Wind turbine model validation based on state interval and error calculation

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Abstract: In order to simulate and evaluate wind farm low-voltage ride through capability, wind turbine should be modelled and simulated as real-life system operation. In this paper, a validation method based on state interval and error calculation is proposed. The model validation specified in domestic and international standards is introduced. The necessity of steady- and transient-state interval definition is analysed through wind turbine transient behaviour research. Meanwhile, allowed tolerances are studied by wind farm simulation and comparison, using wind turbine models with different behaviours. A double-fed induction generator (DFIG) wind turbine model is validated and the results show that the proposed method with different tolerance in steady- and transient-state intervals is suitable for wind turbine model validation.

1 Introduction

The electrical behaviours of wind farm such as low-voltage ride through (LVRT) capability are specified in the grid codes [1]. The wind turbine LVRT capability can be tested with the short circuit emulator. However, this kind of test cannot be performed for wind farm, because the testing equipment is not available and economical for the large capacity and high voltage. The wind farm model simulation is the mainstream method for wind farm LVRT capability assessment. Thus, as the most important component of wind farm, wind turbines have to be modelled precisely. In order to verify the wind turbine model operation corresponds to the real-life system operation, the models should be validated with measured data.

Each wind turbine should be modelled in detail for wind farm LVRT simulation. Normally, a typical wind farm in China has more than 30 wind turbines. Electromagnetic transient (EMT) models are not proper for so many wind turbine models operating simultaneously, because of the computational complexity and efficiency. Electromechanical transient (RMS) models are widely used in power system studies for dynamic simulation. It is adequate to analyse the wind farm LVRT characteristics by RMS model generally. The validation method studied in this paper is mainly used for RMS model.

In order to give a common method for model validation, International Electrotechnical Commission (IEC) has published a standard that specifies the wind turbine models and model validation process [2]. Several countries, such as China, Germany and Spain, issued the standard for wind turbine model validation as well [3–5].

Besides the study of wind turbine generic model, the WECC Modelling and Validation Working Group also made efforts on model validation research. As a summarisation of ad hoc task force on wind generation model validation, the concept of model validation was described, and some examples with different validation methods were introduced, but the definition of allowed tolerance was not mentioned [6]. In [7], German model validation approach was implemented to show that the validation approach can be applied both to balanced and unbalanced faults effectively. In [8–10], the wind turbine models were studied and validated according to German and Spanish standards. The validation methods were adopted for modelling, but have not studied on the method details, like the necessity of steady- and transient-state interval and allowed tolerance definition, which are researched on this paper.

This paper is organised as follows: In Section 2, IEC 61400-27-1, NB/T 31053, FGW-TR4 and PVVC standards for wind turbine model validation are introduced. The wind turbine model validation method is studied in Section 3. Three aspects are discussed: the requirement of measurement data, the necessity of steady and transient interval in grid fault and recovery period, and the allowed tolerances definition by wind turbine active and reactive current/power influence analysis. Section 4 shows the feasibility of proposed method through a typical DFIG wind turbine model validation. Finally, Section 5 summarises the conclusions.

2 Validation method in different standards

2.1 IEC 61400-27-1

The standard in [2] specifies wind turbine modelling and validation procedures. In the standard, the validation focuses on voltage dips, reference point changes and grid protection, which is used to show the accuracy of wind turbine model for grid stability analysis. For voltage dip validation, the balance and unbalance dips should be validated with measured data. The measured data can be divided into three windows:

\begin{itemize}
  \item $W_{\text{pre}}$ is the pre-fault window covering the time period from $t_{\text{begin}}$ to $t_{\text{fault}}$.
  \item $W_{\text{fault}}$ is the fault window covering the time period from $t_{\text{fault}}$ to $t_{\text{clear}}$.
  \item $W_{\text{post}}$ is the post-fault window covering the time period from $t_{\text{clear}}$ to $t_{\text{end}}$.
\end{itemize}

where $t_{\text{fault}}$ is the fault time of voltage, $t_{\text{clear}}$ is the clear time of voltage dip, generally $t_{\text{begin}} = t_{\text{fault}} - 1000$ ms and $t_{\text{end}} = t_{\text{clear}} + 5000$ ms.
Meanwhile, two steady-state intervals are defined because of the EMTs of wind turbine LVRT process.

