Benchmark System for Frequency Stability Studies Based on the Northeast Subsystem of the Brazilian Interconnected Power System

Technical Report

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1. Introduction

This report introduces an equivalent system based on the Northeast (NE) electrical power subsystem of the Brazilian Interconnected Power System (BIPS) and presents a preliminary frequency stability study conducted using the ANAREDE and ANATEM software from CEPEL/Brazil [1-3].

The NE subsystem of the BIPS serves as an example of an Electrical Power System (EPS) characterized by a high penetration of converter-interfaced generation (CIG) based on renewable energy sources (RESs), particularly wind and solar energy. In 2020, the BIPS exceeded 16 GW of installed wind power generation capacity, spread across 751 wind farms with a total of 8.800 wind turbines. Nearly 90% of this capacity is concentrated within the NE subsystem of the BIPS.

According to the 2032 Energy Expansion Plan (PDE) [4], the next decade is expected to witness a 10 GW increase in installed CIG-based renewable generation capacity (including not only wind but also solar photovoltaic generation) in the north/northeast region of Brazil. On the other hand, the number of hydroelectric and fossil fuel power plants in the NE subsystem (corresponding currently to less than 50% of this subsystem's total power generation capacity) is projected to remain unchanged [4]. Consequently, the NE subsystem may increasingly rely on other subsystems of the BIPS to provide frequency support, even for contingency events occurring internally in this subsystem.

Hence, the high penetration of wind and solar generation makes the NE subsystem of the BIPS an excellent testbed to study the behavior of CIG-based RESs and the problem of overall inertia reduction and primary frequency control from a large-scale point of view. However, it is important to remark that our report treats the NE subsystem from a geographical perspective, which differs from the approach used by the Brazilian National Operator (ONS)[1]. Therefore, although the operation of the NE subsystem currently does not have the frequency stability problems shown in this report due

[1] In the BIPS, the ONS determines that all hydroelectric power plants (HPPs) and thermal power plants (TPPs) equipped with speed regulation systems must participate in the primary frequency control mechanism of the system in a distributed and integrated manner. This participation is mandatory, even if the disturbance occurs in a different subsystem from where the generator is located. On the other hand, the NE subsystem is considered in this report as a control area of the BIPS and, therefore, it is responsible for handling its own power imbalances, so the power exchanges with the other subsystems are kept constant.

to the manner in which the BIPS is operated, the report offers insight on problems that might occur (regardless of the ONS operation strategy) if the penetration level of CIG-based renewable generation keeps increasing as expected, and points out to the fact that local solutions to increase the inertia of the NE subsystem are needed to avoid such problems.

To facilitate comprehension, this report is divided into six Sections (including the Introduction), three Appendixes, and a list of References:

2. The BIPS and the NE electrical power subsystem.
3. Description of the proposed benchmark system based on the NE electrical power subsystem.
4. Load flow analysis (from software ANAREDE).
5. RMS dynamic simulation of the nonlinear model (from software ANATEM) and a frequency stability study.
6. Conclusions and future works.

Appendix A: Data for load flow analysis.
Appendix B: Power flow solution for the base case.
Appendix C: Data for dynamic analysis.
List of references.

2. The BIPS and the NE electrical power subsystem

The base case of the BIPS used in this report comprises 7,304 buses, 6,984 AC transmission lines and transformers, 14 HVDC links, 301 conventional power plants based on synchronous generators, and more than 700 wind farms and 400 solar photovoltaic (PV) plants. The generation expansion of the BIPS from 2020 to 2024 is displayed in Table 1 [5]. One can see that the installed capacity increase is led by different new energy sources, mainly from gas (3,534 MW), wind (3,191 MW), and solar photovoltaic (1,124 MW). These three sources account for 85% of the expansion that occurred between 2020 and 2024. It is worth mentioning that most of the increase in wind generation capacity happened in the NE electrical power subsystem, the same being true for solar generation if small PV panels connected to medium and low voltages are not considered.

Table 1: Installed capacity in the BIPS in 2020 and in 2024, values expressed in MW [5].

Energy source	2020	2024
Hydro	114,240	114,709
Nuclear	1990	1990
Gas	14,318	17,861
Coal	3017	3017
Biomass	13,810	14,137
Oil and Diesel	4554	4840
Wind	16,412	19,603
Solar	2820	3944
Others	745	1108
Total	**171,907**	**181,209**

Figure 1 shows the current transmission system of the BIPS. The NE electrical power subsystem is the region highlighted in yellow (in the map on the left side of the figure), including the states of Piaui (PI), Ceara (CE), Rio Grande do Norte (RN), Paraiba (PB), Pernambuco (PE), Alagoas (AL), Sergipe (SE) and Bahia (BA). In this report, the state of Maranhao (MA) is also considered part of the NE electrical power subsystem, as it belongs to the NE geographic region of Brazil, and it presents an important set of conventional thermal power plants and interconnection lines with others electrical subsystems of the BIPS.

Considering a forecast expansion for the year 2026, the NE electrical power subsystem will be constituted of 2,674 buses (including transmission and sub-transmission voltage levels), 3,643 AC transmission lines and transformers, and close to 30 interconnection lines among the NE subsystem and its neighboring subsystems, given by the north (N) and southeast/middle west (SE/CO) subsystems, highlighted in orange and purple/blue, respectively, in Figure 1. In addition, the installed power capacity in the NE subsystem is predicted to be about 31 GW, distributed through 28 hydroelectric power plants (HPPs), 104 thermal power plants (TPPs), and more than 1000 wind farms (WFs), corresponding to, respectively, 14%, 26% and 57% of the total generation capacity.

There is also an important solar PV power capacity installed in the NE subsystem (following Table 1), corresponding to about 6 GW of installed power capacity, that comes from more than 200 solar PV plants (SPPs). The total power demand of the NE subsystem will be approximately 17 GW, which means this subsystem is expected to be capable of exporting more than 10 GW to the N and SE/CO subsystems (without considering the solar PV generation).

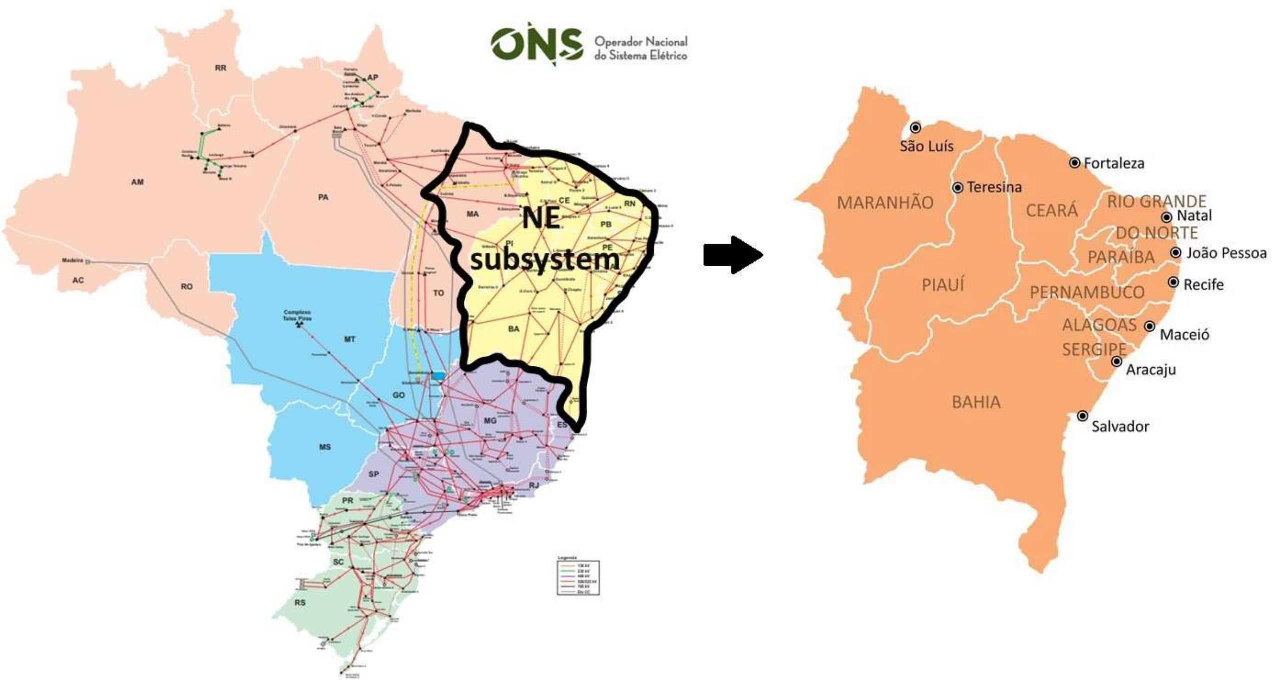

Figure 1: The transmission system of the BIPS [6].

Due to the high penetration of wind and solar PV generation in the NE subsystem and the need to perform several studies considering these generation and their interaction with the other conventional power plants, a test system based on the NE subsystem composed of 232 buses exhibiting a mix of wind, solar PV, hydroelectric and thermal power plants was developed and presented in this report. The proposed test system is based on the forecast expansion of the NE subsystem for the year 2026 [4]. The next section presents the proposed test system.

3. Description of the proposed benchmark system based on the NE electrical power subsystem

The proposed benchmark system comprises 232 buses, 420 AC transmission lines and transformers, with voltage levels of 500 kV (68 buses) and 230 kV (60 buses). Furthermore, the equivalent system contains 60 wind farms (WFs), 7 solar PV plants (SPPs), 19 hydroelectric power plants (HPPs), and 18 thermal power plants (TPPs). The total power generation in the base case is approximately 23,862 MW, where the WFs, SPPs, HPPs, and TPPs correspond to 10,580 MW (44.3% of the total), 3,410 MW (14.3% of the total), 4,760 MW (19.9% of the total) and 5,098 MW (21.3% of the total), respectively. Hence, almost 60% of the total power generation comes from wind and solar sources. This mix of synchronous and asynchronous generation represents the main feature of this equivalent system since it allows the analysis of the main issues that may arise in power systems in the transition to a high penetration of renewable sources connected to the grid by inverters.

In the base case, the NE subsystem is exporting 13,400 MW to the N and SE subsystems, represented by 11 equivalent generators (PV-type buses) connected to the front-end of the interconnection lines among the NE subsystem and the external subsystems. This highlights a key characteristic of the NE subsystem, which is its role as a significant exporter to other Brazilian subsystems. As discussed in Section 5, the loss of some of these interconnection lines could lead to frequency stability issues due to the activation of over-frequency relays in conventional generators.

It is important to highlight that, in the real operation of the BIPS, the power exchanged among the subsystems may vary due to several factors. However, in this report, the NE subsystem was considered as a control area of the BIPS and, therefore, it is responsible for handling its own power imbalances, so the power exchanges with the other subsystems are constant. This is the main difference between our proposed system and the actual operation of the NE subsystem of the BIPS and does not reflect the actual way this subsystem is operated in practice by the ONS. However, as previously mentioned, the main value of our proposed equivalent is the fact that it allows the study of possible local solutions for frequency stability problems related to events occurring internally in this subsystem, as well as other problems related to the high penetration of wind generation.

The simplified model of the NE subsystem was developed by first extracting the complete NE subsystem from the BIPS model. To do this, 20 internal boundary buses in the NE subsystem were identified. Each one was considered to be an equivalent generator (PV-type bus) exporting or importing an active power value equivalent to the power exchanged between the internal (NE) and external (N and SE/CO) subsystems for the nominal case.

Figure 2 illustrates this simplification process for bus 539, one of these twenty internal boundary buses, which is in the Imperatriz substation in the state of Maranhao. The internal boundary bus 539 was considered as a PV-type bus, where the generated active power is P_{int} (equivalent to the total power exchanged between buses 539 and 599, which is the external boundary bus located in the state of Para). In addition, the voltage magnitude of bus 539 was specified according to the voltage value calculated from the power-flow of the base case.

After extracting the complete NE subsystem from the BIPS model, some reduction steps (using the software ANAREDE, from CEPEL/Brazil) and simplifications were applied to it, as follows:

1. All the HPPs and TPPs with capacities below 30 MW were excluded from the application of the extended Ward equivalent method [5], leading to some buses exhibiting negative active loads;
2. Buses related to radial configurations of transmission and sub-transmission lines, as well as internal boundary buses in the Northeast (NE) subsystem exporting or importing less than 100 MW, were also neglected. Additionally, all transmission and sub-transmission buses in the NE subsystem with voltage levels below 230 kV were disregarded, except for certain 34.5 kV subtransmission buses associated with wind farms (WFs), as discussed in next item;
3. All WFs connected to the same sub-transmission bus (in the level of 34.5 kV) were grouped as one aggregated WF. Aggregated WFs with a power capacity below 100 MW were neglected from the application of the extended Ward equivalent method, causing some buses to have a negative active load. However, equivalent WFs with a power capacity greater than 100 MW were retained;
4. Buses between the aggregated WFs (over 100 MW) and primary 230 kV or 500 kV buses were neglected, ensuring a direct connection through transformers. Figure 3 illustrates this simplification for the Ourolandia substation in Bahia, where numerous wind farms were consolidated into a single aggregated WF. Also, all buses between the terminal 34.5 kV subtransmission buses and the 230 kV bus labeled 11261 were excluded. Similar procedures were applied at each 500/230 kV substation to maintain essential buses connected to other substations;
5. All the buses with SPPs were eliminated from the application of the extended Ward equivalent method. Hence, the 7 SPPs considered in the proposed benchmark system were added to the system after the network reduction step described in this section.

The one-line diagram of the proposed test system is shown in Figure 4. In this one-line diagram, the WFs, SPPs, HPPs, and TPPs are identified by the letters (and colors) ‘W’ (green), ‘S’ (yellow), ‘H’ (blue), and ‘T’ (gray), respectively. The equivalent generators representing the external subsystems are represented by ‘E’ (and purple). The original numbering and the names of the buses (from the BIPS) were preserved in this proposed system. About 40% of the total lines are original ones from the BIPS, while the remaining are fictitious lines (or transformers) that originated from the application of the extended Ward equivalent method. All data for power flow analysis of this equivalent model are shown in Appendix A.

The HPPs and TPPs are represented by salient pole and round rotor synchronous machines, respectively. The salient pole units are modeled by a 5th-order dynamic model. Similarly, the generator model to represent the round rotor units is a 6th-order dynamic model. In both cases, the saturation effects were represented by exponential functions. The corresponding parameters for these models can be found in Appendix C.

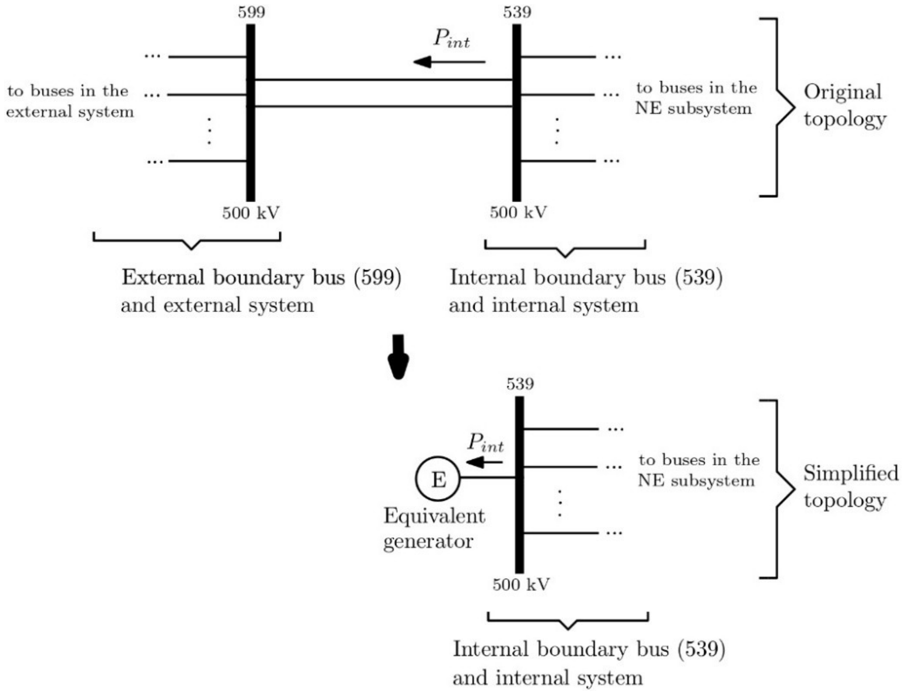

Figure 2: Internal boundary bus 539 in the substation of Imperatriz: the original topology (on the leftand the simplified one (on the right).

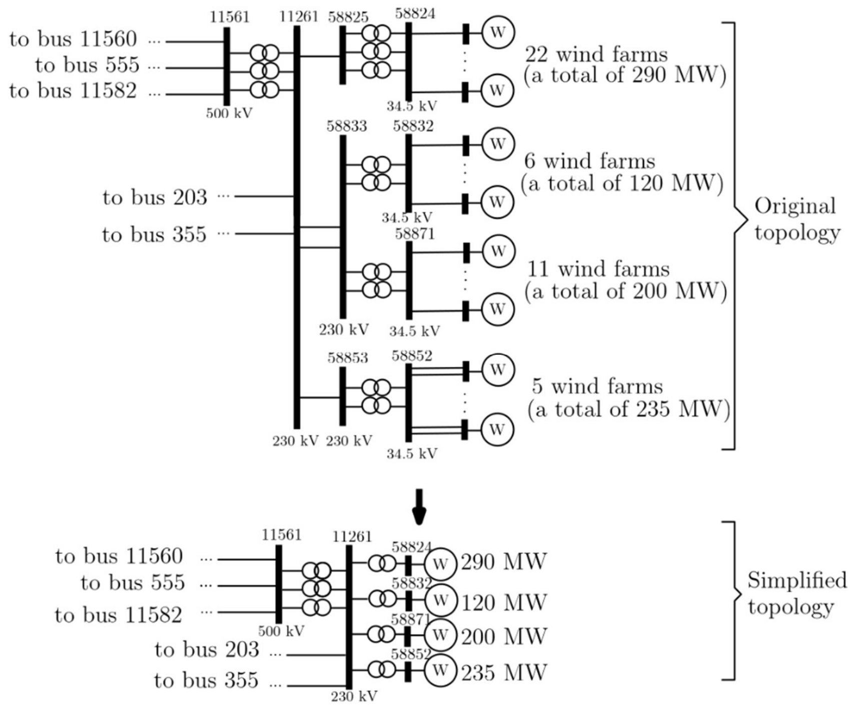

Figure 3: The substation of Ourolandia, located in Bahia: original and simplified topologies.

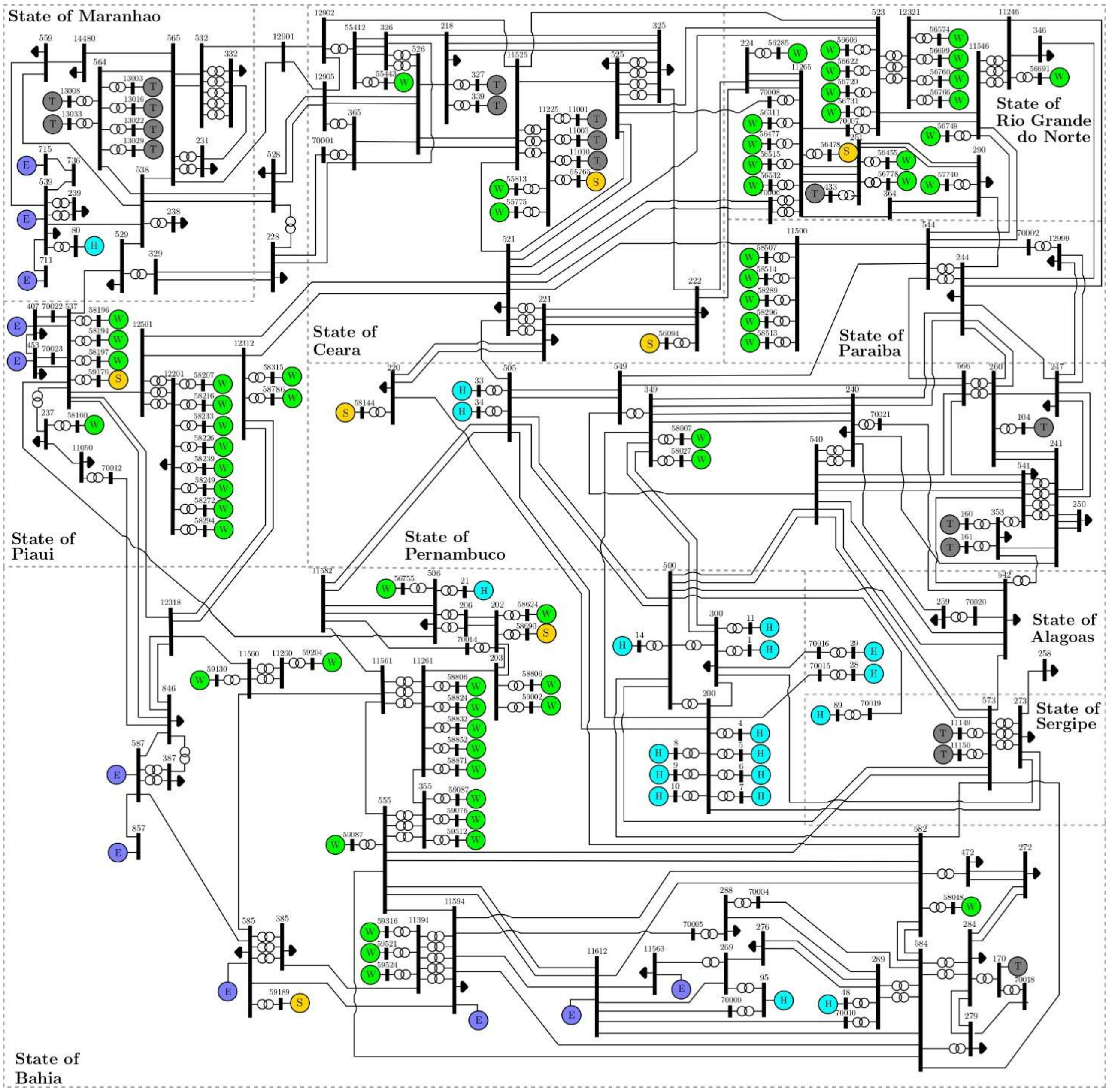

Figure 4: The one-line diagram of the proposed benchmark system based on the NE subsystem of the BIPS.

