Analysis of Harmonic Propagation and Coupling among Wind Farm Groups

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Abstract. Although wind energy itself has the conditions of large-scale development and utilization, power quality has always been the focus and difficulty of wind power generation. Harmonics generated by power electronic equipment in doubly-fed generators may lead to overheating damage and faults of transmission lines and transformer equipment. To improve the safe operation and harmonic control ability of power grid and reduce the loss of electrical equipment, a model of double-fed wind farm group with voltage level of 690V/35kV/110kV was established in Matlab/Simulink. By analyzing the characteristics of harmonic propagation and coupling between wind farms under different conditions, it is found that when the harmonic source was on the fan side, the harmonic is transmitted from the fan side to the grid side. If the harmonic content of wind power station is large, it will have a greater impact on power quality. In addition, due to harmonic coupling, 110 kV bus current has the highest harmonic distortion rate and the highest harmonic content.

Keywords: doubly-fed wind turbine; doubly-fed wind farm group; harmonic propagation; harmonic coupling.

1. Introduction

With the large-scale use of transformers, rotating electrical machines and power electronics in wind power plants, the harmonic hazards caused by non-linear loads are attracting more and more attention from the industry. Harmonics are also increasingly becoming a problem that cannot be ignored in the field of wind power[1]. Regardless of domestic and foreign, harmonic problems have long attracted the attention of practitioners and scholars in the power industry, and have also achieved many achievements.

Foreign research results: The literature [2] through the establishment of a non-traditional doubly-fed wind turbine generator model, simulation analysis, can more intuitively show the impact of harmonic distortion on power quality. Literature [3] outlines the improvement of harmonic evaluation methods based on large-scale wind farms, and also analyzes harmonic phenomena. Literature [4] analyzed the harmonic characteristics of wind farms. Literature [5] discusses whether the harmonics generated by fixed-speed wind turbines are affected by wind speed.

Domestic research results: The literature [6] discusses the use of MATLAB and PSCAD simulation software to simulate the single-number and multi-number DFIG grid-connected cases, and obtain the difference of harmonic currents at the grid-connected points and analyze and distinguish them. Literature [7] discusses the problems existing in the grid connection of single-fan and multi-fan in large-capacity doubly-fed wind power generation system, and proposes a method to solve the problem...
of grid connection. The literature [8] discusses the relationship between the propagation characteristics of harmonics and the voltage level and the relationship between the harmonic transfer coefficient and the harmonic order. Reference [9] discusses the basic relationship between harmonic voltage propagation and voltage level.

According to the research status at home and abroad, wind farm harmonics research mainly focuses on the localization of internal harmonic sources [10], the influence of electric field voltage level on harmonics and the harmonic propagation characteristics of transmission lines in electric field. From the macro point of view, the study of harmonic propagation and coupling among wind farm groups is relatively rare.

In this paper, based on MATLAB/SIMULINK, wind farms with different capacities are built to form two wind farm groups, and the fast Fourier transform of each wind farm current waveform is performed. By comparing the harmonic amplitude, it can be obtained that when the harmonic source is measured by the fan, the harmonics are transmitted from the fan side to the grid side, which will increase the harmonic current of each power generation field in the power grid and increase the current distortion rate. For wind farms with small installed capacity, the sudden increase of harmonic current content of the power grid has a significant impact on the power quality. The harmonic superposition and cancellation phenomenon between the multi-harmonic sources, harmonic stacking on the 110kV bus bar in this experiment, the current harmonic distortion rate is the largest, and the current with the highest harmonic content is generated.

### 2. Harmonic Current Permissible Value of Power Grid

In order to ensure the quality of power, countries have promulgated national standards to limit the harmonic content in the power grid to the normal operation of the power system. The allowable harmonic currents of public power grids are shown in Table 1 below.

