when there is a failure of some bar, for example. For this reason, the study aims to study the synthetic inertia extracted through the blades of wind generators, analyzing the influence caused on the 14 bus system, applied to the SIN.

**Key Words:** Dfig, renewable energy, synthetic inertia, variable speed wind turbine, wind generators.

### 1. Introduction

In order to meet carbon emission reduction targets, in addition to meeting the sustainable part aimed at improving the environment, many countries have begun to look more carefully at renewable energy sources, such as hydroelectric, photovoltaic, biomass and wind [1]. The diversification of the energy matrix aims not to depend heavily on non-renewable energy matrices, such as oil. In addition to diversification towards renewable sources, it is also ideal not to depend on just one, since, for example, for generation in hydroelectric plants, there is a strong dependence on the water level of the rivers, and in some months of the year, there is a drop in rainy period. In recent years, wind energy has shown an accelerated growth rate over renewable energy sources, largely due to government incentives, the need to diversify the energy matrix, reliability, among other factors [2]. However, some problems, such as its low inertial response, will be felt in the near future, given this rapid insertion of renewable energies, thus inducing instability to the system [3].

Faced with the aforementioned problem, the aim of this work is to observe the influence of synthetic inertia on a 14-bar electrical system at Cigrè. The simulations will be performed using the Matlab – Simulink software. This study aims to analyze the influence of renewable sources on the electrical system, in particular wind energy, connected through large-scale energy converters. For this purpose, some steps need to be fulfilled. as the modeling of the electrical system to be studied and evaluation of its behavior in steady state; replacement of the ideal source by a properly controlled synchronous machine; choice of wind turbine model, in this case, it is intended to use the DFIG model, which is already in MATLAB; parameterization of the wind turbine, always maintaining, for the sake of understanding and better comparison of results, constant wind speed; Implementation of the control loop to emulate the inertial response in the wind turbine.

It is known that since the Kyoto Protocol, all countries have been developing and investing massively in renewable energy, but this thought comes from before the technology became so popular. It started with windmills, where their main activity was the grinding of cereals in or for lifting or pumping water [4].

Over the past few years, technology has been improving more and more, where small turbines have been updated and expanded due to installed and renewed technology [5]. In some countries, wind energy is very significant, such as in Denmark, where the sector was responsible for 43% of the energy consumed in the country in 2017 [6].

All services required by the local energy operator, whether transmission or distribution, consist of maintaining the quality of electrical energy, that is, maintaining completeness and stability [7]. With regard to the installation of wind farms, some assumptions, variables, must be met or properly monitored, such as [8]: Frequency control; Voltage

control; Congestion management; Improved power quality; Compensation of active energy losses.

This work will contribute with the following aspects: Understanding what synthetic inertia is and how important it is for current energy systems; Computational implementation of Cigrè's 14 bus test system; Analysis of the implementation of a wind farm in the base system, making comparisons with the ideal system; Contribute with modeling for the development of studies using synthetic inertia by wind turbines.

In view of the technical issues raised and discussed here, this work is divided into the following sections: Session 2 will be devoted to the modeling of the DFIG wind turbine and a better understanding of the model found in MATLAB Simulink. Modeling involves available wind power, extracted power, control systems and synchronous generator modeling. It also addresses the emulation of synthetic inertia by implementing the test model. Session 3 in question will be devoted to the analysis of the results found in the simulations carried out. Section 4 discusses the conclusions of the work carried out and presents suggestions for future work.

## 2. Methodology

To select the location where the wind turbines will be installed, some fundamental aspects must be taken into account, one of them being the wind speed. This wind regime has to be monitored for approximately one year to guarantee the reliability and viability of the project [2]. In addition to wind speed, the presence of birds in the area must be observed, as a wind power plant cannot be installed in areas where birds migrate. For this reason, several environmental licenses are required for construction [9].

Onshore turbines are often installed on higher ground to take advantage of the high wind speed, but most of the time there is difficulty in project approval due to visual, sound and environmental pollution [2].

