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REVIEW

Dynamic Modeling Guidelines for Wind Power Plants: Australian Test Case

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ABSTRACT

As wind power generation increases, power system operators are challenged by the detailed modeling and simulation of wind power plants to realize the behavior and to maintain the stability of their power systems. In order to investigate the performance of the wind power plants, dynamic root mean square (RMS, 50 Hz phasor dynamics) and electromagnetic transient (EMT) models are very crucial with standards and guidelines. These dynamic models have been developed in the last two decades by the wind turbine manufacturers and plant and power system tool developers. In accordance with this progress, Australian Energy Market Operator (AEMO) has published a dynamic modeling acceptance test (DMAT) to assess the accuracy, consistency, and robustness of RMS and EMT models used for power system analysis. In this paper, DMAT is summarized to introduce how AEMO guides the modeling aspects of wind power plants in their power system. Additional inputs have been discussed to improve the modeling perspective for the future guidelines.

Index Terms—Dynamic modeling, grid codes, wind power plants, wind turbines

I. INTRODUCTION

Renewable energy is a type of alternative energy that is a candidate to solve problems of traditional carbon-based electricity generation regarding sustainability and ecology. Due to problems such as global warming, the reliability of energy supply, the accessibility of fossil resources, the limited diversity of energy sources, and fluctuations in energy prices, almost every country in the world has started to question the method of electrical energy production and accelerated the investments in renewable energy methods such as wind and solar energy (Fig. 1). First of all, there should be a good financial potential for the development of the electrical grid and the sustainability of the renewable energy investments. In addition, the power systems planned to be implemented must be suitable for the technical infrastructure in the region where it will be installed. The grid integration criteria to be provided for the technical infrastructure are specified in the grid code requirements of each country [1-3]. Grid codes vary from country to country, and they are technical documents for the electricity generation and consumption facilities created specifically for that country and global standards.

For island countries that do not have electrical connections to neighbor electrical grids, grid codes are more demanding compared to other grid code requirements. Due to their geographical conditions, the island power systems, which need to be self-sufficient in terms of energy balance, have been required to meet more stringent technical requirements for stable and reliable operation. Japan, UK, and Australia are examples of these island power systems. Although Australia has a geographically very large area among these island countries, human settlement and most of the energy needs of the country are on the west and south coasts (Fig. 2). Furthermore, the established and planned wind power plants with high wind potential are in the western and southern parts of the country [4]. Since the wind power plant to be established in these areas will have to transmit the electricity along long lines and there is a high probability of faults in these transmission lines as a result of various natural events, it is desired that the wind power plant to be established will meet challenging conditions regarding the fault management, voltage, and frequency control.

As a result of the advancement of the computing power of computers, power system analysis simulation tools results validated the real time power system behaviour, hence it is desired to report the simulation results of wind power plants as the pre-installation evaluation criteria at the application phase. In order to ensure that these criteria

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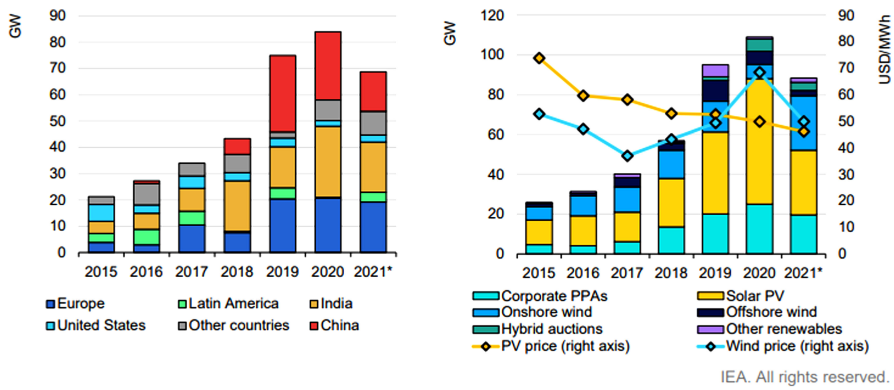

Fig. 1. Distribution of renewable energy investments between 2015 and 2021 according to regions and energy types [5].

