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Impact analysis of COVID-19 pandemic on the electricity demand, frequency control and electromechanical oscillation modes of the Brazilian Interconnected Power System using low voltage WAMS data

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A B S T R A C T
COVID-19 pandemic presented unique features among the range of threats encountered over the last century. Its impact echoes throughout the world affecting societies and their patterns of behavior, hence affecting the usage of electricity and the operation of power systems. This paper provides an analysis of the impact of COVID-19 Pandemic on the electricity demand, frequency control and electromechanical oscillation modes of the Brazilian Interconnected Power System (BIPS), taking into account public data disclosed by the Brazilian Independent System Operator (BISO) and data acquired through the MedFasee Project, the Brazilian low voltage wide area monitoring system (WAMS) leaded by the Federal University of Santa Catarina. Main results indicate that the BISO has been successful on controlling the system frequency and the main electromechanical interarea modes, despite the occurrence of a significant demand reduction in the BIPS in a certain period of time due to the COVID-19 pandemic. The total time of operation in underfrequency or overfrequency registered during the months with most demand reduction is at most 20% lower than the maximum time registered in the other months studied. The damping of the modes observed in the months with demand reduction has not reached values lower than 10% and the frequencies of oscillation have varied in a range of 0.05Hz, in agreement to what has been observed in other months.

1. Introduction
Since the end of 2019, the world has been dealing with the devastating consequences of the COVID-19 pandemic, a global health crisis that has also caused severe social and economic impacts. Due to the contagious characteristics of the disease, many countries have been adopting mitigating measures such as lockdowns and mandatory or voluntary social distancing. As a consequence, patterns of behavior of the society have changed, either temporarily or permanently, affecting the usage of electricity and operation of power systems around the world.

In Brazil, small changes in the patterns of behavior were noticed after the confirmation of the first human case of COVID-19 in February 2020. These changes were intensified after the spread of the disease at national level in the end of March 2020 [1]. The first efforts to contain the contagion consisted on temporary banning of foreign flights and lockdown measures, the latter adopted at different levels according to local governmental decisions. In the months that followed, mandatory or voluntary social distancing has been practiced locally, according to the levels of regional contagion and its impacts on the healthcare system, especially on hospital bed occupancy rates.

The effects on the energy sector are under investigation, with many papers analyzing the consequences of the pandemic worldwide from the point of view of consumption [2–6], operation [3,7–9], pricing [10] and policy assistance [9,11]. Regarding the impacts on the consumption, in [2], the changes on electricity consumption are investigated at household level, analyzing AC, non-AC and whole-home loads separately. In [3], it is shown that the electricity demand around the world has decreased in comparison to existing forecasts disregarding COVID-19 pandemic and even in comparison to patterns extracted from data of previous years. In [4], results indicate a decrease from 25% to 36% (30% in average) on the Chinese electricity consumption from February to May, the most affected period in that country. In [5], the impacts on the electricity consumption profile as results of different containment measures adopted in European countries against the spread of the...
pandemic have been analyzed. In [6], a study of the Brazilian case highlighted the existence of different drop levels in electricity demand according to load characteristics and social distancing in each region of the country.

With the demand reduction, many countries have also experienced an increase on the share of inverter-based Renewable Energy Source (RES) power generation [3], which brought additional challenges to the operation of power systems [7]. The impacts of the pandemic on the integration of RES are also approached in [8], where technical challenges faced by system operators during the COVID-19 pandemic as well as expected challenges on expansion planning are discussed. In [9], recommendations are provided for a smooth operation of a power system under lockdown conditions, based on a case study in India. Observing the consequences of the increase of residential electricity demand as opposed to commercial/industrial demand, technical and economic aspects have been analyzed to evaluate how India managed to control frequency and voltage, with respect to changes in the power system load. The consequences of the increase on the share of RES during the pandemic has also been analyzed in [10], but from the point of view of the Iberian electricity market. With the preference in curtailing non-RES generation in consequence of the demand decrease, the market faced a situation that represented a risk for the financial viability of dispatching utilities that are in fact important to guarantee the stability of the system, coping with the inverter-based RES generation.

In the context of investigating the effects of the pandemics on power system operation, this paper presents a case study of the BIPS, based on public data of electricity demand and power generation disclosed by the BISO and based on synchrophasor data acquired by Phasor Measurement Units (PMUs) installed at low voltage level. The synchrophasors are collected through the MedFasee Project, an 18 year old initiative lead by the Federal University of Santa Catarina (Brazil) with PMUs connected to public outlets at different countries of South-America and Europe, constituting an independent research observatory of the dynamics of large power systems [12–18].

In this paper, the public data disclosed by the BISO has been used to investigate the impacts of the pandemics in the demand and generation, while synchrophasors acquired from September 2019 to April 2021 at 28 PMUs covering all geo-electric regions of Brazil were used to investigate the impacts on the frequency control of the BIPS and in the behavior of the main electromechanical oscillation modes during the periods with and without regulated mobility restrictions. The main motivation for such studies is to evaluate the performance of the BIPS under the conditions faced during the pandemic, taking into consideration the changes in the demand and in the percentage of inverter-based RES in the generation in such period, serving as reference for the future.

Sections 2 and 3 present a contextualization about the Brazilian power system, the period of study and the data used in the analysis. In Section 2 the main characteristics of the BIPS, in terms of load and energy consumption, installed capacity and power generation by source, and transmission system are introduced. In Section 3, descriptions of the evolution of the pandemics in Brazil and the mobility restriction measures adopted, as well as details of the data provided by the BISO and the data acquired through MedFasee project are provided. After the contextualization of the study, Sections Sections 4 and 6 present the impacts of the COVID-19 pandemics on many aspects of the BIPS operation, including impacts on load and power generation, frequency control, and the behavior of main electromechanical oscillation modes. Main conclusions are reported in Section 7.

2. The Brazilian interconnected power system

This section presents the general characteristics of the BIPS in order to provide a contextualization about the power system and enable the understanding of the impact analysis of the pandemics.

The BIPS is a hydro-thermo-wind power system constituted by four main subsystems: south (S), southeast/center-west (SE/CW), northeast (N) and the majority of the northern (N) region, as show in Fig. 1. All subsystems are serving regions with distinct socioeconomic characteristics and different availability of primary energy sources, impacting on energy consumption profiles and system operation, especially power interchanges between areas.