- $W_{\text{faultQS}}$ is the quasi steady state part of the fault window.
- $W_{\text{postQS}}$ is the quasi steady state part of the post-fault window.

The voltage dip windows are shown in Fig. 1. The main method of validation is to calculate maximum error (MXE), mean error (ME), and mean absolute error (MAE) between simulation results and measurement data of active power, reactive power, active current and reactive current. The calculated error values and calculation windows are summarised in Table 1. The allowed tolerances of errors are not defined in IEC standard.

### 2.2 Chinese standard NB/T 31053

For wind farm LVRT simulation, the Chinese standard NB/T 31053 [4] was published in October 2014. The standard specifies wind turbine model validation procedure including error calculation method and tolerances. Similar to IEC 61400-27-1, test data are also divided into three windows – pre-fault, fault and post-fault window. The errors include maximum error (MXE), mean error (ME), mean absolute error (MAE) and weighted mean absolute error (WMAE). WMAE is a global error based on a weighted average value over the entire LVRT-test. The MAE should be calculated both in steady- and transient-state intervals.

The NB/T 31053 defines the different tolerances of active power, reactive power and reactive current errors in different periods as shown in Table 2.

### 2.3 German standard FGW-TR4

German standard FGW-TR4 also defines three windows for LVRT procedure, and transient/steady-state intervals [3]. The differences with Chinese standard have two points, one is FGW-TR4 also defined the negative sequence validation tolerance which is two times of Table 3. The other is the mean absolute error is not stipulated in FGW-TR4.

### 2.4 Spanish standard PVVC

Spanish standard ‘Procedure for verification and certification of the requirements of the PO 12.3 on the response of wind farms and photovoltaic plants in the event of voltage dip’ (PVVC) also specifies the validation method to verify the accuracy of wind turbine model [5]. The active or reactive power errors are calculated as expression (1). If more than 85% of the absolute errors are not exceeding 10%, the model can be declared as validated.

\[
\Delta \varepsilon(\%) = \frac{|x_{\text{measurement}} - x_{\text{simulation}}|}{x_{\text{nominal}}} \times 100 \leq 10\% \quad (1)
\]

### 2.5 Comparison

The validation methods are compared as follows:

- The test and simulation data are divided into pre-fault, fault and post-fault window in IEC 61400-27-1, NB/T 31053 and FGW-TR4.
- The tolerance bands are defined in NB/T 31053, FGW-TR4 and PVVC, except IEC 61400-27-1.
- The errors in transient state interval are specified as well as steady-state interval in NB/T 31053 and FGW-TR4, but not calculated in IEC 61400-27-1. There is no transient- and steady-state definition in PVVC.

### 3 Model validation method study

#### 3.1 Measurement data

The LVRT measurement set-up is shown in Fig. 2. $Z_1$ is the serial impedance to minimise the impact on grid during voltage dip. $Z_2$ is the short-circuit impedance to make short circuit at wind turbine side. Three-phase voltage and current are measured at the point MP1. Data at MP1 avoid the influence of transformer model and

### Table 3 Tolerance of error in FGW-TR4

| Data     | $\Delta P/P_n$ | $\Delta Q/P_n$ | $\Delta I_a$ |
|----------|----------------|----------------|-------------|
| $x_{\text{MRE}}$ | 0.07 | 0.05 | 0.07 |
| $x_{\text{MET}}$ | 0.20 | 0.20 | 0.20 |
| $x_{\text{MAES}}$ | 0.10 | 0.25 | 0.20 |
| $x_{\text{MAET}}$ | 0.25 | 0.25 | 0.30 |
| $x_{\text{MXES}}$ | 0.15 | 0.10 | 0.30 |
| $x_{\text{WMAE}}$ | 0.15 | 0.15 | 0.15 |

$x_{\text{MRE}}$ is mean error in steady-state intervals, $x_{\text{MET}}$ is mean error in transient-state intervals, $x_{\text{MAES}}$ is mean absolute error in steady-state intervals, $x_{\text{MAET}}$ is mean absolute error in transient-state intervals, $x_{\text{MXES}}$ is maximum error in steady-state intervals, $x_{\text{WMAE}}$ is weighted mean absolute error over the entire LVRT-test.

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**Fig. 1** Voltage dip windows

**Fig. 2** Diagram of LVRT measurement

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reflect the wind turbine behaviour directly. If it is difficult to measure this point (some transformer of wind turbines are setup on the nacelle), measured data at MP2 can be used for model validation.