are met, it is requested to certify the dynamic model acceptance test (DMAT) [6] results to the Australian Energy Market Operator (AEMO) during a project application phase. Dynamic model acceptance tests must be successfully carried out by all technology providers (conventional generators, wind turbines, and solar plants) and companies. Dynamic model acceptance tests, which will be explained in detail later, aim to show the performance of the dynamic models of the power plants during fault and normal operating conditions. The DMATs mentioned here will be performed for electromagnetic transient (EMT) dynamics and root mean square (RMS, 50 Hz phasor dynamics) models using the Power Systems Computer Aided Design (PSCAD) and Power System Simulation for Engineers (PSS/E) software. Some tests in DMAT require only EMT analysis, while some tests require analysis for both EMT and RMS models. In addition, RMS and EMT test results should be benchmarked in the DMAT report with the results.

In this paper, DMATs required by AEMO for the connection of power plants are explained in detail, and the tests during faults and normal operating conditions are summarized, respectively, in the second section. In the third section, the DMAT procedure is discussed regarding the parameters and information that are given in the DMAT and possible improvements in future DMAT releases for clarity. In the conclusion section, the difficulties in the Australia electricity grid, caused by Australian island country conditions, are briefly summarized. Furthermore, some of the Australian grid issues that can be used in Turkey, are summarized in the conclusion section.

Main Points

- This study revealed the effects of weak grids on the performance of power plants.
- It analyzes the importance of Dynamic modelling of power plants at grid integration.
- It analyzes the impact of the steady-state operation and fault conditions at wind farm level in EMT and RMS models.
- It discusses for future requirements and studies in Turkish Power System.

A. Grid Codes and Dynamic Model Acceptance Tests

When a wind power plant is connected to the transmission system, some of the technical capacities of the wind turbine have to comply to specific requirements which are published by countries' transmission system operators (TSOs). These technical requirements usually named as grid codes. Grid codes have an important role in sustaining the stability and reliability of transmission systems. The advantages of the conventional power plants are the inertia of the generator, voltage backup to the grid during faults, and power synchronizing. Because of these advantages, power plants having synchronous generators help to create sustainable and reliable electrical power grids. However, inverter-based resources do not have not the same capabilities. Grid codes define the operation ranges of frequency and voltage. Active and reactive power controls are checked with grid codes. With fault ride through and reactive current injection requirements, grid codes define adequate and stable performance for wind power plants during grid disturbances.

Furthermore, wind power plant operation must be stable and predictable during both grid disturbances and normal operating

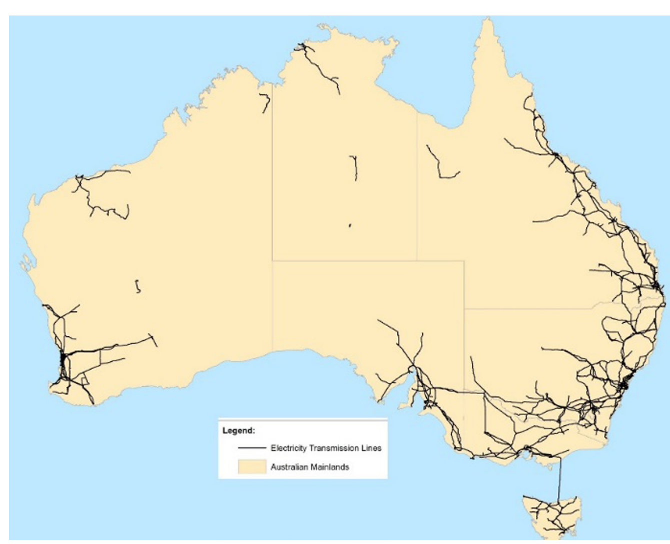

Fig. 2. Map of Australia power transmission lines [7].

conditions without any problems. There are frequency and voltage operating ranges that wind power plants should operate without changing their active and reactive power outputs. In addition to these ranges, there are limited and sudden disconnection operation ranges to protect both wind power plants and the power systems [6]. Since reactive power and voltage dynamics are closely correlated, through voltage control of the wind power plant, reactive power capability can be realized and can support the power system.