All the HPPs and TPPs are equipped with an excitation system represented by the IEEE-type ST2A model, for which the block diagram and the parameters are presented in Appendix C. This is another feature of the system that does not exactly reproduce the equipment models of the actual NE subsystem of the BIPS. However, the choice of simple standard models for controllers was made to facilitate the reproducibility of the equivalent model. In addition, the HPPs and TPPs are equipped with power system stabilizers (PSSs), governor-turbine and speed regulation systems, which are also described in Appendix C.

Regarding the WFs, all the 60 units are represented by a wind turbine generator of type 3, given by a doubly fed asynchronous (induction) generator (DFIG). In this type of wind turbine, the active power is controlled by a power converter connected to the rotor terminals [7].

The DFIG is modeled by the second-generation type 3 generic wind turbine model developed by the WECC [7]. This model comprises seven modules: the generator/converter model, P/Q control and current limit logic, plant-level control, torque control, pitch control, the aerodynamic model, and the drive-train model [7]. The overall structure of these modules is shown in Figure 5. Each of these modules is described by a model recommended by the NERC (as presented in [8]), as shown in Table 2.

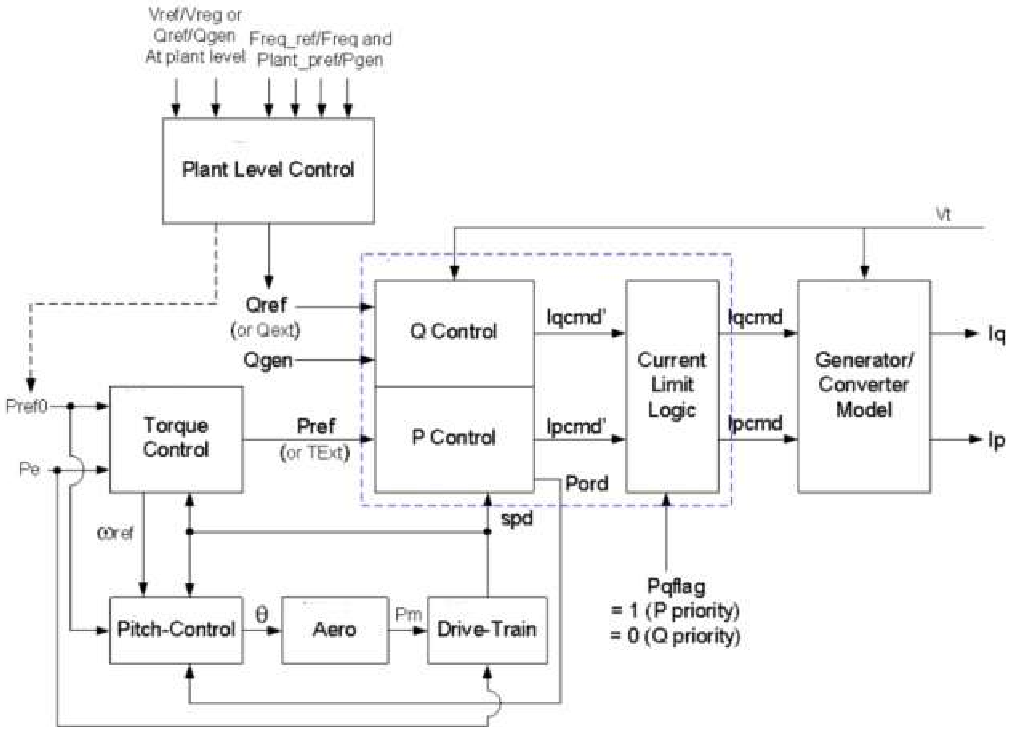

Figure 5: Overall model structure for type 3 wind turbine generator developed by WECC [7].

Table 2: The adopted model for each module of the type 3 wind turbine generator, as described in [7].

Module	The adopted model, as presented in [7]
generator/converter model	REGC_A
P/Q control and the current limit logic	REEC_A
plant level control	REPC_A
torque control	WTGTRQ_A
pitch control	WTGPT_A
aero dynamic model	WTGAR_A
drive-train model	WTGT_A

These units may be operated in voltage or reactive power control modes. In this report, 53 units operate in the reactive power control mode, while the remaining are in the voltage control mode. The values adopted for the parameters of these models are described in Appendix C.

Finally, all the 7 SPPs plants are represented by the WECC generic model for PV plants, as described in [9]. This dynamic representation of PV plants requires the use of three modules, as being: (i) the REGC_A module, used to represent the inverter interface with the grid; (ii) REEC_A module, used to represent the electrical controls of the inverters (P/Q control) and; (iii) REPC_A module, used to represent the plant control. These modules, in addition to others, are also used in the adopted generic model for the WFs, as previously described. All the SPPs operate in the reactive power control mode.

4. Power-flow analysis

The power flow solution (voltage magnitudes and angles, as well as power transfers in transmission lines) is shown in Tables B.1 and B.2, in Appendix B (due to the size of the tables, it was preferable to show these results in an Appendix rather than in the main document). The bus data and the transmission line data are shown in Appendix A. The data is provided in percentage considering a system base of 100 MVA. In this case, all the HPPs and TPPs are in operation, except for the TPPs connected at buses 104, 170 and 11003, that are assumed to be turned off. These specific TPPs are assumed to be turned off because they are smaller in size and more susceptible to losing synchronism during large perturbations. This behavior is not desirable, as the focus here is on investigating frequency stability.

From the results presented in Table B.1, it is possible to observe that the voltages are between 0.97 pu and 1.08 pu, which is comparable to the voltage profile of the NE subsystem obtained from the power flow of the complete model of the BIPS.

5. RMS dynamic simulation of the nonlinear model and a frequency stability study

Regarding the frequency requirements in Brazil, the ONS sets the limits for the frequency variation range to ±0.1 Hz for normal operation. In addition, under contingencies or perturbations, the frequency must return to the range between 59.5 Hz and 60.5 Hz within 30 seconds after it leaves this range if there is a generating reserve able to re-establish the power balance [10].

The ONS also defines the minimum requirements for the protection schemes of the generating units operating outside the nominal value of 60 Hz [11], as shown in Table 3 [11, 12]. From this table, it can be observed that for TPPs, if the frequency falls outside the 57-63 Hz range, the unit is allowed to trip instantaneously. On the other hand, they cannot trip at all if the frequency is within the 58.5-61.5 Hz range. Finally, they must remain in operation below 57.5 Hz for at least 5 seconds and below 58.5 Hz for 10 seconds. The same table presents similar requirements for HPPs, WFs and SPPs.

Regarding the limit value of RoCoF for the actuation of the frequency relays, the ONS only specifies the technical requirements for the protection functions and the operational capabilities of micro and mini-generating plants connected directly to distribution grids. Global standards for RoCoF settings vary for large-scale power systems, but examples of limits are presented in [13, 14]. For instance, the UK power system has increased the RoCoF threshold value from an initial 0.125 Hz/s to 1 Hz/s for asynchronous generators and all new generators, within a measurement window of 500 ms [14].

Table 3: Minimum time required for power plants (HPPs, TPPs, and WFs) to remain connected, for different grid frequencies, before any frequency protection scheme acts [10].

Power plant	Frequency	Operating conditions
HPP	Lower than 56 Hz Between 56 Hz and 58.5 Hz Between 58.5 Hz and 63 Hz Between 63 Hz and 66 Hz Higher than 66 Hz	Instantaneous tripping Tripping after 20s Continuous operation Tripping after 10s Instantaneous tripping
TPP	Lower than 57 Hz Between 57 Hz and 57.5 Hz Between 57.5 Hz and 58.5 Hz Between 58.5 Hz and 61.5 Hz Between 61.5 Hz and 63 Hz Higher than 63 Hz	Instantaneous tripping Tripping after 5s Tripping after 10s Continuous operation Tripping after 10s Instantaneous tripping
WF and SPP	Lower than 56 Hz Between 56 Hz and 58.5 Hz Between 58.5 Hz and 62.5 Hz Between 62.5 Hz and 63 Hz Higher than 63 Hz	Instantaneous tripping Tripping after 20s Continuous operation Tripping after 10s Instantaneous tripping

RMS dynamic simulations were carried out in the Software ANATEM (version 12.5.0) [3]. The main objective associated with the simulated cases is to assess the system frequency response under two different scenarios:

- **Scenario A:** this scenario consists of three operating points, including a base case and two additional points (points A.1 and A.2). In this scenario, the active power exported from the NE subsystem to the N and SE/CO subsystems increases (points A.1 and A.2) due to a rise in the available generation of active power from WFs and SPPs. The objective is to address a frequency stability issue that arises after a disturbance, specifically the loss of interconnection lines that are responsible for transferring power from the NE subsystem to its neighboring subsystems. This loss causes a significant increase in system frequency, which in turn may activate over-frequency relays in the TPPs, WFs and SPPs. This scenario is considered the most likely to lead to frequency stability problems in the actual NE subsystem, given the significant amount of active power exported to neighboring subsystems. Detailed information about this scenario can be found in Table 4.
- **Scenario B:** This scenario is characterized by two operating points, including a base case (the same of Scenario A) and an operating point that results from varying the number of conventional power plants in operation (point B.1). The objective is to analyze a frequency stability issue caused by a considerable decrease in system frequency following a perturbation, specifically the loss of a TPP. This decrease can trigger the under-frequency relays of TPPs. A detailed description of this scenario can be found in Table 5.

As previously mentioned in the last section, the base case for the two scenarios assumes that all HPPs and TPPs are operating, except for the TPPs connected at buses 104, 170, and 11003, which are assumed to be turned off. These specific TPPs are smaller in size and more susceptible to losing synchronization during significant disturbances. Therefore, they are turned off to focus on investigating frequency stability, which is essential for this analysis. This operating point aligns with the base case data presented in Appendix B. In addition, the speed regulation of the HPPs connected to buses 14, 80 and 89 are disable.

In Scenario A, at operating points A.1 and A.2 (as detailed in Table 4), the active power exported by the NE subsystem increases by approximately 2,660 MW and 3,060 MW, respectively, compared to the base case. At point A.1, this increase is attributed to higher available power generation from WFs, while at point A.2, it is due to the SPPs. The total power generation from HPPs and TPPs shows a slight increase to ensure the power balance for the power-flow solution.

With respect to Scenario B, for operating point B.1 (as described in Table 5), 2 TPPs (all located in the state of Maranhao) are also turned off. The total active power that this group of TPPs provided in the base case was approximately 640 MW. This amount of active power is redispatch among the remaining TPPs and HPPs proportionally to their nominal power capacity. Hence, in this operating point, the conventional power plants are responsible for supporting the lack of active power from the TPPs that are turned off from operation. It is important to highlight that the total power exchanged between the NE and external subsystems is kept fixed, even during contingencies and perturbations.

All the numerical simulations were obtained using the ANAREDE and ANATEM[2] software from CEPEL/Brazil [1-3].

5.1 RMS dynamic simulations for Scenario A and discussion

A sudden outage of two interconnection lines between the NE subsystem and the N subsystem was considered as disturbance for the three operating points of Scenario A described in Table 4. These two lines are connected at the boundary buses 407 and 453 of the NE subsystem. It is important to highlight that both lines share the same front-end bus in the N subsystem, specifically the Colinas 2 Substation (bus 594 in the BIPS), which is in the state of Tocantins. Consequently, the loss of these two lines may occur due, for example, to an issue at the Colinas 2 Substation (500 kV), which could lead to its outage and the subsequent loss of both lines. These two lines are responsible for exporting 1,700 MW to N and SE/CO subsystems in the base case. Therefore, the sudden loss of these two lines results in excess power generation in the NE subsystem, which in turn causes an increase in the system's frequency, as demonstrated by the following simulation results.

Figures 6 and 7 show the response of the frequency of all HPPs and TPPs, as well as in some network buses of 230 kV and 500 kV, respectively. The time duration of the simulation is 30 seconds, following reference [15], which indicates the typical period of 20-30 seconds for the actuation of the primary frequency control of conventional generators before the actuation of the automatic generation

[2] The adopted software versions were 10.1.3 for ANAREDE and 11.01.00 for ANATEM.

controls (which were not implemented in this simulation). The considered disturbance is applied in t = 1s.

Table 4: Description of the operating points considered for the time-domain simulations for Scenario A.

Case	The total of active power exported by the NE subsystem	Total power generated by the HPPs and TPPs	Total power generated by WFs	Total power generated by SPPs	Description
Base case	13,400 MW	9,858 MW	10,584 MW	3,406 MW	Reference case, as shown in Appendices A and B
A.1	**16,060 MW**	9,966 MW	**13,760 MW**	3,406 MW	1. Reduction of the equivalent inertia of the system due to the increase of the proportion of the power generated by CIGs with respect to the conventional generators. 2. The active power exported by the NE subsystem is increased.
A.2	**16,460 MW**	10,000 MW	13,760 MW	**3,870 MW**	

Table 5: Description of the operating points considered for the time-domain simulations for Scenario B.

Case	Number of HPPs and TPPs	Total power generated by the HPPs and TPPs	Total power generated by WFs and SPPs	Description
Base Case	34 units	9,858 MW	13,990 MW	Reference case, as shown in Appendices A and B
B.1	32 units (2 TPPs are disconnected)	**10,559 MW**	13,990 MW	1. Reduction of the equivalent inertia of the system due to the disconnection of conventional power plants. 2. The HPPs and TPPs operate close to their power generation capacities. 3.The total power generated by the WFs and SPPs has not changed.

Under this event, the highest value of frequency and the RoCoF are approximately 62.47 Hz and 0.94 Hz/s, respectively. These results are the same when calculated using the rotor speed of any HPP, TPP or the frequency at any WF terminal bus and considering the first window of 500 ms after the disturbance. No frequency protection scheme is activated during this event, according to Table 3. In addition, the frequency tends to a steady-state frequency deviation near to 0.5 Hz, which is a value that could be probably corrected by secondary frequency controls, showing a satisfactory primary frequency response of the synchronous generators.

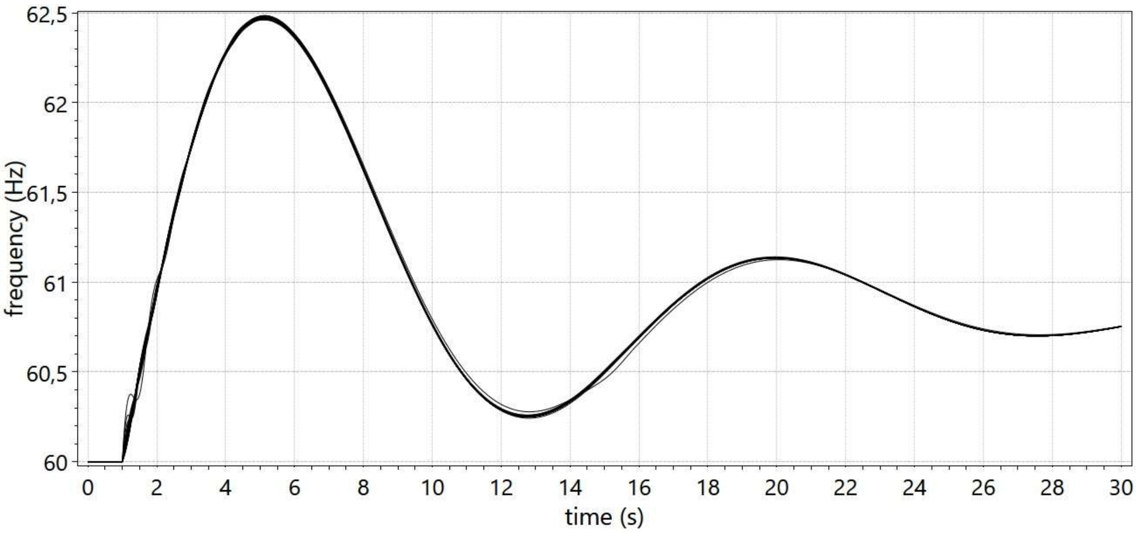

Figure 6: Frequency response in all HPPs and TPPs (base case).

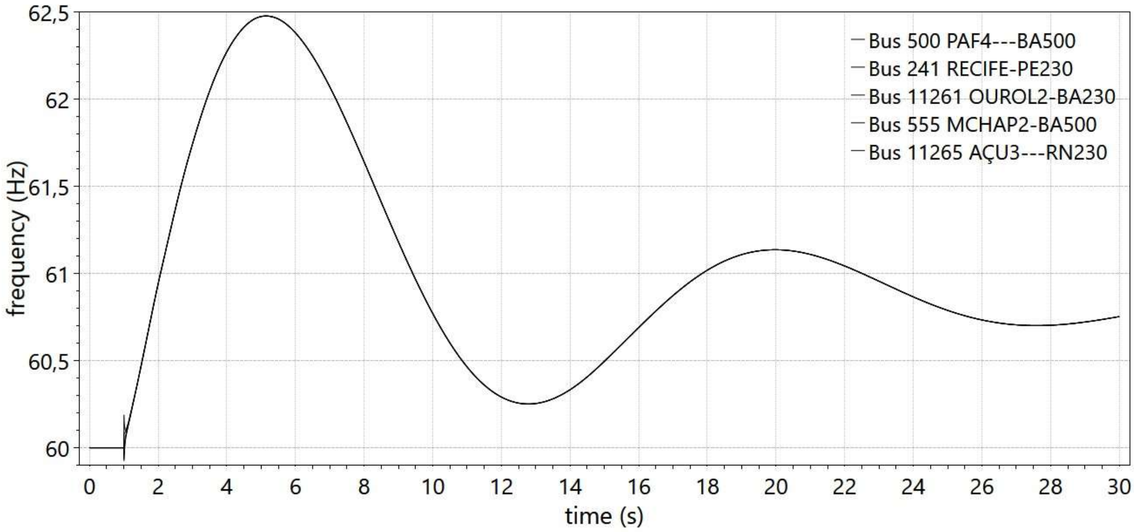

Figure 7: Frequency response in some 500 kV and 230 kV buses (base case).

The same perturbation of the base case was applied to the operating points A.1 and A.2 (a sudden outage of two interconnection lines at t = 1 s). Figure 8 shows the frequency response at bus 11261 (in the Bahia state) for the three operating points (base case and the points A.1 and A.2). This bus was chosen for analysis because there are several WFs connected to it, injecting more than 1 GW into the grid. The RoCoF is 0.94 Hz/s, 0.96 Hz/s and 1.16 Hz/s for the base case and the operating points A.1 and A.2, respectively. Additionally, the highest frequency values are approximately 62.47 Hz, 62.58 Hz, and 63.18 Hz, which suggests that this frequency deviation increases as the exported active power loss rises.

Figure 9 illustrates the active power response generated by some HPPs at point A.2 in response to the considered perturbation. Although the primary frequency control was activated to reduce the generated active power of conventional generators, this action was not quick enough to prevent the significant increase in the system's frequency following the disturbance. It is important to point out, however, that the power generated by the WFs and SPPs are kept constant during all the time interval of the simulation. Upon further analysis of point A.2, it has been observed that the frequencies at the TPPs and WFs bus terminals reach 63 Hz within 4.3 seconds. This situation would activate the over-frequency relays for all TPPs and WFs, as indicated by the frequency stability indicators in Table 3. Such a scenario could lead to a cascade effect among other types of generators, highlighting an imminent frequency stability issue.

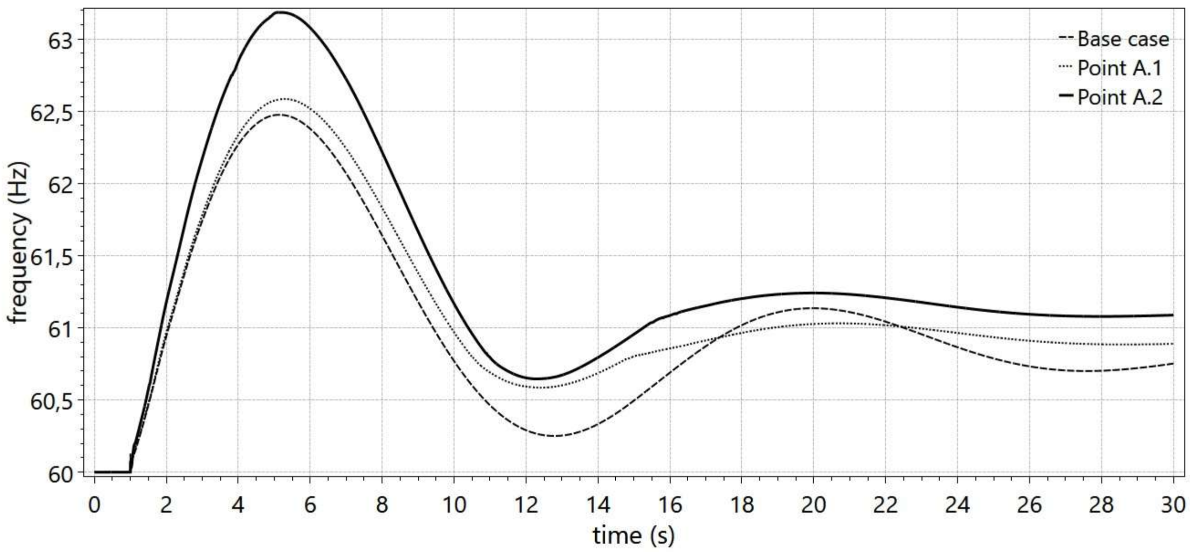

Figure 8: Frequency response at bus 11261 (in the state of Bahia) for the base case (black dashed line), Case A.1 (black dotted line), and Case A.2 (black continuous line).