The SE/CW is the most populous region, counting with the three most density populated states — São Paulo (21.9%), Minas Gerais (10.0%) and Rio de Janeiro (8.2%) – and the capital Brasília (located in the Federal District), with 1.4% of the 211.8 million inhabitants of the country in 2020 [20]. Along with the South region, the SE/CW are responsible for 80% of the national industrial Gross Domestic Product (GDP) of BRL 1.2 trillion. In 2017, the city of São Paulo had an equivalent of 31.6% of the GDP of Brazil, employing 2.9 million workers on industry related activities, as the economic center of the country [21].

2.1. Installed power by source

Due to the vast availability of hydric resources, the Brazilian electricity matrix presents a predominance of hydroelectric generation. In January 2020, from the total amount of 162.1 GW of installed capacity, 66.8% corresponds to hydroelectric power plants. The remaining is composed by 21.3% of thermoelectric plants (oil, gas, coal and biomass, 9.1% of wind power plants, 1.5% of Photovoltaic (PV) and 1.2% of nuclear plants [22].

The electricity matrix has been changing in the last years with the increasing penetration of wind power and solar generation. In January 2021, the percentage of installed capacity of wind power plants have increased 15.7% with respect to the installed capacity registered in January 2019, while the installed capacity of PV power plants have increased in 62.1% in the same period. The installed capacity of other sources have reduced or remained the same (decommissioning), taking into account also the expansion of the total installed capacity in the system [22]. In the 2025 horizon, it is expected a mix of 14.1% of wind power, 4.3% of solar and 58.1% of hydro, in relation to 188.7 GW of installed capacity [23].

In terms of subsystems, the installed capacity by source is presented in Fig. 2. Regarding the SE/CW, the installed capacity is about 49.5% of the total 162.1 GW registered in January 2020. The region counts...
with a lot of hydro units, but thermoelectric is still necessary to feed the most populous and industrial region, as presented in the preamble of this section. The NE, N, and S represent 19.7%, 16.4% and 14.4% of the total installed capacity, respectively [22], the NE with a significant share of wind power, the N and S with significant hydropower generation.

2.2. Energy generation and consumption

The energy generation and load in 2019 for each subsystem can be verified in Fig. 3.a and Fig. 3.b, respectively.

Comparing generation and consumption, SE/CW, S and NE regions presented approximated energy deficit of 2%, 3% and 1%, respectively, in 2019. These deficits are supplied by the surplus of 6% of the N, and eventually by importing energy from Argentina, Paraguay or Uruguay.

In fact, the N region generated 83.5 TWh which corresponds to around 14% of the energy generated in the BIPS, as shown in Fig. 3.a, while it consumed 48.8 TWh which corresponds to around 8% of the energy consumption in the BIPS, as shown in Fig. 3.b. Therefore, it is observed that the N region can be interpreted as an energy exporter region, with surplus utilized to supply large consumer centers such as in the SE/CW and S regions.

2.3. HVAC/HVDC transmission system

The BIPS subsystems are interconnected by long High-Voltage Alternating Current (HVAC) corridors, forming a large synchronous power system. Moreover, interconnections include six High-Voltage Direct Current (HVDC) bipoles in multi-infeed configuration, two of them embedded in the main alternating current (AC) system. The HVAC and HVDC interconnections, indicated in Fig. 1, allow energy transfer between the subsystems and allow exploiting the existing diversity between the hydrological regimes of the basins.

From the point of view of the system dynamic performance, the most critical scenarios occur when the HVAC and HVDC subsystem interconnections operate highly loaded. Scenarios with generation surplus in the N region, for instance, lead to operation with reduced number of generators in the SE region. As consequence, short circuit level and inertia are reduced, resulting in decreased system strength where the dynamic impact of contingencies is greater. Moreover, as highlighted in blue in Fig. 1, two HVDC links are embedded in the main AC system, constituting parallel transmission routes to the 500 kV AC interconnections. As a consequence of the strong AC–DC dynamic interaction, contingencies in these HVDC links may affect the stability of the synchronous generators, especially those from the north region.

A summary of the bulk AC transmission system is provided in Table 1, in terms of the voltage level and extension of the transmission lines in the year of 2021 [24].

The main details of the HVDC links are presented in Table 2. Besides the minor extension in comparison to the AC interconnections, the DC links enable the transfer of a significant amount of power to the SE/CW, the major load center of the BIPS.

3. Data utilized in the analysis

This section presents the description of the period of study and the data used in this paper. The period of study is directly related to the beginning of the contagion in Brazil, the lockdowns imposed and the restrictions on the mobility of population. The context of evolution of the pandemic in the country is relevant to understand its effects on the operation of the BIPS, and general information is presented in Section 3.1. The data used on the evaluation of the operation performance is presented in Section 3.2, describing the Wide Area Monitoring System (WAMS) used, its validity in power system studies and general previous applications.

3.1. Context of the evolution of the pandemic in Brazil and delimitation of the period of study

The starting point of COVID-19 in Brazil has been considered the first case registered in February 26, 2020. The contagious spread to 1000 infections by the end of March [1], and the first counteraction attempts have been taken progressively by governors and mayors [25–27], imposing curfews, restricting public transportation, suspending public events, suspending educational activities in loco and suggesting remote work. Since state governments have been given autonomy to impose the rules for combating the pandemic [28], distinct initiatives have emerged and have been applied on different moments throughout the country.

Notwithstanding, it is possible to affirm that the period from late March to the early April of 2020 was the most rigid in terms of rules for social distancing, with most regions of the country adopting lockdowns. In the city of São Paulo, a first related decree has been imposed in
March 22 [25], suspending any services but the essential ones. As consequence, social distancing increased from 28% (one week prior) to 59% (one week after), during week days and weekends. The mobility trends of driving, public transportation and walking activities, reported originally in [29] and reproduced here in Fig. 4, indicate the social distancing practiced. As governors relaxed the rules, social distancing decreased 5% to 10% in late April 2020 [30,31].

In the following months, some measures have been kept, such as remote educational activities and suspension of public events. Others have become recommendations, such as remote work in activities that are not characterized as essential in a pandemic situation. Social distancing, however, became mostly a voluntary decision. This heterogeneous context of countermeasures to combat the pandemic makes it difficult to observe the effects on the BIPS. Still, the period from late March to the end of April is the most affected by the measures imposed, and therefore the most significant for the studies.

