Sociedade Brasileira de Automática (SBA)
XXV Congresso Brasileiro de Automática - CBA 2024, 15 a 18 de outubro de 2024

Dynamic Changes in the Models of Wind and Photovoltaic Power Plants in the ONS Electromechanical Database: After the Partial Black-out of August 2023

Bruno H. de A. Catão, IEEE Member *
Zulmar S. Machado Jr, IEEE Senior Member **
Robson Pires, IEEE Senior Member **

* *Companhia Energética de Minas Gerais - Distribuição S.A. (CEMIG) Belo Horizonte, MG 30190-924 Brasil (e-mail: bcatao@cemig.com.br).*
** *Universidade Federal de Itajubá - UNIFEI, Instituto de Sistemas Elétricos e Energia - ISEE Grupo de Engenharia de Sistemas - GESis Itajubá, MG 37500-903, Brasil (e-mail: zulmar@unifei.edu.br) e (e-mail: rpires@unifei.edu.br)*

Abstract: This work analyzes a very relevant and recent event in the memory of the Brazilian electricity sector, which was the partial black-out of 08/15/2023. The post-operation analyses of this event identified modeling flaws in wind and photovoltaic generators which meant that the database used until then behaved differently from the equipment in the field. This paper explores the suitability of system modeling for previously defined purposes and the reasons for the adjustments made to the ONS database for electromechanical transient studies so that it is representative of the various events to which the power system is subject.

Keywords: modeling, fault ride throught; phase locked loop; topology; wind and PV power plants.

1. INTRODUCTION

Power flow and short-circuit analyses are the initial analyses in electrical power system planning (EPS). After these initial studies, others are carried out to ensure that the EPS operation is stable and reliable, and one of these is the dynamic stability study according to Electricity Systems Expansion Planning Coordinating Committee (Comitê Coordenador do Planejamento da Expansão dos Sistemas Elétricos - CCPE *in Portuguese*) and the National Electricity System Operator (Operador Nacional do Sistema Elétrico - ONS), *in Portuguese*) CCPE (2002), ONS (2022).

For the development of this study, databases are used that contain the mathematical modeling of the electrical system. These databases are managed and maintained by government agencies in electrical sector, who normally perform the functions of operation and expansion planning, which in Brazil are ONS and the Energy Research Company (Empresa de Pesquisa Energética - EPE, *in Portuguese*). Among the bases used in the various studies is electromechanical transient simulation, the purpose of which, in a brief and simplified way, is to analyze and to determine the state and behavior of the network during major disturbances that affect the stability of the EPS within the Bulk Power System (BPS or National Interconnected System - SIN, *in Portuguese*).

In the production chain of the electricity system, different phases in which dynamic stability analyses are carried out stand out, namely: operational planning and expansion.

Considering operational planning, it is known that this has further subdivisions, namely: pre-operational and post-operational. However, recently, a very notable post-operation study within the BPS described the event that took place on 08/15/2023, a date that marked a partial "*black-out*" in Brazil, affecting the northeast and southeast regions of the country. This event began with the opening of the Quixadá terminal of 500 kV Quixadá-Fortaleza II transmission line (TL), followed by the opening of others 500 and 230 kV lines that make up the transmission grid in the following states: Bahia, Ceará, Maranhão, Piauí, Rio Grande do Norte and Tocantins.

The ONS's Disturbance Analysis Report (DAR) ONS (2023a) found that the lack of reactive power support from wind and photovoltaic power plants in the area of influence of the event caused the loss of a large block of load, leading the BPS to a voltage collapse and, therefore, a possible load shed of around 23,000 MW.

However, the DAR showed that there are differences between the results obtained from the mathematical models of the wind and photovoltaic power plants in dynamic studies and the oscillography records measured in the field. However, the performance trend of electricity system in the two situations, it was observed that the trajectories analyzed went in opposite directions, with the first restoring adequate operating conditions for the BPS and the second directing system towards an informed load shed in order to avoid even greater consequences.

By the conclusions obtained via the DAR, it was identified that one of main causes of *black-out* was mathematical modeling that differed from what is considered realistic for wind power plants, or Wind Farm (WF) and photovoltaic power plants (PV). Therefore, this paper will take a closer look at this issue.

This document is organized as follows: Section 2 will briefly describe the occurrence of August 15, 2023 in the

National Interconnected System. Section 3 will deal with the main considerations and objectives to be addressed in this work. Section 4 will present the dynamic models of wind and photovoltaic plants in the ONS database. Section 5, in turn, will highlight the characteristics of the ONS electromechanical database, as well as the modifications that should be suggested. Section 6 will show the statistics of the wind and photovoltaic plant models in the ONS database. Section 7 presents the simulations and performance comparisons of the wind and photovoltaic plant models. Finally, Section 8 will present the conclusions and suggestions for further research to deepen the studies carried out in this work.

It should be noted that *CEMIG Distribuição's* licenses to use the `Anarede` and `Anatem` programs were used for this publication.