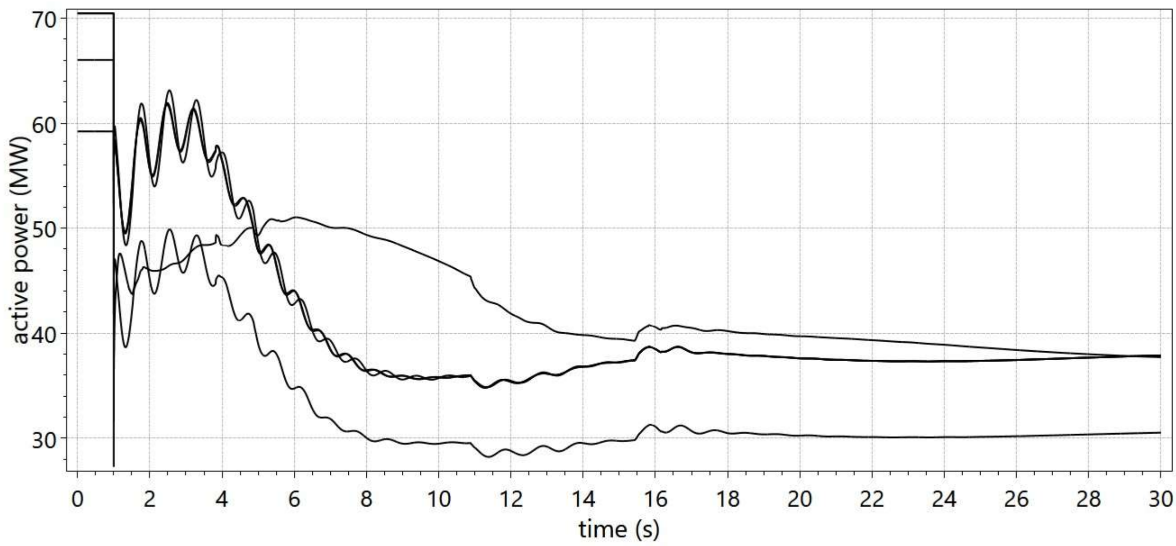

Figure 9: Generated active power response in some HPPs (point A.2).

5.2 RMS dynamic simulations for Scenario B and discussion

A sudden outage of the TPP (Porto Sergipe) connected to bus 11150 at t = 1 s was considered as the perturbation for the two operating points in Scenario B, as described by Table 5. Initially, the following analyses will focus on the base case. Figures 10 and 11 show the response of the frequency of all HPPs and TPPs, as well as in the terminal buses of some network buses, respectively.

Under this event, the lowest value of frequency and the RoCoF are approximately 58.33 Hz and 0.64 Hz/s, respectively. The results remain consistent when calculated using the rotor speed of any HPP, TPP, or the frequency at any WF terminal bus. During this event, no frequency protection scheme was activated. Additionally, the frequency tends to stabilize with a deviation smaller than 0.5 Hz, a value that could be corrected by secondary frequency controls. This indicates a satisfactory primary frequency response from the synchronous generators.

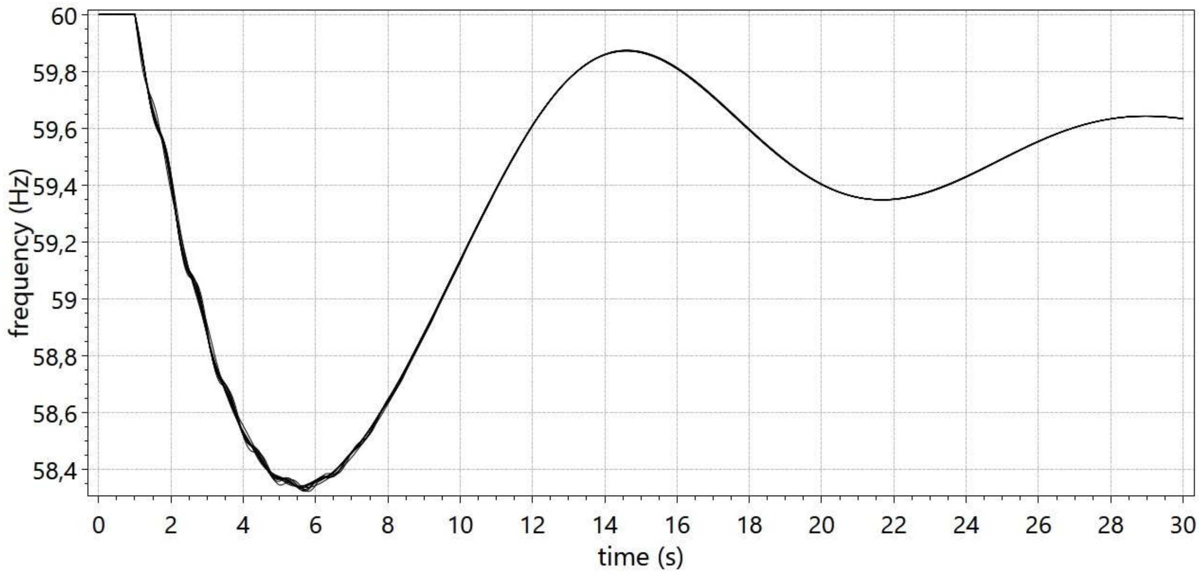

Figure 10: Frequency response in all HPPs and TPPs (base case).

The same perturbation of the base case was applied to the operating point B.1 (a sudden outage of the TPP connected to bus 11150 at t = 1 s). Figure 12 shows the frequency response at bus 11261 (in the Bahia state) for the two operating points. The RoCoF is 0.64 Hz/s and 0.94 Hz/s for the base case and the operating points B.1, respectively. The simulations obtained for the operating point B.1 requires more detailed explanations and discussions. The frequencies at the TPPs bus terminals reach 57 Hz within 6 s, approximately. This would trigger the under-frequency relays of all TPPs, according to the frequency stability indicators of Table 3, which could induce a cascade of similar events on other types of generators.

To explore this scenario even further, the responses of the frequencies of all HPPs and TPPs are depicted in Figure 13, for the actuation of the under-frequency protection in five TPPs at t = 6 s (for simplicity, the time-delay for protection actuation is neglected). This figure indicates that after disconnecting these five TPPs, the system loses frequency stability.

6. Conclusions and future works

In this report, a test system based on the NE electrical power subsystem of the BIPS was presented and discussed. The proposed test system comprises 232 buses and 420 AC transmission lines and transformers, corresponding to 8.6% and 11.47% of the total number of buses and transmission lines/transformers, respectively, of the complete NE subsystem model. In addition, the proportion of synchronous and asynchronous generation seen in the complete NE subsystem is preserved in the proposed model, in which almost 60% of the total active power generation is provided by a set of 60 wind farms and 7 SPPs. The other part of active generation comes from 37 conventional power plants (HPPs and TPPs). The external subsystems (as seen in Figure 1) are represented equivalently by constant active and reactive power injections into equivalent PV buses located in the states of

Maranhao, Piaui, and Bahia. As previously discussed, although this does not correspond to the actual way the BIPS is operated by the ONS, the proposed equivalent enables studies of possible strategies to make the NE subsystem self-sufficient to deal with frequency stability problems. This is highly desirable given the forecast of large growth in the penetration of wind and solar generation and relative stagnation of synchronous generation expansion in this region.

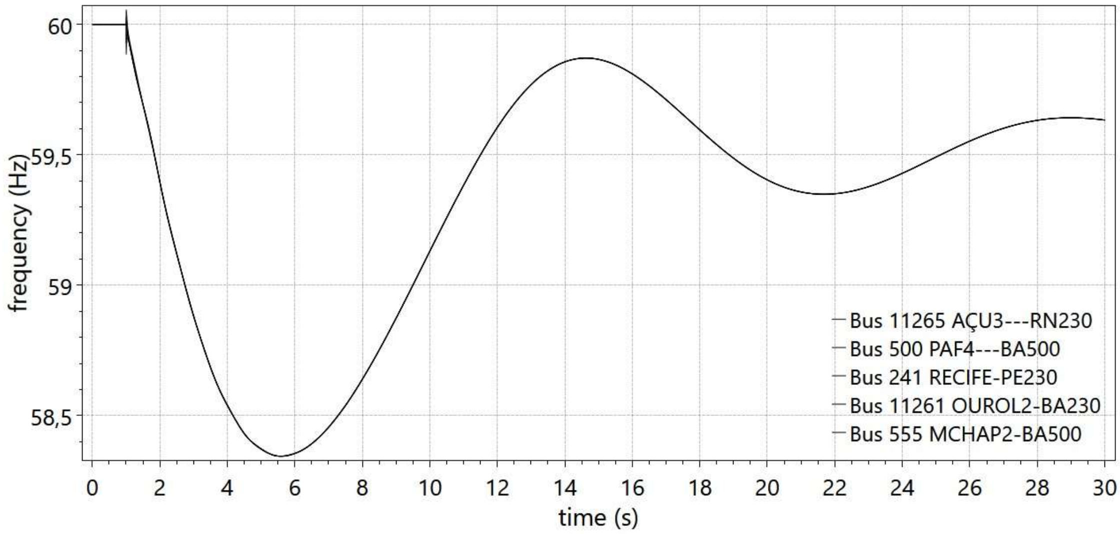

Figure 11: Frequency response in some 500 kV and 230 kV buses (base case).

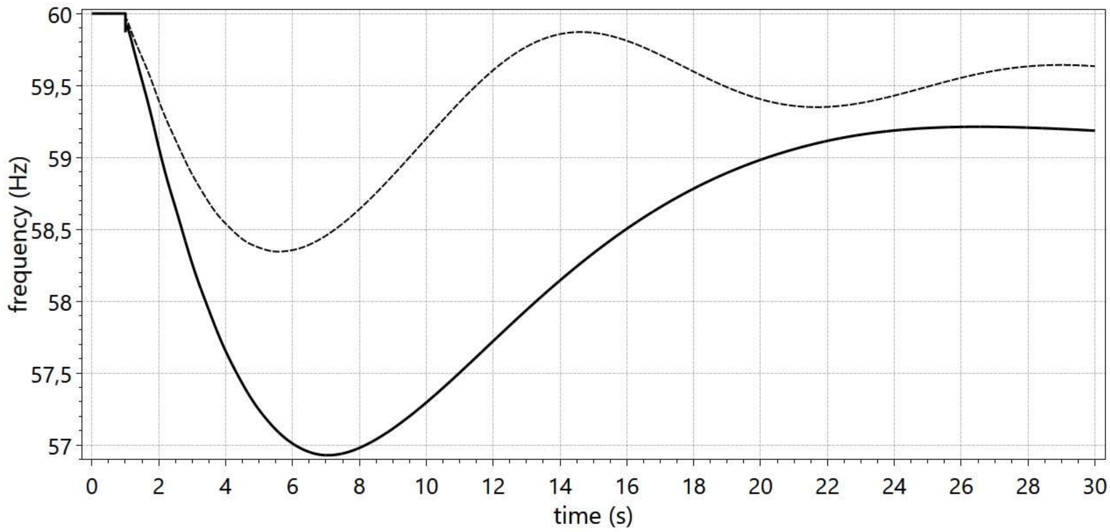

Figure 12: Frequency response at bus 11261 (in the state of Bahia) for the base case (black dashed line) and Case B.1 (black continuous line).

For Scenario A, the dynamic RMS simulations show an increase of the maximum value of system’s frequency after the perturbation, as the exported active power from NE subsystems to N/SE subsystems increases. This illustrates a key feature of the NE subsystem as a major exporter to other Brazilian subsystems, making it more suitable to increase frequency when part of the exported power is lost. For the point A.2, the primary frequency control was activated to reduce the generated active power of conventional generators, but this action was not quick enough to prevent the significant increase in the system's frequency following the disturbance. Therefore, implementing local solutions and control strategies may enhance the system's efficiency for primary frequency control.

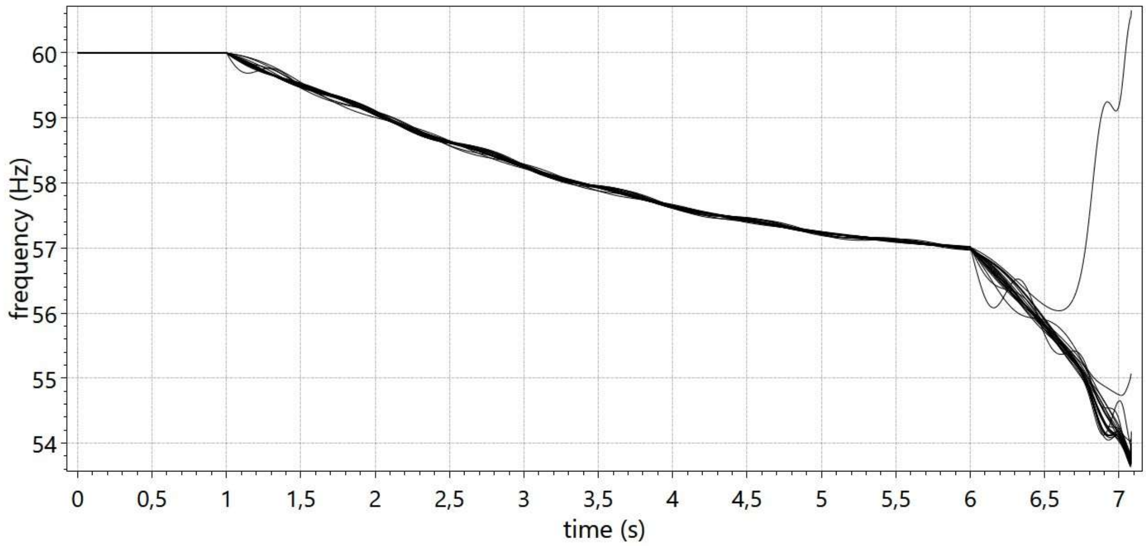

Figure 13: Frequency response in all the HPPs and TPPs for point B.1, considering the actuation of the under-frequency relays in five TPPs in t = 6 s.

For Scenario B, the dynamic RMS simulations show an increase of the RoCoF in scenarios where some TPPs are inoperative and, hence, the equivalent inertia of the system is reduced. It is important to highlight this is not an uncommon operating scenario, since thermal power plants are usually activated only at peak times for a specific time range due to their higher generation costs, or when the HPPs reservoirs are in their lower levels. On the other hand, keeping the TPPs permanently activated to guarantee a minimum acceptable system equivalent inertia is not an interesting solution from both economic and environmental perspectives.

In a simulated scenario in which the under-frequency relays of some TPPs are triggered, a cascade tripping of all HPPs and TPPs due to under-frequency is potentially induced (the operating point given by B.1, after the disconnection of TPP at bus 11150). This is caused by the reduction of the equivalent inertia of the system, which is also influenced by an operating condition where the conventional generators are close to their power generation capacity.

Hence, the simulated Scenario A (corresponding to point A.2) and Scenario B (point B.1) in this report are proposed as a candidate to become one of the benchmark systems that will compose the results of the IEEE PES PSDP Task Force on Benchmark Networks for Low-Inertia Systems. The authors believe this is an interesting equivalent system for the purposes of the Task Force, since it allows the study of possible local solutions (based on the use of energy storage systems, for example) and control strategies that may be able to improve the RoCoF to secure levels under different operating conditions and in response to different events, as well as, to prevent frequency stability issues arising from both over-frequency and under-frequency behavior.

Research to create better equivalent representations of the actual dynamics of the interconnections between this benchmark model and the remaining of the BIPS is planned as a future step of this work, together with the inclusion of better equivalent representations of the existing protection schemes in this subsystem.

Appendix A

This appendix presents the power flow solution for the base case. The solution is presented in Tables A.1 and A.2.

Table A.1: Power flow solution for the base case – voltages magnitudes and angles.

Bus Number	Bus Name	Voltage (pu)	Angle (degrees)	Bus Number	Bus Name	Voltage (pu)	Angle (degrees)
1	PAF1-1UHE013	0.97	1.05	11394	IGAPO3-BA230	1.00	-50.63
4	PAF2A1UHE013	0.97	0.10	11500	SLUZI2-PB500	1.04	1.10
5	PAF2A2UHE013	0.97	0.42	11525	PECEM2-CE500	1.02	-4.06
6	PAF2A3UHE013	0.98	2.82	11546	CMRIM2-RN500	1.04	11.23
7	PAF2B1UHE013	0.98	-1.83	11560	GOURO2-BA500	1.04	-34.72
8	PAF2B2UHE013	0.99	-0.81	11561	OUROL2-BA500	1.04	-23.74
9	PAF2B3UHE013	0.99	-0.88	11563	M.NETO-BA500	1.03	-63.14
10	PAF3-1UHE013	0.99	-0.87	11582	JUAZE3-BA500	1.05	-15.00
11	PAF3-2UHE013	0.98	-0.94	11594	IGAPO3-BA500	1.04	-52.36
14	PAF4-1UHE013	0.97	-0.00	11612	POCOE3-BA500	1.03	-51.03
21	SOBRA1UHE013	0.99	-12.08	12201	CNOVO2-PI230	1.00	-6.05
28	ASALE1UHE013	0.99	-0.97	12312	QNOVA2-PI500	1.04	-15.82
29	ASALE2UHE013	0.99	-1.78	12318	BURITI-BA500	1.08	-32.82
33	LGONZ1UHE013	1.04	-4.83	12321	JCMR3--RN230	1.00	16.06
34	LGONZ2UHE013	1.04	-4.83	12501	CNOVO2-PI500	1.05	-11.63
48	PCAVA1UHE013	1.00	-36.58	12901	PARNAI-PI500	1.02	-18.21
80	ESTREIUHE013	1.01	-32.10	12902	ACARA3-CE500	1.02	-11.77
89	XINGO1UHE013	0.98	8.77	12905	TIANG2-CE500	1.04	-15.30
95	ITAPE1UHE013	0.99	-47.20	12999	JPSII--PB230	0.99	-11.84
160	TERPEGUTE013	1.01	-3.75	13003	MARA4GUTE013	1.01	-19.35
161	TERPEVUTE013	1.01	-4.36	13008	MARA5GUTE013	1.01	-19.97
200	PAF3-A-BA230	1.02	-5.62	13016	MARA3GUTE013	1.00	-19.36
202	JUAZE2-BA230	1.03	-10.24	13022	MARA3VUTE013	0.99	-18.49
203	S.BONF-BA230	1.02	-8.42	13029	N.VE.GUTE013	1.01	-18.48
206	SOBRAD-BA230	1.00	-12.44	13033	PARNAVUTE013	1.03	-23.07
218	CAUIPE-CE230	0.99	-1.57	14480	S.LUZ3-MA500	1.01	-33.74
220	BOM-NO-PE230	1.03	-2.88	55412	ACARA2-CE230	0.98	-9.10
221	MILAGR-CE230	1.02	-4.51	55443	ITAREM-CE034	1.00	-4.42
222	BANABU-CE230	1.01	3.24	55765	DNPARA-CE034	1.01	5.55
224	MOSSR2-RN230	1.01	14.00	55775	CFAISA-CE034	1.00	6.14
228	TERES--PI230	1.01	-27.62	55813	SERROT-CE034	1.00	8.28
231	MIRAND-MA230	0.99	-31.85	56094	ALEX---CE034	1.00	11.80
237	S.J.PI-PI230	1.00	-20.70	56285	AMAZB1-RN034	1.00	23.96
238	P.DUTR-MA230	1.02	-32.65	56311	MEL2---RN034	1.00	32.65
239	IMPERA-MA230	1.02	-41.02	56455	ALEGRI-RN034	1.00	22.62
240	ANGELI-PE230	1.01	-9.15	56477	MEL1---RN034	1.00	34.38
241	RECIFE-PE230	1.01	-11.68	56478	MEL2---RN034	1.00	18.19
244	CGRD2B-PB230	0.99	-2.89	56515	VSTERZ-RN034	1.00	38.60