Unsymmetrical fault is the major fault type in power system. Symmetrical fault is the most severe impact on traditional power system. The grid code specified both symmetrical and unsymmetrical fault requirements for wind farm. So the measurements need to be carried out in balance and unbalance fault. The requirements of wind farm LVRT capability normally focus on power and current in positive sequence. The voltage, active power, reactive power, active current and reactive current in fundamental positive sequence are the main concerned variables for model validation.

3.2 State internal definition

To verify the model with the same initial condition as real wind turbine, pre-fault window should be included in validation process. On the other hand, it is also necessary to validate post-fault window to make sure the model performs recovery behaviour as real-life. Then, the LVRT process for validation normally includes pre-fault, fault and post-fault window.

There are two electromagnetic transitions in the LVRT process which are caused by voltage dip and recovery. Taking the DFIG transient characteristics as an example, the stator flux will oscillate when grid voltage dip \[11, 12\]. Then, the stator flux contains DC component and also negative component when the unsymmetrical fault happens. Figs. 3 and 4 show the measured stator current in time domain and frequency attributes at symmetrical fault happens and clears moment. The DC components in Figs. 3b and 4b are presented obviously, which is difficult to simulate in RMS model.

Owing to the high speed of generator, the slip ratio is large according to DC and negative component in stator flux. The rotor voltage and current will increase due to the large slip ratio. This transient response at rotor side is also difficult to simulate in RMS model as the stator flux EMT is ignored.

It can be concluded that RMS model cannot simulate the transient behaviour accurately as stationary behaviour. The transient and steady interval should be validated separately. Thus, the fault window and post-fault window can be divided into transient- and steady-state interval. The error of transient- and steady-state interval should be calculated separately. The requirement of model accuracy in transient interval needs to be lower than steady interval.

3.3 Allowed tolerance

How to define the model adequacy for wind farm simulation is an important issue for model validation. The influences of wind turbine active and reactive current/power on wind farm LVRT behaviour are analysed by wind farm simulation, to give advice on tolerance band definition.

3.3.1 Simulation model: A wind farm is modelled in detail, with an equivalent external grid. There are two radial feeders in this wind farm, with 60 MW installed capacity in total. Each feeder has 12 wind turbines connected in a string. The short circuit capability of grid is set to 270 MVA.

A controlled current source is modelled to simulate wind turbine, which is used to analyse the effect of active current and reactive current behaviour to wind farm LVRT capability. The current controller gives variable current reference; thus, the wind turbine active current and reactive current can be represented as needed. The current control model is shown in Fig. 5. It notes that the model is not a wind turbine mathematical model, so the simulation results are not as fluctuated as real wind turbine operation.

The requirements of wind farm LVRT capability include three aspects in GB/T 19963-2011 \[1\]:

![Fig. 3 Time domain and frequency attributes of stator current at voltage dip](image)

- **Fig. 3 Time domain and frequency attributes of stator current at voltage dip**
  - a Time domain
  - b Frequency domain

![Fig. 4 Time domain and frequency attributes of stator current at voltage recovery](image)

- **Fig. 4 Time domain and frequency attributes of stator current at voltage recovery**
  - a Time domain
  - b Frequency domain

![Fig. 5 Current control model for wind turbine](image)

- **Fig. 5 Current control model for wind turbine**
Wind turbines do not trip-off during specified low voltage at wind farm POI.

The increase speed of active power after fault clearance should not be <10% of rated power per second.

The reactive current injection behaviour during fault should fulfil the grid code requirement.

Owing to the effect between voltage and power, the wind turbine voltage fluctuates according to power flow. If the terminal voltage is high or low enough, the wind turbine may trip-off. It is necessary to simulate the power and voltage exactly as real wind farm, to give a conclusion whether the wind turbine may trip-off or not. The credibility of conclusion is based on the model accuracy. So the power of wind turbine should be validated to make sure the error of active and reactive current/power will not lead to big deviation of voltage. The allowed tolerances are studied from this aspect.

3.3.2 Reactive current influence to voltage: The simulation results are compared when wind turbine models perform different reactive current injection during fault and transient response at voltage recovery period.