2. BRIEF DESCRIPTION OF THE START OF THE 08/15/2023 EVENT IN BPS - BRAZIL

A detailed description of the partial *black-out* of 08/15/2023 is presented in ONS (2023a). The event began with the accidental opening of the TL 500 kV Quixadá-Fortaleza II, whose shutdown was caused by the accidental activation of the Switch Onto Fault protection, without there having been a fault that triggered this protection.

Following this first disconnection, the power flow was redistributed in the 500 and 230 kV networks interconnected to the Fortaleza II substation, which were subjected to a significant voltage drop. After 530 ms [milliseconds] from the start of the event, the power oscillation trip protection was activated on the TL 1 500 kV Presidente Dutra - Boa Esperança, located in the state of Maranhão and heading towards the border with Piauí. The power oscillation protection triggered the loss of synchronism function at Presidente Dutra, which led to the opening of the transmission systems between the North and Northeast regions.

The separation of these systems triggered the opening of several 230 kV TLs in the Northeast region, redistributing the power flow, which led to the opening of several 500 kV lines, since the BPS was in a fragile condition.

Most of the transmission line shutdowns occurred from the start of the event up to approximately 30 seconds, but there were other shutdowns from the start of the partial *black-out* within a time window of just over 7 minutes.

3. CONSIDERATIONS AND PURPOSE

During the construction of any project, there will be project uncertainties throughout its life cycle. This degree of uncertainty decreases as the project progresses. This is no different for generation projects. Definitions, such as the choice of equipment, are made as construction of the plant progresses.

Parallel to the implementation of a power plant, the process of interconnecting it to the electricity system is accompanied by uncertainties during its design phases, so that, once minimum performance requirements have been met, some uncertainties about which equipment will actually be used to generate energy are admissible.

In this way, a model used during connection studies can be a typical one that meets the minimum specifications required and is also in line with the expectations of the studies to be carried out ONS (2023b), NERC (2023). As an example, such uncertainties occur in the design of: typical models for medium and long-term expansion studies and access studies, manufacturer's models for pre-operational studies, and validated manufacturer's models for commissioning phases.

With regard to the models supplied by frequency converter manufacturers, it should be noted that, as a rule, these are kept secret by the suppliers, so there are no references to them in the public domain. Therefore, given the proportional nature of the object to be modeled with the purpose to be achieved in this article of exploratory and investigative characteristics (Silva and Menezes (2005)), some considerations are necessary for its elaboration.

Given the degree of secrecy surrounding the mathematical modeling of converter models supplied by manufacturers, and that for certain types of study it is possible to use typical models, the basic mathematical framework used for converters in this work will be the one developed for the generic models of the Western Electricity Coordinating Council (WECC) for photovoltaic generators and type 3 and 4 wind generator models.

4. WIND AND PHOTOVOLTAIC POWER PLANT MODELING

The topologies of modern wind power plants (WF) and photovoltaic power plants (PV) are generally similar, both using power electronic converters to deliver alternating current energy to the electrical system. The type of converter normally used in WF and PV is the Voltage Source Converter (VSC). Fig. 1 illustrates the macro structure of the plants mentioned.

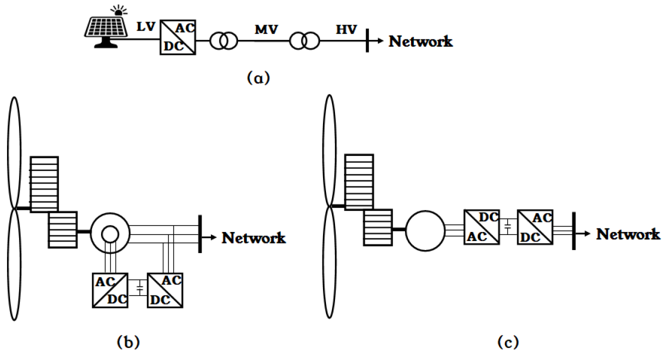

Figure 1. Topologies: (a) PV, (b) WF type 3 – DFIG, (c) WF type 4 – Full Converter. Source: (WECC and EPRI (2013); WECC (2019)), adapted by the authors.

For the plants under discussion, WECC has been developing models since around 2010, which are widely used in dynamic stability planning studies carried out by agents in the North American electricity sector. These models are divided into modules, which are common to both PV and WF, with the exception of WF type 3.

There are a total of three modules in common and one specific to WF type 3, due to the plant's different configuration. In summary, WF type 3 uses an asynchronous generator, whose rotor is connected to electrical system via an alternating current (AC) to direct current (DC) converter and this converter is connected to another DC-AC converter, which in turn is connected to the grid. As for the type 3 generator's stator, it is connected directly to alternating current grid. This generator is commonly referred to as a doubly-fed induction generator (DFIG). PV and WF type 4 generators are connected to the AC grid using converters.