While grid codes differ from country to country and TSO to TSO, countries are updating their grid codes and additional technical requirements. One of the examples for this country is Australia. The Australian electricity grid, one of the island electricity grids that is not interconnected to operate, is undergoing a transformation because of the increased connectivity of renewable energy sources and energy storage systems. Compared to conventional power grids that have mostly synchronous generators, wind, and solar power plants with power electronics (converter and inverter based) interfaces react differently to failures and changes in the electricity grid [3]. Considering these different reactions, there are different electricity grid regulations for wind and solar power plants. The experience gained after failure during the operation of the wind farms in operation in Australia requires that these network regulations be updated over time. During these updates, AEMO requires both EMT and RMS dynamic models from all power plants to model the entire electrical power system and to predict future problems. When requesting these models, it is necessary to perform the tests in DMAT before the power plants' grid connection. The aim of the challenging conditions required in the simulation is to observe the performance of power plants in the weak grid condition that may be encountered in the island power systems. The definition of a weak grid is often understood by looking at the low short circuit rate (SCR) value. Short circuit rate is the ratio of the short circuit power of the power plant at the connection point to the nominal power of the power plant [(1) and (2)].

$$SCR = \frac{Scc(MVA)}{Pn(MW)} \tag{1}$$

$$SCR = \frac{Sb(MVA)/Xpu}{Pn(MW)} \tag{2}$$

S_b and P_n are equal $X_{pu} = \frac{1}{SCR}$

Although the common calculation method of SCR is mentioned above, there are three other SCR calculation methods. Equivalent short circuit ratio (ESCR) is preferable when the wind plant to be evaluated does not share connection point with other wind plants (3).

Composite short circuit ratio (CSCR) can be preferable when the wind power plant shares medium voltage (MV) connection. Specifically, in this case, both power plants are directly summed, and evaluation is done as they are single elements (4).

Weighted short circuit ratio (WSCR) can be employed for checking the contribution of each plant to the power system (5).

$$ESCR = \frac{Scc(MVA)}{Pn(MW) + \sum_{j} MIIF_{j,i} Pn_j}, \tag{3}$$

where $MIIF_{j,i}$ is a participation factor that $MIIF_{j,i} = \frac{\Delta Vi}{\Delta Vj}$

$$CSCR = \frac{Scc_i(MVA)}{\sum_i Pn_i(MW)} \tag{4}$$

$$WCR = \frac{\sum_i^N Scc_i(MVA) Pn_i}{(\sum_i^N Pn_i()^2} \tag{5}$$

Table I details all methods and provides a comparison of all of them [8].

In general, electrical systems with SCR 3 or below are considered as weak grids [9]. Extra tests have been added within the DMAT to ensure that wind power plants in particular are likely to obtain stability issues in weak grids and to see the performance of these power plants planned to be built in Australia. While SCR values of 14 and 10 are used for performance as a normal network condition, it is desirable to analyze models for SCR value 3 and below for the performance of the same tests.

For preparation DMAT results, the model of the power plants must be modeled in the computer environment (PSCAD and PSS/E software) with the electrical model of wind turbine grid connection given in Fig. 3 and perform many different scenarios completely and stably. In the DMAT, it is requested to analyze many different scenarios such as FRT (fault ride through) performance, active power, reactive power, the attitude of the control system in the model against changes in voltage reference, observation of the effect of frequency

TABLE I.
COMPARISON OF DIFFERENT SCR CALCULATION METHODS

Index	Simplicity	Determine Maximum Capacity of a Specific Bus	Consider Other Plants Adjacent	Considers STATCOM or SVC
SCR	++	++	X	X
ESCR	X	X	++	++
CSCR	+	+	+	X
$WSCR_{MW}$	+	X	++	++
$WSCR_{MVA}$	+	X	++	X

++, high; +, medium; X, low.
CSCR, composite short circuit ratio; ESCR, equivalent short circuit ratio; SCR, short circuit ratio; WSCR, weighted short circuit ratio.