3.2. Data description

To evaluate the impact of the COVID pandemic in the performance of the BIPS, data coming from two different main sources have been analyzed. First, recordings of generation and load consumption disclosed by the BISO in [24] have been used. The data are public and can be accessed with respect to subsystems or the entire system.

At second, the Low-Voltage (LV) WAMS of the MedFasee Project [32] has been used to provide synchrophasors for frequency analysis and identification of electromechanical oscillations. The MedFasee Project started in 2003 as a partnership between Federal University of Santa Catarina (UFSC) and Reason/GE, an equipment manufacturer, with the financial support of the Brazilian government R&D agency FINEP. The main goal was to develop synchronized phasor measurement technologies in Brazil, prototyping and manufacturing the first PMUs and the first Phasor Data Concentrator (PDC) installed in the country [12]. After almost two decades, the project counts with 28 PMUs covering all geo-electric regions of Brazil, as depicted in Fig. 5, where the acronyms denote the universities where the PMUs are installed.

The current equipment used in the MedFasee initiative are the digital fault recorders RPV311 and DR60 developed by Reason/GE, with PMU functions. The devices are capable of acquiring three-phase voltage samples and frequency signals synchronized through Global Positioning System (GPS). A Phasor Data Concentrator (PDC) located at UFSC receives the collected data at a rate of 60 data frames per second, through the C37.118.2-2011 IEEE protocol [33] and a Virtual Private Network (VPN) link, as shown in Fig. 6. In the Figure, it is also represented the backup PDC installed at UFSC, the database stored with the use of openHistorian and mySQL softwares, and our client applications MedPlot and MedPlot_RT, for offline and online analysis, respectively.

The MedFasee Project constitutes an independent observatory of the dynamics of the BIPS. Through the data acquired by the PMUs installed at the partner universities, it has been possible to monitor the dynamic performance of the system [12–16] and perform multiple application studies, such as help auditing the quality of energy supply, performing event analysis [17,34] or analyzing oscillations [18,35]. Moreover, the MedFasee Project initiative has been providing important inputs for the BISO, namely on supporting the design and the implementation of WAMS installed at the BIPS high voltage grid.
4. Impact of the pandemic on the load and generation of the BIPS

This section investigates the impacts of the pandemic on the load and generation of the BIPS in 2020, focusing on comparisons with data collected in adjacent years.

In Section 4.1, the impact of COVID-19 on the forecasted energy load is evaluated. In Section 4.2, data of Instantaneous Peak Demand (IPD) and Energy Load Curves (ELC) of the years 2019 and 2020 are compared. In Section 4.3, two Hourly Load Curves (HLC) for typical days of the years 2019 and 2020 are shown in order to analyze how the pandemic has impacted the shape of the curve. Finally, in Section 4.4, historical data of generation, separated by source and by electrical subsystem are presented, to make comparative analysis with respect to the load data presented in the previous sections.

4.1. Energy load

This section compares the energy load forecast of the BIPS presented in [36] with the registered data of the years of 2019, 2020 and 2021 (partial), disclosed in [37]. The data presented in [36] may differ slightly from the data presented in the next section as it has been acquired through monthly reports from different institutions, as in [38–40]. The objective is to observe how the registered data differed from the predictions, taking into consideration that the studies presented in [36] have been made in early 2019, therefore pre-pandemic. These studies were based on the assessment of economic indices such as GDP and data of demand and energy load during 2018 and the first months of 2019. According to [36], the yearly average Energy Load of the system should grow from 68733 avgMW in 2019 to 79822 avgMW in 2023, an increase of 3.8% per year.

The results can be seen in Fig. 7, where the forecast is plotted in blue and the registers in red. As it can be seen, the average Energy Load registered in 2019 were very close to the forecasts, while the year 2020 showed a greater discrepancy between predicted and verified values. In 2019, the verified value was only 1.3% below the forecast, while in 2020 the verified value was 6.4% below. Moreover, it can be seen that the energy load registered in 2020 is lower than the value registered in 2019, contradicting the forecast of growth and evidencing an impact caused by the effects of the pandemic.

4.2. Daily load data

In this section, the daily load data of the BIPS is analyzed in terms of its IPD, evaluated according to the maximum value of demand (in MW) registered daily, and in terms of the energy (in GWh) that supplies the load of the system for one day. Each point that composes the ELC is obtained through an average of 24 h energy load value.

The IPD of the BIPS during the years of 2019 and 2020 can be seen in Fig. 8, where the pattern presented in the year 2019 is very similar to the pattern of the previous years [24], and therefore taken as reference as a pre-pandemic year. As it can be observed, there was a clear and significant detachment of the curves from the end of March to the end of July 2020, coinciding with the beginning of the imposition of stricter rules to ensure social distancing as described in Section 3.1. This corroborates with the outcomes of a detailed study provided in [6], where the progressive decline on electricity load has been intensified since March 21, 2020, after the enforcement of measures to contain the dissemination of COVID-19, also it was observed that the decrease in the consumption led to a decline in the dispatched power in the generating units. The IPD data related to the specific period between the end of March and the end of July can be seen in details in Fig. 9, and for the purposes of this paper, this period will serve as reference from now on, being called Most Affected Period.

It can be observed in Fig. 9 that the maximums of the curve in 2020 are in some cases closer to the minimums of the curve of 2019 especially in April. Additionally, comparing the maximums of April of 2019 and 2020 are analyzed, a large discrepancy is observed. As examples, the Maximum Demand was approximately 82 GW in 2019, while in 2020 it reached only 71.8 GW, presenting a reduction of 12.5%.

Considering the second semester of 2020, it can be seen in Fig. 8 that the IPD reached similar values and in some days surpassed the registers of 2019, due to a general resume of industrial activities in the country. These results and the data presented in Figs. 8 and 9 corroborate the data and partial analysis presented in [41].

A similar analysis can be done regarding the ELC. The registers for the years of 2019 and 2020 can be seen in Fig. 10, where dashed lines represent annual average values. It can be seen that, as observed in the IPD, the effects of the pandemic clearly affected the load behavior in the BIPS. The average values decreased from 1549 GWh to 1522 GWh which represents a reduction of approximately 1.8%.

The Most Affected Period is presented in details in Fig. 11. As depicted, the average value decreased from 1525 GWh in 2019 to 1395 GWh in 2020, which represents a reduction of approximately 9.3%, a 5.2 times greater reduction compared to the whole year.