247	GOIANI-PE230	0.98	-11.60	56532	VSRICA-RN034	1.00	35.67
250	MIRUEI-PE230	0.99	-13.57	56574	SCLARA-RN034	1.00	26.33
251	AÇU2---RN230	1.01	16.37	56606	ASABRA-RN034	1.00	21.66
258	PENEDO-AL230	1.01	-24.63	56622	C.PRE2-RN034	1.00	23.53
259	MACEIO-AL230	1.01	-15.53	56691	CUTIA--RN034	1.00	27.95
260	PAU-FE-PE230	1.01	-10.47	56699	CUMARU-RN034	1.00	22.84
269	EUNAPO-BA230	0.99	-55.21	56720	CPFL---RN034	1.00	22.99
272	CATU---BA230	0.99	-38.51	56731	JERUSA-RN034	1.00	19.59
273	JARDIM-SE230	1.01	-18.10	56749	RIOVT2-RN034	1.00	16.97
276	FUNIL--BA230	1.00	-51.04	56755	ARIZON-BA034	1.00	-13.70
279	COTEGI-BA230	0.99	-38.70	56760	MRONCA-RN034	1.00	21.94
284	CAMAC4-BA230	1.00	-37.16	56766	ANGICO-RN034	1.00	22.08
288	IBICOA-BA230	1.00	-50.75	56778	MACAU--RN034	1.00	23.08
289	SAPEAC-BA230	1.01	-39.26	57740	SRMNOV-RN034	1.00	17.11
290	PARAIS-RN230	0.99	10.94	58007	CAETE2-PE034	1.00	-2.74
300	PAF3-B-BA230	1.02	-6.46	58027	SCLEME-PE034	1.00	1.12
325	FORTA2-CE230	0.99	-3.61	58048	TUCANO-BA034	1.00	-7.98
326	SOBRA3-CE230	0.99	-10.84	58144	BLMNTE-PE034	1.00	3.69
327	FORTAGUTE013	1.01	3.66	58160	LABAR1-PI034	1.00	-17.20
329	BESPER-MA230	1.01	-23.50	58194	LGVN-A-PI034	1.00	-12.30
332	SLUIS2-MA230	1.00	-29.05	58196	LGVN-B-PI034	1.00	-12.46
339	TERCEGUTE013	1.00	5.67	58197	LGVN-C-PI034	1.00	-10.37
346	NATAL3-RN230	1.00	7.65	58207	CHAPA1-PI034	1.00	0.70
349	GARANH-PE230	1.01	-8.68	58216	CHAPA2-PI034	1.00	0.02
353	SUAPE2-PE230	1.01	-9.99	58239	VEDPI2-PI034	1.00	-1.19
355	MCHAP2-BA230	1.00	-26.64	58249	CDNHA1-PI034	1.00	-1.24
364	LNOVA2-RN230	1.00	14.62	58272	SBASIL-PI034	1.00	8.82
365	IBIAP2-CE230	1.01	-16.31	58289	NORTE--PB034	1.00	7.86
385	BJLAP2-BA230	0.99	-46.29	58294	VEDPI3-PI034	1.00	-0.93
387	REGUA--BA230	1.01	-50.50	58296	SUL2---PB034	1.00	8.73
407	RG-CO1CAP500	1.02	-20.48	58315	OITIS--PI034	1.00	-11.89
433	VDOACUUTE013	1.00	25.58	58507	SSERID-PB034	1.01	4.20
453	RG-CO2CAP500	1.02	-20.54	58513	SSER1A-PB034	1.00	5.10
472	OLINDI-BA230	1.01	-31.63	58514	OESRDO-RN034	1.00	4.57
500	PAF4---BA500	1.04	-7.51	58624	DELFIN-BA034	1.00	-3.70
505	L.GONZ-PE500	1.05	-8.73	58690	FUTURA-BA034	1.01	-2.51
506	SOBRAD-BA500	1.06	-16.44	58786	LGVEN3-PI034	1.00	-10.72
521	MILAGR-CE500	1.02	-4.28	58806	C.FORM-BA034	1.00	-13.31
523	JCMR3--RN500	1.04	14.23	58824	UMBURA-BA034	1.00	-12.56
525	FORTA2-CE500	1.01	-2.85	58832	C.LAR1-BA034	1.00	-11.09
526	SOBRA3-CE500	1.03	-11.19	58852	BABILS-BA034	1.00	-13.87
528	TERES2-PI500	1.06	-25.01	58871	C.LAR2-BA034	1.00	-11.32
529	BESPER-MA500	1.05	-22.61	59002	FLARG2-BA034	1.00	0.92
532	SLUIS2-MA500	1.01	-28.34	59057	MCHAPS-BA034	1.00	-21.36
537	S.J.PI-PI500	1.06	-19.45	59076	SBABIL-BA034	1.00	-15.43
538	P.DUTR-MA500	1.06	-30.65	59087	MCHAS2-BA034	1.00	-25.32

539	IMPERA-MA500	1.07	-40.78	59130	VSEUGE-BA034	1.00	-21.10
540	ANGEL2-PE500	1.05	-8.57	59176	SGONCA-PI034	1.00	4.17
541	RECIFE-PE500	1.03	-10.16	59189	SDSER3-BA034	1.00	-39.77
542	MESSIA-AL500	1.02	-14.02	59204	VSVTR--BA034	1.00	-24.52
544	CGRD3--PB500	1.02	-0.87	59316	ARACAS-BA034	1.00	-45.51
549	GARANH-PE500	1.05	-8.21	59512	VBAHI3-BA034	1.00	-18.60
555	MCHAP2-BA500	1.03	-29.16	59521	AURA---BA034	1.00	-44.19
559	ACAILA-MA500	1.05	-39.17	59524	CAETNO-BA034	1.00	-45.90
564	SALOPE-MA500	1.05	-25.90	70001	FICT01	1.03	-19.99
565	MIRAND-MA500	1.02	-28.97	70002	FICT02	1.00	-7.82
566	PAU-FE-PE500	1.03	-8.71	70003	FICT03	1.02	-32.43
573	JARDIM-SE500	1.04	-16.92	70004	FICT04	0.99	-47.10
582	OLINDI-BA500	1.02	-24.43	70005	FICT05	1.01	-51.16
584	CAMAC4-BA500	1.00	-34.17	70006	FICT06	1.00	11.99
585	BJLAP2-BA500	1.03	-45.39	70007	FICT07	1.02	14.96
587	R.EGUA-BA500	1.04	-49.80	70008	FICT08	1.00	11.98
711	IM-CO1CAP500	1.02	-31.50	70009	FICT09	1.00	-47.67
715	IM-CO2CAP500	1.01	-31.46	70010	FICT10	1.01	-41.29
736	IP2TCS-MA500	1.04	-37.16	70011	FICT11	1.01	-50.83
846	BARRER-BA500	1.03	-44.31	70012	FICT12	1.04	-36.78
857	RE-LUZCAP500	1.03	-41.84	70014	FICT14	1.04	-11.85
11001	PPECE1UTE020	1.00	6.09	70015	FICT15	0.99	-1.88
11010	PPECE2UTE020	1.00	6.19	70016	FICT16	0.99	-2.69
11050	B.JESU-PI230	1.04	-35.55	70018	FICT18	0.99	-38.70
11149	PSER1VUTE024	0.99	-9.72	70019	FICT19	1.02	-4.34
11150	PSER1GUTE025	0.98	-11.88	70021	FICT21	1.02	-12.50
11225	PECEM2-CE230	1.00	-1.46	70022	FICT22	1.06	-19.90
11246	CMRIM2-RN230	1.00	11.79	70023	FICT23	1.06	-19.86
11260	GOURO2-BA230	1.00	-33.41				
11261	OUROL2-BA230	1.00	-20.42				
11265	AÇU3---RN230	1.01	15.25				

Table A.2: Power flow solution for the base case – active and reactive powers in transmission lines (for the 400 lines with the highest values of active power).

Bus Number (From)	Bus Number (To)	Active Power (MW)	Reactive Power (MVAr)	Active Losses (MW)	Bus Number (From)	Bus Number (To)	Active Power (MW)	Reactive Power (MVAr)	Active Losses (MW)
846	587	2833.18	-619.65	52.65	11394	11594	164.61	-24.09	0.00
538	539	2108.02	-265.68	59.94	11394	11594	164.61	-24.09	0.00
11560	585	2085.24	8.49	55.35	13022	564	164.50	2.51	0.00
537	453	1887.38	-794.15	89.58	56606	523	161.30	-39.14	0.00
582	584	1719.74	122.70	26.78	58197	537	159.20	-45.04	0.00
587	857	1700.00	-213.82	0.00	532	565	158.99	-264.48	0.38
537	407	1533.79	458.23	53.61	200	300	157.49	22.60	0.46
555	11612	1504.34	-227.87	40.41	251	11265	153.54	-15.05	0.58

506	537	1467.74	-419.35	18.43	251	11265	153.54	-15.05	0.58
12318	846	1427.96	111.21	21.20	251	11265	153.54	-15.05	0.58
14	500	1414.98	-112.39	0.00	56755	506	153.10	-161.55	0.00
564	538	1300.43	-197.45	8.59	244	260	152.82	-36.00	2.88
11561	11560	1189.60	-165.47	15.91	58027	349	151.80	6.81	0.00
12312	12318	1180.75	-490.27	24.80	10	200	151.00	-42.05	0.00
12312	12318	1180.75	-490.27	24.80	11	300	151.00	24.06	0.00
500	582	1159.25	166.49	26.60	244	247	150.73	-3.57	4.21
89	70019	1137.00	-68.68	0.00	56574	12321	150.40	11.83	0.00
70019	500	1137.00	-338.33	0.00	365	228	148.78	-9.22	5.94
539	736	1100.00	-458.94	0.00	244	260	148.45	-35.65	2.89
539	711	1100.00	-438.85	0.00	11260	11560	148.25	-12.50	0.00
736	715	1100.00	-379.45	0.00	11260	11560	148.25	-12.50	0.00
11546	544	1057.88	-13.03	14.04	56720	523	147.60	-26.36	0.00
11546	544	1057.88	-13.03	14.04	58194	537	147.20	-56.21	0.00
544	566	1055.58	-188.66	9.24	540	541	145.42	-41.19	0.42
573	584	992.26	6.98	21.80	500	542	145.41	25.22	1.59
505	582	945.49	-37.89	25.73	284	279	145.40	63.40	1.01
11150	573	934.10	-512.59	2.58	346	244	144.49	-5.82	4.39
11612	11563	909.24	-360.21	13.52	58196	537	144.00	-56.61	0.00
12501	12312	908.72	-114.45	4.75	540	573	143.62	7.42	2.11
11561	555	881.95	-78.01	5.82	300	500	142.16	109.07	0.00
521	12312	875.84	-62.41	12.62	565	538	141.68	-337.88	0.67
538	559	875.79	-23.69	17.32	59512	355	136.90	10.60	0.00
585	11594	868.73	-138.77	6.64	58249	12201	135.80	-0.75	0.00
59176	537	865.00	176.56	0.00	58239	12201	135.30	-2.22	0.00
537	846	855.62	134.53	46.34	58513	11500	135.10	-71.11	0.00
11525	12902	851.60	-157.97	7.99	56699	12321	134.70	5.70	0.00
11582	11561	845.05	-59.22	8.10	55443	55412	134.50	38.99	0.00
11265	70008	839.51	89.29	0.00	58294	12201	132.20	-1.47	0.00
70008	525	839.51	41.01	13.26	240	259	131.14	-31.49	3.99
12501	537	837.79	-219.55	7.81	349	240	129.47	-77.03	0.24
58690	202	837.00	189.94	0.00	58226	12201	129.30	5.37	0.00
523	11546	819.28	-182.10	2.74	284	279	129.20	56.54	0.84
523	11546	819.28	-182.10	2.74	244	240	129.18	-37.60	2.79
526	12905	797.94	-124.91	3.62	55412	12902	128.43	-116.62	0.00
12901	532	779.41	87.93	9.39	58160	237	128.40	-0.28	0.00
566	541	755.42	-235.73	7.76	56731	523	128.20	-44.68	0.00
12318	846	752.31	152.96	19.60	58296	11500	126.80	-31.69	0.00
573	582	732.68	98.34	5.68	55775	11225	126.40	6.48	0.00
11525	526	697.53	-219.93	5.70	12905	365	125.64	132.56	0.26
11525	526	697.53	-221.33	5.70	11612	269	124.68	48.56	1.17
526	12905	686.72	-132.29	3.19	55765	11225	124.00	25.15	0.00
11001	11225	684.20	67.31	0.51	241	250	120.29	37.60	0.91
565	14480	676.74	-70.11	3.53	58289	11500	118.60	-35.33	0.00
537	529	676.15	-15.47	8.98	58806	11261	115.40	3.16	0.00

12905	528	665.70	-287.34	7.24	241	250	115.09	36.99	0.84
544	549	645.28	-290.53	5.49	241	250	114.71	36.92	0.83
12905	528	636.46	-295.46	6.98	58514	11500	113.30	-71.59	0.00
12902	12901	600.17	-3.13	4.69	59057	355	113.20	5.21	0.00
500	573	594.19	10.69	9.19	224	222	113.18	-27.20	4.07
529	538	590.71	-185.26	6.39	59316	11394	112.60	-2.26	0.00
202	70014	589.56	-169.41	2.47	58007	349	112.50	-1.73	0.00
70010	11612	587.30	-23.96	3.76	11246	244	112.30	3.36	3.76
289	70010	587.30	-3.08	0.00	58624	202	112.20	-25.77	0.00
70014	11582	587.09	-186.69	2.47	59524	11394	111.20	-3.22	0.00
70006	521	573.97	-2.98	14.43	58207	12201	111.20	0.90	0.00
11265	70006	573.97	29.72	0.00	220	221	111.09	24.77	0.88
70006	521	573.97	-2.98	14.43	202	206	110.56	53.04	1.13
11265	70006	573.97	29.72	0.00	202	206	110.56	53.04	1.13
584	11612	564.63	-24.75	18.47	532	332	109.39	87.42	0.00
11225	11525	563.24	-41.74	0.00	532	332	109.39	87.42	0.00
11225	11525	563.24	-41.74	0.00	532	332	109.39	87.42	0.00
11225	11525	563.24	-41.74	0.00	532	332	109.39	87.42	0.00
584	289	539.29	-44.85	1.75	289	276	109.36	-18.64	4.08
521	12501	523.96	-103.52	4.75	300	273	107.70	-8.73	4.18
14480	559	513.61	-439.85	3.63	525	325	106.08	-41.89	0.00
559	539	505.94	-335.18	1.01	525	325	106.08	-41.89	0.00
11582	506	503.41	-93.04	0.93	525	325	106.08	-41.89	0.00
582	289	502.40	65.26	2.64	525	325	106.08	-41.89	0.00
528	538	490.96	-27.69	3.03	58507	11500	105.60	-58.58	0.00
528	538	490.96	-27.74	3.03	58216	12201	105.30	0.61	0.00
12905	12901	480.21	8.03	1.79	56778	251	104.50	-1.72	0.00
500	505	478.55	-243.74	1.02	349	240	103.91	-60.55	0.18
500	505	478.55	-243.74	1.02	59521	11394	103.60	0.47	0.00
11246	346	471.60	-20.69	3.81	56766	12321	103.10	2.48	0.00
549	540	470.94	98.58	0.34	284	272	101.25	26.05	0.50
290	244	468.87	-27.48	21.37	56455	251	101.00	-4.48	0.00
584	284	456.82	154.03	0.00	540	541	100.55	52.10	0.36
584	284	456.82	154.03	0.00	57740	290	100.00	9.10	0.00
59189	585	450.00	26.80	0.00	269	11563	99.75	-32.22	1.87
58144	220	450.00	-12.27	0.00	284	272	99.19	25.93	0.48
11149	573	449.30	-142.92	1.50	95	269	99.09	-3.48	1.28
544	70002	413.59	100.53	1.48	364	290	95.39	-16.99	1.14
70002	12999	412.11	48.46	0.00	349	240	94.35	-51.29	0.13
80	539	411.10	-112.98	1.41	200	273	93.74	-4.91	3.90
11500	521	403.28	73.92	2.68	218	325	92.90	-18.79	0.47
12902	12905	400.86	-226.03	1.81	537	70022	90.66	-429.36	2.60
21	506	399.00	-38.46	0.00	537	407	90.66	-429.36	2.60
12201	12501	396.40	-14.39	0.00	544	244	90.58	76.92	0.11
12201	12501	396.40	-14.39	0.00	385	11394	89.33	-17.02	0.66

12201	12501	396.40	-14.39	0.00	218	325	89.15	-10.79	0.44
584	279	391.24	69.43	2.70	222	221	88.36	-46.75	2.86
523	521	388.53	46.85	11.69	70022	407	88.06	-429.36	0.00
505	11582	377.44	-200.78	3.12	349	240	87.14	-44.40	0.10
505	11582	377.44	-200.78	3.12	237	11050	86.07	-17.54	4.10
11261	11561	376.20	-12.30	0.00	555	584	85.19	20.47	0.82
11261	11561	376.20	-12.30	0.00	244	240	85.14	-20.52	1.37
11261	11561	376.20	-12.30	0.00	532	332	85.08	64.25	0.05
12901	565	363.39	9.95	4.63	222	221	82.91	-16.33	2.62
56094	222	360.00	7.96	0.00	353	241	82.55	-27.31	0.47
582	472	359.33	-10.74	0.00	584	11594	82.33	-4.34	2.99
56477	11265	350.70	53.76	0.00	532	565	81.48	-199.76	0.18
56515	11265	350.50	67.13	0.00	11261	355	80.08	-7.57	1.71
56532	11265	350.10	57.07	0.00	260	241	76.42	-11.56	0.22
11010	11225	346.70	31.65	0.26	260	241	76.42	-11.56	0.22
523	525	340.90	57.05	9.05	326	365	76.23	-30.71	1.56
56749	11546	327.50	-124.12	0.00	251	290	75.44	-12.55	1.36
13008	564	320.70	60.59	0.00	251	290	75.44	-12.55	1.36
13016	564	320.70	20.09	0.00	584	289	74.14	-15.57	1.08
13003	564	320.70	53.86	0.00	218	326	74.02	-6.79	2.21
56478	11265	320.00	195.73	0.00	537	237	72.07	-73.03	0.00
160	353	308.20	26.58	0.63	500	540	70.02	-184.88	0.12
564	565	306.97	29.95	1.56	6	200	70.00	8.39	0.00
433	251	306.40	8.68	1.40	4	200	70.00	5.36	0.00
58048	582	304.90	25.02	0.00	5	200	70.00	5.45	0.00
355	555	299.76	-33.07	0.00	70001	528	67.07	-19.59	0.44
355	555	299.76	-33.07	0.00	365	70001	67.07	-15.00	0.00
355	555	299.76	-33.07	0.00	260	247	66.35	76.50	0.74
521	505	294.66	-116.15	2.16	70016	300	65.90	-22.20	0.05
12318	11560	290.73	81.54	1.07	28	70015	65.90	-23.50	0.00
11500	544	287.92	26.23	0.86	29	70016	65.90	-21.04	0.00
582	11612	283.82	32.90	12.43	70015	200	65.90	-24.68	0.06
56691	11246	279.60	37.70	0.00	472	272	62.00	0.39	1.21
56311	11265	277.20	37.81	0.00	540	240	61.91	81.22	0.00
12321	11246	275.42	-16.85	2.02	540	240	61.91	81.22	0.00
58272	12201	273.20	29.27	0.00	70007	523	61.85	-120.43	0.16
222	325	269.47	-7.59	7.49	11265	70007	61.85	-118.92	0.00
59130	11560	265.30	-17.50	0.00	70007	523	61.85	-120.43	0.16
70023	537	263.80	497.74	4.34	11265	70007	61.85	-118.92	0.00
453	70023	263.80	472.74	0.00	222	221	61.74	-28.68	1.54
525	11525	262.44	-238.35	0.50	353	542	60.94	-5.47	0.05
59204	11260	257.30	15.01	0.00	70009	11612	60.11	-30.95	0.00
200	500	252.93	23.68	0.00	95	70009	60.11	-30.33	0.00
58786	12312	250.00	-105.10	0.00	218	325	59.48	-15.04	0.40
58315	12312	250.00	-142.29	0.00	585	385	58.58	-10.73	0.00
289	276	249.92	-6.53	9.80	585	385	58.58	-10.73	0.00

59076	355	249.80	24.50	0.00	585	385	58.58	-10.73	0.00
528	228	247.66	220.89	2.36	1	300	58.00	5.34	0.00
555	70003	246.54	41.72	1.11	289	288	57.65	8.84	0.00
70003	289	245.43	27.27	0.00	584	70004	56.14	5.78	0.81
58871	11261	237.30	13.92	0.00	846	387	55.33	5.21	0.94
58824	11261	236.50	8.81	0.00	70004	288	55.32	-6.84	0.00
585	587	235.43	-278.67	1.25	220	200	54.13	-30.10	0.64
58852	11261	234.80	4.58	0.00	276	269	53.70	-10.13	1.18
525	11525	234.23	-161.02	0.45	11612	11594	51.60	-21.16	0.11
58233	12201	231.60	10.70	0.00	9	200	51.00	12.01	0.00
541	241	226.96	120.43	0.00	7	200	51.00	12.47	0.00
582	584	226.44	14.46	3.81	8	200	51.00	12.52	0.00
59087	555	223.70	-95.13	0.00	326	526	50.50	-53.77	0.00
12321	523	221.43	-9.84	0.00	326	526	50.50	-53.77	0.00
12321	523	221.43	-9.84	0.00	529	329	50.16	-36.27	0.00
12321	523	221.43	-9.84	0.00	332	231	47.31	-14.42	0.48
206	506	218.43	14.77	0.00	549	566	46.57	-107.46	0.09
206	506	218.43	14.77	0.00	70012	846	46.56	-1.64	1.21
58832	11261	212.70	11.71	0.00	11050	70012	46.56	-0.64	0.00
339	218	209.00	32.91	0.00	539	239	43.40	-31.70	0.00
327	218	206.90	38.64	0.05	549	505	43.24	-183.16	0.03
472	272	203.93	-7.19	4.98	549	349	42.60	-200.24	0.00
273	258	200.94	-20.39	4.54	48	289	42.30	-11.45	0.05
70021	542	200.04	-47.16	2.22	542	573	41.92	-19.35	0.24
240	70021	200.04	-34.99	0.00	582	11594	40.25	4.45	1.91
541	241	197.22	104.65	0.00	220	221	39.17	3.18	0.25
541	241	197.22	104.65	0.00	525	521	38.00	-27.42	0.13
541	241	197.22	104.65	0.00	329	228	37.97	-18.86	0.51
542	259	195.76	24.21	0.41	329	228	37.90	-18.62	0.50
541	542	194.47	26.42	1.26	523	11525	36.99	5.13	0.95
161	353	193.50	8.91	0.36	549	505	36.42	-160.72	0.03
59002	203	190.30	-7.70	0.00	11246	11546	35.70	-20.56	0.00
537	12318	185.82	7.47	0.00	11246	11546	35.70	-20.56	0.00
224	222	184.78	-23.49	7.61	11246	11546	35.70	-20.56	0.00
34	505	183.70	-21.06	0.00	521	221	33.82	-16.15	0.00
33	505	183.70	-21.06	0.00	521	221	33.82	-16.15	0.00
565	231	181.83	-54.10	0.00	521	221	33.82	-16.15	0.00
565	231	181.83	-54.10	0.00	540	542	33.39	8.88	0.34
544	244	180.61	153.38	0.22	11265	224	32.98	-20.39	0.16
364	290	177.50	-22.79	1.53	11265	224	32.98	-20.39	0.16
56760	12321	176.50	5.63	0.00	539	239	32.60	-23.81	0.00
566	260	175.30	133.32	0.00	587	387	30.40	-30.86	0.00
566	260	175.30	133.32	0.00	587	387	30.40	-30.86	0.00
55813	11225	174.20	12.78	0.00	55412	326	28.92	-28.55	0.29
13033	564	172.50	-66.67	0.00	55412	326	28.92	-28.55	0.29

573	273	172.39	26.08	0.00	55412	326	28.92	-28.55	0.29
573	273	172.39	26.08	0.00	200	349	27.89	-14.62	0.28
573	273	172.39	26.08	0.00	240	241	26.52	-21.93	0.23
56285	224	170.70	2.68	0.00	300	349	25.78	-19.91	0.12
555	11612	168.80	16.69	6.37	500	540	25.40	-11.78	0.05
538	238	168.20	-32.87	0.00	582	555	24.73	-5.21	0.19
56622	523	168.20	-25.75	0.00	555	11594	24.19	2.14	1.00
13029	564	167.30	22.03	0.00	203	202	21.40	-14.68	0.18
203	11261	166.77	3.43	5.49					
11394	11594	164.61	-24.09	0.00					
11394	11594	164.61	-24.09	0.00					
11394	11594	164.61	-24.09	0.00					

Appendix B

This appendix presents the input data necessary for power flow analysis. The data are shown in Tables B.1 to B.8.