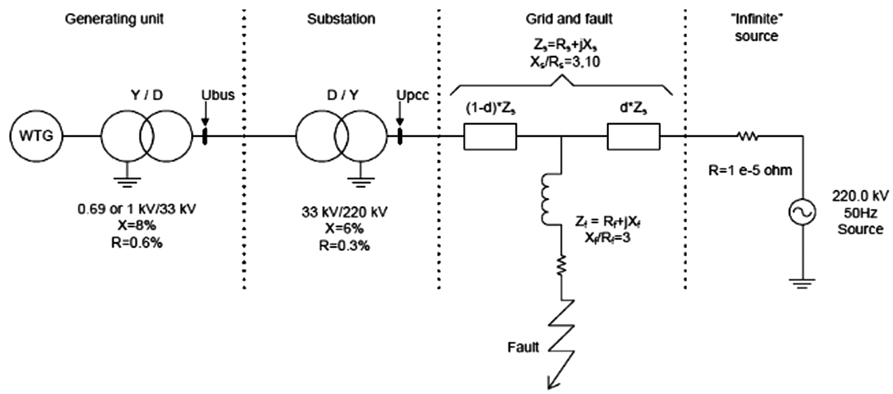

Fig. 3. Wind turbine dynamic modeling acceptance test diagram.

changes in the model, how the model will perform in the weak network conditions. In the DMAT setup (Fig. 3), the signals that should be recorded and analyzed as the outputs of the simulation are indicated in Table II.

Fault ride through is a test scenario in which wind power plants must sustain the fault conditions and support the power system even for very low voltage levels. For checking these scenarios, after the grid disturbance occurs and the voltage dip happened at Point of Common Coupling (PCC), wind turbine would stay connected and after the fault cleared, it must return to its initial operating point condition. After having the simulation results of the FRT test cases, the performance of the model should be evaluated considering the grid connection requirements and the performance.

Dynamic modeling acceptance tests such as active power reference, voltage reference, and reactive power reference tests are purposed to check wind power plant controller response together with wind turbine model against reference changes. Moreover, some of the power reference tests are requested at a very low SCR grid (SCR = 1). For changing the input power of the wind turbine with changing wind speed, the dynamics of the model for following the active power reference is tested in DMAT.

TABLE II.
IMPORTANT SIMULATION OUTPUT SIGNALS

Active Power	Active Power Reference	Reactive Power	Reactive Power Reference
Inside turbine voltage	Outside turbine voltage	Grid frequency	Active power current
Active power current reference	Reactive power current	Reactive power current reference	Total current
Negative sequence current	Negative sequence voltage	Negative sequence current reference	Terminal voltage
Terminal voltage phase angle	Rotor speed	One-phase terminal RMS voltage	

RMS, root mean square.

Additionally, the frequency tests in DMATs are proposed over an extended range of the nominal operating points. Wind power plant response against temporary frequency deviations under and over the nominal frequency value has been captured applying these frequency tests. Dynamic modeling acceptance tests include additional and unique tests due to Australia's unique geographic conditions. With these additional test cases, wind power plant's low SCR capability is tested and analyzed for its sustainable performance.

B. Three-Phase Balanced Fault Ride Through Cases

In this DMAT scenario, it is aimed to assess the response of the wind power plant model during and after a three-phase fault of 0.43 and 0.5 s. The active power reference of the wind power plant is 1 pu and 0.05 pu, and the reactive power reference value is 0, 0.3, and –0.3 pu. The SCR values are 3–10, and the *X*/*R* (ratio of the reactance value to the resistance value at the connection point) values are specified as 3, 10, and 14 to form the strong and weak operating conditions of the power system. In total, 36 simulations are required using different combinations of parameters considering the SCR, *X*/*R*, active power, reactive power reference, voltage reference, fault impedance, and fault duration.

C. Unbalanced Fault Cases

For unbalanced fault situations (phase-to-phase, two phase-to-ground, and single phase-to-ground), it is aimed to observe the behavior of the wind power plant model considering various active and reactive power references. In general, the fault durations are 0.43 s, but for some of the specific cases, the line-to-line fault duration is 2 s. As it can be understood from this long fault duration, the model should be tested in extreme cases. In these cases, the performance of the wind power plant model should again be reported with different combinations of active power reference, reactive power reference, *X*/*R* and SCR values, and fault impedance parameters.