A problem highlighted due to the large-scale implementation of wind and solar generation in the National Interconnected System - SIN, consists of the low, or null, inertial response of these sources, as they are coupled to the electrical networks by means of static converters, thus reducing the robustness of the system.

In this aspect, a feasible methodology consists of emulating the inertial response through the control of the converters. This technique is commonly called "synthetic inertia". Based on the balance equation, given by equation (1), the rate of change of frequency (ROCOF) will be inversely proportional to the total inertia of the system. For this reason, what is called "synthetic inertia" [3][10] is executed.

$$J \frac{d\omega}{dt} = T_m - T_e - D_T \Delta\omega \quad (1)$$

where  $J$  is the moment of inertia of the generator,  $T_m$  represents the mechanical torque of the shaft,  $T_e$  the

electromagnetic torque and  $D_t$  the sensitivity of the load in frequency [10].

The concept of synthetic inertia consists of temporarily extracting the rotational energy stored in the turbine and transforming it into active power, during underfrequency events, by additional control functions in the wind turbine converter controller. It is expected that, in this way, it will achieve a greater expansion of the sector, contributing with a greater participation along with hydroelectric and nuclear [10].

In conventional systems, generators are coupled directly to grid connection points. The so-called oscillation equation (balance equation) governs the rotational dynamics and was presented in equation (1).

There is an imbalance between generation and load and with that  $T_m \neq T_e$  and  $\Delta\omega \neq 0$ . As a result, the rotor speed changes. It is also noted that the greater the moment of inertia of the generator, the lower the speed variation rate. Equation (2) demonstrates the synthetic inertia and equation (3) is the oscillation equation, if the variations are small around the nominal frequency [10].

$$E_C = \frac{J\omega^2}{2} \quad (2)$$

$$\bar{P}_m - \bar{P}_e - D\Delta\bar{\omega} = 2H \frac{d\bar{\omega}}{dt} \quad (3)$$

Thus, implementing the equations for conventional synchronous generators in wind turbines, equation (4) is used, where  $P_m$  and  $P_e$  must be in pu [10],[19].

$$P_m - P_e = \frac{2H}{fn} \frac{df}{dt} \quad (4)$$

Based on the balance equation, the rate of change of frequency (ROCOF) will be inversely proportional to the total inertia of the system. For this reason, what is called "synthetic inertia" [19] is executed.

The system inertia ( $H_{sys}$ ) can be quantified by the amount of kinetic energy stored in the rotating masses of conventional generators, as well as motors that are connected to the AC grid using equation (5), where  $kE$  represents the stored kinetic energy (MJ) and  $s_{Rating}$  represents the machine rating (MVA). ROCOF will initially be determined by the total system inertia. This relationship is shown in equation (6) [19].

$$H_{sys} = \frac{kE}{s_{Rating}} \quad (5)$$

$$\frac{df}{dt} = \frac{fn}{2H} (P_m^{pu} - P_e^{pu}) \quad (6)$$

After presenting the equations and based on a prior understanding of inertia, it can be better defined. Therefore, the inertia of the power system is the result of synchronously rotating masses (angular velocity) that cannot be drastically varied. Thus, the frequency of the system is proportional to the weighted average of these changes [20].

The change in kinetic energy is similar to the changing state of the rotation mass of motion, causing the frequency to change according to the angular velocity and how much the generating unit has influence on the system [20].

Wind turbine generators cannot respond instantaneously to imbalances, as with the mechanical power extracted from the rotating mass. Controllers are used to complement this missing phenomenon that emulates the inertial response of synchronous generators [20].

With this, it is concluded that the contribution of the synthetic inertia is not enough to avoid high frequency dips in the case of failures of several generation units. With this control, there is the disadvantage of delaying frequency restoration and imposing a greater demand on the primary control, but as an advantage, it reduces the frequency drop in the system in the cited cases [20] [21].