Table B.1: PV-type bus data with Hydroelectric Power Plants (HPPs).

Bus Number	Bus Name	Location (State)	Voltage base (kV)	Voltage (pu)	Active power generation (MW)	Reactive power (MVAr) – lower bound	Reactive power (MVAr) – upper bound
1	PAF1-1UHE013	Bahia	13.8	0.970	58.0	-9.0	12.0
4	PAF2A1UHE013	Bahia	13.8	0.974	70.0	-39.0	23.0
5	PAF2A2UHE013	Bahia	13.8	0.974	70.0	-39.0	23.0
6	PAF2A3UHE013	Bahia	13.8	0.978	70.0	-39.0	25.0
7	PAF2B1UHE013	Bahia	13.8	0.985	51.0	-67.0	54.0
8	PAF2B2UHE013	Bahia	13.8	0.988	51.0	-67.0	54.0
9	PAF2B3UHE013	Bahia	13.8	0.987	51.0	-67.0	54.0
10	PAF3-1UHE013	Bahia	13.8	0.993	151.0	-144.0	97.0
11	PAF3-2UHE013	Bahia	13.8	0.977	151.0	-144.0	97.0
14*	PAF4-1UHE013	Bahia	13.8	0.972	1397.6	-690.0	615.0
21	SOBRA1UHE013	Bahia	13.8	0.994	399.0	-204.0	291.0
28	ASALE1UHE013	Alagoas	13.8	0.988	65.9	-73.0	78.0
29	ASALE2UHE013	Alagoas	13.8	0.986	65.9	-73.0	78.0
33	LGONZ1UHE013	Pernambuco	13.8	1.038	183.7	-156.0	161.0
34	LGONZ2UHE013	Pernambuco	13.8	1.038	183.7	-156.0	161.0
48	PCAVA1UHE013	Bahia	13.8	1.000	42.3	-67.4	56.2
80	ESTREIUHE013	Maranhao	13.8	1.014	411.1	-286.0	285.5
89	XINGO1UHE013	Sergipe	13.8	0.981	1137.0	-880.0	750.0
95	ITAPE1UHE013	Bahia	13.8	0.992	159.2	-321.0	235.0
Total					**4760,0**		

*Bus 14 is the reference bus for the power flow.

Table B.2: PV-type bus data with Fossil Fuel (Thermal) Power Plants (TPPs).

Bus Number	Bus Name	Location (State)	Voltage base (kV)	Voltage (pu)	Active power generation (MW)	Reactive power (MVAr) – lower bound	Reactive power (MVAr) – upper bound
160	TERPEGUTE013	Pernambuco	13.8	1.013	308.2	-188.0	283.0
161	TERPEVUTE013	Pernambuco	13.8	1.009	193.5	-157.0	201.9
327	FORTAGUTE013	Ceara	13.8	1.006	207.0	-80.0	159.0
339	TERCEGUTE013	Ceara	13.8	1.002	209.0	-100.0	152.0
433	VDOACUUTE013	R. G. Norte	13.8	1.003	306.4	-101.0	215.0
11001	PPECE1UTE020	Ceara	20.0	1.004	684.0	-250.0	420.0
11010	PPECE2UTE020	Ceara	20.0	1.003	346.7	-125.0	210.0
11149	PSER1VUTE024	Sergipe	23.0	0.989	449.3	-370.0	451.0
11150	PSER1GUTE025	Sergipe	23.0	0.984	934.1	-927.0	1080.0
13003	MARA4GUTE013	Maranhao	13.8	1.012	320.7	-94.0	218.0

13008	MARA5GUTE013	Maranhao	13.8	1.011	320.7	-94.0	218.0
13016	MARA3GUTE013	Maranhao	13.8	1.000	320.7	-181.0	146.0
13022	MARA3VUTE013	Maranhao	13.8	0.993	164.5	-110.0	64.9
13029	N.VE.GUTE013	Maranhao	13.8	1.008	167.3	-50.4	112.4
13033	PARNAVUTE013	Maranhao	18.0	1.028	172.5	-120.0	120.0
Total					**5098,0**		

Table B.3: PV-type bus data with Wind Farms (WFs).

Bus Number	Bus Name	Location (State)	Voltage base (kV)	Voltage (pu)	Active power generation (MW)	Nominal power (MW)	Reactive power (MVAr) – lower bound	Reactive power (MVAr) – upper bound	Fixed shunt (MVAr) (-): inductive (+): capacitive
55443	ITAREM-CE034	Ceara	34.5	0.998	134.5	220.0	-58.0	58.0	50.0
55775	CFAISA-CE034	Ceara	34.5	0.997	126.4	210.0	-55.0	55.0	0.0
55813	SERROT-CE034	Ceara	34.5	0.997	174.2	280.0	-66.0	66.0	0.0
56285	AMAZB1-RN034	R. G. Norte	34.5	0.998	170.7	280.0	-52.0	52.0	30.0
56311	MEL2---RN034	R. G. Norte	34.5	1.000	277.2	470.0	-50.0	50.0	50.0
56455	ALEGRI-RN034	R. G. Norte	34.5	0.996	101.0	180.0	-30.0	30.0	0.0
56477	MEL1---RN034	R. G. Norte	34.5	1.000	350.7	420.0	-100.0	100.0	150.0
56515	VSTERZ-RN034	R. G. Norte	34.5	0.999	350.5	420.0	-70.0	70.0	150.0
56532	VSRICA-RN034	R. G. Norte	34.5	0.999	350.1	420.0	-100.0	100.0	150.0
56574	SCLARA-RN034	R. G. Norte	34.5	0.998	150.4	250.0	-50.0	50.0	0.0
56606	ASABRA-RN034	R. G. Norte	34.5	0.997	161.3	250.0	-50.0	50.0	-20.0
56622	C.PRE2-RN034	R. G. Norte	34.5	0.999	168.2	310.0	-25.0	25.0	0.0
56691	CUTIA--RN034	R. G. Norte	34.5	0.998	279.6	380.0	-90.0	90.0	22.0
56699	CUMARU-RN034	R. G. Norte	34.5	0.998	134.7	220.0	-50.0	50.0	0.0
56720	CPFL---RN034	R. G. Norte	34.5	0.998	147.6	250.0	-50.0	50.0	0.0
56731	JERUSA-RN034	R. G. Norte	34.5	1.000	128.2	220.0	-50.0	50.0	-20.0
56749	RIOVT2-RN034	R. G. Norte	34.5	1.000	327.5	390.0	-90.0	90.0	-80.0
56755	ARIZON-BA034	Bahia	34.5	1.000	153.1	240.0	-60.0	60.0	-160.0
56760	MRONCA-RN034	R. G. Norte	34.5	0.998	176.5	280.0	-70.0	70.0	0.0
56766	ANGICO-RN034	R. G. Norte	34.5	0.997	103.1	180.0	-50.0	50.0	0.0
56778	MACAU--RN034	R. G. Norte	34.5	0.998	104.5	180.0	-50.0	50.0	0.0
57740	SRMNOV-RN034	R. G. Norte	34.5	0.998	100.0	170.0	-50.0	50.0	15.0
58007	CAETE2-PE034	Pernambuco	34.5	0.998	112.5	200.0	-55.0	55.0	-12.0
58027	SCLEME-PE034	Pernambuco	34.5	0.998	151.8	240.0	-60.0	60.0	0.0
58048	TUCANO-BA034	Bahia	34.5	1.000	304.9	460.0	-80.0	80.0	0.0
58160	LABAR1-PI034	Piaui	34.5	0.998	128.4	250.0	-60.0	60.0	0.0
58194	LGVN-A-PI034	Piaui	34.5	1.000	147.2	270.0	-60.0	60.0	-50.0
58196	LGVN-B-PI034	Piaui	34.5	1.000	144.0	270.0	-60.0	60.0	-50.0
58197	LGVN-C-PI034	Piaui	34.5	0.998	159.2	250.0	-60.0	60.0	-30.0
58207	CHAPA1-PI034	Piaui	34.5	0.997	111.1	210.0	-50.0	60.0	-10.0
58216	CHAPA2-PI034	Piaui	34.5	0.998	105.3	220.0	-50.0	50.0	-10.0
58226	CHAPA3-PI03	Piaui	34.5	0.998	129.3	220.0	-60.0	60.0	-10.0
58233	CHAPA4-PI03	Piaui	34.5	0.988	231.6	360.0	-100.0	100.0	-10.0
58239	VEDPI2-PI034	Piaui	34.5	0.998	135.3	230.0	-60.0	60.0	-10.0

58249	CDNHA1-PI034	Piaui	34.5	0.999	135.3	230.0	-50.0	50.0	0.0
58272	SBASIL-PI034	Piaui	34.5	0.997	273.2	350.0	-100.0	100.0	15.0
58289	NORTE--PB034	Paraiba	34.5	0.997	118.6	200.0	-50.0	50.0	-20.0
58294	VEDPI3-PI034	Piaui	34.5	0.998	132.2	220.0	-50.0	50.0	0.0
58296	SUL2---PB034	Paraiba	34.5	0.997	126.8	210.0	-50.0	50.0	-20.0
58315	OITIS--PI034	Piaui	34.5	0.999	250.0	390.0	-100.0	100.0	-150.0
58507	SSERID-PB034	Paraiba	34.5	1.008	105.6	180.0	-50.0	180.0	-60.0
58513	SSER1A-PB034	Paraiba	34.5	1.000	135.1	220.0	-60.0	60.0	-50.0
58514	OESRDO-RN034	R. G. Norte	34.5	0.999	113.3	190.0	-50.0	50.0	-50.0
58624	DELFIN-BA034	Bahia	34.5	0.999	112.2	190.0	-50.0	50.0	0.0
58786	LGVEN3-PI034	Piaui	34.5	0.999	250.0	400.0	-100.0	100.0	-100.0
58806	C.FORM-BA034	Bahia	34.5	0.998	115.4	210.0	-60.0	60.0	0.0
58824	UMBURA-BA034	Bahia	34.5	0.998	236.5	350.0	-100.0	100.0	0.0
58832	C.LAR1-BA034	Bahia	34.5	0.998	212.7	350.0	-100.0	100.0	0.0
58852	BABILS-BA034	Bahia	34.5	0.998	234.8	300.0	-100.0	100.0	-11.0
58871	C.LAR2-BA034	Bahia	34.5	0.999	237.3	360.0	-100.0	100.0	0.0
59002	FLARG2-BA034	Bahia	34.5	0.998	190.3	300.0	-50.0	50.0	17.0
59057	MCHAPS-BA034	Bahia	34.5	0.997	113.2	210.0	-50.0	50.0	0.0
59076	SBABIL-BA034	Bahia	34.5	0.997	249.8	380.0	-100.0	100.0	0.0
59087	MCHAS2-BA034	Bahia	34.5	1.000	223.7	340.0	-100.0	100.0	-110.0
59130	VSEUGE-BA034	Bahia	34.5	0.999	265.3	400.0	-120.0	120.0	-50.0
59204	VSVTR--BA034	Bahia	34.5	0.998	257.3	400.0	-120.0	120.0	0.0
59316	ARACAS-BA034	Bahia	34.5	0.998	112.6	220.0	-50.0	50.0	0.0
59512	VBAHI3-BA034	Bahia	34.5	0.998	136.9	250.0	-51.0	51.0	0.0
59521	AURA---BA034	Bahia	34.5	0.998	103.6	180.0	-50.0	50.0	0.0
59524	CAETNO-BA034	Bahia	34.5	0.998	111.2	200.0	-50.0	50.0	0.0
Total					**10580.0**				

Table B.4: PV-type bus data with Solar Photovoltaic Plants (SPPs).

Bus Number	**Bus Name**	**Location (State)**	**Voltage base (kV)**	**Voltage (pu)**	**Active power generation (MW)**	**Nominal power (MW)**	**Reactive power (MVAr) – lower bound**	**Reactive power (MVAr) – upper bound**	**Fixed shunt (MVAr) (-): inductive (+): capacitive**
55765	DNPARA-CE034	Ceara	34.5	1.012	124.0	300.0	-22.0	22.0	30.0
56094	ALEX---CE034	Ceara	34.5	1.000	360.0	500.0	-36.0	36.0	20.0
56478	MEL2---RN034	R. G. do Norte	34.5	1.000	320.0	400.0	-52.0	52.0	300.0
58144	BLMNTE-PE034	Pernambuco	34.5	1.004	450.0	550.0	-45.0	45.0	0.0
58690	FUTURA-BA034	Bahia	34.5	1.006	837.0	950.0	-83.0	83.0	200.0
59176	SGONCA-PI034	Piaui	34.5	1.004	865.0	950.0	-85.0	85.0	180.0
59189	SDSER3-BA034	Bahia	34.5	1.001	450.0	550.0	-65.0	65.0	50.0
Total					**3406.0**				

Table A.5: PV-type bus data for buses that represent the behavior of the external system.

Bus Number	**Bus Name**	**Location (State)**	**Voltage base (kV)**	**Voltage (pu)**	**Active power generation (MW)**	**Reactive power (MVAr)**	**Reactive power (MVAr)**	**Active power**	**Reactive power**	**Fixed shunt (MVAr)**

					(-): consumption (+): generation	– lower bound	– upper bound	demand (MW) (+): consumption (-): generation	demand (MVAr) (+): inductive (-): capacitive	(-): inductive (+): capacitive
407	RG-CO1CAP500	Piaui	500	1.022	-900.0	-9999.0	9999.0	756.3	-123.0	500.0
453	RG-CO2CAP500	Piaui	500	1.021	-800.0	-9999.0	9999.0	734.0	-153.0	500.0
539	IMPERA-MA500	Maranhao	500	1.067	-600.0	-9999.0	9999.0	86.7	0.0	200.0
585	BJLAP2-BA500	Bahia	500	1.034	-1200.0	-9999.0	9999.0	0.0	103.7	0.0
587	R.EGUA-BA500	Bahia	500	1.036	-1200.0	-9999.0	9999.0	53.9	-15.1	200.0
711	IM-CO1CAP500	Maranhao	500	1.015	-1100.0	-9999.0	9999.0	0.0	0.0	200.0
715	IM-CO2CAP500	Maranhao	500	1.012	-1100.0	-9999.0	9999.0	0.0	0.0	200.0
857	RE-LUZCAP500	Bahia	500	1.028	-1700.0	-9999.0	9999.0	0.0	0.0	0.0
11563	M.NETO-BA500	Bahia	500	1.031	-956.0	-9999.0	9999.0	37.6	0.0	0.0
11594	IGAPO3-BA500	Bahia	500	1.037	-1888.0	-9999.0	9999.0	0.0	0.0	100.0
11612	POCOE3-BA500	Bahia	500	1.029	-1952.0	-9999.0	9999.0	57.6	0.0	130.0

Table B.6: PQ-type bus data.

Bus Number	Bus Name	Location (State)	Voltage base (kV)	Active power demand (MW) (+): consumption (-): generation	Reactive power demand (MVAr) (+): inductive (-): capacitive	Fixed shunt (MVAr) (-): inductive (+): capacitive
200	PAF3-A-BA230	Bahia	230	101.3	65.2	130.0
202	JUAZE2-BA230	Bahia	230	180.8	80.9	0.0
203	S.BONF-BA230	Bahia	230	-19.1	0.0	0.0
206	SOBRAD-BA230	Bahia	230	-218.0	0.0	-80.0
218	CAUIPE-CE230	Ceara	230	100.3	77.0	0.0
220	BOM-NO-PE230	Pernambuco	230	245.6	49.1	105.0
221	MILAGR-CE230	Ceara	230	476.6	15.0	50.0
222	BANABU-CE230	Ceara	230	143.8	-20.5	0.0
224	MOSSR2-RN230	R. G. Norte	230	-53.0	0.0	0.0
228	TERES--PI230	Piaui	230	463.0	107.00	-80.0
231	MIRAND-MA230	Maranhao	230	410.5	-127.00	0.0
237	S.J.PI-PI230	Piaui	230	114.4	23.10	90.0
238	P.DUTR-MA230	Maranhao	230	168.2	-39.00	0.0
239	IMPERA-MA230	Maranhao	230	76.0	-56.00	0.0
240	ANGELI-PE230	Pernambuco	230	390.5	-59.00	0.0
241	RECIFE-PE230	Pernambuco	230	714.8	183.0	0.0
244	CGRD2B-PB230	Paraiba	230	300.7	152.0	0.0
247	GOIANI-PE230	Pernambuco	230	217.9	222.0	0.0
250	MIRUEI-PE230	Pernambuco	230	347.5	114.2	0.0
251	AÇU2---RN230	R. G. Norte	230	-101.0	0.0	0.0
258	PENEDO-AL230	Alagoas	230	196.4	18.10	60.0
259	MACEIO-AL230	Alagoas	230	322.5	-27.0	0.0
260	PAU-FE-PE230	Pernambuco	230	426.9	151.2	66.0
269	EUNAPO-BA230	Bahia	230	174.1	39.0	0.0
272	CATU---BA230	Bahia	230	459.2	17.0	0.0
273	JARDIM-SE230	Sergipe	230	509.6	114.8	80.0
276	FUNIL--BA230	Bahia	230	291.7	-54.0	0.0

279	COTEGI-BA230	Bahia	230	661.3	152.0	0.0
284	CAMAC4-BA230	Bahia	230	438.6	84.0	0.0
288	IBICOA-BA230	Bahia	230	94.9	44.0	0.0
289	SAPEAC-BA230	Bahia	230	393.8	-177.0	0.0
290	PARAIS-RN230	R. G. Norte	230	49.5	11.1	0.0
300	PAF3-B-BA230	Bahia	230	136.2	34.5	96.0
325	FORTA2-CE230	Ceara	230	926.5	-242.0	0.0
326	SOBRA3-CE230	Ceara	230	-19.5	0.0	-77.0
329	BESPER-MA230	Maranhao	230	-25.7	0.0	0.0
332	SLUIS2-MA230	Maranhao	230	475.3	417.9	0.0
346	NATAL3-RN230	R. G. Norte	230	323.3	40.9	90.0
349	GARANH-PE230	Pernambuco	230	-34.8	0.0	-55.0
353	SUAPE2-PE230	Pernambuco	230	337.8	-35.0	-200.0
355	MCHAP2-BA230	Bahia	230	-321.0	0.0	-45.0
364	LNOVA2-RN230	R. G. Norte	230	-257.0	0.0	-55.0
365	IBIAP2-CE230	Ceara	230	-15.8	0.0	-110.0
385	BJLAP2-BA230	Bahia	230	86.4	-18.0	0.0
387	REGUA--BA230	Bahia	230	115.2	-64.0	0.0
472	OLINDI-BA230	Bahia	230	93.4	16.3	65.0
500	PAF4---BA500	Bahia	500	-4.3	0.0	100.0
505	L.GONZ-PE500	Pernambuco	500	-5.8	0.0	-150.0
506	SOBRAD-BA500	Bahia	500	23.7	126.8	0.0
521	MILAGR-CE500	Ceara	500	146.9	-80.0	0.0
523	JCMR3--RN500	R. G. Norte	500	-1012.0	0.0	250.0
525	FORTA2-CE500	Ceara	500	190.8	228.0	-150.0
526	SOBRA3-CE500	Ceara	500	0.0	0.0	-100.0
528	TERES2-PI500	Piaui	500	125.0	0.0	50.0
529	BESPER-MA500	Maranhao	500	26.3	59.6	-100.0
532	SLUIS2-MA500	Maranhao	500	6.9	51.0	50.0
537	S.J.PI-PI500	Piaui	500	-1538.0	0.0	-620.0
538	P.DUTR-MA500	Maranhao	500	-159.0	0.0	0.0
540	ANGEL2-PE500	Pernambuco	500	5.8	0.4	-150.0
541	RECIFE-PE500	Pernambuco	500	-0.9	0.0	460.0
542	MESSIA-AL500	Alagoas	500	391.1	-40.0	0.0
544	CGRD3--PB500	Paraiba	500	-10.9	0.0	-550.0
549	GARANH-PE500	Pernambuco	500	0.0	0.0	-450.0
555	MCHAP2-BA500	Bahia	500	-5.4	0.0	80.0
559	ACAILA-MA500	Maranhao	500	862.5	130.0	0.0
564	SALOPE-MA500	Maranhao	500	-141.0	0.0	-90.0
565	MIRAND-MA500	Maranhao	500	-278.0	0.0	-320.0
566	PAU-FE-PE500	Pernambuco	500	0.0	0.0	-280.0
573	JARDIM-SE500	Sergipe	500	-94.6	0.0	1060.0
582	OLINDI-BA500	Bahia	500	-72.4	0.0	400.0
584	CAMAC4-BA500	Bahia	500	349.0	100.0	530.0
736	IP2TCS-MA500	Maranhao	500	0.0	0.0	0.0
846	BARRER-BA500	Bahia	500	105.6	535.0	-150.0
11050	B.JESU-PI230	Piaui	230	35.4	-40.0	0.0
11225	PECEM2-CE230	Ceara	230	-235.0	0.0	-70.0