According to reference WECC (2021), the modules of generic models developed by this institution are listed below:

- Renewable Energy Generator/Converter ($REGC_*$): models the generator itself and/or the converter and

ISSN: 2525-8311

DOI: 10.20906/CBA2024/4805

interfaces it with the electrical system. This module acts on the generator's real and imaginary current outputs to the grid;

- Renewable Energy Electrical Controls ($REEC_*$): responsible for the electrical controls at the level of the generating unit, either the wind turbine or the photovoltaic inverter. It acts on the output signals from the $REPC$ module, also using the negative feedback signal from the generator's terminal voltage and output power, delivering intermediate real and imaginary current signals to the $REGC$ module.
- Renewable Energy Plant Controller ($REPC_*$): controls the active and reactive power produced by the plant at the point where it connects to the electrical system. To do its job, the module uses output voltage and reactive power signals to process Volt/Var control and also uses frequency and active power signals at the point of common coupling (PCC) to control the active power generated;
- Wind Turbine Generators (WTGs): represent the mechanical controls of the type 3 wind generator, for example: turbine control, generator blade pitch control, torque control, among others.

Except for the WTG module, the asterisk at the end of the acronym of the other modules signifies the sub-type of each one, which can be used depending on the particularities of the plant under analysis and the resources available. Apart from the WTG module, Fig. 2 illustrates a block diagram for the generic WECC model.

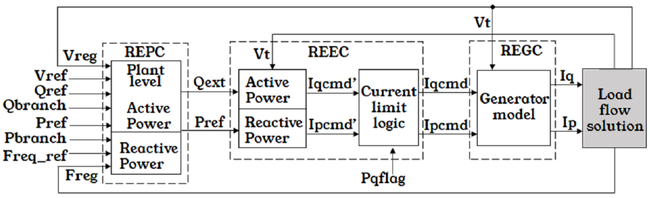

Figure 2. Block diagram for the generic WECC model. Source: WECC (2019), adapted by the authors.

The scope of this work does not aim to cover the generic WECC wind and photovoltaic power plant models in depth; more details can be found in WECC and EPRI (2013); WECC (2019); EPRI (2013).

Once the mathematical modeling of the dynamic components adopted by the plants targeted in this work has been defined, the next step is to incorporate them into a database, which contains not only the elements with static behavior, but also the others with dynamic behavior, which together are the input data for dynamic simulations.

In Brazilian case, the ONS (2023c) database, which includes all the dynamic and static elements, is compiled by the Brazilian Independent System Operator (ONS) in collaboration with the electricity sector agents, who provide information on the various equipment and installations via BPS and the high-voltage distribution systems that make up the supervision network.

The referenced database is systematically updated more than once a year. In addition, its revisions generally coincide with the four-monthly operational studies carried out by the ONS.

5. ONS ELECTROMECHANICAL DATABASE × MODIFICATIONS

In addition to modeling wind and photovoltaic power plants, the ONS electromechanical database includes dynamic modeling of hydroelectric plants, thermoelectric plants, HVDC links, among other elements whose behavior is modeled by differential equations.

According to the references ONS (2023b), ONS (2023d), the changes to the database for the dynamic models of wind and photovoltaic power plants aimed to take into account, more specifically, the following changes:

- Modifications to the Power Plant Control (PPC), which compared to the WECC models is equivalent to the $REPC_*$ module. This control has a slower response time than others in the converters and behaves more in line with existing controls in the field. The PPC was set to the constant reactive power control mode, which better represents the behavior of the devices in the plants in question.
- Changes were made to the fault current injection control in order to limit this resource to the capacity values of the PV and WF converters, since in the modeling of some plants the fault injection was set to values above the limit of the equipment; the injection actuation time was also adjusted, removing instantaneous injection responses.

5.1 Phased Locked Loop × PCC Control Dynamics

This section presents the theoretical basis for the changes made to the database used in this work.

A control that is present in any type of power plant is the one that synchronizes it with the electricity grid. In the case of WF and PV plants, this procedure uses a technique that currently is widely known as Phase Locked-Loop (PLL). Fig. 3 shows a simplified diagram of the connection of a VSC to the electricity grid, where you can see the interactions between some of the converter's control loops.

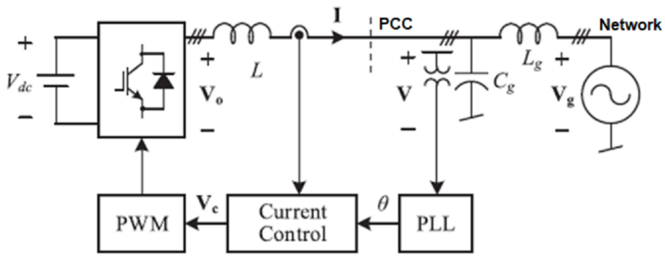

Figure 3. Single line diagram of a VSC's connection to the power grid. Source: Wang et al. (2018), adapted by the authors.

Considering how the PLL works, this is an algorithm that samples a signal at the PCC with the network. This signal is made up of frequency, phase and amplitude data. Through circuits that identify the phase and modulation error, a voltage signal is then produced in sync with the network JUNIOR and M.E.T.S. (2020).

Mathematically, when designing the PLL control block, the Park transform is used to change the reference of the three-phase system to an orthogonal system, so that the mathematical calculations of the control loop are made in two dimensions Yang et al. (2021). The PLL circuit includes a controller for stabilizing the signals, which commonly uses a proportional-integral (PI) or proportional-resonant (P+Res) controller JUNIOR and M.E.T.S. (2020), Wang et al. (2018).