D. Multiple Fault Ride Through Test Cases

Due to the extreme weather events (e.g., lightning strikes) in Australia, there had been a large number of consecutive faults on the transmission lines. These multiple faults caused disconnection of wind power plants and endanger the operation of the Australian

TABLE III.
MFRT RANDOM EVENT SELECTION FOR EMTP MODEL TEST

Randomly Created	
Fault type	6× 1 PHG, 7 × 2 PHG, 2 × 3 PHG
Fault duration (ms)	8× 120 ms, 6× 220 ms, 1× 430 ms
Time between recurring events (s)	0.01, 0.01, 0.2, 0.2, 0.5, 0.5, 0.75, 1, 1.5, 2, 2, 3, 5, 7, 10
Fault impedance	7× $Z_f = 0$, 5 × $Z_f = 3 \times Z_s$, 3 × $Z_f = 2 \times Z_s$

MFRT, multiple fault ride through.

power system. Therefore, the wind power plants have been required to sustain the multiple fault ride through (MFRT) operation. The variable number of consecutive faults, which occur at different times, is selected from the values specified in Table III. The main aim is to show the sustainable operation of the wind power plant model together with the control and protection systems.

E. Temporary Overvoltage Test Cases

The performance of the wind power plant model, which is operating at 1 pu, is tested against the overvoltage situations for the level of 1.15 pu voltage of 0.9 s and 1.2 pu voltage for 0.1 s. These overvoltage test scenarios are set up by activating the capacitor group after the PCC to the grid side. The reactive power reference was determined as 0, 0.3, and –0.3 pu. The SCR values of the over-voltage testcases are 10, 3 and the actual SCR value of the region where the project is going to be installed, the *X*/*R* value is 14, 3 and the actual *X*/*R* value of the project site.

F. Voltage/Reactive Power/Power Factor Reference Change Test Cases

During the 45-s simulation, the wind power plant model reacts to the 5% voltage rise and fall (Figs. 4 and 5) that will occur in the grid voltage and wind power plant's voltage reference change. In addition to these tests, the performance of the model is considered after the increase and decrease of 0.3 pu in the reactive power and power factor reference. In each reference scenario, SCR values set to 10, 3 and project-specific SCR value, X/R values set to 14, 3 and project-specific X/R value.

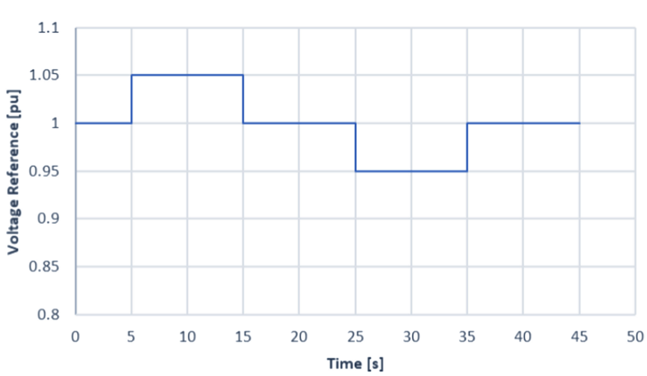

Fig. 4. Five percent reference voltage change or grid voltage change.

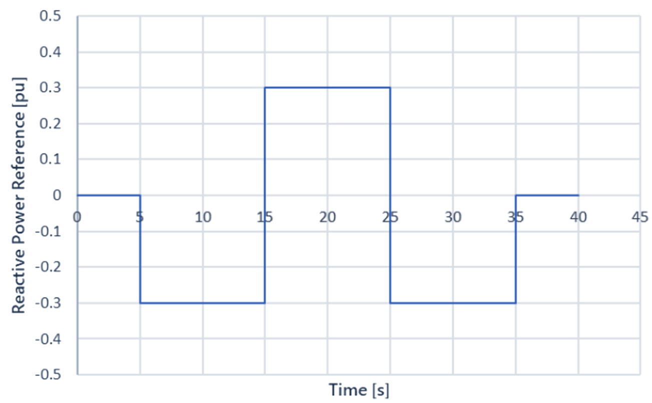

Fig. 5. Reactive power or power factor reference change.

G. Active Power Reference Change Test Cases

In these test cases where the active power starts from 1 pu, the capacity of the active power to follow the reference is changed by gradually setting the active power reference to 0.05 and 0.5 pu (Fig. 6). Reactive power reference is kept constant at 0 and 1 pu for this test case. Three test cases are proposed, with SCR and X/R combinations being 10 and 14 and 3 and 14, respectively, including also the actual PCC values.