11246	CMRIM2-RN230	R. G. Norte	230	-138.0	0.0	0.0
11260	GOURO2-BA230	Bahia	230	-39.2	0.0	0.0
11261	OUROL2-BA230	Bahia	230	-10.7	0.0	90.0
11265	AÇU3---RN230	R. G. Norte	230	-94.3	0.0	0.0
11394	IGAPO3-BA230	Bahia	230	-407.0	0.0	-60.0
11500	SLUZI2-PB500	Paraiba	500	-91.8	0.0	400.0
11525	PECEM2-CE500	Ceara	500	-25.3	0.0	-90.0
11546	CMRIM2-RN500	R. G. Norte	500	-48.1	0.0	400.0
11560	GOURO2-BA500	Bahia	500	-60.1	0.0	-150.0
11561	OUROL2-BA500	Bahia	500	-106.0	0.0	-250.0
11582	JUAZE3-BA500	Bahia	500	-15.2	0.0	-150.0
12201	CNOVO2-PI230	Piaui	230	64.7	0.0	100.0
12312	QNOVA2-PI500	Piaui	500	-94.3	0.0	-490.0
12318	BURITI-BA500	Bahia	500	26.7	0.0	180.0
12321	JCMR3--RN230	R. G. Norte	230	-375.0	0.0	0.0
12501	CNOVO2-PI500	Piaui	500	-38.1	0.0	0.0
12901	PARNAI-PI500	Piaui	500	-68.9	0.0	0.0
12902	ACARA3-CE500	Ceara	500	-29.0	0.0	-90.0
12905	TIANG2-CE500	Ceara	500	-31.1	0.0	-400.0
12999	JPSII--PB230	Paraiba	230	420.1	168.8	200.0
14480	S.LUZ3-MA500	Maranhao	500	159.6	-14.0	-601.0
55412	ACARA2-CE230	Ceara	230	-80.7	0.0	-240.0
70001	FICT01	Ceara	500	0.0	0.0	0.0
70002	FICT02	Paraíba	500	0.0	0.0	0.0
70003	FICT03	Bahia	500	0.0	0.0	0.0
70004	FICT04	Bahia	500	0.0	0.0	0.0
70005	FICT05	Bahia	500	0.0	0.0	0.0
70006	FICT06	R. G. Norte	500	0.0	0.0	0.0
70007	FICT07	R. G. Norte	500	0.0	0.0	0.0
70008	FICT08	R. G. Norte	500	0.0	0.0	0.0
70009	FICT09	Bahia	500	0.0	0.0	0.0
70010	FICT10	Bahia	500	0.0	0.0	0.0
70011	FICT11	Bahia	500	0.0	0.0	0.0
70012	FICT12	Bahia	500	0.0	0.0	0.0
70014	FICT14	Bahia	500	0.0	0.0	0.0
70015	FICT15	Alagoas	230	0.0	0.0	0.0
70016	FICT16	Bahia	230	0.0	0.0	0.0
70018	FICT18	Bahia	500	0.0	0.0	0.0
70019	FICT19	Sergipe	230	0.0	0.0	0.0
70021	FICT21	Pernambuco	230	0.0	0.0	0.0
70022	FICT22	Piauí	230	0.0	0.0	0.0
70023	FICT23	Piauí	230	0.0	0.0	0.0

Table A.6: Transmission lines and transformers data for load flow analysis (100 MVA Base).

L: Line T: Transformer	Bus Number (from)	Bus Number (to)	Circuit number	Resistance (%)	Inductance (%)	Capacitance (MVAr)	Tap
T	28	70015	1	0.00	2.35	0.00	1.00
T	29	70016	1	0.00	2.35	0.00	1.00
T	33	505	1	0.00	4.04	0.00	1.00
T	34	505	1	0.00	4.04	0.00	1.00
T	48	289	1	0.25	11.10	0.00	1.00
T	80	539	1	0.08	3.95	0.00	1.00
T	89	70019	1	0.00	2.00	0.00	1.00
L	70019	500	1	0.00	0.52	0.00	--
T	95	269	1	1.28	13.82	0.00	1.00
T	95	70009	1	0.00	1.35	0.00	1.00
T	104	260	1	0.01	4.83	0.00	1.00
T	160	353	1	0.07	3.60	0.00	1.00
T	161	353	1	0.10	5.15	0.00	1.00
T	170	284	1	0.20	9.37	0.00	1.00
T	170	70018	1	0.00	1.41	0.00	1.00
T	200	4	1	0.00	13.48	0.00	1.05
T	200	5	1	0.00	14.22	0.00	1.05
T	200	6	1	0.00	19.91	0.00	1.05
T	200	7	1	0.00	12.40	0.00	1.05
T	200	8	1	0.00	15.78	0.00	1.05
T	200	9	1	0.00	15.52	0.00	1.05
T	200	10	1	0.00	5.55	0.00	1.00
L	200	220	1	2.31	9.19	53.16	--
L	200	273	1	4.60	23.58	0.00	--
L	200	300	2	0.19	0.99	0.00	--
L	200	349	1	3.68	20.07	34.32	--
T	200	500	1	0.00	1.41	0.00	0.97
L	202	203	1	2.70	13.90	26.26	--
L	202	203	2	2.74	13.72	0.00	--
T	202	58624	1	1.77	15.47	0.00	1.00
T	202	70014	1	0.07	0.49	0.00	--
L	203	11261	1	11.04	34.77	0.00	--
T	203	59002	1	0.00	8.66	0.00	1.00
L	206	202	1	0.78	4.00	7.50	--
L	206	202	2	0.78	4.00	7.50	--
T	206	506	1	0.00	3.56	0.00	0.97
T	206	506	2	0.00	3.56	0.00	0.97
L	218	325	4	0.54	3.88	0.00	--
L	325	218	1	0.53	3.72	14.68	--
L	325	218	3	1.08	5.73	9.98	--
L	218	326	1	3.94	21.08	0.00	--
T	218	327	1	0.01	4.41	0.00	1.00

T	218	339	1	0.00	5.98	0.00	1.00
L	220	221	1	1.61	8.07	14.56	--
L	220	221	2	0.72	2.85	0.00	--
L	221	222	1	4.04	21.81	38.24	--
L	221	222	2	3.59	14.93	56.46	--
L	221	222	3	3.74	15.95	0.00	--
T	221	521	1	0.00	1.27	0.00	1.01
T	221	521	2	0.00	1.27	0.00	1.01
T	221	521	3	0.00	1.27	0.00	1.01
L	222	224	1	3.21	16.54	31.34	--
L	222	224	2	2.24	10.04	0.00	--
L	222	325	1	1.05	4.42	0.00	--
L	224	11265	3	3.33	51.99	0.00	--
L	224	11265	4	4.52	48.30	0.00	--
T	224	56285	1	0.73	14.22	0.00	1.00
L	228	365	1	2.75	13.28	0.00	--
T	228	528	1	0.24	2.17	0.00	1.00
T	237	537	1	0.00	3.48	0.00	0.93
L	237	11050	1	5.32	29.95	0.00	--
T	237	58160	1	0.06	4.75	0.00	1.00
T	238	538	1	0.00	2.33	0.00	0.95
T	239	539	1	0.00	1.10	0.00	0.96
T	239	539	2	0.00	1.46	0.00	0.96
L	240	241	2	3.09	16.15	29.48	--
L	240	244	1	1.51	8.00	0.00	--
L	240	244	2	1.75	12.38	0.00	--
L	240	259	1	2.23	8.09	0.00	--
T	240	540	1	0.00	1.78	0.00	1.00
T	240	540	2	0.00	1.78	0.00	1.00
T	240	70021	1	0.00	3.00	0.00	1.00
L	70021	542	1	0.55	1.25	0.00	
L	241	247	1	1.31	6.79	12.27	--
L	241	247	2	1.31	6.79	12.27	--
L	241	250	1	0.58	3.09	5.30	--
L	241	250	2	0.58	3.10	5.34	--
L	241	250	3	0.58	2.96	5.54	--
L	241	260	1	0.39	2.80	10.42	--
L	241	260	2	0.39	2.80	10.42	--
L	241	353	1	0.64	3.44	0.00	--
T	241	541	1	0.00	1.40	0.00	1.01
T	241	541	2	0.00	1.40	0.00	1.01
T	241	541	3	0.00	1.40	0.00	1.01
T	241	541	4	0.00	1.22	0.00	1.01
L	244	247	1	1.82	9.70	0.00	--
L	244	260	1	1.22	8.63	0.00	--
L	244	260	2	1.15	8.40	0.00	--

L	244	290	1	0.96	4.97	0.00	--
L	244	346	1	2.09	12.45	0.00	--
T	244	544	1	0.04	2.01	0.00	1.00
T	244	544	2	0.08	4.01	0.00	1.00
L	244	11246	1	2.98	22.46	0.00	--
L	247	12999	1	0.86	4.43	8.05	--
L	247	12999	2	0.86	4.43	8.05	--
T	251	433	1	0.15	5.28	0.00	1.00
L	251	11265	1	0.25	1.27	2.21	--
L	251	11265	2	0.25	1.27	2.21	--
L	251	11265	3	0.25	1.27	2.21	--
T	251	56455	1	2.33	14.80	0.00	1.00
T	251	56778	1	0.60	11.23	0.00	1.00
L	258	273	1	1.14	5.66	0.00	--
T	259	542	1	0.11	1.39	0.00	1.00
L	260	247	1	0.69	3.78	8.29	--
L	269	276	3	3.93	12.71	0.00	--
L	269	11612	1	0.69	6.25	0.00	--
L	269	11513	1	1.68	13.63	0.00	--
L	272	284	1	0.46	2.45	4.26	--
L	272	284	2	0.46	2.50	4.14	--
L	272	472	1	3.19	19.34	0.00	--
L	272	472	2	1.21	5.83	0.00	--
L	273	300	1	3.69	18.96	0.00	--
T	273	573	1	0.00	1.27	0.00	0.99
T	273	573	2	0.00	1.27	0.00	0.99
T	273	573	3	0.00	1.27	0.00	0.99
L	276	289	2	1.61	8.23	0.00	--
L	279	284	2	0.40	2.01	0.00	--
T	279	584	1	0.17	2.03	0.00	1.00
L	284	279	1	0.42	2.25	3.88	--
L	288	289	1	0.00	35.07	0.00	--
T	288	70004	1	0.00	11.436	0.00	1.00
L	70004	584	1	2.57	40.00	0.00	--
T	288	70005	1	0.00	6.92	0.00	1.00
L	70005	11594	1	0.90	20.00	0.00	--
T	288	70011	1	0.00	2.00	0.00	1.00
L	70011	11612	1	0.11	4.11	0.00	--
L	289	276	1	3.50	18.84	32.76	--
T	289	70003	1	0.00	5.00	0.00	1.00
L	70003	555	1	0.19	2.46	0.00	--
T	289	582	1	0.11	5.27	0.00	1.00
L	289	584	1	1.90	11.77	0.00	--
L	289	584	2	0.06	1.67	0.00	--
T	289	70010	1	0.00	0.62	0.00	1.00

L	290	251	2	2.43	12.53	23.24	--
L	290	251	3	2.43	12.53	23.24	--
T	290	57740	1	1.55	26.66	0.00	1.00
T	300	1	1	0.00	21.12	0.00	1.05
T	300	11	1	0.00	6.02	0.00	1.05
L	300	349	1	3.68	20.07	34.32	--
L	300	349	2	1.82	15.63	46.38	--
T	300	500	1	0.00	1.41	0.00	0.96
T	325	525	1	0.00	1.27	0.00	0.98
T	325	525	2	0.00	1.27	0.00	0.98
T	325	525	3	0.00	1.27	0.00	0.98
T	325	525	4	0.00	1.27	0.00	0.98
L	326	365	1	2.27	11.66	0.00	--
T	326	526	1	0.00	1.28	0.00	0.96
T	326	526	2	0.00	1.28	0.00	0.96
L	329	228	1	3.59	19.24	33.76	--
L	329	228	2	3.61	19.20	34.12	--
T	329	529	1	0.00	3.44	0.00	0.96
L	332	231	1	2.08	9.96	18.33	--
T	532	332	1	0.00	1.13	0.00	1.00
T	532	332	2	0.00	1.13	0.00	1.00
T	532	332	3	0.00	1.13	0.00	1.00
T	532	332	4	0.00	1.13	0.00	1.00
T	332	532	5	0.04	1.48	0.00	--
L	346	11246	1	0.17	1.52	0.00	--
L	349	240	1	0.12	0.82	2.96	--
L	349	240	2	0.11	0.58	3.98	--
L	349	240	3	0.10	0.90	2.69	--
L	349	240	4	0.13	0.73	3.60	--
T	349	549	1	0.00	2.23	0.00	0.94
T	349	58007	1	0.68	9.23	0.00	1.00
T	349	58027	1	0.89	11.25	0.00	1.00
T	353	541	1	0.02	1.44	0.00	1.00
T	353	542	1	0.14	11.81	0.00	1.00
T	355	555	1	0.00	1.56	0.00	0.98
T	355	555	2	0.00	1.56	0.00	0.98
T	355	555	3	0.00	1.56	0.00	0.98
L	355	11261	1	2.65	13.27	0.00	--
T	355	59057	1	0.21	8.07	0.00	1.00
T	355	59076	1	0.50	7.73	0.00	1.00
T	355	59512	1	0.46	10.16	0.00	1.00
L	364	290	1	0.48	3.55	23.40	--
L	364	290	2	1.23	6.52	12.04	--
T	365	70001	1	0.00	10.00	0.00	1.00
L	70001	528	1	0.95	13.92	0.00	--
L	365	12905	1	0.08	1.57	0.00	--

T	385	585	1	0.00	2.85	0.00	0.96
T	385	585	2	0.00	2.85	0.00	0.96
T	385	585	3	0.00	2.85	0.00	0.96
L	385	11394	1	0.79	8.30	0.00	--
T	387	846	1	3.22	20.48	0.00	1.00
L	407	70022	1	0.00	-0.87	0.00	--
L	70022	537	1	0.15	0.001	0.00	
L	407	537	2	0.23	0.06	0.00	
L	453	70023	1	0.00	-0.89	0.00	
L	70023	537	1	0.15	0.001	0.00	--
L	453	537	1	0.15	-0.89	0.00	--
L	453	537	2	0.24	0.06	0.00	--
T	500	14	1	0.00	0.89	0.00	1.05
L	500	505	1	0.04	0.47	46.42	--
L	500	505	2	0.04	0.47	46.42	--
L	500	540	1	0.22	2.79	284.68	--
L	500	540	2	0.75	7.61	0.00	--
L	500	542	1	0.79	8.38	0.00	--
L	500	573	1	0.28	2.97	0.00	--
L	500	582	1	0.21	2.69	0.00	--
L	505	521	1	0.22	2.73	0.00	--
L	505	549	1	0.28	2.79	291.87	--
L	505	549	2	0.15	2.35	335.55	--
L	505	582	1	0.31	3.10	318.94	--
T	506	21	1	0.00	1.90	0.00	1.05
L	506	537	1	0.09	0.38	0.00	--
L	506	11582	2	0.04	0.55	55.40	--
T	506	56755	1	0.00	3.30	0.00	1.00
L	521	523	1	0.82	8.76	0.00	--
L	521	525	1	0.60	6.26	0.00	--
L	521	525	2	2.44	28.80	0.00	--
L	70006	521	1	0.44	5.00	0.00	--
L	70006	521	2	0.44	5.00	0.00	--
T	11265	70006	1	0.00	1.00	0.00	1.00
T	11265	70006	2	0.00	1.00	0.00	1.00
L	521	11500	1	0.17	2.50	0.00	--
L	521	11525	1	21.84	286.15	0.00	--
L	521	12312	1	0.17	2.42	0.00	--
L	521	12501	1	0.17	2.57	0.00	--
L	523	525	1	0.82	9.14	0.00	--
T	11265	70007	1	0.00	0.85	0.00	1.00
T	11265	70007	2	0.00	0.85	0.00	1.00
L	523	70007	1	0.09	2.00	0.00	--
L	523	70007	2	0.09	2.00	0.00	--
L	523	11525	1	7.36	90.81	0.00	--

T	523	56606	1	0.00	8.31	0.00	1.00
T	523	56622	1	0.00	9.97	0.00	1.00
T	523	56720	1	0.00	10.69	0.00	1.00
T	523	56731	1	0.00	7.56	0.00	1.00
L	525	11525	3	0.06	0.88	0.00	--
L	526	11525	1	0.12	1.86	272.40	--
L	526	11525	2	0.12	1.86	275.08	--
L	528	12905	1	0.17	2.75	421.69	--
L	528	12905	2	0.18	2.88	441.19	--
L	529	537	1	0.22	0.90	0.00	--
L	529	538	1	0.20	2.61	263.28	--
L	532	565	4	0.04	0.64	0.00	--
L	532	12901	1	0.16	2.34	0.00	--
L	537	846	1	0.69	5.46	0.00	--
L	537	12318	1	0.00	14.20	0.00	--
L	537	12501	1	0.12	1.79	275.20	--
T	537	58194	1	0.00	8.96	0.00	1.00
T	537	58196	1	0.00	8.96	0.00	1.00
T	537	58197	1	0.00	10.48	0.00	1.00
L	538	528	1	0.14	2.23	27.48	--
L	538	528	2	0.14	2.23	27.58	--
L	538	539	1	0.15	0.92	0.00	--
L	538	559	1	0.25	1.87	0.00	--
L	538	564	1	0.06	0.70	68.95	--
L	538	565	2	0.13	2.07	300.00	--
L	540	541	1	0.17	2.15	218.68	--
L	540	541	2	0.31	3.13	0.00	--
L	540	542	1	3.13	31.11	0.00	--
L	540	566	1	0.31	3.04	320.02	--
L	540	573	1	1.12	11.03	0.00	--
L	541	542	1	0.35	3.67	0.00	--
L	541	566	1	0.14	1.33	136.79	--
L	542	573	1	1.18	12.14	0.00	--
L	544	566	1	0.09	1.36	197.36	--
L	544	11546	1	0.13	2.13	313.43	--
L	544	11546	2	0.13	2.13	313.43	--
T	70002	12999	1	0.00	1.68	0.00	1.00
L	544	70002	1	0.08	3.00	0.00	--
L	549	540	1	0.02	0.15	15.60	--
L	549	544	1	0.13	2.09	298.69	--
L	549	566	1	0.14	2.26	322.39	--
L	555	582	1	3.06	34.46	0.00	--
L	555	584	1	1.14	10.89	0.00	--
L	555	11594	1	17.96	175.92	0.00	--
L	555	11612	1	0.19	2.65	790.09	--
L	555	11612	2	2.36	23.66	0.00	--