As it could be seen, there was a severe decrease in the IPD and ELC during the Most Affected Period. As a consequence of the load reduction, the BISO reported operation under unconventional conditions, with 70% of compulsory generation and consequential drop in the marginal costs of operation [41].

4.3. Hourly Load Curve for typical days

To investigate the impacts on the behavior of the load, the HLC of typical days in Brazil in the years of 2019 and 2020 have been analyzed. For the comparison, week days have been chosen as a typical working day, and the dates have been selected according to similar weather conditions in the city of São Paulo (the load center of the BIPS), aiming at minimizing the impacts of temperature changes.

The first pair of dates selected were 05/20/2019 and 05/18/2020, which correspond to Monday, when the maximum/minimum temperatures in São Paulo were 23.5/15.5 °C and 23.7/15.3 °C, respectively [42]. The HLCs, composed by data of Energy Load per hour (MWh/h) can be seen in Fig. 12, in Brazilian Time (UTC-3). In these graphs, each point corresponds to the value integralized in one hour.

As it can be seen, the shape of the curve changed from 2019 to 2020, due to the change in patterns of consumption.

A second pair of dates of the following month have been observed: 06/17/2019 and 06/15/2020, which correspond to Monday, with maximum/minimum temperatures in São Paulo were 23.5/15.5 °C and 25.6/12.9 °C, respectively [42]. The HLCs, composed by data of Energy Load per hour (MWh/h) can be seen in Fig. 12, in Brazilian Time (UTC-3). In these graphs, each point corresponds to the value integralized in one hour.

As seen in Fig. 9, there are considerable differences in the peak values of IPD from 2019 and 2020, specially on the Most Affected Period. To visualize this effect on the HLC, data from early April is shown in Fig. 14. The selected dates were 04/05/2019 and 04/03/2020, Fridays, with maximum/minimum temperature of 31.2/21.3 °C and 28.1/28.1 °C [42], respectively. As expected, the discrepancies have been even higher in comparison to Figs. 12 and 13.
4.4. Generation data

Given the clear impact on the load during the Most Affected Period in comparison to the year of 2019, this subsection aims at investigating the impacts on the total Energy Generation (EG) of the BIPS, by source and by subsystem. Evaluating the impacts of EG is important to provide further information to understand changes in the power flow between subsystems and changes in the percentage of RES penetration, which affects the performance of the mean frequency of the system and the behavior of the oscillation modes, approached in the following sections.

The energy generation by electrical subsystem for the years 2017 to 2020 can be verified in Fig. 15, together with the total energy generation of the BIPS presented in the last column.

It can be observed that, from 2017 to 2019, there was a clear growth in the energy generation by the Northeast and North, great exporters, as described in Section 2.2. In the year of 2020, the growth in the North is much less significant, while in the south there was a clear decrease. Evaluating the total EG, there was an increase of 1.45% from 2017 to 2018, 2% from 2018 to 2019 and a decrease of 1.57% from 2019 to 2020. This frustration of growth from 2019 to 2020 is an effect of the
average reduction in the load, lower industry activities and reduction in the Brazilian economy (shrank 4.1% at the end of 2020 [43]).

The generation and consumption by subsystem for the year of 2020 can be seen in Fig. 16. In comparison to Fig. 3, it is evidenced the lower amount of energy generation and consumption in 2020.

Comparing the contributions of each subsystem to the total amounts, the energy generated by S decreased 5%, while in SE/CW, N and NE it increased 1%, 0.5% and 2.5%, respectively, from 2019 to 2020. These variations are more perceptible in the bases of each subsystem: −24.4% S, 0.3% SE/CW, 2.8% N and 12.2% NE. The Energy consumption by subsystem in 2020, in relative terms, was approximately equal to the values observed in 2019. As a consequence, the role of the N and NE as exporters have increased in the year of 2020, while the S imported much more than in 2019. This may be explained by the installed capacity in the North/Northeast for the years 2019 and 2020, which increased 7.4 GW in the period, while the installed capacity in South increased only 0.915 GW [22].

The energy generation by source, from 2017 to 2020, can be seen in Fig. 17. The results evidences a growth in wind-power and solar power generation, and a decrease in generation by hydropower, nuclear and thermoelectric sources.

The results seen in Fig. 17 corroborate with the tendencies of growth of wind and solar based generation pointed out in Section 2.1, and also indicates that, with the average reduction in the load during the Most Affected Period, there was a higher penetration of wind power generation in comparison to the previous years.

In Fig. 18 are presented indexes that quantify the penetration of wind power generation in the BIPS during the years of 2019 and 2020. The left Y-axis represent the percentage of monthly hours when the total load of the system has been supplied by specific percentages of wind power generation, represented in the colored column bars. As an example, during January 2019, more than 8% of the total load has been supplied by wind power generation during 51.0% of the time. The purple curve represents the Energy Load, in avgGW, indicated in the right Y-axis.

The seasonal profile of wind power generation in the country is evident in Fig. 18, such that June to October is the period when wind power resources are more abundant. Regarding the months of April and May 2020, it can be seen the minimum values of energy load, and a significant increase on percentage of wind power generation in comparison to the year 2019. From June, the results of 2020 were closer to the results of 2019.

5. Impact of the pandemic on the frequency control performance

This section approaches the frequency control performance of the BIPS. The first figure of merit analyzed is given by [44]

\[ A_r = \int |\Delta f(t)| dt \quad [\text{Hz/min}] \]  (1)

where \( \Delta f(t) = f(t) - f_0 \) is the deviation of the system frequency \( f(t) \) from its nominal value \( f_0 \) of 60 Hz.

According to the values of \( A_r \) and \( \Delta f(t) \), the system is considered in different states, as presented in Table 3.

As inputs for Eq. (1), frequency recordings from PMUs installed in 6 different universities have been selected, representing most of the regions of the country: UFSC (south), USP - São Carlos (southeast), UNB (central), UFAM (northwest), UFPA (north) and UFPE (northeast), as depicted in Fig. 5.