Considering the references Yang et al. (2021) and Wang et al. (2018), it's shown that by applying the Nyquist criterion to the impedance modeling of converter (IM), the situations in which it'll work under stable conditions are verified.

The IM analysis takes into account the interactions between the converter circuit and the inductor and capacitor installed near the PCC.

Fig. 4 illustrates the behavior of the PLL control loop during a fault situation in an electrical system where a particular converter is operating.

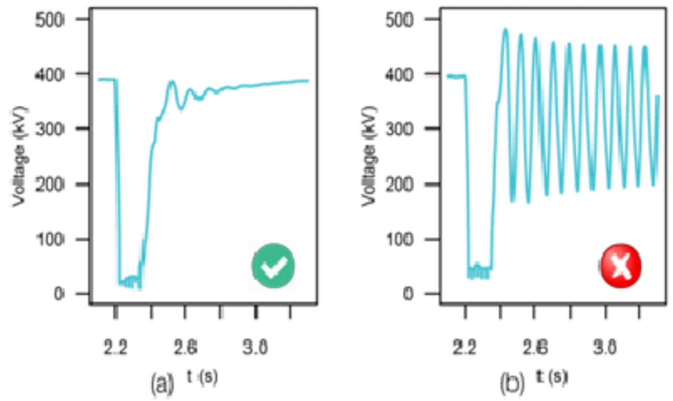

Figure 4. Converters operating with a PLL mechanism during a fault: (a) successful synchronization, (b) instability due to loss of voltage tracking during a fault. Source: GRID (2017).

In Fig. 4 (a) you can see the output voltage of a certain converter before, during and after a short-circuit in the network, where the PLL control loop functioned satisfactorily. In opposite to Fig. 4 (a), in Fig. 4 (b), also during a fault in the electrical system, the control loop of converter under analysis acted in an unstable manner, and the unstable behavior of the converter shown in Fig. 4 (b) can damage both the converter and equipment in the electrical network.

In order to avoid the instability illustrated, the gain margins of the PI or P+Res controllers are adjusted, using smaller gains that bring stable behavior to the converter.

In addition to lower gain values for the PLL control loop, the volt/var control of converters also uses low gain values in order to bring stability to the converter, hence the justification for the PPC to be set to the constant reactive power control mode CIGRE (2018).

When it comes to the PLL's performance in electromechanical stability studies, modeling this algorithm for studies of this nature is a simpler matter, since the dynamics of this control's performance is faster than the frequency of electromechanical transients, whereas for electromagnetic transient (EMT) simulations, detailed modeling of the PLL is required. According to CIGRE (2018), the simplified representation of the PLL algorithm in generic WECC models is found in the $REGC_*$ module.

5.2 Fault current injection

With the increase in inverter-based generating units (IBGs) in electricity systems, performance criteria and requirements for stable operation have been developed and improved over time. One of these criteria refers to the behavior of converter-based generation when faults occur in the systems.

As for the faults and protections inherent in the electrical system, it should be noted that IBGs have two types, namely: internal and external CIGRE (2018). Internal are those intrinsic to the integrity of the converter that are part of the devices that make up this, and external are those that observe the behavior of the network and act to minimize the impacts of both the network and the IBGs.

With regard to the internal protections of inverters, because this equipment can withstand very strenuous operating conditions, it's the practice of the manufacturers of these items to recommend sensitive adjustments to the internal protections. With this in mind, considering the binomial nature of the protection philosophies of equipment integrity and impact reduction, it has become necessary for electrical system operating agents to establish minimum operating requirements for IBGs.

In this sense, a certain analysis in the work developed in CIGRE (2018) compares the characteristics of conventional generation, based on synchronous generators, and generation based on IBGs. Conventional generation responds instantaneously to short-circuit situations, providing greater reactive power support to the system.

IBGs do not have the capacity to respond instantaneously to symmetrical or asymmetrical faults; there's a delay in the injection of current to support the short circuit, which is inherent in the physical devices that make up these instruments.

To this end, combining the electrical system's need to support reactive power with protection requirements, the scientific community specializing in EPS has created the so-called *Fault Ride Throught* curve, which relates the voltage value in the PCC to the time this parameter remains under certain values. Thus, during faults in the EPS, WFs and PVs are not allowed to disconnect from the grid if the voltage at the connection point is within the regions delimited in Fig. 5.