H. Grid Frequency Change Test Cases

Grid frequency change tests are proposed according to a 2 Hz increase and to a 3 Hz decrease in network frequency with different rates. Furthermore, test cases are created by setting the potential power that the wind power plant can produce as 5%, 50%, and 100% and setting the active power reference differently. For 2 Hz increase scenarios, the active power reference is set to 0.05 and 0.5 pu, and for a frequency drop of 3 Hz, the active power reference is set to 0.05, 0.5, and 1 pu. The aim of this test case scenario is observing whether the results of frequency changes are that the system follows the active power reference (Figs 7 and 8).

I. Grid Voltage Oscillation and Angle Change Test Cases

These are the cases created to test the response of the wind power plant model to 10-s oscillations in the grid voltage with different

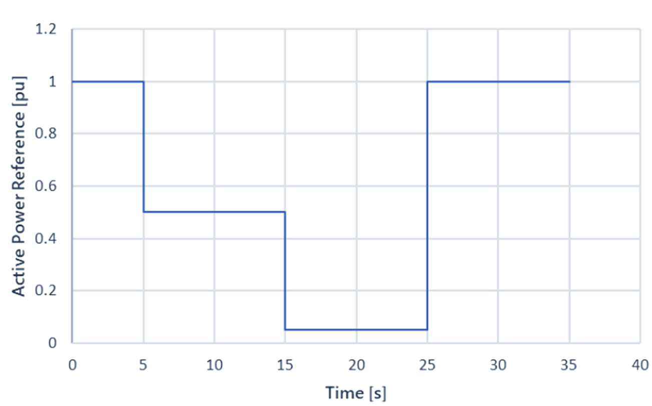

Fig. 6. Active power reference.

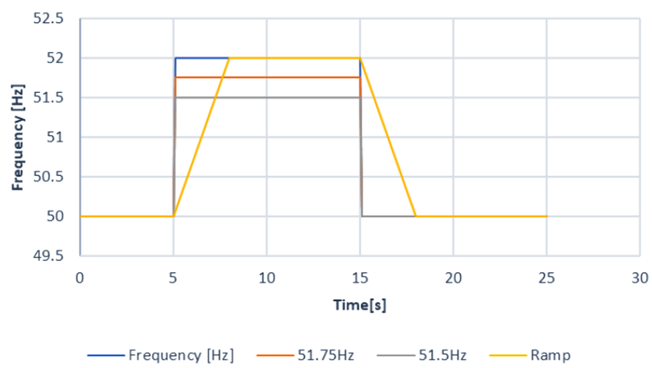

Fig. 7. Grid frequency test—overfrequency.

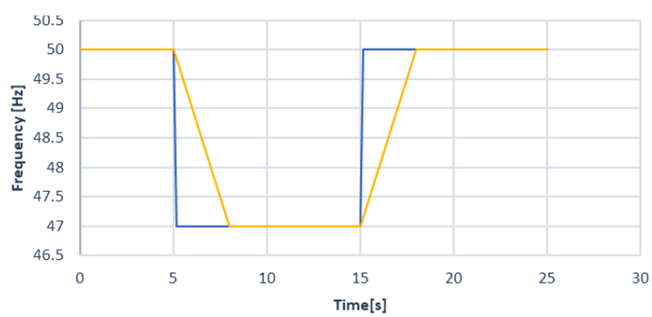

Fig. 8. Grid frequency test—underfrequency.

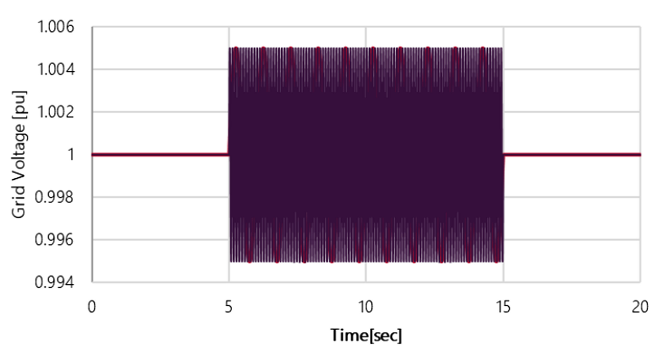

Fig. 9. Oscillatory rejection tests (example of 1–10 Hz in steps of 1 Hz per modulation).

oscillation frequencies. For 10 s, nine different cases from 0.1 Hz to 0.9 Hz and additionally 45 different oscillations from 1 Hz to 45 Hz are listed (e.g., Fig. 9).