**Reactive current in steady-state interval:** A short-circuit fault is simulated as 20% \( U_n \) voltage dip. The reactive current injection value during fault is set to 1, 0.93, 0.86 and 0.79 p.u., respectively. The active power is 1 p.u. and reactive power is 0 before fault. During fault, the active power is set to 0. The current and voltage simulation waves are shown in Fig. 6. From the simulation, it is shown that every 0.07 p.u. reactive current deviation will make 0.16 p.u. voltage change at the wind turbine terminal, which means that if the error between simulation data and measurement data is 0.07 p.u., it will make 0.16 p.u. error of voltage.

**Reactive current in transient-state interval:** Fig. 7 shows the effect of reactive current transient response to wind turbine voltage. If wind turbines consume reactive power because of transient operation such as crowbar switch on, the voltage at wind turbine terminal may be <0.2 p.u. Wind turbine LVRT is not required if the terminal voltage <0.2 p.u. normally. So the wind farm may not realise the LVRT capability because of wind turbine low-voltage protection. On the other hand, when the fault clear, if reactive current cannot decrease because of control delay, the voltage maybe >1 p.u. and lead to over voltage protection. So it is necessary to define the error tolerance in transient-state interval to make the simulation convinced.

Figs. 8 and 9 show the comparison of different reactive current response at voltage dip and recovery transition. The deviation of each reactive current at the peak value is 0.1 p.u. Owing to the short duration of reactive current during transient interval, the effect on the voltage is not as big as steady-state interval. Thus, the allowed tolerance of transient interval can be defined a larger value than steady interval.

3.3.3 Active current influence to voltage: Active current in steady-state interval: A short-circuit fault is simulated as 20% \( U_n \) voltage dip. The initial active power of wind turbines is 1 p.u., and initial reactive power is 0. There is no reactive current injection...
then, the active current during fault is set from 0 to 1 p.u. by 0.1 p.u. increasingly. The active current, voltage and active power waves are shown in Figs. 10 and 11. The voltage is changed by active power deviation due to reactive power consuming of transformers, transmission lines and other electrical devices. It can be seen that the bigger active power and current, the larger impact on voltage of 0.1 p.u. active current difference. For example, 0–0.1 p.u. active current deviation can make 0.001 p.u. variation of voltage, 0.9–1 p.u. active current deviation can make 0.02 p.u. variation of voltage. It means that if the active current error between simulation and measurement is 0.1 p.u., the voltage error is 0.01–0.02 p.u. in this wind farm.

Active current in transient-state interval: Fig. 12 shows the effect of active power transient response to wind turbine voltage. It is shown that the lack of active power will lead to voltage increase after fault clearance. The over voltage protection may be tripped if the voltage exceeds 1.1 p.u. for a certain time. So the error of active current/power should be calculated and limited in a certain value. Due to the transient simulation problem, the requirement of active current in transient state interval cannot be as strict as steady-state interval.

4 Example of wind turbine model validation

According to Chinese standard NB/T 31053, a software platform for model validation is developed. A DFIG wind turbine RMS model is validated by simulation and measurement data. An example of model validation results is presented when the medium voltage of wind turbine dip to 0.2 p.u. for 625 ms.

Based on the test data, the test and simulation are divided into three windows: A (pre-fault), B (during fault) and C (post-fault). B and C windows have steady and transient intervals. The MXE, ME, MAE and WMAE are calculated for each interval. The errors are shown in Fig. 13. The red lines in error figures of
Fig. 13 are the tolerance bands. The blue lines in error figures of Fig. 13 are the errors. The blue lines are below the red lines, showing a good matching between simulation and measurement data. The results show the practicable of method for model validation.

5 Conclusions

In this paper, wind turbine model validation methods are studied and a typical wind turbine model is validated. Based on the research, it can be illustrated that model validation is a feasible method to verify the wind turbine model accuracy for wind farm LVRT capability assessment.

Normally, the wind turbine LVRT measurement data including voltage, active power, reactive power, active current and reactive current in fundamental positive sequence are essential for validation. Due to EMT behaviour of wind turbine at voltage dip and recovery moment, it is very difficult to simulate transient characteristics with RMS model. The transient interval should be distinguished from steady interval. Meanwhile, from the simulation study, it is shown that the transient response simulation is necessary for wind farm LVRT simulation. The allowed tolerance of active and reactive current error should be different between the two state intervals. In this paper, the research of tolerance is based on a wind farm simulation with a weak grid. The influence of simulation errors on wind farm LVRT verification should be studied in future research.

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