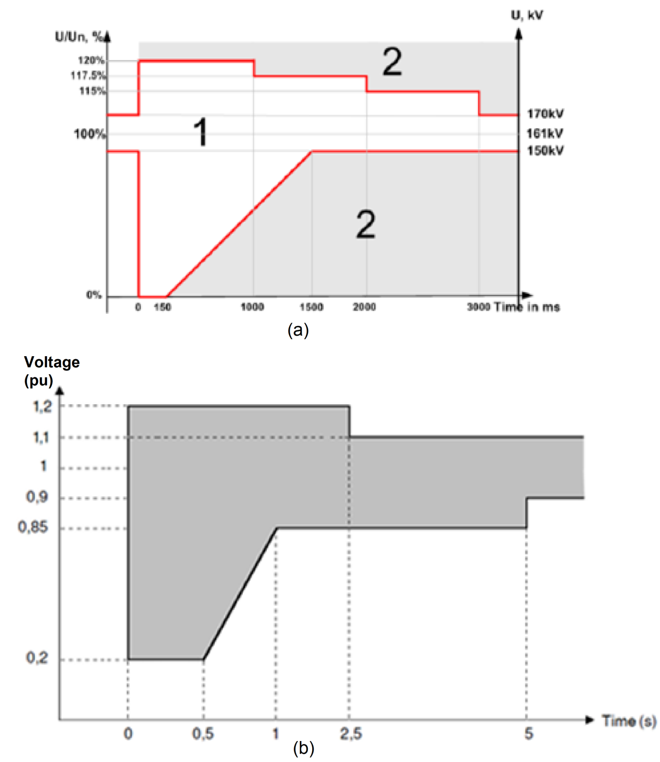

Figure 5. FRT curve: (a) curve adopted in Israel (b) curve adopted by ONS in Brazil. Source: (CIGRE (2018); ONS (2023e)).

The FRT curves illustrated in Fig. 5 comprise an upper and lower envelope, respectively called High Voltage Ride

Throught (HVRT) and Low Voltage Ride Throught. The areas demarcated by these indicates the operating region of the IBGs and, as can be seen by looking at Figs. 5 (a) and 5 (b), there are differences in the shapes of the curves shown, but in essence the reasons for these markings are the same.

A relevant factor to comment on regarding the FRT curve is that it defines the times when, from a voltage point of view, the IBGs must be connected to the grid and those when they are allowed to be disconnected Thengius (2020). Fig. 6 shows the current characteristic to be injected in fault situations on the grid, and how it can provide voltage support to the grid. Thus, in Brazil within the BPS, according to the reference ONS (2023e), the nature of current injection under faults is defined.

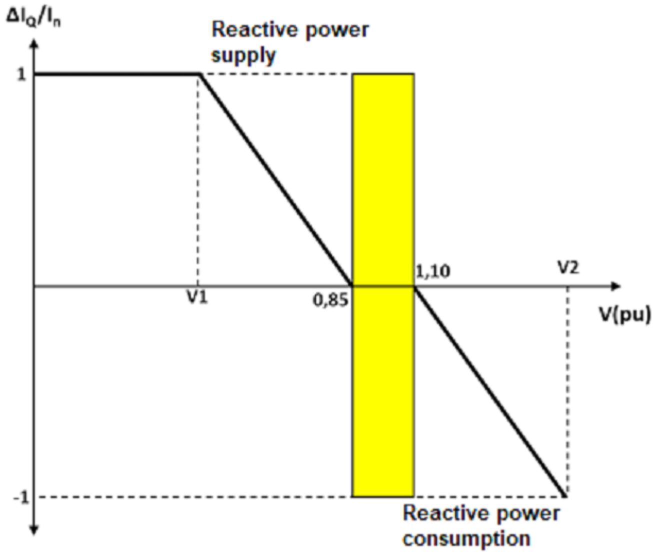

Figure 6. Requirement for reactive current injection in fault situations. Source: ONS (2023e), adapted by the authors.

The values of $V1$ and $V2$ in Fig. 6 correspond to 0.5 and 1.2 p.u. respectively. The yellow band indicates that the IBG is free to vary the injection current according to operational convenience.

According to the observations in Thengius (2020) and Weise (2014), another aspect that influences current injection is the k factor, which is the dependence that exists between the additional reactive current and the voltage deviation in the event of a fault. The k factor is adjusted in a PI controller of the converter and this influences the recovery of voltage sags during faults. As can be seen from the lower envelope of Figs. 5 (a) and 5 (b), the curve adopted in Israel has a lower slope, while the curve adopted in Brazil has a higher slope, where each is linked to the rate of increase of the current during the moment of a short circuit in the network.

According to the reference WECC (2019), the fault current injection command is related to the $REEC_*$ and $REGC_*$ modules.

6. DATABASE STATISTICS

In order to carry out a quantitative and qualitative analysis of the ONS (2023c) database, the database prior to the 08/15/2023 event, published in March 2023, was compared with the database published in November of the same year, after the aforementioned event, which included the changes reported at the beginning of Section 4. Figs. 7 and 8 show histograms of the number of wind and photovoltaic plant converter models in the database. The representation of converter models in the `Anatem` program is called topologies.