Eq. (1) has been applied with a 1 min sliding window every 24 h to the data acquired at each PMU. The total time that the data collected at each PMU remained in each range of \( A_r \) and \( \Delta f(t) \) indicated in
Table 3 has been computed, and the maximum values have been taken as representative (since some of the PMUs may be affected by loss of data). As an example, the methodology indicated that the system has operated in overfrequency ($A_i > 0.1$ and $0 \leq \Delta f(t) < 0.5$) during 7 min in December 2019, since this is the maximum result obtained with the data of the 6 PMUs evaluated. The complete results in terms of overfrequency and underfrequency, from September 2019 to March 2021, are presented in Fig. 19. In Fig. 20, the total time the system operated under disturbance (in s) is shown.

Analyzing the corresponding outcomes, it can be verified in Fig. 19 that the system operated a significant longer time in underfrequency in March 2020 and both in underfrequency and overfrequency in April 2020, in comparison to February and May of the same year. Fig. 20 also evidences disturbances in March and April. However, it must be pointed out that, besides the behavior in March and April 2020 is clearly different from February and May, the results obtained are not "out of the curve" taking into consideration all the months analyzed, i.e., not out of the normal performance of the system. The total time under operation in underfrequency or overfrequency (computed together) in March and April correspond to 22 min and 44 min, respectively, approximately 140% and 20% smaller than the maximum time observed in the study period, registered in January 2021.

Comparing the index related to the percentage of wind power generation presented in Fig. 18, no direct relation could be inferred. The increase of time under operation in underfrequency and overfrequency (according to Table 3) during the months of March and April does not coincide precisely with the months with the load fed by the highest percentages of wind power generation (August and September). Still, even in August and September the percentage of the total load fed by wind power generation is rarely over 15%, a relatively reduced percentage in comparison to countries that are facing the impacts of operation with high percentages of asynchronous generation. In addition, evaluating the results obtained applying Eq. (1) to the data of each subsystem separately, no significant correlation has been observed.

From Fig. 19 it can be observed, additionally, that the frequency control of the system presented its best performance from June to September 2020. This is consistent with the results disclosed by the BISO in [45]. No seasonal behavior has been observed, such that it is possible to infer that the results observed from June to September 2020 are a consequence of the particular conditions of operation during these months.

Additionally, another index has been analyzed to evaluate the performance of the frequency control of the system. The duration of the frequency excursions in the range of $60.1 \leq f(t) \leq 60.05$ (overfrequency) and $59.9 \leq f(t) \leq 59.95$ (underfrequency) were computed, independent of Eq. (1). The results are presented in Fig. 21.

From Fig. 21, it can be observed that the system tends to be operated in the range of $60.1 \leq f(t) \leq 60.05$ more often than in the range of $59.9 \leq f(t) \leq 59.95$. This tendency inverted from September to November 2020. Regarding the Most Affected Period, the month with longer time of operation in overfrequency and underfrequency (computed together) was March 2020, with 50 min registered. This result is still 26% lower than the maximum time observed in all the period of study, registered in March 2021.

Therefore, taking into consideration all the indexes analyzed, no significant impact has been observed in the behavior of the frequency control during the period of study. Additionally, consulting the annual report on the performance of the frequency control [45] and the monthly reports detailing the perturbations that caused disconnections or violations of pre-determined limits [46] disclosed by the BISO, it has not been observed any increase in the number of perturbations nor an increase in severity of the impacts in the Most Affected Period. It should be noted that throughout the COVID-19 Pandemic, the BISO has been adopting specific procedures for the power system when operating at minimum load, focusing on establishing the minimum number of conventional generators in operation, in each subsystem of the BIPS [47]. Moreover, the system operator redefined some power exchange transmission limits among subsystems according to the N-2 security criterion, in order to avoid UFLS scheme actions during double transmission contingencies [48].

6. Impact of the pandemic on the electromechanical oscillation modes

This section is divided in two subsections. In Section 6.1, the general aspects about the methodology applied for modal identification are
presented. In Section 6, the modal analysis of the North/South and Acre-Rondônia/BIPS modes of the BIPS is approached, aiming at evaluating possible impacts of the pandemic. As input for the methodology, frequency signals provided by the PMUs of the MedFasee project have been used.

6.1. Methodology applied for modal identification

Electromechanical oscillations result from the interactions between the synchronous machines of an interconnected system in specific operating conditions. Poorly damped oscillations can take the system to unstable operation points, leading to load and generation outages. Therefore, mode monitoring is an important tool for the dynamic security of the system, since the identification of poorly damped modes may support appropriate control actions.

The study of oscillations is based on the representation of the system in state-space equations. The eigenvalues of the state matrix \( A \) provide the characteristics of an oscillation mode: frequency and damping. A conjugated complex eigenvalue may be written as:

\[
\lambda = \sigma \pm j \omega
\]  

(2)

The frequency is given by

\[
f = \frac{\omega}{2\pi} \quad [Hertz]
\]  

(3)

The damping ratio is given by:

\[
\zeta = -\frac{\sigma}{\sqrt{\sigma^2 + \omega^2}} \quad [pu/pu]
\]  

(4)

There are different groups of methods for the study of oscillations based on ringdown analysis or ambient conditions. In this paper, the Canonical Correlation Analysis (CCA) is applied. The CCA is a parametric method that has already been applied for modal identification in ambient conditions in [49]. Electrical signals used for monitoring modes are characterized by small load variations modeled as random excitation on the system, such that, for this conditions, the assumption of purely stochastic system is attended. The CCA method, as all the parametric methods, depends on building a model and pre-setting inherent parameters. A subspace is identified based on the analysis of cross-covariance matrices, from which it is possible to retrieve the state matrix \( A \), the eigenvalues, and consequently the frequency and damping of the modes. The interested reader may refer to [49,50] for the complete formulation.

To apply the CCA method with real data, pre-processing techniques on the measured signals are needed. This process is important to remove flawed, redundant and irrelevant data [18]. The first pre-processing steps adopted in this paper have been: removal of outliers, linear interpolation of removed data and removal of signal average in order to remove deterministic components that may deteriorate the results of the method with stochastic application. Then, as next step, the frequency components outside of the band of interest (0,1–2,5 Hz) have been filtered. Thus, the noise and high frequencies associated with the action of slow dynamics of the power system have been neglected [49]. As last step, down-sampling is applied, consisting on resampling the input signal with a lower sampling rate, with the aim of removing redundant data that may affect the numerical conditioning of the method.