#### Table 1. Harmonic current permissible value of public grid.

| Standard voltage/kV | Reference Short Circuit Capacity/MVA | Harmonic frequency and allowable value of harmonic current/A |
|---------------------|-------------------------------------|----------------------------------------------------------|
| 0.38                | 10                                  | 78 62 39 62 26 44 19 21                                 |
| 6                   | 100                                 | 43 34 21 34 14 24 11 11                                 |
| 10                  | 100                                 | 26 20 13 20 8.5 15 6.4 6.8                              |
| 35                  | 250                                 | 15 12 7.7 12 5.1 8.8 3.8 4.1                            |
| 66                  | 500                                 | 16 13 8.1 13 5.4 9.3 4.1 4.3                            |
| 110                 | 750                                 | 12 9.6 6.0 9.6 4.0 6.8 3.0 3.2                           |

For harmonic analysis, it is necessary to understand the current distortion rate. The formula for calculating the total current harmonic distortion rate is as follows:

$$THD = \frac{1}{I_1} \sqrt{\sum_{n=2}^{\infty} I_n^2} = \sqrt{\left(\frac{I_{rms}}{I_1}\right)^2 - 1}$$  \hspace{1cm} (1)

In the formula, $I_1$ means the peak value of fundamental current.

### 3. Wind Farm Group Modeling

Based on the DFIG model that comes with MATLAB/SIMULINK, five wind farms are built to construct two wind farm groups (the wind farm group capacity is 27MW and 22.5MW respectively). The grid voltage is 690V/35kV/110kV and the frequency is 50Hz. The wind farms are connected to the common grid to form a wind farm group. The wind farm and its parameters are shown in Table 2.
Table 2. Wind farm installed capacity and wind speed distribution.

| Wind farm name | Installed capacity (MW) | Rated wind speed (m/s) |
|----------------|-------------------------|------------------------|
| Wind farm A    | 12                      | 10                     |
| Wind farm B    | 9                       | 5                      |
| Wind farm C    | 6                       | 8                      |
| Wind farm D    | 15                      | 9                      |
| Wind farm E    | 7.5                     | 7                      |

The wind farm A, the wind farm B, and the wind farm C are combined into a wind farm group A; the wind farm D and the wind farm E are combined into a wind farm group B.

4. Prediction Model

Since the wind speed is random in the wind farm, in order to get closer to the actual operating conditions of the wind turbine, a white noise module is added based on the rated wind speed.

4.1. Analysis of Harmonic Characteristics of Doubly-fed Wind Farm Group

Firstly, running the wind farm group model. In order to obtain the harmonic characteristics of the wind farm group, the wind farm output working waveform and the wind farm group grid current waveform are analyzed. The results are shown in the Fig. 1.

In Fig. 1, a, b, c, d and e respectively represent 690V bus FFT harmonic analysis of wind farm A, wind farm B, wind farm C, wind farm D and wind farm E; f and g respectively represent wind farm groups A and wind farm group B 35kV bus FFT harmonic analysis; h map shows 110kV grid point FFT harmonic analysis. Because it is in normal working state, the harmonic content of the bus bars at all levels is very small, and the distortion rate is also very low. The power quality of each power station and grid side meets the requirements.

The waveforms obtained under normal working conditions are analyzed, and the distortion rate of the bus bars at the same time is statistically tabulated in the table 3:

Table 3. Distortion rate on bus under normal working conditions.

| Bus Bar            | THD%  | Bus Bar                  | THD%  |
|--------------------|-------|--------------------------|-------|
| Wind farm A (690V) | 0.96  | Wind farm E (690V)       | 2.30  |
| Wind farm B (690V) | 2.49  | Wind farm group A (35kV) | 0.88  |
| Wind farm C (690V) | 2.34  | Wind farm group B (35kV) | 1.37  |
| Wind farm D (690V) | 2.08  | Connecting point (110kV) | 0.93  |
4.2. Analysis of Simulation Results of Harmonic Propagation in Wind Farm Group

In order to analyze the harmonic propagation law of harmonics in the wind farm group, the distribution of the 3rd and 5th harmonics of each bus bar in the wind farm group model is observed after the 3rd and 5th harmonic sources are injected into the wind farm A. The simulation results are as follows Fig. 2 shows.

![Harmonic Amplitude Graphs](image)

**Figure 2.** Wind farm current spectrum analysis.

In Fig.1 and Fig.2, each FFT harmonic analysis map still corresponds to the same 690V/35kV/110kV bus. Because the wind farm A generates the 3rd and 5th harmonics, the 3rd and 5th harmonics in the harmonic analysis itself are very high. In the harmonic analysis of the Wind farm group A bus (35kV) and the 110kV grid point of the wind farm group, it can be seen that the content of the 3rd and 5th harmonics is significantly higher than the normal working state.