J. Wind Speed Change Test Scenarios

When the active power reference is set to 0.5 and 1 pu, a 20% increase and decrease in input source (wind speed variations) is tested to see if the model can follow the active power reference. These tests are important for the control performance when the available power is different from the active power reference value during the simulation duration. For normal operating conditions, active power reference will follow the available power coming from the actual wind speed value. However, if there is a need for active power curtailment according to market conditions, a frequency control requirement, or a contingency as an immediate action, the control performance is very important.

K. Test Cases for the Low Short Circuit Rate at the PCC

These are cases where the X/R value is set to 3 and 10 when the SCR value is selected as 1, and the active power reference is proposed to start from 0.05 pu and gradually increase to 0.2, 0.4, 0.6, 0.8, and 1 pu, respectively. These cases are special tests for wind power plants' connection to the South Australia region. This population density of South Australia is not as much as eastern part of the country. Thus, most of the generated electrical power should be transmitted with longer transmission lines. Long transmission lines create weak grid conditions for the wind power plants in South Australia. Together with the extreme events and faults, wind power plants must obtain the expected minimum SCR value conditions in DMAT. One of the purposes of these cases is to observe the maximum power that the wind power plant can sustain a stable operation with the given low SCR value. In addition to the test cases which have same SCR value during the simulation, additional test cases have been required to understand how the wind farm will perform when the SCR value changes after the fault (e.g., reducing it from 3 to 1 as an example of N-2 tripping a line after a fault). In these additional cases, it is aimed to observe that, at severe fault conditions, wind power plant's protection and control systems activated and deactivated properly.

II. DISCUSSION

Australian Energy Market Operator prepared the DMAT guidelines to assess the accuracy, consistency, and robustness of dynamic models with a wide scope according to the specific characteristics of both the weak grid, the normal grid, and the grid where the turbine will be installed. However, the operating conditions of the power plants can be defined in more detail. For example, while the SCR values and X/R values of the tests are defined precisely, the parameters such as fault type, fault duration, fault impedance, active power reference, reactive power/voltage/power factor reference, and the operating conditions on the electrical network side can be defined also in terms of the grid voltage magnitude. Another important point is to define or give a range for the power plant transformer's tap changer settings depending on the load flow. At the same reactive power reference, there can be different cases when the combination of the tap change, the grid voltage, and the PCC voltage magnitude. They all affect the load flow.

Since wind power plants consist of tens of turbines, instead of modeling the performance of the whole power plant individually with each turbine, it is aimed to model it as a single aggregated wind turbine model. However, the methodology in DMAT is not specified whether it will be on the low-voltage side of the wind turbine or on the medium-voltage side at the collector grid of the power plant. When the saturation curve is modeled in both unit and power plant transformers, the aggregated and detailed models might have different results especially in EMT simulations.

III. CONCLUSION

The transition from conventional to renewable energy generation has been progressing to reach sustainable and clean power system goals. Among the renewable energy, wind energy is the prominent way with the efficiency and the wind resource distribution. The integration of the power plants into power systems is important for a stable and reliable operation. The grid codes and requirements are very crucial and should be progressive. Although the grid codes that vary from country to country are shaped according to the specific conditions of the countries, the technical conditions and the desired criteria that are not available in other countries provide new ideas in creating and strengthening the network control and operations. Since the simulation models contain sufficient information about the performance and capability of the power plants, they are required in the pre-evaluation of the power plant application in Australia.

The DMATs are required by AEMO to guarantee the robustness and functionality of the power plant models before the grid connection. DMAT can be accepted as ambitious sets of tests, since the details of test cases, and their compliance requirements are not the same for the other power systems in the world. Although it does not have an island network operation like Australia, in Turkey, the DMATs can give ideas for the future progress of the renewable energy and provide benefits by performing simulations of possible faults and events with the help of RMS and EMT simulation environments. Because of the simulation results that are close to the real performance of the power plants for the normal and transient conditions, the measures to be taken will be determined, and possible solutions will be produced in advance. In this way, time and cost savings will be realized.

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