6.2. Temporal evolution of the frequency and damping of main oscillation modes

The CCA method is applied as proposed in [49] to identify the main modes of the SIN. In this paper, the results obtained monitoring the North–South (N–S) and the mode between the states of Acre and Rondônia against the BIPS are presented (denoted as AC-RO/BIPS). The N–S is the main mode since its behavior is related mainly to the power transfer to the center of load in the SE/CW. The AC-RO/BIPS also shows relevance since the states of Acre and Rondônia are in the region where the network is mostly radial, and therefore weaker in terms of angle stability.

For the identification of the N–S mode, frequency signals acquired by the LV PMUs installed at UFSC (in the city of Florianópolis, south) and at UFC (in the city of Fortaleza, northeast) have been processed. These signals have been chosen empirically over other types of signals and other terminals, according to the performance of the CCA method on identifying accurately the mode in relation to the typical values of frequency and damping reported by the BISO. The data stored in the PDC have been collected at every five-days and the modes were estimated every minute for the 24 h of the selected day. Then, the daily average of frequency of oscillation and damping ratio were calculated. The evolution of the North/South mode between September 2019 and May 2021 is presented in Figs. 22 and 23. In the figures, the vertical black lines indicate the start of the years of 2020 and 2021, while the red dashed line indicates the date of March 16, selected as a representative start of the most restrictive period of social distancing.

As it can be noticed in Fig. 22, the frequency of oscillation of the North/South mode presented a small increase in its average values after the March 16, remaining around 0,45 Hz and reaching peaks of 0,5–0,55 Hz. In the Most Affected Period, the frequency remained in a stricter range, from 0,4 to 0,45 Hz. In Fig. 23, the damping ratio shows a wider standard deviation than the frequency during the whole window, because it is more sensitive to power flow and load normal variations. Therefore, the daily average can be seen with a trend of the behavior. The damping ratio varied between 10 and 25% during the Most Affected Period, higher values than the damping observed out of this period, as at the end of the year of 2019 and at the end of 2020.

The AC-RO/BIPS mode has been monitored with frequency measurements acquired at UNIR (city of Porto Velho, at Rondônia state) and at UNICAMP (city of Campinas, in SE). The corresponding frequency of oscillation and damping are presented in Figs. 24 and 25.
be noted that throughout the COVID-19 Pandemic, the BISO has been monitoring the frequency and damping of the main oscillation modes of the BIPS, performing punctual readjustments of some power system stabilizers. Therefore, possible impacts might have been mitigated by the BISO, such that no significant impact could be observed. The damping of the monitored modes remained in a typically adequate range of values (10% to 25%) for the operation of large interconnected power systems, while in other months lower damping has been observed. The frequency of oscillation of both modes varied in a stricter range (of 0.05 Hz) during the Most Affected Period than the range registered in the rest of the studied months.

7. Conclusions and final remarks

This paper presented an analysis of the impact of COVID-19 Pandemic on the BIPS, based on public data disclosed by the BISO and data acquired through the MedFasee Project, an 18-year old independent research observatory leaded by the Federal University of Santa Catarina, counting with 28 PMUs in public outlets widespread in all regions of Brazil.

From the point of view of the electricity demand, a significant reduction have been seen in the months of March and April 2020 (9.3% in the average energy load), with slow recovery in the following months. Such period was the most rigid in terms of rules of social distancing, what influenced on the mobility trends and consequently in the patterns of consumption of energy. Regarding the entire year of 2020, there was a frustration of growth, registering a total energy load 6.4% below the prediction, lower also than the values registered in 2019. The impact on the electricity demand has been evaluated comparing curves of instantaneous peak demand, energy consumption, hourly load and total energy generated by subsystem.

Regarding the impacts on the frequency control performance, no significant change has been observed. The investigation has been performed through the monthly observation of frequency synchrophasor-based recordings, evaluating the time of operation in underfrequency, overfrequency and under disturbances. Two different criteria have been used to determine operation in underfrequency and overfrequency: one based on ranges of frequency and one based on frequency variation. With the criteria adopted, no discrepant results have been observed, not even in the periods with low load (consequence of the social distancing) and higher percentage of wind power generation (with respect to the Brazilian scenario). Therefore, it has been inferred that possible outcomes of the reduction in the electricity demand in the behavior of the overall frequency of the system have been mitigated by the BISO.

Also, no significant impact of the pandemic has been observed on the frequency and damping of the main electromechanical interarea oscillation modes of the BIPS. The CCA method have been used to identify the modes and the evolution of the frequency and damping have been analyzed in the study period. Between March and April 2020, no significant excursions in the frequency of oscillation could be observed, and the damping of the observed modes remained in the range of 10% and 25%, adequate values for the operation of large interconnected power systems.

In a possible future scenario with expanded electrification of the economy as well as constraints on deploying novel large hydroelectric power plants and long transmission lines, the share of the load to be matched by intermittent/inverter-based generation units is envisioned to be augmented considerably. With the increase of integration of prosumers to the system, the share of load matched by intermittent/inverter-based generation units connected to medium/low voltage networks is also envisioned to rise, inputting more uncertainties to the forecasting of the net loading on each substation bus. These future scenarios are characterized by enlarged complexity of spinning reserve scheduling, amplifying the challenges on maintaining the system frequency under the appropriate ranges. Moreover, gradual

The frequency of the AC-RO/BIPS mode presented values near 0.9 Hz between October and December 2019, dropping to 0.8 Hz among January and June 2020 and increasing again in mid-July 2020 through early 2021. These variations in the frequency of oscillation are possibly related to the operating point of the power system at each time, consequence of the power generation in that region. In Fig. 26 are shown the registers of power generation at the hydropower plants of Samuel and Santo Antônio HPP (in RO), between September 2019 and May 2021. When the generation is high in RO, more power is exported to the BIPS and the frequency of the mode tends to fall to 0.8 Hz. When the generation is low, instead, the frequency of the mode tends to present values around 0.85 Hz.

Regarding the Most Affected Period, neither of the monitored modes presented unusual behavior in terms of frequency or damping. It should
altered on unit commitment profiles in each region of the country, resulted from the large-scale integration of intermittent/inverter-based generation units, are envisioned to contribute to modifications on the frequency and damping values of the main electromechanical interarea oscillation modes of the BIPS. The load reduction and change in consumption profile caused by a possible future pandemic can further aggravate the uncertainties and complexities of system operation, making more prominent the corresponding impacts on the frequency control performance and electromechanical oscillation modes.