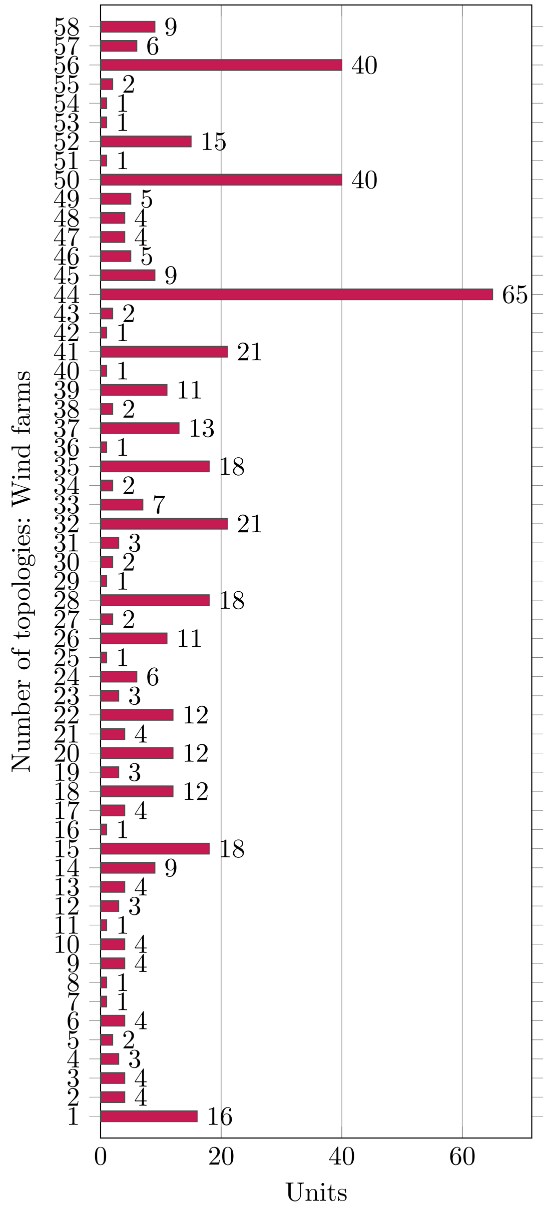

Figure 7. Histogram of the number of wind farm converter models.

The labels on the graphs in Figs. 7 and 8 have been omitted in order to make them easier to interpret. As can be seen, there are some topologies that stand out in terms of quantity compared to others.

There are a total of 58 topologies for wind power plants, the most common of which has 65 plants (topology 44) that use this wind turbine/converter and whose manufacturer is GE company, type DFIG, model *WTG DFG v3*. This model of converter/generator is being used on a temporary basis for future plants that are still undefined as to the equipment that will be used in them, but this topology meets the minimum requirements, according to ONS (2023e).

There are a total of 20 topologies for photovoltaic plants, the one that stands out the most has 77 (topology 12) plants using it. Through ONS (2023f) it was found that

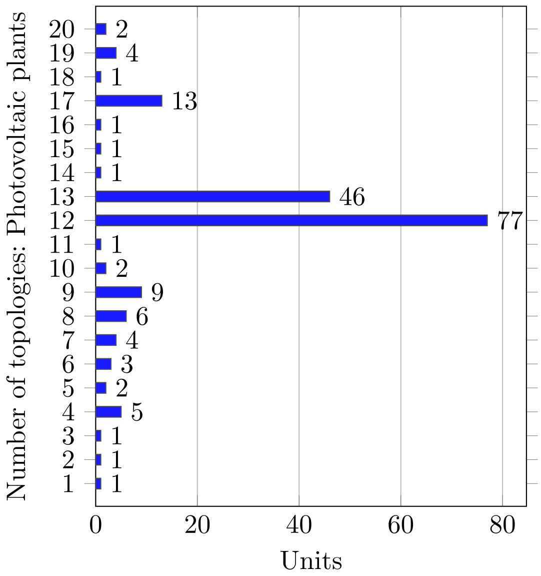

Figure 8. Histogram of the number of photovoltaic plant converter models.

this topology is being used for converter models from different manufacturers. It's therefore assumed that, just as a provisional topology was used for wind generators, the same procedure was adopted for photovoltaic plants.

It should also be noted that the number of WF and PV plant topologies in the March and November 2023 databases does not vary; both have the same number of generators and converter models. Therefore, based on the data collected, a performance analysis will be made of the topologies that are most present in the March and November 2023 databases.

7. COMPARISONS AND SIMULATIONS

Based on the statistics in the previous section, was took WF and PV converter models most present in the ONS (2023c) database and compared them to all the modeling of these topologies in the `Anatem` program.

To carry out the comparison, the UDC (User Defined Control) text files of the selected topologies were used and the free text editor program `Notepad++` was used to compare the files using the file comparison functionality, which easily shows the differences between them.

Differences were found in the control modes for WF and PV plant and in a minimum voltage parameter for the latter. In the March 2023 databases, both topologies are set to voltage control mode, while in the November databases, they are set to reactive power control mode.

A 5-bus test system was created in the program `Anarede`, by the authors themselves, which is shown in Fig. 9, whose image shows an operating point of this converged system.

The system in Fig. 9 is made up of two generators, with bus nº 1 being the reference bus and bus nº 2 where the IBG generation of 85 MW was allocated, there is also a 120 MW load with a 41 $Mvar$ capacitor bank compensating it. Based on this system and topologies 90763 and 95019, dynamic simulations were carried out considering a major disturbance in this system. A single-phase fault was simulated in bus nº 20, culminating in the loss of one of the transformers and one of the circuits feeding the load.