T	555	59087	1	0.02	3.09	0.00	1.00
L	559	539	1	0.03	0.60	86.70	--
L	559	14480	1	0.12	1.91	419.38	--
L	564	565	1	0.15	1.94	190.89	--
T	564	13003	1	0.03	3.60	0.00	1.05
T	564	13016	1	0.00	3.55	0.00	1.05
T	564	13022	1	0.00	7.78	0.00	1.05
T	564	13029	1	0.00	7.78	0.00	1.05
T	565	231	1	0.00	2.67	0.00	1.07
T	565	231	2	0.00	2.67	0.00	1.07
L	565	532	3	0.07	1.27	130.80	0.00
L	565	12901	1	0.37	5.38	0.00	0.00
T	566	260	1	0.00	1.84	0.00	0.97
T	566	260	2	0.00	1.84	0.00	0.97
L	573	582	1	0.11	1.89	0.00	--
L	573	584	1	0.23	3.15	317.02	--
T	573	11149	1	0.07	2.84	0.00	1.00
T	573	11150	1	0.02	0.95	0.00	1.00
L	582	472	1	0.00	3.50	0.00	1.05
L	582	584	1	0.09	1.01	0.00	--
L	582	584	2	0.77	7.70	0.00	--
L	582	11594	1	12.05	124.28	0.00	--
L	582	11612	1	1.58	16.72	0.00	--
T	582	58048	1	0.03	2.45	0.00	1.00
T	584	284	1	0.00	1.17	0.00	1.00
T	584	284	2	0.00	1.17	0.00	1.00
L	584	11594	1	4.44	39.29	0.00	--
L	584	11612	1	0.58	5.29	0.00	--
L	585	11560	1	0.14	0.96	0.00	--
T	587	387	1	0.00	4.00	0.00	1.04
T	587	387	2	0.00	4.00	0.00	1.04
L	587	585	1	0.24	3.49	496.85	--
L	587	846	1	0.07	0.35	0.00	--
L	587	857	1	0.00	-0.87	0.00	--
L	711	539	1	0.00	-1.59	0.00	--
L	715	736	1	0.00	-0.95	0.00	--
L	736	539	1	0.00	-0.64	0.00	--
L	846	12318	1	0.11	1.58	453.21	--
L	846	12318	2	0.39	3.02	0.00	--
L	846	70012	1	6.06	30.00	0.00	--
T	11050	70012	1	0.00	4.99	0.00	1.00
T	11001	11225	1	0.01	1.93	0.00	1.00
T	11003	11225	1	0.01	2.30	0.00	1.00
T	11010	11225	1	0.02	3.85	0.00	1.00
T	11225	11525	1	0.00	0.83	0.00	0.98

T	11225	11525	2	0.00	0.83	0.00	0.98
T	11225	11525	3	0.00	0.83	0.00	0.98
T	11225	55775	1	1.20	12.42	0.00	1.00
T	11225	55813	1	0.51	9.67	0.00	1.00
T	11246	11546	1	0.00	2.97	0.00	1.00
T	11246	11546	2	0.00	2.97	0.00	1.00
T	11246	11546	3	0.00	2.97	0.00	1.00
L	11246	12321	1	0.27	2.69	0.00	--
T	11246	56691	1	0.71	9.94	0.00	1.00
T	11260	59204	1	0.58	6.00	0.00	1.00
T	11261	58806	1	2.52	10.73	0.00	1.00
T	11261	58824	1	0.18	5.78	0.00	1.00
T	11261	58832	1	0.55	7.62	0.00	1.00
T	11261	58852	1	0.28	4.86	0.00	1.00
T	11261	58871	1	0.48	6.67	0.00	1.00
L	11265	224	1	1.21	6.18	10.78	--
L	11265	224	2	1.21	6.18	10.78	--
L	11265	364	1	1.49	7.69	14.22	--
T	11265	56311	1	0.10	10.84	0.00	1.00
T	11265	56477	1	0.00	9.39	0.00	1.00
T	11265	56515	1	0.00	11.35	0.00	1.00
T	11265	56532	1	0.00	10.01	0.00	1.00
T	11265	70008	1	0.00	0.68	0.00	1.00
T	11265	70013	1	0.00	5.43	0.00	1.00
T	11394	59316	1	0.16	7.94	0.00	1.00
T	11394	59521	1	0.36	10.83	0.00	1.00
T	11394	59524	1	0.16	7.42	0.00	1.00
L	11500	544	1	0.09	1.31	203.06	--
T	11500	58289	1	0.62	10.31	0.00	1.00
T	11500	58296	1	0.47	10.87	0.00	1.00
T	11500	58507	1	0.05	5.38	0.00	1.00
T	11500	58513	1	0.05	5.38	0.00	1.00
T	11500	58514	1	0.05	5.56	0.00	1.00
L	11525	525	2	0.05	0.79	114.94	--
L	11546	523	1	0.04	0.69	99.30	--
L	11546	523	2	0.04	0.69	99.30	--
T	11546	56749	1	0.06	3.19	0.00	1.00
T	11560	11260	1	0.00	1.56	0.00	1.02
T	11560	11260	2	0.00	1.56	0.00	1.02
L	11560	11561	1	0.12	1.73	269.59	--
L	11560	12318	1	0.09	1.36	288.50	--
T	11560	59130	1	0.06	3.26	0.00	1.00
L	11561	555	1	0.08	1.15	177.18	--
T	11561	11261	1	0.00	1.56	0.00	1.03
T	11561	11261	2	0.00	1.56	0.00	1.03
T	11561	11261	3	0.00	1.56	0.00	1.03

L	11582	505	1	0.24	3.18	326.18	--
L	11582	505	2	0.24	3.18	326.18	--
L	11582	11561	1	0.12	1.98	289.80	--
L	11594	585	1	0.09	1.50	217.70	--
T	11594	11394	1	0.00	1.87	0.00	1.03
T	11594	11394	2	0.00	1.87	0.00	1.03
T	11594	11394	3	0.00	1.87	0.00	1.03
T	11594	11394	4	0.00	1.87	0.00	1.03
T	11594	11394	5	0.00	1.87	0.00	1.03
L	11594	11612	1	0.38	4.68	0.00	--
L	11612	11563	1	0.17	2.45	725.30	--
T	12201	12501	1	0.00	2.67	0.00	0.93
T	12201	12501	2	0.00	2.67	0.00	0.93
T	12201	12501	3	0.00	2.67	0.00	0.93
T	12201	58207	1	1.69	10.57	0.00	1.00
T	12201	58216	1	2.33	10.05	0.00	1.00
T	12201	58226	1	1.91	11.54	0.00	1.00
T	12201	58233	1	0.55	6.72	0.00	1.00
T	12201	58239	1	0.07	6.27	0.00	1.00
T	12201	58249	1	0.07	6.19	0.00	1.00
T	12201	58272	1	0.30	9.39	0.00	1.00
T	12201	58294	1	0.16	6.76	0.00	1.00
T	12312	58315	1	0.07	2.85	0.00	1.00
T	12312	58786	1	0.04	3.70	0.00	1.00
L	12318	12312	1	0.19	2.78	830.68	--
L	12318	12312	2	0.19	2.78	830.68	--
T	12321	523	1	0.00	1.55	0.00	0.93
T	12321	523	2	0.00	1.55	0.00	0.93
T	12321	523	3	0.00	1.55	0.00	0.93
T	12321	56574	1	0.00	11.83	0.00	1.00
T	12321	56699	1	0.00	8.75	0.00	1.00
T	12321	56760	1	0.00	5.80	0.00	1.00
T	12321	56766	1	0.00	10.16	0.00	1.00
L	12501	12312	1	0.06	0.88	249.52	--
L	12901	12902	1	0.14	1.95	0.00	--
L	12901	12905	1	0.08	1.14	175.57	--
L	12902	11525	1	0.11	1.64	254.96	--
T	12902	55412	1	0.00	3.64	0.00	1.00
L	12905	526	1	0.06	0.96	146.63	--
L	12905	526	2	0.07	1.11	170.65	--
L	12905	12902	1	0.11	1.60	248.46	--
T	13008	564	1	0.03	3.60	0.00	0.95
T	13033	564	1	0.04	3.09	0.00	1.00
L	14480	565	1	0.08	1.28	277.58	--
L	55412	326	1	2.13	8.66	15.51	--

L	55412	326	2	2.13	8.66	15.51	--
L	55412	326	3	2.13	8.66	15.51	--
T	55412	55443	1	0.00	5.92	0.00	1.00
T	56094	222	1	0.0	4.1916	0.00	0.9973
T	59176	537	1	0.0	5.1851	0.00	0.9504
T	58690	202	1	0.0	1.75	0.00	0.9537
T	59189	585	1	0.0	2.333	0.00	0.9671
T	58144	220	1	0.0	2.6666	0.00	0.985
T	56478	11265	1	0.0	1.6666	0.00	0.966
T	55765	11225	1	0.0	10.0	0.00	0.9958
L	70008	525	1	0.19	3.08	0.00	--
L	70009	11612	1	0.00	10.00	0.00	--
L	70010	11612	1	0.11	3.00	0.00	--
L	70013	11525	1	1.13	45.43	0.00	--
L	70014	11582	1	0.07	1.00	0.00	--
L	70015	200	1	0.11	10.00	0.00	--
L	70016	300	1	0.11	10.00	0.00	--
L	70018	279	1	0.25	14.00	0.00	--

Appendix C

This appendix presents the input data necessary for dynamic analysis. The generator models to represent the salient pole units and the round rotor units are shown in the block diagrams in Figures C.1 and C.2, respectively. The saturation curve model for the synchronous generators is shown in Figure C.3. The parameters for the models are presented in Tables C.1 to C.4.

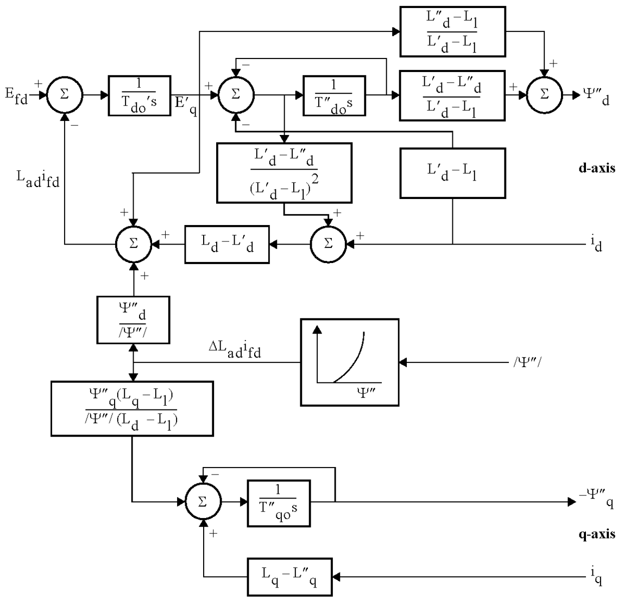

Figure C.1: Block Diagram for the Salient Pole Machine Model.

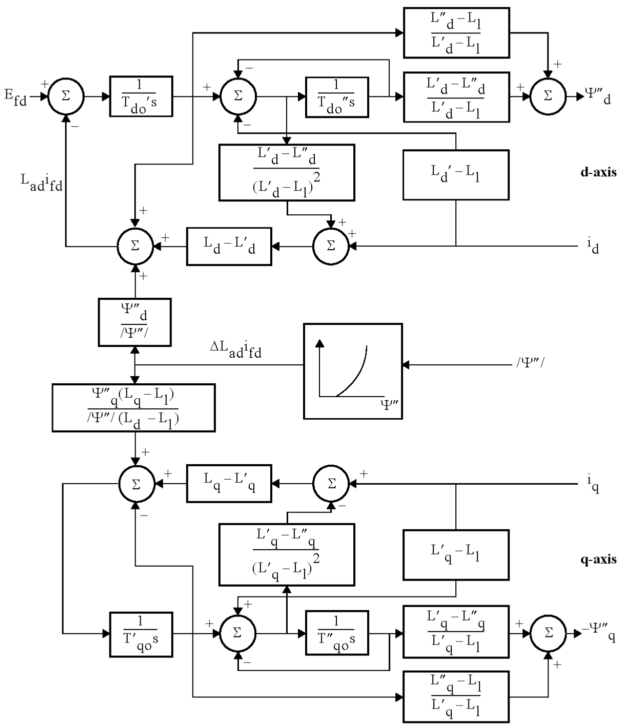

Figure C.2: Block Diagram for the Round Rotor machine model.

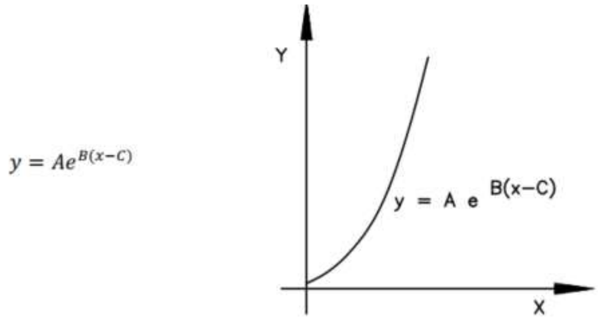

Figure C.3: Saturation curve model for synchronous generators.

Table C.1: Dynamic Model Data for the Salient Pole Units (Part 1).

Parameters			Buses Numbers / Units Names							
Description	Symbol	Unit	1 HPP Paulo Afonso I	4, 5, 6 HPP Paulo Afonso II-A	7, 8, 9 HPP Paulo Afonso II-B	10, 11 HPP Paulo Afonso III	14 HPP Paulo Afonso IV	28, 29 HPP Apolonio Sales	33 HPP Luiz Gonzaga	89 HPP Xingo
Rated apparent power	MBASE	MVA	61.2	69.52	80.0	209.0	456.0	122.0	274.0	520.0
d-axis open circuit transient time constant	T'_{do}	s	5.78	5.00	5.5	4.62	6.63	4.40	5.35	5.10
d-axis open circuit sub-transient time constant	T''_{do}	s	0.0305	.0352	0.04	0.0485	0.064	0.0435	0.044	0.06
q-axis open circuit sub-transient time constant	T''_{qo}	s	0.059	0.052	0.0786	0.0984	0.132	0.1055	0.089	0.094
Inertia	H	MW.s/ MVA	6.69	5.91	5.42	4.95	4.46	4.05	3.85	4.5
Speed damping	D	pu	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
d-axis synchronous reactance	X_d	pu*100	54	58.2	83.44	90.0	86.64	76.5	98.0	95.0
q-axis synchronous reactance	X_q	pu*100	39.2	42.0	55.0	57.0	66.58	54.5	55.9	66.0
d-axis transient reactance	X'_d	pu*100	20.4	28.45	28.0	24.81	25.99	22.5	29.0	36.0
sub-transient reactance	$X''_d = X''_q$	pu*100	20.0	24.25	21.0	17.39	23.26	15.5	26.0	29.0
Leakage reactance	X_ℓ	pu*100	0.1775	21.55	18.8	11.0	20.52	13.42	15.	28.0
Armature resistance	Ra	pu*100	2.056	0.625	0.700	0.369	0.2	0.3	0.2	0.19
Saturation curve	A	–	0.0267	0.0267	0.00227	0.053094	0.0377	–	0.0195	0.029406
Saturation curve	B	–	7.25	6.609	11.20	5.576756	6.600	–	7.465	5.42112
Saturation curve	C	–	0.80	0.80	0.80	0.80	0.80	–	0.80	0.80

Table C.2: Dynamic Model Data for the Salient Pole Units (Part 2).

Parameters			Buses Numbers / Units Names					
Description	Symbol	Unit	**1** HPP Sobradinho	**48** HPP Pedra do Cavalo	**80** HPP Estreito	**95** HPP Itapebi	**104** TPP Pernambuco III	**13029*** HPP Curua-Una
Rated apparent power	MBASE	MVA	194.5	90.0	151.8	160.0	11.03	10.84
d-axis open circuit transient time constant	T'_{do}	s	5.40	6.29	7.5	5.45	3.0	3.6
d-axis open circuit sub-transient time constant	T''_{do}	s	0.060	0.07	0.07	0.0305	0.0273	0.0256
q-axis open circuit sub-transient time constant	T''_{qo}	s	0.100	0.17	0.11	0.059	0.1197	0.03
Inertia	H	MW.s/ MVA	4.25	2.17	3.55	3.08	0.96	2.630
Speed damping	D	pu	1.0	1.0	1.0	1.0	1.0	1.0
d-axis synchronous reactance	X_d	pu*100	80.0	102.0	103.5	97.0	165.0	91.11
q-axis synchronous reactance	X_q	pu*100	55.0	67.0	69.6	65.0	82.0	63.0
d-axis transient reactance	X'_d	pu*100	32.0	32.0	35.3	30.0	34.0	32.0
sub-transient reactance	$X''_d = X''_q$	pu*100	23.0	28.0	30.1	22.0	24.9	25.0
Leakage reactance	X_ℓ	pu*100	13.0	18.0	14.0	15.0	14.9	13.0
Armature resistance	Ra	pu*100	0.2	0.0	0.0	0.317	0.0	0.661
Saturation curve	A	–	0.02473	.0252939	0.00608	0.0215323	0.0733	.0232474
Saturation curve	B	–	6.50956	7.541311	8.60332	9.352927	5.2203	4.377344
Saturation curve	C	–	0.80	0.8	0.8	0.8	0.8	0.55

*There are two power plants connected to bus 13029. The injected active and reactive powers from HPP Curua-Una correspond, respectively, to 4% and 3% of the total of power generated in this bus.

Table C.3: Dynamic Model Data for the Round Rotor Units (Part 1).

Parameters			Buses Numbers / Units Names							
Description	Symbol	Unit	**11010, 11001** TPP Porto de Pecem I and II	**13003, 13008, 13029*** TPP Mar. IV, V and Nova Venecia II	**160** TPP Termoper nambuco - gás	**161** TPP Termoper nambuco - vapor	**170** TPP Celso Furtado	**339** TPP Termoce ará	**433** TPP J. S. Pereira	**327** TPP Fortaleza

Rated apparent power	MBASE	MVA	435.0	208.0	211.7	284.6	300.0	71.18	204.4	131.6
d-axis open circuit transient time constant	T'_{do}	s	7.137	7.0	6.689	5.524	9.48	9.67	6.7	7.89
q-axis open circuit transient time constant	T'_{qo}	s	0.793	0.55	0.562	0.504	0.99	2.95	0.55	0.76
d-axis open circuit sub-transient time constant	T''_{do}	s	0.047	0.04	0.039	0.037	0.023	0.05	0.039	0.018
q-axis open circuit sub-transient time constant	T''_{qo}	s	0.067	0.081	0.081	0.074	0.035	0.05	0.081	0.027
Inertia	H	MW.s/ MVA	3.46	5.14	5.35	4.975	6.40	1.787	5.55	8.15
Speed damping	D	pu	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
d-axis synchronous reactance	X_d	pu*100	207.0	187.0	191.8	171.2	217.0	235.0	185.0	181.0
q-axis synchronous reactance	X_q	pu*100	204.2	177.0	182.5	165.2	205.0	215.0	176.0	168.0
d-axis transient reactance	X'_d	pu*100	42.12	23.5	23.5	24.7	22.3	24.5	22.50	18.3
q-axis transient reactance	X'_q	pu*100	58.74	42.5	43.2	44.5	36.0	35.0	42.00	30.0
sub-transient reactance	X''_d	pu*100	31.78	17.5	17.8	19.4	16.9	18.1	17.00	13.8
Leakage reactance	X_ℓ	pu*100	26.23	13.0	13.5	14.7	15.0	15.0	15.0	12.0
Armature resistance	Ra	pu*100	0 .265	0.26	0.1617	0.1384	0.0775	0.0	0.27	0.0
Saturation curve	A	–	0.028310	0.0047	0.0074	0.0084	0.04525	0.00159	0.04525	0.0153636
Saturation curve	B	–	6.56520	12.1635	10.22	9.011	2.8485	3.3870	2.8485	7.542594
Saturation curve	C	–	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8

*There are two power plants connected to bus 13029. The injected active and reactive powers from TPP Nova Venecia correspond, respectively, to 96% and 97% of the total of power generated in this bus.

Table C.4: Dynamic Model Data for the Round Rotor Units (Part 2).

Parameters			**Buses Numbers / Units Names**						
Description	**Symbol**	**Unit**	**11003*** TPP CSPecem – TGR1 and TGR2	**11003**** TPP CSPecem TRT	**13016** TPP Maranhão III - Gas	**13022** TPP Maranhão III - Vapor	**11150** TPP Porto Sergipe - Gás	**11149** TPP Porto Sergipe - Vapor	**13033** TPP Parnaiba V
Rated apparent power	MBASE	MVA	118.5	20.0	208.0	224.0	422.0	720.0	490.0
d-axis open circuit transient time constant	T'_{do}	s	7.90	2.1	7.0	7.0	6.60	4.62	6.70

q-axis open circuit transient time constant	T'_{qo}	s	1.0	2.0	0.55	0.57	0.54	0.59	0.570
d-axis open circuit sub-transient time constant	T''_{do}	s	0.04	0.05	0.04	0.04	0.037	0.017	0.036
q-axis open circuit sub-transient time constant	T''_{qo}	s	0.15	0.158	0.081	0.08	0.066	0.028	0.062
Inertia	H	MW.s/ MVA	4.3	1.515	5.14	4.507	4.599	5.017	5.560
Speed damping	D	pu	1.0	1.0	1.0	1.0	1.0	1.0	1.0
d-axis synchronous reactance	X_d	pu*100	222.0	203.0	187.0	202.0	192.0	207.0	206.0
q-axis synchronous reactance	X_q	pu*100	211.0	80.4	177.0	190.0	185.0	203.0	198.0
d-axis transient reactance	X'_d	pu*100	28.0	21.0	23.5	25.0	30.0	28.0	32.0
q-axis transient reactance	X'_q	pu*100	50.0	70.0	42.5	45.0	49.0	47.0	51.5
sub-transient reactance	X''_d	pu*100	20.0	18.0	17.5	19.0	23.5	27.0	24.50
Leakage reactance	X_ℓ	pu*100	14.0	10.0	13.0	14.0	18.0	20.0	19.5
Armature resistance	Ra	pu*100	0.15	0.0	0.26	0.0	0.16	0.128	0.3
Saturation curve	A	–	0.031200	0.03	0.0047	0.0034	0.02783	0.005849	0.005825
Saturation curve	B	–	7.58188	6.0	12.1635	12.2214	2.815	7.35	10.63824
Saturation curve	C	–	0.8	0.8	0.8	0.8	0.7984	0.8	0.8

All excitation systems are considered identical and are represented by the same dynamic model, shown in Figure C.4. The parameters for the model are presented in Table C.5.