The activation of the synthetic inertia is based on finding the high degree of frequency change, monitored by the ROCOF or in addition to placing a tolerance by entering the absolute value of the frequency or detection of the absolute deviation from the moving average of frequency [20].

### 3. Computacional Implementation

The computational simulation of the study was performed on the MATLAB computational platform, within the module specialized in block diagrams and simulation of engineering systems, Simulink. The base system used to carry out the simulation, for testing the studied theory, was the CIGRÉ with 14 buses, based on the configuration of North America [21]. This system was implemented with some changes in values, since components were added to some bars of the system.

#### A. Case 1: North America Cigre Configuration

The distribution feeders are all three-phase, thus allowing a degree of flexibility in structuring the system grids. The system has 14 buses, with nominal voltage in the three-phase sections of 12.47 kV, with a frequency of 60Hz. It contains voltage drops represented by resistors [21]. The system used is an adaptation of the one mentioned above. Figure 1 shows the topology used. There are two branches at the input of the circuit, both powered by step-down transformers, whose configuration is delta/star [21].

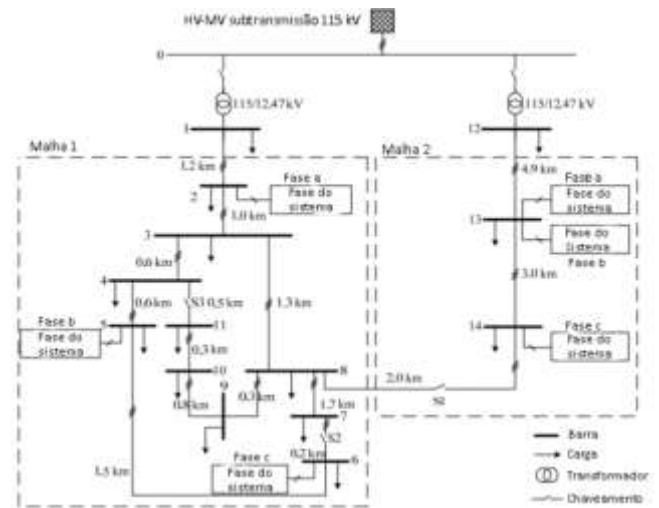


Fig 1. topology of the test system

Meters were placed on all the bars so that, in this way, it was possible to visualize the resulting voltages and currents in the same. The total power demanded by the system is 12.7307 MW.

#### A. Case 2 : MATLAB Components

MATLAB has several tools for working in a computer simulation environment. The entire simulation was developed in the discrete system – for this, the powergui block (PSB Option menu block) was used. This block allows you to choose circuit resolution methods, which is required for all Simulink models containing specialized Simscape power system blocks [22]. To represent the size of the lines, the Three-phase series RLC Branch block was used. This block represents a balanced three-phase resistance, consisting of a resistor, capacitor and inductor placed in series [22]. In the circuit used in this study, only resistors and inductors were considered.

The bars were placed as three-phase measurement blocks (Three-phase VI Measurement), as it was necessary to measure the instantaneous voltages and currents of the circuit. The power block (3ph, Phasor) was inserted at the output of the bars. This block displays the total active and reactive power. In addition to these, the RMS block and a Display were used so that the voltage values in each bus were accessible [22].

In order to verify the frequency in some bars, the PLL block (3ph) and a display were used. Connected to the transformer is a synchronous machine. The basis for this connection was made using a model available from MATLAB, which has a diesel generator coupled. Figure 2 shows the synchronous generator model.