To summarize, results indicated that the BIPS have experienced a significant demand reduction provoked by COVID-19 pandemic, but no further consequences on the performance of the frequency control and on the behavior of the main electromechanical interarea modes have been observed. Notwithstanding, the BISO must continue its efforts on evolving the processes devoted to coordinating, controlling and monitoring the system operation, aiming to handle possible future scenarios with increased share of intermittent/inverter-based generation and/or the advent of novel market structures, thus assuring the adequacy and security of supply of the BIPS.

CRediT authorship contribution statement

Guido R. Moraes: Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Supervision. Bryan A.S. Amêndoa: Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization. Juliana L. Pereiha: Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization. Diego Issicaba: Conceptualization, Methodology, Investigation, Writing – original draft, Writing – review & editing, Supervision, Project administration. Antônio F.C. Aquino: Conceptualization, Methodology, Investigation, Writing – original draft, Writing – review & editing, Supervision, Project administration. Ildemar C. Decker: Conceptualization, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] Painel coronavírus brasil. 2021, https://covid.saude.gov.br/. [Accessed 07 July 2021].
[2] Kewka E, Cotin K. Impacts of COVID-19 on residential building energy use and performance. Build Environ 2021;205:108200.
[3] COVID-19 impact on electricity. Tech. rep., International Energy Agency (IEA); 2021.
[4] Wang Q, Li S, Jiang F. Uncovering the impact of the COVID-19 pandemic on energy consumption: New insight from difference between pandemic-free scenario and actual electricity consumption in China. J Cleaner Prod 2021;127897.
[5] Bahmanyar A, Estebarsi A, Ernst D. The impact of different COVID-19 containment measures on electricity consumption in Europe. Energy Res Soc Sci 2020;68:101663.
[6] Delgado DBM, de Lima KM, Cancela MdG, Siqueira CdS, Carvalho M, de Souza DdB. Trend analyses of electricity load changes in Brazil due to COVID-19 shutdowns. Electr Power Syst Res 2021;193:107009.
[7] Impros S, Nene SV, Oral B. Challenges of renewable energy penetration on power system flexibility: A survey. Energy Strateg Rev 2020;31:100539.
[8] Navon A, Machlev R, Carmnon D, Onile AE, Belikov J, Levan Y. Effects of the COVID-19 pandemic on energy systems and electric power grids—A review of the challenges ahead. Energies 2021;14(4):1056.
[9] Elavarasan RM, Shaffaliil MH, Raju K, Mudgal V, Aarif MT, Jamal T, et al. COVID-19: Impact analysis and recommendations for power sector operation. Appl Energy 2020;279:115739.
[10] Bento P, Mariano S, Calado M, Pomba J. Impacts of the COVID-19 pandemic on electric energy load and pricing in the Brazilian electricity market. Energy Rep 2021;7:4833–49.
[11] Graff M, Carley S. COVID-19 assistance needs to target energy insecurity. Nat Energy 2020;5(5):352–4.
[12] Decker IC, Dotta D, Agostini MN, Zimath SL, De Silva AS. Performance of a synchronized phasor measurements system in the Brazilian power system. In: 2006 IEEE Power engineering society general meeting. IEEE; 2006, p. 8–pp.
[13] Decker IC, Dotta D, Agostini MN, Silva AS, Meyer BT, Zimath SL. Installation and monitoring experiences of the first synchronized measurement system in the Brazilian grid. In: 2008 IEEE/PIES Transmission and distribution conference and expositions: latín America. IEEE; 2008, p. 1–7.
[14] Decker IC, Agostini MN, e Silva AS, Dotta D. Monitoring of a large scale event in the Brazilian power system by WAMS. In: 2010 IREP Symposium bulk power system dynamics and control-VIII. IEEE; 2010, p. 1–8.
[15] Decker IC, e Silva AS, Agostini MN, Prioste FB, Mayer BT, Dotta D. Experience and applications of phasor measurements to the Brazilian interconnected power system. Euro Trans Electr Power 2011;21(4):1557–73.
[16] Decker IC, e Silva AS, Da Silva RLG, Agostini MN, Martins N, Prioste FB. System wide model validation of the Brazilian interconnected power system. In: IEEE PES general meeting. IEEE; 2010, p. 1–8.
[17] Var R, Moraes GR, Arruda EHZ, Terceiro JCRs, Aquino AFG, Decker IC, et al. Event detection and classification through wavelet-based method in low voltage wide-area monitoring systems. Int J Electr Power Energy Syst 2021;130:106919.
[18] Pereira JL, Leandro RB, Decker IC, Moraes GR. A cross-validation strategy for the installation of electromechanical oscillations in real ambient data. J Control Autom Electr Syst 2021;1:1–12.
[19] Operador Nacional do Sistema Elétrico - (ONS). Mapa do sistema de transmissão - horizonte 2024. 2021, http://www.ons.org.br/paginas/sobre-o-sistema. [Accessed 12 November 2021].
[20] Instituto Brasileiro de Geografia e Estatística (IBGE). IBGE divulga estimativa da população dos municípios para 2020. 2021, https://agenciaednoticias.ibge.gov.br/agencia-sala-de-imprensa/2015-agencia-de-noticias/releases/28668-ibge-divulga-estimativa-da-populacao-dos-municipios-para-2020.html#:~:text=%20IBGE%20divulga%20a%20populao%20de%202020.&text=%20IBGE%20divulga%20a%20populao%20de%202020.&text=%20IBGE%20divulga%20a%20populao%20de%202020. [Accessed 25 June 2021].
[21] Indústria no Brasil. 2021, https://pt.wikipedia.org/wiki/Ind%C3%A1stria_no_Brasil. [Accessed 22 October 2021].
[22] Operador Nacional do Sistema Elétrico - (ONS). Capacidade Instalada de Geração. 2021, http://www.ons.org.br/Paginas/resultados-da-operacao/historico-da-operacao/capacidade-instalada.aspx. [Accessed 23 June 2021].

[23] Operador Nacional do Sistema Elétrico - (ONS). O sistema em números. 2021, http://www.ons.org.br/paginas/sobre-o-sino-o-sistema-em-numeros. [Accessed 21 November 2021].

[24] Operador Nacional do Sistema Elétrico - (ONS). Histórico da Operação do SIN. 2021, http://www.ons.org.br/paginas/resultados-da-operacao/historico-da-operacao. [Accessed 26 June 2021].