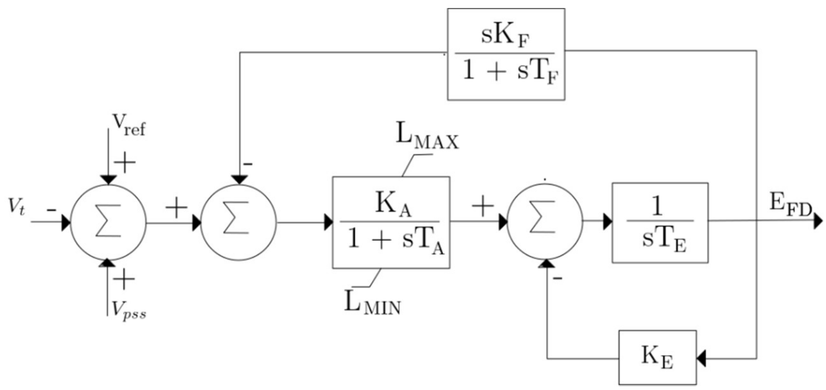

Figure C.4: Block Diagram for the Excitation Systems.

Table C.5: Data for the excitation system model.

Parameters			
Description	**Symbol**	**Value**	**Unit**
Regulator gain	K_A	100	pu
Regulator time constant	T_A	0.05	s
Exciter gain	K_E	1.00	pu
Exciter time constant	T_E	1.50	s
Stabilization feedback gain	K_F	0.30	pu
Stabilization feedback time constant	T_F	3.00	s
Max. AVR output	Lmin	–4	pu
Min. AVR output	Lmax	8	pu

The governor-turbine and speed regulation models adopted for HPPs and TPPs are shown in Figures C.5 and C.6, respectively.

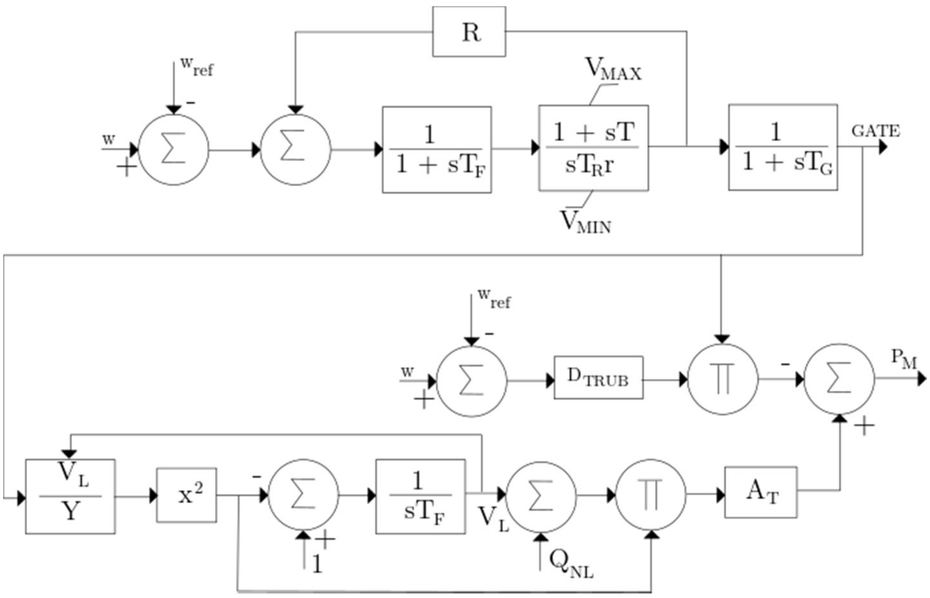

Figure C.5: Block diagram of the governor-turbine and speed regulation model adopted for the HPPs.

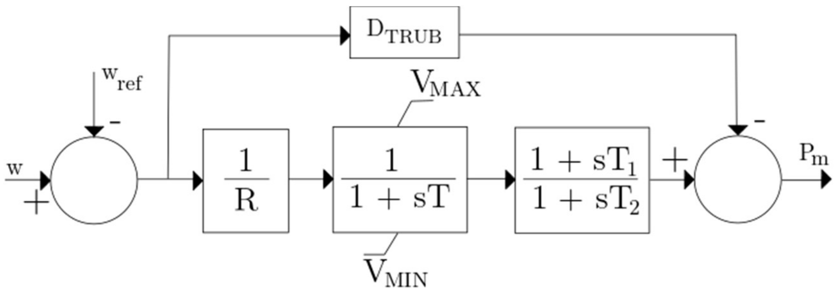

Figure C.6: Block diagram of the governor-turbine and speed regulation model adopted for the TPPs.

Table C.6: Data for the governor-turbine and speed regulation adopted for the HPPs.

Parameters			Buses Numbers							
Description	**Symbol**	**Unit**	**1, 4, 5, 6**	**7, 8, 9**	**10, 11**	**28, 29**	**33, 34**	**21**	**95**	**48**
Permanent droop	R	pu	0.05	0.04	0.05	0.10	0.04	0.05	0.05	0.05
Temporary droop	r	–	0.20	0.35	0.40	(28): 0.40 (29): 0.60	0.23	0.77	0.38	0.50
Turbine gain	A_T	pu/pu	1.2	1.218	1.250	1.250	1.320	1.520	1.20	1.667
No-load flow at nominal head	Q_{NL}	Pu	0.10	0.11	0.10	0.20	0.09	0.11	0.15	0.20
Water inertia time constant	T_w	S	1.8	2.31	1.25	1.90	2.47	2.20	1.5	1.19
Regulator time constant	T_R	S	2.0	4.6	2.0	2.5	5.9	4.0	7.05	1.00
Filter time constant	T_F	S	0.05	0.05	0.05	0.05	0.05	0.05	0.5	0.5
Gate-servo time constant	T_G	S	0.5	0.1	0.1	1.5	0.29	0.50	0.50	0.15
Minimum gate opening	V_{MIN}	Pu	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Maximum gate opening	V_{MAX}	pu	(1) 1.001 (4) 1.014 (5) 1.100 (6) 1.014	(7): 0.958 (8): 0.958 (9): 1.100	0.961	(28): 1.500 (29): 0.823	0.915	0.902	0.984	1.000
Turbine damping factor	D_{TRUB}	Pu	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.5

Table C.7: Data for the Governor-Turbine and Speed Regulation Adopted for the TPPs.

Parameters			Buses Numbers						
Description	**Symbol**	**Unit**	**13022, 170, 327, 161, 11010, 11003**	**13029*, 11003**	**13016, 13008, 13029**,**	**339**	**160**	**104**	**11149**
Permanent droop	R	pu	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Governor mechanism time constant	T	s	0.50	0.50	0.50	0.50	0.50	0.50	0.5
Time constant	T_1	s	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Turbine time constant	T_2	s	5.0	5.0	5.0	5.0	5.0	5.0	5.0
Lower bound of the regulator	V_{MIN}	pu	-1.0	-1.0	-1.0	-5.0	-5.0	-1.0	-1.0
Upper bound of the regulator	V_{MAX}	pu	1.0	1.0	1.0	5.0	5.0	20.0	1.0
Turbine damping factor	D_{TRUB}	pu	0.0	0.0	0.0	0.0	0.0	0.0	0.0

*There are two power plants connected to bus 13029. This model corresponds to the Curua-Una Unit.

**There are two power plants connected to bus 13029. This model corresponds to the Nova Venecia Unit.

The PSS1A model contained in the IEEE Std. 421.5(2005) was used to represent the power system stabilizers and is shown in Figure C.7. Its corresponding parameters are given in Tables C.8 and C.9. It should be noted that the parameters A1 to A6 are set in a way that leads to the whole filter block to be bypassed.

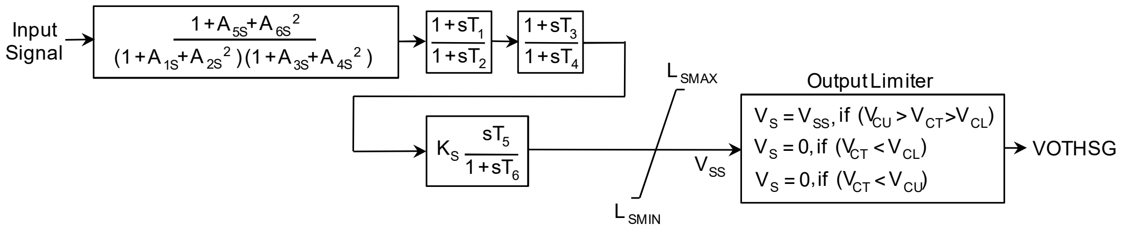

Figure C.7: Block Diagram for the PSS1A model.

The PSS output limits were set to +/– 10%, while the logic to switch off the PSS for voltages outside a normal operation range has been ignored (parameters V_{CU} and V_{CL} set to zero).

Table C.8: Data for the PSS model (Part 1).

Parameters			**Buses**					
Description	**Symbol**	**Unit**	**1**	**4**	**5**	**6**	**10**	**433**
2nd order denominator coefficient	A_1	–	0	0	0	0	0	0
2nd order denominator coefficient	A_2	–	0	0	0	0	0	0
2nd order numerator coefficient	A_3	–	0	0	0	0	0	0
2nd order numerator coefficient	A_4	–	0	0	0	0	0	0
2nd order denominator coefficient	A_5	–	0	0	0	0	0	0
2nd order denominator coefficient	A_6	–	0	0	0	0	0	0
1st lead-lag numerator time constant	T_1	s	0.209	0.240	.239	0.221	0.398	0.279
1st lead-lag denominator time constant	T_2	s	0.077	0.063	.064	0.073	0.027	0.041
2nd lead-lag numerator time constant	T_3	s	0.209	0.240	.239	0.221	0.398	0.279
2nd lead-lag denominator time constant	T_4	s	0.077	0.063	.064	0.073	0.027	0.041
Washout block numerator time constant	T_5	s	3.0	3.0	3.0	3.0	3.0	3.0
Washout block denominator time constant	T_6	s	3.0	3.0	3.0	3.0	3.0	3.0
PSS gain	K_S	pu	5.0	5.0	5.0	5.0	7.2	1.2
PSS max. output	L_{Smax}	pu	0.1	0.1	0.1	0.1	0.1	0.1
PSS min. output	L_{Smin}	pu	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1
Upper voltage limit for PSS operation	V_{CU}	pu	0	0	0	0	0	0
Lower voltage limit for PSS operation	V_{CL}	pu	0	0	0	0	0	0

Table C.9: Data for the PSS model (Part 2).

Parameters			**Buses**			
Description	**Symbol**	**Unit**	**11010**	**11001**	**80**	**11150**
2nd order denominator coefficient	A_1	–	0	0	0	0
2nd order denominator coefficient	A_2	–	0	0	0	0
2nd order numerator coefficient	A_3	–	0	0	0	0
2nd order numerator coefficient	A_4	–	0	0	0	0
2nd order denominator coefficient	A_5	–	0	0	0	0
2nd order denominator coefficient	A_6	–	0	0	0	0
1st lead-lag numerator time constant	T_1	s	0.264	2.481	2.00	0.267
1st lead-lag denominator time constant	T_2	s	0.041	0.008	0.013	0.045
2nd lead-lag numerator time constant	T_3	s	0.264	2.481	2.00	0.267
2nd lead-lag denominator time constant	T_4	s	0.041	0.008	0.013	0.045
Washout block numerator time constant	T_5	s	3.0	3.0	3.0	3.0
Washout block denominator time constant	T_6	s	3.0	3.0	3.0	3.0
PSS gain	K_S	pu	5.0	0.44	1.6	5.0

PSS max. output	L_{Smax}	pu	0.1	0.1	0.1	0.1
PSS min. output	L_{Smin}	pu	-0.1	-0.1	-0.1	-0.1
Upper voltage limit for PSS operation	V_{CU}	pu	0	0	0	0
Lower voltage limit for PSS operation	V_{CL}	pu	0	0	0	0

Regarding the WFs, all the 60 units are represented by a wind turbine generator of type 3, given by a doubly fed asynchronous (induction) generator (DFIG). In this type of wind turbine, the active power is controlled by a power converter connected to the rotor terminals [7].

The DFIG is modeled by the second-generation type 3 generic wind turbine model developed by the WECC [7]. This model comprises seven modules: the generator/converter model, P/Q control and current limit logic, plant-level control, torque control, pitch control, the aerodynamic model, and the drive-train model [7]. The overall structure of these modules is shown in Figure C.8. Each of these modules is described by a model recommended by the NERC (as presented in[8]), as shown in Table C.10.

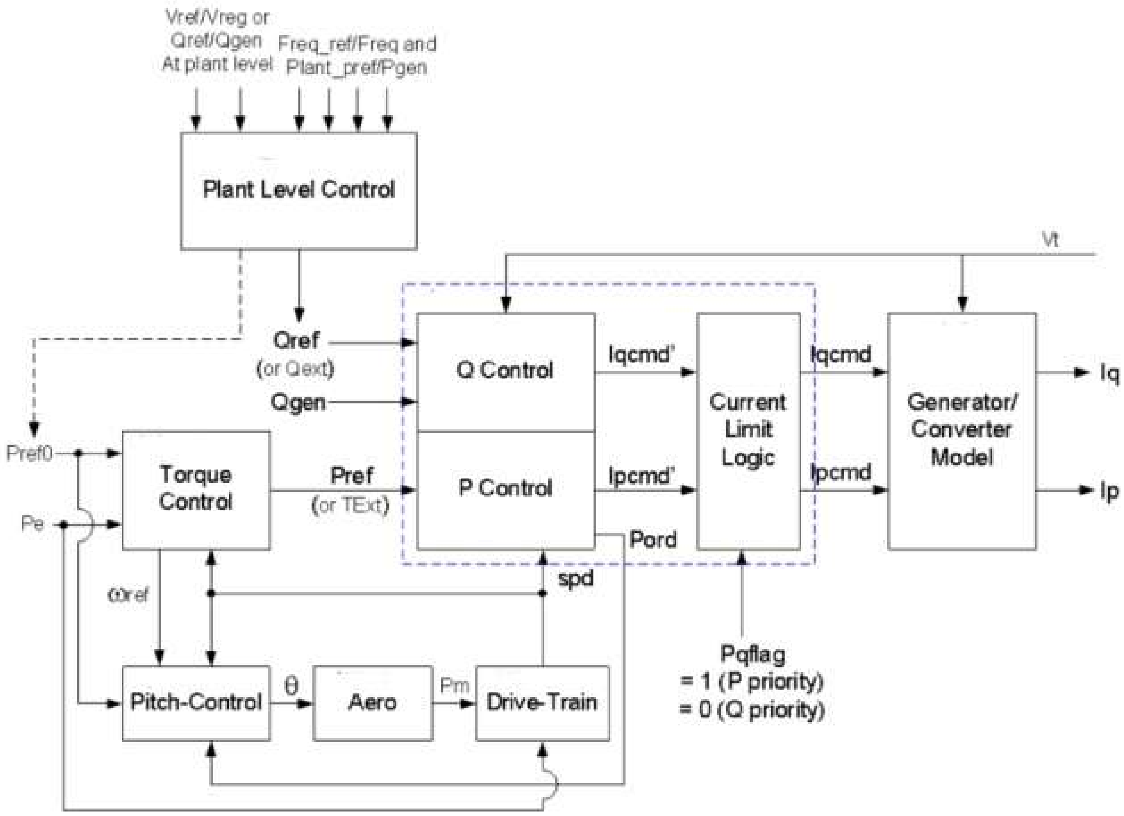

Figure C.8: Overall model structure for type 3 wind turbine generator developed by WECC [7].

Table C.10: The adopted model for each module of the type 3 wind turbine generator, as described in [7].

Module	The adopted model, as presented in [7]
generator/converter model	REGC_A
P/Q control and the current limit logic	REEC_A
plant level control	REPC_A
torque control	WTGTRQ_A
pitch control	WTGPT_A
aero dynamic model	WTGAR_A
drive-train model	WTGT_A

These units may be operated in voltage or reactive power control modes. In this report, 53 units operate in the reactive power control mode, while the remaining are in the voltage control mode. The values adopted for the parameters of these models are described in Appendix B.

The block diagram of each of these models are shown in the reference [7]. The parameters values adopted in this report are shown in Tables C.11 to C.17.

Finally, the 7 SPPs plants are represented by the WECC generic model for PV plants, as described in [8]. This dynamic representation of PV plants requires the use of three modules, as being: (i) the REGC_A module, used to represent inverter interface with the grid; (ii) REEC_A module, used to represent the electrical controls of the inverters (P/Q control) and; (iii) REPC_A module, used to represent the plant control. These modules, in addition to others, are also used in the second-generation type 3 generic wind turbine model for the WFs, as previously described. The parameters used to model the SPPs are the same ones adopted by the WF model.

Table C.11: Data for the generator/converter model (regc_a)

Parameters			
Description	Symbol	Unit	Value
Inverter current regulator lag time constant	Tg	s	0.02
Terminal voltage filter (for LVPL) time constant	Tfltr	s	0.02
LVPL zero crossing	Zerox	pu	0.4
LVPL breakpoint	Brkpt	pu	0.9
Current limit for high voltage clamp logic	Iolim	pu	-1.3
Voltage limit for high voltage clamp logic	Volim	pu	1.2
High voltage clamp logic acceleration factor	Khv	--	1.5
Maximum rate-of-change of reactive current	Iqrmax	pu/s	999.9
Minimum rate-of-change of reactive current	Iqrmin	pu/s	-999.9
Active current up-ramp rate limit on voltage recovery	rrpwr	pu/s	10.0
Low voltage active current management breakpoint	lvpnt0	pu	0.05

Low voltage active current management breakpoint	Lvpnt1	pu	0.2

Table C.12: Data for the P/Q control model (reec_a)

Parameters			
Description	**Symbol**	**Unit**	**Value**
Filter time constant for electrical power measurement	Tp	s	0.01
Integral gain	Kqi	pu	3.0
Proportional gain	Kqp	pu	0.5
Integral gain	Kvi	pu	15.0
Proportional gain	Kvp	pu	4.5
Time constant on lag delay	Tiq	s	0.02
High voltage clamp logic acceleration factor	Khv	--	1.5
Filter time constant for electrical power measurement	Tp	s	0.05
The voltage below which the reactive current injection (Iqinj) logic is activated	Vdip	pu	0.85
The voltage above which the reactive current injection (Iqinj) logic is activated	Vup	pu	1.20
Filter time constant for voltage measurement	Trv	s	0.01
Deadband in voltage error when voltage dip logic is activated	dbd1	pu	0.05
Deadband in voltage error when voltage dip logic is activated (for undervoltage)	dbd2	pu	0.05
Gain for reactive current injection during voltage dip (and overvoltage) conditions	Kqv	pu/pu	0.8
Maximum limit of reactive current injection (Iqinj)	Iqh1	pu	0.75
Minimum limit of reactive current injection (Iqinj)	Iql1	pu	-0.75
VDL1 Curve			(Vq, Iq) (0.0, 0.75) (0.2, 0.750001) (0.5, 0.750002) (1.0, 0.750003)
VDL2 Curve			(Vp, Ip) (0.2, 1.11) (0.5, 1.110001) (0.75, 1.110002) (1.0, 1.110003)

Table C.13: Data for the drive-train model (wtgt_a) and aero-dynamic model (wtgar_a)

Parameters			
Description	**Symbol**	**Unit**	**Value**
Turbine inertia	Ht	MWs/MVA	3.96305
Generator inertia	Hg	MWs/MVA	0.72695
Damping coefficient	Dshaft	pu	1.5
Spring constant	Kshaft	pu	160
Aero-dynamic gain factor	Ka	pu/degrees	0.007
Initial pitch angle	\theta_a	degrees	0

Table C.14: Data for the pitch controller model (wtgpt_a)

Parameters			
Description	**Symbol**	**Unit**	**Value**
Pitch-control proportional gain	Kpw	pu/pu	150.0
Pitch-control integral gain	Kiw	pu/pu	25.0
Proportional gain	Kcc	pu/pu	0.0
Pitch-compensation integral gain	Kic	pu/pu	30.0
Pitch time constant	Tth	s	0.3
Pitch-compensation proportional gain	Kpc	pu/pu	3.0
Maximum pitch angle	θmax	degrees	27.0
Minimum pitch angle	θmin	degrees	0.0
Maximum pitch angle rate	dθmax	degrees/s	10.0
Minimum pitch angle rate	dθmin	degrees/s	-10.0

Table C.15: Data for the torque controller model (wtgtrq_a)

Parameters			
Description	**Symbol**	**Unit**	**Value**
Power measurement lag time constant	Tp	s	0.05
Speed reference time constant	Twref	s	30.0
Proportional gain	Kpp	pu/pu	3.0
Integral gain	Kip	pu/pu	0.6
Maximum torque	Temax	pu	1.2
Minimum torque	Temin	pu	0.0
P x speed curve			(P, speed) (0.0, 0.7999) (0.04, 0.800) (0.2, 1.000) (1.0, 1.0001)

Table C.16: Data for the plant level control model (repca_a)

Parameters			
Description	**Symbol**	**Unit**	**Value**
Voltage or reactive power measurement filter time constant	Tfltr	s	0.01
Lead time constant	Tft	s	0.0
Lag time constant	Tfv	s	0.15
Proportional gain	Kp	pu/pu	18.0
Integral gain	Ki	pu/pu	5.0
Deadband downside	Dbl1	pu	-0.00333
Deadband upside	Dbl2	pu	0.00333
Flag to turn on (1) or off (0) the active power control loop within the plant controller	Freq_flag		0
Selection of droop (0) or line drop compensation (1)	Vcompflag		0
Minimum Q control output	Qmin	pu	-0.436
Maximum Q control output	Qmax	pu	0.296
Maximum error limit	Emax	pu	-999.0
Minimum error limit	Emin	pu	999.0

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