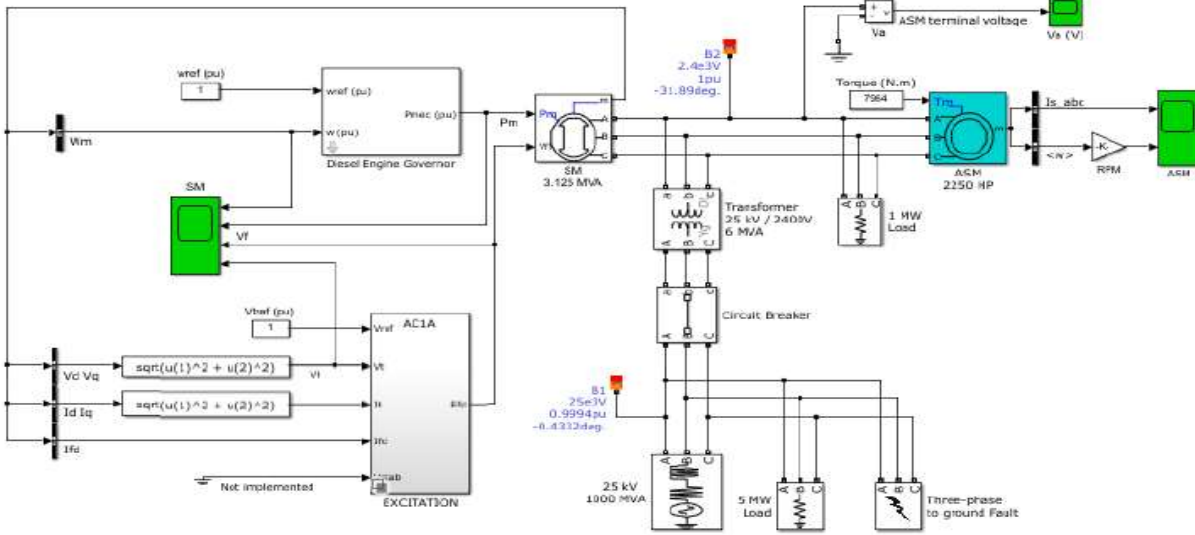


Figure 2 : - Synchronous diesel generator

The system in this model is continuous and to initialize the synchronous machine you must follow some steps contained in the help of the model. For the circuit used, it was necessary to adapt the model available in the program so that it would suit the wind system in question. The wind system was connected to bus 7 in parallel with the existing load. For this, a Y/ $\Delta$  transformer is connected.

The wind generator model presented is the detailed one. In this it is possible to observe the harmonics and control the performance of the system in short periods. The ideal simulation time to be used in discrete time is 5 microseconds [23]. The original wind farm of the studied model consists of 9MW of power, using six turbines connected to a 25 kV distribution system that exports energy to the 120 kV grid through a 30 km and 25 kV feeder [22]. The number of turbines was changed to 5 turbines of 1.5 MW, totaling a power of 7.5 MW.

#### 4. Simulation Results

After simulating the circuit explained in the previous items, the result obtained in the system buses was first observed – in order to observe all the voltage drops that were being imposed on the system as a whole, in addition to evaluating their coherence. Table 1 displays the bus RMS voltages. Table 1 shows the imbalance between the phases, a fact that has already been pointed out in the previous items – this condition was used here to make the simulated system as close as possible to a real context. It is also noted that there are losses when advancing the bars, this is due to the existing lines between them. Then, the outputs of the synchronous generator are verified and the influence that the load upon entering had on the system as a whole

Table 1 : voltage in the bars

Bars	Tension [RMS][a/b/c]	Bars	Tension [RMS][a/b/c]
1	6907 / 6932 / 6913	8	6236 / 6274 / 6245
2	6589 / 6619 / 6596	9	6149 / 6187 / 6159
3	6350 / 6383 / 6357	10	6106 / 6145 / 6116
4	6275 / 6308 / 6283	11	6095 / 6071 / 6049
5	6214 / 6247 / 6222	12	378.6 / 379.7 / 378.6
6	6078 / 6111 / 6086	13	376.2 / 377.4 / 376.3
7	6268 / 6312 / 6278	14	375.8 / 376.9 / 375.9

. Figures 4 to 10 are the results displayed by the synchronous generator.