Fig. 10 shows the curves of the imaginary output current injected into the test system by the WF plant in bus nº 2,

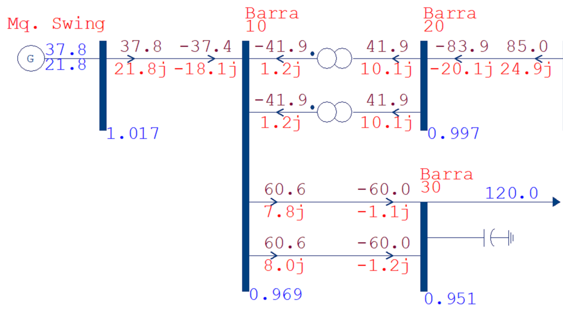

Figure 9. Converged operating point of the 5-bus test system.

with the red curve referring to the November 2023 base and the blue curve to March 2023. The IBG imaginary current variable was selected for plotting because it represents the effect of the additional reactive power that the converter will inject into the grid.

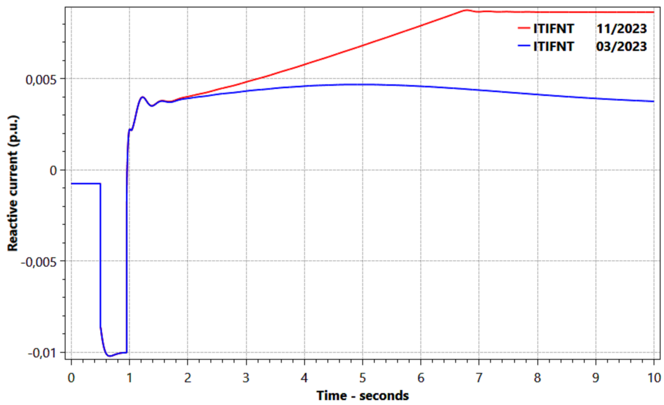

Figure 10. Curves of the imaginary terminal current injected into the test system by the WF considering the March 2023 and November 2023 modeling.

Examining Fig. 10, it can be seen that the imaginary current curves of the WF plant detach shortly after the fault is cleared, with the red curve growing in module and stabilizing after around 6 seconds. Figs. 11 and 12 show the reactive power generated by the IBG and also the voltage in the bus where it is connected.

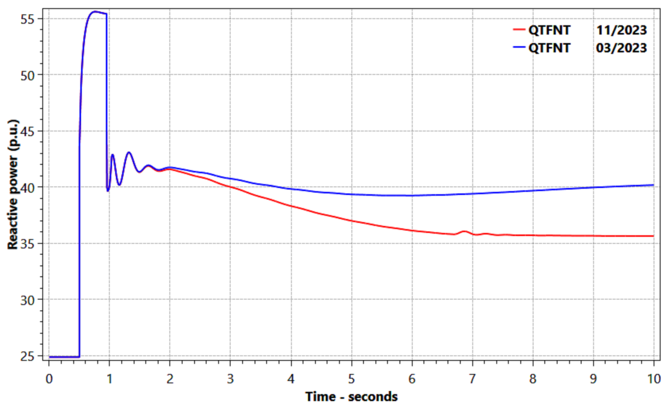

Figure 11. Curves of the reactive power generated by the WF, considering the modeling of March 2023 and November 2023.

The behavior seen in Figs. 11 and 12 of the reactive power and voltage is consistent with what was expected by the

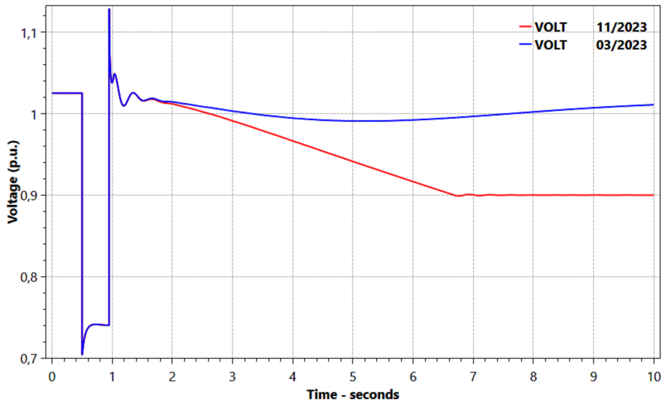

Figure 12. Voltage curves in the bus where the IBG is connected, considering the March 2023 and November 2023 modeling.

modifications to the database. A slower response from the converter was expected from the constant reactive power control mode and, in relation to the FRT curve, it can be seen that the IBG exploited its reactive power resource in such a way that the voltage obtained, after reaching steady state, was at its lower limit.

8. CONCLUSION

This work sought to explore the reasons for the modifications that were made to the ONS electromechanical simulation databases. Due to the size and proportions of this database, the tests were focused on the wind turbine converter, which is the one most present in the database, and satisfactory results were obtained.

One of the central themes of this article is converter modeling, which is currently a topic of fundamental importance for electrical studies, since it allows analyses to be carried out that can lead to predictability and reproducibility in the face of a wide variety of events.