[25] Governo do Estado de São Paulo. Decretos 2020–2021. 2021, https://www.saopaulo.sp.gov.br/coronavirus/quarentena. [Accessed 21 July 2021].

[26] Procuradoria Geral do Estado do Rio de Janeiro. Decretos 2020–2021. 2021, https://pge.rj.gov.br/covid19/estadual/decretos. [Accessed 21 July 2021].

[27] Secretaria de Estado de Saúde de Minas Gerais. Decretos 2020–2021. 2021, https://coronavirus.saude.mg.gov.br/decretos. [Accessed 21 July 2021].

[28] A. M. Arguição de descumprimento de preceito fundamental 672 - Descrição e Análises de Situações Até 2015;26(4):441–53.

[29] Zimmer V, Decker IC, Agostini MN. Disturbance location in the Brazilian electric power system using synchrophasors. In: 2013 IEEE PES Conference on Innovative Smart Grid Technologies. IEEE; 2013, p. 1-4.

[30] Goonalves CP, Ramos DS, Rosa PS, Balan MH, Cavalleri M, et al. The impact of COVID-19 on the Brazilian power sector: operational, commercial and regulatory aspects. IEEE Lat Am Trans 2021;100(1e).

[31] Nakada LYK, Urban RC. COVID-19 pandemic: Impacts on the air quality during the partial lockdown in São Paulo state, Brazil. Sci Total Environ 2020;730:139087.

[32] Leandro RB, e Silva AS, Decker IC, Agostini MN. Identification of the oscillation modes of a large power system using ambient data. J Control Autom Electr Syst 2022, https://sintegre.ons.org.br/sites/9/51/Produtos/516/2020-07-R1-ONS%20DPL-REL-0104-2020-20%20Restri%C3%A7%C3%B5es%20de%20AFerias%20para%20Processo%20de%20Otimiza%C3%A7%C3%A3o%20da%20Programa%C3%A7%C3%A3o%202022.pdf. [Accessed 04 February 2022].

[33] Operador Nacional do Sistema Elétrico - (ONS). Submódulo 9.7: Indicadores de qualidade de energia elétrica da rede básica. 2020, http://www.ons.org.br/Pub/SP/2020Programa%C3%A7%C3%A3o%20dA%20Sistema%20-%202q2020.pdf. [Accessed 04 February 2022].

[34] GDP drops 4.1% in 2020 and closes the year at R$ 7.4 trillion. 2021, https://agenciadonoticias.ibge.gov.br/en/agencia-press-room/2185-news-agency/releas6es-en/30169-pib-cai-4-1-em-2020-e-fecha-o-ano-em-r-7-4-trilhnes-2. [Accessed 17 November 2021].

[35] Instituto Nacional de Meteorologia - (INMET). Historico de Dados Meteorológicos. 2021, https://portal.inmet.gov.br/. [Accessed 28 June 2021].

[36] Procuradoria Geral do Estado do Rio de Janeiro. Decretos 2020–2021. 2021, http://www.stf.jus.br/arquivo/cms/noticiaNoticiaStf/anexo/ADPF672liminar.pdf. [Accessed 21 July 2021].

[37] Gomçalves CP, Ramos DS, Rosa PS, Balan MH, Cavalleri M, et al. The impact of COVID-19 on the Brazilian power sector: operational, commercial and regulatory aspects. IEEE Lat Am Trans 2021;100(1e).

[38] Apple Inc. Relatórios de tendências de movimentação. 2021, https://covid19.apple.com/mobility. [Accessed 19 November 2021].

[39] Câmara de Comercialização de Energia Elétrica - (CCEE). Boletim de Dados e Análises do Mercado. 2021, https://www.ccee.org.br/acervo-ccee?especie=39005&assunto=39116&keyword=Mercado%20mensal&periodo=365. [Accessed 26 November 2021].

[40] Empresa de Pesquisa Energética - (EPE). Resenha Mensal do Mercado de Energia Elétrica. 2021, https://www.epe.gov.br/pt/publicacoes-dados-abertos/publicacoes/resenha-mensal-do-mercado-de-energia-electrica. [Accessed 26 November 2021].

[41] Goonalves CP, Ramos DS, Rosa PS, Balan MH, Cavalleri M, et al. The impact of COVID-19 on the Brazilian power sector: operational, commercial and regulatory aspects. IEEE Lat Am Trans 2021;100(1e).

[42] Instituto Nacional de Meteorologia - (INMET). Historico de Dados Meteorológicos. 2021, https://portal.inmet.gov.br/. [Accessed 28 June 2021].

[43] GDP drops 4.1% in 2020 and closes the year at R$ 7.4 trillion. 2021, https://agenciadonoticias.ibge.gov.br/en/agencia-press-room/2185-news-agency/releas6es-en/30169-pib-cai-4-1-em-2020-e-fecha-o-ano-em-r-7-4-trilhnes-2. [Accessed 17 November 2021].

[44] Operador Nacional do Sistema Elétrico - (ONS). Relatório gerencial dos indicadores de frequência - DFP e DFD. RT-ONS DOP 0117/2021. 2021, Internal report.

[45] Operador Nacional do Sistema Elétrico - (ONS). Relatório de Síntese Gerencial de Perturbações Ocorridas no Sistema Interligado Nacional. RT-ONS DPL-REL 2021, Internal report.

[46] Operador Nacional do Sistema Elétrico - (ONS). Operação de Carga. 2021, http://www.ons.org.br/Paginas/sobre-o-sin/o-sistema-em-numeros.aspx. [Accessed 23 July 2021].

[47] Operador Nacional do Sistema Elétrico - (ONS). IO-CG.BR.01 - Controle da Geração em Condição Normal. 2022, http://www.ons.org.br/Paginas/comercializacao-de-energia-elétrica. [Accessed 21 November 2021].

[48] Operador Nacional do Sistema Elétrico - (ONS). O sistema em números. 2021, http://www.ons.org.br/Paginas/sobre-o-sino-o-sistema-em-numeros. [Accessed 21 November 2021].

[49] Câmara de Comercialização de Energia Elétrica - (CCEE). Boletim de Dados e Análises do Mercado. 2021, https://www.ccee.org.br/acervo-ccee?especie=39005&assunto=39116&keyword=Mercado%20mensal&periodo=365. [Accessed 26 November 2021].

[50] Van Overschee P, De Moor BL. Subspace identification for linear systems: theory—implementation—applications. Springer Science & Business Media; 2012.