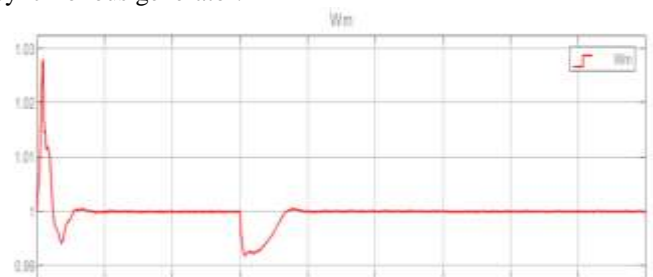


Fig. 4: Wm (speed)

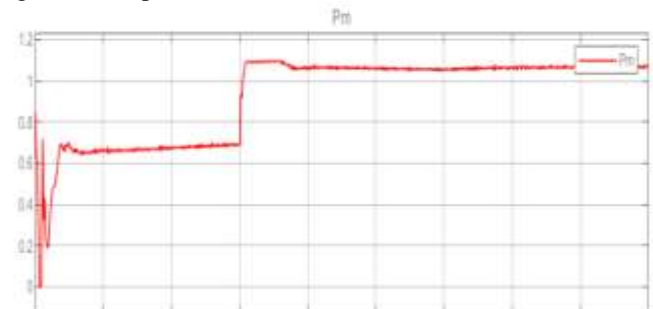


Fig. 5: – Pm (power)

Figures 4 and 5 show that the synchronous machine has an initial period of a few seconds to stabilize. When the load enters, at 15 seconds, there is a drop in speed, which is returned close to 18 seconds. With regard to power, it appears that it increases with the entry of the load and is maintained, jumping from 0.7 to 1.06.

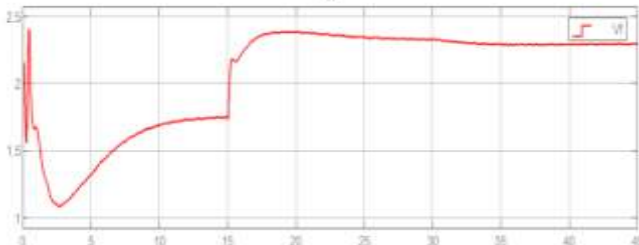


Fig 6 : Vf

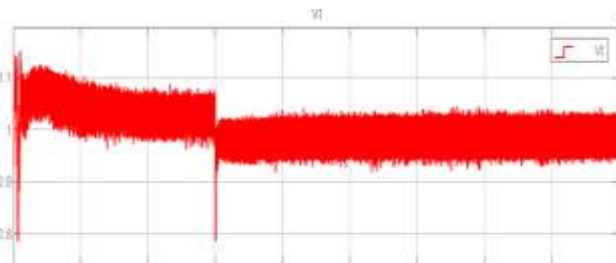


Fig. 7 : Vt

In figure 6 it can be seen that after machine stabilization, there is an increase and when the load enters the system, it stabilizes at 2.3. In figure 7 it can be seen that it was remaining close to 1 pu, when the load entered, it had a sudden drop and stabilized again at 0.97.