ACKNOWLEDGEMENTS

For carrying out this work, I, Bruno Catão, would like to express my immense gratitude to my wife, Camila Lopes Malveira Catão, to Professors Zulmar Machado Jr and Robson Pires for their patience and trust, and also to CEMIG and UNIFEI for their support.

REFERENCES

CCPE (2002). Improving Processes and Methodologies for Transmission Expansion (Aperfeiçoamento dos Processos e Metodologias para a Expansão da Transmissão, *in Portuguese*), pages 22–30, Brazil.

CIGRE (2018). Modelling of Inverter-Based Generation for Power System Dynamic Studies, page 70, CIRED.

EPRI (2013). Proposed Changes to the WECC WT4 Generic Model for Type 4 Wind Turbine Generators, page 2, USA.

GRID, N. (2017). Performance of Phase-Locked Loop Based Converters, page 1, URL: National Grid.

JUNIOR and M.E.T.S. (2020). Study and Development of Control for Islanded and Grid-connected AC Microgrids, (Estudo e Desenvolvimento de Controle para Microrredes CA Ilhadas e Conectadas à Rede Elétrica, *in Portuguese*) pages 84–85, UFU, Uberlândia - Brazil.

NERC (2023). Dynamic modeling recommendations, recommended modeling practices and list of unacceptable models, pages 2–3, USA.

ONS (2022). Grid Procedures: Submodule 2.3, Assumptions, criteria and methodology for electrical studies - methodology (Procedimentos de Rede: Submódulo 2.3, Premissas, critérios e metodologia para estudos elétricos - Metodologia, *in Portuguese*), pages 4-5, Brazil.

ONS (2023a). Disturbance Analysis Report - Analysis of the Disturbance of 08/15/2023 at 08:30 a.m. (Relatório de Análise de Pertubação - RAP, Análise da Perturbação do dia 15/08/2023 às 08h30 min, *in Portuguese*), page 15, Brazil.

ONS (2023b). Workshop to Present Actions to Consolidate Data and Mathematical Models for Wind and Photovoltaic Plants (Workshop para Apresentação das Ações de Consolidação de Dados e Modelos Matemáticos de Usinas Eólicas e Fotovoltaicas, *in Portuguese*), Youtube, Brazil.

ONS (2023c). Electromechanical transients database for the anatem software (Base de Dados de Transitórios Eletromecânicos para o Programa Anatem, *in Portuguese*), Rio de Janeiro - Brazil.

ONS (2023d). New Electromechanical Transients Database (DB Anatem) Available after Event of 15.08.2023, News, (Disponibiliza Nova Base de Dados Base de Transitórios Eletromecânicos (BD Anatem) Após Evento do dia 15.08.2023, *in Portuguese*), Brazil.

ONS (2023e). Grid Procedures: Submodule 2.10, Minimum technical requirements for connection to transmission facilities, (Procedimentos de Rede: Submódulo 2.10, Requisitos técnicos mínimos para a conexão às instalações de transmissão, *in Portuguese*), page 30, Brazil.

ONS (2023f). DPL-REL 0214/2023 - Representation of Photovoltaic Generation in the BPS in Electromechanical Transient Analysis - Instructions and Data for Simulation (DPL-REL 0214/2023 - Representação da Geração Fotovoltaica no SIN nas Análises de Transitórios Eletromecânicos – Instruções e Dados para Simulação, *in Portuguese*), pages 9–37, Rio de Janeiro, Brazil.

Silva, E. and Menezes, E. (2005). Research Methodology and Dissertation Writing (Metodologia da Pesquisa e Elaboração de Dissertação, *in Portuguese*) - UFSC, page 21, Florianópolis - Brazil.

Thengius, S. (2020). KTH Royal Institute of Technology – School of Electrical Engineering and Computer Science. Fault Current Injection from Power Electronic Interfaced Devices, page 16, Estocolmo - Suécia.

Wang, X., Harnefors, and L. Blaabjerg, F. (2018). Unified Impedance Model of Grid-Connected Voltage-Source Converters, IEEE Transactions on Power Eletronics, Vol. 33 (nº 2), page 1776.

WECC (2019). Modeling and Validation Subcommittee, Solar Photovoltaic Power Plant Modeling and Validation Guideline, page 9, USA.

WECC (2021). RES Model Summary Guide, Brief Summary of all 2nd Generation Generic Renewable Energy System Dynamic Models, pages 1–3, USA.

WECC and EPRI (2013). Wecc Type 3 Wind Turbine Generator Model, Phase II, Proposed Changes to the WECC WT3 Generic Model for Type 3 Wind Turbine Generators, Practices and List of Unacceptable Models, page 2, USA.

Weise, B. (2014). IET Renewable Power Generation, Impact of K-factor and Active Current Reduction During Fault-Ride-Through of Generating Units Connected via Voltage-Sourced Converters on Power System Stability, page 26, Gomaringen, Alemanha.

Yang, Z., T., C., X., L., P., S., and W., D.R. (2021). Margin Balancing Control Design of Three-Phase Grid-Tied PV Inverters for Stability Improvement. IEEE Transactions on Power Eletronics, Vol. 36 (nº 9), page 10716.