The distortion rate of the bus bars at the same time is taken for statistical calculation in the table 4:

| Bus Bar                  | THD% | Bus Bar                  | THD% |
|--------------------------|------|--------------------------|------|
| Wind farm A (690V)       | 4.95 | Wind farm E (690V)       | 6.88 |
| Wind farm B (690V)       | 8.28 | Wind farm group A (35kV) | 3.76 |
| Wind farm C (690V)       | 8.47 | Wind farm group B (35kV) | 5.66 |
| Wind farm D (690V)       | 5.26 | Connecting point (110kV) | 3.81 |

Making two sets of data into Fig.3 to compare and analyze:

![Comparison Graphs](image)

**Figure 3.** Current distortion rates under different states of wind farm.

By comparing and analyzing the distortion rate, it can be seen that when the 3rd and 5th harmonics are emitted by the wind farm A, the current distortion rates in the wind farm line increase a lot. At the same time, the harmonic current of wind farm A is not only propagated from the fan side along the
690V line to the wind farms B and C, but also through the 35kV bus to another wind farm group B, resulting in increasing THD up to 5%, even to 8%. And the grid connection point has also increased. Obviously, the harmonics of wind farm A also affect the working state of other wind farms to some extent and the power quality is seriously polluted. In this way, it can be judged that when the harmonic source is on the fan side, the harmonics are transmitted from the fan side to the grid side. When the harmonic content of the fan side is large, the power quality of the entire power grid is greatly affected, and this result agrees with the principle of harmonic propagation.

4.3. Analysis of Harmonic Coupling Simulation Results of Wind Farm Group

In order to analyze the coupling law of harmonics in the wind farm group, after injecting the 3rd and 5th harmonics in the wind farm A and the wind farm D, it can observe the node currents of the 35kV bus and the 110kV bus of the grid, especially the 2nd, 3rd, 4th and 5th harmonics distribution, the simulation results are shown in Fig.4:

The diagrams of a and b show 35kV bus FFT harmonic analysis, c shows the 110kV bus FFT harmonic analysis of the grid connection point. It can be seen from Fig.5 that the harmonic content of the 110kV bus bar increases sharply, because of the 3rd and 5th harmonics in each wind farm group. Except for the fundamental wave, the amplitudes of the 2nd, 3rd, 4th and 5th harmonics are very high. Taking the distortion rate of the 35kV bus bar and the 110kV bus bar of the grid point at the same time for statistical calculation.

Table 5. Bus bar distortion rates.

| Bus Bar                      | THD% |
|------------------------------|------|
| Wind farm group A (35kV)     | 5.84 |
| Wind farm group B (35kV)     | 6.41 |
| Connecting point (110kV)     | 9.88 |

Figure 5. Current distortion rate of wind farm groups under different conditions.

It can be seen that the electric energy of the whole power grid is seriously polluted. The distortion rate of 110 kV current at the grid-connected point is nearly 10%. The normal working state of the grid side is seriously affected.
5. Conclusion
In this paper, based on the principle of harmonic propagation and coupling, the simulation of harmonic propagation and coupling between electric field groups in MATLAB/SIMULINK environment is carried out, and the following conclusions are obtained:
(1) Under normal working conditions, the FFT fast Fourier transform is used to decompose 690V, 35kV and 110kV bus current waveforms in MATLAB/SIMULINK environment. Then the 3rd and 5th harmonic sources are injected into the wind farm A, and the fast Fourier transform is used to harmonize the bus current waveforms of all levels again in MATLAB/SIMULINK environment. By comparing and analyzing the distortion rate THD, it can be found that the harmonic current of wind farm lines propagates from the fan side to the grid side. When the harmonic content of the fan side is large, the power quality of the grid will be greatly affected. With the inflow of common bus, its amplitude and harmonic number show a weakening trend along the line.
(2) By injecting 3rd and 5th harmonics into wind farm A and D and decomposing 35kV and 110kV bus current waveform, it can be found that the current waveform contains higher 2nd, 3rd, 4th and 5th harmonics, resulting in the coupling superposition of harmonics, that is, all harmonic coupling superimposed together, resulting in the current with the highest harmonic content, and generates new harmonic components at the same time. By comparing and analyzing the distortion rate THD, it is found that the harmonic content in the fault line is very large, which will not only affect the current of buses at all levels, but also increase the current harmonic content of adjacent wind farms. The current distortion rate THD of the whole power grid will increase, which will affect its safe and stable operation.

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