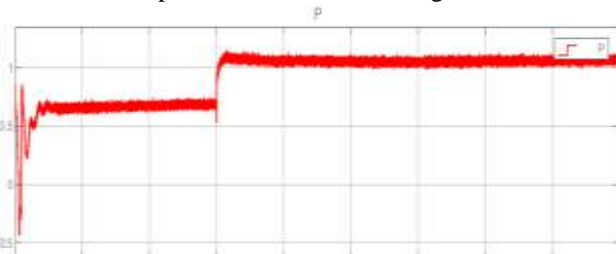


Fig 8: P

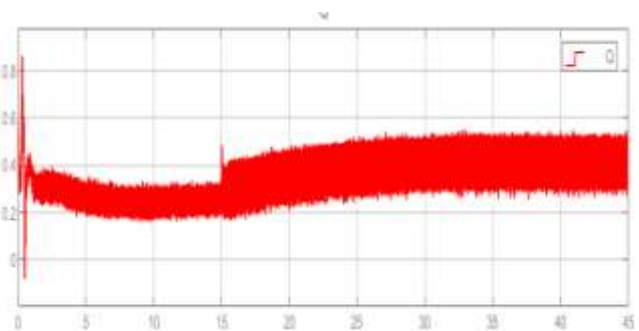


Fig. 9: Q

Figures 8 and 9 show the active and reactive powers of the machine. The first was at 0.65 pu and with the entry of the load, it changed to 1 pu. The reactive one was at 0.2 pu

and had a small increase, changing to 0.35 pu. Later, the power of the wind generator can be observed: it remained at 3.05 MW and, after 15 seconds, it went to 2.9 MW. The reactive power was close to the value of 0.5 MVar. With the input of the load, the wind system, in order to help maintain the frequency, increases the reactive power, which goes to 0.9 MVar.

In bar 7, a frequency meter was placed to check if it was being kept close to 60 Hz.

Figure 10 outlines the system frequency. There is a variation at the beginning of the simulation, as the synchronous machine is stabilizing. The frequency before system stabilization had its maximum value at 61.5 Hz and its trough at 59.64 Hz. At the load entrance, in 15 seconds, a new valley is observed for 4.478 seconds, returning to stability and remaining with some small oscillations in the course. In this valley, the frequency reached a value of 59.52 Hz.



Fig. 10 : System Frequency

Sequentially, there is the explanation of the synthetic inertia, shown in figure 10. At 15 seconds, it has a small increase and then returns to the steady state. Note that, regardless of inertia, it always remains close to zero pu.

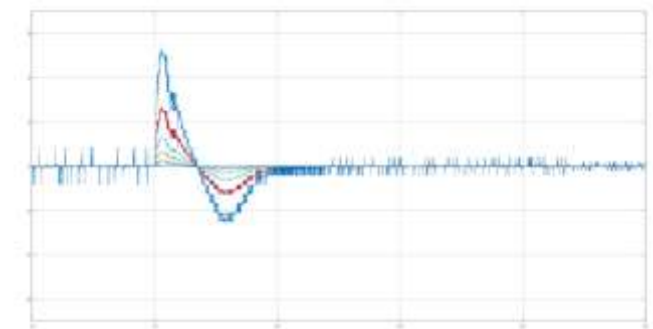


Fig 11 : Delta P

In figure 11, it is possible to better observe the load entry period. It is observed that the greater the Hsys value, the greater the amplitude reached during the instability period. Table 2 displays the peak, trough and time to stabilize again values of the simulated Hsys values. Analyzing Table 2, there is evidence that the higher Hsys, the greater the amplitude of oscillations, however the system manages to stabilize with similar times, showing that the control performed is correct.

Table 2 : variation values of Hsys

Hsys	Peak Value	Valley Value	Period
1	0.2402	-0.04785	2.885
5	0.07292	-0.03138	2.906
9	0.1313	-0.05649	2.906
13	0.1896	-0.0816	2.906
20	0.2917	-0.01255	2.906
50	0.7292	-0.3138	2.906
100	1.458	-0.6277	2.906
200	2.917	-1.255	2.906
400	5.833	-2.511	2.906

## 5. Conclusion

The increase in the share of renewable energy sources, with a greater emphasis on those interfaced by converter, in the global energy matrix has been presenting major challenges. In this work, the problem of effective inertia in the electrical system was exposed, which can cause large oscillations and instabilities to the system. . After parameterizing the blocks used, the results obtained by making changes to the Hsys are compared and seeing that the larger it is, the greater the peak will be, but the response time is similar for all. In this work, basic concepts were also presented for understanding the presented problem, such as the nature of wind generation, methods of controlling wind turbines, influence of wind energy on the Brazilian system, being the second largest source of energy in the country.

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